Exotic Branes, Double Bubbles, & Superstrata

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1004.2521, 1107.2650, 1110.2781

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

Introduction

Exotic branes

Exotic branes

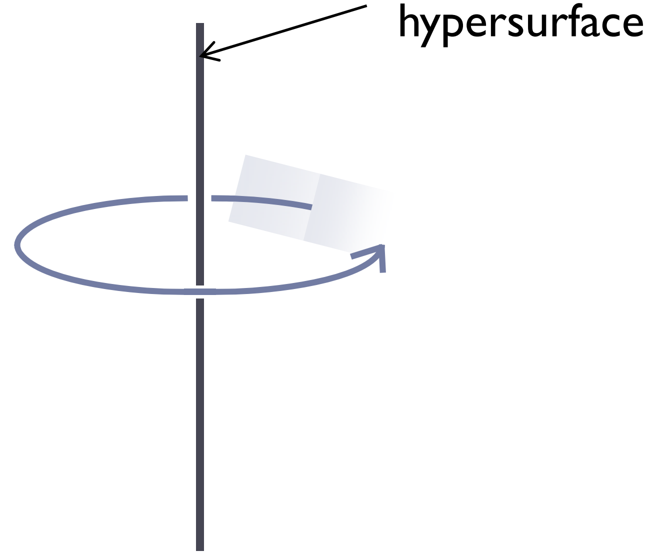
- "Forgotten" branes in string theory

  [9707217 Elitzur+Giveon+Kutasov+Rabinovici]
  [9712047 Blau+O'Loughlin]
  [9809039 Obers+Pioline]

Type IIA	P ($\mathbf{7}$), F1 ($\mathbf{7}$), D0 ($\mathbf{1}$), D2 ($\mathbf{21}$), D4 ($\mathbf{35}$), D6 ($\mathbf{7}$), NS5 ($\mathbf{21}$), KKM ($\mathbf{42}$), 5^2_2 ($\mathbf{21}$), 0^7_3 ($\mathbf{1}$), 2^5_3 ($\mathbf{21}$), 4^2_3 ($\mathbf{35}$), 6^1_3 ($\mathbf{7}$), $0^{(1,6)}_4$ ($\mathbf{7}$), 1^6_4 ($\mathbf{7}$)
Type IIB	P ($\mathbf{7}$), F1 ($\mathbf{7}$), D1 ($\mathbf{7}$), D3 ($\mathbf{35}$), D5 ($\mathbf{21}$), D7 ($\mathbf{1}$), NS5 ($\mathbf{21}$), KKM ($\mathbf{42}$) , 5^2_2 ($\mathbf{21}$), 1^6_3 ($\mathbf{7}$), 3^4_3 ($\mathbf{35}$), 5^2_3 ($\mathbf{21}$), 7_3 ($\mathbf{1}$), $0^{(1,6)}_4$ ($\mathbf{7}$), 1^6_4 ($\mathbf{7}$)
M-theory	P ($\mathbf{8}$), M2 ($\mathbf{28}$), M5 ($\mathbf{56}$), KKM ($\mathbf{56}$), 5^3 ($\mathbf{56}$), 2^6 ($\mathbf{28}$), $0^{(1,7)}$ ($\mathbf{8}$)

Exotic branes

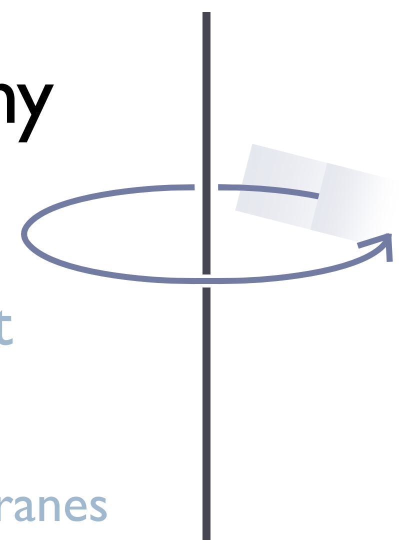
- "Forgotten" branes in string theory
- Co-dimension 2



Exotic branes

- "Forgotten" branes in string theory
- Co-dimension 2
- Charge = U-duality monodromy

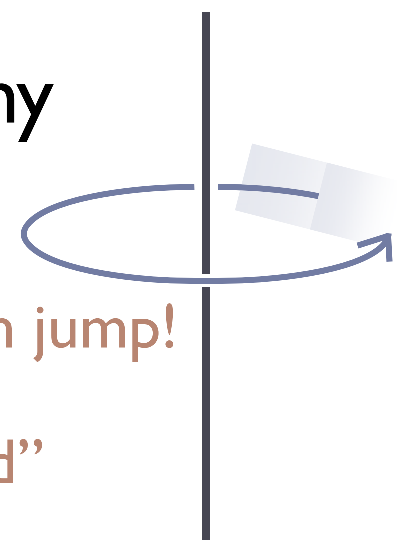
Jump by a U-duality
as one goes around it



Generalization of F-theory 7-branes

Exotic branes

- "Forgotten" branes in string theory
- Co-dimension 2
- Charge = U-duality monodromy
- Non-geometric



Even metric can jump!

"U-fold"

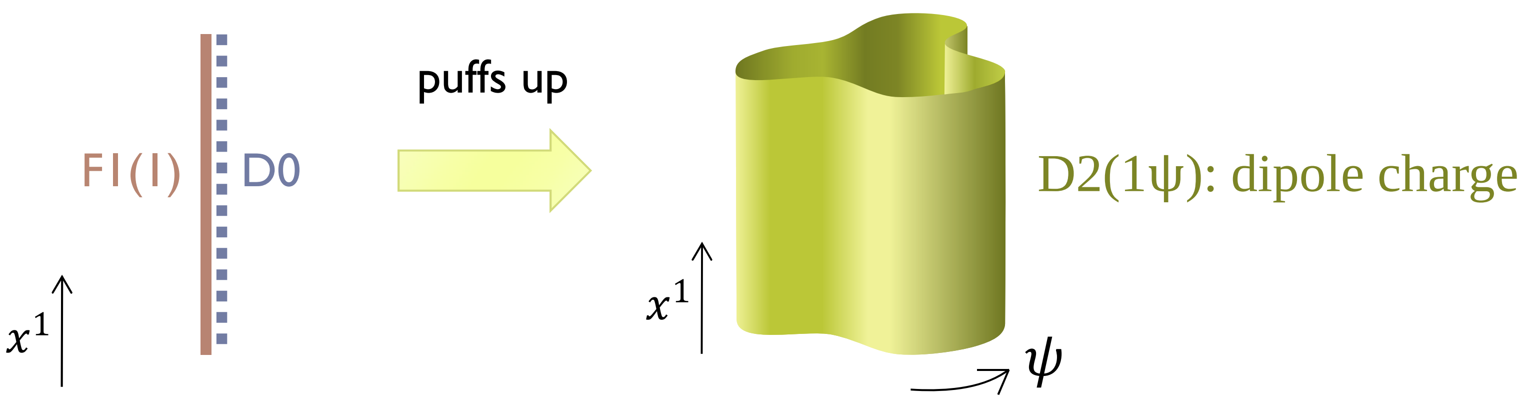
Supertube effect – “bubbling”

- Codim-2 object problematic?
  - Log divergences

$$V \sim \frac{1}{r^{d-2}} \xrightarrow{d=2} V \sim \log\left(\frac{\mu}{r}\right)$$

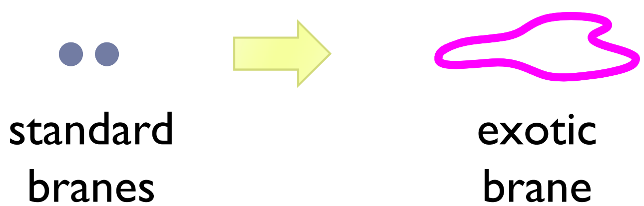
- Supertube effect = spontaneous polarization

[Mateos+Townsend]



Exotic bubbling

- Ordinary branes can puff up to produce exotic *dipole* charges

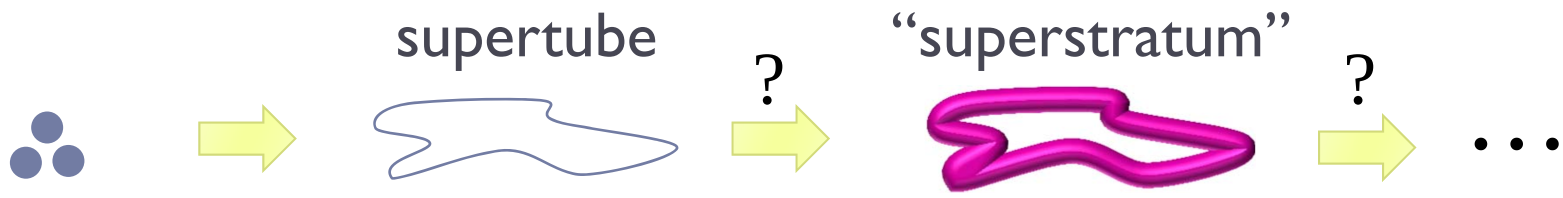


→ No log divergence

→ Exotic branes relevant to non-exotic physics;
More common than previously thought!

Double bubbling

- Bubbling can occur at multiple stages

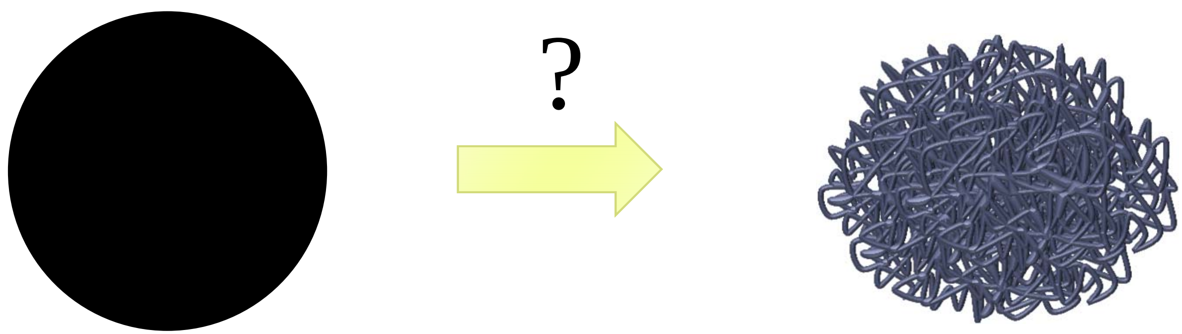


→ “Superstratum” – arbitrary surface

→ Bubbling may occur repeatedly, producing all kinds of exotic charges

Black hole microstates

- Black holes: bound states of branes
  - → Generic microstates involve exotic superstrata
  - → Microstate (non-)geometries?



Claim:

Generic microstates
of black holes involve
exotic non-geometric
superstrata.

Outline

- Introduction ✓
- Exotic states & their higher-D origin
- Supertube effect
- Black hole microstates
- Conclusion

Exotic states and their higher-D origin

Compactification to 3D

- M on T^8 or Type II on T^7
  - → 3D $\mathcal{N} = 16$ sugra
  - → U-duality group $E_{8(8)}(\mathbb{Z})$: generated by T- and S-dualities
  - → 128 moduli scalars (in 3D, scalar = vector) $\in SO(16)\backslash \mathrm{E}_{8(8)}(\mathbb{R})/E_{8(8)}(\mathbb{Z})$
- Particle multiplet:
  - → Start from a point-like object

    e.g. D7(3456789) wrapped on T^7
  - → Take T- and S-dualities to get other states

Exotic states in 3D

- Particle multiplet:

[9707217 Elitzur+Giveon+Kutasov+Rabinovici]
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- Notation for exotic states

$$b_n^c : M = \frac{R^b (R^c)^2}{g_s^n} \qquad b_n^{(d,c)} : M = \frac{R^b (R^c)^2 (R^d)^3}{g_s^n}$$

Example: $5^2_2(34567{,}89)$: $M = \dfrac{R_3 \cdots R_7 \, (R_8 R_9)^2}{g_s^2 l_s^8}$

Duality rules

- Duality rules can be read off from:

$$T_y: \quad R_y \to \frac{l_s^2}{R_y}, \quad g_s \to \frac{l_s}{R_y} g_s \qquad\qquad S: \quad g_s \to \frac{1}{g_s}, \quad l_s \to g_s^{1/2} l_s$$

- Example:

$$\mathrm{NS5}(34567) \xrightarrow{\mathrm{T}_8} \mathrm{KKM}(34567,8) \xrightarrow{\mathrm{T}_9} 5_2^2(34567,89)$$

$$M = \frac{R_3 \cdots R_7}{g_s^2 l_s^6} \xrightarrow{\mathrm{T}_8} \frac{R_3 \cdots R_7}{(g_s l_s/R_8)^2 l_s^6} = \frac{R_3 \cdots R_7 R_8^2}{g_s^2 l_s^8} \quad : 5_2^1 = \mathrm{KKM}$$

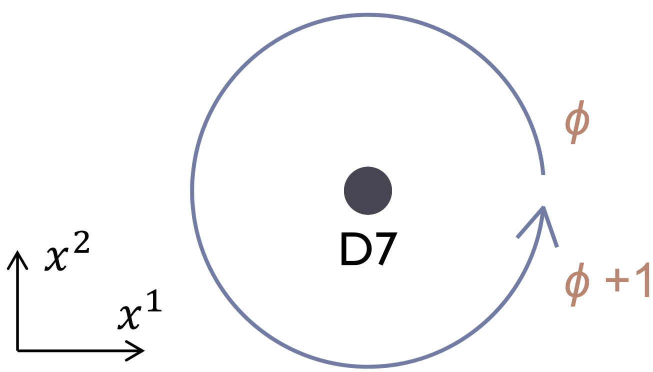
$$\xrightarrow{\mathrm{T}_9} \frac{R_3 \cdots R_7 R_8^2}{(g_s l_s/R_9)^2 l_s^8} = \frac{R_3 \cdots R_7 (R_8 R_9)^2}{g_s^2 l_s^{10}} \quad : 5_2^2$$

Higher D origin = U-folds (1)

- Claim: higher D origin is
  U-fold = non-geometric background

E.g. D7 on T^7

- (Magnetically) coupled to RR 0-form C_0
- 3D scalar $\phi = C_0$
- Monodromy: $\phi \rightarrow \phi + 1$ shift (part of $SL(2,\mathbb{Z})$ duality of IIB)



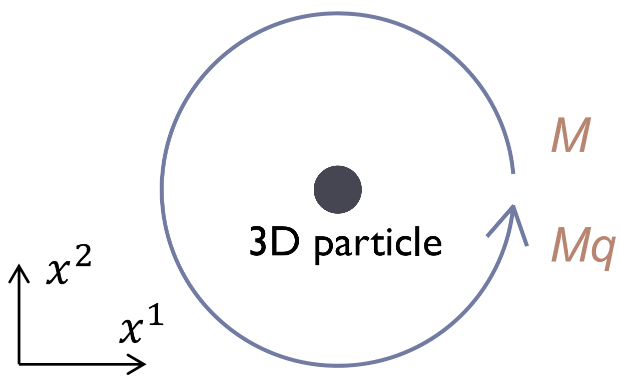
Higher D origin = U-folds (2)

- ϕ gets combined with other scalars to form moduli matrix

$$M \in \mathcal{M} = SO(16)\backslash E_{8(8)}(\mathbb{R})/E_{8(8)}(\mathbb{Z})$$

- Shifting symmetry + S, T-dualities $\Rightarrow$ $E_{8(8)}(\mathbb{Z})$
- Can consider a particle with general U-duality monodromy

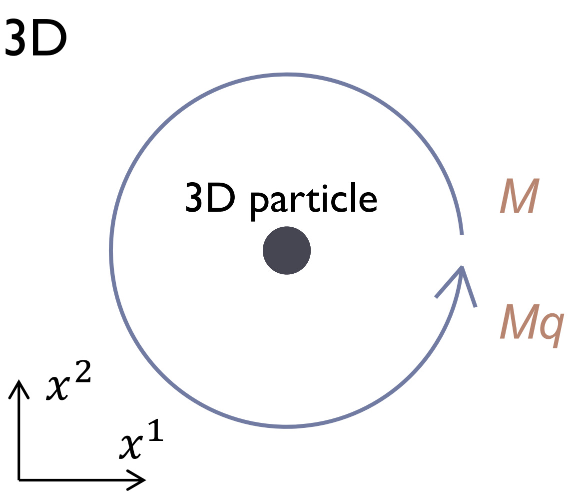
$$q \in E_{8(8)}(\mathbb{Z}) \equiv G(\mathbb{Z})$$

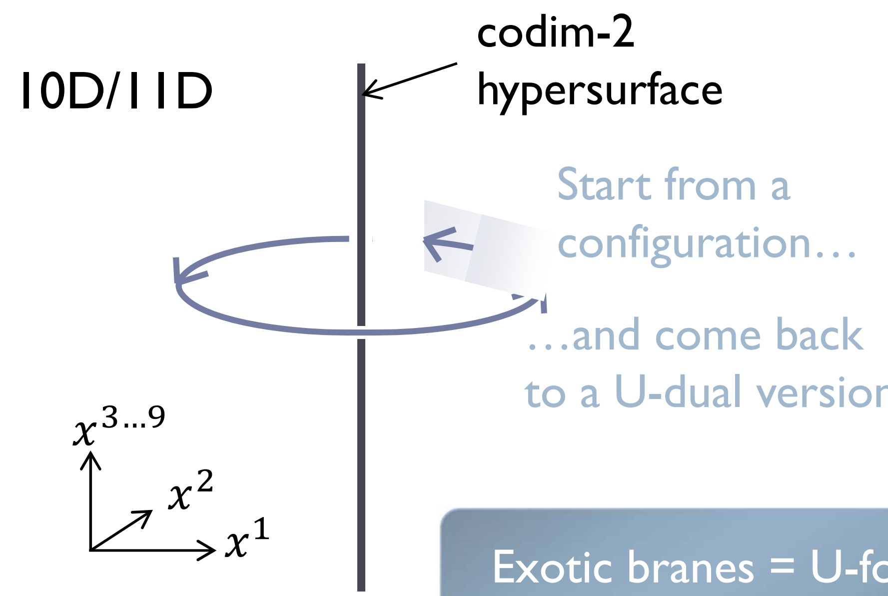


"Charge" of a 3D particle is U-duality monodromy around it!

Higher D origin = U-folds (3)

- In 10D/11D, we have a non-geometric U-fold





Exotic branes = U-folds

Cf. F-theory, U-branes & non-geom bg

[Greene+Shapere+Vafa+Yau] [Vafa] F-theory
[Kumar+Vafa] [Liu+Minasian] [Hellerman+McGreevy+Williams] contractible U-branes
[Dabholkar+Hull] [Flournoy+Wecht+Williams] … non-contractible U-branes & moduli stabl’n

Sugra solution for 5_2^2

5_2^2(56789,34) metric:

$$ds^2 = -dt^2 + H(dr^2 + r^2 d\theta^2) + HK^{-1} dx_{34}^2 + dx_{56789}^2$$

$$B_{34} = -K^{-1}\theta\sigma, \qquad e^{2\Phi} = HK^{-1}, \qquad K \equiv H^2 + \sigma^2\theta^2$$

r, θ: $\mathbb{R}^2$
$x^{3,4}$: T^2
$x^{5\ldots9}$: T^6

$$H(r) = h + \sigma \log\left(\frac{\mu}{r}\right) \qquad \sigma = \frac{R_3 R_4}{2\pi\alpha'}$$

Cf. [Blau+O'Loughlin]: 6_3^1

- T-fold structure:

$$\theta = 0: \quad G_{33} = G_{44} = H^{-1},$$

$$\theta = 2\pi: \quad G_{33} = G_{44} = \frac{H}{H^2 + (2\pi\sigma)^2}$$

→ x_3-x_4 torus size doesn't come back to itself!

T-fold structure of 5_2^2

- Package 3-4 part of G, B:

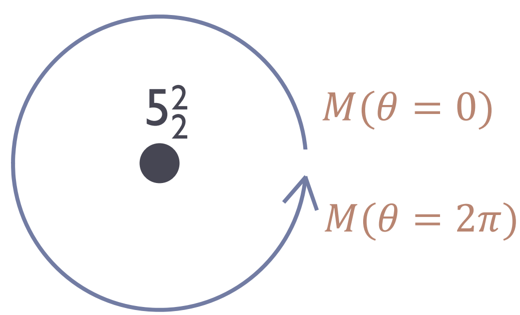
$$M = \begin{pmatrix} G^{-1} & G^{-1}B \\ -BG^{-1} & G - BG^{-1}B \end{pmatrix}$$

T-duality acts as

$$M \to M' = \Omega^t M \Omega, \qquad \Omega \in SO(2,2,\mathbb{R})$$

T-duality monodromy around 5_2^2:

$$\Omega = \begin{pmatrix} 1 & 0 \\ 2\pi\sigma & 1 \end{pmatrix}: \qquad M(\theta = 0) \to M(\theta = 2\pi)$$



Comments

- Not well-defined as stand-alone objects
  - Log divergence

    → Superpositions (cf. F-theory 7-branes)

    → Configs with higher codims. (we turn to this next!)
- Easy to get sugra metric for other exotic branes
  - Questionable for states with $M \sim g_s^{-3}, g_s^{-4}$

Lesson 1:

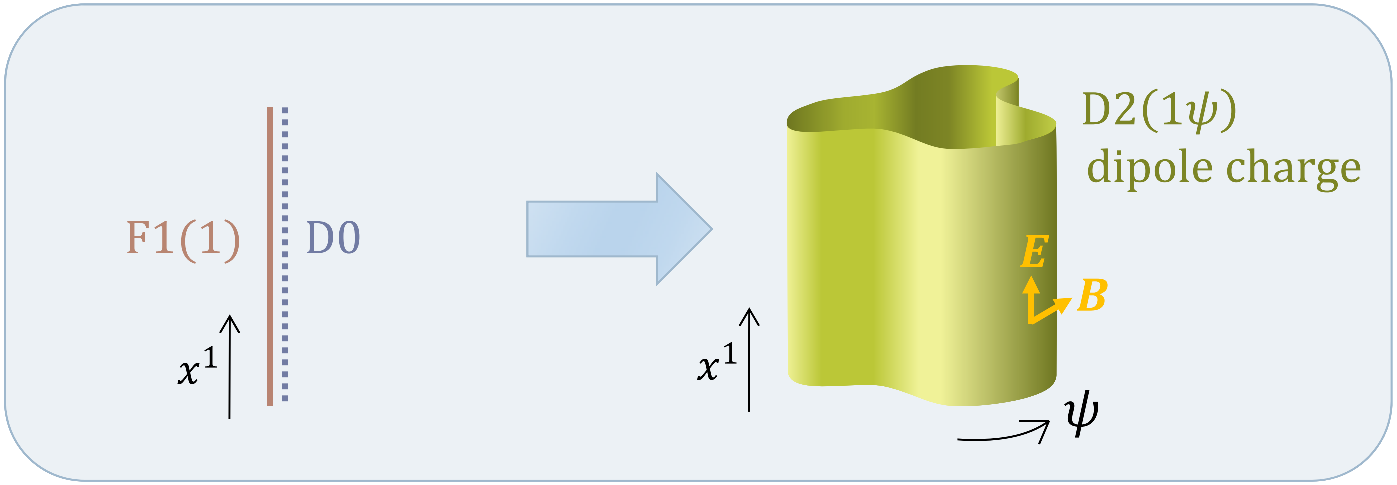
Exotic branes
= Non-geometric U-folds

Supertube effect and exotic branes

Supertube effect

“puffs up”

$\mathrm{D0} + \mathrm{F1}(1) \longrightarrow \mathrm{D2}(1\psi)$ [Mateos+Townsend]



- Spontaneous polarization effect (cf. Myers effect)
- Produces new dipole charge
- Cross section = arbitrary curve
- Fluctuations of curve → large degeneracy $\sim e^{\#\sqrt{N_{F1}N_{D0}}}$

Dualizing supertubes

Original supertube effect:

$$\mathrm{D0} + \mathrm{F1}(1) \to \mathrm{D2}(1\psi)$$

dualize!

Various other known puff-ups:

$$\mathrm{F1}(1) + \mathrm{P}(1) \to \mathrm{F1}(\psi) \qquad \text{FP sys}$$

$$\mathrm{D1}(1) + \mathrm{D5}(12345) \to \mathrm{KKM}(2345\psi, 1) \qquad \text{LM geom}$$

$$\mathrm{M2}(12) + \mathrm{M2}(34) \to \mathrm{M5}(1234\psi) \qquad \text{black ring}$$

"Exotic" supertubes

$$\mathrm{D0} + \mathrm{F1}(1) \to \mathrm{D2}(1\psi)$$

dualize

Exotic puff-up:

$$\mathrm{D4}(6789) + \mathrm{D4}(4589) \to 5_2^2(4567\psi, 89)$$

More exotic:

$$\mathrm{D3}(589) + \mathrm{NS5}(46789) \to 5_3^2(4567\psi, 89)$$

Still more exotic:

$$\mathrm{NS5}(46789) + \mathrm{KKM}(46789{,}5) \to 1_4^6(\psi, 456789)$$

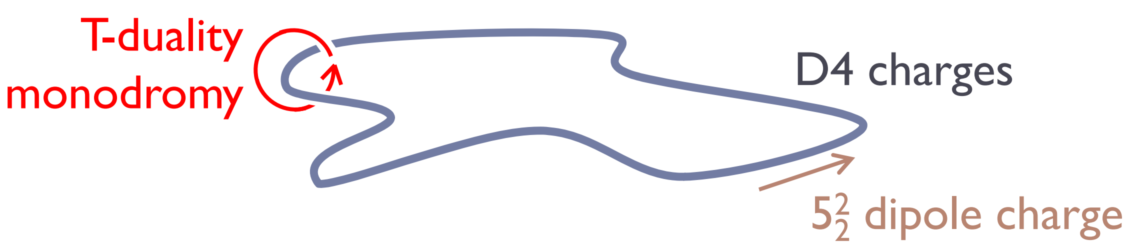
- Ordinary branes can polarize into exotic branes
- Only dipoles → no log divergence

Example: D4+D4$\rightarrow 5^2_2$

- Basic sugra supertube

dualize

- Exotic 2-charge solution



Metric for D4+D4$\longrightarrow 5^2_2$

D4(6789)+D4(4589)$\longrightarrow 5^2_2$(4567ψ,89)

$$ds^2 = -\frac{1}{\sqrt{f_1 f_2}}(dt - A)^2 + \sqrt{f_1 f_5}\, dx_{123}^2 + \sqrt{\frac{f_1}{f_2}}\, dx_{45}^2 + \sqrt{\frac{f_2}{f_1}}\, dx_{67}^2 + \frac{\sqrt{f_1 f_2}}{f_1 f_2 + \gamma^2}\, dx_{89}^2,$$

$f_i\,,\, A$: sourced along curve

$$f_1 = 1 + \frac{Q_1}{L}\int_0^L \frac{dv}{|\vec{x} - \vec{F}(v)|}, \quad f_2 = 1 + \frac{Q_1}{L}\int_0^L \frac{\left|\dot{\vec{F}}(v)\right|^2}{|\vec{x} - \vec{F}(v)|}\, dv, \quad A_i = -\frac{Q_1}{L}\int_0^L \frac{\dot{F}_i(v)}{|\vec{x} - \vec{F}(v)|}$$

$$d\gamma = *_3\, dA, \quad d\beta_I = *_3\, df_I$$

- $\gamma\,,\, \beta_i$ have monodromy around curve

$$\gamma \to \gamma - 2q, \quad \beta_I \to \beta_I - 2Q_I$$ → T-fold structure just as before

- Asymptotically flat 4D

Metric for D4+D4$\longrightarrow 5_2^2$

Other fields:

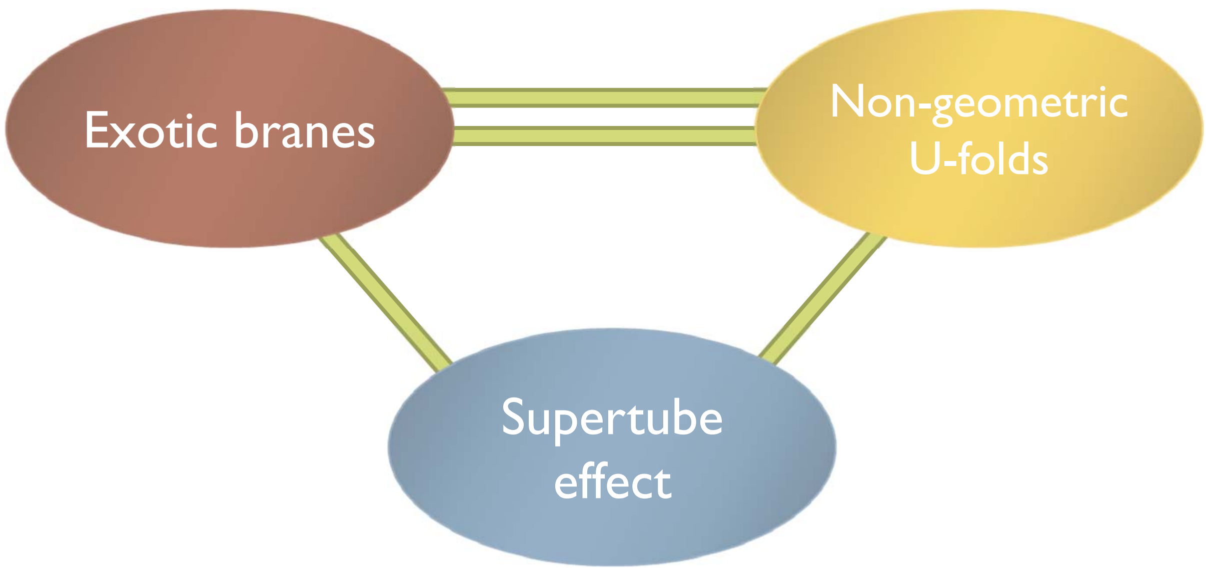
$$e^{2\Phi} = \frac{\sqrt{f_1 f_2}}{f_1 f_2 + \gamma^2}, \qquad B_{89}^{(2)} = \frac{\gamma}{f_1 f_2 + \gamma^2}, \qquad C^{(3)} = -\gamma\rho + \sigma$$

$$\rho = (f_2^{-1} + dt - A) \wedge dx^4 \wedge dx^5 + (f_1^{-1} + dt - A) \wedge dx^6 \wedge dx^7$$

$$\sigma = (\beta_1 - \gamma dt) \wedge dx^4 \wedge dx^5 + (\beta_2 - \gamma dt) \wedge dx^6 \wedge dx^7$$

Lesson 2:

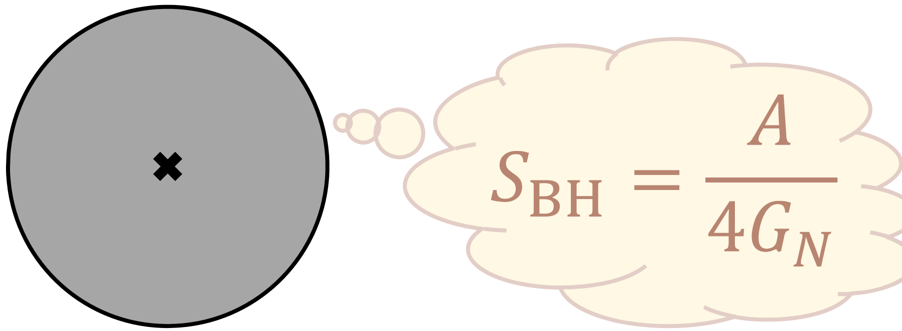
Exotic branes are important
for generic physics of string theory



Exotic branes and black hole microstates

Black hole microstates

- BH has thermodynamic entropy

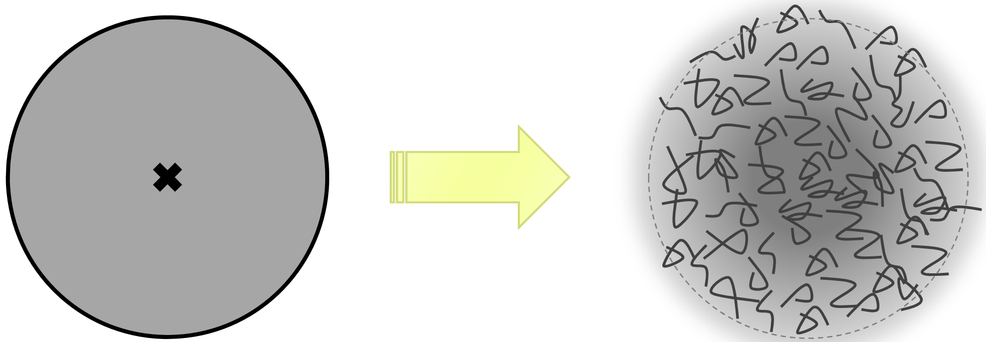


$$S_{\mathrm{BH}} = \frac{A}{4G_N}$$

- Is a BH an ensemble?
  If so, where are microstates?
  - Not visible in gravity?
  - No-hair theorem in 4D Einstein gravity

Mathur's fuzzball proposal

- A BH is filled with stringy "fuzz"



"Conventional" picture of BH

"Fuzzball" picture of BH

No horizon
No singularity

- BH microstates = different configurations of the fuzz
- BH entropy = stat. mech. entropy of the fuzz

$$S_{\mathrm{BH}} = \frac{A}{4G_N} \stackrel{?}{=} S_{\mathrm{fuzz}}$$

Sugra microstates

Supersym. BHs → Microstates describable *within sugra* as *smooth, horizonless* solutions?

- 2-charge system: Successful [Lunin+Mathur] [Lunin+Maldacena+Maoz] [Rychkov]
  - All microstates have been constructed within sugra
  - Counting sugra sol'ns reproduces micro entropy: $S_{\mathrm{sugra}} = S_{\mathrm{micro}}$
  - But horizon vanishes classically
- 3-charge system: Not so successful
  - Many sugra microstates have been constructed [Bena+Warner] [Berglund+Gimon+Levi]
  - Evidence that they are *not* enough [de Boer+El-Showk+Messamah+Van de Bleeken] [Bena+Bobev+Ruef+Warner]

They looked for *geometric* solutions in sugra and didn't find enough microstates.

But this seems just in accord with what we saw:

Generic BH microstates involve exotic charges and are non-geometric!

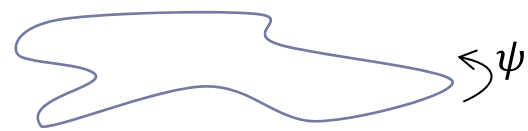
"Single bubbling"

- 2-charge system ("small" BH)

D1(5)
D5(56789)

puff up

KKM(6789ψ;5)



1-dim curve $\in \mathbb{R}^4$

geometric microstates
(Lunin-Mathur)

$$S_{\text{micro}} = S_{\text{geom}}$$

“Double bubbling” (1)

- 3-charge system: 5D BH : Well studied for microstate geometry

M2(56) M2(78) M2(9A)	M5(789Aψ) M5(569Aψ) M5(5678ψ)	5^3(789Aϕ,56ψ) 5^3(569Aϕ,78ψ) 5^3(5678ϕ,9Aψ)

arbitrary curve “supertube” cf. black ring	arbitrary surface “superstratum” non-geometric microstates

$$S_{\text{micro}} \stackrel{?}{=} S_{\text{nongeom}}$$

“Double bubbling” (2)

- 4-charge system: 4D BH : Well studied for microstate counting

[Maladacena+Strominger+Witten]

D0
D4(6789)
D4(4589)
D4(4567)

NS5(6789ψ) $5^2_2(6789,45\psi)$
NS5(4589ψ) $5^2_2(4589,67\psi)$
NS5(4567ψ) $5^2_2(4567,89\psi)$

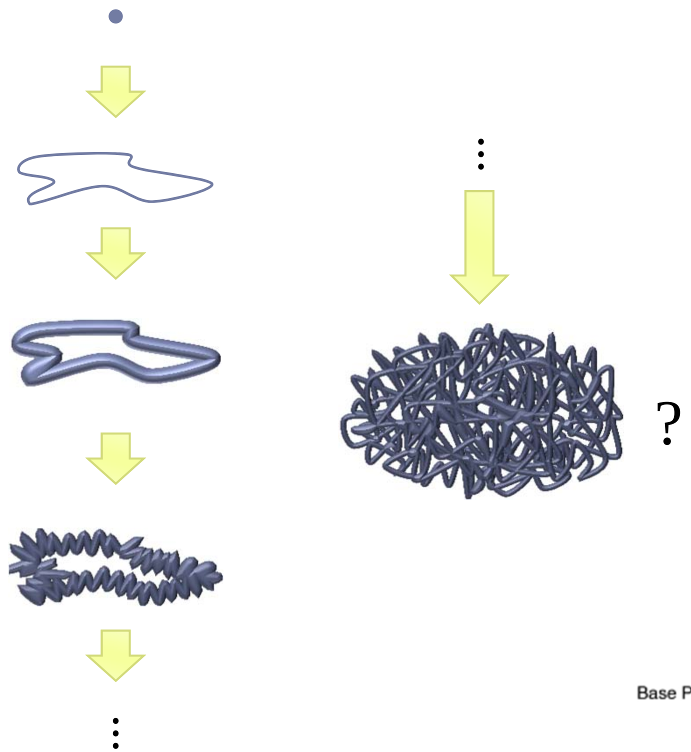
More exotic branes

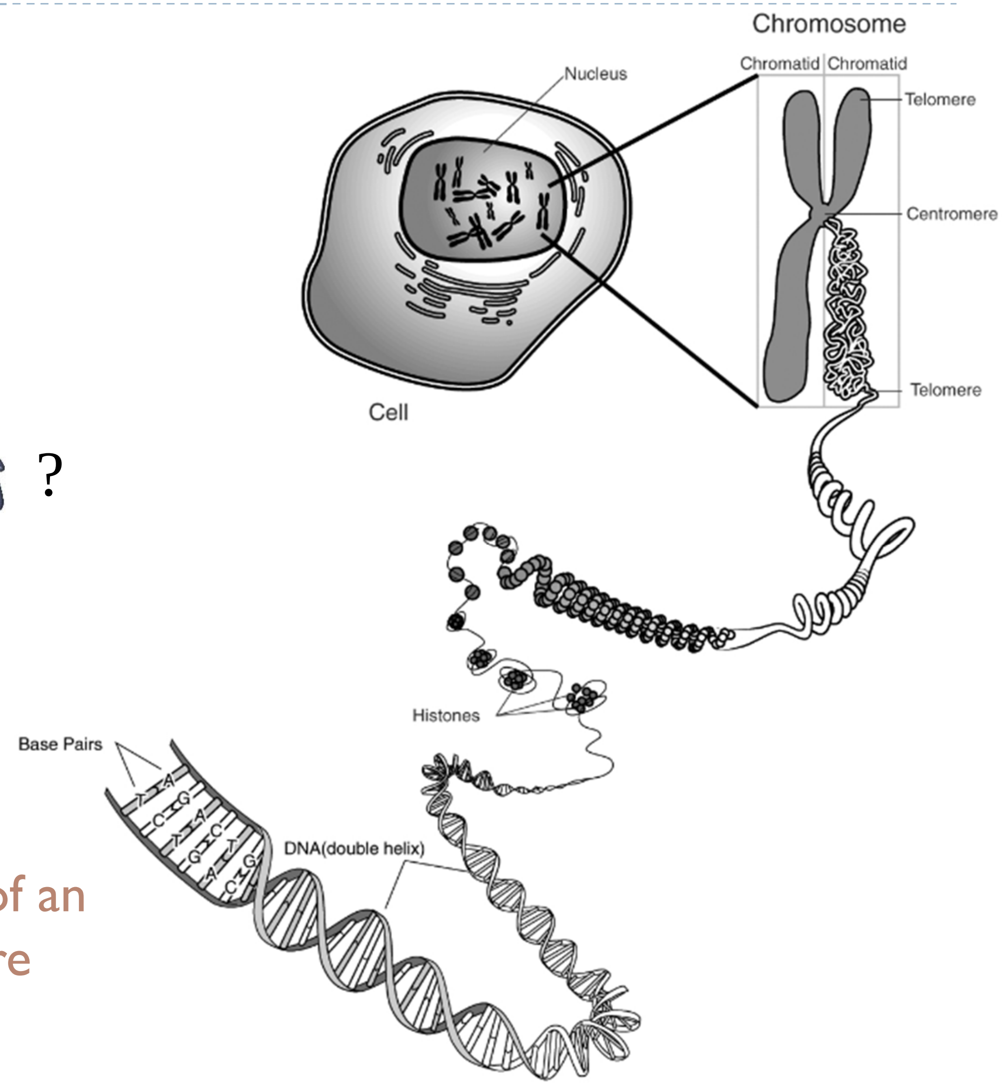
exotic supertube

exotic superstratum

$$S_{\rm micro} \stackrel{?}{=} S_{\rm nongeom}$$

Endless bubbling??





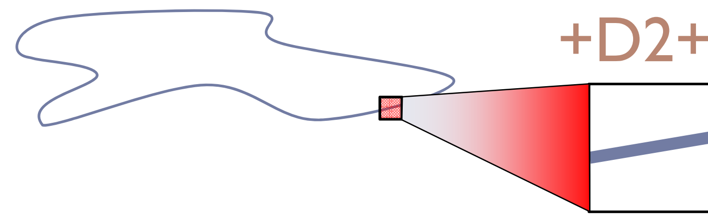
Presumably, a black hole is made of an extremely complicated structure (fuzzball) of exotic branes.

Susy in supertube

[Bena+de Boer+Warner+MS 1107.2650]

F1+D0

supertube

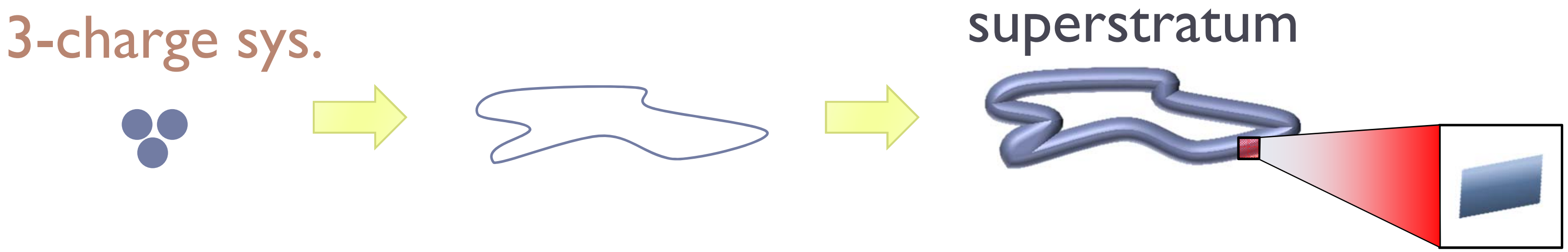


- Preserves $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ susy

- Locally $\frac{1}{2}$ BPS
- Which $\frac{1}{2}$ is preserved depends on local orientation
- Common susy preserved = original $\frac{1}{4}$ susy

This is why supertube can be along an arbitrary curve.

Susy in superstratum

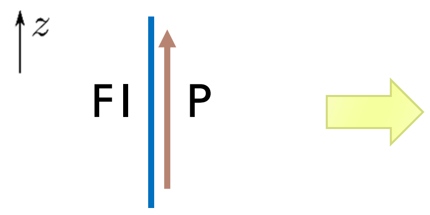


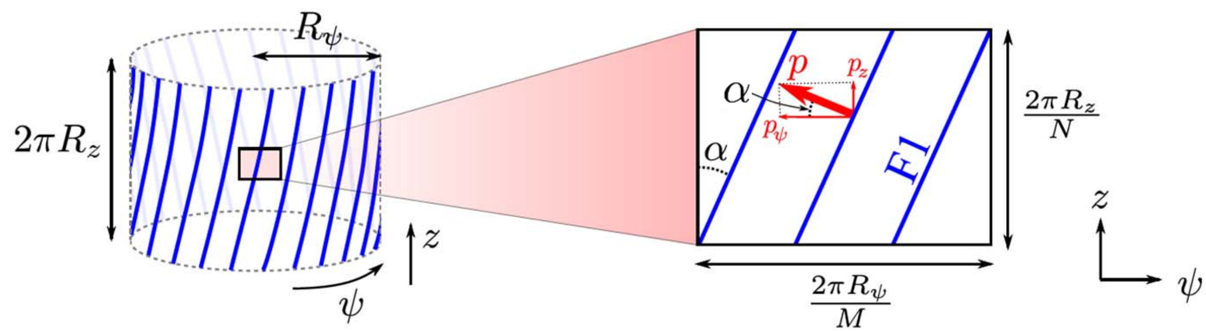
- Preserves $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$ susy

- Locally $\frac{1}{2}$ BPS
- Which $\frac{1}{2}$ is preserved depends on local orientation
- Common susy preserved = original $\frac{1}{8}$ susy

If true, superstratum can be along an arbitrary surface in principle!

Example: F1-P → D2





Tilted and boosted F1-P

Susy preserved by original config:

$$\Pi_{F1(z)}\mathcal{Q} = \Pi_{P(z)}\mathcal{Q} = 0,$$

$$\mathcal{Q} = \begin{pmatrix} Q \\ \tilde{Q} \end{pmatrix}$$

$$\Pi_{F1(z)} = \frac{1}{2}(1 + \Gamma^{0z}\sigma_3)$$

$$\Pi_{P(z)} = \frac{1}{2}(1 + \Gamma^{0z})$$

Projector after puffing up:

$$\Pi = \frac{1}{2}[1 - s(c\Gamma^{0\psi} - s\Gamma^{01}) + c(c\Gamma^{01} + s\Gamma^{0\psi})\sigma_3]$$

$$= c(c + s\Gamma^{z\psi})\Pi_{F1(z)} + s(s - c\Gamma^{z\psi}\sigma_3)\Pi_{P(z)},$$

$$c = \cos\alpha, \qquad s = \sin\alpha.$$

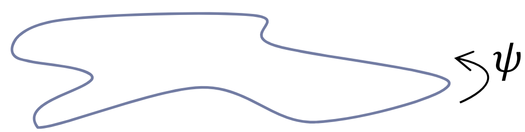
Common susy preserved
= same as original ¼ susy

General formula for 1→2 puff-up

Projectors before puffing up:

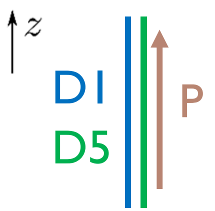
$$\Pi_1 = \frac{1}{2}(1 + P_1), \qquad \Pi_2 = \frac{1}{2}(1 + P_2)$$

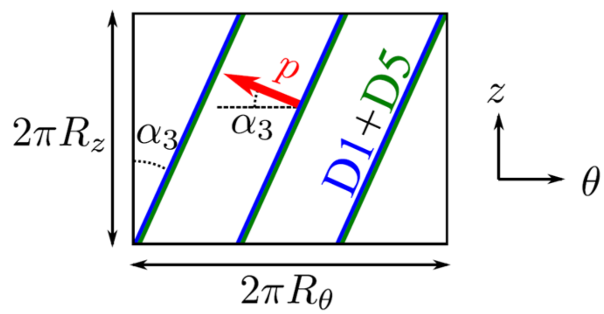
Projector after puffing up:

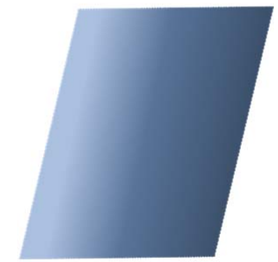


$$\begin{aligned}\Pi &= \frac{1}{2}[1 + c^2 P_1 + s^2 P_2 - sc\Gamma^{0\psi} + sc\Gamma^{0\psi} P_1 P_2] \\ &= c\left(c - s\Gamma^{0\psi}\right)\Pi_1 + s\left(s - c\Gamma^{0\psi}\right)\Pi_2 + 2sc\Gamma^{0\psi}\Pi_1\Pi_2\end{aligned}$$

D1-D5-P (1)







Original config.

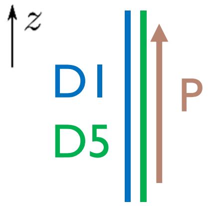
Infinite straight supertube
= tilted and boosted D1-D5

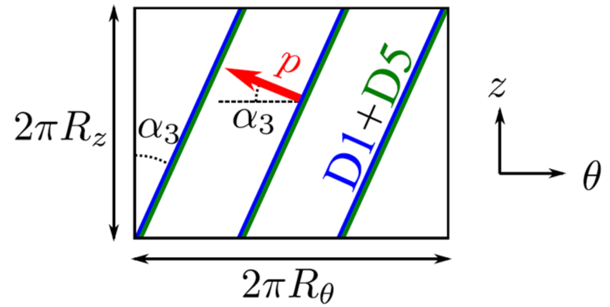
puffs up just like D1-D5 → KKM (LM geom.)

Infinite straight superstratum

Special case; superstratum is purely geometric

D1-D5-P (2)





$$\Pi_1 = \frac{1}{2}(1 + \Gamma^{0z}\sigma_1)$$

$$\Pi_2 = \frac{1}{2}(1 + \Gamma^{01234z}\sigma_1)$$

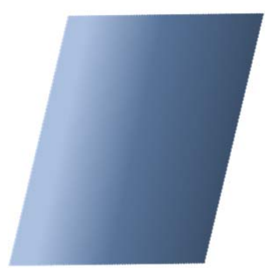
$$\Pi_3 = \frac{1}{2}(1 + \Gamma^{0z})$$

$$\widehat{\Pi}_i = \frac{1}{2}(1 + \hat{P}_i)$$

$$\hat{P}_1 = c_1 c_2 \Gamma^{0\hat{z}}\sigma_1 + s_1 s_2 \Gamma^{01234\hat{z}}\sigma_1 + c_1 s_2 \Gamma^{0\hat{\theta}} - s_1 c_2 \Gamma^{01234\hat{\theta}}$$

$$\hat{P}_2 = s_1 s_2 \Gamma^{0\hat{z}}\sigma_1 + c_1 c_2 \Gamma^{01234\hat{z}}\sigma_1 - s_1 c_2 \Gamma^{0\hat{\theta}} + c_1 s_2 \Gamma^{01234\hat{\theta}}$$

$$\Gamma^{\hat{z}} = c_3 \Gamma^z + s_3 \Gamma^\theta, \quad \Gamma^{\hat{\theta}} = c_3 \Gamma^\theta - s_3 \Gamma^z$$

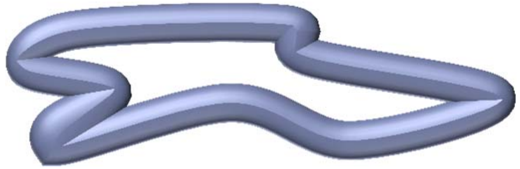


$$\widehat{\Pi} = \frac{1}{2}(1 + s_4^2 \hat{P}_1 + c_4^2 \hat{P}_2 - s_4 c_4 \Gamma^{0\psi} + s_4 c_4 \Gamma^{0\psi} \hat{P}_1 \hat{P}_2)$$

Same 1/8 susy preserved

Backreacted strata

- Dynamics of superstrata
  - Arbitrary surface possible?



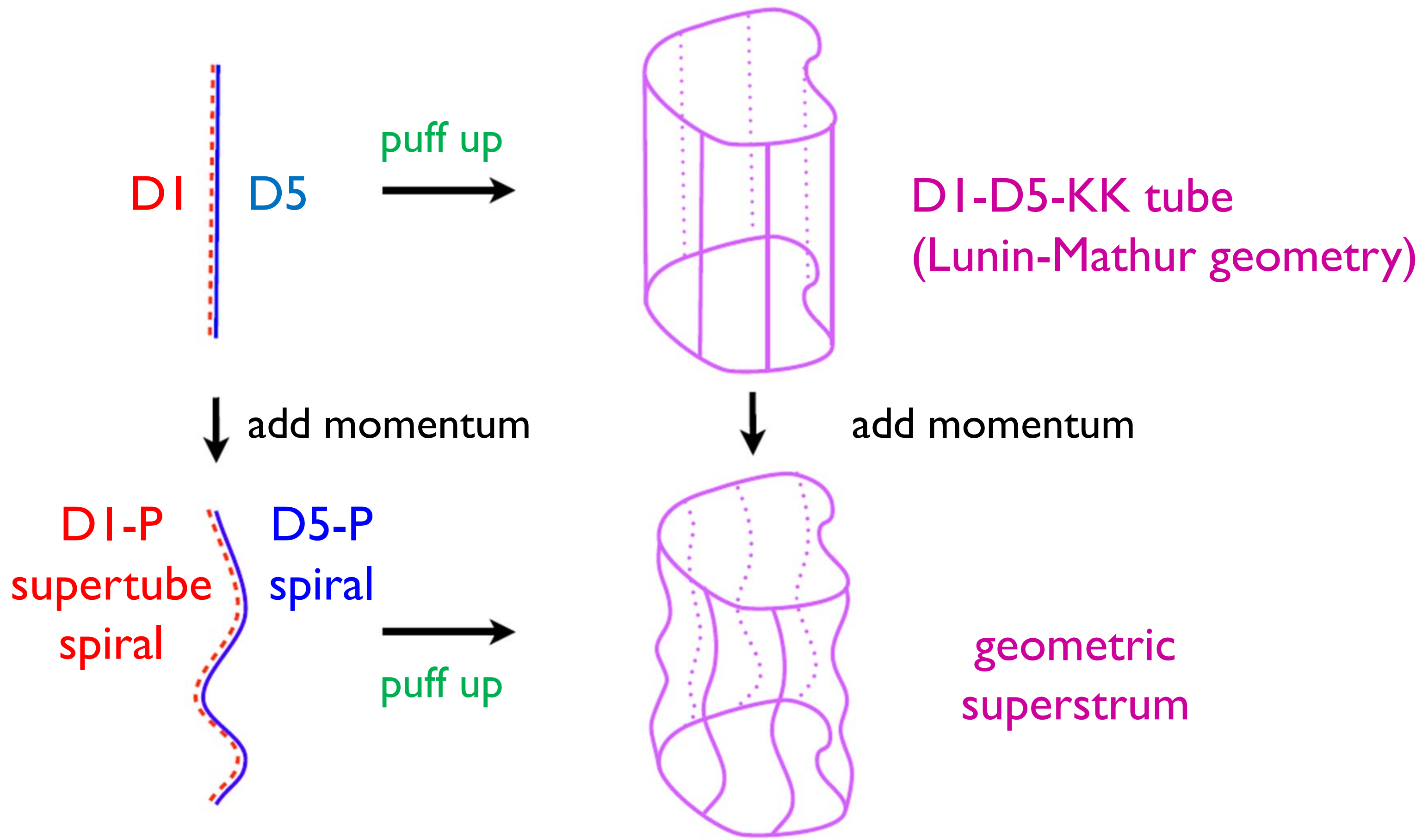
- 6D sugra (D1-D5-P) [Gutowski+Martelli+Reall] [Cariglia+Mac Conamhna] [Bena+Giusto+Warner+MS 1110.2781]
  - Linear problem, if solved in the right order

    → Linearity was crucial for previous microstate solutions.

    → x^5-dep 4D almost-HK base. Functions & forms on it.
  - Given superstratum data, should be possible to find solutions

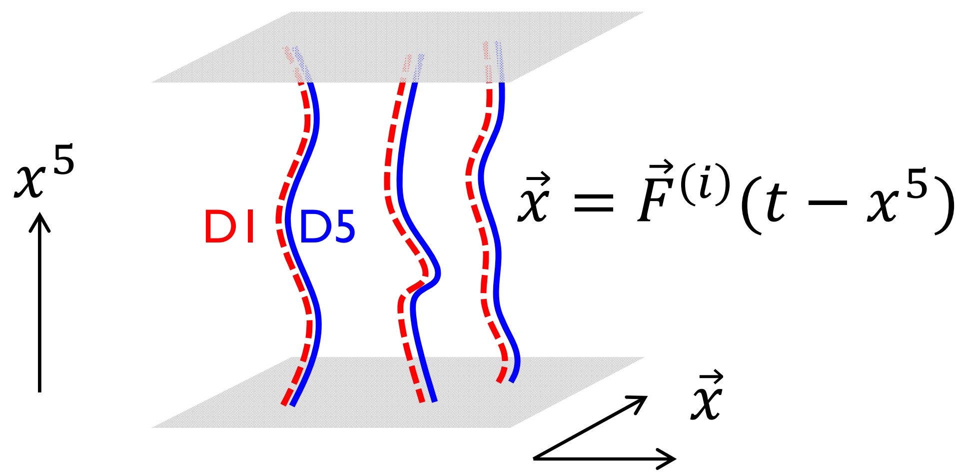
Geometric superstrum (1)

- Double bubbling of D1-D5-P system



Geometric superstrata

- So far we could construct:



N strands of D1-P and D5-P supertube spirals along arbitrary curves $\vec{F}^{(i)}, i = 1, \ldots, N$

Next step: KKM dipole (work in progress)

Lesson 3:

Exotic branes are ingredients of BHs

Conclusions

Conclusions

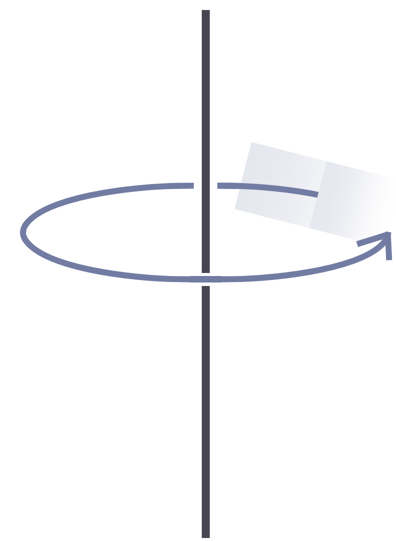
- Exotic branes = non-geometries (U-folds)
- Exotic charges = U-duality monodromies
- Relevant even for non-exotic physics by supertube effect

  ⇒ **Exotic branes are not at all exotic; They are everywhere!**

- Essential ingredients of BHs

Future directions

- Geometric superstrata
- Non-geometric superstrata
  - More generic
  - Locally geometric
  - Generalize susy sol'n ansatz
  - Generalized geometry, DFT



[Berman, Hohm, Hull, Perry, Zwiebach, …]

Conjecture:

Generic microstates of black holes involve non-geometric superstrata.

Thanks!