Effective Microstructure

Raphaël Dulac, IPHT CEA-Saclay

[**RD**-Heidmann, 2024], [Bena-**RD-**Martinec-Shigemori-Turon-Warner, 2025]

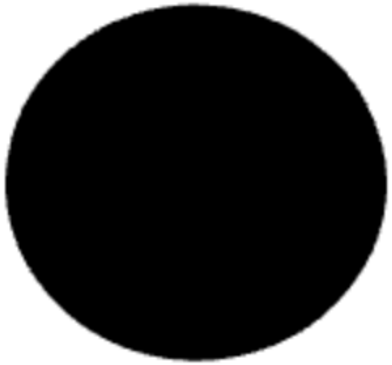
The information paradox: an entropy puzzle

Large entropy

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

$$S_{BH} = \log(N_{\text{micro}})$$

No hair theorems in GR



The Komar charges (M,Q,J) completely fix the geometry

$$S = 0$$

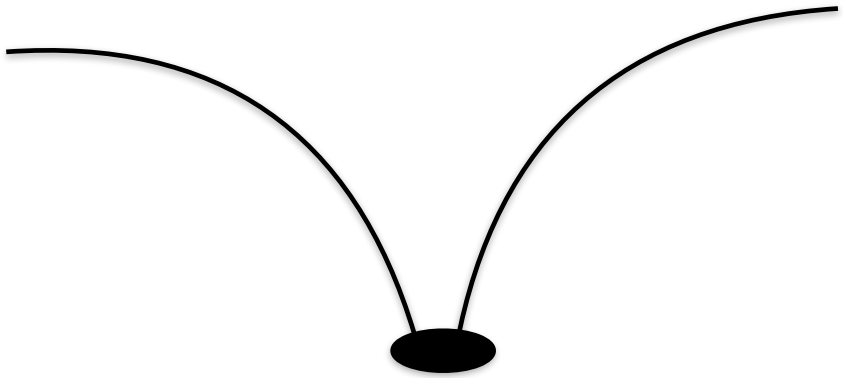
General relativity is unable to capture the micro-states.

String theory is able to give a microscopic interpretation to the black hole entropy.

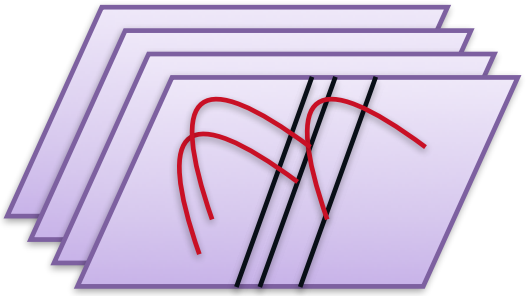
D1-D5-P black hole: a 5d supersymmetric black hole

Regime of parameters at which black holes exist

$$S = \frac{A}{4G_N} = 2\pi\sqrt{N_1 N_5 N_P}$$



$G_N = 0$: gas of D-branes



$$S = 2\pi\sqrt{N_1 N_5 N_P}$$

A number protected by supersymmetry, hence valid at any G_N

[Strominger—Vafa, 96]

Microscopic interpretation of the D1-D5-P black hole

$G_N = 0$, a gas of D-branes

$$S = 2\pi\sqrt{N_1 N_5 N_P}$$

Regime of parameters at which black holes exist

$$S = \frac{A}{4G_N} = 2\pi\sqrt{N_1 N_5 N_P}$$

What does each micro-state look like?

Microscopic interpretation of the D1-D5-P black hole

$G_N = 0$: gas of D-branes

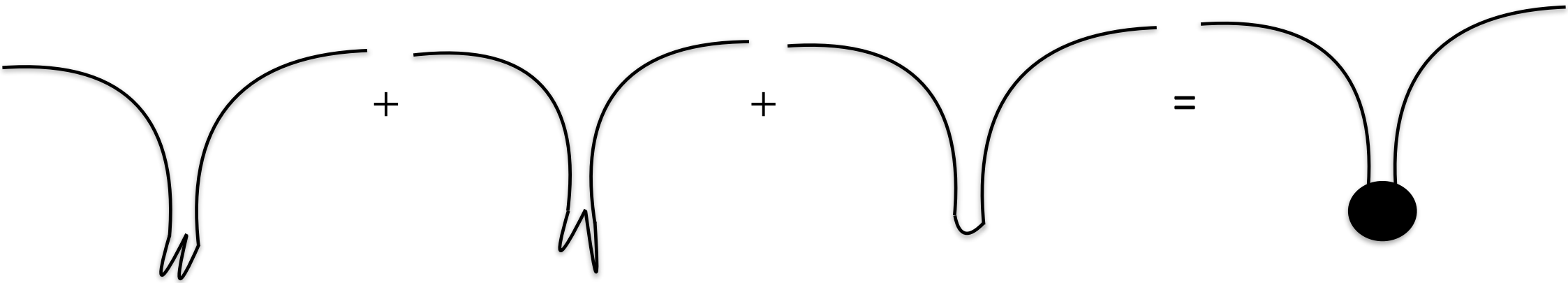
$$S = 2\pi\sqrt{N_1 N_5 N_P}$$

Regime of parameters at which black holes exist

$$S = \frac{A}{4G_N} = 2\pi\sqrt{N_1 N_5 N_P}$$

What are the micro-states at finite G_N ?

Fuzzball proposal: black hole micro-states are **smooth and horizonless**



Only the average over micro-states is captured by GR and leads to black holes.

Biggest class of black hole micro-states of the D1-D5-P black hole is called Superstrata:

$$S_{\text{Superstrata}} = \sqrt{N_1 N_5 \sqrt{N_P}} \ll \sqrt{N_1 N_5 N_P} = S_{\text{BH}}$$

[Bena and al , 2015]

Complicated geometries, functions of 3 variables, hard to extract physics.

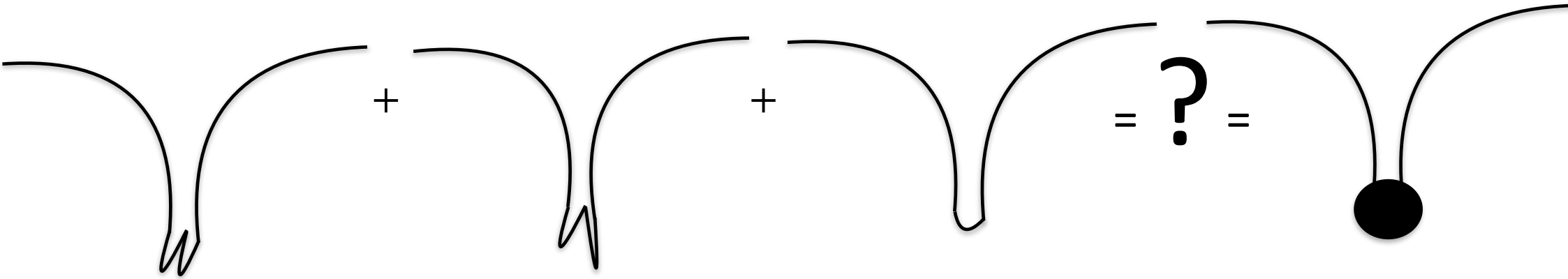
Superstrata: largest known class of black hole micro-states of D1-D5-P black hole

$$S_{\text{Superstrata}} = \sqrt{N_1 N_5 \sqrt{N_P}} \ll \sqrt{N_1 N_5 N_P} = S_{\text{BH}}$$

[Bena and al , 2015]

Complicated geometries, functions of 3 variables, hard to extract physics.

Is there an intermediate coarse-grained description?



At the price of non-smoothness, we have a 5D effective description:

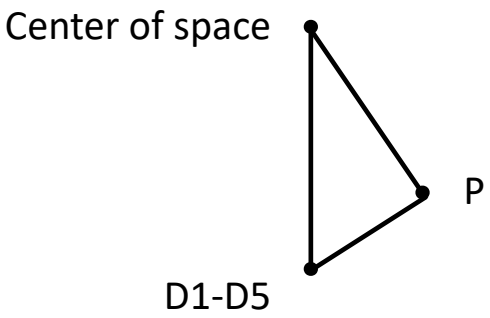
[Bena-**RD**-Martinec-Shigemori-Turton-Warner , 2025]

Averaging: center of mass physics

In supergravity, averaging leads to three centers 5D BPS solutions:

$$\mathrm{d}s_5^2 = -Z^{-2}(\mathrm{d}t + \mathbf{k})^2 + Z\,\mathrm{d}s_4^2(\mathbf{B}),$$

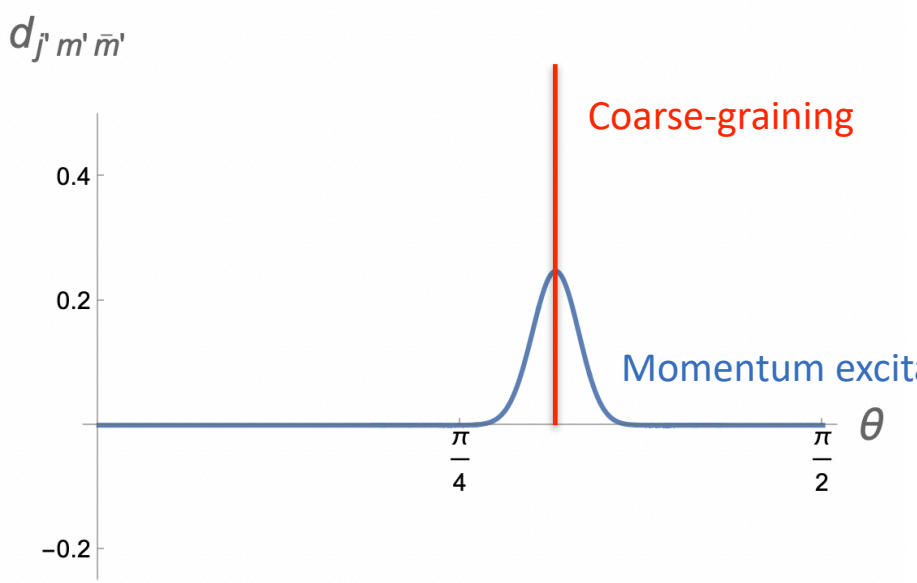
- $\mathbf{B}$ a multi-center Gibbons-Hawking metric.
- Much **simpler** to study! Solution depends on **harmonic functions** on a 3D base.
- Only **three** δ **functions sources** for the Harmonic.



The positions are determined by the asymptotic charges

Effective Microstructure

Dual description seen from the String-Worldsheet:



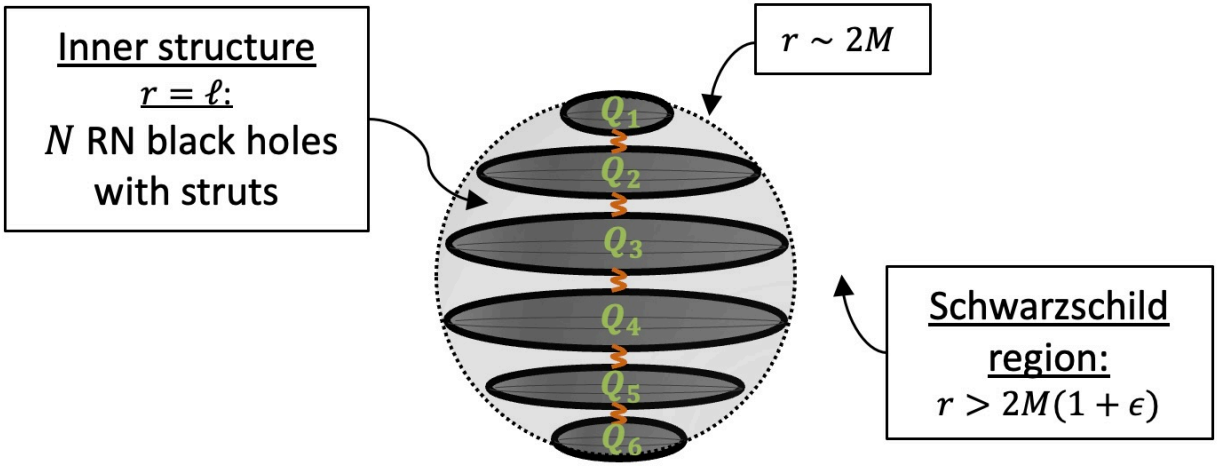
Momentum wave function : before and after coarse-graining

- From the world-sheet point of view the two charge geometry is the background.
- The momentum is an excitation on top
- Coarse-graining of wave-function leads to singularities

Allows for a match of quantum numbers in the world sheet description and in supergravity.

An effective description of non supersymmetric black holes?

Give an effective description of Schwarzschild as a succession of Near-Extremal BH: [**RD** and Heidmann, 2024]

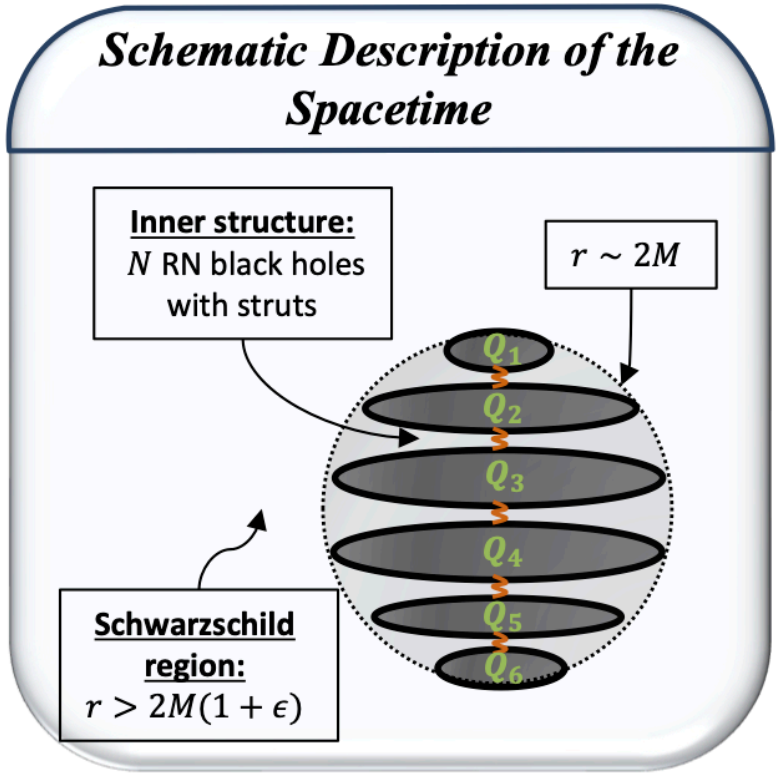


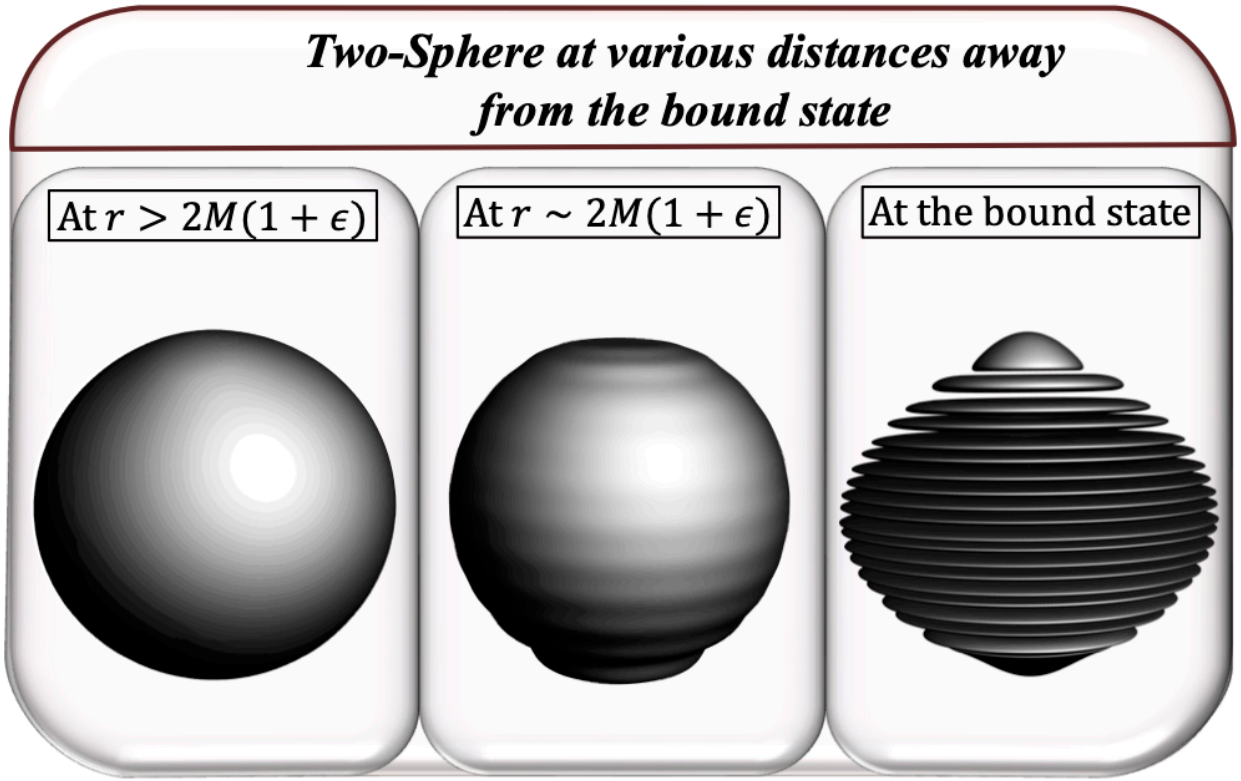
$$\epsilon \sim \frac{1}{N}$$

Far from the BH, it looks like Schwarzschild. Near the BH it looks like a succession of Reissner-Nordström black holes and struts. Struts are negative mass objects. They correspond to a conical excess when a circle shrinks.

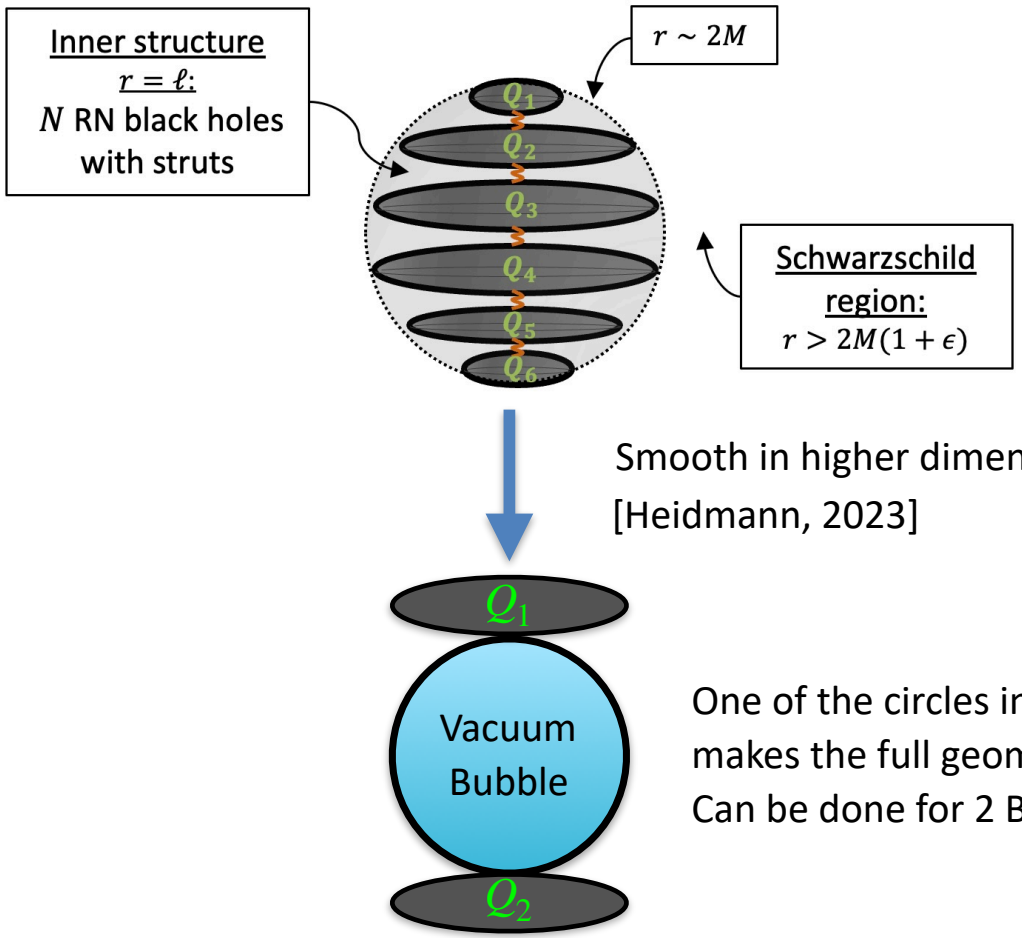
Effective Microstructure

$$ds^2_{SCH} = -\left(1 - \frac{2M}{r}\right) dt^2 + \frac{dr^2}{1 - \frac{2M}{r}} + r^2 d\Omega_2^2$$, r is the radial distance.





Struts seem unphysical objects in 4d general relativity.



Smooth in higher dimensions thanks to topology
[Heidmann, 2023]

One of the circles in higher dimension shrinks, and makes the full geometry smooth.
Can be done for 2 BH but could be done for more in practice

Conclusion:

- We obtained two effective descriptions for black holes.
- In low dimensions, the solutions are not smooth. Topology in higher dimensions can make the geometry smooth .
- Many features of black hole micro-states can already be obtained by non smooth effective description .

Thank you for your attention!