Quantum Corrected Effective Action of String and F-theory

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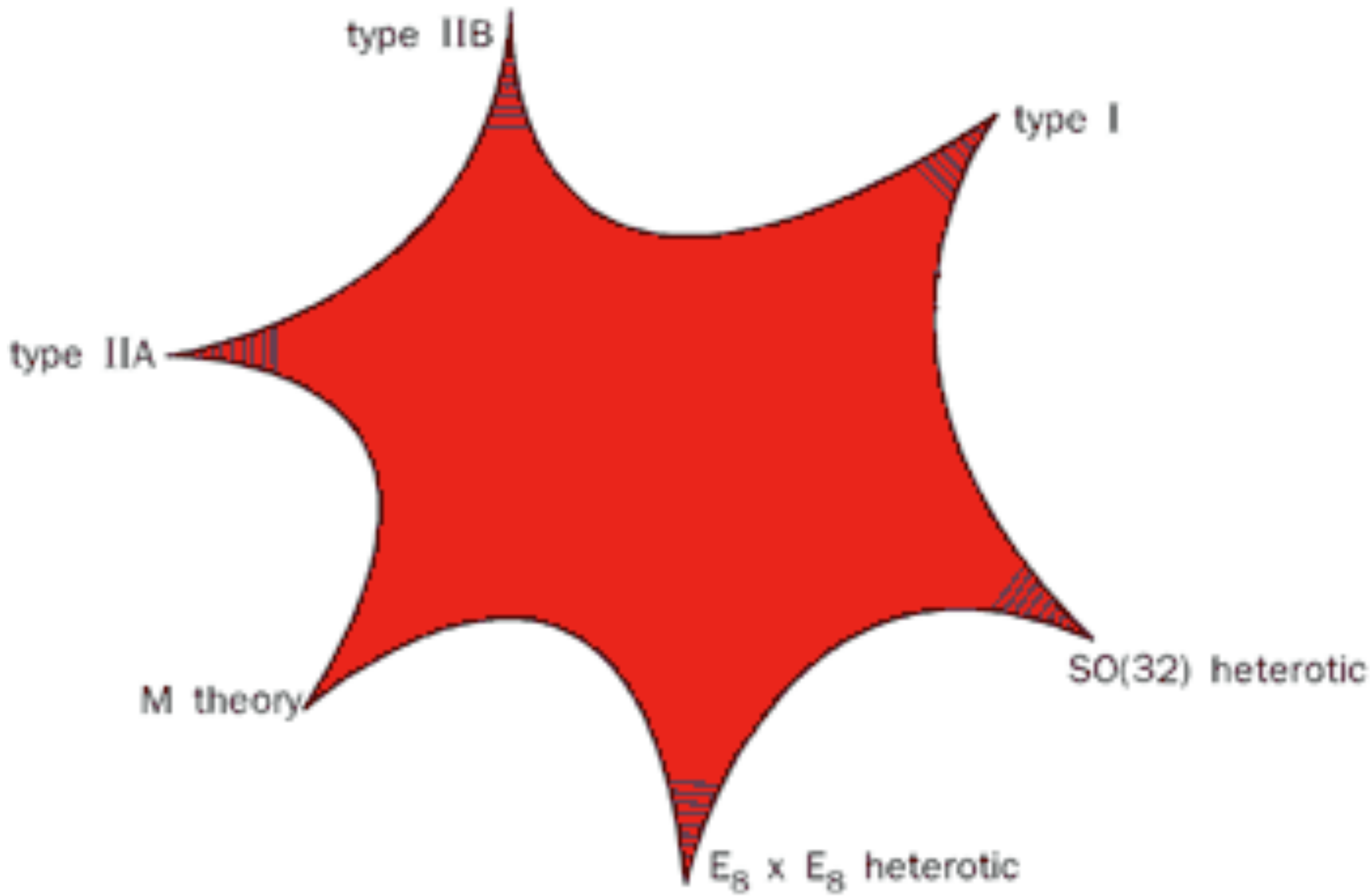
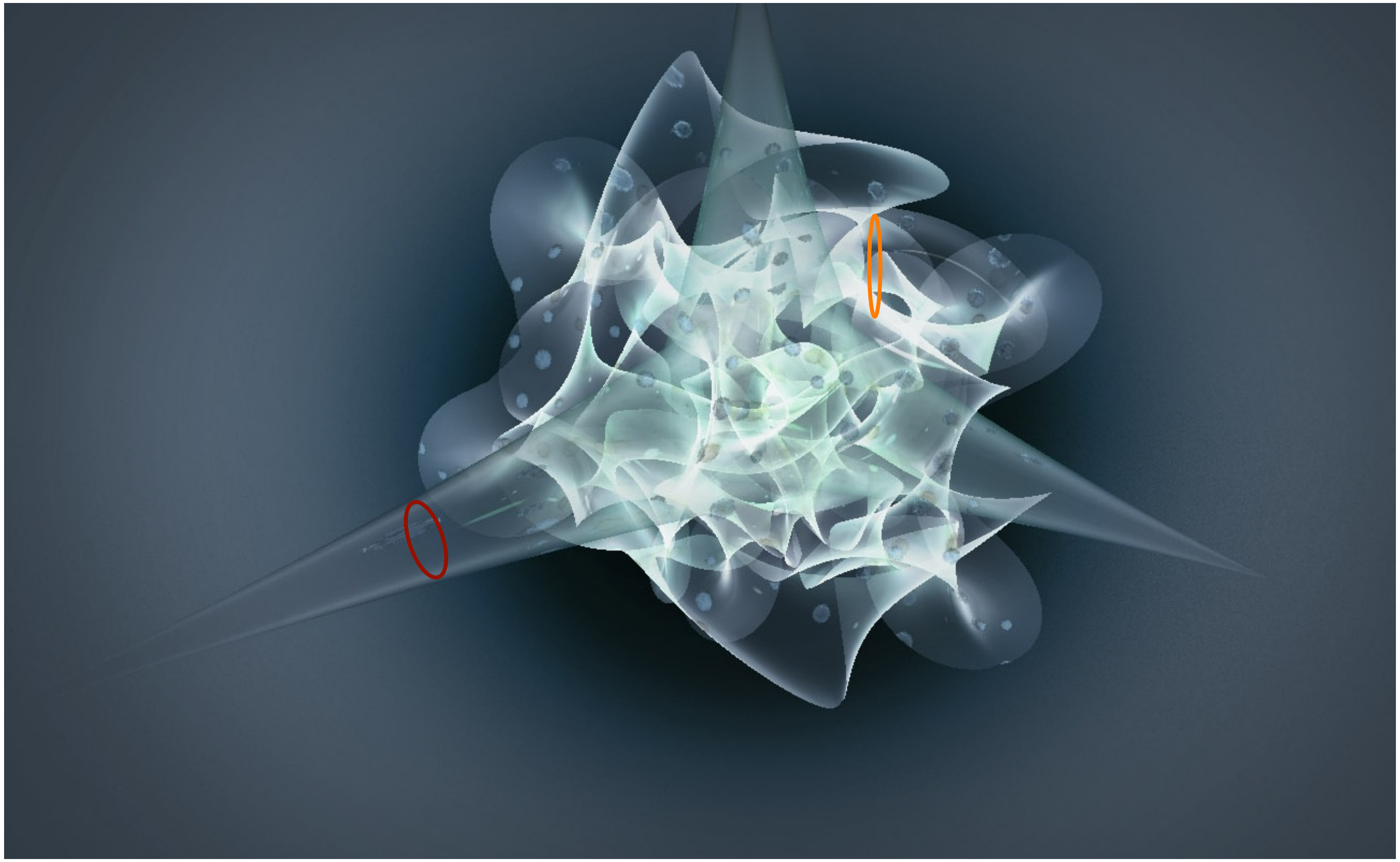
Prologue



Mid to late 90s: a sense of unity and optimism

Prologue

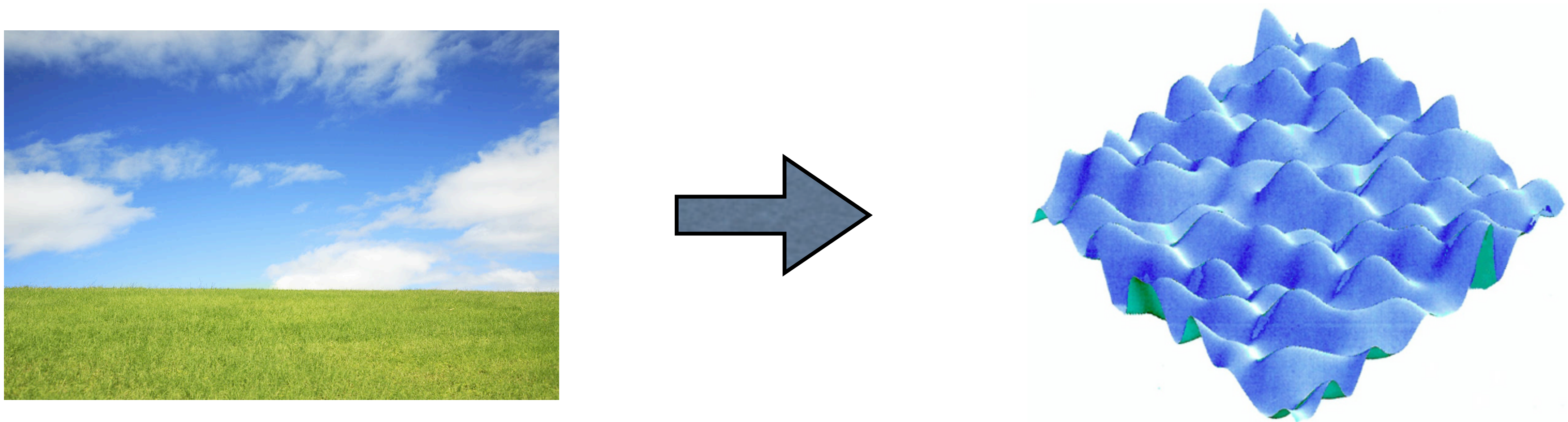


Prologue

Post mid 2000s: full of uncertainty!

Motivation

- 10^{500} vacua or not, need to have control of quantum corrections (in g_s and α') to understand the *vacuum structure* of string theory

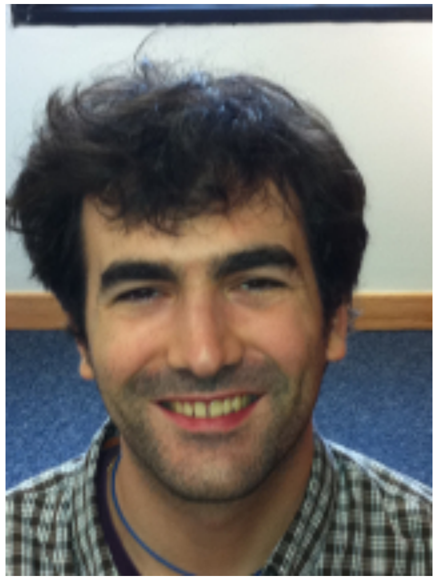


- Some key issues in particle physics and cosmology are sensitive to Planck suppressed operators (e.g., gravity mediated ~~SUSY~~, inflation,..).
- Non-perturbatively generated and higher dim. operators may explain small #s in Nature (e.g., Yukawa/flavor hierarchies, ***ν***-masses, μ-term).

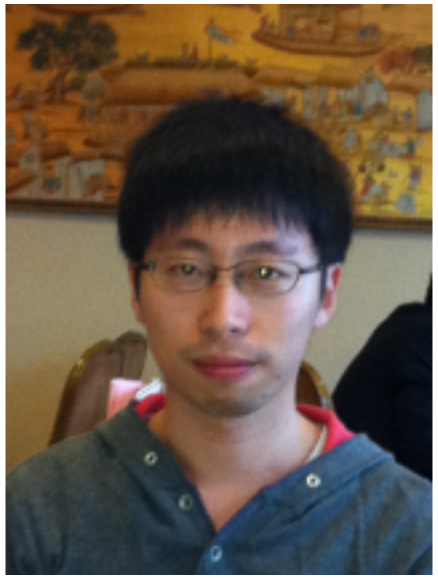
Summary of Our Work

- A modest attempt to compute *exact results* on quantum corrected EFT of string compactifications (GHSS):

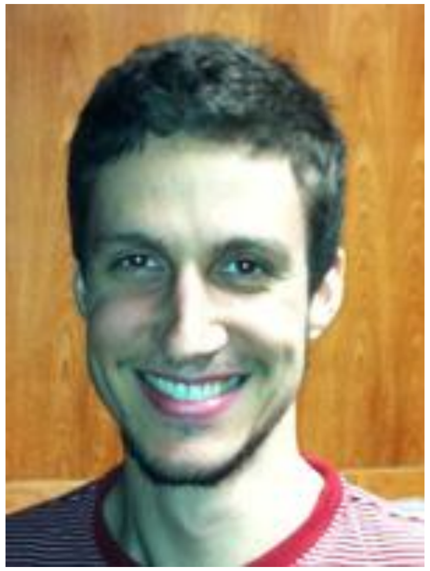
  I. Garcia-Etxebarria, H. Hayashi, R. Savelli, GS, JHEP **1303**, 005 (2013).



I. Garcia-Etxebarria



H. Hayashi



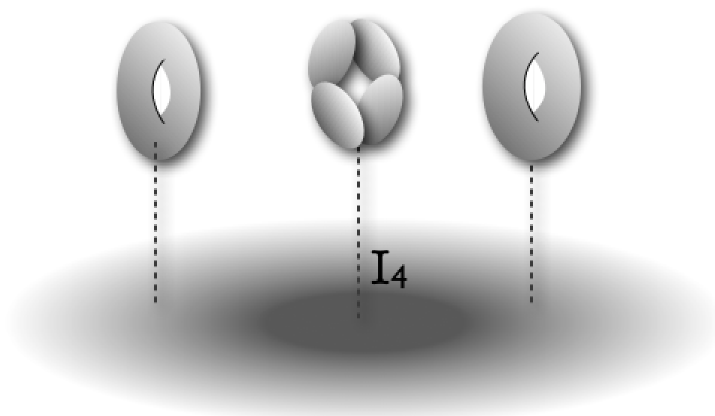
R. Savelli

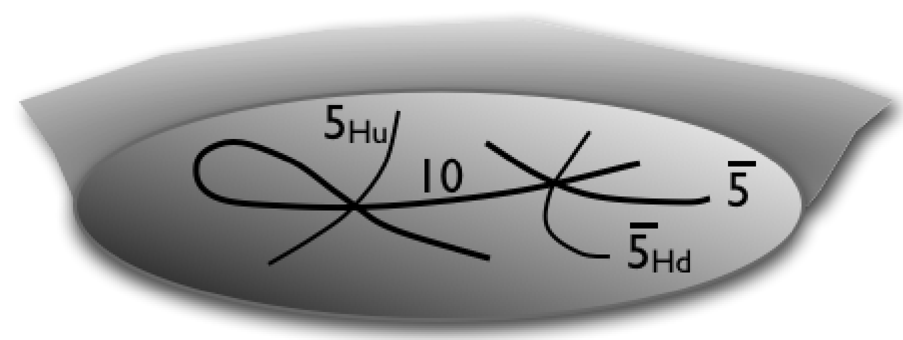
- Make use of string dualities to compute exact in g_s (albeit perturbatively exact in α') Kahler potential in String/F-theory.

- See also Savelli's parallel talk on Tuesday.

F-theory

- Non-perturbative formulation of IIB string theory [Weigand's talk]
- SL(2,Z) symmetry on axiodilaton $\tau = C_0 + i\, e^{-\phi}$ ➪ *geometrize* τ as complex structure of a two-torus [Vafa];[Morrison, Vafa];...





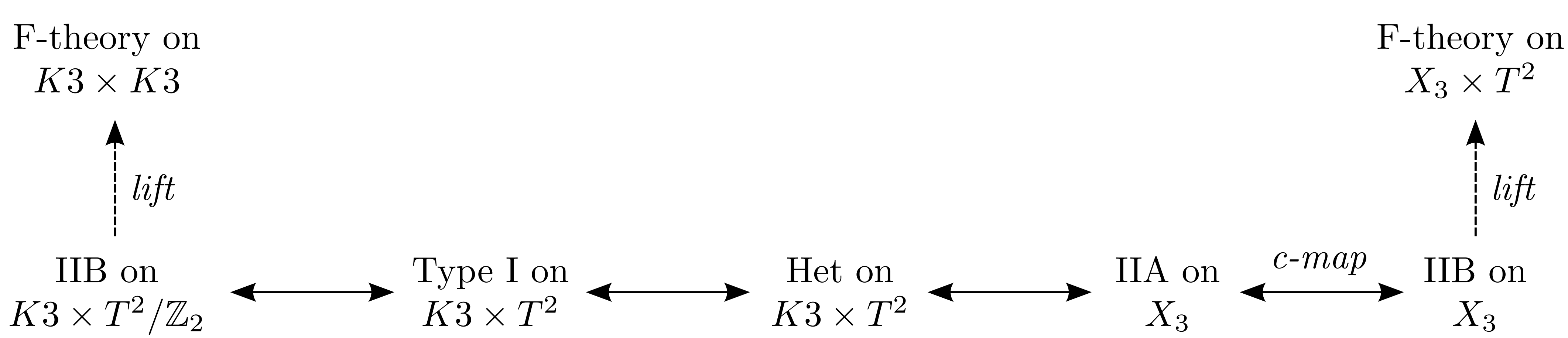
- Aspects of F-theory EFT obtained so far have not fully exploited the geometrical nature of F-theory to describe non-perturbative physics; *non-perturbative symmetries not manifest.*
- GHSS: Geometric interpretation of quantum corrections in terms of Gopakumar-Vafa invariants; SL(2,Z) symmetry manifest.

Moduli Stabilization

- Perturbative α' corrections to K have played a key role in moduli stabilization, e.g, [Balasubramanian, Berglund, Conlon, Quevedo]
- O (α'^3) correction to K [Becker^2, Haack, Louis] was heavily used.
- O $(g_s^2 \, \alpha'^2)$ corrections to K were found for some N=1,2 toroidal orientifolds, cancellations in V ("extended no-scale") [Berg, Haack, Kors];[Hebecker, von Gersdorff];[Cicoli, Conlon, Quevedo]
- We found an *exact in* g_s and *all orders in* α' generalization of these results. [Garcia-Etxebarria, Hayashi, Savelli, GS]
- Generalization is particularly important for moduli stabilization in F-theory GUTs as strong g_s coupling effects are invoked. [Cicoli, Mayrhofer, Valandro]; [Cicoli, Krippendorf, Mayrhofer, Quevedo, Valandro]

Summary of Strategy

- Consider a particular N=2 model: F-theory on K3 x K3
  - ➡ obtain exact in g_s, perturbatively exact in α' Kahler potential
  - ➡ more constraining than N=1 but yet exhibit similar features
  - ➡ pattern of corrections N=4→N=2 as guide for N=1 case.
- Extensive use of string dualities and the c-map:



F-theory Effective Action

Effective Action

- F-theory is an exact completion (in g_s) of IIB but is perturbatively defined in α'. At tree-level in α': $\mathcal{K} = \mathcal{K}_K + \mathcal{K}_c\,,$

where $\mathcal{K}_K = -3\log \mathcal{V}_{\mathrm{CY}_4}\,,$ $\mathcal{K}_c = -\log \int_{\mathrm{CY}_4} \Omega_4 \wedge \bar{\Omega}_4\,,$

- In the weakly coupled IIB orientifold limit (Sen's limit):

$$\mathcal{K}_c = -\log(\mathrm{Im} S_0) - \log i \int_{\mathrm{CY}_3} \Omega_3 \wedge \bar{\Omega}_3 + \frac{g_s}{2i\int_{\mathrm{CY}_3} \Omega_3 \wedge \bar{\Omega}_3} \mathcal{K}_{\mathrm{D7}} + \mathcal{O}(g_s^2)$$

- Kc contains all g_s corrections sum in an SL(2,Z) invariant way.
- Physics depends on intrinsic fibration structure! ⇨ Labels (monodromies) of 7-branes change, not their mutual relations.
- Target space duality in M-theory when CY4 is trivially fibered but this symmetry holds generally for elliptically fibered CY4.

SL(2,Z)

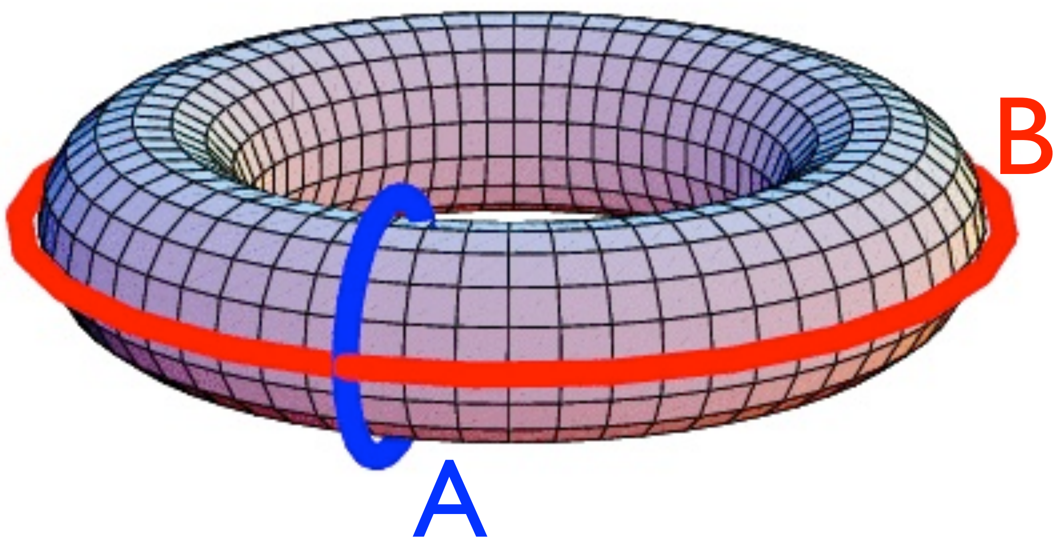
- Strong-weak coupling transformation: Local Lagrangian?
- Gauge couplings of gauge fields from KK reduction of bulk SUGRA or 7-branes do not change under SL(2,Z), e.g.,

$$\frac{1}{g_{\rm YM}^2} \sim \frac{\mathrm{Vol(4\text{-}cycle)}}{g_s} = \widehat{\mathrm{Vol}}(\text{4-cycle}),$$

  only Einstein frame volumes are involved, SL(2,Z) inv.

- We shall verify that each α'-tower of corrections displays an SL(2,Z) symmetry for F-theory on K3xK3.
- More general than the case in [Collinucci, Soler, Uranga] as fibration is non-trivial; yet enjoy the non-renormalization theorems for N=2, and admits multiple dual descriptions.

F/M-theory Picture



- Reduce M to IIA along *A*.
- T-dualize IIA to IIB along *B*.
- Take the v^0 =Vol(T^2)$\rightarrow$0 limit.

➡ Type IIB string theory with varying axio-dilaton.

- IIB metric in Einstein frame and 10d Poincaré $r = (v^0)^{-3/4}$.
- The finite quantity $v_s^\alpha = \sqrt{v^0} v_M^\alpha$ is the 2-cycle size in string units.

• M-theory scale is small compared to string length $l_M / l_s = (v^0)^{1/4}$.

➡ Look for higher derivative corrections to 11d sugra which survive the F-theory limit v^0 =Vol(T^2)$\rightarrow$0 .

Our Model & Its Heterotic Dual

Our Model

- Consider Type IIB orientifold on K3 x T^2/Z_2
- 4 Fixed points: positions of 4 O7-planes wrapping $R^{1,3}$ x K3
- N=2, D=4 Compactification:
  - ❖ Vector multiplets:
    - 3 bulk: axio-dilaton (S), K3 volume (T), T^2 cplx str. (U).
    - 16 brane: transverse positions of D7-branes (C^i).
    - No D3-moduli (16 rigid, space-time-filling, "half" D3s).
  - ❖ Hypermultiplets: complex structure of K3 and Kahler modulus of T^2.
- Focus on quantum corrections to the metric of the vector multiplet moduli space (a Special Kahler manifold).

Duality Dictionary

- We computed such corrections by following the duality

$$\text{Heteroric} \quad \overset{\text{S-duality}}{\longleftrightarrow} \quad \text{Type I} \quad \overset{\text{T-duality}}{\longleftrightarrow} \quad \text{Type I}'$$

- Heterotic & Type I are a strong-weak coupling dual-pair in 10d:

$$\begin{aligned} \phi^H_{10} &= -\phi^I_{10}, \\ G^H &= e^{-\phi^I_{10}} G^I, \end{aligned}$$

[Witten]

- Upon further T-duality, the vector moduli space gets mapped to:

$$\begin{aligned} S_H &= B^d + ie^{-2\phi^H_{10}}\mathrm{Vol}(T^2\times K3)^H \\ T_H &= \int_{T^2} B_{45} + i\mathrm{Vol}(T^2)^H \\ U_H &= \frac{G^H_{45} + i\sqrt{G^H_{T^2}}}{G^H_{44}} \\ A^i_H &= U_H A^i_4 - A^i_5 \quad (16 \text{ Wilson lines}) \end{aligned} \quad \leftrightarrow \quad \begin{aligned} T_{I'} &= \int_{K3} C_4 + ie^{-\phi^{I'}_{10}}\mathrm{Vol}(K3)^{I'} \\ S_{I'} &= C_0 + ie^{-\phi^{I'}_{10}} \\ U_{I'} &= U_I \\ C^i_I &= U_{I'} p^i_4 - p^i_5 \quad (16 \ D7 \text{ positions}) \end{aligned}$$

- 5-brane instantons & worldsheet instantons in heterotic become D3 instantons and D(-1) instantons in Type I'.

Threshold Corrections

- Special Kahler geometry (N=2 prepotential):

$$K = -\log i \left[2\mathcal{F} - 2\bar{\mathcal{F}} - \sum_{\alpha} (\phi^{\alpha} - \bar{\phi}^{\alpha}) \left(\partial_{\phi^{\alpha}} \mathcal{F} + \partial_{\bar{\phi}^{\alpha}} \bar{\mathcal{F}} \right) \right]$$

- Use CFT techniques to compute all α' corrections in heterotic dual by going to orbifold limit (2-cycle volumes in hypers.)

    ➡ Kahler potential for Type IIB orientifold, exact in g_s

- First, ignore the Wilson Lines: [Harvey, Moore];[Henningson, Moore]

$$\mathcal{F}_H(S_H, T_H, U_H) = \hat{S}_H T_H U_H + h(T_H, U_H),$$
$$\hat{S}_H = S_H + \frac{1}{2} \partial_{T_H} \partial_{U_H} h(T_H, U_H),$$

exact in α', perturbatively exact in g_s.

- $S_H \rightarrow S_H + \lambda$ is an exact symmetry in perturbation theory. F_H (and S_H) has no perturbative corrections beyond one loop in $g_s = 1/\text{Im}\, S_H$.

Threshold Corrections

- Prepotential for Type IIB Orientifold:

$$\mathcal{F}(S,\hat{T},U) = S\hat{T}U + h(S,U)\,,$$

$$\hat{T} = T + \frac{1}{2}\partial_S\partial_U h(S,U)\,.$$

exact in g_s=1/Im S, perturbatively exact in α'^2 = 1/Im T.

- In the region Im S > Im U

$$h(S,U) = -\frac{i}{(2\pi)^4}\left[\mathrm{Li}_3\left(e^{2\pi i(S-U)}\right) + \sum_{\substack{k,l\geq 0\\(k,l)\neq(0,0)}} c(kl)\mathrm{Li}_3\left(e^{2\pi i(kS+lU)}\right)\right] + \frac{15i}{2\pi^4}\zeta(3) + \frac{U^3}{12\pi}\,,$$

where $\mathrm{Li}_m(z) = \sum_{n=1}^{\infty}\frac{z^n}{n^m}\,,\qquad \sum_{n=-1}^{\infty}c(n)z^n = \frac{E_6E_4}{\eta^{24}}(z)$

S, U interchanged when Im U > Im S.

Threshold Corrections

- Kahler potential is invariant under shift of F (also h) by a polynomial at most quadratic in Φ^a with real coefficients.
- Ambiguity in h is related to non-trivial monodromies at special regions of moduli space.
- h develops co-dim. 1,2 singularities due to *enhanced gauge symmetry*.
- Classical duality group is modified, but K should be unaffected.

Perturbative α' Corrections

- Expand the log to get perturbative α' corrections to K:

$$
\begin{aligned}
K(S,T,U) &= K^{(0)}(S,T,U) + \sum_{n=1}^{\infty} \frac{1}{n} K^{(n)}(S,T,U)\,, \\
K^{(0)}(S,T,U) &= -\log\left[-i(S-\bar{S})(T-\bar{T})(U-\bar{U})\right]\,, \\
K^{(n)}(S,T,U) &= -\frac{(-1)^n}{(T-\bar{T})^n}\left[\frac{2h-2\bar{h}}{(S-\bar{S})(U-\bar{U})} - \frac{\partial_S h + \partial_{\bar{S}}\bar{h}}{U-\bar{U}} - \frac{\partial_U h + \partial_{\bar{U}}\bar{h}}{S-\bar{S}}\right. \\
&\qquad \left. -\frac{1}{2}(\partial_S\partial_U h - \partial_{\bar{S}}\partial_{\bar{U}}\bar{h})\right]^n .
\end{aligned}
$$

- Only $(g_s\ \alpha')^{2n}$ terms survive since $\partial_S h \longrightarrow 0$ exponentially for $S \longrightarrow i\infty$
- $\alpha'^{\,3}$ term of BBHL is absent since χ (K3 x T^2)=0.
- Odd powers of g_s are absent as open string moduli are frozen.

Perturbative α' Corrections

- Kahler modulus and axio-dilaton mix at α'^{2} order (n=1):

$$K^{(1)} = -\frac{\mathcal{E}(U,\bar{U})}{(T-\bar{T})(S-\bar{S})} \qquad \mathcal{E} := \lim_{S\to i\infty} \frac{2h-2\bar{h}}{U-\bar{U}} - \partial_U h - \partial_{\bar{U}}\bar{h}\,.$$

  agrees with 1-loop open string computation [Berg, Haack, Kors]

- Such corrections come from (i) KK exchange between D7s and non-mobile D3s, or (ii) Mobius amplitude between parallel D7s.

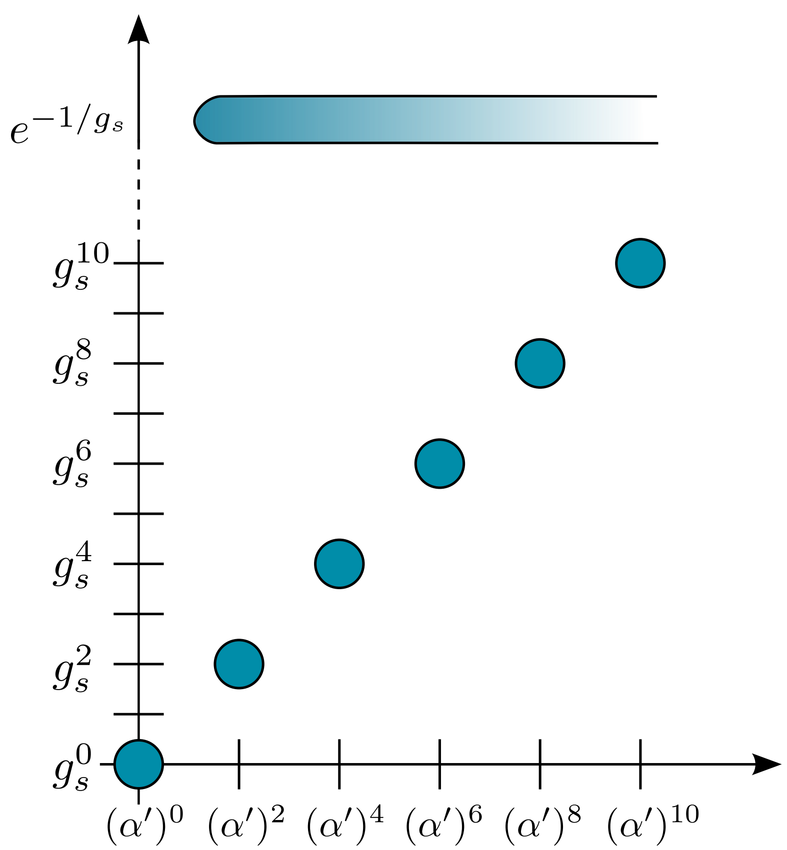
- $(1/\mathrm{Im}\,T)^2\,(1/\mathrm{Im}\,S)^0$ correction which comes from exchange of strings wound around the intersection of D7s is absent as two D7s either do not intersect or coincide, and K3 has no 1-cycle.

- At each perturbative α' order, the Kahler potential is inv. under

$$O(2,2,\mathbb{Z}) = SL(2,\mathbb{Z})_S \times SL(2,\mathbb{Z})_U \rtimes \mathbb{Z}_2$$

- Generalized to include Wilson lines & checked SL(2,Z) invariance.

Summary of Corrections



✓ Terms non-perturbative in g_s from D(-1) instantons.

✓ Only $(g_s\ \alpha')^{2n}$ terms survive at perturbative level

✓ $\alpha'^{\,3}$ term of BBHL is absent since $\chi\ (K3 \times T^2) = 0$.

✓ No odd powers of g_s, as open string moduli are frozen.

Non-perturbative in α' corrections are not included in this analysis:

- WS & D1 instantons are absent due to orientifold projection.
- ED3 wrapping T^2 x (2-cycle of K3) correct hyper. moduli sp. metric.
- SL(2,Z) invariant ED3 branes wrapping K3 (more later) not included here.

Non-perturbative α' Corrections

- ED3 wrapping K3 are non-perturbative in both α' and g_s.
- Their contribution is trivially SL(2,Z) invariant.
- The exact prepotential:

$$\mathcal{F} = \hat{S}\hat{T}U - \frac{\hat{T}}{2}\sum_{i=1}^{16}(C^i)^2 + \tilde{h}(\hat{S},U,C^i) + \sum_m \mathcal{A}_m(\hat{S},U,C^i)e^{2\pi i m T}$$

- The A-factor can be computed from the Type IIA dual on a CY_3 which admits a K3 fibration over S^2.
- D3 instantons→worldsheet instantons wrapping S^2 on the IIA side. Partial results were obtained in [Berglund, Mayr].

Lift to F-theory

Heterotic Picture

- Type IIB orientifold on K3 x T^2/Z_2 is related by two T-dualities to the BSGP model [Bianchi,Sagnotti];[Gimon,Polchinski]
- The BSGP model is S-dual to heterotic SO(32) theory w/o vector structure [Bianchi];[Witten], though its maximal gauge group is U(16).
- Heterotic SO(32) without vector structure is dual to heterotic E_8 x E_8 with instanton embedding (12,12).
  - ❖ At generic points of the hypermultiplet moduli space, only $U(1)^4$ is left, corresponding to S_H, T_H, U_H, and the graviphoton.
- Heterotic SO(32) with vector structure is dual to heterotic E_8 x E_8 with different instanton embedding.
  - ❖ Not enough instantons for complete Higgsing to U(1)s. Need to turn on WLs, e.g., (24,0) instanton embedding requires 8 WLs.

Heterotic Picture

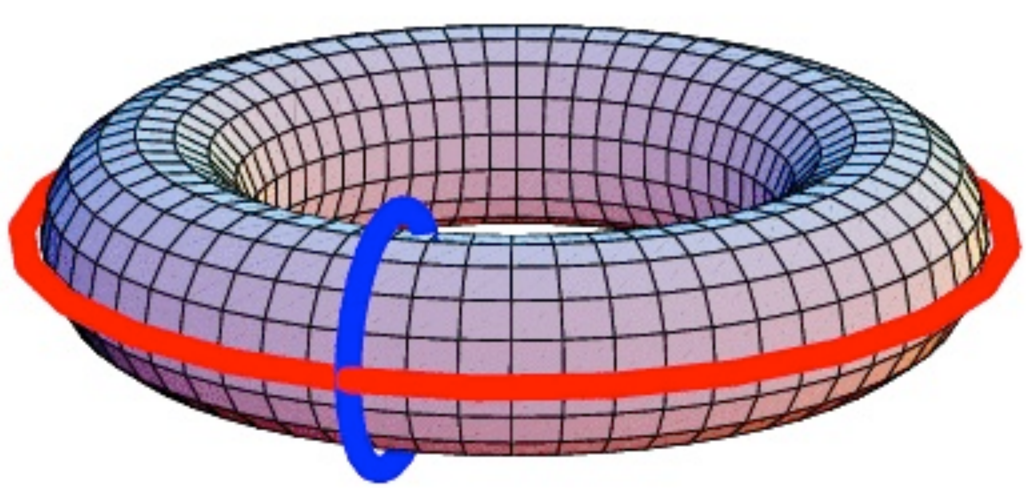
- We focus on the vector multiplet moduli space.
- When WLs are turned off, prepotential of the theory w/o vector structure matches that w/ vector structure.
- This insensitivity to instanton embedding (and hence 4D gauge groups) can be explained using the relation to SUSY index [Lopes Cardoso, Curio, Lust]. We also showed this by explicit computation.
- Expressions for heterotic SO(32) and $E_8 x E_8$ with general instanton embeddings & WLs can be found in [Henningson, Moore].

F-theory Picture

- 8D duality: Heterotic on T^2 = F-theory on K3
- Heterotic on K3 x T^2 = F-theory on K3 x K3
- Our model actually admits more F-theory duals.
- If the heterotic K3 admits an elliptical fibration over P^1, we get an F-theory dual on X_3 x T^2 where X_3=K3 fibration over P^1:
  - ➡ Same X_3 on which the dual IIA theory compactified [Louis, Sonnenschein, Theisen, Yakielowicz].
  - ➡ Base of X_3 as an elliptical fibration is an Hirzebruch surface F_n, with n related to the instanton embedding of the dual heterotic E_8xE_8 theory [Morrison, Vafa].
    - $X_3 = WP_{1,1,2,8,12}(24)$ for (12,12) instanton embedding [Klemm, Lerche, Mayr];[Hosono, Klemm, Theisen, Yau]

Quantum Corrections

- We checked that the classical vector multiplet moduli space matches the classical moduli space of K3'.
- Quantum corrections → Quantum moduli space of K3'.
    - Factorization destroyed but SK-geometry preserved.
- Identify BPS objects in M-theory which generate the corrections found. Recall the M-theory definition of F-theory:



Quantum Corrections

- Non-perturbative g_s corrections: D(-1) instantons in IIB → D0-brane in IIA looping along S_T → KK particle in 11D with non-trivial p_M & w_T.
  - For trivial fibration: higher derivative corrections to 11D SUGRA [Green,Gutperle];[Green,Vanhove];[Green,Gutperle,Vanhove];[Green,Sethi]

    → Contribute to R^4 coupling → α'^3 correction of BBHL
  - Non-trivial fibration: contributions already at order α'^2
  - For these l_M corrections to stay finite in the F-theory limit, they should appear as powers of $l_M^2/\sqrt{v_0}$ because of the relation:

$$l_M/l_s = (v_0)^{1/4}$$

  - A subset of higher derivative corrections to 11D SUGRA (F-theory limit)

Quantum Corrections

- Perturbative g_s corrections when combined with the non-perturbative ones lead to SL(2,Z) invariant sets of g_s corrections for each α' tower. This suggest:
  - 11D supergravitons with non-trivial w_T but no p_M
  - 11D supergravitons with non-trivial w_M, and possibly p_T

  (c.f. [Green, Vanhove])

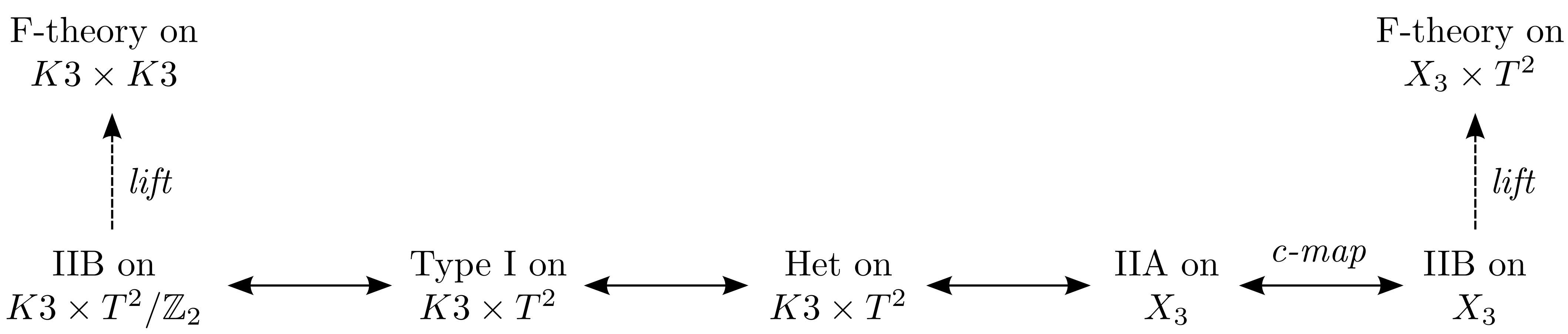
  Being loops of 1-cycle of the fiber, these sources should generate corrections proportional to $l_M^2/\sqrt{v_0}$, thus survive the F-theory limit.

Explicit Computation

Explicit Computation

- We have identified the BPS objects in M-theory responsible for the corrections to the vector multiplet moduli space metric for F-theory on K3xK3'.
- Direct Schwinger-loop calculation on K3' along the lines of [Collinucci, Soler, Uranga] is hard, due to non-trivial fibration.
- We make use of other F-theory duals to bypass this difficulty.

Chain of Dualities



- Swapping the role of elliptic fiber of X_3 and F-theory fiber
  - ➡ Hypermultiplet moduli space of a *braneless* F-theory
  - ➡ M-theory method [Collinucci, Soler, Uranga] to compute corrections.
- However, this procedure gives more corrections than needed!
  - ✦ IIA vector multiplet moduli space metric has only α' corrections.
  - ✦ IIB hypermultiplet moduli space receives both α' & g_s corrections.
  - ➡ Extract *tree-level* in g_s part of Schwinger-loop computation

(Note g_s here is *neither* g_s *nor* α' of the original F-theory on K3xK3!)

M-theory Computation

- Hypermultiplet moduli space of F-theory on $X_3 \times T^2$
- D-instantons ↔ D-particles via c-map [Seiberg,Shenker];[Ooguri,Vafa]
- Compute corrections to the hypermultiplet moduli space (equiv. Einstein term (~R) in 3d effective action)

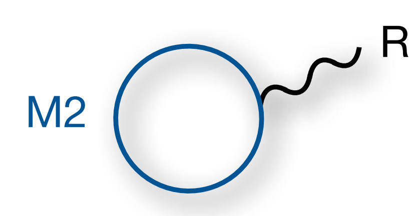
D1/D(-1) instantons in IIB on CY

⇕ c-map

D2/D0 particles in IIA on CY x S

⇑

M2 particles (and gravitons) in M-th on CY x T^2



M-theory Computation

- Compute Schwinger-loops for X_3 =$WP_{1,1,2,8,12}$ (24)

$$\mathcal{F}_{\rm class} = \frac{1}{6}\kappa_{\alpha\beta\gamma}\, t_\alpha t_\beta t_\gamma\,,$$

$$\mathcal{F}_{\rm pert} = -\frac{i}{4(2\pi)^3(\tau_2)^{3/2}}\,\chi(X_3)\sum_{(m,n)\neq(0,0)}\frac{\tau_2^{3/2}}{|m\tau+n|^3}\,,$$

$$\mathcal{F}_{\rm non-pert} = \frac{i}{2(2\pi)^3(\tau_2)^{3/2}}\sum_{\mathbf{d}} n_{d_\alpha}\sum_{(m,n)\neq(0,0)}\frac{\tau_2^{3/2}}{|m\tau+n|^3}\,e^{2\pi i d_\alpha(mc_\alpha+nb_\alpha+i|m\tau+n|j_\alpha)}$$

  - $\kappa_{\alpha\beta\gamma}$ = classical intersection # of X_3
  - $n_{d\alpha}$ = genus-zero Gopakumar-Vafa invariants of X_3
  - c_α, b_α, j_α = zero modes of the RR 2-form, the B-field, & the Kahler form expanded in a basis of $H^{1,1}(X_3,Z)$

- Displays SL(2,Z) for each perturbative α' tower; also contains non-perturbative α' corrections again in SL(2,Z) inv. manner.

Final Result

- To derive corrections to the vector multiplet moduli space metric of the *original* F-theory on K3xK3, consider the limit:

$$g_s \to 0, \quad i.e., \quad \tau_2 \to \infty$$

- Matches with the heterotic computation. Identify:

$$-\frac{1}{2} n_{l+k,-k,l-k} = c(lk)$$

- Counting rational curves via modular forms [Henningson, Moore].

- c(lk) agree with GV invariants in [Hosono, Klemm, Theisen, Yau].

- Given GV invariant for the 0-class is the Euler number:

$$n_{0,\cdots,0} = -\frac{\chi(X_3)}{2}$$

- GV invariants ≃ non-perturbative (in g_s) generalization of the BBHL term (albeit here the α' corrections are of order α'^2).

Generalizations

- To generalize this result to include 7-brane moduli C^i, one considers X_3 with the right number of vector multiplet.

- For example, with 8 C^i switched on, use $X_3 = WP_{1,1,12,28,42}(84)$ as $\mathcal{F}_{\text{vector multiplet.}}$ should be insensitive to instanton embedding.

- Repeat the Schwinger-loop computation with a different set of topological invariants.

Summary

- Computed the *exact* in g_s, perturbatively exact in α', vector multiplet moduli Kahler potential $\mathcal{K}$ of an N=2 F-theory model.

- Provided an M/F-theory interpretation of corrections to the Kahler potential and identified the contributing BPS states.

- Shown explicitly that quantum corrections to the Kahler potential are SL(2,Z) invariant at each α' level.

- Shown that Kahler moduli & complex structure moduli start to mix when perturbative α' corrections are taken into account.

- Provided a genuine (albeit indirect) M-theory computation.

Outlook

- A modest step towards the ambitious goal of computing exact results for realistic compactifications.

- Even within the realm of N=2 compactifications, we have focussed on the easiest half of the problem, i.e., *vector multiplet* moduli.

- It'd be interesting to apply the remarkable work on understanding quantum corrections to the *hypermultiplet moduli* space, see e.g.,: [Robles-Llana,Rocek,Saueressig,Theis,Vandoren];[Alexandrov,Saueressig,Vandoren];[Pioline,Persson];[Bao,Kleinschmidt,Nilsson,Persson,Pioline];[Alexandrov];[Alexandrov,Saueressig];[Alexandrov,Manschot,Pioline]; ...

  in F-theory as we have done for the vector multiplet moduli.

Outlook

- The Holy Grail is to find non-pert. results for $N\leq 1$ compactifications.
- The pattern of corrections from $N=4\rightarrow N=2$ that we found may serve as a guide for further breaking to $N=1$. More concretely:
  - ★ Compute directly D-particle loops for non-trivial elliptic fibration
  - ★ Spontaneously breaking $N=2\rightarrow N=1$ (e.g, by fluxes); sometimes inherit structure of N=2 effective action. See, e.g., [Ferrara, Girardello,Porrati]; [Fre,Girardello,Pesando,Trigiante][Louis,Symth,Triendl], ...
- More α' corrections arise in N=1 String/F-theory vacua (albeit only tree-level g_s result in [Grimm, Savelli, Weißenbacher];[Pedro, Rummel, Westphal])
- Any such progress would undoubtedly shed light on the vacuum structure of string theory and its low energy descriptions.


THANKS