Gauge-Mediation of Supersymmetry Breaking in String Compactifications

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SLAC and Stanford

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Abstract

Based on

- hep-th/0512170 w/ D.-E. Diaconescu, S. Kachru and P. Svrček
- work in progress w/ S. Kachru, J. McGreevy and N. Saulina

1. Overview

- Introduction
  - Gauge mediation versus gravity mediation
  - Embedding of gauge mediation scenarios into string theory
- Field Theory Models with Dynamical Supersymmetry Breaking
  - Dynamical supersymmetry breaking in quiver gauge theories
  - Noncalculable models of supersymmetry breaking
- Fractional Brane Supersymmetry Breaking and GUT Models
  - F-theory geometry
  - Dual heterotic compactification
- String Theory Embeddings of the Noncalculable Models
  - Heterotic bundles construction
  - Dual F-theory geometry
- Conclusions

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  - Construction of MSSM vacua with all moduli stabilized
  - Engineer moduli-stabilized GUT or MSSM-like configurations that exhibit low-scale supersymmetry breaking
  - This talk
    * constructions incorporating a toy model of the MSSM or a SUSY GUT and a sector realizing dynamical supersymmetry breaking
    * tuning of closed string parameters $\rightsquigarrow$ dominant mechanism of transmitting supersymmetry breaking to the Standard Model is gauge mediation

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    - tuning of closed string parameters $\rightsquigarrow$ dominant mechanism of transmitting supersymmetry breaking to the Standard Model is gauge mediation
  - Type II flux vacua w/ intersecting D-branes $\rightsquigarrow$ calculable SUSY breaking soft terms induced by fluxes have typically too large an order of magnitude $\rightsquigarrow$ lose natural connection between supersymmetry and GUT models

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    - gaugino masses $m_\lambda \sim \alpha F/M$ and squark and slepton masses $m_Q^2 \sim \alpha^2 F^2/M^2$; F is the supersymmetry breaking F-term, M is the messenger mass
    - messenger fields are charged under the Standard Model and contribute to the running of the gauge coupling at energy scales higher than M
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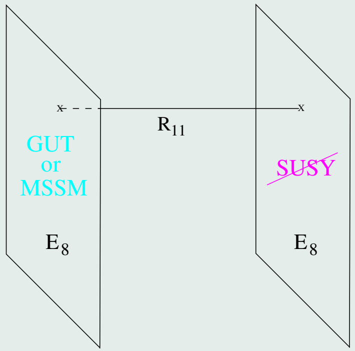
  - Will not be very concerned with numerical considerations (messenger mass, messenger index, strong coupling scale of the hidden gauge group)

- Embedding of gauge-mediation scenarios into string theory
  - Most natural construction: strongly coupled $E_8 \times E_8$ heterotic string



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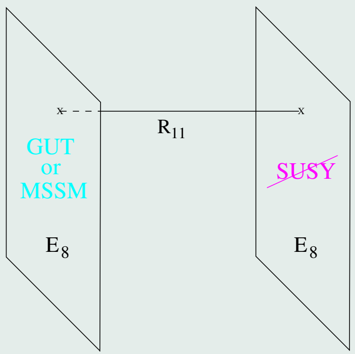

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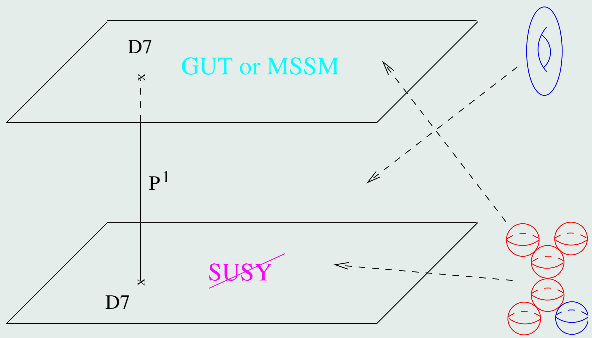
  - F-theory picture: the gauge symmetry is realized on the worldvolume of stacks of D7-branes wrapping surfaces in the base of the Calabi-Yau 4fold



* D7-brane moduli correspond to complex structure moduli of CY 4fold;
* sometimes possible to bring the two stacks of D7-brane close: $d \ll l_s$
* messengers: open strings streched between the D7-brane stacks

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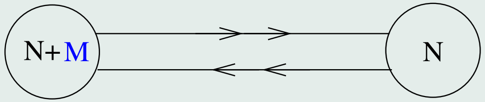
3. Dynamical SUSY Breaking in Field Theory

- Dynamical supersymmetry breaking in quiver gauge theories (Berenstein, Herzog, Ouyang, Pinansky; Franco, Hanany, Saad, Uranga; Bertolini, Bigazzi, Cotrone)
  - (Klebanov, Witten) Place a stack of N D3-branes at the tip of the conifold, $\sum_{i=1}^4 z_i^2 = 0 \rightsquigarrow SU(N)\times SU(N)$ superconformal gauge theory with pairs of bifundamentals in the $(\mathbf{N},\overline{\mathbf{N}})$ and $(\overline{\mathbf{N}},\mathbf{N})$ representations



  - (Klebanov, Strassler) Add M D5-branes wrapping the collapsed two-cycle $\rightsquigarrow$ $SU(N+M)\times SU(N)$ gauge theory with pairs of bifundamentals in the $(\mathbf{N}+\mathbf{M},\overline{\mathbf{N}})$ and its conjugate representations
    - the theory is no longer conformal $\rightsquigarrow$ flows to a strongly coupled gauge theory in the IR via an infinite series of Seiberg duality transformations
    - in the IR, the theory exhibits chiral symmetry breaking and confinement
    - the dual supergravity description is the warped deformed conifold $\sum_{i=1}^4 z_i^2 = \epsilon$, where the deformation parameter ϵ is related to the gaugino condensate in the field theory

– Consider a more complicated singularity: the cone over del Pezzo surface dP_1

  * while the singularity admits a first-order deformation, it is obstructed at second order (Altmann)
  * place N D3-branes and M fractional D5-branes at the singularity $\rightsquigarrow$ conflict between gaugino condensation and other scalar vevs lead to dynamical supersymmetry breaking

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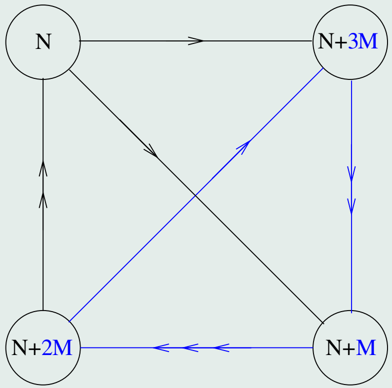
* the gauge theory is described by the following quiver diagram



* the fractional brane triggers a duality cascade: the effective number of D3-branes decreases while the number of fractional D5-branes remains constant
* blue: the quiver corresponding to the gauge theory of the end of the flow
* $U(3M) \times U(2M) \times U(M)$ gauge theory with that spectrum of bifundamental matter fields exhibits dynamical breaking of supersymmetry

– Impossible to satisfy all the D-term and F-term constraints

– Wait! This was too fast.

  * in the noncompact geometry, the D-term constraints can not be imposed since the $U(1)$'s are massive (Franco et al; Intriligator, Seiberg) $\rightsquigarrow$ runaway direction and no supersymmetry breaking

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* once the above configuration is embedded in a compact geometry, the Kähler parameters become dynamical (they play the role of field dependent Fayet-Iliopoulos terms) $\rightsquigarrow$ **need** to stabilize the Kähler parameters. Otherwise, runaway direction and no supersymmetry breaking.

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– Other possibility (Franco, Uranga): add noncompact D7-branes to the system

  * the system admits metastable supersymmetry breaking vacua (string theory realization of Intriligator, Seiberg, Shih- type vacua)
  * (Garcia-Etxebarria, Saad, Uranga): local models of gauge mediation using this construction for the SUSY breaking sector
  * issue of moduli stabilization still open – but (∃) quite promising compact embedding of the ISS model (work w/ Diaconescu,...)

- Noncalculable models of supersymmetry breaking
  - Simple class of models which exhibit dynamical breaking of supersymmetry (Affleck, Dine, Seiberg)
    - $SU(5)$ gauge theory w/ one generation of $\overline{\mathbf{5}} \oplus \mathbf{10}$
    - $SO(10)$ gauge theory w/ one generation of $\mathbf{16}$
  - These models do not have any flat directions or adjustable parameters
  - $(\exists)$ $U(1)_R$ symmetry
    - if the $U(1)_R$ is preserved in the IR $\rightsquigarrow$ implausible charge assignments for the low-energy fields in order to satisfy the anomaly constraints
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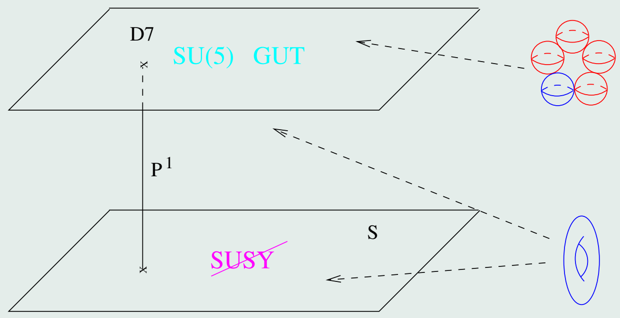
  - If $(\exists)$ unbroken supersymmetry $\rightsquigarrow$ Goldstone bosons are complexified into scalar multiplets whose scalar vevs are not constrained
    - But this is implausible in theories w/out tree-level flat directions $\rightsquigarrow$ supersymmetry is dynamically broken
  - Additional evidence (Murayama): consider models with extra vector-like fields
    - the Witten index vanishes when the mass is small; obtain the noncalculable model in the decoupling limit

4. Fractional Brane SUSY Breaking and GUT Models

- Engineering Goal of the Section:



  - $X \rightsquigarrow$ elliptic Calabi-Yau 4fold fibered over a base P
  - P is itself a $\mathbb{P}^1$ bundle over a del Pezzo surface S (dP_5)
  - the elliptic fiber is constant along the negative section S
  - the elliptic fiber is Kodaira type I_5 along the positive section S_∞

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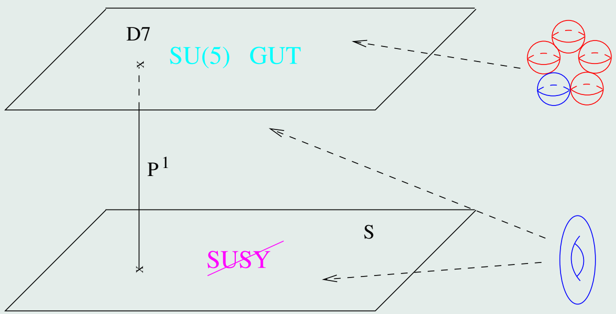

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- IIB Calabi-Yau orientifolds ...
  - Let Z be a Calabi-Yau 3fold equipped w/ a holomorphic involution $\sigma : Z \to Z$

$$\sigma^* \Omega_Z = -\Omega_Z$$

  - Z is a double cover of P

$$Z \xrightarrow{2:1} P$$

    branched along B, the fixed locus of σ

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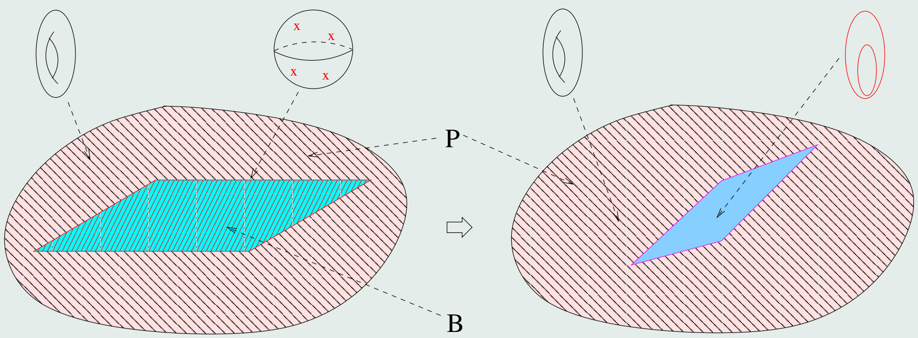
– IIB orientifold $\rightsquigarrow$ gauge discrete symmetry $(-1)^{F_L}\Omega\sigma$

* F-theory compactification on $X = (Z \times T^2)/\mathbb{Z}_2$, where $\mathbb{Z}_2 \equiv (\sigma, -\mathbb{1})$
* the Calabi-Yau 4fold $T^2 \to X \to P$ has D_4 singularities along B



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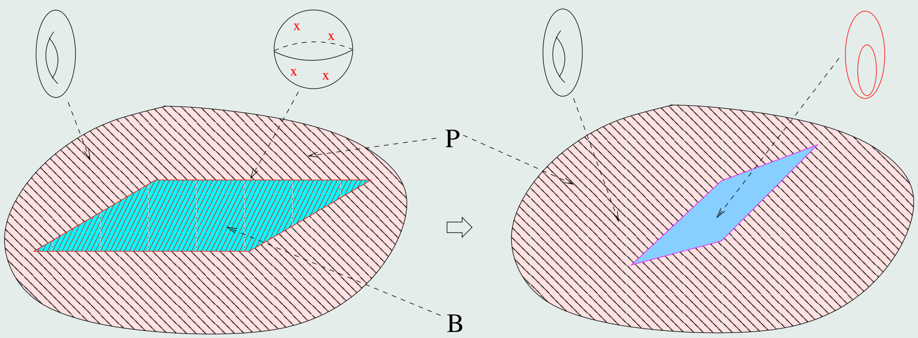


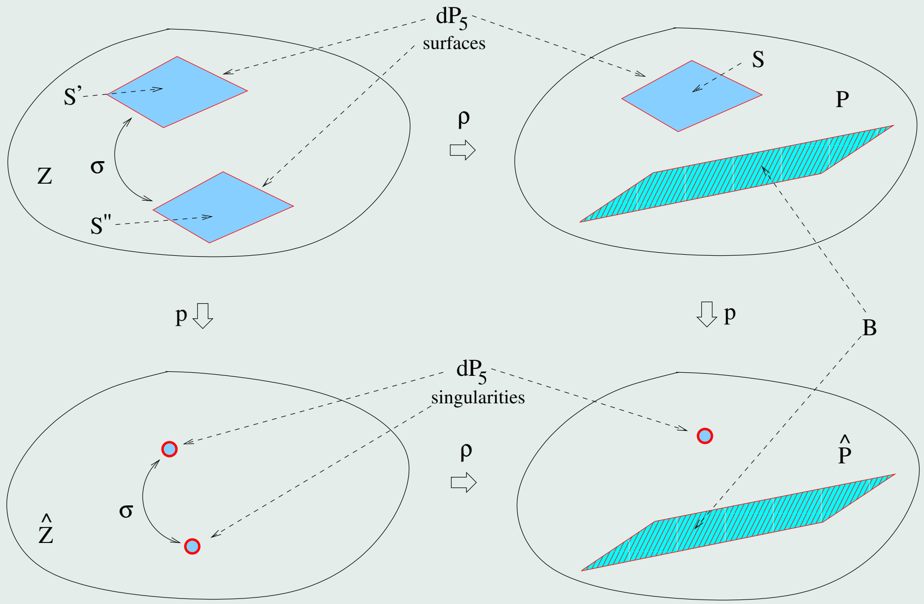
- ... w/ fractional branes at del Pezzo singularities

– Engineer models in which P develops del Pezzo singularities away from the branch locus of $\rho : Z \to P$

* del Pezzo surface S on P such that $S \cap B = 0$
* map $p : P \to \widehat{P}$ which contracts S to a singular point p on $\widehat{P}$

– Inverse image of the surface S via the double cover $\rho : Z \to P$ is a pair of disjoint surfaces $S', S'' \subset Z$

  * the involution $\sigma : Z \to Z$ maps isomorphically S' to S''



– The infinitesimal neighborhood of S in P is isomorphic to the infinitesimal neighborhood of S' (or S'') in Z

* S is a locally Calabi-Yau surface on P
* the local physics of fractional D5-branes at the singularities of $\widehat{P}$ is identical to the local physics of Calabi-Yau del Pezzo singularities
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– Physical configuration

  - * place N D3-branes and M D5-branes at the singularity in $\widehat{Z}$ obtained by collapsing S'
  - * orientifold projection $\rightsquigarrow$ N D3-branes and M anti-D5-branes at the singularity in $\widehat{Z}$ obtained by collapsing S''

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– What about tree-level supersymmetry?

- at the quiver point, the D3-brane and D5-brane central charges are aligned
- the central charges of the two configurations are

$$Z' = NZ_{D3} + MZ_{D5}, \quad Z'' = NZ_{D3} - MZ_{D5}$$

- Z' and Z'' will also be collinear if $N \gg M$

- Concrete example
  - Consider S a del Pezzo dP_5 surface and take the base $P = \mathbb{P}(\mathcal{O}_S \oplus K_S)$
    - P has two canonical sections S, S_∞ with normal bundles

$$N_{S/P} \simeq K_S, \quad N_{S_\infty/P} \simeq -K_S$$

      $\rightsquigarrow$ S is locally Calabi-Yau in P
    - pick B a generic smooth divisor in the linear system $|-2K_P| = |4S_\infty|$
    - the double cover $\rho : Z \to P$ of P branched along B is a smooth Calabi-Yau 3fold containing two disjoint surfaces S', S'' isomorphic to dP_5
  - $(\exists)$ a toric contraction map $p : P \to \widehat{P}$ which contracts S to a point

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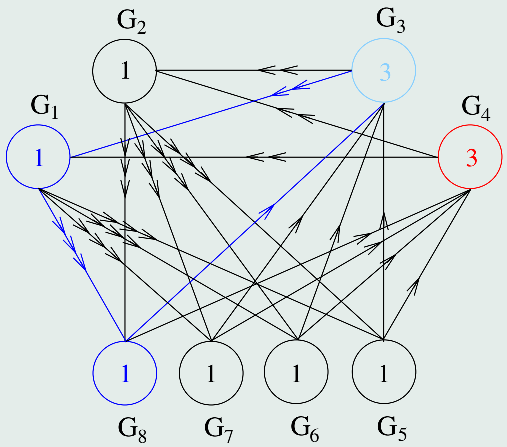

- the diagram describes the quiver gauge theory associated with a collapsing dP_5 surface
- the quiver gauge theory accommodates the desired supersymmetry breaking model; choose the following multiplicities:
$$n_1 = M, \; n_3 = 3M, \; n_5 = 2M$$
  and all the other n_i vanishing

– Enforce an A_4 singularity of the elliptic fibration along the S_∞ section $\rightsquigarrow$ on S_∞, D7-brane w/ $SU(5)$ gauge theory on its worldvolume

  * S_∞ does not intersect S_0, but can be brought arbitrarily close to S_0 by complex structure deformations

  * mass of the open strings between fractional branes at the dP_5 singularity and GUT D7-branes is controlled by a complex structure moduls of the 4fold

– Dual heterotic description $\rightsquigarrow$ realize a three-generation $SU(5)$ theory on S_∞

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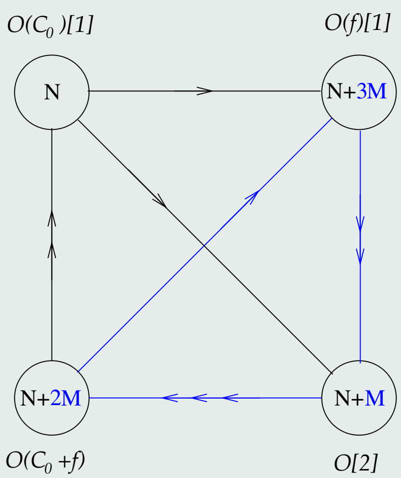
– Kähler moduli stabilization: possible way out; return to the dP_1 model



  * consider all axions obtained by integrated RR forms over even cycles in the geometry preserved by the orientifold action which are charged under the $U(1)$ gauge symmetries
  * determine their charges by demanding that the $U(1)$ anomalies are canceled by Green-Schwarz mechanism
  * write down gauge invariant contributions to the superpotential of the form Be^{iS} and understand if and how these can be generated by D3-brane instantons

5. String Theory Embeddings of Noncalculable Models

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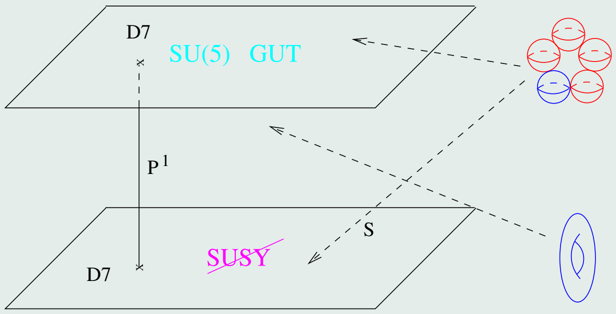

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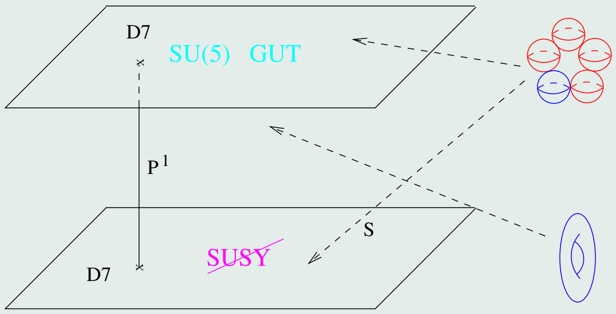

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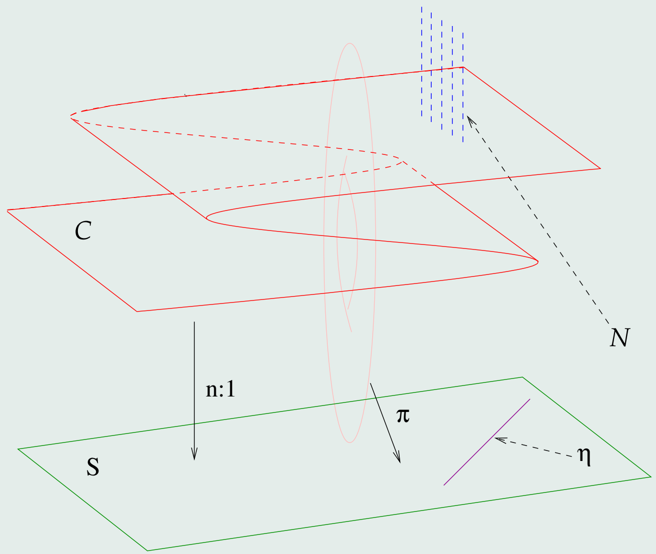
- Dual heterotic wish list:
  - Heterotic $E_8 \times E_8$ compactification on smooth Weierstrass model $\pi : Y \to S$;
  - Background bundle $V_1 \times V_2 \to Y$, with V_1, V_2 stable $SU(5)$ bundles
    * required number of generations: $\mathrm{ch}_3(V_1) = \pm 1, \quad \mathrm{ch}_3(V_2) = \pm 3$
    * anomaly cancellation: $c_2(V_1) + c_2(V_2) + \Lambda = c_2(Y)$, Λ effective curve on Y
  - Kähler moduli stabilization $\rightsquigarrow$ if $\Lambda = \Xi + N_5 E$, then the connected components of Ξ are smooth irreducible (-1) curves on S

- Spectral cover construction for $SU(n)$ bundles (Friedman, Morgan, Witten; Donagi)
  - ($\exists$) $1:1$ correspondence between flat bundles $V \to Y$ and spectral data $(\mathcal{C}, \mathcal{N})$
    - $\mathcal{C} = n\sigma + \pi^*\eta$ is an effective divisor on Y; σ is the section of $\pi : Y \to S$ and η is a divisor class on S
    - $\mathcal{N} \to \mathcal{C}$ is a torsion free rank one sheaf



- The topological invariants of V are determined by the linear equivalence class of $\mathcal{C}$ and the Chern class of $\mathcal{N}$.
- Stability
  - If $\mathcal{C}$ is irreducible, ($\exists$) a polarization J such that V is stable with respect that polarization
  - (Batyrev, Popov) $\rightsquigarrow$ sufficient conditions on η for the spectral cover to be irreducible

- The GUT bundle
  - Obtain a stable bundle V_2 with $\mathrm{ch}_1(V_2) = 0,\ \mathrm{ch}_3(V_2) = -3$ by taking $S \simeq dP_8$ and picking a spectral cover $\mathcal{C}$ and line bundle $\mathcal{N}$

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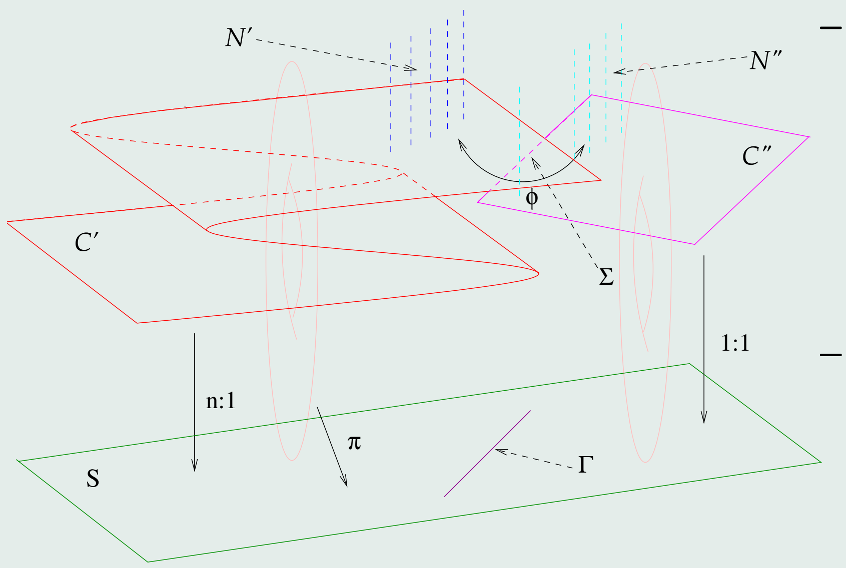
- Above construction: not possible to obtain a single generation bundle $\rightsquigarrow$ reducible spectral covers and extensions (Bershadsky, Johansen, Pantev, Sadov)



  - $\mathcal{C} \rightsquigarrow$ reducible spectral cover with two smooth irreducible components

$$\mathcal{C} = \mathcal{C}' + \mathcal{C}''$$

intersecting along a smooth irreducible curve $\Sigma = \mathcal{C}' \cap \mathcal{C}''$.

  - $\mathcal{N}', \mathcal{N}'' \rightsquigarrow$ spectral line bundles such that $(\exists)$ an isomorphism

$$\phi : \mathcal{N}'|_C \longrightarrow \mathcal{N}''|_C$$

    * the data $(\mathcal{N}', \mathcal{N}'', \phi)$ determines a line bundle $\mathcal{N} \to \mathcal{C}$

- The hidden sector bundle
  - Possible to pick spectral data such that $(\exists)!$ rank 5 stable bundle V_1 with

$$\mathrm{ch}_1(V_1) = 0, \quad \mathrm{ch}_3(V_1) = -1$$

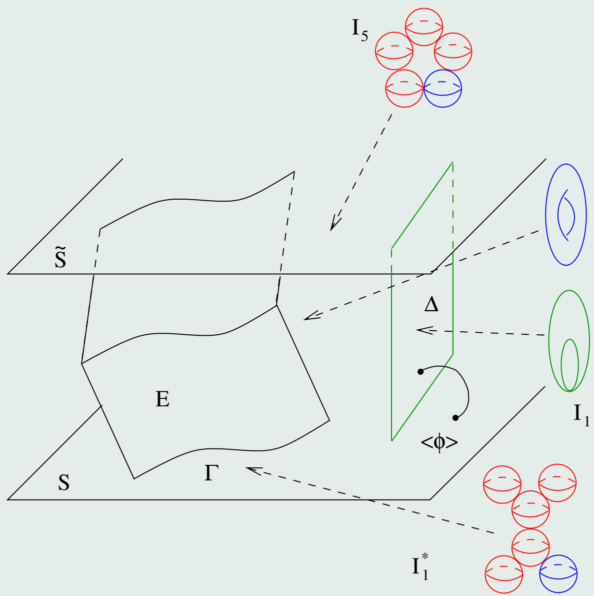
  - Need to introduce a horizontal fivebrane wrapping a (-1) curve $\Gamma \subset S$.

- The hidden sector bundle
  - Possible to pick spectral data such that $(\exists)!$ rank 5 stable bundle V_1 with

$$\mathrm{ch}_1(V_1) = 0, \quad \mathrm{ch}_3(V_1) = -1$$

  - Need to introduce a horizontal fivebrane wrapping a (-1) curve $\Gamma \subset S$.

- Dual F-theory geometry



  - Horizontal heterotic fivebranes wrapped along $\Gamma \subset S \rightsquigarrow$ to blow-ups of the base B along a curve isomorphic to Γ
  - $\tilde{S}$ has trivial normal bundle in the base B and moves in a one dimensional system
  - Heterotic enhanced gauge symmetry $\rightsquigarrow$ singular elliptic fibers along the sections S and $\tilde{S}$
  - D7-D7 strings localized at the intersection of S with nodal component of discriminant locus condense and break the apparent enhaced $SO(10)$ gauge symmetry to $SU(5)$

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- Complex structure moduli stabilization
  - Possible to pick fluxes such that the movable section supporting the $SU(5)$ GUT bundle is brought arbitrarily close to the section supporting the hidden $SU(5)$
    - tune the messenger masses such that gauge mediation is the dominant source of supersymmetry breaking in the visible sector

- Kähler moduli stabilization
  - F-theory $\rightsquigarrow$ D3-brane instantons which correspond to holomorphic Euler characteristic 1 divisors in the Calabi-Yau 4fold X; there $\exists$ enough contributions to the nonperturbative superpotential to stabilize the Kähler moduli
    - the $\mathbb{P}^1$ bundle over the 240 generators of the Mori cone of S
    - the exceptional divisor E contributes since Ξ is a (-1) curve
    - gaugino condensation on the worldvolume of the D7 brane wrapping S_0

6. Conclusions

- Provided examples of string theory compactifications incorporating a toy model of a supersymmetric GUT along with a gauge sector that breaks supersymmetry dynamically
  - Possible to arrange for the dominant mediation mechanism transmitting supersymmetry breaking to the visible sector to be gauge mediation
- Would like to have a better understanding of the stabilization of the Kähler moduli
- Would like to find models with smaller strong coupling scale Λ_H of the hidden gauge theory, messenger mass M and messenger index
- Realize similar constructions incorporating the Penn Heterotic Standard Models
- Statistical analysis of such models