# Small black holes, light species, and the emergent string conjecture?

**Carmine Montella**

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# Ingredients

- *When a gravitational EFT breaks down?*
- *Moduli space, distance, and tower of states*
- *The quantum gravity scale*
- *Black holes, and tower of states*

# When a gravitational EFT breaks down?

- The graviton is the most sociable particle of all

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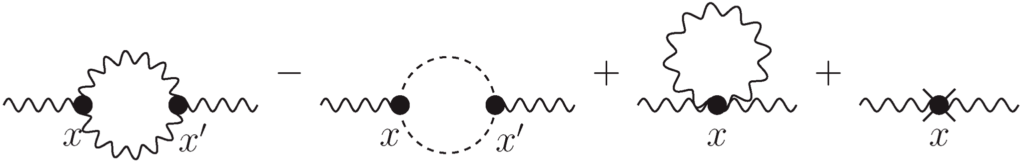
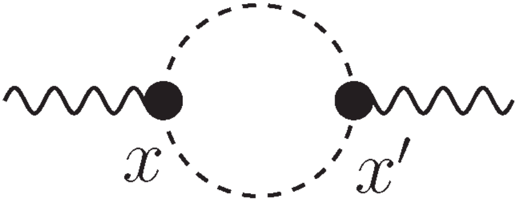



**Figure:** Diagrams contributing to the one-loop graviton self-energy

# When a gravitational EFT breaks down?

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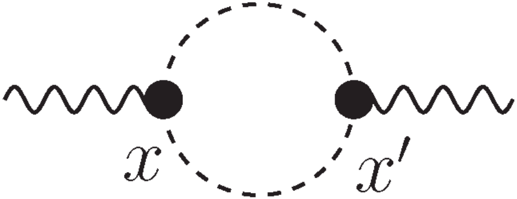
# When a gravitational EFT breaks down?

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$$\alpha_{\text{grav}} \sim \left(\frac{E}{M_{\text{pl}}}\right)^{d-2}$$

$$G_{\text{N}}^{\text{ren}} = N_{sp}\, G_{\text{N}} \quad \longleftrightarrow \quad M_{\text{pl}}^{\text{ren}} = \frac{M_{\text{pl}}}{N_{sp}^{\frac{1}{d-2}}} \equiv \Lambda$$

# Moduli space, tower of states, and distance

**Moduli space** Roughly speaking, a moduli space refers to the space of vacuum expectation values of scalar fields (and other background fields). It represents the set of all possible configurations for these fields that yield stable, classical vacuum states.

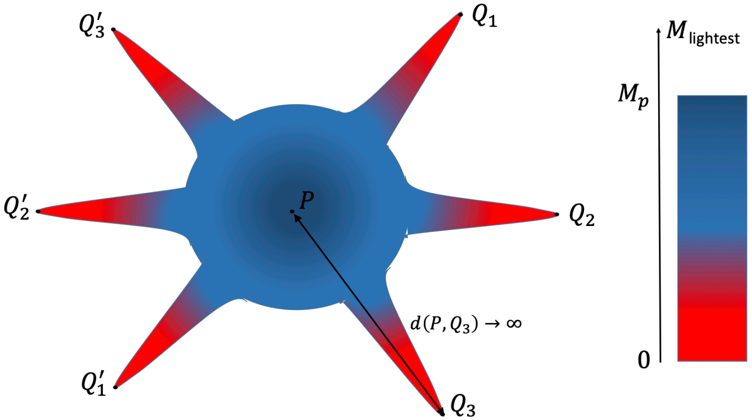


**Figure:** Palti's review, 2019

## Distance in the moduli space

$$\mathcal{L}_\Phi \supset \frac{1}{2}\int_{\mathcal{M}} g_{IJ}(\Phi)\partial_\mu \Phi^I \partial^\mu \Phi^J$$

$$\Delta_\Phi \equiv \int_{s(P)}^{s(Q)} ds \sqrt{g_{IJ}(\Phi)\dot{\Phi}^I(s)\dot{\Phi}^J(s)}$$

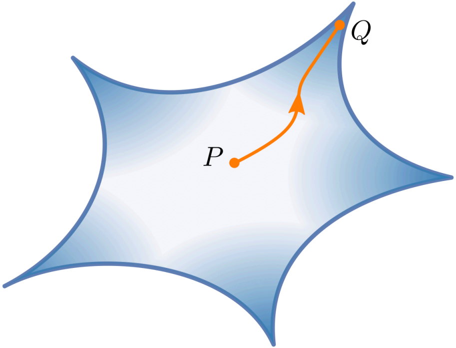


**Figure:** Valenzuela et al. review, 2021

# The quantum gravity scale

- 1st **The UV scale**

$$S_{\text{eff}} \supset \frac{M_{\text{pl}}^{d-2}}{2} \int d^d x \sqrt{-g} \left( R + \sum_n \frac{c_n}{\Lambda_{\text{UV}}^{2n-2}} O_n \left( g, \text{Riem}, \nabla \right) \right) .$$

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- 2nd **The species scale** [Dvali et al., 2009]

$$\Lambda_{\text{sp}} \equiv M_{\text{pl}} N_{\text{eff}}^{-\frac{1}{d-2}} \ll M_{\text{pl}}$$

# The quantum gravity scale

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- 2nd **The species scale** [Dvali et al., 2009]

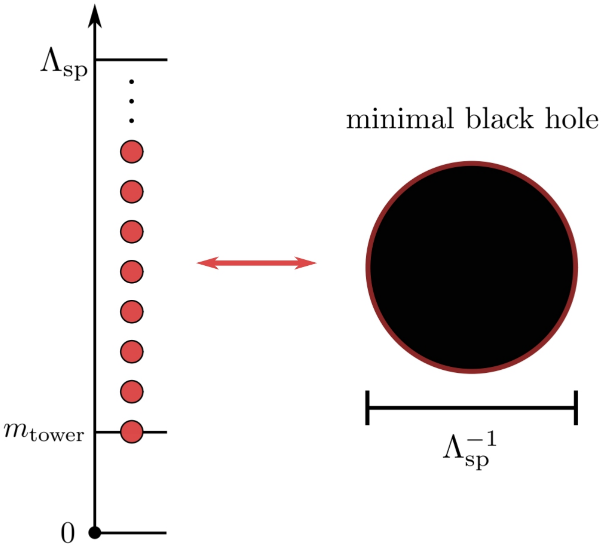
$$L_{\text{sp}}^{d-2} \equiv N_{\text{eff}} \; ( \sim S_{\text{sp}} \; )$$

**Tower mass spectrum**

$$m_n = f(n)\, m_{\text{tow}}$$

$$\implies \Lambda_{\text{sp}} = f(N)\, m_{\text{tow}}$$

**Degeneracy of states**: for each level $n$, there could be $d_n \geq 0$ states.



# Black holes

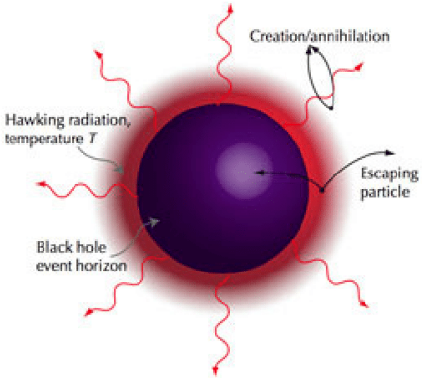
They are geometric objects:

$$ds^2 = f(r)\,dt^2 - \frac{dr^2}{f(r)} - r^2 d\Omega^2_{d-2}$$

$$\mathrm{S}: f(r) \sim 1 - \frac{G_N M_{BH}}{r^{d-3}} + \text{corr.}$$

They are thermodynamic objects

$$\Longrightarrow \begin{cases} M_{BH} \sim R_H^{d-3} \\ S_{BH} = \frac{A_H}{4G_N} \sim R_H^{d-2} \\ T_{BH} = \frac{\kappa}{8\pi G_N} \sim R_H^{-1} \end{cases} + \text{corr.}$$



# The thermodynamic picture of the moduli space

- *Energy, entropy, and temperature*
- *Small black holes, and the moduli space*
- *Small black holes, and the emergent string conjecture*

# Energy, entropy, and temperature

**Energy**

The minimum energy is the sum over the masses of the species present in the tower

$$E_{\text{sp}} = m_{\text{tow}} \sum_{n=1}^{N} d_n f(n) + \epsilon_{grav} \,, \qquad \frac{E_{\text{sp}}}{\epsilon_{grav}} \gg 1$$

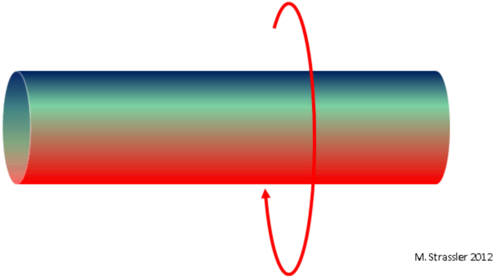
**Entropy**

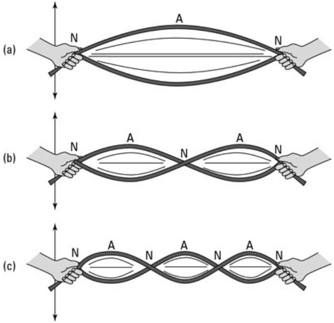
The logarithm of the number of microstates fixing the thermodynamics quantities

$$S_{\text{sp}} = \log D(E_{\text{sp}})$$

# Top-down

$$\begin{cases} \text{Kaluza-Klein tower} \\ \text{String tower(HS tower)}^* \end{cases} \implies \begin{cases} E_{\text{sp}} \sim L_{\text{sp}}^{d-3} + \mathcal{O}(L_{\text{sp}}^{-1}) \\ S_{\text{sp}} \sim L_{\text{sp}}^{d-2} + \mathcal{O}\left(\log(L_{\text{sp}}^{d-2})\right) \\ T_{\text{sp}} \sim L_{\text{sp}}^{-1} + \mathcal{O}(L_{\text{sp}}^{1-d}) \end{cases}$$



# Question

**Bottom-up**

$$\begin{cases} E_{\text{sp}} \sim L_{\text{sp}}^{d-3} + \mathcal{O}(L_{\text{sp}}^{b<0}) \\ S_{\text{sp}} \sim L_{\text{sp}}^{d-2} + \mathcal{O}\left(\log(L_{\text{sp}}^{d-2})\right) \end{cases} \implies \textbf{?}$$

**What are the only states that can form a black hole at the infinite distance in the moduli space?**

# Results [Basile, Lüst, CM; 2023]

**Light tower**

The only light tower that can form a black hole at infinite distance in the moduli space, is a KK-like tower.

$$\Lambda_{\text{sp}} \sim m_{\text{tow}}^{\frac{1}{1+(d-2)\frac{1}{p}}} \gg m_{\text{tow}}$$

**Heavy tower**

The only 'heavy tower' that can form a black hole at infinite distance in the moduli space, is a string-like tower.

$$\Lambda_{\text{sp}} \sim m_{\text{tow}}$$

**Light tower**

The only light tower that can form a black hole at infinite distance in the moduli space, is a KK-like tower.

**Heavy tower**

The only 'heavy tower' that can form a black hole at infinite distance in the moduli space, is a string-like tower.

$$\overset{?}{\Longleftrightarrow}$$

**Emergent string conjecture**

Any infinite field distance limit is either

- a decompactification limit, or
- a limit in which a weakly coupled string becomes tensionless.

Thank you!

# The laws of black hole/species thermodynamics

- **The $0^{\text{th}}$ law**: The surface gravity $\kappa$ is constant over the event horizon.

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# The laws of black hole/species thermodynamics

- **The 0th law**: At fixed large distance, $\Delta_\phi \gg \text{diam}(\mathcal{M})$, the quantum gravity cut-off $T_{\text{sp}} \sim \Lambda_{\text{sp}}$ is constant all over the moduli space.

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# The laws of black hole/species thermodynamics

- **The 0th law**: The surface gravity $\kappa$ is constant over the event horizon.
- **The 1st law**: For two stationary black holes differing only by small variations in the parameters $M$, $Q$, and $J$

$$\delta M = \frac{\kappa}{8\pi G}\,\delta A_H + \Phi_H\,\delta Q + \Omega_H\,\delta J$$

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# The laws of black hole/species thermodynamics

- **The 0th law**: The surface gravity $\kappa$ is constant over the event horizon.
- **The 1st law**: For two stationary towers differing only by small variations $\delta\Delta_\phi \geq 0$

$$\delta E_{\rm sp} = \frac{\Lambda_{\rm sp}}{8\pi G}\,\delta N_{\rm sp} + \underbrace{\Phi_{\rm sp}\,\delta Q + \Omega_{\rm sp}\,\delta J}_{\text{work in progress}}$$

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# The laws of black hole/species thermodynamics

- **The 0th law**: The surface gravity $\kappa$ is constant over the event horizon.
- **The 1st law**: For two stationary black holes differing only by small variations in the parameters $M, Q$, and $J$

$$\delta M = \frac{\kappa}{2G}\,\delta A_H + \Phi_H\,\delta Q + \Omega_H\,\delta J$$

- **The 2nd law**: The area of the event horizon of a black hole never decreases

$$\delta A_H \geq 0$$

-

# The laws of black hole/species thermodynamics

- **The 0th law**: The surface gravity $\kappa$ is constant over the event horizon.
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$$\delta M = \frac{\kappa}{2G}\,\delta A_H + \Phi_H\,\delta Q + \Omega_H\,\delta J$$

- **The 2nd law**: The quantum gravity cut-off, at large distance $\Delta_\phi \gg \text{diam}(\mathcal{M})$, never decreases for $\delta\Delta_\phi \geq 0$

$$\delta\Lambda_{\text{sp}} \leq 0$$

-

# The laws of black hole/species thermodynamics

- **The $0^{th}$ law**: The surface gravity $\kappa$ is constant over the event horizon.
- **The $1^{st}$ law**: For two stationary black holes differing only by small variations in the parameters $M$, $Q$, and $J$

$$\delta M = \frac{\kappa}{2G}\,\delta A_H + \Phi_H\,\delta Q + \Omega_H\,\delta J$$

- **The $2^{nd}$ law**: 2. The area of the event horizon of a black hole never decreases

$$\delta A_H \geq 0$$

- **The $3^{rd}$ law**: It is impossible by any procedure to reduce the surface gravity $\kappa$ to zero in a finite number of steps.

# The laws of black hole/species thermodynamics

- **The 0$^{\text{th}}$ law**: The surface gravity $\kappa$ is constant over the event horizon.
- **The 1$^{\text{st}}$ law**: For two stationary black holes differing only by small variations in the parameters $M$, $Q$, and $J$

$$\delta M = \frac{\kappa}{2G}\,\delta A_H + \Phi_H\,\delta Q + \Omega_H\,\delta J$$

- **The 2$^{\text{nd}}$ law**: 2. The area of the event horizon of a black hole never decreases

$$\delta A_H \geq 0$$

- **The 3$^{\text{rd}}$ law**: It is impossible by any procedure to reduce the quantum gravity cut-off $\Lambda_{\text{sp}}$ to zero in a finite number of steps, i.e. the limit $\Lambda_{\text{sp}} \to 0$ is at infinite distance