Low energy perspectives on quantum gravity

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String Theory as a powerful framework

.. where to investigate properties of gravity

MAJOR SUCCESSES

- First quantitative realization of **holography (AdS/CFT)**
- Black hole microstates counting

What does string theory predict for effective field theories?

The Swampland Program

Semiclassical black holes

String Theory Landscape

Depending on the geometry of the internal (10-d) compact space, and the strings and branes constituents, the resulting theory is a (strongly coupled) QFT.

Only certain gauge groups can be obtained from string theory. A generic QFT may not come from a 10dim setup.

Does this mean only certain QFTs admit a UV completion to a theory of gravity?

What constraints String Theory imposes on the landscape EFT?

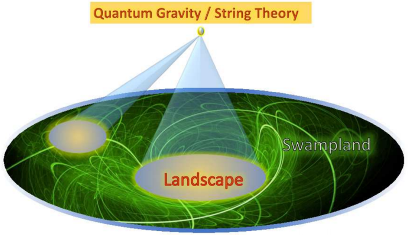


Image by E. Palti

The Swampland Program

What effective field theories can be consistently coupled to a theory of gravity in the UV and why?

Develop a set of principles for an EFT to be compatible with a theory of quantum gravity

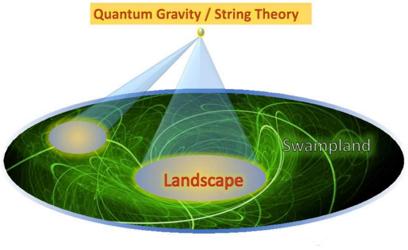


Image by E. Palti

The effects of the UV completion in the low energy physics are called a UV-IR mixing phenomenon.

UV-IR mixing

Bekenstein Bound

$$S_{QFT} \leq \frac{Area}{4G_N} = \pi M_P^2 L^2$$

Argument: if $S_{matter} > S_{BH}$, by throwing more matter in the system one would create a black hole, thus reducing the entropy, against the second law.

't Hooft, Susskind: holographic proposal– The QFT naively overcounts the number of states as

$$S_{QFT}(\Lambda) \sim \Lambda^3 L^3$$

Bekenstein bound implies that the states in the local QFT will collapse into black holes when their entropy reach $S \sim A$.

$\rightarrow$ UV and IR cutoffs in a local field theory might be related due to gravity

UV-IR mixing – CKN bound

BB could be violated, naively. In order to have a local QFT which respects the Bekenstein Bound one naively assumes

$$S_{QFT} \sim \Lambda^3 L^3 \leq \pi L^2 M_P^2$$

However, in order for the highly entropic states in the EFT to be able to physically collapse into black holes, we must require that their Schwarzschild radius is contained in the volume of the system so

$$r_S = 2G_N M(L,\Lambda) \sim M_P^{-2}(L^3 \Lambda_{UV}^4) \leq L \qquad \Rightarrow \qquad \Lambda_{UV} \leq \sqrt{\frac{M_P}{L}}$$

This implies that the highest entropy for the states in the QFT before collapsing to black holes, given by the saturation of the previous bound, is

$$S_{max,QFT} = S_{QFT}(r_S \sim L) \sim L^3 \Lambda_{UV}^{sat\,3} = (L^2 M_P^2)^{3/4} \sim A^{3/4} \; .$$

[Cohen, Kaplan, Nelson, '98]

UV-IR mixing

The presence of light fields in the EFT lowers the effective QG cutoff

The gravitational effective field theory has an effective cutoff lower than the Planck scale given by (in 4d)

$$\Lambda_{QG} = \frac{M_p}{\sqrt{N}}$$

- Perturbative argument: Each particle species renormalizes the Planck Mass by a factor Λ^2
- Non-perturbative argument: evaporation of a black hole of mass $M_{BH} = N\Lambda$ through heavy particles when its temperature drops to $T_H \sim \Lambda$

[Dvali, Gabadaze, Porrati '00][Dvali '07]

Recent applications in the context of Swampland constraints

[Castellano, Herráez, Ibáñez, '21-'23] [Cribiori, Lüst, Montella '23]

- Entropy bound in generic dimension
- Contribution to the cutoff

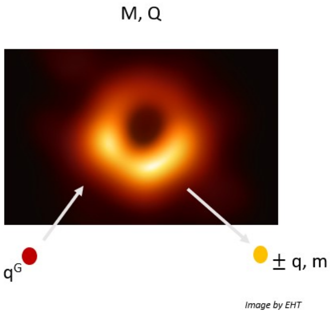
$$M_{tower} < \Lambda_{IR}^{\frac{1}{D-1}} M_P^{(D-2)/(D-1)}$$

Why black holes?

[Brennan, Vafa '17],[Palti, '19]
[Van Beest et al. '21]

Black holes as a lamp in the Swampland

- Statistical interpretation of entropy: what are black hole microstates? – *no hair theorem*
- Unitary description of black hole evaporation? black hole information paradox
- What happens to extremal black hole? can they decay?
- How to reconcile the EFT with semiclassical black hole physics?



Signatures of UV physics on the low energy theory

- existence of microstates in the UV theory gives rise to black hole entropy

Constraints on IR Physics

Weak Gravity Conjecture

Consider a black hole that has reached extremality: $M = Q$

It can only decay if in the spectrum of the theory there are particles such that

$$m < gqM_P$$

[Arkani-Hamed et al. '06]

to preserve the bound $M \geq Q$

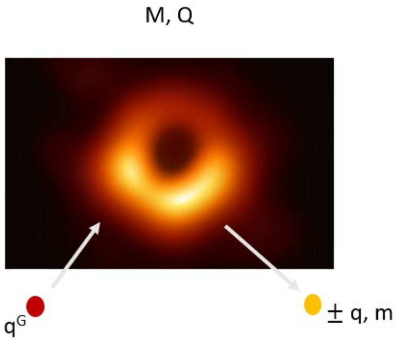


Image by EHT

Assumption: absence of remnants in the EFT

Corrections to the extremality bound from higher derivative [Cheung, Liu, Remmen '18] [Hamada, Noumi, Shiu '18], or for generic perturbations [Aalsma '21]. Black holes could themselves be WGC particles.

Constraints on IR Physics

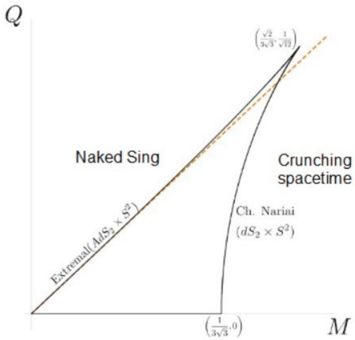
Festina-Lente bound - Evaporation of black holes in de Sitter

Preventing decay to a singular cosmological spacetime requires particles in the spectrum to have masses bounded by

$$m^2 > gqM_PH$$

[Montero, Van Riet, Venken, '19]

[Montero, Van Riet, Vafa, Venken, '21]



Constraints on IR Physics

No global symmetries in quantum gravity

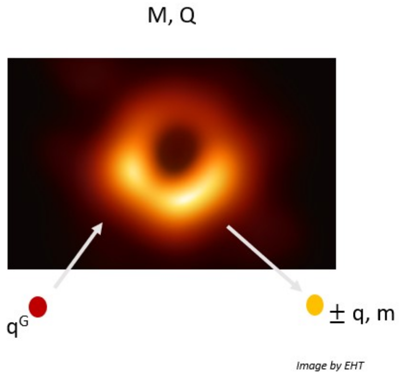
Give a black hole a global charge by throwing a particle in it.

The charge will not be conserved due to black hole evaporation.

(Black holes can emit charge particles if there is a gauge field mediator)

[Banks-Dixon,'88]

[Horowitz,Strominger..,Sussking][Banks,Seiberg '11]

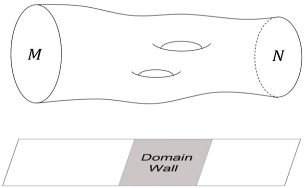


Constraints on IR physics

Generalized global symmetries [Gaiotto, Kapustin, Seiberg, Willet '14]

p-form charged operators (Wilson lines, surface defects..). Charged fields are q-dimensional objects (cfr. particles charged under 0-dimensional global symmetries).

It would introduce higher form symmetries, that cannot be global in the UV QG theory



Generalizations: A consistent theory of quantum gravity can be deformed to any other via physical processes with finite action.

Cobordism conjecture

$\Omega_k^{QG} = 0$ to avoid (D-k-1)-form global symmetry

[McNamara, Vafa '19]

Swampland distance conjecture

[Vafa, Ooguri, '06]

Large variations of fields values are problematic in a UV complete theory of gravity.

When the geodesic distance in moduli space grows large, this is accompained by a tower of states becoming light

$$mL_p \sim e^{-\lambda\Delta(\phi)}$$

If we decouple gravity, swampland constraints become irrelevant so the tower of states is identified by those states with mass

$$m \sim L_P^{-1} \text{ for } L_P \to 0$$

What happens when the variation of $\mathcal{S}$ and $\mathcal{T}$ becomes large? Are there states becoming massless?

$\to$ using the distance defined in the space of *metrics* in [Bonnefoy, Ciambelli, Lüst, Lüst, '19] was found that at $\mathcal{T} = 0$

$$\Delta(g) \sim |\log \mathcal{S}| \qquad m_{\mathcal{S}} \sim \mathcal{S}^{-\lambda} \qquad \lambda > 0$$

$\to$ *Entropy distance conjecture*

Going beyond the distance in space of metrics

There are reasons to investigate other definitions of distance

- ♣ The distance formula is not diffeomorfism invariant (possible ways to refine it are investigated in Bonnefoy et al. '19)
- ♡ There is no general connection of the distance in metric space and a notion of distance in moduli space
- → Black holes from string theory naturally couple to scalar fields, which are moduli of the compactification

Strategy: Consider systems at finite temperature

Systems at finite temperature

A finite temperature system is described by a compact Euclidean time direction of length $\beta = \frac{\hbar}{\mathcal{T}}$.
Associated tower of states corresponding to the Matsubara frequencies:

$$\omega_n = \frac{2\pi n}{\beta} = \frac{2\pi n}{\hbar}\mathcal{T}$$

Could suggest a tower of states become light associated to a distance in temperature space

$$\Delta_{\mathcal{T}} \sim \left| \frac{1}{\lambda} \log \mathcal{T} \right|$$

- Matsubara modes become light as $\mathcal{T} \to 0$
- Dual tower of winding modes becoming light as $\mathcal{T} \to 0$

Temperature is an interesting parameter.
Gravitational systems can develop instabilities or phase transitions at high T.

Examples

Unruh Temperature

Flat space in Rindler coordinates $x_0 = \rho \sinh(a\eta)\,, \qquad x_1 = \rho \cosh(a\eta)$

$$ds^2 = (-a^2\rho^2 d\eta^2 + d\rho^2) + (dx_2)^2 + (dx_3)^2$$

Unruh Temperature leads to the identification of thermal modes ω_U

$$\mathcal{T}_U = \frac{\hbar}{\beta_U} = \frac{\hbar a}{2\pi} \qquad \omega_U = \frac{2\pi}{\hbar}\mathcal{T}_U = a$$

Thus there is no mass scale associated to this temperature and there is no light tower of states appearing at $L_P \to 0$.

To obtain a significant Swampland scenario we need to consider gravitational states.

Examples

Schwarzschild black hole

$$\mathrm{d}s^2 = -f(r)\mathrm{d}t^2 + f(r)^{-1}\mathrm{d}r^2 + r^2\mathrm{d}\Omega_2^2\,, \qquad f(r) = 1 - \frac{2MG_N}{r}$$

Entropy and Hawking temperature

$$\mathcal{S} = \frac{L_p^2 M^2}{2\hbar^2}\,, \qquad \mathcal{T} = \frac{\hbar\kappa}{2\pi} = \frac{\hbar^2}{L_p^2 M}$$

Hawking modes decouples when $L_p \to 0$

$$\omega_H = \frac{2\pi}{\hbar}\mathcal{T} = \frac{2\pi\hbar}{L_p^2 M} = \frac{\sqrt{2}\pi}{L_p\sqrt{\mathcal{S}}}\,,$$

Distance in parameter space, when $\mathcal{S} \to +\infty$

$$\Delta_{BH} = \left|\frac{1}{\lambda}\log\left(\frac{2\pi L_p}{\hbar}\mathcal{T}\right)\right| = \left|\frac{1}{\lambda}\log\left(\frac{\sqrt{2}\pi}{\sqrt{\mathcal{S}}}\right)\right| \to +\infty$$

in order to have two independent parameters we need to consider charged black holes.

Examples

Reissner-Nordstrom black hole

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega_2^2 \,, \qquad f(r) = 1 - \frac{2MG_N}{r} + \frac{Q^2 G_N}{r^2} \,, \qquad r_\pm = M \pm \sqrt{M^2 - Q^2}$$

Non extremality parameter

$$c = \sqrt{M^2 - Q^2} = 2\mathcal{S}\mathcal{T}$$

Hawking modes

$$\omega_H = \frac{2\pi}{\hbar}\mathcal{T} = \frac{G_N\, c}{r_+^2}$$

effectively decouple when $L_p \to 0$.

However No connection with the microscopics since the metric is only coupled to the massless gauge fields.

Need coupling with other fields that may signal a tower of light states

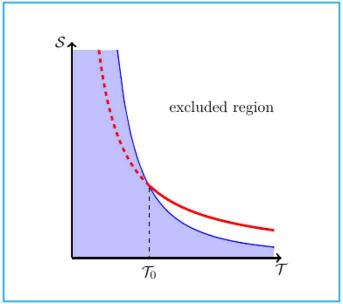
Coupling to scalars

- Einstein-Maxwell-Dilaton theory

$$S_{\rm EMd} = \int d^4x\sqrt{-g}\left(\tfrac{1}{2}M_p^2\left(R - \partial_\mu\phi\partial^\mu\phi\right) - \tfrac{1}{4}e^{-2\lambda\phi}F_{\mu\nu}F^{\mu\nu}\right)$$

- N=2 matter coupled Supergravity (bosonic sector)

$$S_{N=2} = \int d^4x\sqrt{-g}\left(-\frac{R}{2} + g_{i\bar{\jmath}}\partial_\mu z^i\partial^\mu\bar{z}^{\bar{\jmath}} + \right.$$
$$\left. + \mathcal{I}_{\Lambda\Sigma}F^\Lambda_{\mu\nu}F^{\Sigma\,\mu\nu} + \frac{1}{2\sqrt{-g}}\mathcal{R}_{\Lambda\Sigma}\,\epsilon^{\mu\nu\rho\sigma}F^\Lambda_{\mu\nu}F^\Sigma_{\rho\sigma}\right)$$



Do limits in parameter space correspond to infinite distance in moduli space?

e.g. Small black holes [Hamada, Montero, Vafa, Valenzuela '21]

$$\mathcal{V}_h = \frac{4\pi\mathcal{V}_\infty}{\mathcal{S}}\left(\mathcal{S}\mathcal{T} + \sqrt{\mathcal{S}^2\mathcal{T}^2 + \frac{2q_0^2}{\mathcal{V}_\infty}}\right)^2,$$

Limits in parameter space - $\mathcal{S}$

t_1 limit. $\quad \mathcal{V}_h \simeq 2\pi \frac{q_0^2}{\mathcal{S}} \to \infty, \qquad m_{KK} \to 0,$
$\mathcal{S} \to 0.$

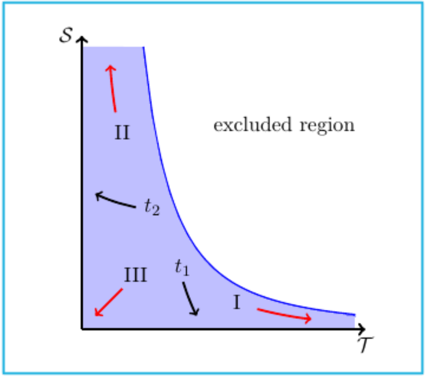
Expect stringy effects to play a role when one reaches $\mathcal{S} \sim L_P$.

Region II. Following $\mathcal{T} \sim \mathcal{S}^{-1/(2-\epsilon)}$,

$$\mathcal{V}_h \sim \mathcal{S}^{-\frac{\epsilon}{2-\epsilon}} \to 0 \qquad \mathcal{S} \to +\infty$$

Region III. $\mathcal{V}_h \sim (\mathcal{S}\mathcal{T})^{3/2}$ - Small black holes
Singularities of the geometry can be cured by α' corrections
Region I. Decompactification limit giving a breakdown of the EFT

$$\mathcal{T} \to \infty : \quad \mathcal{V}_h \simeq q_0^2 \mathcal{T}^2 \to \infty\,, \quad m_{KK} \simeq (q_0 \mathcal{T})^{-1/3} \to 0$$



[Cribiori, Dierigl, AG, Lüst, Scalisi, '22]

Comments

Relations among swampland conjectures

Gauge coupling in N=2 Supergravity

$$\mathcal{L}_{gauge} \sim \mathcal{I}_{\Lambda\Sigma}(z^i\,, \bar{z}^{\bar{\imath}})F^{\Lambda}_{\mu\nu}F^{\Lambda\,\mu\nu}\ ,$$

For example, the 00 direction in the model we have considered is

$$\mathcal{I}_{00}(z^i, \bar{z}^{\bar{\imath}}) = -\mathcal{V}$$

linking the tower of states becoming massless with a global symmetry being restored.

→ How (bad) do black holes break the global 1-form symmetries associated to the $U(1)$'s of N=2? wip with I. Basile

Next: Is the relation of black holes and swampland distance conjectures expected? Can we clarify this connection using the knowledge of the microscopic configuration?

Flux vacua and black holes

[Cribiori, AG, Lüst, Scalisi, '23]

N=2 Supergravity provides a framework for a systematic description of vacua and BPS states from CY and flux compactifications

[Curio, Klemm, Lüt, Theisen, '00] [Behrndt, Gukov, Shmakova, '01] [Kallosh, '05]

→ Macroscopic description of different microscopic configurations

$$\mathcal{W}\,, Z = q_\Lambda L^\Lambda - p^\Lambda M_\Lambda$$

Flux vacua potential $U(1)_R$ gauging

$$V(z,\bar{z}) = |D_i\mathcal{W}|^2 - 3|\mathcal{W}|^2 \equiv V_{\mathcal{N}=1}$$

Black holes potential

$$V(z,\bar{z}) = |Z|^2 + g^{i\bar{\jmath}} D_i Z D_{\bar{\jmath}} \bar{Z} \equiv V_{BH}$$

gravitini gauge coupling $\quad g^2_{3/2} = -\frac{1}{2} g_\Lambda \mathcal{I}^{\Lambda\Sigma} g_\Sigma$

compare to black hole entropy $\quad S_{el} = -\pi q_\Lambda \mathcal{I}^{\Lambda\Sigma} q_\Sigma .$

Flux vacua and black holes

[Cribiori, AG, Lüst, Scalisi, '23]

Analogue extremization condition

$$\partial_i |\mathcal{W}| = 0 \ , \qquad \partial_i |Z| = 0$$

give the Supersymmetric vacua

$$\frac{S}{\pi} = |Z(z_*, \bar{z}_*)|^2 \ , \qquad \Lambda = V(z_*, \bar{z}_*) = -3|\mathcal{W}(z_*, \bar{z}_*)|^2.$$

Correspondence

$$Z \quad \Longleftrightarrow \quad m_{3/2} \qquad\qquad V_{BH} \quad \Longleftrightarrow \quad V_{\mathcal{N}=1}.$$

A consistency check of the correspondence is that the ADC and the BHEDC should be satisfied at the same time in the case of black hole and flux vacua.

$$\begin{aligned} \text{ADC}: &\quad m \sim |\Lambda|^{\alpha} \quad \text{with} \quad \alpha > 0 \\ \text{BHEDC}: &\quad m \sim \mathcal{S}^{-\beta} \quad \text{with} \quad \beta > 0 \end{aligned}$$

Summary and Outlook

- Black holes provide a natural setup in which studying properties of quantum gravity
- Infinite Entropy and Temperature distance linked to the appearance of towers of massless states in region of the parameter space
  Temperature distance conjecture
- In the N=2 EFT relations among large distance behaviour and swampland conjectures for Minkowksi, de Sitter and Anti de Sitter

* Formalize the study of moduli space singularities from black hole entropy with mixed Hodge structures

Thank you!