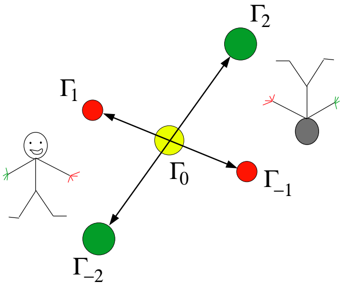
Orientiholes



Frederik Denef, Mboyo Esole and Megha Padi, arXiv:0901.2540

Outline

Motivation and basic idea

Review of $\mathcal{N} = 2$ black hole bound states

Type IIA orientiholes

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The IIB (F-theory) landscape

- Central in modern string phenomenology (Fenomenology)
  - GUT model building [Beasley-Heckman-Vafa,...]
  - models of inflation [Baumann-Dymarsky-Klebanov-McAllister,...]
  - moduli stabilization [Kachru-Kallosh-Linde-Trivedi,...]

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  - genuine, fully consistent compactifications
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  - systematics
- In principle simple [Vafa]:

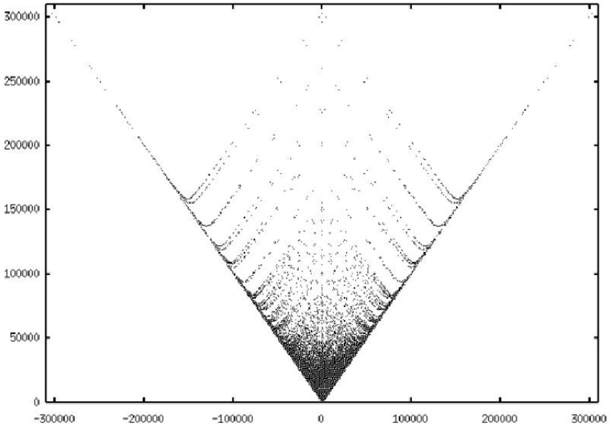
F-theory compactification with 4 susies in 4 dim

$$\Leftrightarrow$$

elliptically fibered CY 4-fold + 4-flux

All CY4 hypersurfaces in weighted $\mathbb{CP}^5$

Total number $= 1,100,055$ [Lynker-Schimmrigk-Wisskirchen]:

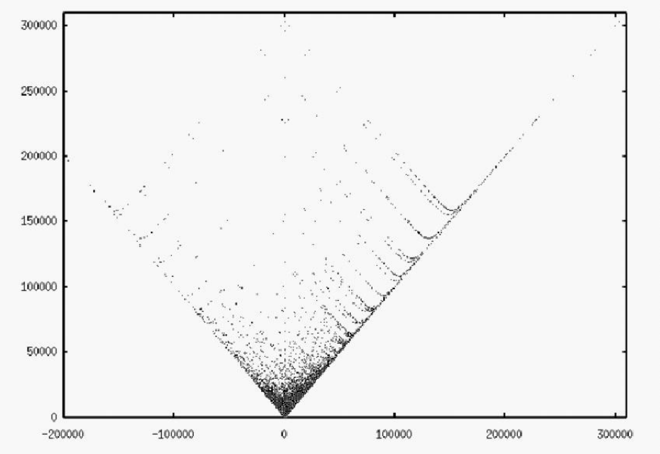


$h_+ \equiv h^{3,1} + h^{1,1}$ versus $h_- \equiv h^{3,1} - h^{1,1}$

$$N_{D3} = \frac{\chi}{24} \approx \frac{h_+}{4}\,.$$

Elliptically fibered subset

At least 49, 751:



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Number of flux vacua

Continuum estimate for number of vacua for *fixed* CY4 within region $\mathcal{M}$ of complex structure moduli space [Ashok-Denef-Douglas]:

$$N_{vac} = \mathrm{Vol}\left[S^{b_4}|_{R^2=\frac{\chi}{12}}\right] \int_{\mathcal{M}} e(D)$$

where

$$\mathrm{Vol}\left[S^{b}|_{R^2=\frac{\chi}{12}}\right] = \frac{(\pi R^2)^{\frac{b}{2}}}{(\frac{b}{2})!}$$

Example with largest χ:

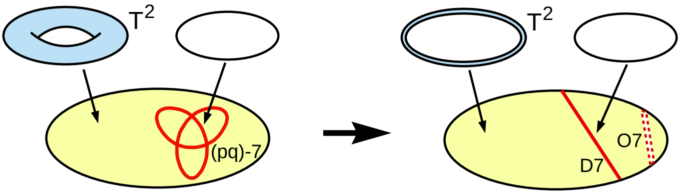
$$w = (1,1,84,516,1204,1806)\,, \quad h^{3,1} = 303148\,, \quad h^{1,1} = 252\,,$$
$$b_4 = 1,819,942\,, \quad \chi = 1,820,448$$

has

$$N_{vac} \propto \mathrm{Vol} = 10^{139598}.$$

Weakly coupled IIB picture

[Sen]



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  - O7 + O3
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  - RR + NSNS 3-flux + worldvolume 2-flux

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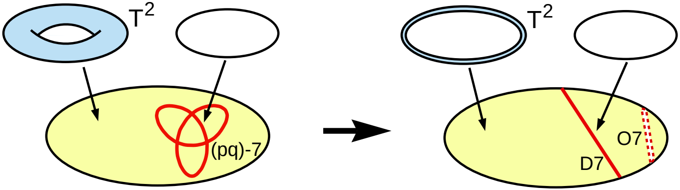

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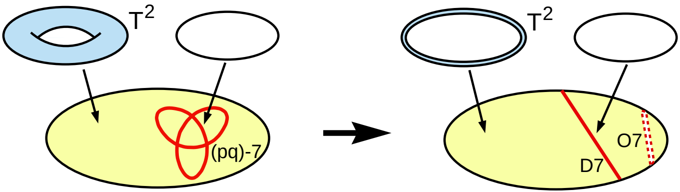

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- Virtually all vacuum degeneracy arises from D-brane d.o.f.
- Constructing all = intractable. Instead: how many D-brane vacua in different sectors? [Douglas]

Problems with conventional approach

- ADD-formula far outside of regime of asymptotic validity $Q_{D3} \gg b_4$ (because $Q_{D3} \sim \frac{b_4}{24}$)
- D7-D3 bound states not taken into account
- No systematic enumeration of different sectors of D7 configuration space
- Even more basic issues such as K-theory constraints and D-term stability have not systematically been addressed.

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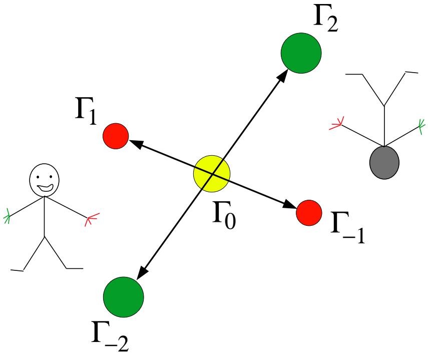
4. Decompactify $\tilde{T}^3 \to \mathbb{R}^3$
5. Take $g_s^{(4)}$ up again

Result: Orientiholes



Key fact:

Witten index vacua $\Leftrightarrow$ index of BPS states

"Experimental" landscapeology

- Estimate numbers of vacua in various sectors landscape by "measuring" (refined) Bekenstein-Hawking entropy of various mesoscopic black hole configurations: $N_{\rm vac} \sim e^{S_{BH}}$

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- brane-brane open string indices $\Leftrightarrow$ angular momenta
- Subtle $\mathbb{Z}_2$ "tadpoles" on IIB side = charge measurable by Aharonov-Bohm experiment

Other motivations

1. funky spacetimes, where you can take a walk around the center of the universe and come back as your mirror image.
2. new invariants and associated modular forms, wall crossing formulae, ...
3. new version of the OSV conjecture: $\mathcal{Z}_{OH} \sim \mathcal{Z}_{top}$ (linear!)

Review of $\mathcal{N} = 2$ black hole bound states

Single centered black holes

Spherically symmetric BPS black hole of charge $\Gamma \equiv (p^\Lambda, q_\Lambda)$:

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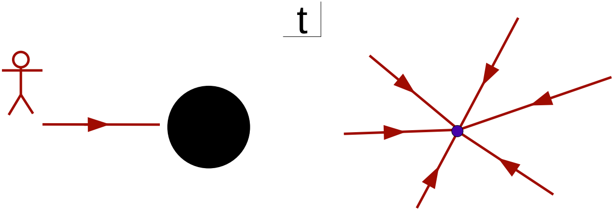

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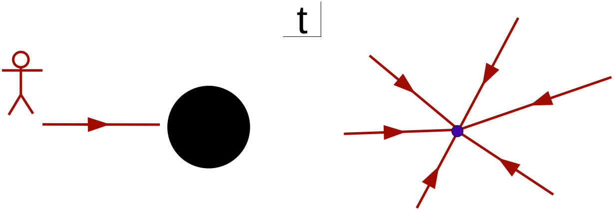


Solutions $\Leftrightarrow$ attractors [Ferrara-Kallosh-Strominger]:

Radial inward flow of vector multiplet moduli $t^A(r)$ is gradient flow of central charge $|Z(\Gamma, t)|$.

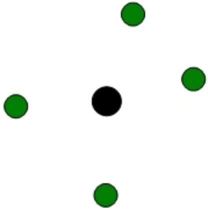
BH entropy:

$$S(\Gamma) = \pi \min_t |Z(\Gamma, t)|^2$$

BPS black hole molecules

More general BPS solutions exist: multi-centered bound states:

$$ds^2 = -e^{2U(\vec{x})}\left(dt - \omega_i dx^i\right)^2 + e^{-2U(\vec{x})} d\vec{x}^2.$$



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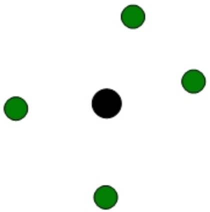

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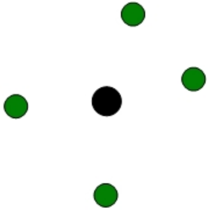

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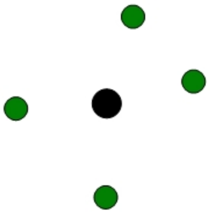

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- Stationary but with intrinsic spin from e.m. field

Explicit multicentered BPS solutions

- N-centered solutions characterized by harmonic function $H(\vec{x})$ from 3d space into charge space:

$$H(\vec{x}) = \sum_{i=1}^{N} \frac{\Gamma_i}{|\vec{x} - \vec{x}_i|} + H_\infty$$

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where $\langle \Gamma_1, \Gamma_2 \rangle = \Gamma_1^{\mathrm{m}} \cdot \Gamma_2^{\mathrm{e}} - \Gamma_1^{\mathrm{e}} \cdot \Gamma_2^{\mathrm{m}}$ and $\alpha = \arg Z(\Gamma)$.

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- All fields can be extracted completely explicitly from the entropy function $S(\Gamma)$ on charge space, e.g.

$$e^{2U(\vec{x})} = \frac{\pi}{S(H(\vec{x}))}$$

2-centered example and decay at marginal stability

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- Equilibrium distance from position constraint:

$$|\vec{x}_1 - \vec{x}_2| = \frac{\langle \Gamma_1, \Gamma_2 \rangle}{2} \frac{|Z_1 + Z_2|}{\mathrm{Im}(Z_1 \overline{Z_2})}\Bigg|_{|\vec{x}|=\infty}$$

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- Spin:

$$J = \frac{\langle \Gamma_1, \Gamma_2 \rangle}{2}$$

Example: pure $D4 = D6 - \overline{D6}$ molecule

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- Instead: realized as bound state of single D6 with $U(1)$ flux $F = P/2$ and anti-(single D6 with flux $F = -P/2$):

Stable for $\mathrm{Im}\, t > \mathcal{O}(P)$.

Transition between $g_s|\Gamma| \gg 1$ and $g_s|\Gamma| \ll 1$ pictures

- Mass squared lightest bosonic modes of open strings between Γ_1 and Γ_2:

$$
\begin{aligned}
M^2/M_s^2 &\sim \frac{|\vec{x}_1 - \vec{x}_2|^2}{\ell_s^2} + \Delta\alpha \\
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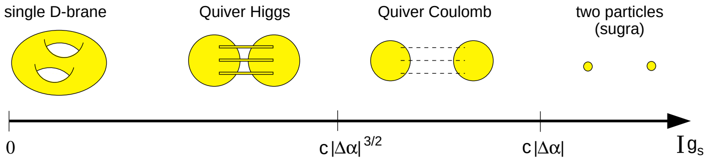
$$= c(t)\, g_s^2 + \Delta\alpha$$

- On stable side of MS wall $\Delta\alpha < 0$, so if g_s gets sufficiently small, open strings become tachyonic and branes condense into single centered D-brane.



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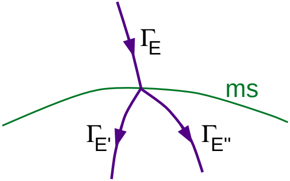
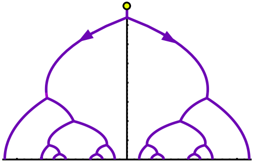
- Conjecture: Branches of multicentered configuration moduli spaces in 1-1 correspondence with attractor flow trees:





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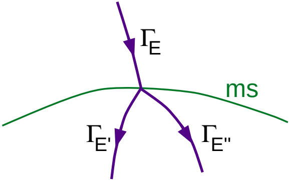

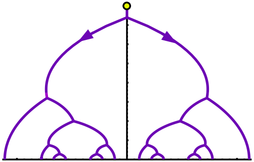

- Much simpler to check & enumerate!

Flow tree decomposition of BPS Hilbert space

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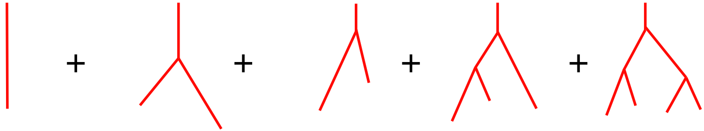
- $\Rightarrow$ Hilbert space of BPS states of charge Γ in background t has canonical decomposition in attractor flow tree sectors:

$$\mathcal{H}(\Gamma, t) =$$



The BPS index

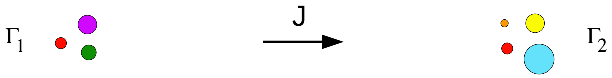
Hilbert space of BPS states in 4d $\mathcal{N} = 2$ theories:

$$\mathcal{H}(\Gamma, t) = (\tfrac{1}{2}, 0, 0) \otimes \mathcal{H}'(\Gamma, t)$$

Index:

$$\Omega(\Gamma, t) = \mathrm{Tr}_{\mathcal{H}'(\Gamma,t)} (-1)^{2J_3'} = (-1)^{\dim_{\mathbb{C}} \mathcal{M}} \chi(\mathcal{M}) \,.$$

Wall crossing formula for primitive splits



- Near marginal stability wall $\Gamma \to \Gamma_1 + \Gamma_2$ (with Γ_1 and Γ_2 primitive), the decaying part of $\mathcal{H}'(\Gamma, t)$ has following factorized form:

$$\Delta\mathcal{H}'(\Gamma, t) = (J) \otimes \mathcal{H}'(\Gamma_1, t) \otimes \mathcal{H}'(\Gamma_2, t)$$

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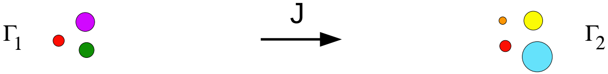

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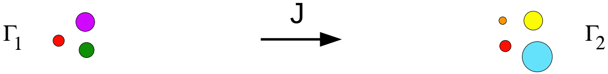

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- Implies index jump

$$\Delta\Omega = (-)^{2J}(2J+1)\,\Omega(\Gamma_1, t_{\text{ms}})\,\Omega(\Gamma_2, t_{\text{ms}}).$$

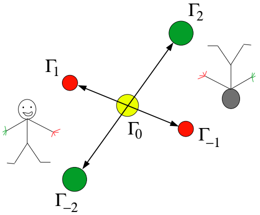
Type IIA orientiholes

Solutions

$= \mathcal{N} = 2$ solutions invariant under τ'. Two cases:

$$\tau_{O4/O0} = \Omega\,\sigma^* \mathcal{P}^*$$
$$\tau_{O6/O2} = \Omega\,(-1)^{F_L}\,\sigma^* \mathcal{P}^* \,.$$

where $\mathcal{P} : \vec{x} \to -\vec{x}$ and σ is internal involution.



E.g. O4/O0 one modulus case:

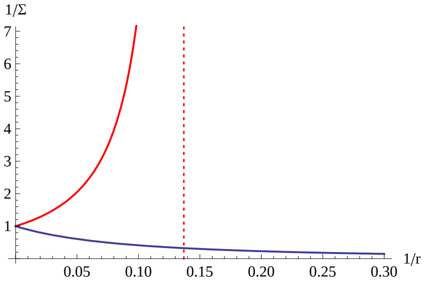
$$\Gamma_1 = (P^0, P^1, Q_1, Q_0)_1\,, \quad \Gamma_{-1} = \Gamma_1' = (-P^0, P^1, -Q_1, Q_0)_1\,,$$
$$\Gamma_0 = (0, P^1, 0, Q_0)_0\,.$$

Main difference

Phase α_∞ is fixed by choice of orientifold projection:

$$\alpha_\infty = 0 \quad (O4/O0)\,, \qquad \alpha_\infty = -\frac{\pi}{2} \quad (O6/O2)$$

Consequence: if $\alpha_\infty = \pi + \arg Z$: neg. mass, grav. repuslive, inverted attr. flow, attr. point $\to$ repulsor point, sol. singular.



Basic bound state

- Simplest possibility:

$$\Gamma = \Gamma_1 + \Gamma_0 + \Gamma_1'$$

i.e. bound state of charge with its own image (+ charge in the middle of the universe)

- From integrability constraint:

$$\frac{I(\Gamma_1, \Gamma_0)}{|\vec{x}_1|} = 2\mathrm{Im}[e^{-i\alpha} Z_1]_\infty \,.$$

where

$$I(\Gamma_1, \Gamma_0) := \frac{\langle \Gamma_1, \Gamma_1' \rangle}{2} + \langle \Gamma_1, \Gamma_0 \rangle = 2J$$

- $\Rightarrow$ Stability condition:

$$I(\Gamma_0, \Gamma_1)\, \mathrm{Im}[e^{-i\alpha} Z_1]_\infty > 0 \,.$$

Wall crossing formula

- Index counting orientifold invariant BPS states:

$$\Omega_{\rm inv}(\Gamma, t) = {\rm Tr}_{\mathcal{H}'_{\rm inv}(\Gamma,t)}(-)^{2J_3'} = (-1)^{\dim_{\mathbb{C}} \mathcal{M}_{\rm inv}}\, \chi(\mathcal{M}_{\rm inv})\,.$$

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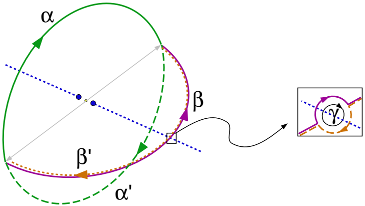
- Corollary, by comparing to microscopic picture:

  angular momentum of pair = open string Witten index

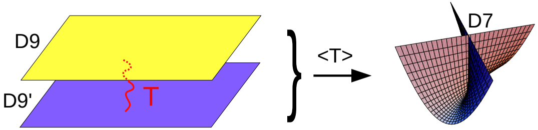
$\mathbb{Z}_2$ torsion charge



- For charge odd under τ (e.g. D6 in O4/O0 case): Aharonov Bohm experiment can distinguish between odd and even number of dipoles.
- Related to subtle anomalies on IIB side.

Application to counting basic D7 vacua

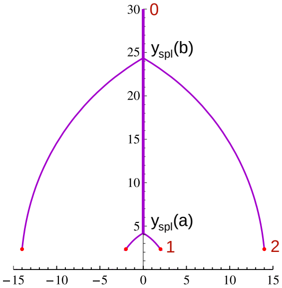
- Example: pure D7 branes in degree 8 hypersurface in $CP^4_{4,1,1,1,1}$ O3/O7 orientifolded by reflection of first coordinate.
- Complicated story (cf. previous talk at Rutgers)



D7 (possibly with flux) obtained from two D9-D9′ pairs with a, b units of flux.

Application to counting basic D7 vacua

Orientihole split flow:



Predicts Euler characteristics moduli spaces:

a	2	3	4	5	6	7
$\chi(\mathcal{M})$	3729	33540	104825	223440	388905	598884

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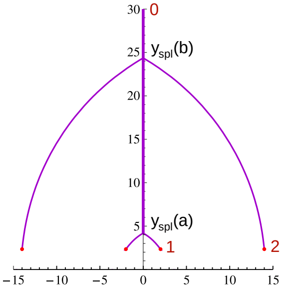

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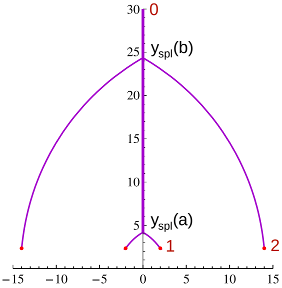

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✓

Note: decays at quite large vol.!

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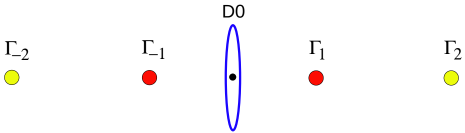
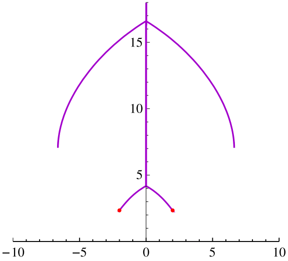
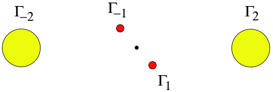
- Do single centered solutions exist in fully corrected theory? Physical argument: scaling solutions exist (for $a = 2$).



General tadpole canceling D7 vacua

Fat multicentered solutions:





$S = 1540$ in large vol. approx. (ok $\mathrm{Im}\, t_* \approx 7$)

$\Rightarrow$ In this sector $N_{\mathrm{vac}} \approx 10^{668}$.

Directions for future work

- lift to M-theory
- solutions in T^3. MS $=$??
- corrections to Z
- map different landscape sectors to different kinds of BH configurations
- implications stability issues for fenomenology
- nonprimitive wall crossing
- OSV, modular forms
- bulk fluxes
- nonsusy