KKLT in ten dimensions and scale separation

Mariana Graña
CEA / Saclay
France

Work in collaboration with

Nicolas Kovensky	arXiv: 2209.xxxxx
N. Kovensky, A. Retolaza	arXiv: 2002.01481
I. Bena, N. Kovensky, A. Retolaza	arXiv: 1908.01785

Swampland workshop, Madrid, September 2022

Introduction

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- DGKT prominent example of power law scale-separation

DeWolfe, Giryavets, Kachru, Taylor 05

$$\frac{\ell_{KK}}{\ell_{AdS}} \sim \frac{1}{R^p}$$

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Lust, Vafa, Weisner, Xu 22

see Severin's talk

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← Nico Kovensky (digging in the landscape)

4) Scale separation

$\mathcal{N}$=1 SUSY AdS equations with gaugino condensate

- Warped product metric

$$ds^2 = e^{2A}(\underset{\substack{\big\uparrow \\ \text{AdS with } \Lambda = -|\mu|^2}}{g_{\mu\nu}} dx^\mu dx^\nu) + ds_6^2$$

- Lorentz-invariant fluxes

$$\hat{F} = F + e^{4A}\mathrm{vol}_4 \wedge \tilde{F} \qquad \tilde{F} = \pm *_6 F$$

$$\hat{H} = H$$

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- Supersymmetry spinors

$$\epsilon^1 = \xi \otimes \eta^1$$

$$\epsilon^2 = \xi \otimes \eta^2$$

in general not parallel

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- Taylor-made for formalism of generalized complex geometry

even forms

$$\Psi_{\pm} = \sum_p \left(\eta_\pm^{2\dagger}\gamma_{m_1\ldots m_p}\eta_+^1\right) dy^{m_1}\wedge\ldots\wedge dy^{m_p}$$

odd forms

Encode all info about internal geometry

$\mathcal{N}$=1 SUSY AdS equations with gaugino condensate

- Pure spinors

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- CY (or more generally SU(3) structure) with O3-planes: $i\eta^2 = \eta^1$

$$\Psi_+ = e^{iJ} \qquad \Psi_- = i\Omega_3$$

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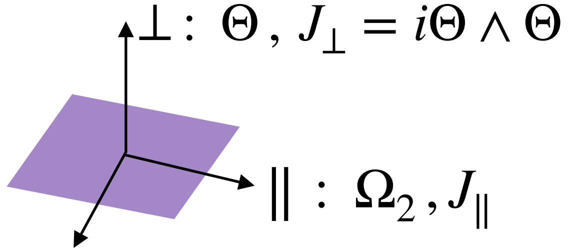

may not be globally defined

- "Local SU(2) structure": $i\eta^2 = \cos\varphi\,\eta^1 + \sin\varphi\,\Theta_m\gamma^m\eta^1$

$$\Psi_+ = e^{iJ_\perp}\wedge\left[\cos\varphi\left(1-\frac{1}{2}J_\|^2\right) + iJ_\| + \sin\varphi\,\mathrm{Im}\Omega_2\right]$$

$$\Psi_- = \Theta\wedge\left[\sin\varphi\left(1-\frac{1}{2}J_\|^2\right) + i\mathrm{Re}\Omega_2 - \cos\varphi\,\mathrm{Im}\Omega_2\right]$$

Type IIB $\mathcal{N}$=1 SUSY AdS equations (up to warp factors and dilaton) (Type IIA $\Psi_- \leftrightarrow \Psi_+$)

$$\boxed{\begin{aligned} d_H \Psi_- &= 2i\mu \, \mathrm{Im}\Psi_+ \\ d_H \, \mathrm{Re}\Psi_+ &= 3\,\mathrm{Re}\left(\bar{\mu}\Psi_-\right) + *F \\ \left(\underset{\overset{\uparrow}{d - H\wedge}}{d_H}\mathrm{Im}\Psi_+ = 0\right) \end{aligned}}$$

$(\Lambda = -|\mu|^2)$

Graña, Minasian, Petrini, Tomasiello 05

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$$\Psi_+ = e^{iJ} \qquad \Psi_- = i\Omega_3 \qquad \Rightarrow \qquad d_H\Omega = 2i\mu\left(J - \frac{1}{6}J^3\right) \Bigg\} \quad \begin{aligned} \mu &= 0 \\ d\Omega &= 0 \\ H\wedge\Omega &= 0 \end{aligned}$$

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d_H ↑ $d - H\wedge$

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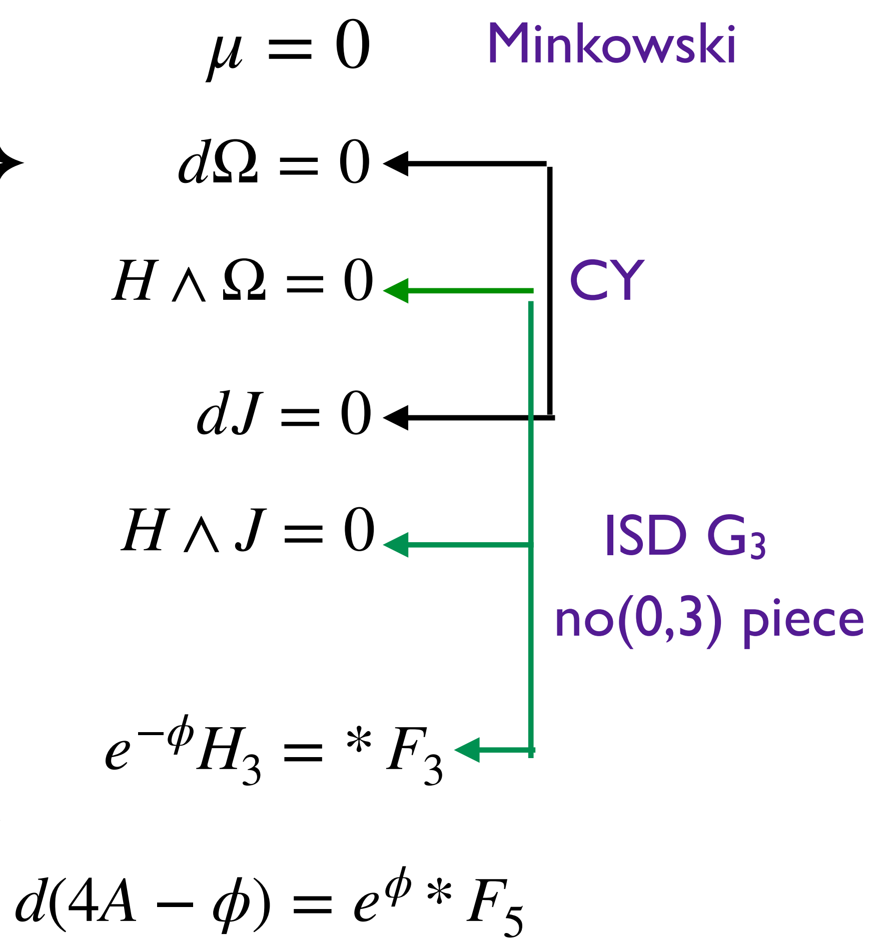

$\mu = 0$ Minkowski

$d\Omega = 0$

$H \wedge \Omega = 0$

CY

$dJ = 0$

$H \wedge J = 0$

ISD G₃

no(0,3) piece

$e^{-\phi}H_3 = *\,F_3$

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$G_3 = F_3 - ie^{-\phi}H_3$

$\mathcal{N}$=1 SUSY AdS$_4$ equations $\Longleftrightarrow$ 4d EFT, F-terms =0

Koerber, Martucci 07
Cassani 07

- $\mathcal{N}$=1 chiral multiplets:

$$Z = \Psi_-$$ complex structure moduli

SU(3) : Ω

$$T = C + ie^{-\phi}\,\mathrm{Re}\Psi_+$$ axio-dilaton and Kahler moduli

SU(3) : $\tau\,, C_4 + ie^{-\phi}J^2$

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$$\mu = e^{K/2} < W_0 >$$

$$\Longleftrightarrow \qquad \begin{array}{l} D_T W_0 = 0 \\ D_Z W_0 = 0 \end{array}$$

$$W_0 = \int Z \wedge d_H T$$

$$\Omega \wedge G_3$$

Generalization of GVW

M.G, Louis, Waldram 05
Benmachiche, Grimm 06

$\mathcal{N}$ =1 SUSY AdS equations with gaugino condensates

- Space-time filling Dp-branes wrapping a (p-3) calibrated (susy) internal cycle Σ with vev for gaugino condensate $<\lambda\lambda>$. Here: D7-branes wrapping a 4-cycle Σ_4

parts of these equations in
Dymarsky, Martucci, 10
Kachru, Kim, Mc Allister, Zimet, 19

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2-form dual to 4-cycle
with support only on cycle

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0-form s. t

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Dymarsky, Martucci, 10 $D_T(W_0 + W_{\mathrm{NP}}) = 0$

$$<W_{\mathrm{NP}}> = Ae^{iaT} = Ae^{-a\int_\Sigma \mathrm{Re}\Psi_+} = \frac{1}{2a} <\lambda\lambda>$$

$$D_Z W_0 = 0$$

$\mathcal{N}$=1 SUSY AdS equations with gaugino condensates

- Space-time filling Dp-branes wrapping a (p-3) calibrated (susy) internal cycle Σ with vev for gaugino condensate $<\lambda\lambda>$. Here: D7-branes wrapping a 4-cycle Σ_4

2-form dual to 4-cycle
with support only on cycle

0-form s. t

$$\int_{M_6} \delta^{(0)}[\Sigma] = vol(\Sigma) \equiv \sigma_4$$

parts of these equations in
Dymarsky, Martucci, 10
Kachru, Kim, Mc Allister, Zimet, 19

$$\boxed{\begin{aligned} d_H\Psi_- &= 2i\mu\,\mathrm{Im}\Psi_+ - 2i <\lambda\lambda>\ \delta^{(2)}[\Sigma_4] \\ d_H\,\mathrm{Re}\Psi_+ &= 3\,\mathrm{Re}\left(\bar{\mu}\Psi_-\right) + *F - \mathrm{Re}\left(<\lambda\lambda>\Psi_-\right)\ \delta^{(0)}[\Sigma_4] \end{aligned}}$$

$$\Updownarrow$$

Dymarsky, Martucci, 10

$$D_T(W_0 + W_{\mathrm{NP}}) = 0$$

$$D_Z(W_0 + W_{\mathrm{NP}}) = 0$$

$$<W_{\mathrm{NP}}> = Ae^{iaT} = Ae^{-a\int_\Sigma \mathrm{Re}\Psi_+} = \frac{1}{2a} <\lambda\lambda>$$

$$\mu = e^{K/2} < W_0 + W_{\mathrm{NP}} >$$

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2-form piece cannot be satisfied

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2-form piece cannot
be satisfied

- Need local SU(2) structure. Unless… $\delta^{(2)} \rightarrow J$

Smearing the D7
with gaugino condensate

Koerber, Martucci 08

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

$$d_H\Omega = 2i\mu \left(J - \frac{1}{6} J^3 \right) - 2i < \lambda\lambda > \ \delta^{(2)}[\Sigma_4]$$

$$d_H \left(1 + \frac{1}{2} J^2 \right) = 3 \, \mathrm{Re} \left(\bar{\mu}\Omega \right) + {}^*F - \mathrm{Re} \, (< \lambda\lambda > \Omega) \ \delta^{(0)}[\Sigma_4]$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

$$d_H\Omega = 2i\mu\left(J - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \ \delta^{(2)}[\Sigma_4]$$

$$\downarrow$$

$$\frac{\sigma_4}{3V}J$$

$$\int_{M_6} \delta^{(2)} \wedge \frac{1}{2}J^2 = \sigma_4$$

$$\downarrow$$

$$\int_{M_6} \frac{\sigma_4}{3V}J \wedge \frac{1}{2}J^2 = \sigma_4$$

$$d_H\left(1 + \frac{1}{2}J^2\right) = 3\,\mathrm{Re}\left(\bar{\mu}\Omega\right) + {}^*F - \mathrm{Re}\,(\ < \lambda\lambda > \Omega)\ \delta^{(0)}[\Sigma_4]$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

$$d_H\Omega = 2i\mu\left(J - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \underset{\displaystyle \frac{\sigma_4}{3V}J}{\underset{\displaystyle\downarrow}{\delta^{(2)}[\Sigma_4]}}$$

$$d_H\left(1 + \frac{1}{2}J^2\right) = 3\,\mathrm{Re}\left(\bar{\mu}\Omega\right) + {}^*F - \mathrm{Re}\left(< \lambda\lambda > \Omega\right)\, \underset{\displaystyle \frac{\sigma_4}{V}}{\underset{\displaystyle\downarrow}{\delta^{(0)}[\Sigma_4]}}$$

$$\int_{M_6}\delta^{(2)} \wedge \frac{1}{2}J^2 = \sigma_4$$

$$\downarrow$$

$$\int_{M_6}\frac{\sigma_4}{3V}J \wedge \frac{1}{2}J^2 = \sigma_4$$

$$\int_{M_6}\delta^{(0)}[\Sigma] = \sigma_4$$

$$\downarrow$$

$$\int_{M_6}\frac{\sigma_4}{V} = \sigma_4$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

(smeared) $< \lambda\lambda >$

$$d_H\Omega = 2i\mu \left(J - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \frac{\sigma_4}{3V} J$$

$$d_H \left(1 + \frac{1}{2}J^2\right) = 3\,\mathrm{Re}\left(\bar{\mu}\Omega\right) + {}^*F - \mathrm{Re}\,(< \lambda\lambda > \Omega)\, \frac{\sigma_4}{V}$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

(smeared) $<\lambda\lambda>$

$$\left. d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i <\lambda\lambda> \cancel{\frac{\sigma_4}{3V}}\, J \quad \right\} \quad \mu = <\lambda\lambda> \frac{\sigma_4}{3V}$$

$$d_H\left(1 + \frac{1}{2}J^2\right) = 3\,\mathrm{Re}\left(\bar{\mu}\Omega\right) + {}^*F - \mathrm{Re}\,(<\lambda\lambda>\Omega)\,\frac{\sigma_4}{V}$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

(smeared) $<\lambda\lambda>$

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(smeared) $< \lambda\lambda >$

$$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \cancel{\frac{\sigma_4}{3V}}\, J \quad \left.\begin{matrix} \mu = < \lambda\lambda > \dfrac{\sigma_4}{3V} \\ d\Omega = 0 \\ H \wedge \Omega = \frac{1}{3}\mu J^3 \end{matrix}\right\}$$

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$$e^{-\phi}H_3 = {}^*F_3$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

(smeared) $< \lambda\lambda >$

$$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \cancel{\frac{\sigma_4}{3V}}\, J \quad \Bigg\}$$

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$$e^{-\phi}H_3 = *\,F_3$$

$$d_H\left(J - \frac{1}{6}J^3\right) = 0$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

(smeared) $<\lambda\lambda>$

$$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \cancel{\frac{\sigma_4}{3V}}\, J \quad \Bigg\}$$

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$$dJ = 0$$

$$H \wedge J = 0$$

$\mathcal{N}$=1 SUSY AdS solution with smeared gaugino condensate

	(smeared) $<\lambda\lambda>$	$<\lambda\lambda> = 0$
$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i <\lambda\lambda> \cancel{\frac{\sigma_4}{3V}}\, J$	$\mu = <\lambda\lambda> \frac{\sigma_4}{3V}$ $d\Omega = 0$ $H \wedge \Omega = \frac{1}{3}\mu J^3$	$\mu = 0$ $d\Omega = 0$ $H \wedge \Omega = 0$
$d_H\left(1 + \frac{1}{2}J^2\right) = 3\,\cancel{\mathrm{Re}}(\bar{\mu}\Omega) + {*F} - \mathrm{Re}\,(<\cancel{\lambda}\lambda> \Omega)\,\frac{\sigma_4}{V}$	$e^{-\phi}H_3 = *\,F_3$	$e^{-\phi}H_3 = *\,F_3$
$d_H\left(J - \frac{1}{6}J^3\right) = 0$	$dJ = 0$ $H \wedge J = 0$	$dJ = 0$ $H \wedge J = 0$

- 4d Minkowski
- CY
- $G_3 = G_{2,1}$

$\mathcal{N}$=1 SUSY AdS solution with smeared gaugino condensate

	(smeared) $<\lambda\lambda>$	$<\lambda\lambda> = 0$
$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i <\lambda\lambda> \cancel{\frac{\sigma_4}{3V}}\, J$	$\mu = <\lambda\lambda> \frac{\sigma_4}{3V}$ $d\Omega = 0$ $H \wedge \Omega = \frac{1}{3}\mu J^3$	$\mu = 0$ $d\Omega = 0$ $H \wedge \Omega = 0$
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$d_H\left(J - \frac{1}{6}J^3\right) = 0$	$dJ = 0$ $H \wedge J = 0$	$dJ = 0$ $H \wedge J = 0$
	• Still CY! • Still ISD G_3!	• 4d Minkowski • CY • $G_3 = G_{2,1}$

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$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i <\lambda\lambda> \cancel{\frac{\sigma_4}{3V}}\, J$	$\boxed{\mu = <\lambda\lambda> \frac{\sigma_4}{3V}}$ $d\Omega = 0$ $\boxed{H \wedge \Omega = \frac{1}{3}\mu J^3}$	$\boxed{\mu = 0}$ $d\Omega = 0$ $\boxed{H \wedge \Omega = 0}$
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- CY
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- Still CY!
- Still ISD G_3!
- But:

$$\boxed{\begin{array}{c} G_3 = G_{(2,1)} + \mu\,\bar{\Omega} \\ \text{AdS}_4 \text{ (and SUSY)!} \end{array}}$$

$\mathcal{N}$ =1 SUSY AdS solution with smeared gaugino condensate

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$d_H\Omega = 2i\mu\left(\cancel{J} - \frac{1}{6}J^3\right) - 2i<\lambda\lambda>\cancel{\frac{\sigma_4}{3V}}\,J$	$\boxed{\mu = <\lambda\lambda>\frac{\sigma_4}{3V}}$ $d\Omega = 0$ $\boxed{H\wedge\Omega = \frac{1}{3}\mu J^3}$	$\boxed{\mu = 0}$ $d\Omega = 0$ $\boxed{H\wedge\Omega = 0}$
$d_H\left(1+\frac{1}{2}J^2\right) = 3\,\mathrm{Re}\cancel{(\bar{\mu}\Omega)} + *F - \mathrm{Re}\,(<\cancel{\lambda}\lambda>\Omega)\,\frac{\sigma_4}{V}$	$e^{-\phi}H_3 = *F_3$	$e^{-\phi}H_3 = *F_3$
$d_H\left(J - \frac{1}{6}J^3\right) = 0$	$dJ = 0$ $H\wedge J = 0$	$dJ = 0$ $H\wedge J = 0$

- Note: $\mu = <\lambda\lambda>\frac{\sigma_4}{3V}$

- Still CY!
- Still ISD G₃!
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$$d_H\left(1 + \frac{1}{2}J^2\right) = 3\,\mathrm{Re}\cancel{(\bar{\mu}\Omega)} + {}^*F - \mathrm{Re}\,(< \cancel{\lambda}\lambda > \Omega)\,\frac{\sigma_4}{V}$$

$$d_H\left(J - \frac{1}{6}J^3\right) = 0$$

(smeared) $< \lambda\lambda >$	$< \lambda\lambda > = 0$
$\mu = < \lambda\lambda > \frac{\sigma_4}{3V}$	$\mu = 0$
$d\Omega = 0$	$d\Omega = 0$
$H \wedge \Omega = \frac{1}{3}\mu J^3$	$H \wedge \Omega = 0$
$e^{-\phi}H_3 = *\,F_3$	$e^{-\phi}H_3 = *\,F_3$
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AdS4 (and SUSY)!

- Note: $\mu = < \lambda\lambda > \frac{\sigma_4}{3V}$

$$\Downarrow$$

$$\frac{1}{V} < W_0 + W_{\rm NP} > = < W_{\rm NP} > \frac{2a\sigma_4}{3V}$$

$\mathcal{N}$=1 SUSY AdS solution with smeared gaugino condensate

	(smeared) $< \lambda\lambda >$	$< \lambda\lambda > = 0$
$d_H\Omega = 2i\mu \left(\cancel{J} - \frac{1}{6}J^3\right) - 2i < \lambda\lambda > \cancel{\frac{\sigma_4}{3V}} J$	$\mu = < \lambda\lambda > \frac{\sigma_4}{3V}$ $d\Omega = 0$ $H \wedge \Omega = \frac{1}{3}\mu J^3$	$\mu = 0$ $d\Omega = 0$ $H \wedge \Omega = 0$
$d_H \left(1 + \frac{1}{2}J^2\right) = 3\,\cancel{\mathrm{Re}}(\bar{\mu}\Omega) + {}^*F - \mathrm{Re}\,(< \cancel{\lambda}\lambda > \Omega)\, \frac{\sigma_4}{V}$	$e^{-\phi}H_3 = * F_3$	$e^{-\phi}H_3 = * F_3$
$d_H \left(J - \frac{1}{6}J^3\right) = 0$	$dJ = 0$ $H \wedge J = 0$	$dJ = 0$ $H \wedge J = 0$

- Note: $\mu = < \lambda\lambda > \frac{\sigma_4}{3V}$

$$\Downarrow$$

$$\frac{1}{V} < W_0 + W_{\rm NP} > = < W_{\rm NP} > \frac{2a\sigma_4}{3V}$$

$$< W_0 > = - < W_{\rm NP} > \left(1 + \tfrac{2}{3}a\sigma_4\right)$$

Exactly as in KKLT

- Still CY!
- Still ISD G_3!
- But:

$$G_3 = G_{(2,1)} + \mu\,\bar{\Omega}$$

AdS$_4$ (and SUSY)!

- 4d Minkowski
- CY
- $G_3 = G_{2,1}$

$\mathcal{N}$ =1 SUSY AdS solution with localised gaugino condensate

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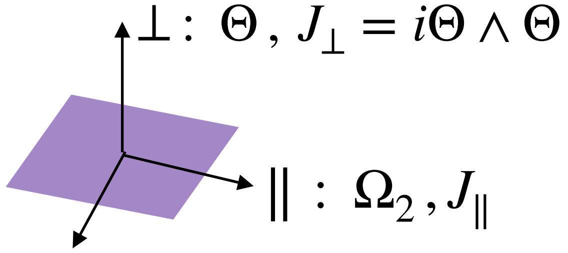

- Local SU(2) structure: $i\eta^2 = \cos\varphi\,\eta^1 + \sin\varphi\,\Theta_m\gamma^m\eta^1$

$$\Psi_+ = e^{iJ_\perp}\wedge\left[\cos\varphi\left(1-\frac{1}{2}J_\parallel^2\right) + iJ_\parallel + \sin\varphi\,\mathrm{Im}\Omega_2\right]$$

$$\Psi_- = \Theta\wedge\left[\sin\varphi\left(1-\frac{1}{2}J_\parallel^2\right) + i\mathrm{Re}\Omega_2 - \cos\varphi\,\mathrm{Im}\Omega_2\right]$$

$\mathcal{N}$=1 SUSY AdS solution with localised gaugino condensate

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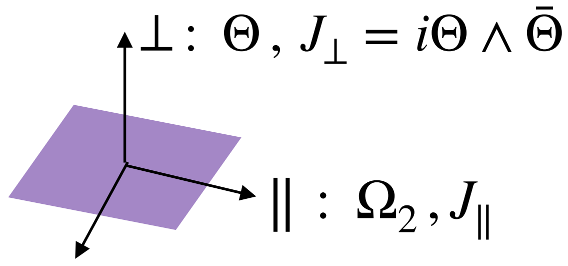
$$d_H \mathrm{Im}\Psi_+ = 0$$



$\perp :\ \Theta\,,\ J_\perp = i\Theta \wedge \bar{\Theta}$

$\| \,:\ \Omega_2\,, J_\|$

- Local SU(2) structure: $i\eta^2 = \cos\varphi\,\eta^1 + \sin\varphi\,\Theta_m\gamma^m\eta^1$

$$\Psi_+ = e^{iJ_\perp} \wedge \left[\cos\varphi\left(1 - \frac{1}{2}J_\|^2\right) + iJ_\| + \sin\varphi\,\mathrm{Im}\Omega_2\right]$$

$$\Psi_- = \Theta \wedge \left[\sin\varphi\left(1 - \frac{1}{2}J_\|^2\right) + i\mathrm{Re}\Omega_2 - \cos\varphi\,\mathrm{Im}\Omega_2\right]$$

- At first order in φ

$$d\,(\varphi\Theta) = 2i\mu\,(J_\perp + J_\|) - 2i < \lambda\lambda > \ \delta^{(2)}[\Sigma_4]$$

$$\vdots$$

Dymarsky, Martucci, 10
($\mu = 0$)

$\mathcal{N}$=1 SUSY AdS solution with localised gaugino condensate

$$d_H\Psi_- = 2i\mu\,\mathrm{Im}\Psi_+ - 2i < \lambda\lambda > \delta^{(2)}[\Sigma_4]$$

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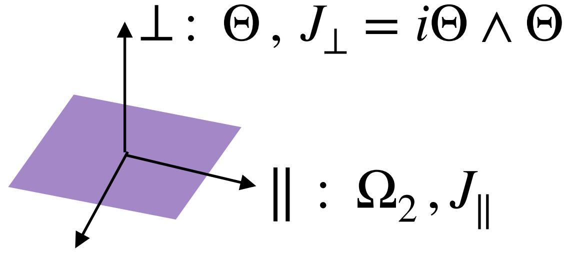

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$$\Psi_+ = e^{iJ_\perp}\wedge\left[\cos\varphi\left(1-\frac{1}{2}J_\parallel^2\right) + iJ_\parallel + \sin\varphi\,\mathrm{Im}\Omega_2\right]$$

$$\Psi_- = \Theta\wedge\left[\sin\varphi\left(1-\frac{1}{2}J_\parallel^2\right) + i\mathrm{Re}\Omega_2 - \cos\varphi\,\mathrm{Im}\Omega_2\right]$$

- At first order in φ

Dymarsky, Martucci, 10
$(\mu = 0)$

$$d\left(\varphi\Theta\right) = 2i\mu\left(J_\perp + J_\parallel\right) - 2i < \lambda\lambda > \delta^{(2)}[\Sigma_4]$$

$$\vdots$$

- For any φ

Recap (before we get to scale separation)

- $\mathcal{N} = 1$ AdS equations with gaugino condensates on spacetime filling Dp-branes

Recap (before we get to scale separation)

- $\mathcal{N} = 1$ AdS equations with gaugino condensates on spacetime filling Dp-branes

- Solved for smeared D7-brane

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  - Internal space is CY
  - ISD flux $G_3 = G_{(2,1)} + \mu\,\bar{\Omega}$ where $|\mu|^2 = -\Lambda$

Recap (before we get to scale separation)

- $\mathcal{N} = 1$ AdS equations with gaugino condensates on spacetime filling Dp-branes

- Solved for smeared D7-brane
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