Black hole mimickers from string theory

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[Based on 1705.10172, 1712.00511, and 2110.10542]

Black hole mimickers: the what and the why

Black hole information puzzle: Pure state $\rightarrow$ Mixed state

to solve, need:

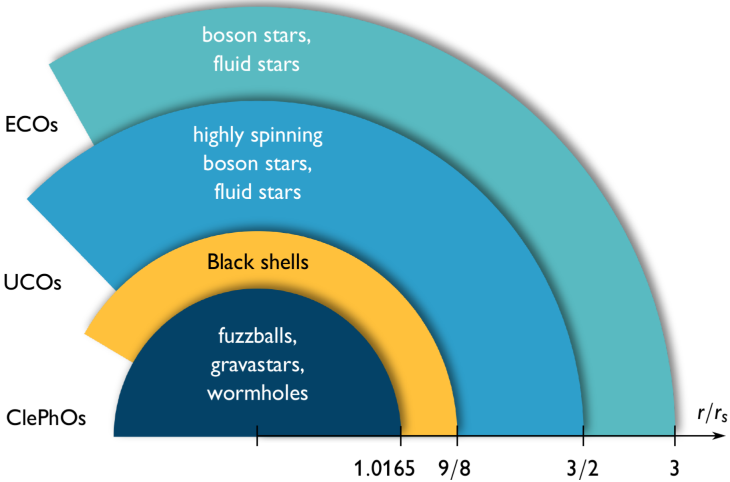
- ✦ way to store information in Hawking radiation
  [claimed to be solved by string theory with branes and extra dimensions]
- ✦ why can information fall inside the horizon without violating no-cloning
  [claimed to be solved by BH complementarity]

No general agreement that this works.

$\hookrightarrow$ What if there is no horizon?

$\hookrightarrow$ Exotic compact objects could very closely mimic BHs

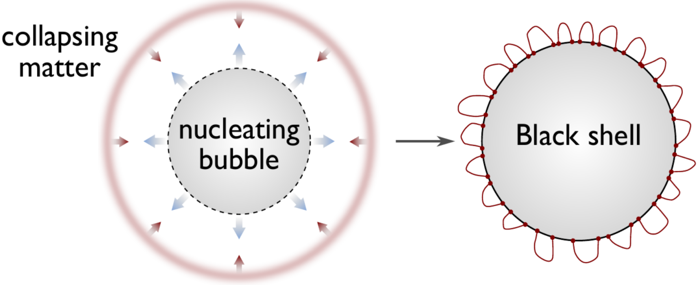
Black hole mimickers: the what and the why



What is a black shell?

[Danielsson, Dibitetto, Giri '17]

✦ Assume that spacetime is unstable, wants to decay to AdS_4 true vacuum
  $\hookrightarrow$ Decay channel: spherical brane nucleation, but highly supressed.



Entropy of matter stuck to the shell as a finite temperature gas
with a large number of degrees of freedom

$\downarrow$

Phase space enhancement of nucleation probability

How to construct a black shell in general relativity?

For the shell to be static, it must solve Israel's junction conditions:

$$\rho = \frac{1}{4\pi r}\left(\sqrt{1+k^2r^2} - \sqrt{1-2M/r}\right) ,$$

$$p = \frac{1}{8\pi r}\left(\frac{1-M/r}{\sqrt{1-2M/r}} - \frac{1+2k^2r^2}{\sqrt{1+k^2r^2}}\right) .$$

✦ naive solution is an unstable critical point. non-trivial to stabilize

Rewrite as energy conservation:

$$4\pi r^2 - r\left(\sqrt{1+k^2r^2} - 1\right) = E = r\left(1 - \sqrt{1-2M/r}\right) .$$

Associate ρ_b, p_b with E: at $r = 9M/4$ (:= Buchdahl's radius), $\rho_b = p_b/2$.
If the nucleated brane "catches" infalling matter at this radius, it can be converted to radiation directly on top of the brane.

How to construct a black shell in string theory?

Dp-brane action:

$$S_{\mathrm{BI}} = -T_p \int \mathrm{d}^{p+1} \sqrt{-\det\left(P[G+B]_{ab} + 2\pi\alpha' F_{ab}\right)}\,,$$

$$S_{\mathrm{WZ}} = \pm T_p \int P\left[\sum C^{(n)} \mathrm{e}^{B}\right] \wedge \mathrm{e}^{2\pi\alpha' F}\,.$$

N coincident Dp-branes: $U(1)^N \to U(N)$: Non-abelian world-vol theory

Myers' effect: dielectric effect for Dp-branes (brane polarization)

Dp-brane in non-trivial $F^{(n)}$ background $\Rightarrow$ new minima in the scalar potential.

$\hookrightarrow$ example:

N D0 branes in a background of $F^{(4)}$

$\downarrow$

D0 branes puff up into a non-commutative 2-sphere

$\downarrow$

bound state of a D2 and N D0 branes

Connecting with general relativity

D2 world volume action, gives potential:

$$V_{\rm BI} = 4\pi T_2\sqrt{r^4+N^2} \xrightarrow{r\to\infty} 4\pi r^2 T_2\left(\boxed{1} + \boxed{\frac{N^2}{2r^4}}\right)$$

- tension: $p = -\rho$
- stiff matter: $p = \rho$
- radiation: $p = \frac{\rho}{2}$ ← Massless fluctuations of gauge fields: N^2 open strings

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Junction conditions:

$$\begin{aligned} \tau + \rho_g + \rho_s &= \frac{k}{4\pi} + \frac{1}{8\pi k r^2} - \frac{1}{4\pi r} + \rho_b, \\ -\tau + p_g + p_s &= -\frac{k}{4\pi} + \frac{1}{8\pi r} + p_b \end{aligned}$$

Solution:

$$\rho_g = \rho_b - \frac{1}{12\pi r}, \quad \tau = \frac{k}{4\pi} - \frac{1}{6\pi r} + \frac{1}{16\pi k r^2}, \quad \rho_s = \frac{1}{16\pi k r^2}.$$

Junction conditions solved at Buchdahl's radius: $r = 9M/4$

Dp-brane wrapped on d internal dimensions

Tension: $\tau \sim \frac{1}{g_s \ell_s^3} \left(\frac{L}{\ell_s}\right)^d$.

- ✦ Junction condition at leading order:

$$\tau \sim \frac{k}{\ell_p^2} \sim \frac{k}{g_s^2} \frac{L^6}{\ell_s^8} \Rightarrow \frac{1}{k} \sim \frac{\ell_s}{g_s} \left(\frac{L}{\ell_s}\right)^{6-d}$$

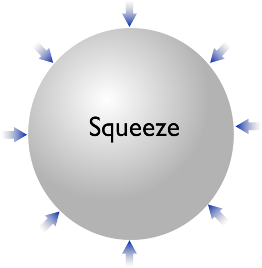
- ✦ Using this, junction condition at sub-leading order gives

$$\frac{\tau N^2 \ell_s^4}{r^4} \sim \frac{1}{\ell_p^2 r^2} \frac{1}{k} \Rightarrow N \sim \frac{r}{\ell_p} \left(\frac{L}{\ell_s}\right)^{3-d}$$

For D5 brane wrapped along $d = 3$ directions, we get the right number of degrees of freedom: $N^2 \sim r^2/\ell_p^2$.

This guarantees that energy $4\pi r^2 \rho_g = M$, with $\rho_g \sim N^2 T^3$ if $T \sim 1/M$.

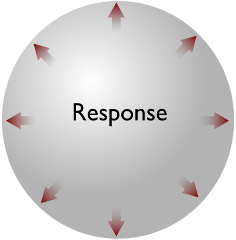
Generically unstable, need energy flux to stabilize



$\Rightarrow$ heat up to local Unruh temperature

- ✦ Energy must come from the system
  - $\hookrightarrow$ Need energy to go into increasing N, by lowering tension

Generically unstable, need energy flux to stabilize



✦ Shell responds by relaxing tension
$\Rightarrow$ Restoring force

Continuity equation:

$$\dot{\rho} + \frac{2\dot{r}}{r}(\rho + p) = 0 \Rightarrow \overbrace{\dot{\rho}_\tau}^{-j} + \overbrace{\left(\dot{\rho}_g + 3\rho_g \frac{\dot{r}}{r}\right)}^{+j} + \overbrace{\left(\dot{\rho}_s + 4\rho_s \frac{\dot{r}}{r}\right)}^{0} = 0$$

Assume the form: $j = 3\rho_g \left(\alpha \frac{\dot{T}}{T} + \beta \frac{\dot{r}}{r}\right)$. [Danielsson, Pretorius, Lehner '21]

$\hookrightarrow$ Stability requires: $\alpha < 4/9, 6\alpha - \beta > 2$,
Relaxation to Buchdahl requires: $\alpha - \beta = 2/3$.

[Was solved numerically in the context of relativistic hydrodynamics]

Rotating black shells: more realistic, more complicated

[Danielsson, Giri '18]

⋆ Kerr metric is unique if there is a horizon.

No horizon $\Rightarrow$ no reason to be Kerr.

$\hookrightarrow$ Rotating black shell with Kerr outside: not possible to solve similar junction conditions.

⋆ Maybe a good thing, because any deviation from Kerr, such as different multipole moments can be useful as an observational signature.

We constructed a generalization of the Kerr metric perturbatively in angular momentum, and solved the junction conditions.

- ✦ Continuity of metric: gives a 2-parameter family of solutions. Pick a physically reasonable choice: AdS inside is non-rotating
- ✦ Junction conditions: Assume that all matter components are perfect fluids: $S^{ij} = (\rho + p)u^i u^j + \rho g^{ij}$. This gives a quadrupole moment:

$$\mathcal{M}_2 = -a^2 M - \frac{2}{15} a^2 M^3 \left(16q - 15p\right) = -0.93 a^2 M - 0.00575 \frac{a^2}{k} + \cdots$$

$\sim$ 7% less compared to Kerr!

How can the matter components support themselves on the shell? [Danielsson, Giri '21]

✦ Centrifugal force pushes the gas towards the equator.

Turns out that the total stress tensor on the shell is covariantly conserved

$$\nabla_i (S_{\text{brane}})^i_\theta + \nabla_i (S_{\text{gas}})^i_\theta + \nabla_i (S_{\text{stiff}})^i_\theta = 0$$

⇒ So no external force required. The components exchange energy between each other to support themselves on the shell.

★ This is exactly the flux that we needed for the non-rotating shell!

⇒ Instead of time component of j, we now have space components.

What condition should α and β satisfy for the shell to remain static?

✦ Turns out that $\alpha = 4/15, \beta = -2/5 \Rightarrow$ boundary of stability

$$j = \frac{\rho_g}{5}\left(4\frac{\nabla_i a_R}{a_R} + 3\frac{\nabla_i R^{(3)}}{R^{(3)}}\right)$$

What now?

- This is an interesting object well motived from string theory, with very promising results from non-linear numerical simulations
- Top down construction in string theory necessary
  Proof of concept from IIA on $\mathbb{T}^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ in [Danielsson, Dibitetto, Giri '17]
- Fast rotating black shell to connect with observations
- Compute observables: black hole shadow [to appear soon…]

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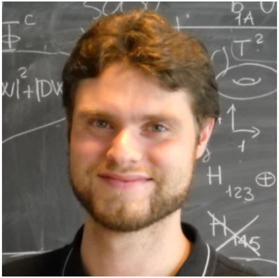
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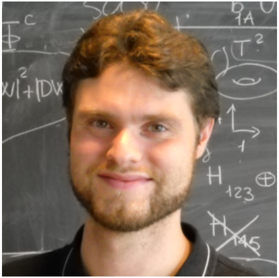
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Thanks for listening!

Black hole shadow