Exotic Branes and Black Hole Microstates

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Progress in Quantum Field Theory and String Theory
Osaka City University, April 4, 2012

with I. Bena, J. de Boer, S. Giusto & N. Warner, 1004.2521, 1107.2650, 1110.2781

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

Message:

"Exotic branes" are important
for non-pert. physics of string theory
— in particular, black holes.

Exotic Branes

Exotic branes (1)

- "Forgotten" branes in string theory

  [Elitzur+Giveon+Kutasov+Rabinovici '97]
  [Blau+O'Loughlin '97]
  [Obers+Pioline '98]

  - Typical mass $\sim g_s^{-3},\ g_s^{-4}$

- Predicted by duality

$$\mathrm{NS5}(56789) \xrightarrow{T_4} \mathrm{KKM}(56789,4)$$

$$\xrightarrow{T_3} \quad ?$$

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$$\mathrm{NS5}(56789) \xrightarrow{T_4} \mathrm{KKM}(56789,4)$$

$$\xrightarrow{T_3} \text{“}5_2^2(56789,34)\text{”}$$

Exotic branes (2)

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

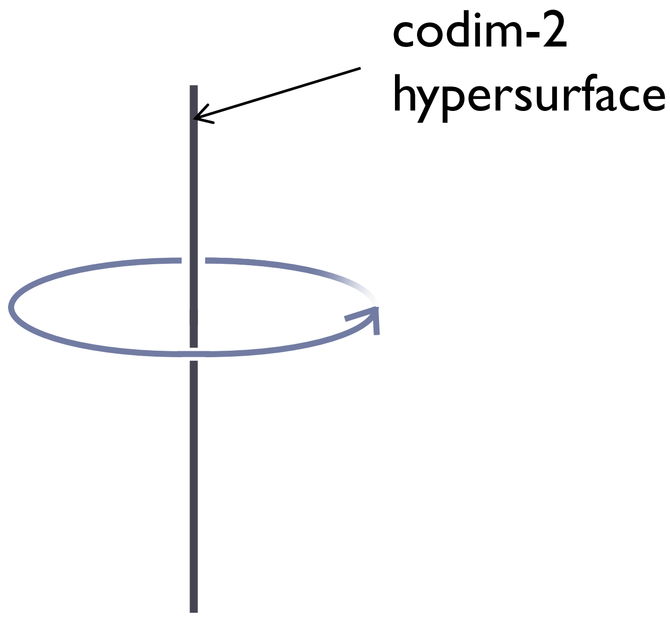
- Notation

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

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

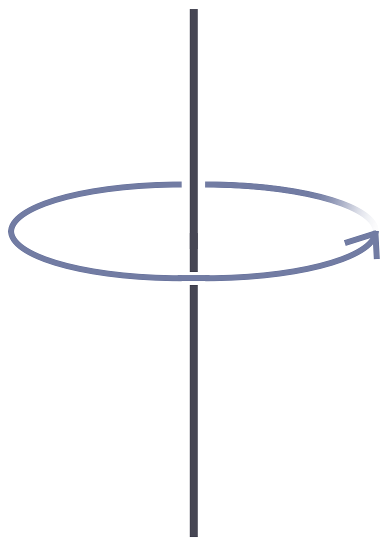
Exotic branes (3)

- Co-dimension 2



Exotic branes (3)

- Co-dimension 2
- Charge = U-duality monodromy



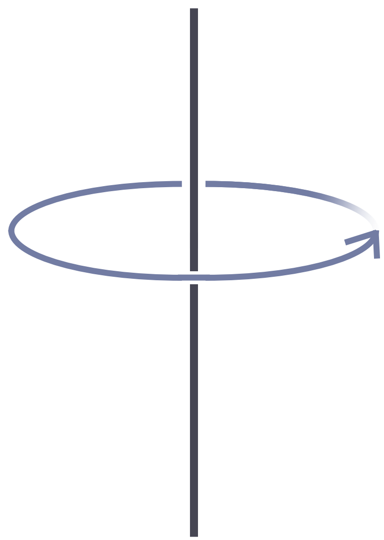
Fields jump by U-duality as we go around

Generalizations of F-theory 7-branes

[Greene+Shapere+Vafa+Yau]
[Vafa] [Kumar+Vafa]

Exotic branes (3)

- Co-dimension 2
- Charge = U-duality monodromy
- Non-geometric [de Boer+MS, 1004.2521]



Even metric can have monodromy!

Examples of "U-folds"

[Liu+Minasian] [Hellerman+McGreevy+Williams] [Dabholkar+Hull] [Flournoy+Wecht+Williams] …

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 1997]: 6_3^1

- T-fold structure:

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

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

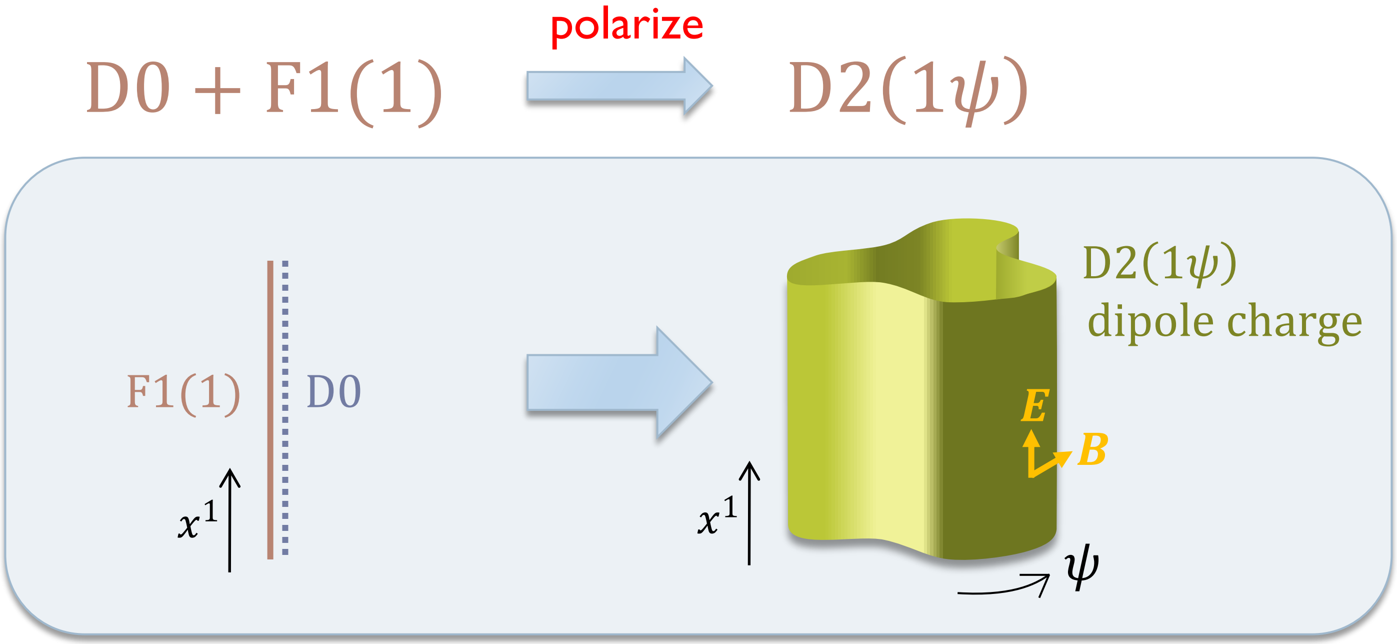
→ x_3-x_4 torus size doesn't come back to itself!

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 metric for other exotic branes
  - Questionable for states with $M \sim g_s^{-3}, g_s^{-4}$?

Supertube Effect and Exotic Branes

Supertube effect [Mateos+Townsend 2001]



- Spontaneous polarization phenomenon
- Produces new dipole charge

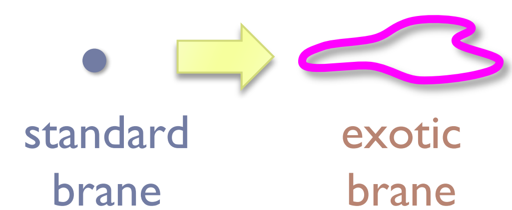
Exotic supertubes [de Boer+MS, 1004.2521]

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

U-dual

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

- *Ordinary* branes can polarize into *exotic* ones
  - Only dipoles → no log div.

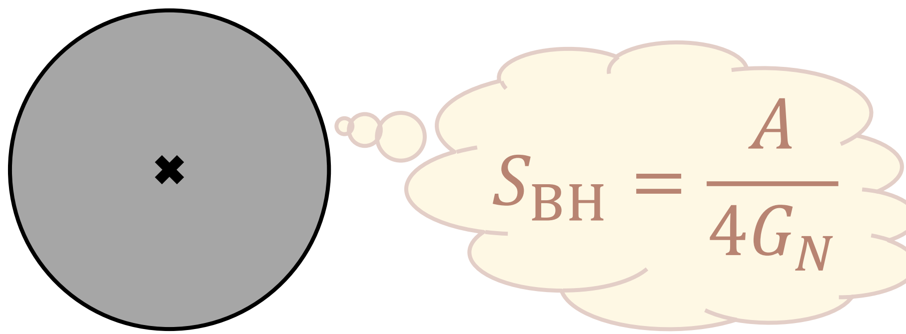


- Exotic branes: *ubiquitous*
  - Important for generic non-pert. physics
  - Notable example: black hole

Exotic Branes
and
BH Microstates

BH microstates

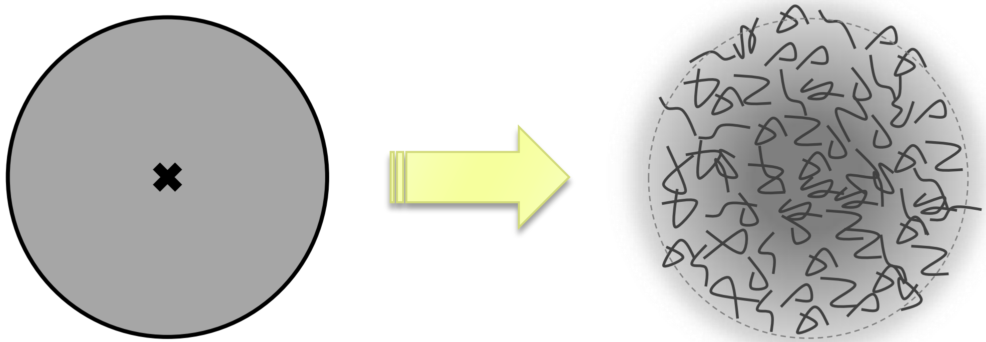
- BH has thermodynamic entropy



- Is a BH an ensemble?
  Where are microstates?

Fuzzball proposal [Mathur ~2001]

- 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

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

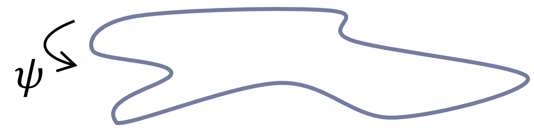
2-charge sys: geometric microstates

- D1-D5 system

D1(5)
D5(56789)

polarize

KKM(6789ψ;5)



arbitrary curve

Lunin-Mathur solutions
"geometric microstates"

$$S_{\text{micro}} \sim S_{\text{geom}} \sim Q$$

[Lunin+Mathur] [Lunin+Maldacena+Maoz] [Rychkov]

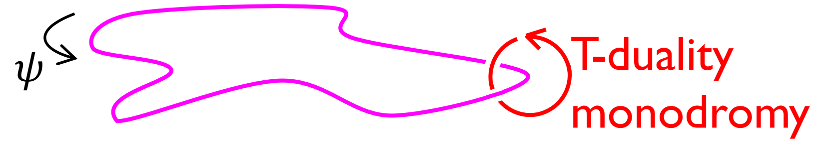
Non-geometric microstates

- D4-D4 system

D4(6789)
D4(4589)

polarize

$5^2_2\,(4567\psi,89)$



arbitrary curve

Non-geometric
microstates!

$$S_{\mathrm{micro}} \sim S_{\mathrm{nongeom}} \sim Q$$

Metric for D4+D4→5_2^2

D4(6789)+D4(4589)→5_2^2 (4567ψ,89) [de Boer+MS, 1004.2521]

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

f_i , A : sourced along curve in $\mathbb{R}^3$

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

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

- γ , β_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:

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

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

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

So far so good ☺

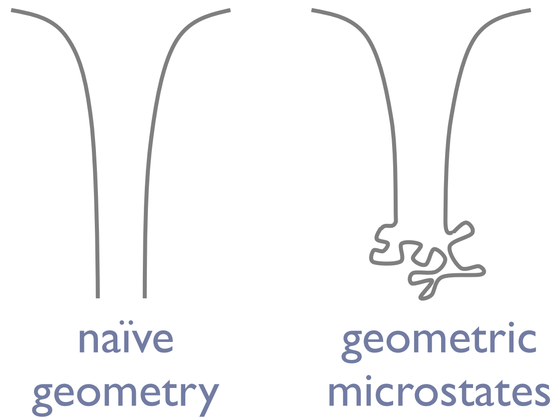
But 2-charge system
is not a real BH;
horizon vanishes classically.

Toward 'real' BHs

3-charge system (D1-D5-P)

— Not so successful ☹

- A huge # of geom. microstates have been constructed
  [Bena+Warner '05] [Berglund+Gimon+Levi '05]



- Evidence that they are *not* enough
  [de Boer+El-Showk+Messamah+Van de Bleeken '08-09] [Bena+Bobev+Ruef+Warner '08]

$$S_{\text{geom}} \sim Q^{\frac{5}{4}} \quad \ll \quad S_{\text{BH}} \sim Q^{\frac{3}{2}}$$

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 branes and are non-geometric!

“Double bubbling” (1) [de Boer+MS, 1004.2521]

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

M2(56)
M2(78)
M2(9A)

●

“Double bubbling” (1) [de Boer+MS, 1004.2521]

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

M2(56)	M5(789Aψ)
M2(78)	M5(569Aψ)
M2(9A)	M5(5678ψ)

arbitrary curve
“supertube”

cf. black ring

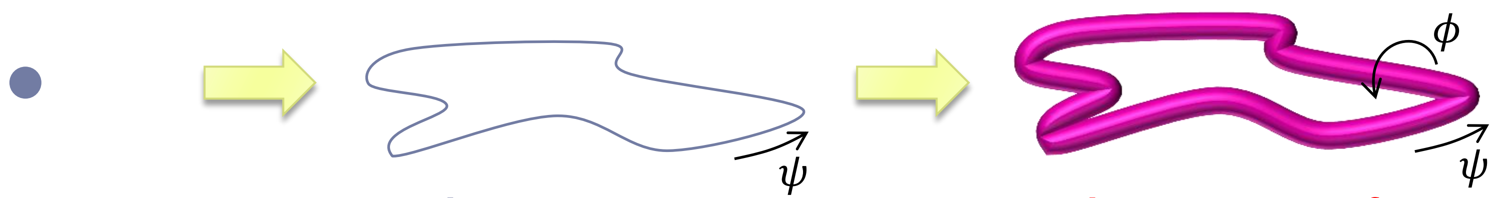
“Double bubbling” (1) [de Boer+MS, 1004.2521]

- 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

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

stra·tum [stréitəm | strá:-]

〖ラテン語「広がったもの」の意から〗

—名C(複-ta [-tə], ~s)

1 【地質】地層; 層.

2 層, 階級.

*

"Double bubbling" (2)

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

[Maladacena+Strominger+Witten]

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

"Double bubbling" (2)

- 4-charge system: 4D BH : Well studied for microstate counting
  [Maladacena+Strominger+Witten]

D0		
D4(6789)	NS5(6789ψ)	$5^2_2(6789,45\psi)$
D4(4589)	NS5(4589ψ)	$5^2_2(4589,67\psi)$
D4(4567)	NS5(4567ψ)	$5^2_2(4567,89\psi)$

exotic
supertube

"Double bubbling" (2)

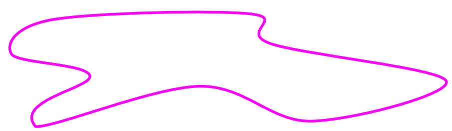
- 4-charge system: 4D BH : Well studied for microstate counting

[Maladacena+Strominger+Witten]

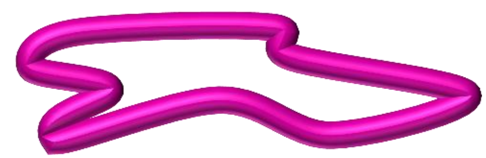
D0
D4(6789)
D4(4589)
D4(4567)

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

More exotic branes



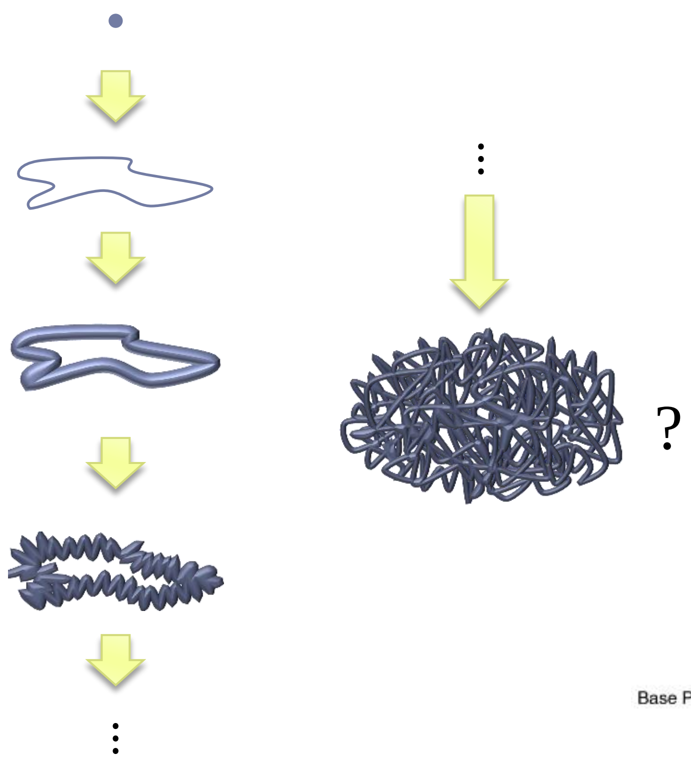
exotic supertube

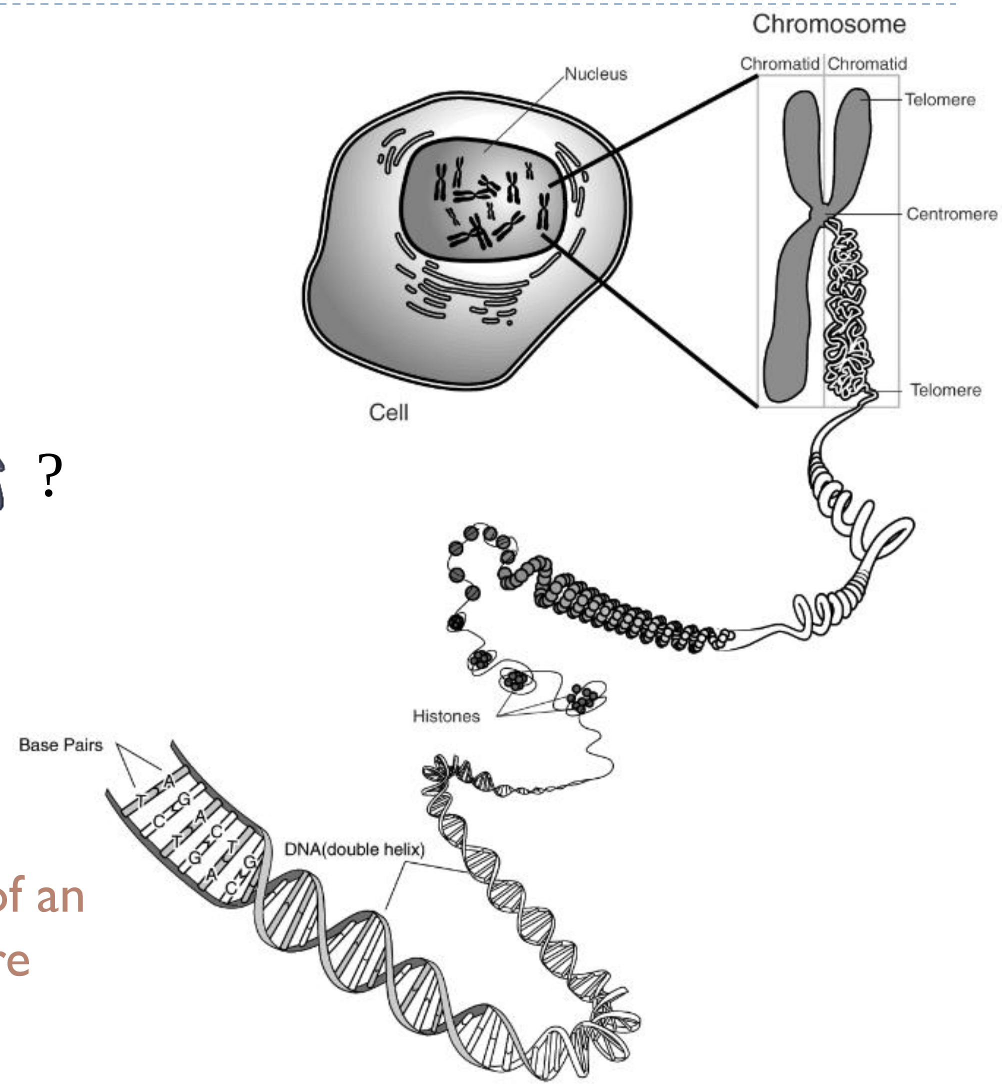


exotic superstratum

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

Endless bubbling??



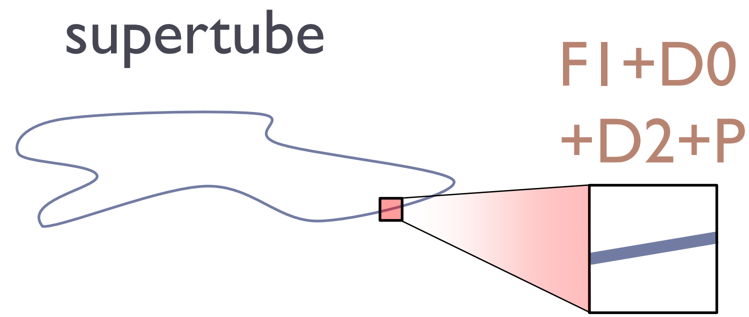


Presumably, a black hole is made of an extremely complicated structure (fuzzball) of exotic branes.

Toward Proving Double Bubbling

Susy in supertube [Bena+de Boer+Warner+MS 1107.2650]

F1+D0

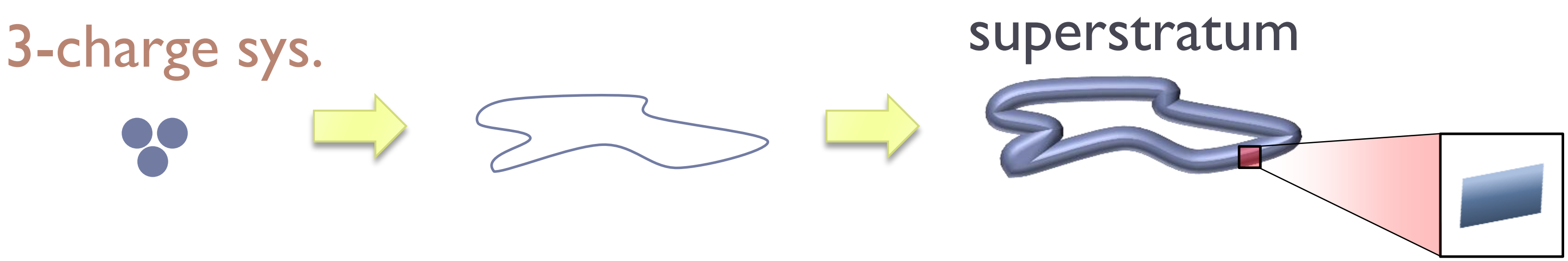


- Preserves $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ susy

- 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

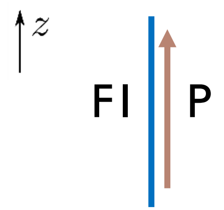


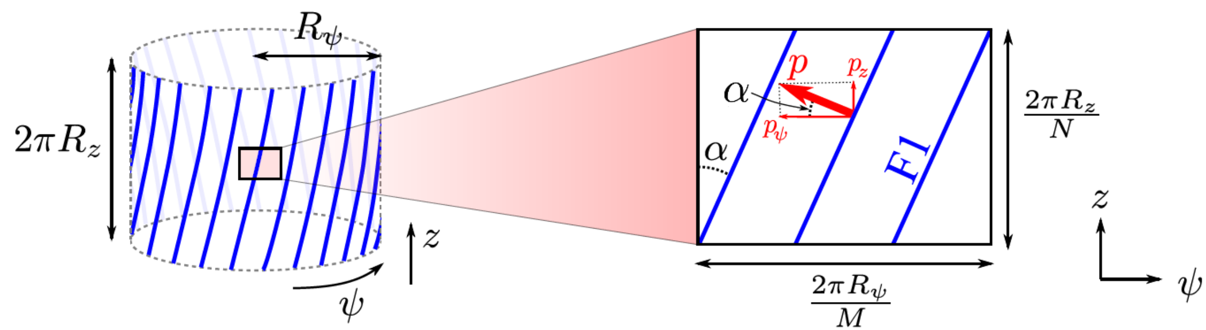
- Preserves $\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}=\frac{1}{8}$ susy

- 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:

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

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

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

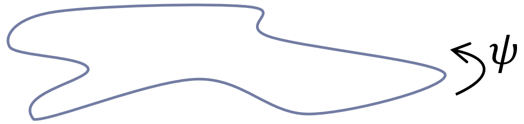
Common susy preserved = same as original ¼ susy

General formula for 1→2 puff-up

Projectors before puffing up:

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

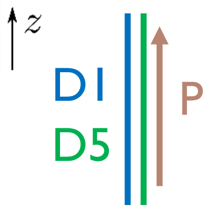
Projector after puffing up:



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

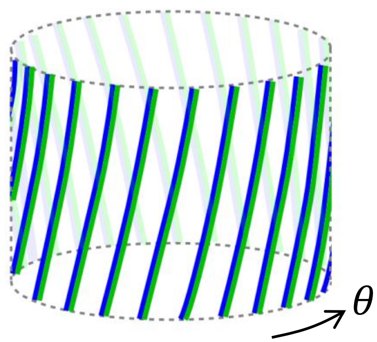
Special case: D1-D5-P (1)

$\mathrm{D1}(z)$
$\mathrm{D5}(z6789)$
$\mathrm{P}(z)$



Original config.

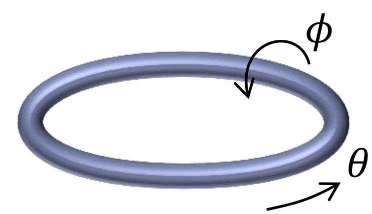
$\mathrm{D1}(\theta)$
$\mathrm{D5}(\theta 6789)$



Supertube: traveling waves on D1-D5

Locally same as D1-D5 2-chg sys.

$\mathrm{KKM}(6789\phi, \theta)$

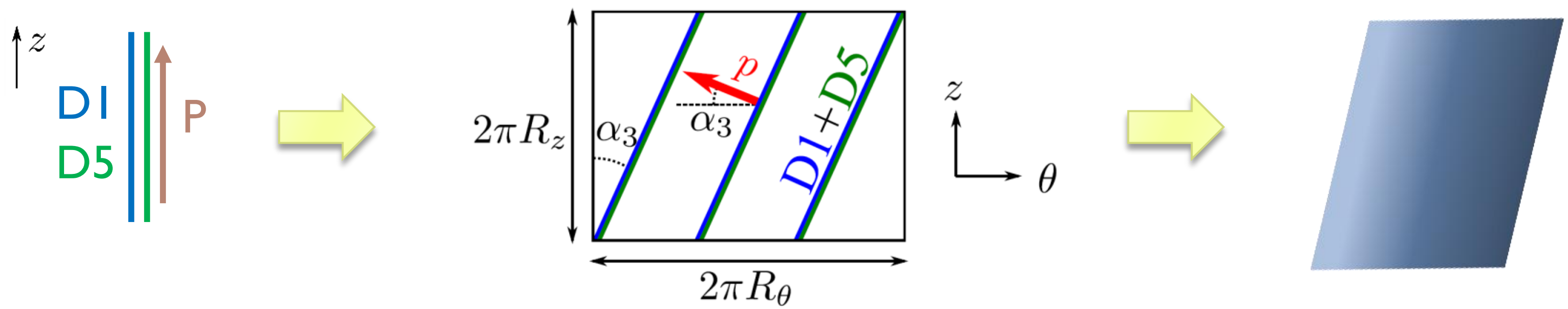


D1-D5-KK Superstratum

Special case; superstratum is geometric

Special case: D1-D5-P (2)

- Local picture

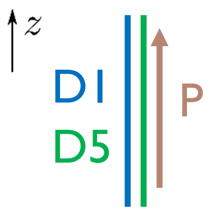


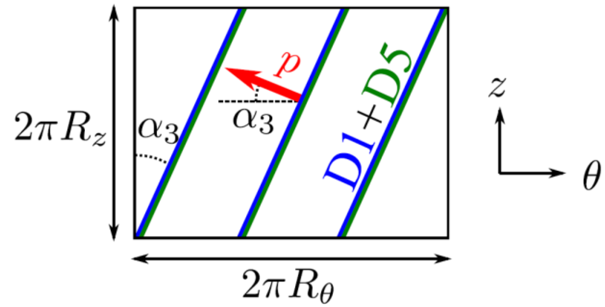
Original config.

Infinite straight supertube = tilted and boosted D1-D5

Infinite straight superstratum

Special case: D1-D5-P (3)





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

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

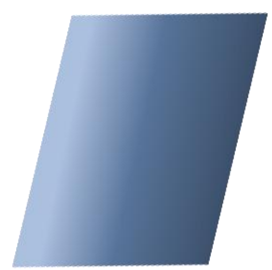
$$\Pi_3 = \frac{1}{2}(1 + \Gamma^{0z})$$

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

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

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

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

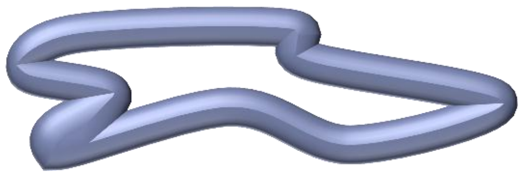


$$\hat{\Pi} = \frac{1}{2}(1 + s_4^2 \hat{P}_1 + c_4^2 \hat{P}_2 - s_4 c_4 \Gamma^{0\psi} + s_4 c_4 \Gamma^{0\psi}\hat{P}_1\hat{P}_2)$$

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
  - Given superstratum data,
    must be possible to find solutions in principle

Linear structure (1)

6D spacetime: (u, v, x^m)

u: isometry

x^m: 4D base

- 4D base $\mathcal{B}^4(v)$: almost hyper-Kähler

$$ds_4^2 = h_{mn}(x, v) dx^m dx^n, \quad m, n = 1,2,3,4$$

$\beta(x, v)$: 1-form (↔ KKM)

$J^{(A)}(x, v)$, $A = 1,2,3$: almost HK 2-forms

$$J^{(A)m}{}_n J^{(B)n}{}_p = \epsilon^{ABC} J^{(C)m}{}_p - \delta^{AB} \delta^m_p$$

$$\tilde{d} J^{(A)} = \partial_v \left(\beta \wedge J^{(A)}\right), \qquad \tilde{d} \equiv dx^m \partial_m$$

Linear structure (2)

- Fields on $\mathcal{B}^4$

Z_1: scalar $\leftrightarrow$ D1(v)
Θ_1: 2-form $\leftrightarrow$ D1(ψ)
ω: 1-form $\leftrightarrow$ J

Z_2: scalar $\leftrightarrow$ D5(v6789)
Θ_2: 2-form $\leftrightarrow$ D5(ψ6789)
$\mathcal{F}$: scalar $\leftrightarrow$ P(v)

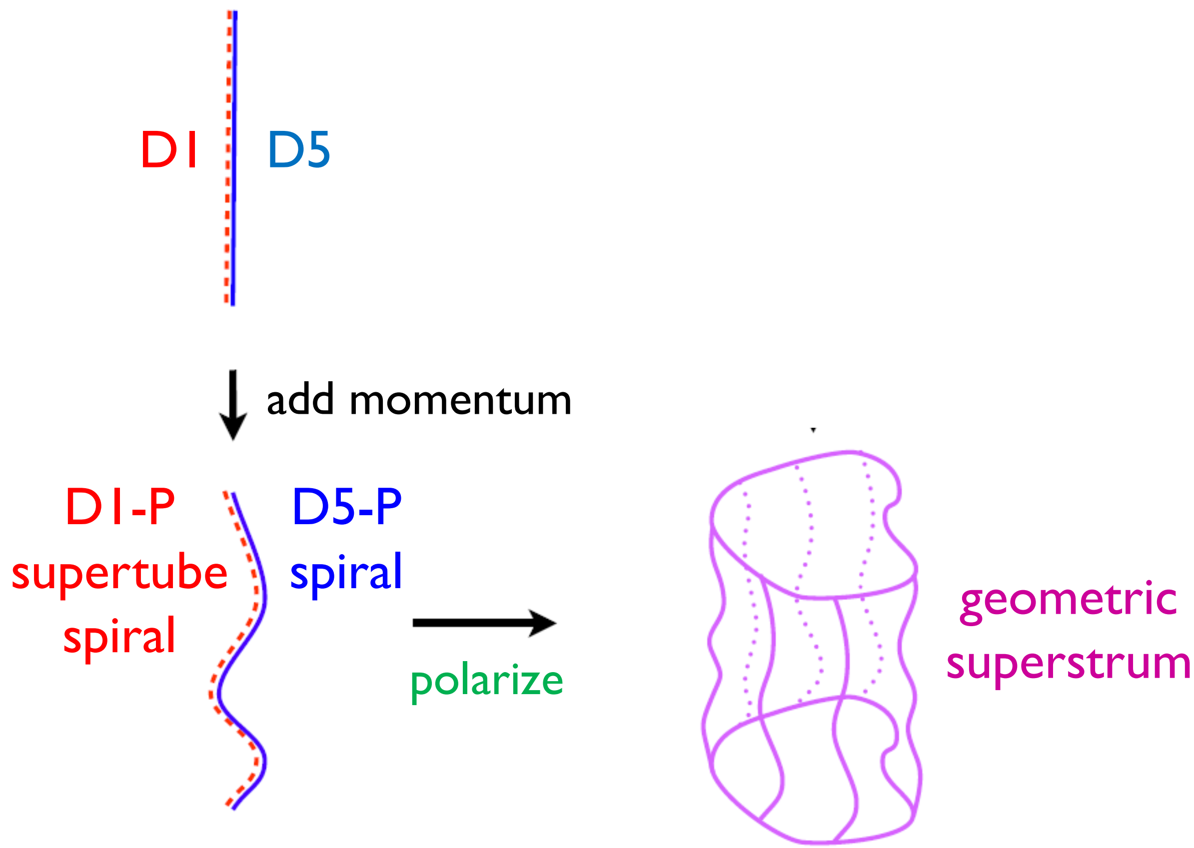
$$D\left[*_4\left(DZ_i + \dot{\beta} Z_i\right)\right] + 2(D\beta)\wedge\Theta_j = 0 \qquad \{i,j\} = \{1,2\}$$

$$D\Theta_j - \dot{\beta}\wedge\Theta_j - \partial_v\left[\frac{1}{2} *_4\left(DZ_i + \dot{\beta} Z_i\right)\right] = 0 \qquad \dot{} \equiv \partial_v$$

$$ds_6^2 = \frac{2}{\sqrt{Z_1 Z_2}}(dv+\beta)\left(du + \omega + \frac{1}{2}\mathcal{F}(dv+\beta)\right) - \sqrt{Z_1 Z_2}\, ds_4^2$$

Geometric superstrata (1)

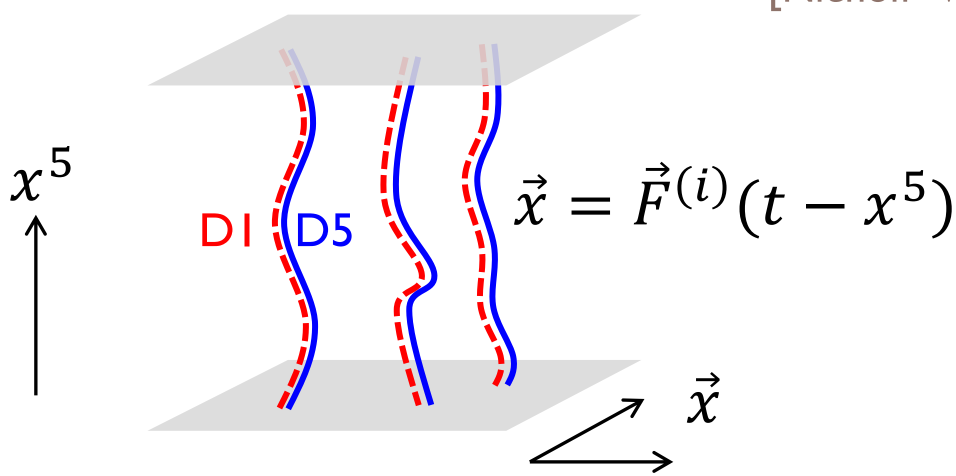
- Double bubbling of D1-D5-P system



Geometric superstrata (2)

- So far it was possible to construct:

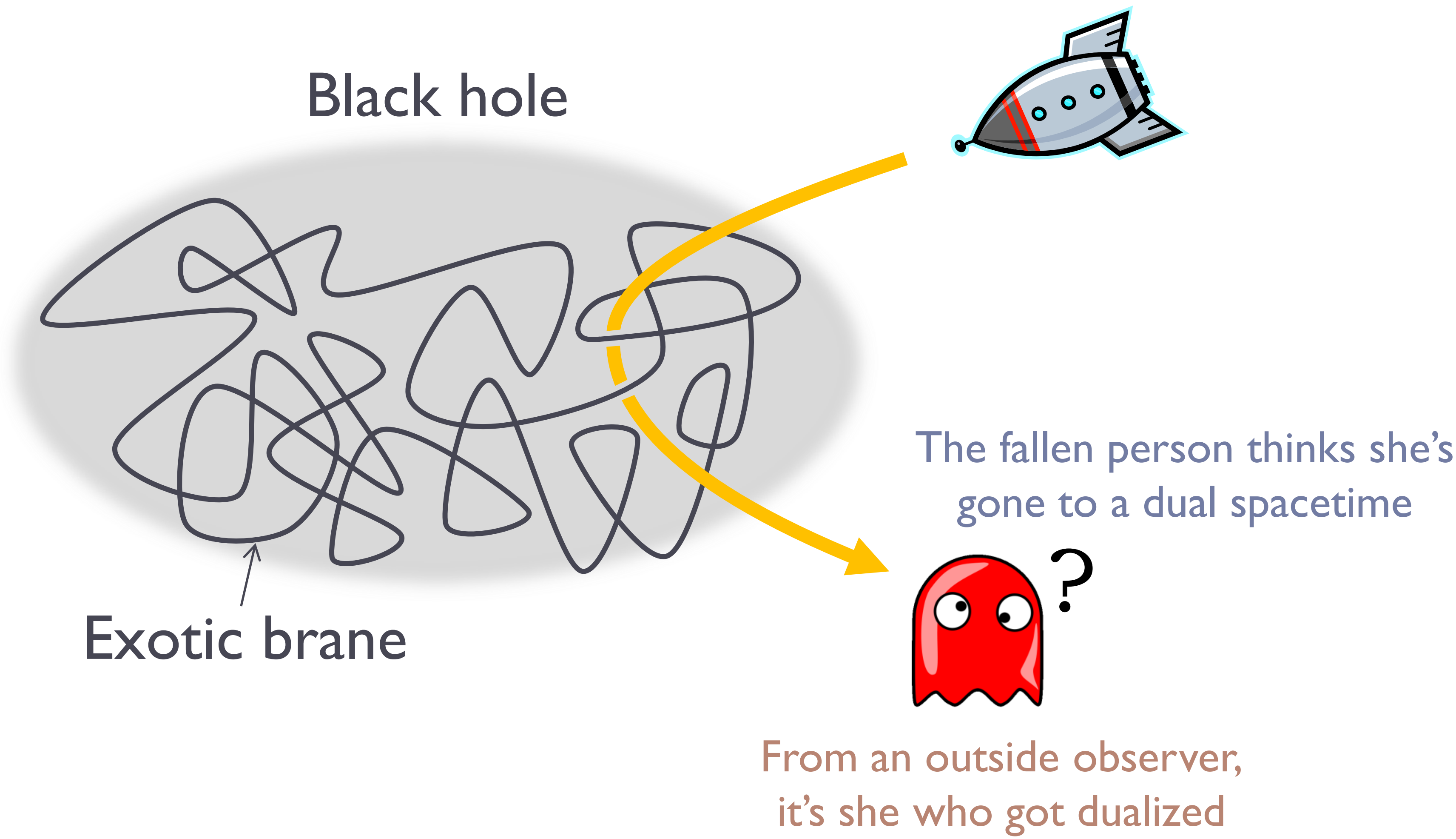
[Niehoff+Vasilakis+Warner 1203.1348]



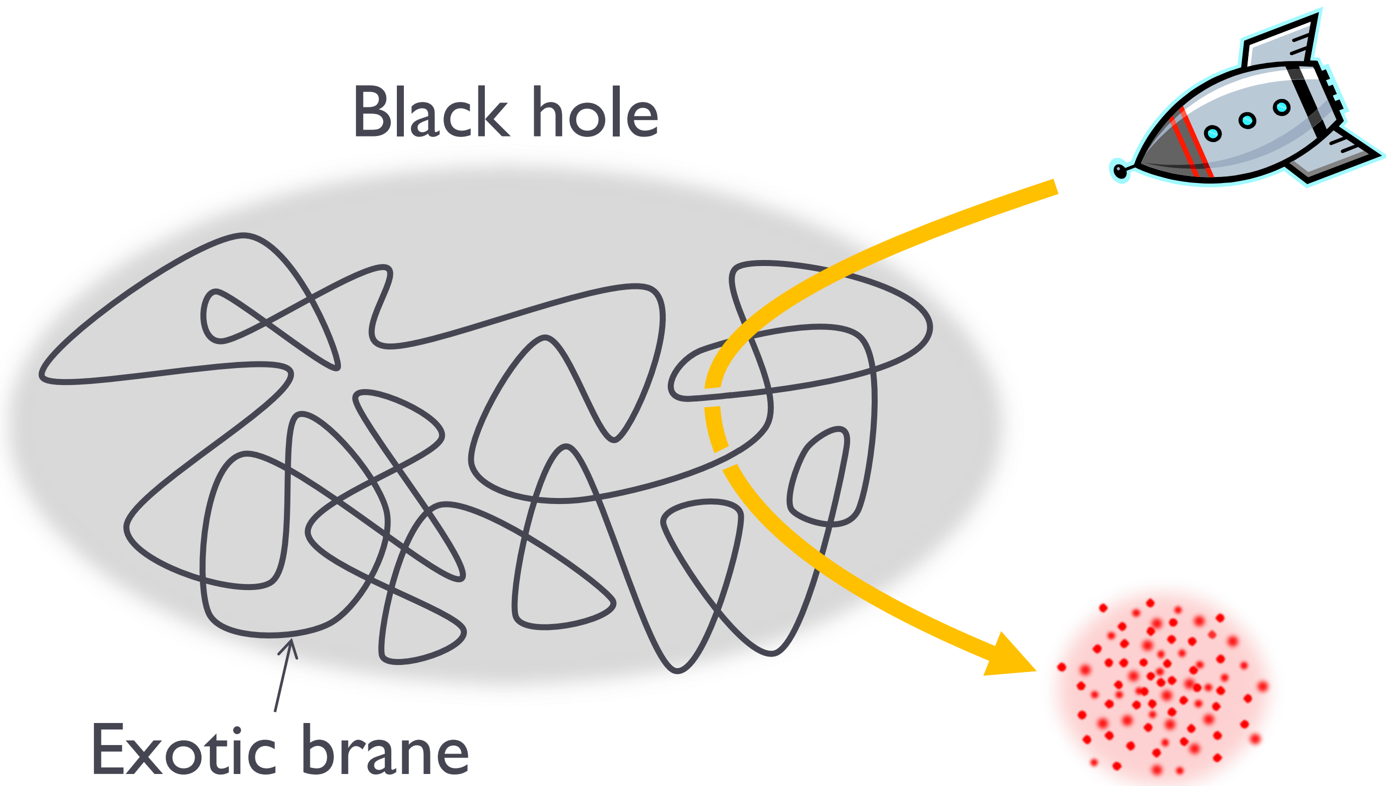
N strands of D1-P and D5-P supertube spirals along arbitrary curves $\vec{F}^{(i)}, i = 1, \ldots, N$

Next step: KKM dipole (work in progress)

Falling into BH



Falling into BH



In reality, she has gone to pieces and
is indistinguishable from Hawking radiation

Conclusions

Conclusions

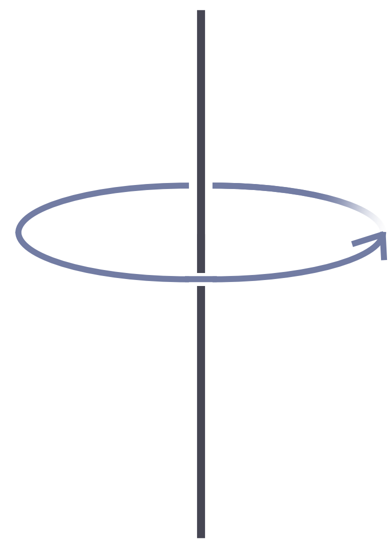
- Exotic branes = non-geometries (U-folds)
- Relevant even for non-exotic physics by supertube effect

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

- Essential ingredients of BHs

Future directions

- Geometric superstrata
  - Hints from string amplitudes [Giusto, Russo, et al.]
- Non-geometric superstrata
  - 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!