MAX-PLANCK-INSTITUT
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Probing the Emergence Proposal in Heterotic/Type IIA Dual String Theories

Based on [2504.05392] with R. Blumenhagen and A. Paraskevopoulou

Manuel Artime | 17th July 2025

Contents

A Familiar QFT Example

- Consider the action:

$$S = M_{\rm Pl}^2 \int d^4x \left[g_{\phi\phi}\, \partial^\mu \phi\, \partial_\mu \phi + \sum_n \left(\frac{1}{2} \partial^\mu h_n\, \partial_\mu h_n + \frac{1}{2} m_n^2(\phi)\, h_n^2 \right) \right] , \quad \text{with} \quad m_n(\phi) = n \cdot m(\phi)$$

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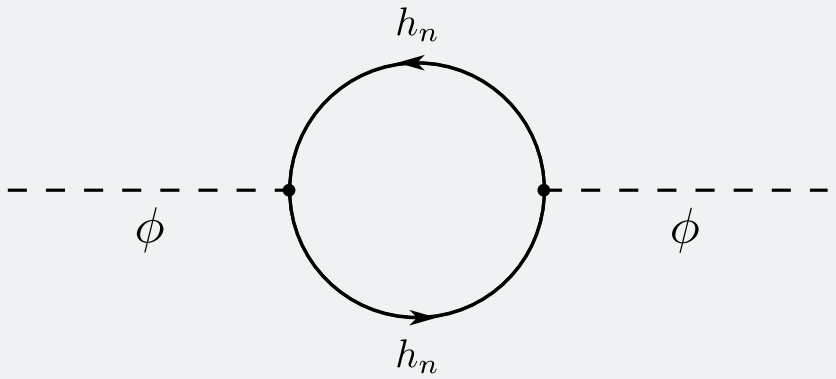
- Expand $m_n(\phi) \longrightarrow$ triple vertex: $(m_n(\phi)\, \partial_\phi m_n(\phi))\, h_n^2 \phi$
- Integrate out h_n below the cut-off scale of the theory $\Lambda_{\rm UV}$

[Grimm, Palti, Valenzuela '18; Castellano, Herráez, Ibáñez '22]



$$\delta g_{\phi\phi}^{1-\text{loop}} \xrightarrow{\Lambda_{\rm UV} \gg m_n} \sum_{n=1}^{\Lambda_{\rm UV}/m(\phi)} n^2 (\partial_\phi m(\phi))^2 \sim \left(\frac{\Lambda_{\rm UV}}{m(\phi)} \right)^3 (\partial_\phi m(\phi))^2$$

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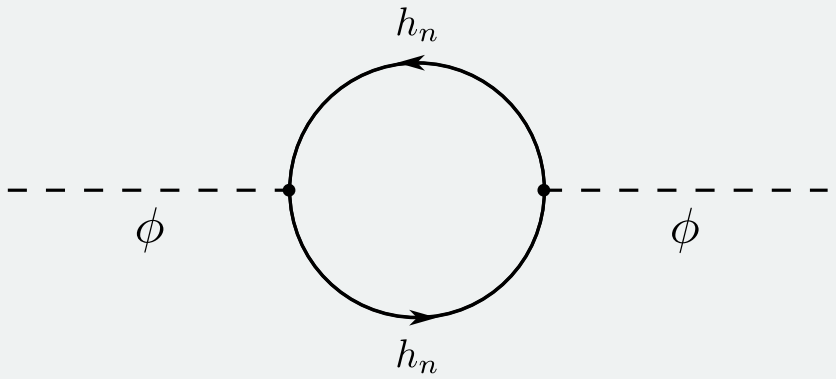

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- **Lesson:** if h_n really light, $\delta g_{\phi\phi}^{1-\rm loop}$ dominates and the kinetic term arises from quantum effects

Goal:

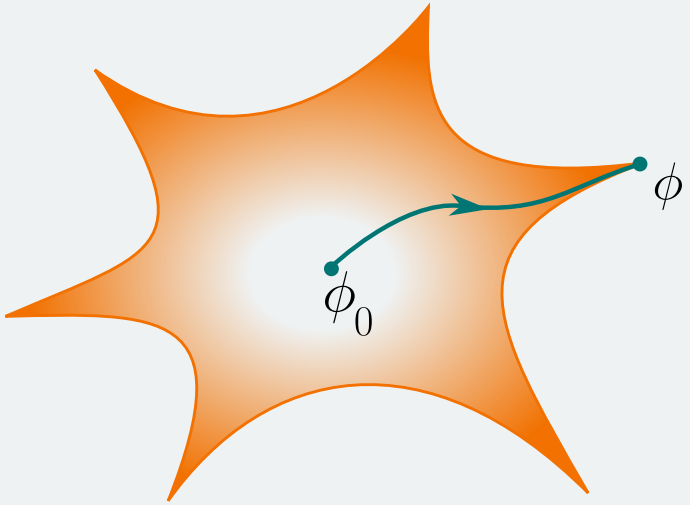
Find a string theory setting in which the entire effective action emerges in this way.

Swampland Program

Swampland Distance Conjecture [Ooguri, Vafa '06]

At an infinite distance point in the moduli space an infinite tower of light states appears with masses scaling as

$$M(\phi) \sim M(\phi_0) e^{-\alpha \mathrm{d}(\phi_0,\phi)} \, .$$



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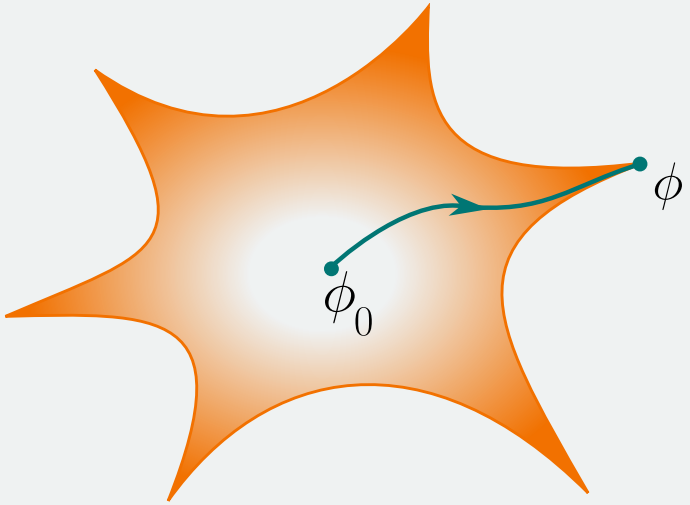

Species Scale **[Dvali '08]**

The UV cutoff in the presence of many light species:

$$\Lambda_{\mathrm{sp}} = M_{\mathrm{Pl}}^{(d)} / N_{\mathrm{sp}}^{\frac{1}{d-2}}$$

[Long, Montero, Vafa, Valenzuela '21; van de Heisteeg, Vafa, Wiesner, Wu '22 & '23; Castellano, Herráez, Ibáñez '23; (Basile), Cribiori, Lüst, Montella ('23) '24; Bedroya, Vafa, Wu '24; ...]

Emergence Proposal

Emergence Proposal **[Palti '19]**

The dynamics (kinetic terms) for all fields are emergent in the infrared by integrating out the states down from a UV scale, which is below the Planck scale.

→ Many works: **[Grimm, Palti, Valenzuela '18; Heidenreich, Reece, Rudelius '18; Castellano, Herráez, Ibáñez '23; Casas, Ibáñez, Marchesano '24; Blumenhagen, Gligovic, Paraskevopoulou '23; Lee, Lerche, Weigand '21; Calderón-Infante, Delgado, Uranga '23; Calderón-Infante, Delgado, Yi, Lüst, Uranga '25; Marchesano, Melotti '22; Anastasi, Angius, Huertas, Uranga, Wang '25 ...]**

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M-theoretic Emergence Proposal **[Blumenhagen, Cribiori, Gligovic, Paraskevopoulou '24]**

In the isotropic decompactification limit to M-theory, the entire effective action emerges via quantum effects by integrating out the full infinite towers of states with a mass scale not heavier than the species scale.

→ Evidence: **[Blumenhagen, Cribiori, Gligovic, Paraskevopoulou '23, '24; Blumenhagen, Gligovic '25]**

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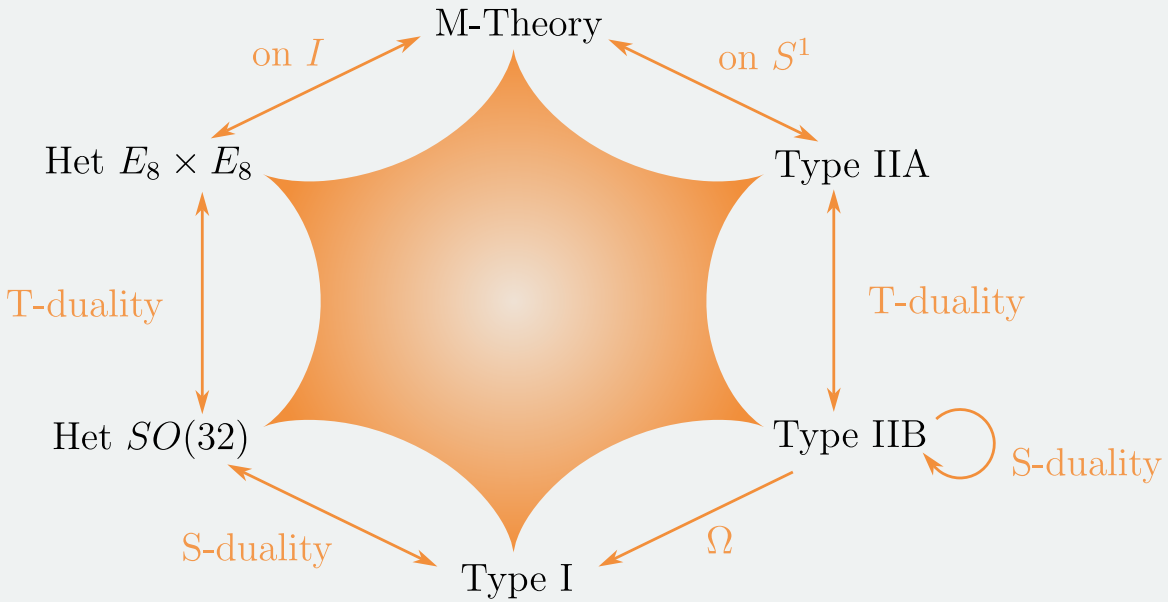
→ F^4-coupling in Heterotic/Type IIA dual theories in 6D

M-theory Limit



- Strongly-coupled type IIA $\leftrightarrow$ M-theory on a large S^1
- Compactify type IIA on a K3 ($T^4/\mathbb{Z}_2$) down to 6d
- Theory dual to heterotic string theory on T^4
  [Sen '95; Witten '95]
- 1/2-BPS particle content:
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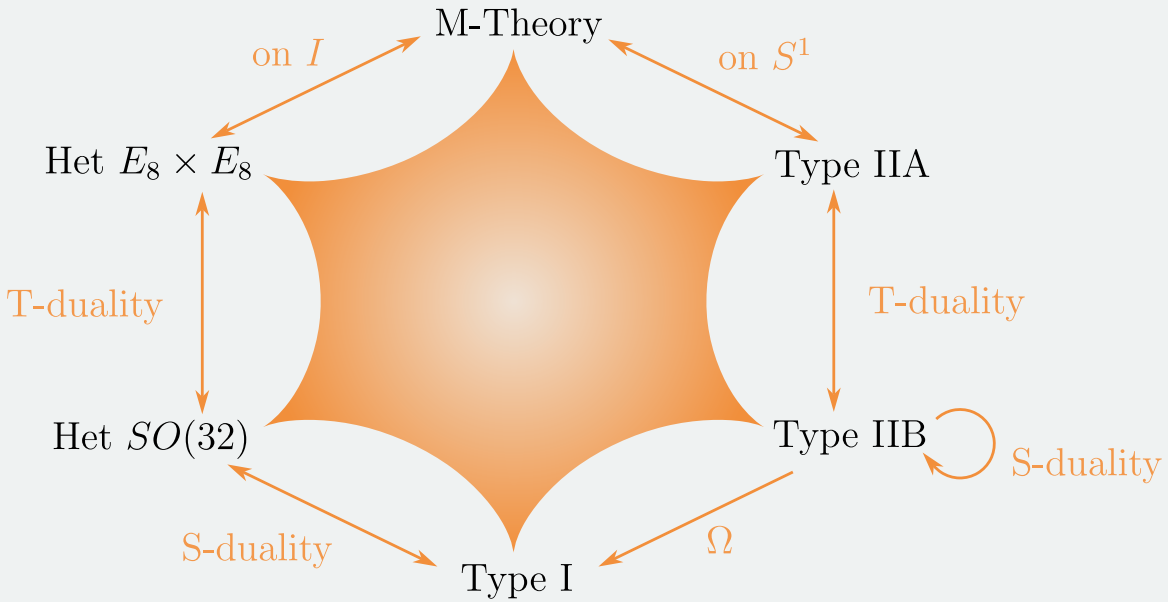

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$\rightarrow$ Isotropic decompactification M-theory limit:

$$R_{11} \to \lambda R_{11}\,, \quad M_* \to \lambda^{-\frac{1}{5}} M_*\,, \quad R_i \to \lambda^{\frac{1}{5}} R_i \qquad (\lambda \to \infty)$$

$\rightarrow$ Species scale:

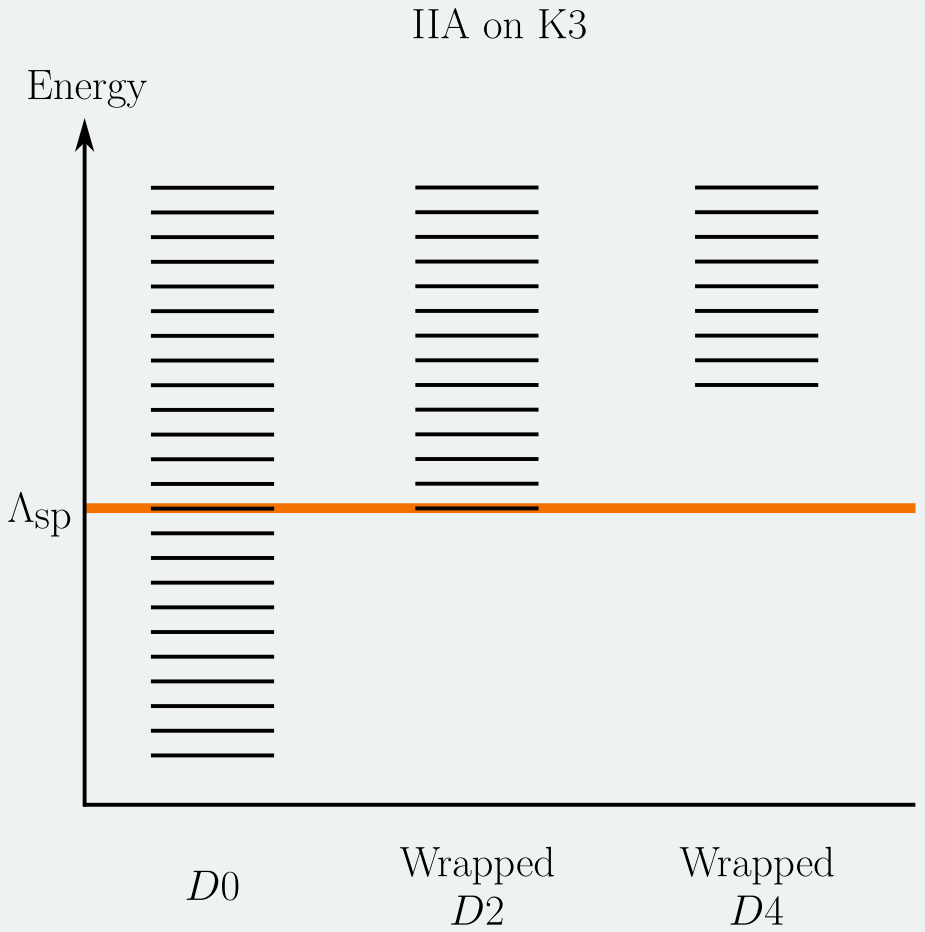
$$\Lambda_{\rm sp} \to \lambda^{-\frac{1}{5}} \Lambda_{\rm sp} \sim M_{\rm Pl}^{(7)}$$

Light towers of states & Emergence

- Light states: $D0$-branes and wrapped $D2$-branes
- Heavy states: wrapped $D4$-branes
- Look at the 1/2-BPS protected term F^4 in the 6d effective action

  [Kiritsis, Obers, Pioline '00]

$$A_{F^4} \sim \sum_{\text{BPS states}} \int_0^\infty \frac{dt}{t^2}\, e^{-\frac{\pi}{t}\mathcal{M}^2}$$



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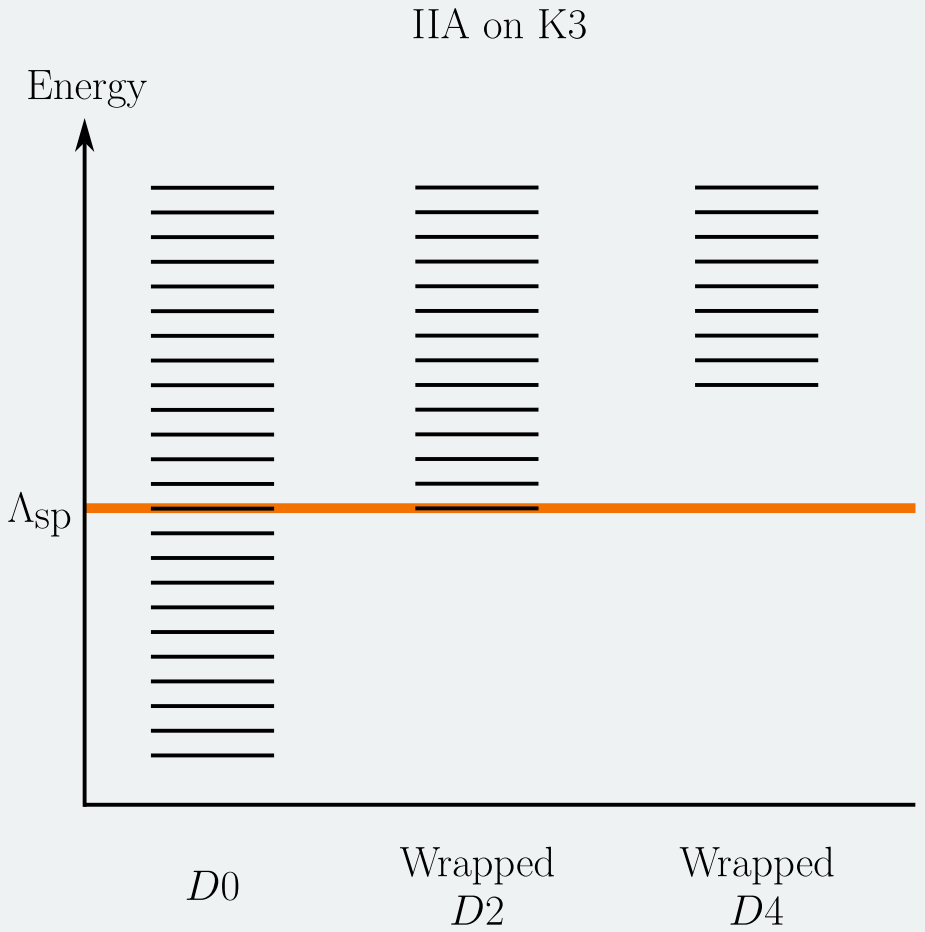
$\rightarrow$ Entire term obtained from a one-loop integration of the light states



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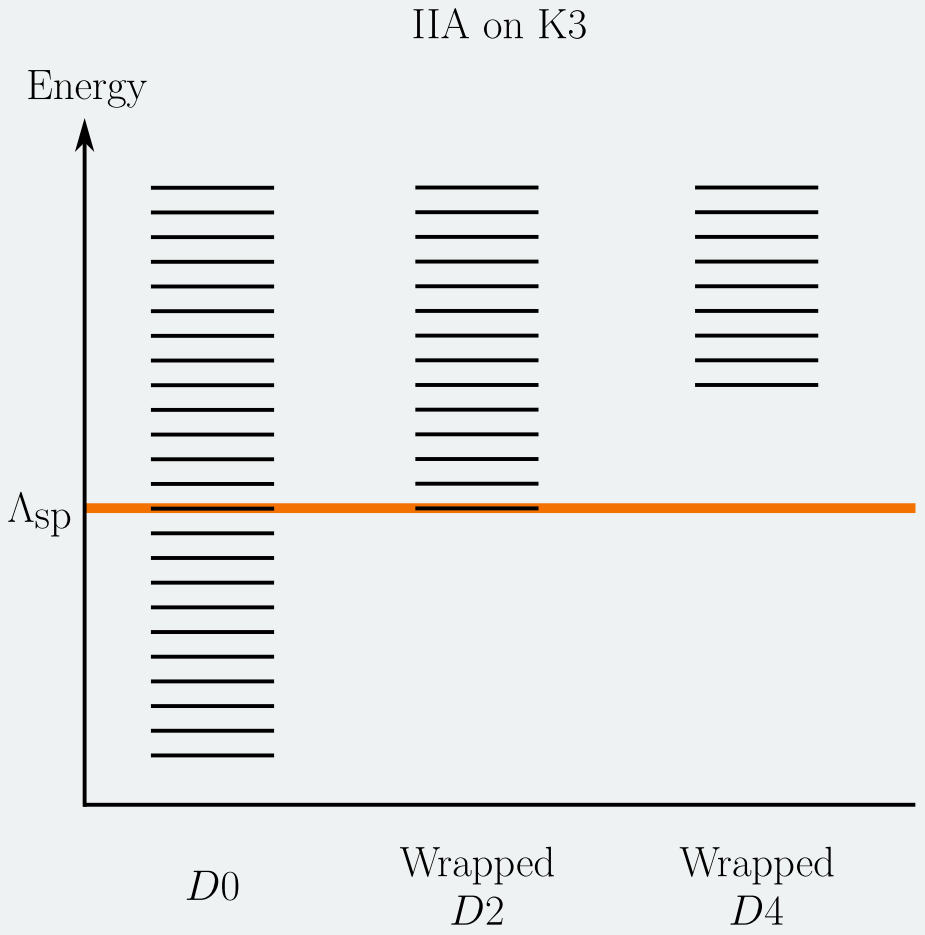
→ Entire term obtained from a one-loop integration of the light states

→ Novel mathematical property

$$\mathcal{E}^{SO(4,4,\mathbb{Z})}_{\mathcal{V};1} \sim \mathcal{E}^{SO(3,3,\mathbb{Z})}_{\mathcal{V}\oplus 1;1}$$



Summary & Outlook

Takeaways:

- **Emergence** has **concrete realizations** in effective actions
- **Light towers of states**, predicted by the Swampland Distance Conjecture, can **generate full terms** in the low-energy action
- **Spacetime emerges** from quantum effects (Einstein-Hilbert term)?

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Results:

- **One-loop effects** from integrating out **light states** ($D0$-branes and $D2$-branes) generate the entire F^4-term in 6d heterotic/type IIA compactified theories
- New **mathematical property** of a string theoretic amplitude

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- New **mathematical property** of a string theoretic amplitude

$\rightarrow$ M-theory is the natural candidate for an emergent description of quantum gravity

What more can we learn about its microscopic description from these principles?

Thank you!

Backup Slides

- Coupling:

$$A_{F^4} \sim \mathcal{E}^{SO(4,4,\mathbb{Z})}_{\mathcal{C};1}$$

$$\mathcal{E}^{SO(4,4,\mathbb{Z})}_{\mathcal{C};1} = \pi \hat{\sum_{n_{ij},m,n_{D4}}} \int_0^\infty \frac{dt}{t^2}\, \delta(\mathrm{BPS})\, e^{-\frac{\pi}{t}\left(\sum_{i,j}(n_{ij}\, r_i r_j)^2 + (m/r_{11})^2 + (n_{D4}\, r_{11}\, v_{T4})^2\right)}$$

$$n_{12}n_{34} + n_{13}n_{24} + n_{14}n_{23} + m n_{D4} = 0$$

- Duality:

$$(m_1; m_2, m_3, m_4; n_2, n_3, n_4; n_1) = (m; n_{12}, n_{13}, n_{14}; n_{34}, n_{42}, n_{23}; n_{D4})\,.$$

- Instanton expansion:

$$A^{\mathrm{H}}_{\mathrm{inst}} = 2\pi\, l^2_{\mathrm{H}}\, V^{\mathrm{H}}_4 \sum_{N>0} \hat{\sum_{C_{ij}|\mathrm{BPS}}} \frac{e^{-N S_{\mathrm{inst}}(\vec{C})}}{S_{\mathrm{inst}}(\vec{C})}\,, \qquad S_{\mathrm{inst}}(\vec{C}) := \sqrt{\sum_{i<j} \vartheta^2_{ij}\, C^2_{ij}}$$

BPS-condition: $C_{[ij}C_{kl]} = 0$

# winding numbers	# worldsheet instantons
1	1, 2, 3
2	1, 2, 3, 4, 5
3	2, 3, 5, 6
4	3, 4, 5, 6

Backup Slides

- An example:

$$A^{\mathrm{H}}_{(EF1_{12},EF1_{13},EF1_{23})} = A[n_1,n_2] + A[n_1,n_3] + A[n_2,n_3] - 2A[n_1,n_2,n_3]\,.$$

- Scalings:

$$g_{\mathrm{IIA}} \to \lambda^{\frac{6}{5}} g_{\mathrm{IIA}}\,, \quad l_{\mathrm{IIA}} \to \lambda^{-\frac{1}{5}} l_{\mathrm{IIA}}\,, \quad g^{(6)}_{\mathrm{IIA}} \to \lambda^{\frac{2}{5}} g^{(6)}_{\mathrm{IIA}}\,, \quad R^{\mathrm{IIA}}_i \to \lambda^{\frac{2}{5}} R^{\mathrm{IIA}}_i$$

$$g_{\mathrm{H}} \to g_{\mathrm{H}}\,, \quad l_{\mathrm{H}} \to \lambda^{\frac{1}{5}} l_{\mathrm{H}}\,, \quad g^{(6)}_{\mathrm{H}} \to \lambda^{-\frac{2}{5}} g^{(6)}_{\mathrm{H}}\,, \quad R^{\mathrm{H}}_{2,3,4} \to R^{\mathrm{H}}_{2,3,4}\,, \quad R^{\mathrm{H}}_1 \to \lambda^{\frac{4}{5}} R^{\mathrm{H}}_1\,,$$

- Type IIA K3 $\times S^1$ with $M^{(5)}_{\mathrm{Pl}}$ fixed $\Rightarrow$ Light states: $D0$'s, wrapped $D2$'s and wrapped $NS5$'s

$$R^{\mathrm{H}}_5 = \frac{1}{g_{\mathrm{IIA}}}\sqrt{R^{\mathrm{IIA}}_1 R^{\mathrm{IIA}}_2 R^{\mathrm{IIA}}_3 R^{\mathrm{IIA}}_4}\, R^{\mathrm{IIA}}_5\,, \qquad (m_5,n_5) \longleftrightarrow (m_5,n_{NS5})$$

For example: $A^{\mathrm{H}}_{EF1_{15}} = A[n_1] + A[n_5] - A[n_1,n_5]$

$$EF1_{15} \longleftrightarrow ED4 \qquad EF1_{i5} \longleftrightarrow ED2$$