Insights on Black Hole Stability from Light Towers

Matteo Zatti

Based on [**2502.02655**], [**2505.15920**], [**2507.17857**] and work in progress
in collaboration with A. Castellano, D. Lüst and C. Montella.

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A simple question

- A BH is a solution of a gravitational EFT.
- As a stringy object it must receive corrections due to the UV completion of the EFT.

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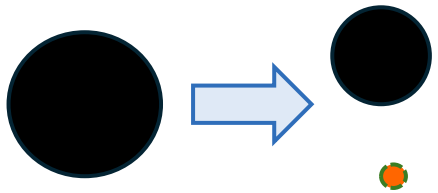
Thermodynamics

$$S = \frac{A}{4} + \dots$$

Stability



Why we need (precise) results for BHs?

- BH **thermodynamics** is a **window on UV physics**: if the macroscopic entropy is not the log of an integer number we are missing something.

- BH physics is at the **core of several Swampland ideas**: possibility of discharge (WGC), entropy bounds (SDC).

- BHs are backgrounds. Understand them is the first step to study the **stability** and **NP corrections** in more **general cases** (de Sitter, non-susy strings, …)

- We understand BHs in EFTs. Which are the **scales** they can **probe**?

Result 1: Beyond the EFT cutoff

We study **(non)perturbative corrections** to **CY BPS black holes** in the **large volume approximation** due to **D0 branes**. The corrections to the **BH entropy glue** a 4d BH and a 5d black object. They are finite at the **EFT transitions**.

[Castellano, M.Z. '25]

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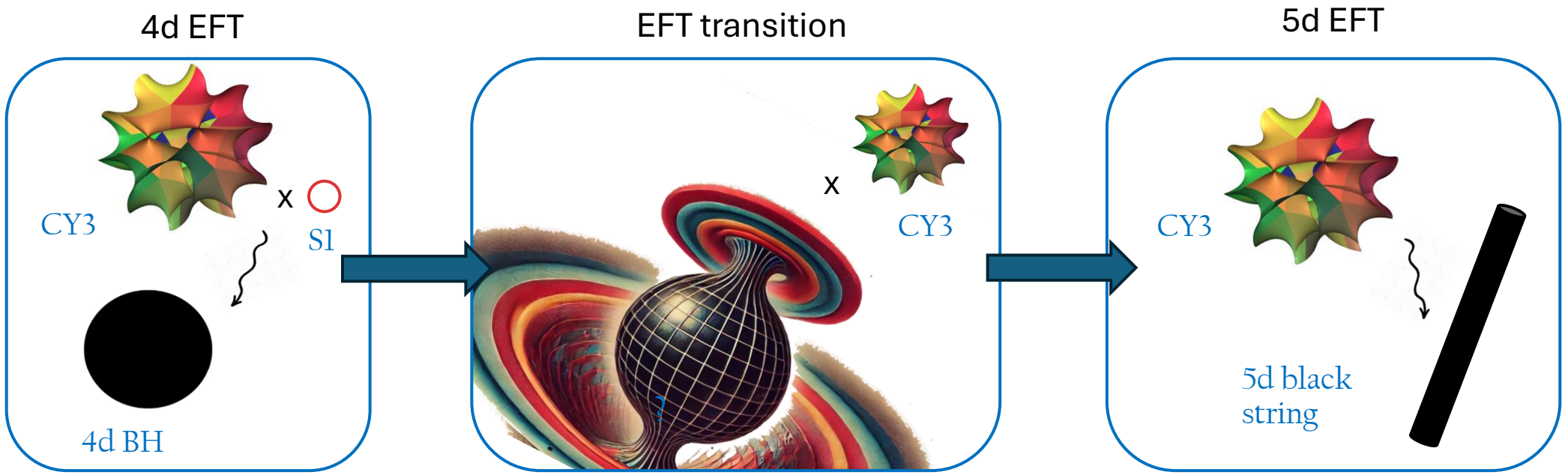

Details Result 1

$4d\ \ N = 2\ \ SUGRA$

(IIA on CY3)

$Higher\ Derivative\ F-terms$

$$\mathcal{L}_{\text{h.d.}} \supset \sum_{g\geq 1} \int \mathrm{d}^4\theta\, \mathcal{F}_g(\mathcal{X}^A)\, \left(\mathcal{W}^{ij}\mathcal{W}_{ij}\right)^g + \text{h.c.}$$

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Wald Entropy

$$S_{BH} = \frac{\mathrm{A}}{4} + \sum_{g\geq 0} S^{(2g)}\, \alpha^{2g}$$

$$\alpha \overset{\text{hor}}{=} \frac{r_{D0}}{r_{BH}}$$

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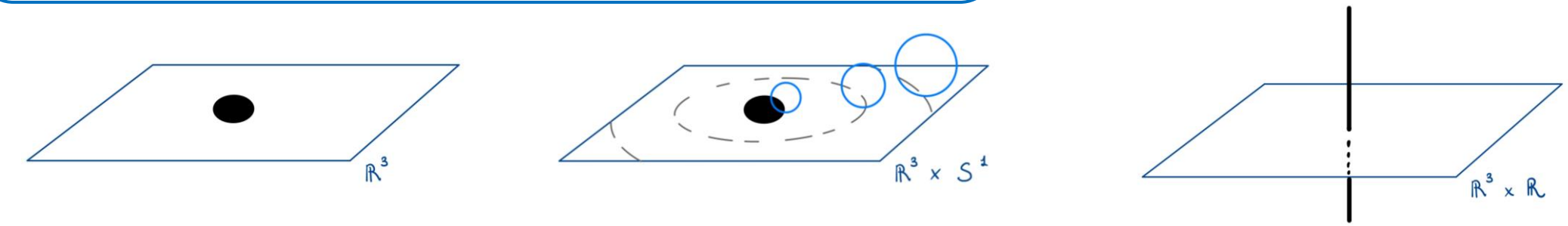


BH in 4d $\quad \alpha \ll 1$

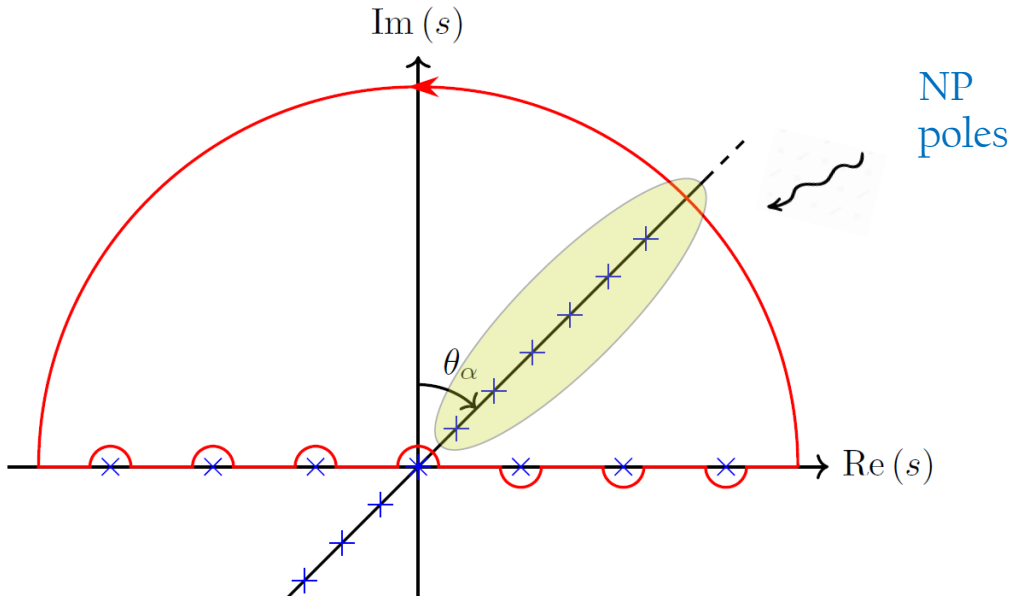
$r_h \sim r_{D0}$

$\alpha \sim 1$

$\alpha \gg 1$ Black string in 5d

Are black strings special?

- Correction for more general CY BHs are **finite**!
- The **structure** of the **NP corrections** depends on the charges we turn on!



Result 2: NP corrections as (virtual) pair production?

We study the **classical trajectories** of particles and their **(virtual) pair production** in $AdS_2 \times S^2$. For BPS particles (in $Mink_4$) we find a nice **correspondence**

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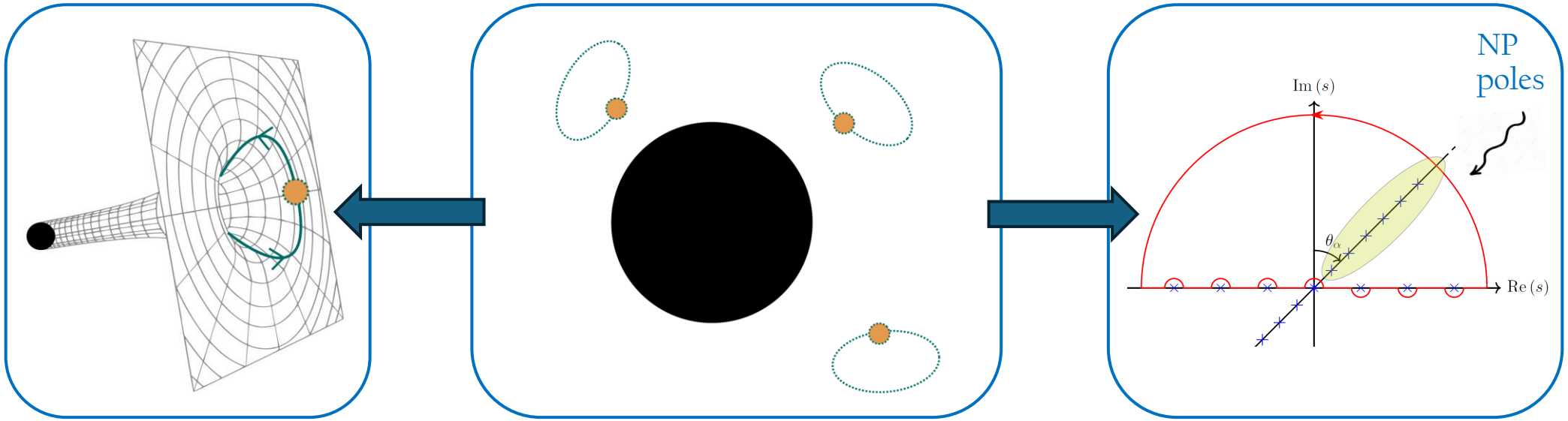
Particles attracted in the $AdS_2 \times S^2$ throat

Pair production of virtual particles

NP corrections to Entropy



Particle probe

We consider a **particle** with charges $(q_A', p^{A\prime})$ moving in $\boldsymbol{AdS_2 \times S^2}$

$$S_{wl} = -2|Z|R_{\mathrm{AdS}} \int_\gamma d\sigma \sqrt{\rho^{-2}\left(\dot{t}^2 - \dot{\rho}^2\right) - \dot{\theta}^2 - \sin^2\theta\dot{\phi}^2} - \int_\Sigma q'_A F^A - p^{A\prime} G_A$$

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The particle-black hole **interaction is dyonic** (electric-electric and magnetic-electric)

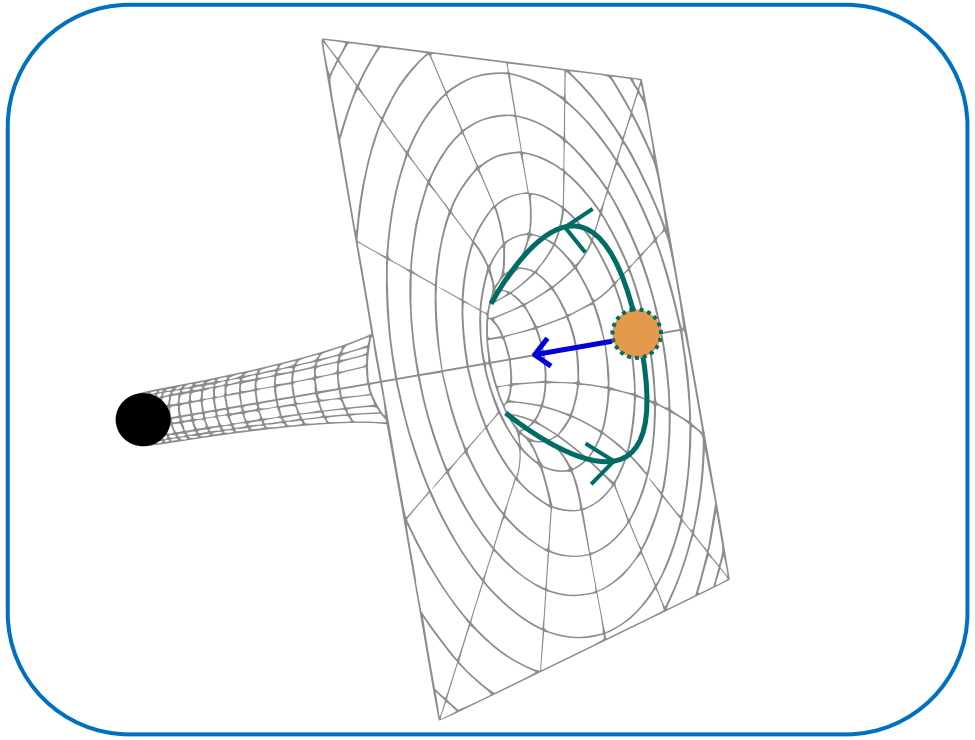
$$q_{ee} = 2\,\mathrm{Re}\left(\bar{Z}_{BH} Z\right) \qquad q_{me} = 2\,\mathrm{Im}\left(\bar{Z}_{BH} Z\right)$$

BPS particles are **effectively subextremal** in $AdS_2 \times S^2$ throat except when the two systems have aligned central charges.

$$Z = e^{K/2}\left(p^{A\prime}\mathcal{F}_A - q'_A X^A\right) \qquad \tilde{m}^2 \equiv 4|Z|^2 R^2_{\mathrm{AdS}} = q^2_{ee} + q^2_{me} \implies \tilde{m} \geq |q_{ee}|$$

Semiclassical stability: Geodesics

Not Aligned / Attraction



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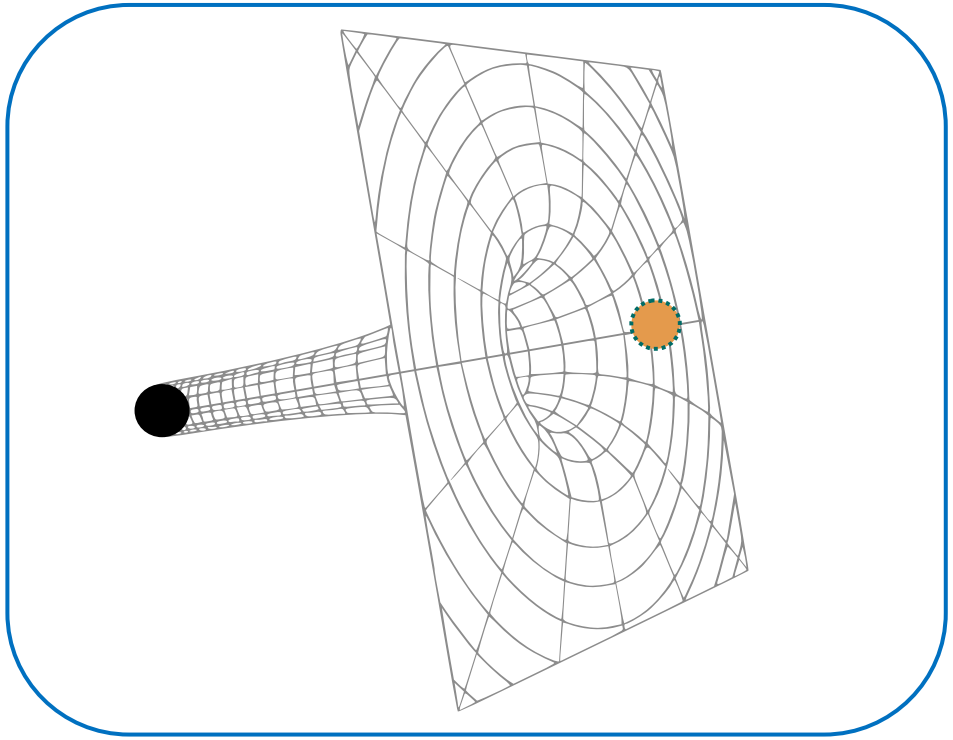

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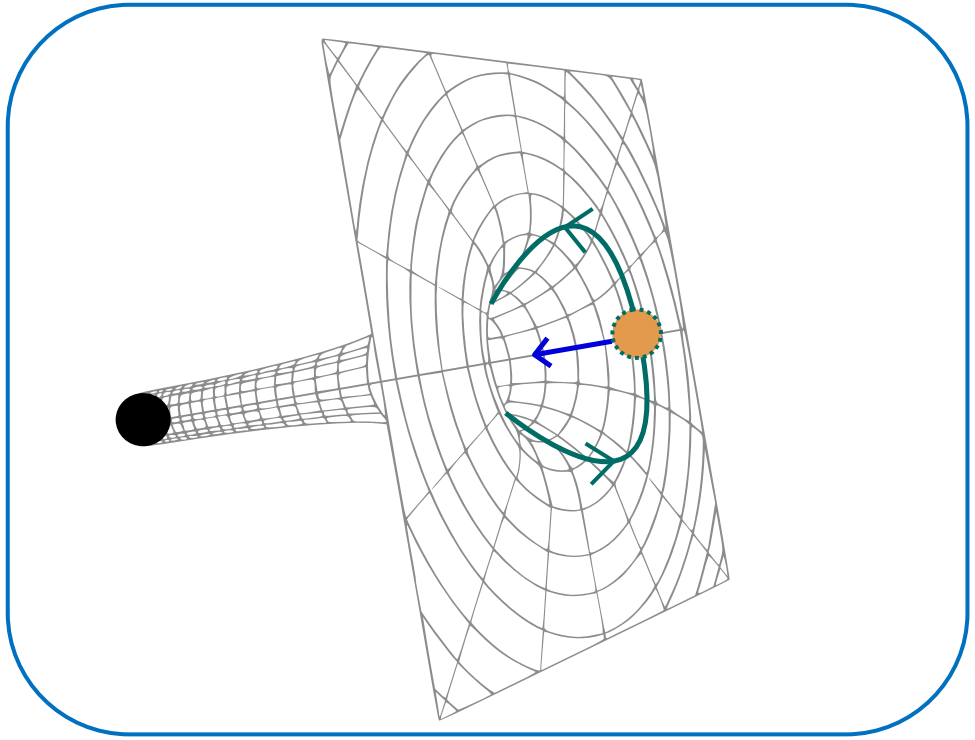

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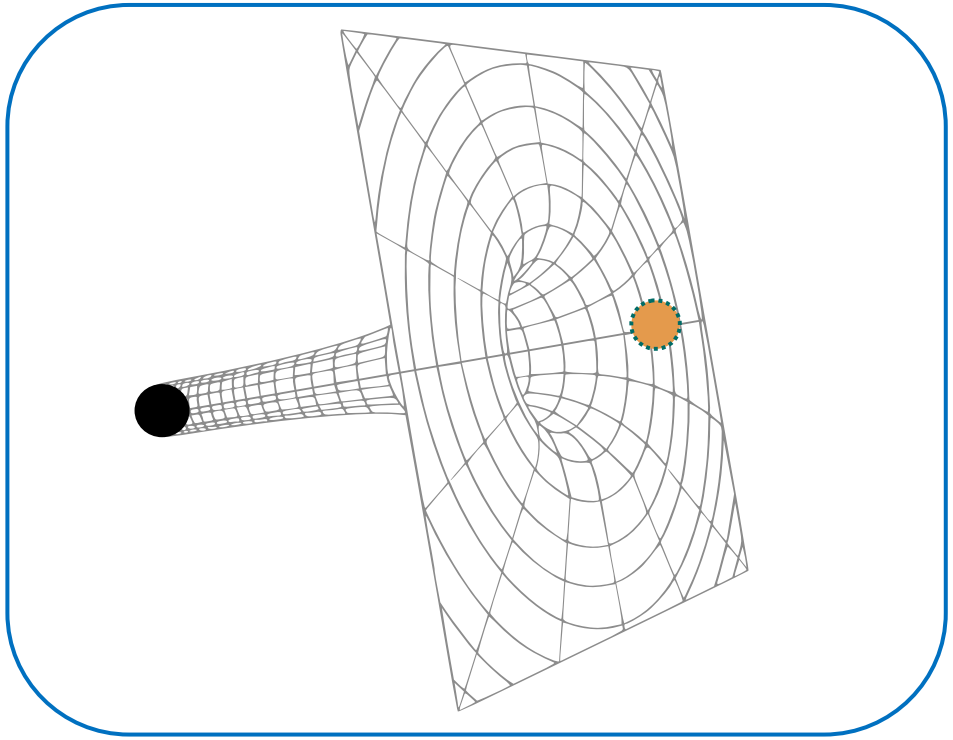

Particle cannot escape

Semiclassical analysis suggest stability

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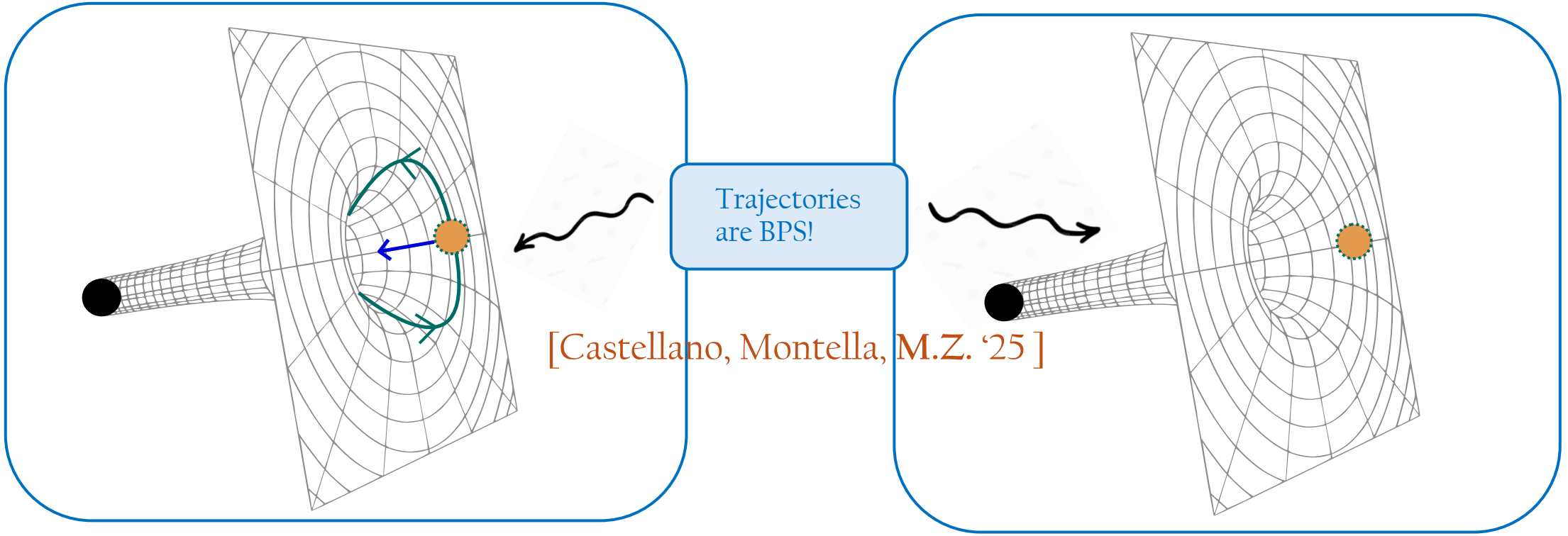

[Castellano, Montella, M.Z. '25]

Particle cannot escape → Semiclassical analysis suggest stability

1-loop stability: Schwinger effect

We compute the 1-loop determinant in **integrating out particles** in $AdS_2 \times S^2$

$$\log \mathcal{Z} = -\int_\epsilon^\infty \frac{d\tau}{\tau} \mathrm{Tr}\left[e^{-\tau\left(-\mathcal{D}^2_{\mathrm{AdS}_2\times S^2}+m^2\right)}\right] \propto \int dt\, du\; f^{\mathrm{AdS}_2}_{B,F}(t)\; f^{\mathbb{S}^2}_{B,F}(u)\; I_\Delta(t,u)$$

[WIP, '25]

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$I_\Delta(t,u)$ captures the dynamical **stability** data associated with fluctuations around the background

$$I_\Delta(t,u) = \Delta \frac{K_1\left[\Delta\, g(t,u)\right]}{\pi\, g(t,u)} \qquad \Delta = \sqrt{m^2 R^2_{\mathrm{AdS}_2} - q^2_{ee} - q^2_{me}}$$

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In the case of a $\boldsymbol{N=2}$ **matter multiplets** and a **BPS black hole** background, the calculation gives

$$\log \mathcal{Z} = \frac{V_{\mathrm{AdS}}}{4\pi R^2}\left[4 q_{ee} q_{me} \tan^{-1}\left(\frac{q_{ee}}{q_{me}}\right) + \Re \int_0^\infty \frac{d\tau}{\tau} \frac{e^{i\,\tau\, \bar{Z}_{\mathrm{BH}}\, Z}}{\sinh^2\left(\frac{\tau}{2}\right)}\right]$$

[WIP, '25]

A nice correspondence for BPS particles

No Pair production

$$\log \mathcal{Z}_{1-\text{loop}} = 0$$

Special conditions on forces

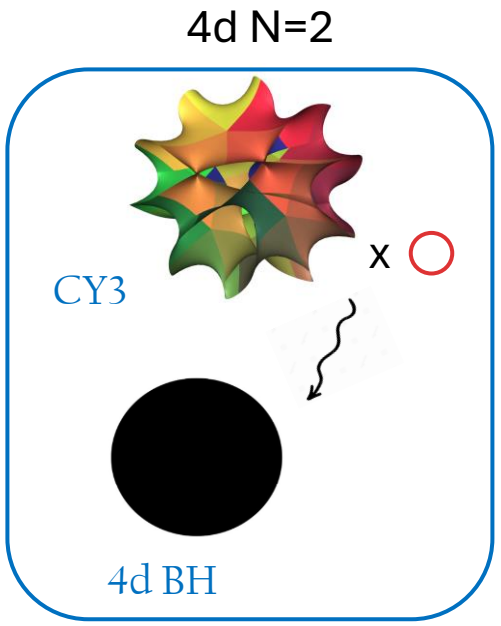
$$\begin{cases} q_{ee} = 0 & \text{Purely magnetic background} \\ q_{me} = 0 & \text{Asymptotic forces cancellation} \end{cases}$$

No NP corrections to entropy

$$S_{BH} = \log \mathcal{Z} - i q_A \phi^A$$

More on NP corrections to entropy

We can test the absence of **NP corrections** with **CY BHs** and **D0 tower**



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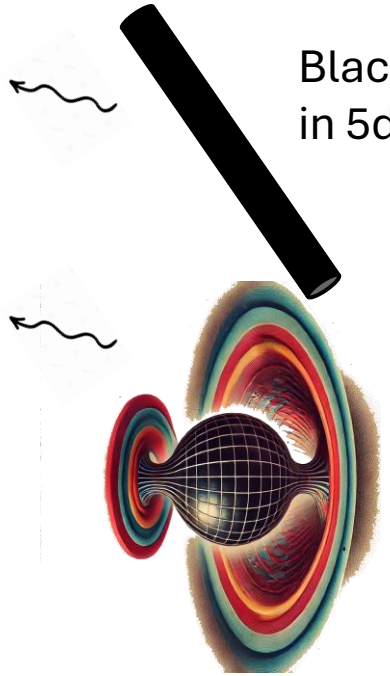
$$\text{D0-D2-D4:} \quad q_{me} = 0$$

$$\text{D2-D6:} \quad q_{ee} = 0$$

$$\text{D0-D2-D4-D6:} \quad \tilde{m} > |q_{ee}|$$



Black string
in 5d N=1

Taub-NUT
in 5d N=1

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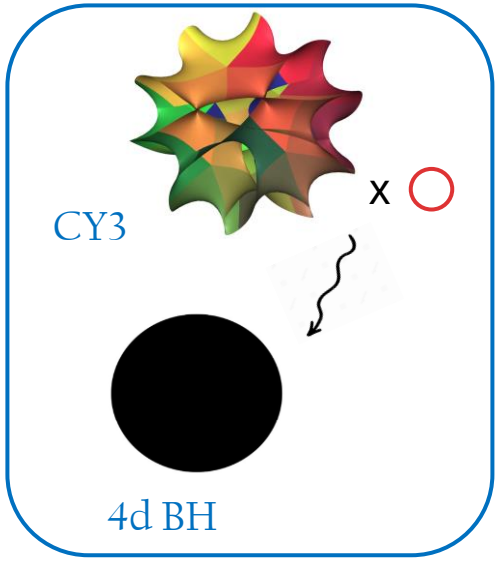
4d N=2



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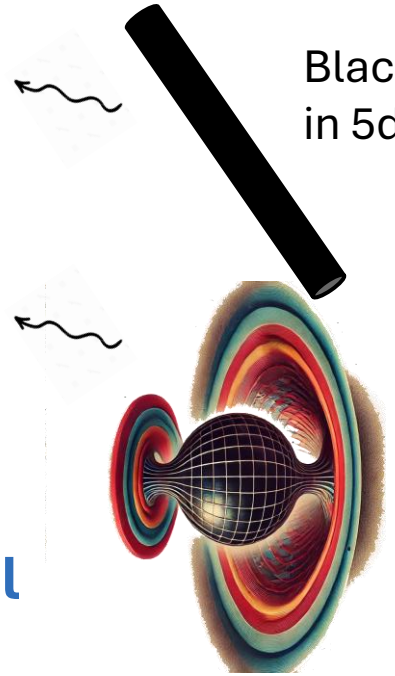

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Taub-NUT
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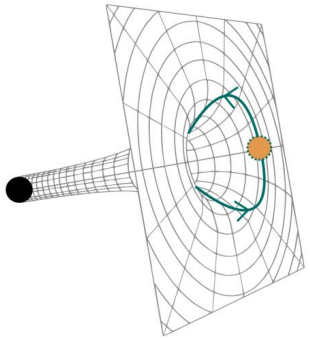
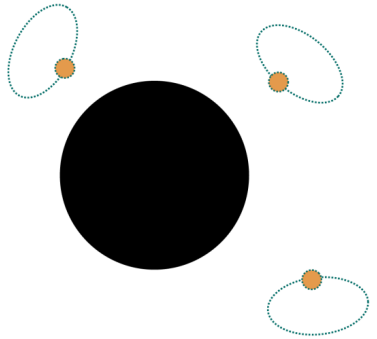
Or with considerations on the **particle Euclidean path integral**

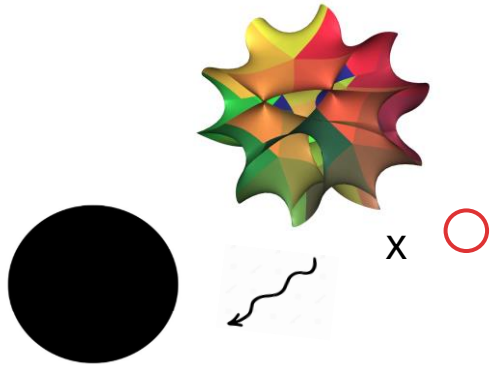
$$\mathcal{A}_{1-\text{loop}} \sim f\left(q_{ee}^2 - \tilde{m}^2\right)$$

Remarks

- We **glued** explicitly a 4d BH with a 5d black string **across** the **EFT transition**
- We explicitly showed that **BPS black holes** are **stable** under **pair production** of charged BPS particles
- We related precisely **multiple descriptions**: cancellation of forces, pair production, NP correction to CY black holes…







Outlook [WIP]

- We can study with the same approach **more vacua** in the the **landscape**: de Sitter, non-susy compactifications, …
- Refinement of **Swampland conjectures** in **non-asymptotically flat backgrounds** (e. g. WGC in AdS2xS2 throat)
- Beyond the large volume approximation: **F-theory limit** in elliptic CYs
- **Small BHs** with NP corrections
- Understand the fate of NP effects in the general case: revisit the **Gopakumar-Vafa** computation in **AdS2xS2**

Thank you for the attention!