HABEMUS SUPERSTRATUM

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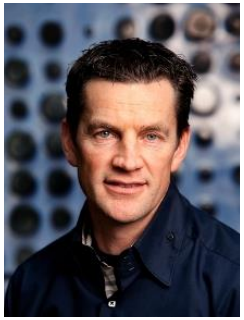
MAIN MESSAGES

- Black hole microstates involve complicated structure of branes called *superstrata*
- Basic superstrata solutions *explicitly* constructed in sugra as smooth geometries

Iosif Bena



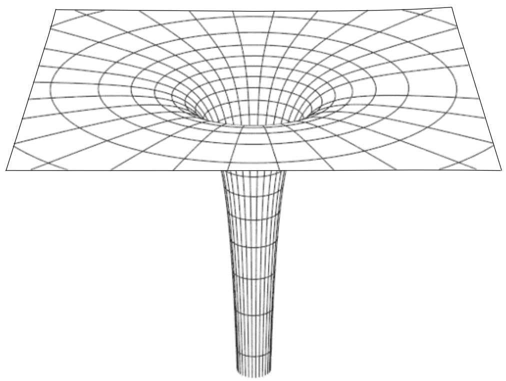
Jan de Boer

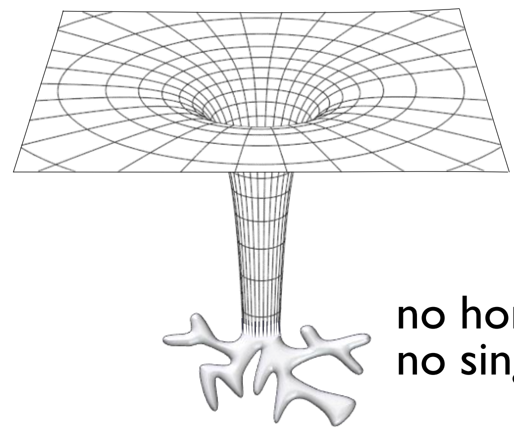
Stefano Giusto

Rodolfo Russo

Nick Warner

MICROSTATE GEOMETRY PROGRAM:





no horizon,
no singularity

How much of black hole entropy can be accounted for by smooth, horizonless solutions of classical gravity?

D1-D5-P BH: $S_{BH} = 2\pi\sqrt{N_1 N_5 N_P}$

SOME HISTORY

1915 Einstein: general relativity

1975 Hawking radiation

1996 Strominger-Vafa (field theory counting of 3-charge BH)

2001 Lunin-Mathur geometries (2-charge microstates)
→ *fuzzball conjecture, microstate geometry program*

2006 Microstate geometries in 5D (3- and 4-charge microstates)

2010 *Double bubbling & superstrata* (into 6D)

2015 *Explicit construction* of superstrata

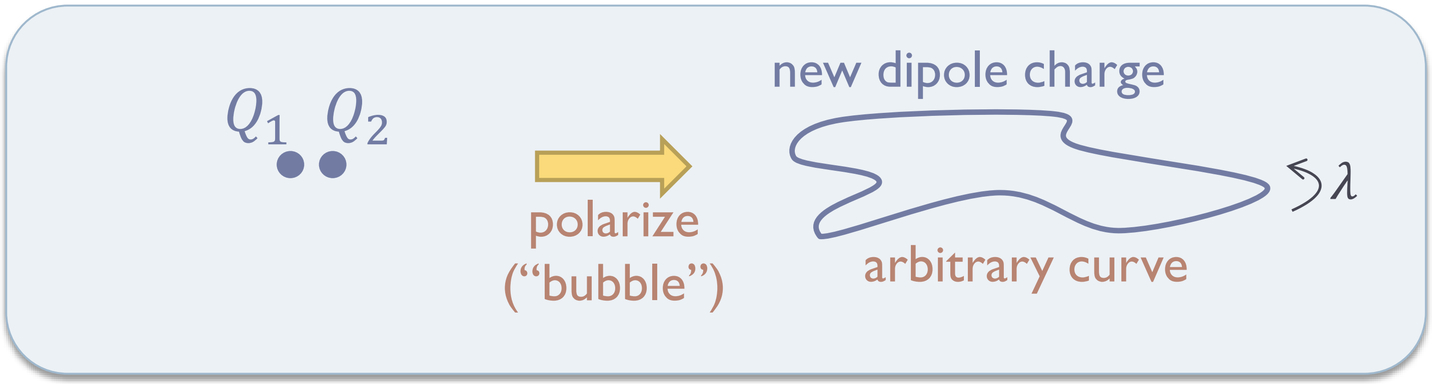
} This talk

DOUBLE BUBBLING

(OR MULTIPLE SUPERTUBE TRANSITION)

SUPERTUBE TRANSITION

[Mateos+Townsend '01]

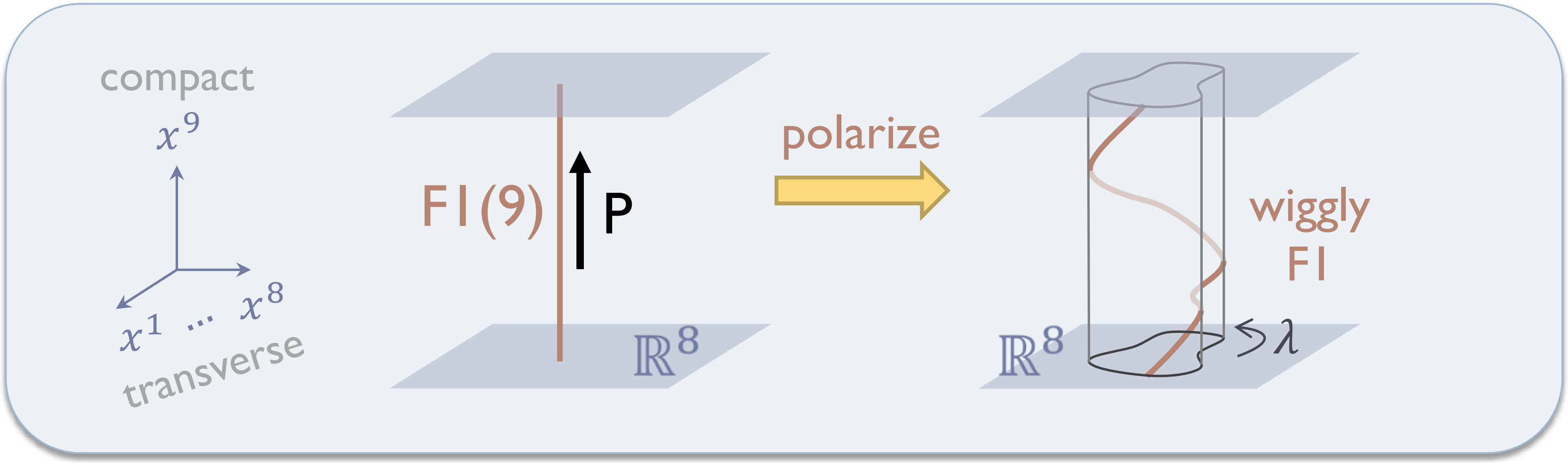


- Spontaneous polarization phenomenon
- Produces new dipole charge
- Cross section = *arbitrary* curve

(cf. Myers effect)

SUPERTUBE: F1-P FRAME

$$\mathrm{F1}(9) + \mathrm{P}(9) \to \mathrm{F1}(\lambda)$$



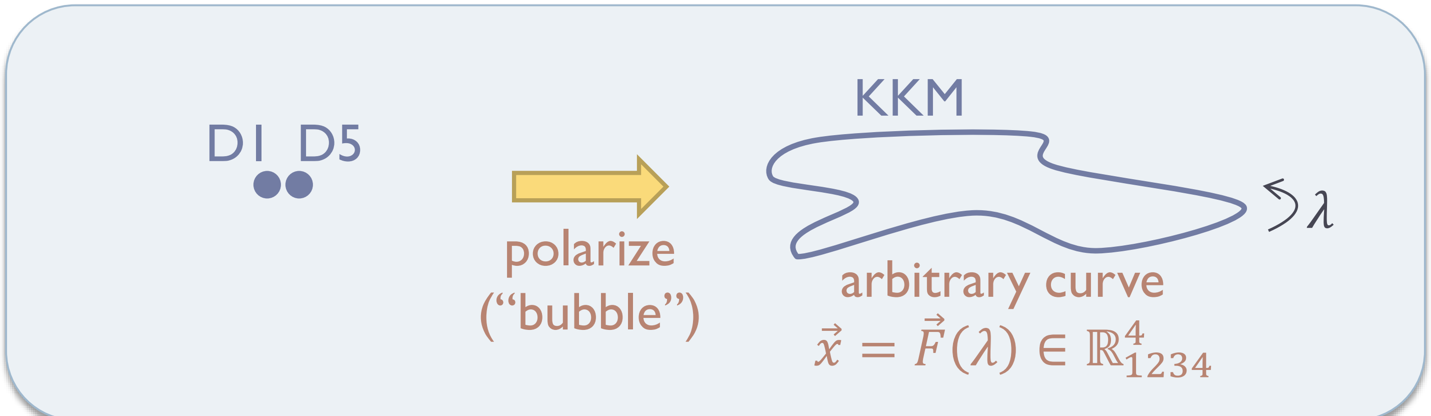
- To carry momentum, F1 must wiggle in transverse $\mathbb{R}^8$

$$x^i = F^i(x^9 - t)$$

- Projection onto transverse $\mathbb{R}^8$ is an arbitrary curve

SUPERTUBE: D1-D5 FRAME

$$\mathrm{D1}(5) + \mathrm{D5}(56789) \to \mathrm{KKM}(\lambda 6789,5)$$



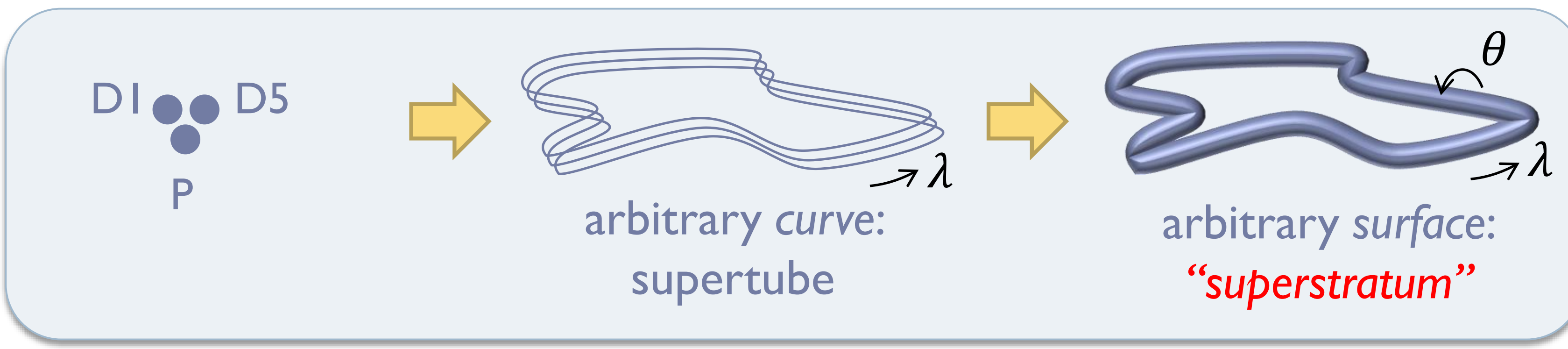
- LM geometries (2-charge microstate geometries) [Lunin-Mathur '01]
- Arbitrary curve → large entropy $S_{\text{geom}} \sim \sqrt{N_1 N_5}$ [Rychkov '05]
- AdS/CFT dictionary well understood [Lunin-Mathur '01] [Kanitscheider-Skenderis-Taylor '06, 07]

DOUBLE BUBBLING

[de Boer-MS '10, '12]
[Bena-de Boer-MS-Warner '11]

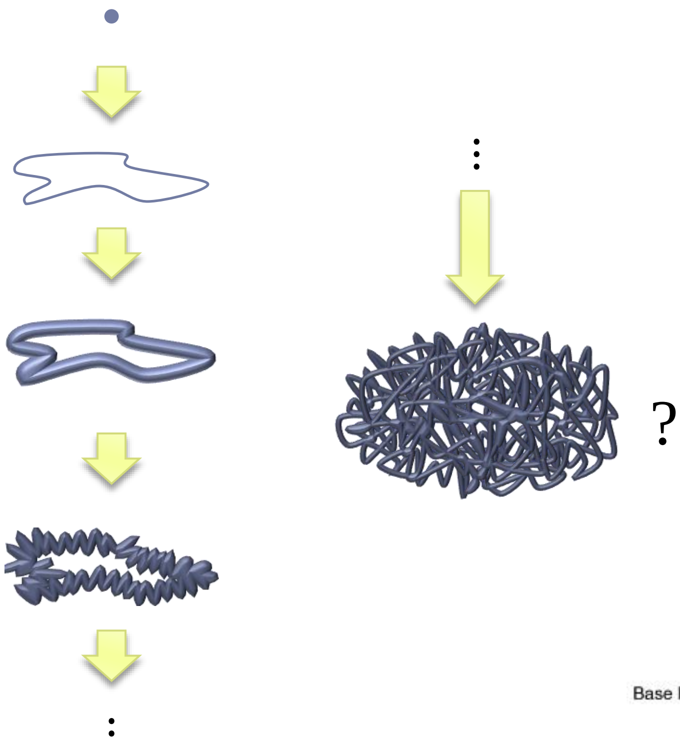
3-charge system: real BH

D1(5) D5(56789) P(5)	⇨	D5(λ6789) D1(λ) KKM(λ6789,5)	⇨	$5^2_3(\theta6789,\lambda)$ $1^6_3(\theta,\lambda56789)$ KKM(λ6789,θ)

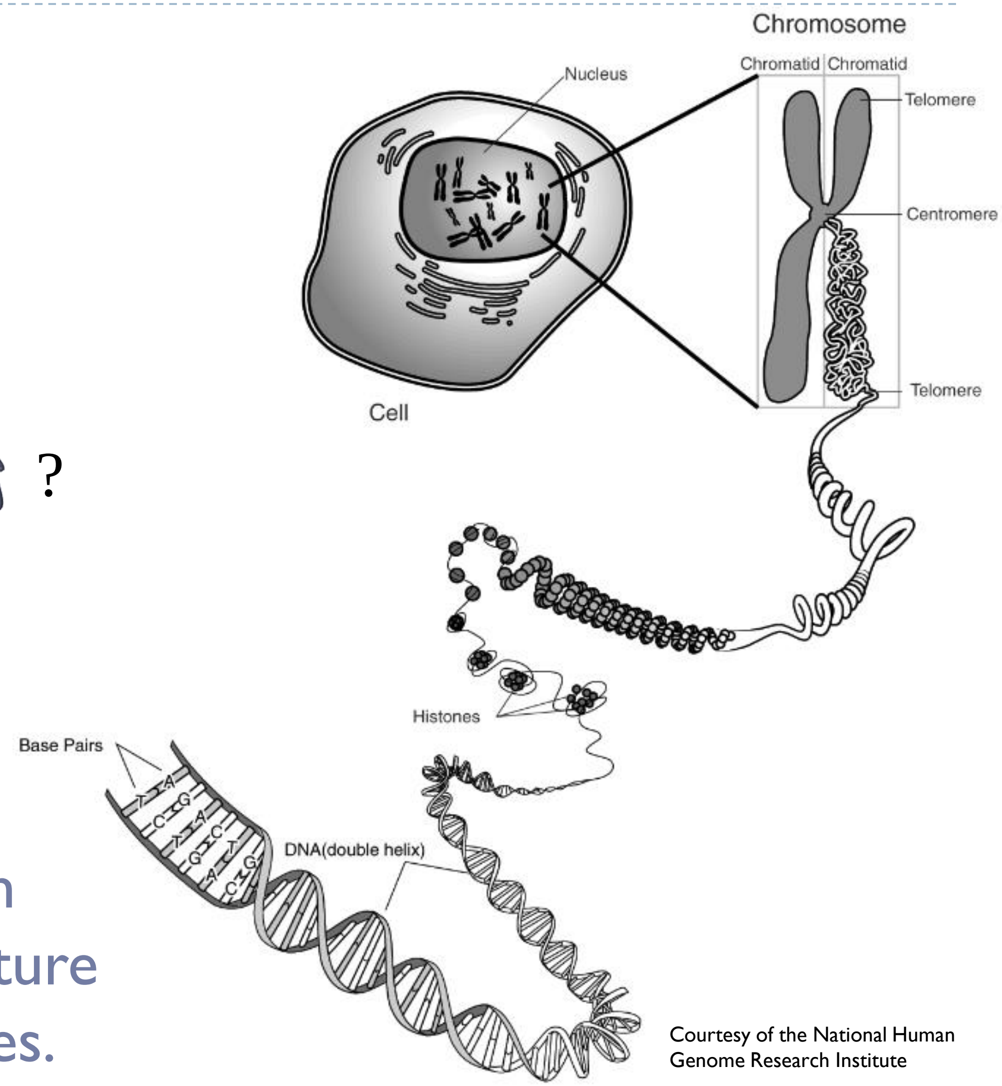


- BH microstates involve arbitrary surface = *superstratum*
- Exotic and non-geometric in general (5^2_3, 1^6_3, ...)
- Arbitrary surface → *larger* entropy $S_{\text{geom}} \sim \sqrt{N_1 N_5 N_P}$?

ENDLESS BUBBLING?



A black hole is made of an extremely complicated structure (fuzzball) of puffed-up branes.



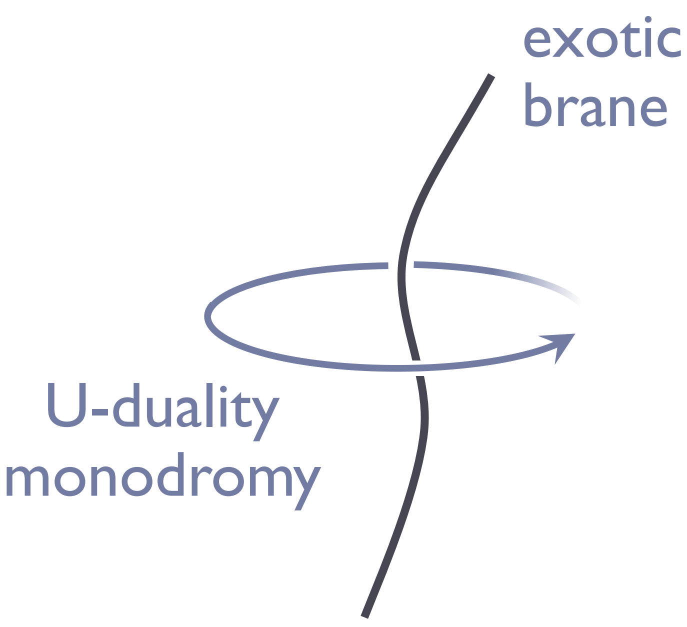
Courtesy of the National Human Genome Research Institute

EXOTIC BRANES [de Boer-MS '10, '12]

- "Forgotten" branes in string theory

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

- Codimension 2
- U-duality monodromy ("U-fold")
- Non-geometric

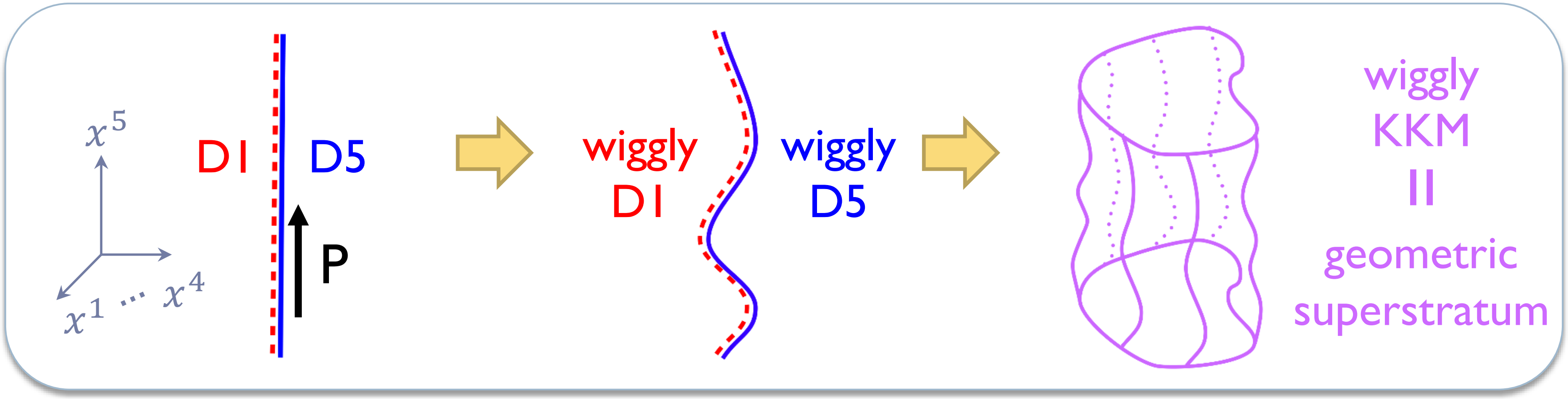


generalization of F-theory 7-branes

A GEOMETRIC CHANNEL

[Bena-de Boer -MS-Warner '11]

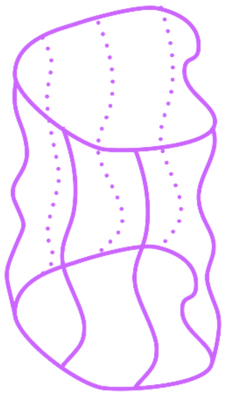
D1(5)
D5(56789)
P(5)
→ D5(λ6789)
D1(λ)
→ KKM(λ6789, θ)



- Can use geometric intuition (smoothness)
- Dependence on x^5 is crucial → 6 dimensions

SUMMARY:

- BH microstates involve double-bubbled superstrata
- Geometric superstratum in 6D is important for microstate geometry program



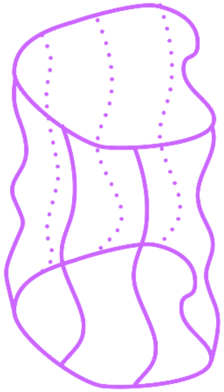
EXPLICIT CONSTUCTION OF SUPERSTRATA

[Bena+Giusto+Russo+MS+Warner ’15]

GOAL:

Explicitly construct "superstrata" = wiggly KKM in 6D

They must depend on functions of two variables: $F(x, y)$



SUSY SOLUTIONS IN 6D

- IIB sugra on T^4_{6789}
- Require same susy as preserved by D1-D5-P

[Gutowski+Martelli+Reall '03] [Cariglia+Mac Conamhna '04]
[Bena+Giusto+MS+Warner '11] [Giusto+Martucci+Petrini+Russo '13]

$$ds^2_{10} = -\frac{2\alpha}{\sqrt{Z_1 Z_2}}(dv+\beta)\left(du+\omega+\tfrac{1}{2}\mathcal{F}(dv+\beta)\right) + \sqrt{Z_1 Z_2}\, ds^2(\mathcal{B}^4) + \sqrt{\frac{Z_1}{Z_2}}\, ds^2(T^4)$$

$$e^{2\Phi} = \frac{\alpha Z_1}{Z_2} \qquad \alpha \equiv \frac{Z_1 Z_2}{Z_1 Z_2 - Z_4^2} \qquad \mathcal{D} \equiv d_4 - \beta \wedge \partial_v \qquad \dot{} \equiv \partial_v$$

$$H_3 = -(du+\omega)\wedge(dv+\beta)\wedge\left(\mathcal{D}\left(\frac{\alpha Z_4}{Z_1 Z_2}\right) - \frac{\alpha Z_4}{Z_1 Z_2}\dot{\beta}\right)$$
$$+(dv+\beta)\wedge\left(\Theta_4 - \frac{\alpha Z_4}{Z_1 Z_2}\mathcal{D}\omega\right) + \frac{\alpha Z_4}{Z_1 Z_2}(du+\beta)\wedge\mathcal{D}\beta + *_4\left(\mathcal{D}Z_4 + Z_4\dot{\beta}\right)$$

$$F_1 = \mathcal{D}\left(\frac{Z_4}{Z_1}\right) + (dv+\beta)\wedge\partial_v\left(\frac{Z_4}{Z_1}\right)$$

$$F_3 = -(du+\omega)\wedge(dv+\beta)\wedge\left(\mathcal{D}\left(\frac{1}{Z_1}\right) - \frac{1}{Z_1}\dot{\beta} + \frac{\alpha Z_4}{Z_1 Z_2}\mathcal{D}\left(\frac{Z_4}{Z_1}\right)\right)$$
$$+(dv+\beta)\wedge\left(\Theta_1 - \frac{Z_4}{Z_1}\Theta_4 - \frac{1}{Z_1}\mathcal{D}\omega\right) + \frac{1}{Z_1}(du+\beta)\wedge\mathcal{D}\beta + *_4\left(\mathcal{D}Z_2 + Z_2\dot{\beta}\right) - \frac{Z_4}{Z_1} *_4\left(\mathcal{D}Z_4 + Z_4\dot{\beta}\right)$$

BPS EQUATIONS

0^{th} layer — Give 4D base

↓

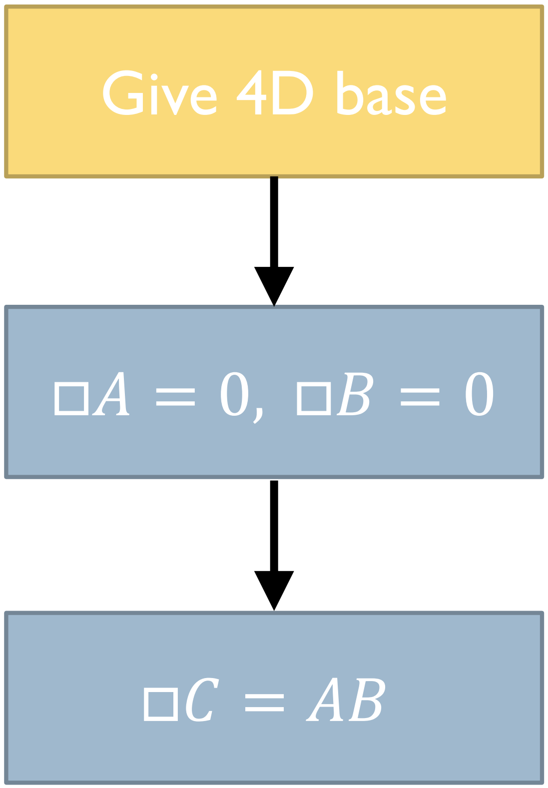
1^{st} layer — $\Box A = 0, \ \Box B = 0$

↓

2^{nd} layer — $\Box C = AB$

Linear if solved in the right order

0TH LAYER



- Take flat $\mathbb{R}^4$
- This is the base for:

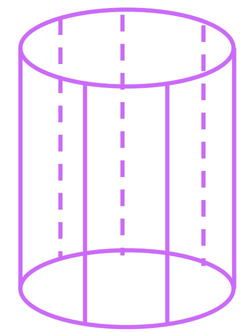
round LM geometry
(2-charge)

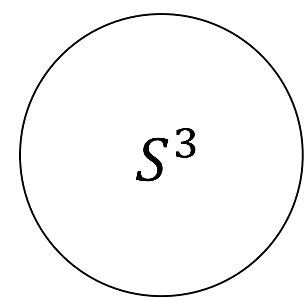
||

round superstratum
with no wiggle (yet)

||

pure $\mathrm{AdS}_3 \times S^3$





1ST LAYER

Give 4D base

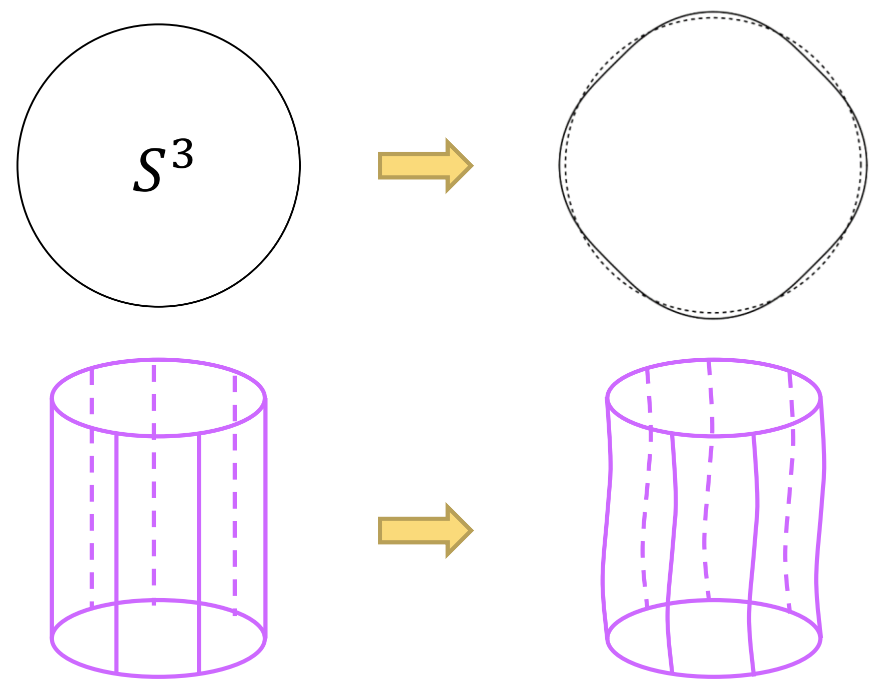
↓

$\Box A = 0, \ \Box B = 0$

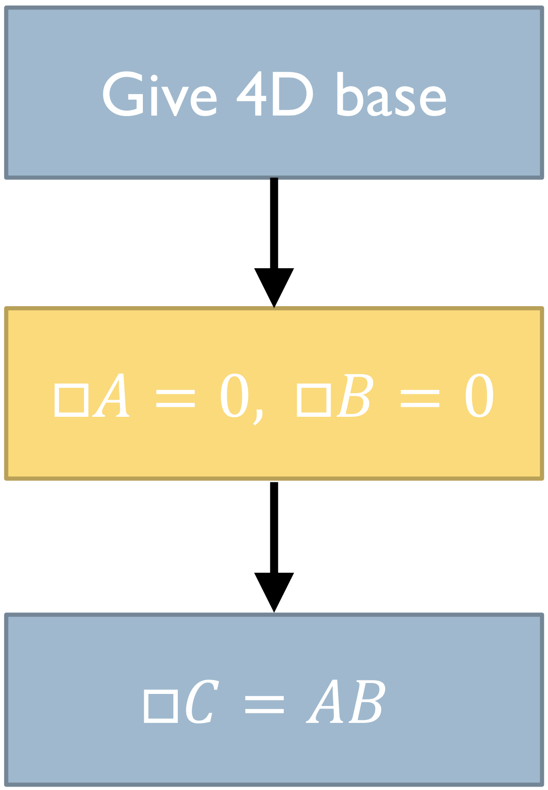
↓

$\Box C = AB$

- Take known linear solution with P
  [Mathur+Saxena+Srivastava '03]
- Mode numbers: (k, m)

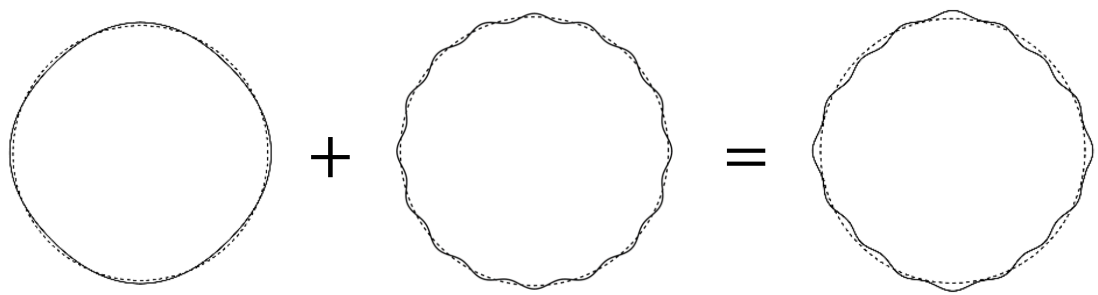


1ST LAYER (2)

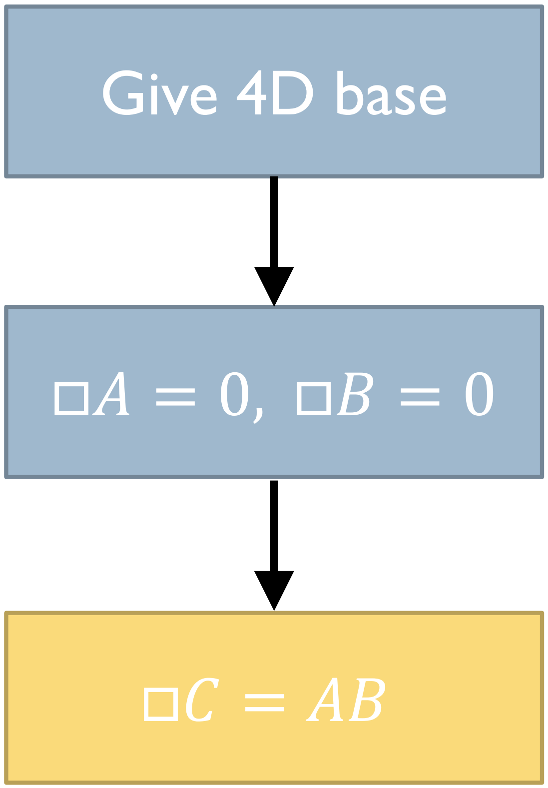


- Superpose modes to get function of 2 variables

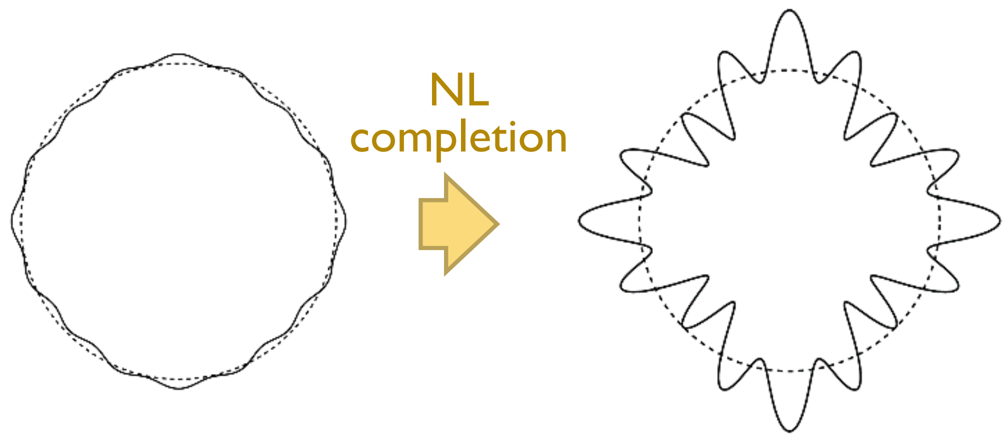
$$A = \sum_{k,m} a_{k,m} Y_{k,m}$$



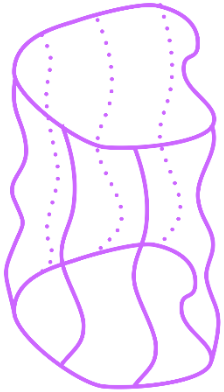
2^{ND} LAYER



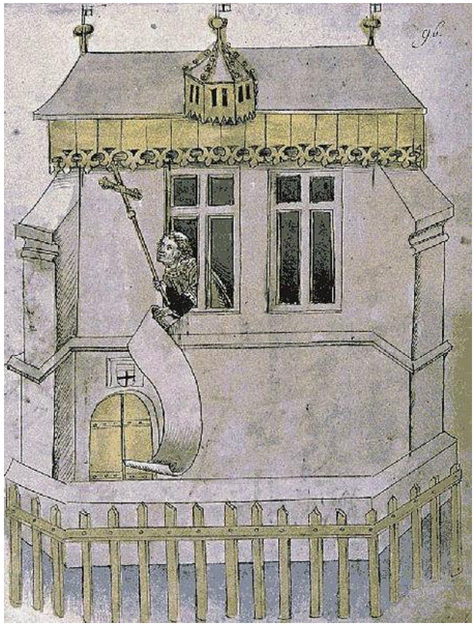
- Find C as non-linear solution
  - → Do it for pair of modes $(k_1, m_1), (k_2, m_2)$
- Regularity fixes solution



SUMMARY:



- Constructive proof of existence of superstrata!
  - → Big step toward general 3-charge microstate geometries

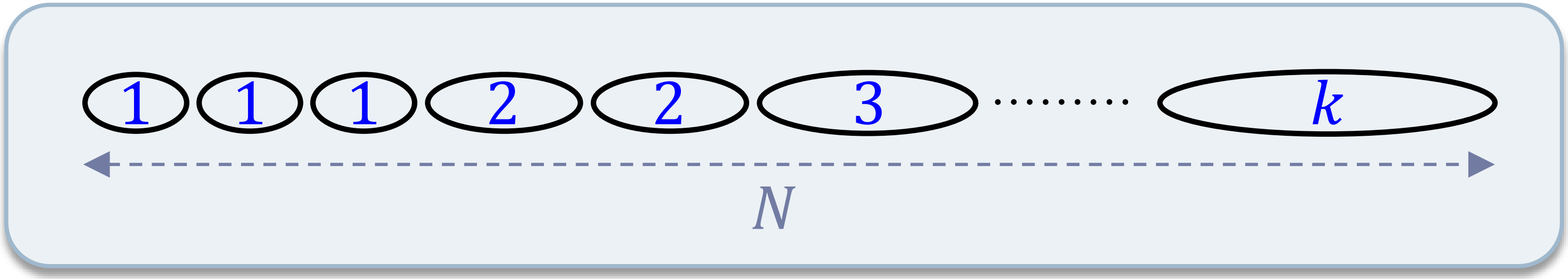


- Most general microstate geometry with known CFT dual

CFT PICTURE

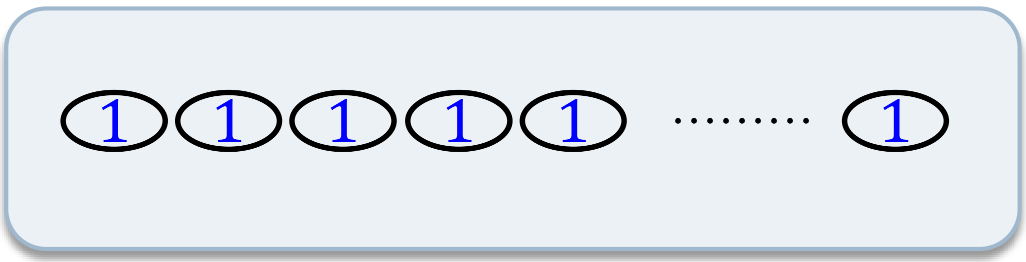
BOUNDARY CFT

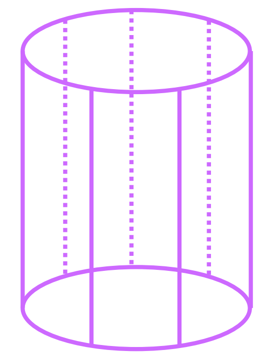
- D1-D5 CFT
  - 2D $\mathcal{N} = (4,4)$ SCFT, $c = 6N$, $N \equiv N_1 N_5$
  - Target space: orbifold $(T^4)^N / S_N$
- Orbifold CFT
  - Twist sectors represented by component strings



2-CHARGE STATES (1)

- Round LM geom

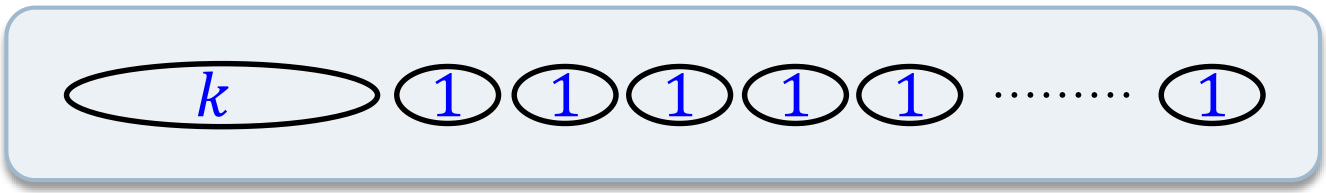


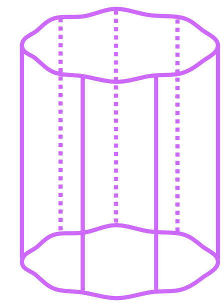


$\leftrightarrow$ NS vacuum

2-CHARGE STATES (2)

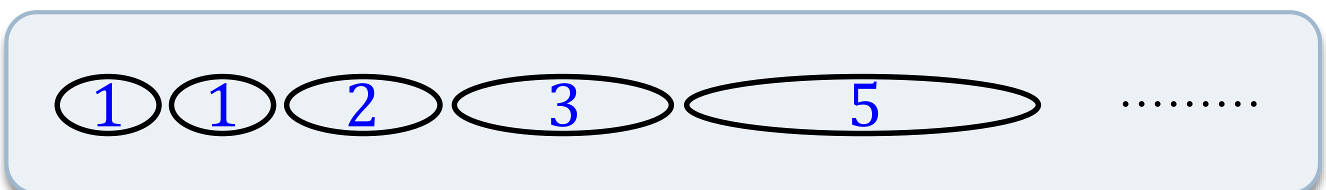
- Linear fluct around round LM

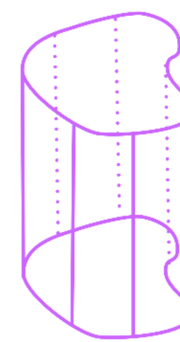




↔ "single-trace" chiral primary

- General LM geom [Lunin-Mathur '01]



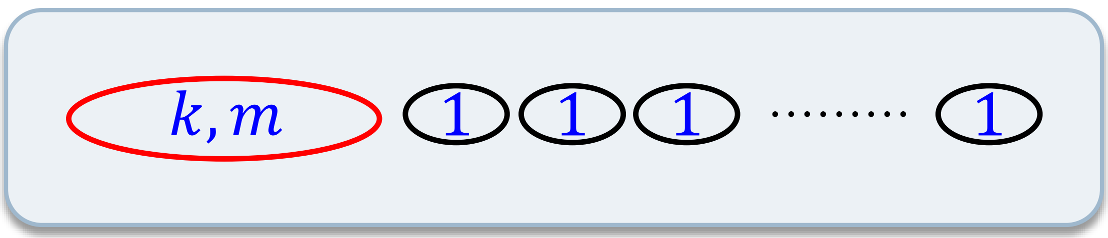


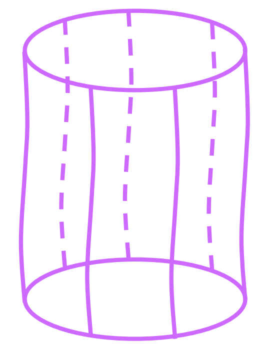
↔ general chiral primary

KNOWN 3-CHARGE STATES

- P-carrying linear fluct around round LM

“known linear solution” [Mathur+Saxena+Srivastava ’03]





→ m: momentum number

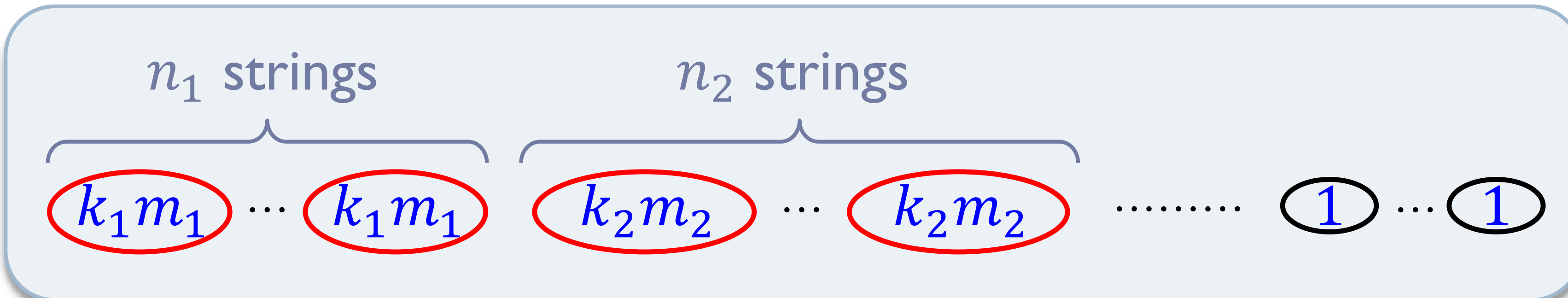
→ State of a single supergraviton with quantum numbers (k, m)

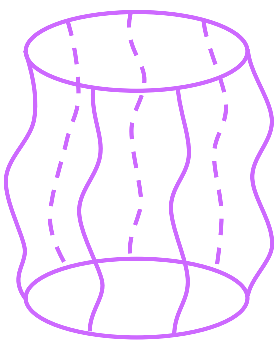
↔ descendant of chiral primary

$$k, m \sim (J^{+}_{-1})^{m} \sigma^{++}_{k}$$

SUPERSTRATA

- General P-carrying fluct around round LM





→ Various modes (k, m) turned on with finite amp.

→ The most general microstate geometry with known CFT dual

→ State of supergraviton gas (D1-D5 1/8-BPS version of LLM)

↔ descendant of *non-chiral* primary

TOWARD MORE GENERAL STRATA

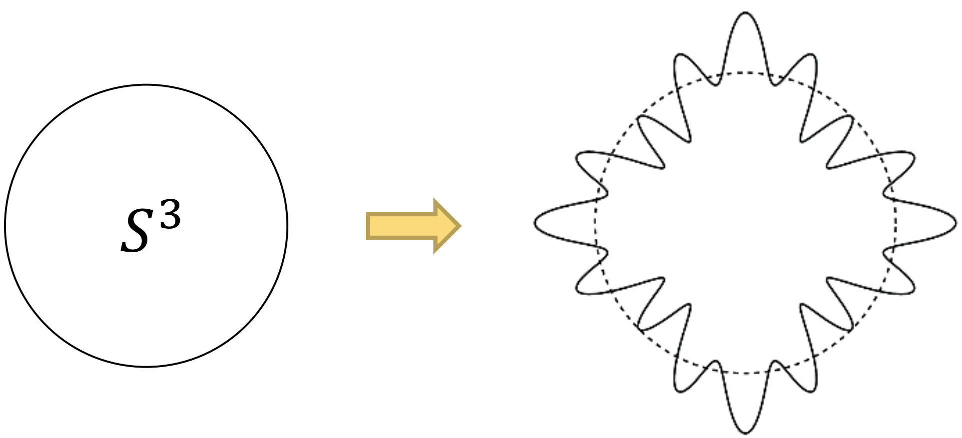
WHAT'S MISSING

- Does this class of superstrata reproduce $S_{\rm BH}$?

  → Not yet ☹

  These correspond to
  supergraviton gas = fluct around S^3.

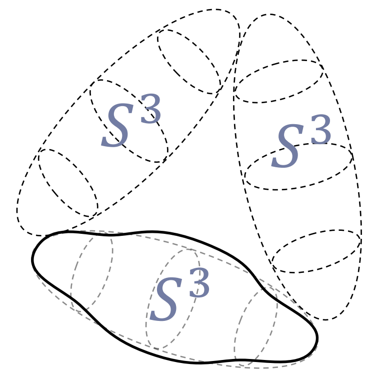
  Entropy parametrically smaller. [de Boer '98]



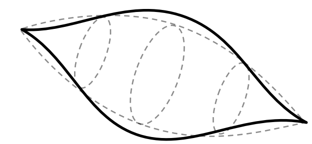
MORE GENERAL SUPERSTRATA

Next steps:

- Other backgrounds
  - → multiple S^3's, $\mathbb{Z}_k$ orbifolds



multi-superstratum



$S^3/\mathbb{Z}_k$

- CFT side:
  - → Need higher and fractional modes of $SL(2,\mathbb{R})_L \times SU(2)_L$

$$(J^+_{-1})^m \, \sigma_k^{++} \quad \rightarrow \quad J^+_{-2} \, \sigma_k^{++} \qquad J^+_{-\frac{1}{k}} J^+_{-\frac{2}{k}} \, \sigma_k^{++}$$

CONCLUSIONS

CONCLUSIONS:

Superstratum

- Represents a new class of microstate geometries
- Depends on functions of two variables
- Represents the most general microstate geometry with known CFT dual
- More general superstrata out there; Construct them. Can they reproduce $S_{\rm BH}$?

STAY TUNED

Thanks!