Slogging through the Swampland:
Weak Gravity and Symmetries

Gregory J. Loges

UW–Madison

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WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

FROGS

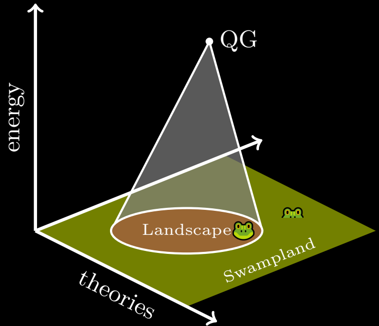
The plan

Part 1: Swamplandology

- A Landscape of possibilities
- Getting muddy in the Swampland

Part 2: Weak Gravity

- Prelude: charged black holes
- The Weak Gravity Conjecture
- WGC with thermodynamics and symmetries



Part 1

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String theory (10D)

highly constrained, essentially only five “flavors”

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Huge (!) number of possibilities in 4D

(chiral matter, dark sector(s), cosmological constant, SUSY?, gauge group, coupling constants, ...)

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Anything goes?

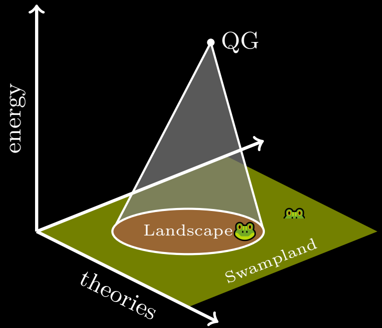
Getting muddy

Observation: explicit string constructions have common features. Is this a coincidence?

Swampland: those low-energy theories which are incompatible with quantum gravity.

Claim: the Landscape is large, but the Swampland is larger.

Swampland conjectures: proposed criteria which distinguish swampland from landscape.



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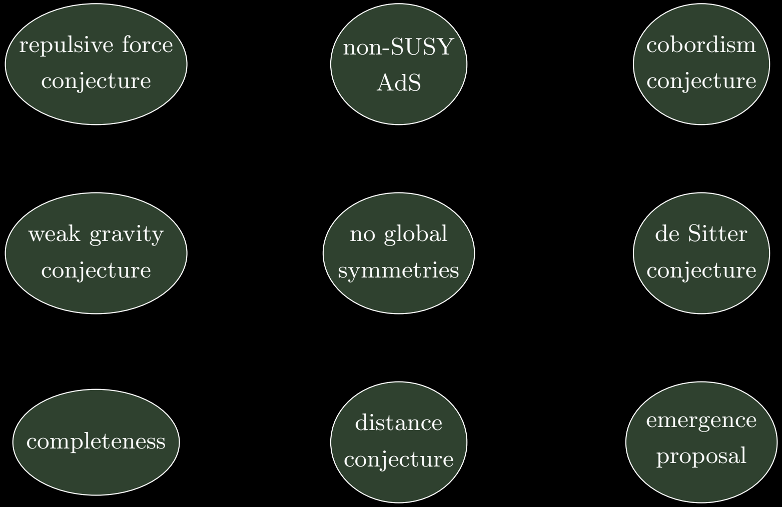
A web of conjectures



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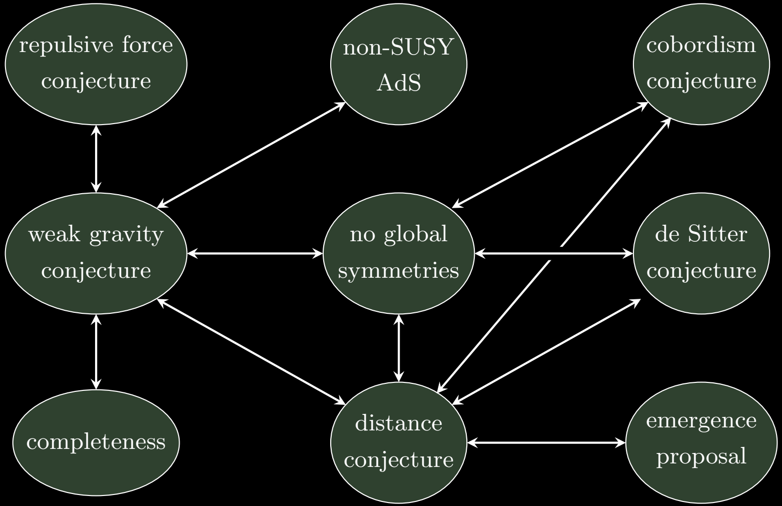


Part 2

Weak Gravity

Prelude: charged black holes

$$\mathcal{L} = \underbrace{\frac{1}{2}R}_{\text{Einstein Gravity}} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Maxwell}}$$

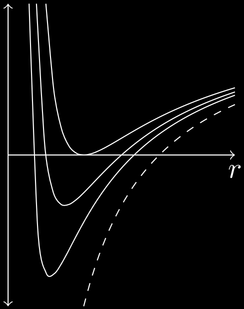
		Rotation: no	Rotation: yes
Charge	no	S.	Kerr
Charge	yes	R–N	K–N

Reissner-Nordström:

- Two horizons: $8\pi r_\pm = M \pm \sqrt{M^2 - 2Q^2}$
- Classical extremality bound: $z \equiv \frac{\sqrt{2}Q}{M} \leq 1$

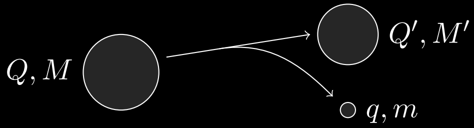
Extremal black holes ($z = 1$):

- Vanishing temperature: $T = \frac{r_+ - r_-}{4\pi r_+^2} \to 0$
- Exactly stable



WGC and its variants

Heuristic motivation:



$$\begin{cases} Q = Q' + q \\ M > M' + m \end{cases}$$

$$\frac{\sqrt{2}Q}{M} = 1 \quad \Longrightarrow \quad \frac{\sqrt{2}Q'}{M'} > 1 \quad \text{and/or} \quad \frac{\sqrt{2}q}{m} > 1$$

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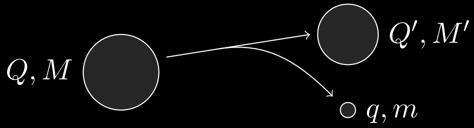

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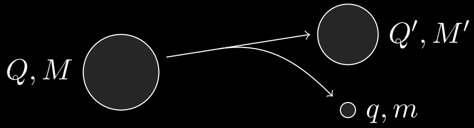

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WGC: $\exists$ state with $z > 1$

mild WGC: extremal black holes have $z > 1$

WGC: Einstein-Maxwell

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$$\mathcal{L} = \underbrace{\tfrac{1}{2}R - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Einstein-Maxwell}} + \underbrace{\alpha_1(\ldots) + \alpha_2(\ldots) + \alpha_3(\ldots)}_{\text{“higher-derivative terms”}} + \cdots$$

- $\alpha_{1,2,3}$ capture some aspects of higher-energy physics
- Corrected extremality bound: $\Delta z_{\text{ext}} = \frac{64\pi^2}{5Q^2}(2\alpha_1 - \alpha_3)$

However, $2\alpha_1 - \alpha_3 > 0$ is quite generic and follows from unitarity, causality, …

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What additional ingredients are needed?

Symmetries/dualities are sufficient. [GL,Noumi,Shiu–20]

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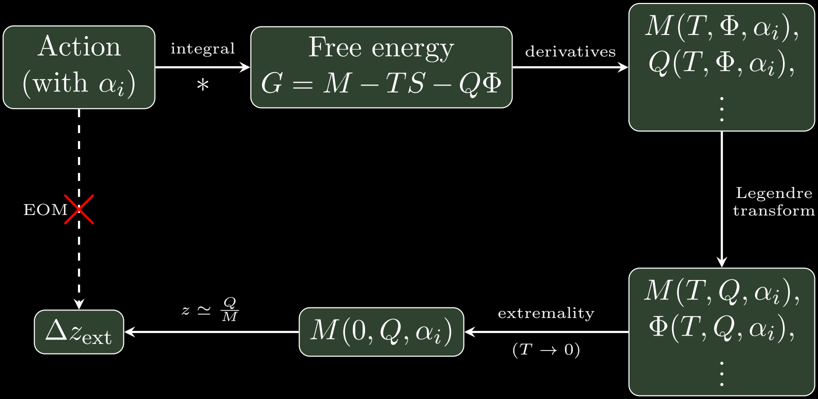
$$\mathcal{L}=\frac{1}{2}R-\frac{\partial_\mu\tau\partial^\mu\bar{\tau}}{4(\mathrm{Im}\,\tau)^2}-\frac{1}{2}\,\mathrm{Im}(\tau F^-_{\mu\nu}F^{-\mu\nu})+\alpha_i(...)_i+\cdots$$

Two goals: find Δz_{ext}, then understand when $\Delta z_{\mathrm{ext}}>0$.

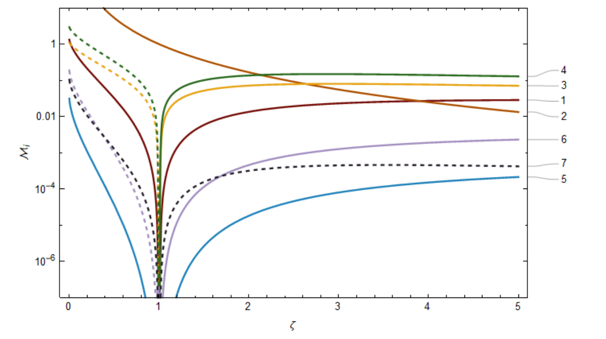
Einstein-Maxwell-dilaton via thermodynamics

Goal 1: find Δz_{ext}



Einstein-Maxwell-dilaton via thermodynamics

Goal 2: when is $\Delta z_{\text{ext}} > 0$?



$$\Delta z_{\text{ext}} = \frac{32\pi^2}{5QP}\alpha_i \mathcal{M}_i$$

Unitarity, &c. tell you that $\alpha_1, \alpha_2, \alpha_5, \alpha_7 \geq 0$ (underconstrained)

Imposing extra structure: $\mathrm{SL}(2,\mathbb{R})$ and $\mathrm{O}(d,d;\mathbb{R})$

By assumption h.d. terms are constrained by one of the following symmetries of the two-derivative action.

<u>$\mathrm{SL}(2,\mathbb{R})$</u>:

$$\tau \to \frac{a\tau + b}{c\tau + d}\,, \quad F^{+}_{\mu\nu} \to (a\tau + b)F^{+}_{\mu\nu}\,, \quad F^{-}_{\mu\nu} \to (c\tau + d)F^{-}_{\mu\nu}$$

<u>$\mathrm{O}(d,d;\mathbb{R})$</u>: more obscure, also very nonlinear.

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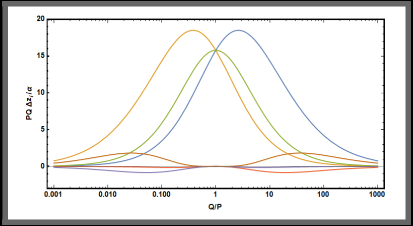
$\mathrm{SL}(2,\mathbb{R})$



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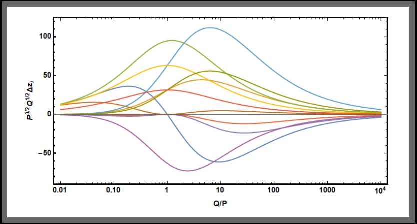
Symmetry + unitarity $\Rightarrow$ WGC

$\mathrm{O}(d,d;\mathbb{R})$



$$\Delta z_{\text{ext}} = \frac{32\pi^2(2\alpha \pm \beta)}{5P(Q+P)}$$

Symmetry + NEC $\Rightarrow$ WGC

Recap

- Perspective on Landscape vs. Swampland and web of conjectures
- Weak Gravity Conjecture: success for Einstein-Maxwell is encouraging but misleading
- With additional light fields: thermodynamics as a computational tool
- Insufficiency of usual assumptions and resolution with symmetries

Thanks!