Black Holes as probes of EFTs

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Personal information

- Master thesis at Max-Planck-Institute for Physics and LMU Munich under supervision of Prof. Dr. Dieter Lüst, Dr. Niccolò Cribiori
  - Title: „Black hole solutions and their consequences on the Swampland“
    - Lead to original results that appeared in 2212.10286 [Cribiori, Lüst, Staudt ‘22], submitted to PLB
  - Expected graduation in April 2023
- Interested in Black Holes, String Theory and String Phenomenology

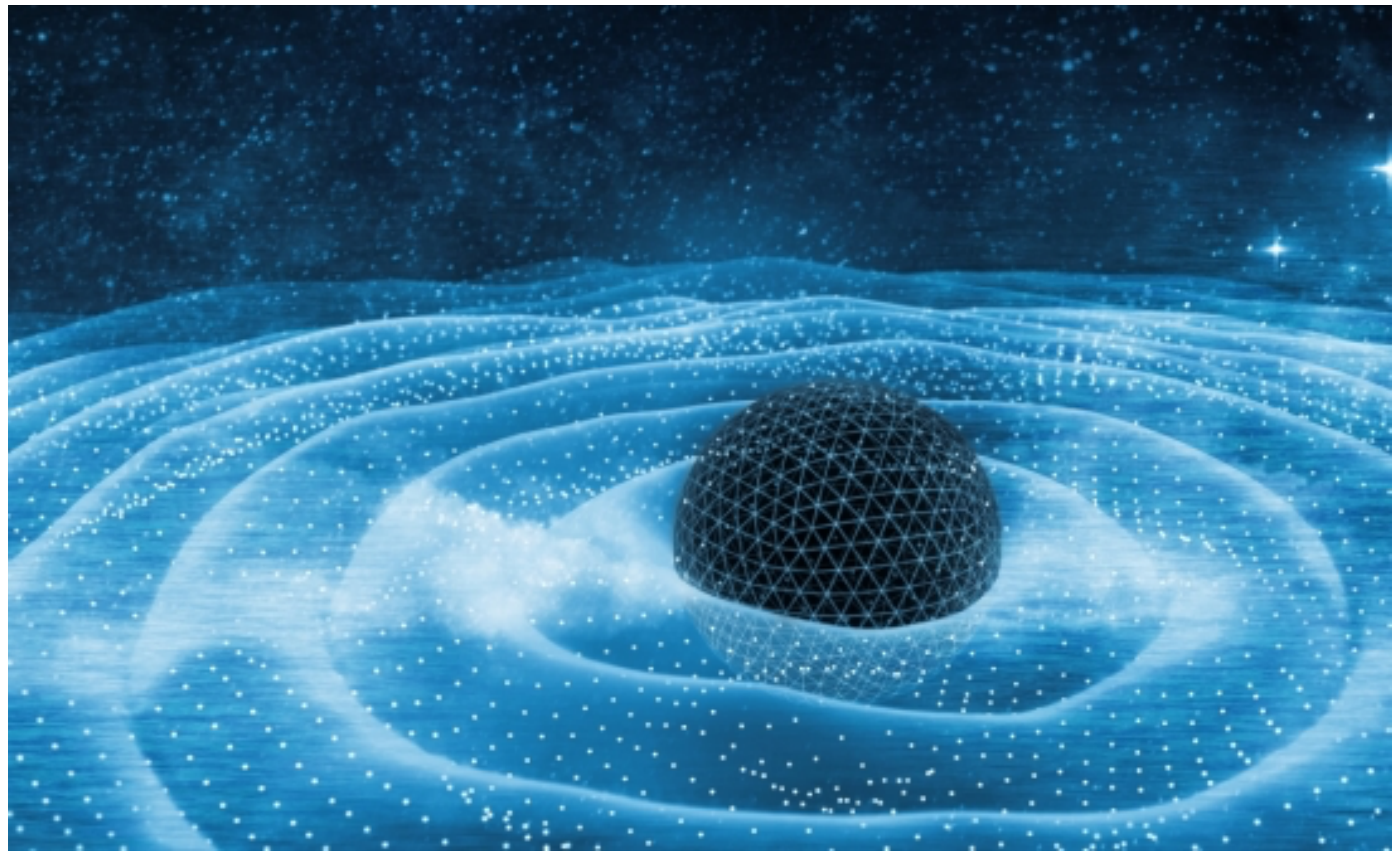
Outline

1. Introduction
2. How can we use Black Hole solutions to study EFTs?
3. Applications
4. Conclusion

Introduction

General Motivation

- Study Black Holes
- Understand effective field theories with (quantum) gravity

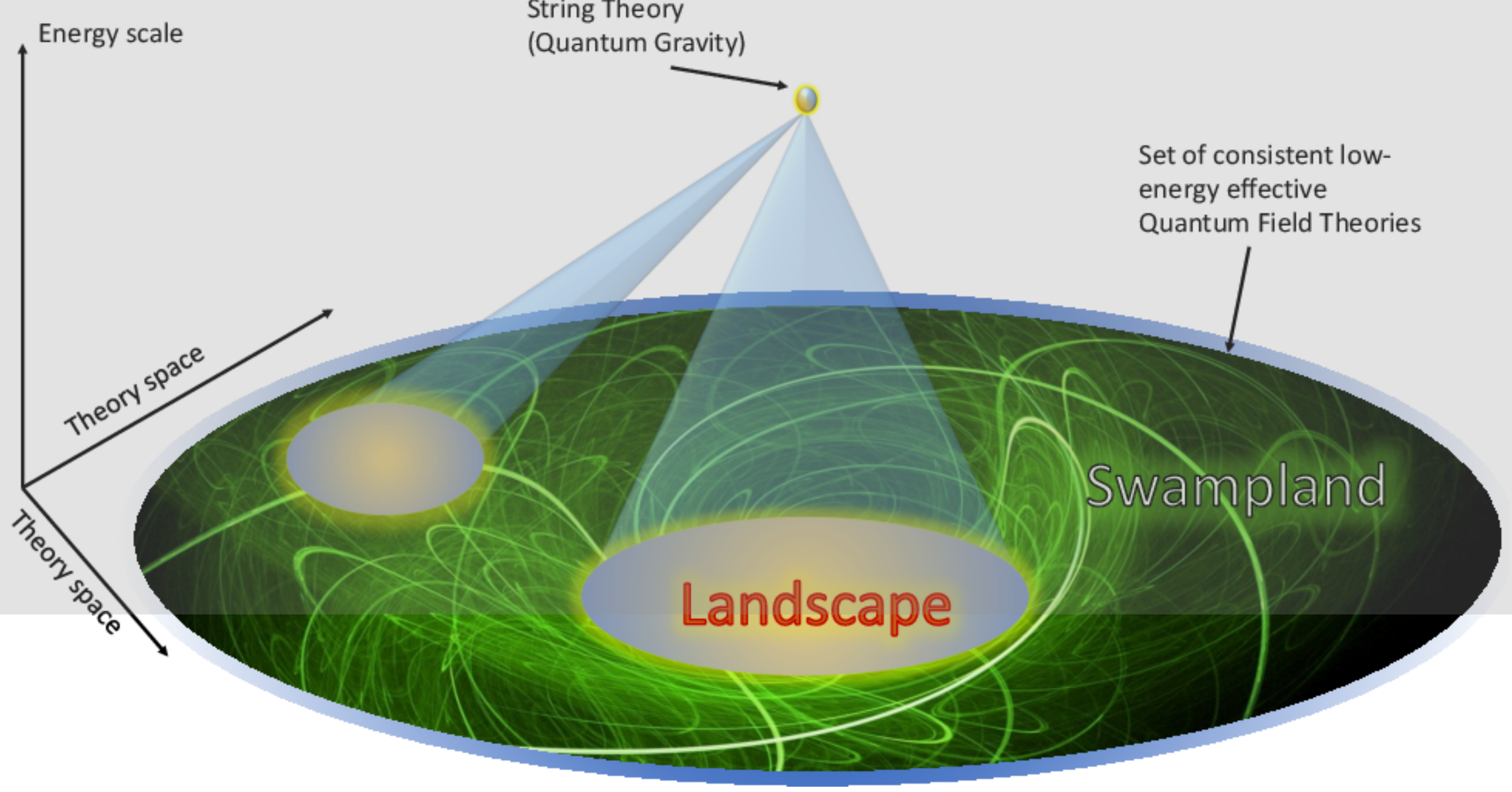


Black Holes

- Black Holes can be observed and can provide information on a theory of quantum gravity
- String Theory gives a prescription on how to construct Black Holes [Strominger, Vafa ’96]
- HOWEVER: for these computations, we need Supersymmetry

Can we use Black Holes to understand Quantum Gravity?

Effective Field Theories



- Not every EFT can be coupled with quantum gravity!
- Swampland Program: distinguish EFTs that are compatible with gravity (Landscape) and those that are not (Swampland)

Idea: use BHs + swampland conjectures to probe EFTs coupled to gravity

Example: UV cutoff of a given EFT? Modified under corrections!

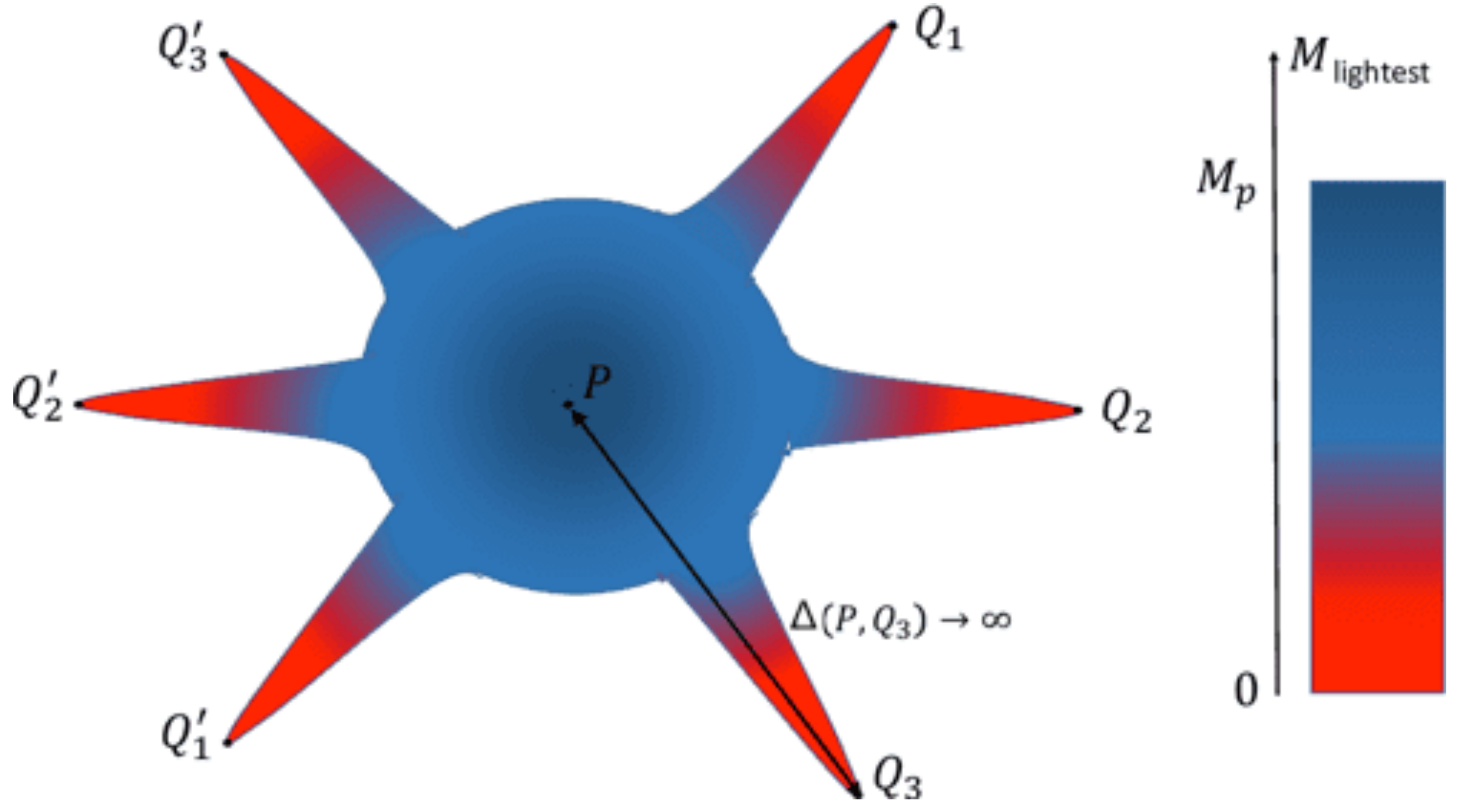
Can we see this with Black Holes?

$$\mathscr{L}_{EFT} = \mathscr{L}_{\text{two derivative}} + \sum_p \frac{\mathscr{O}_p}{\Lambda^p}$$

How can we use Black Hole solutions to study EFTs?

EFTs and moduli space

- EFTs contain scalar fields
- String Theory: all parameters/observables (masses, coupling constants…) are functions of these scalars
- Scalar fields can be seen as coordinates of an abstract space: moduli space.
- Moduli space has geometry



How can we use Black Hole solutions to study EFTs?

The Swampland Program [Vafa '05]

- Distance Conjecture [Ooguri, Vafa '06]: in all examples of String Theory we understand we obtain a relation structured like this:

$$M(P, Q) \sim e^{-\Delta(P,Q)}$$

- Here: mass depending on the moduli (~parameters) is related to exponential of distance in moduli space

- Swampland program: a relation like this is happening for all EFTs

How can we use Black Hole solutions to study EFTs?

Black Holes

- Solutions of General Relativity/Supergravity
- Thermodynamics; they have entropy and temperature

$$\mathcal{S} = \frac{A}{4} + \text{corr.}$$

How can we use Black Hole solutions to study EFTs?

Black Hole Entropy Distance Conjecture [Bonnefoy, Ciambelli, Lüst, Lüst '20]

- Application of Distance Conjecture to Black Holes
- We can view the entropy as a function of moduli fields, $\mathcal{S} = \mathcal{S}(\phi)$
- What happens for $\phi \to \infty$?
- Distance of form $\Delta(r_s) \sim \log|r_s| \to \infty \Rightarrow \Delta(\mathcal{S}) \sim \log|\mathcal{S}| \to \infty$
- Expectation: $\Delta(\phi) \sim \log|\phi| \to \infty \Rightarrow \Delta(\mathcal{S}) \sim \log|\mathcal{S}| \to \infty$
- Therefore, we must have towers of states $m_S \sim S^{-c}$

How can we use Black Hole solutions to study EFTs?

Black Holes

- String Theory looks at the entropy as a function of the moduli fields at the horizon $\mathcal{S} = \mathcal{S}(\phi|_h)$
- The attractor equations equal $\phi|_h$ to the charges, therefore $\mathcal{S} = \mathcal{S}(\text{charges})$
- Study limits of large and small charges to get information on EFTs
- Black Holes as a tool to see when EFT breaks down

How can we use Black Hole solutions to study EFTs?

Comparison of the corrections

$$\mathcal{S} = \frac{A}{4} + \text{corr.}$$

$$\mathscr{L}_{EFT} = \mathscr{L}_{\text{two derivative}} + \sum_p \frac{\mathcal{O}_p}{\Lambda^p}$$

The Species Scale

Dvali ['07]; Dvali, Redi ['07]

$$\Lambda_{sp}^{(d)} \equiv \frac{M_P^{(d)}}{N^{\frac{1}{d-2}}}$$

- $M_P^{(d)}$ is d-dim Planck mass, N is number of light species/states within EFT
- Species scale as true UV cutoff of d-dim EFT $\Lambda_{UV}^{(d)} \equiv \Lambda_{sp}^{(d)}$
- Smallest possible Black Hole inside the EFT gives the species scale [Dvali, Lüst '09]

Applications

Model without higher derivative corrections

see e.g. Cribiori, Dierigl, Gnecchi, Lüst, Scalisi [‘22]

Type IIA compactified on CY_3 in $N = 2$ SUGRA without corrections

- Volume of CY_3: $\phi = \mathscr{V} = \dfrac{q^{3/2}}{\sqrt{p^1 p^2 p^3}}$
- Entropy: $\mathscr{S} = 2\pi\sqrt{q p^1 p^2 p^3} = \dfrac{2\pi q^2}{\mathscr{V}}$

$$= 2\pi \mathscr{V}^{1/3} (p^1 p^2 p^3)^{2/3}$$

Model without higher derivative corrections

Small/large charge limits without corrections

- Entropy: $\mathcal{S} = \dfrac{2\pi q^2}{\mathcal{V}}$
  1. $p^i \to \infty; \mathcal{V} \to 0 \Rightarrow \mathcal{S} \to \infty$
  2. $p^i \to 0; \mathcal{V} \to \infty \Rightarrow \mathcal{S} \to 0$

- Entropy: $\mathcal{S} = 2\pi \mathcal{V}^{1/3}(p^1 p^2 p^3)^{2/3}$
  1. $q \to \infty; \mathcal{V} \to \infty \Rightarrow \mathcal{S} \to \infty$
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Model without higher derivative corrections

Small/large charge limits without corrections

- Entropy: $\mathcal{S} = 2\pi\sqrt{qp^1p^2p^3} = \dfrac{2\pi q^2}{\mathcal{V}}$

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2. $p^i \to 0; \mathcal{V} \to \infty \Rightarrow \mathcal{S} \to 0$

- If entropy shrinks to string scale, one should have incorporated String Theory from the start
- $M_{KK} \sim \dfrac{1}{\mathcal{V}^{1/6}} \to 0$; towers of states that become light appear
- EFT breaks down! (Expect corrections to become important)

Including higher derivative corrections

see e.g. Maldacena, Strominger, Witten ['97]; Cardoso, de Wit, Mohaupt ['98]

Type IIA compactified on CY_3 in $N=2$ SUGRA with corrections

- Volume of CY_3: $\phi = \mathscr{V} \simeq \dfrac{q^{3/2}}{\sqrt{p^1p^2p^3}}$ (plus corrections which are small in the supergravity approximation)
- Corrected entropy with respect to p^1: $\mathscr{S} = 2\pi\sqrt{\dfrac{1}{6}q(p^1p^2p^3 + cp^1)}$

Including higher derivative corrections

Small/large charge limits with corrections

- Entropy: $\mathcal{S} = 2\pi\sqrt{\frac{1}{6}q(p^1p^2p^3 + cp^1)} = 2\pi\sqrt{\frac{q^4}{\mathcal{V}^2}+\frac{1}{6}qcp^1}$

  1. $p^i \to \infty; \mathcal{V} \to 0 \Rightarrow \mathcal{S} \to \infty$

  2. $p^i \to 0; \mathcal{V} \to \infty \Rightarrow \mathcal{S} \to 0$

- Entropy:

  $\mathcal{S} = 2\pi\sqrt{\frac{1}{6}q(p^1p^2p^3 + cp^1)} = 2\pi\sqrt{\mathcal{V}^{2/3}[(\frac{1}{6}p^1p^2p^3)^{4/3}+(\frac{1}{6}p^1p^2p^3)^{1/3}(\frac{1}{6}cp^1)]}$

  1. $q \to \infty; \mathcal{V} \to \infty \Rightarrow \mathcal{S} \to \infty$

  2. $q \to 0; \mathcal{V} \to 0 \Rightarrow \mathcal{S} \to 0$

Including higher derivative corrections

Small/large charge limits with corrections

- Entropy: $\mathcal{S} = 2\pi\sqrt{\frac{1}{6}q(p^1p^2p^3+cp^1)} = 2\pi\sqrt{\frac{q^4}{\mathcal{V}^2}+\frac{1}{6}qcp^1}$

  1. $p^i \to \infty; \mathcal{V} \to 0 \Rightarrow \mathcal{S} \to \infty$
  2. $p^i \to 0; \mathcal{V} \to \infty \Rightarrow \mathcal{S} \to 0$

- If one sends only $p^2, p^3 \to 0$ and leaves p^1 constant, we see that the entropy goes to $\mathcal{S} \to \sqrt{qcp^1} \neq 0$.

- Coincides with smallest possible Black Hole within EFT, which gives the species scale $\Lambda_{Sp} \equiv \Lambda_{UV}$ [Dvali, Lüst '09]

Result

From arxiv:2212.10286 [Cribiori, Lüst, Staudt ‘22]

$$\Lambda_{UV} = \frac{M_P}{\sqrt{qcp^1}}$$

We reproduced a recent paper by van de Heisteeg, Vafa, Wiesner, Wu ['22] who approached the problem via the topological string and the genus one free energy

Conclusion

Conclusion

- General method: how to use Black Holes to study EFT with gravity
- Result: we found Λ_{Sp} precisely as in van de Heisteeg, Vafa, Wiesner and Wu
- Future directions:
    1. Add the temperature (would break SUSY)
    2. Study different corrections
    3. Study different types of Black Holes

Thank you!

Figures

Page 1:

- https://aktuelles.uni-frankfurt.de/english/astronomers-reveal-first-image-of-the-black-hole-at-the-heart-of-our-galaxy/

Page 3:

- https://www.nasa.gov/mission_pages/chandra/news/black-hole-image-makes-history

- https://www.news.ucsb.edu/2021/020427/search-quantum-gravity

Page 6 and 8:

- https://www.semanticscholar.org/paper/An-Introduction-to-the-String-Theory-Swampland-for-Palti/8eab54881df5697d48d4b9743c054b438be9788d