

Title: Quantum Gravity through the lens of Effective Field Theory

Speakers: Alessia Platania

Collection/Series: Emmy Noether Workshop: Quantum Space Time

Subject: Quantum Gravity

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Abstract:

While a complete theory of quantum gravity remains elusive, several alternative approaches are being explored. Which ones are the most promising, and whether they are connected or fundamentally distinct, remain outstanding open questions. I will argue that looking at quantum gravity through the lens of effective field theory offers a promising path to test the internal consistency of different theories and systematically compare their low-energy manifestations. I will illustrate this perspective using asymptotically safe quantum gravity as a case study, discussing its interface with positivity bounds and swampland conjectures. Finally, I will outline how a similar strategy can be utilized to chart the landscape of quantum spacetimes stemming from an asymptotically safe ultraviolet completion.

Quantum Gravity through the lens of Effective Field Theory

Alessia Platania

Emmy Noether Workshop: Quantum Space Time
10.03.2025



The Niels Bohr
International Academy

VILLUM FONDEN

UNIVERSITY OF
COPENHAGEN



- QG is a multi-scale problem

- Different theories / UV completions
- Observations spanning intermediate to large distances (cosmology, dark energy, gravitational waves)
- EFT: consistency constraints in the IR

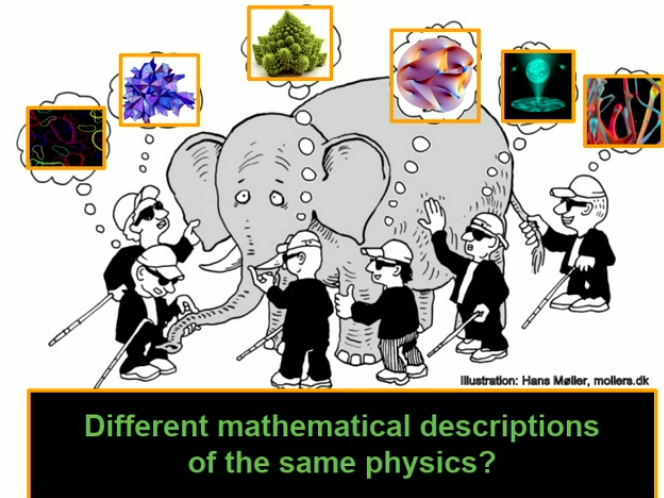
- Technical and conceptual interrelated difficulties in connecting UV and IR, and different UVs

- Theory is not driven by experiment (scale separation)
Different approaches to QG
- Difficult to make predictions from scratch
Same predictions, connections between theories?

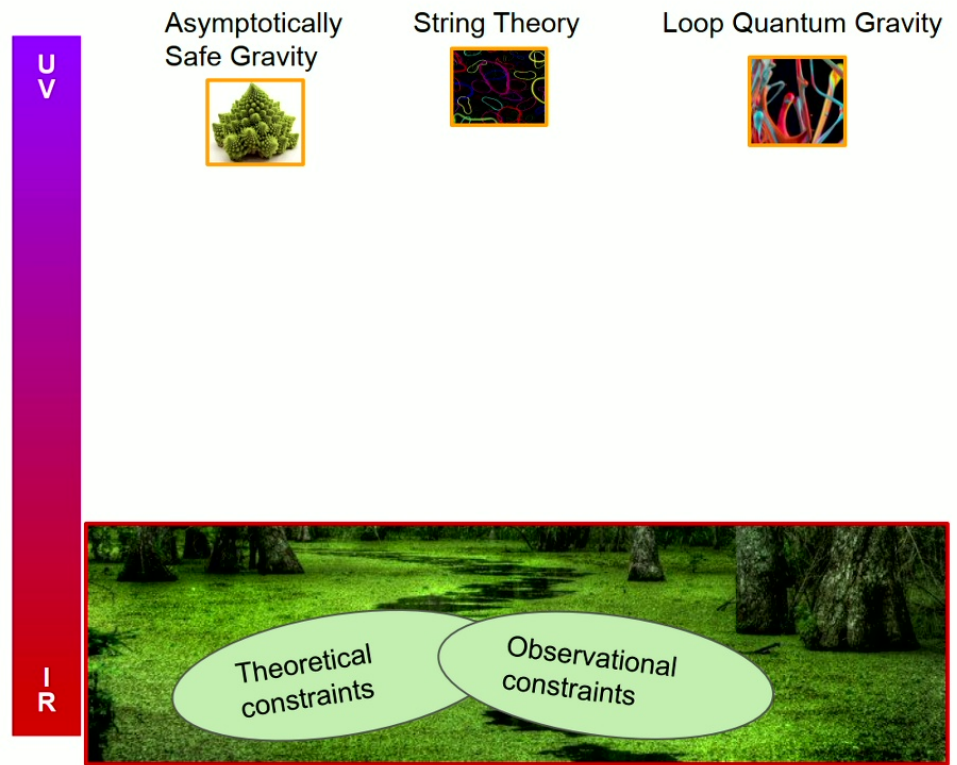
- A “decoupling phenomenon” in gravity

- “Formal” QG communities: mostly focus on the UV
- Pheno & EFT communities: mostly focus on the IR

**One direction for progress in QG:
combining strategies and
concepts across fields?**

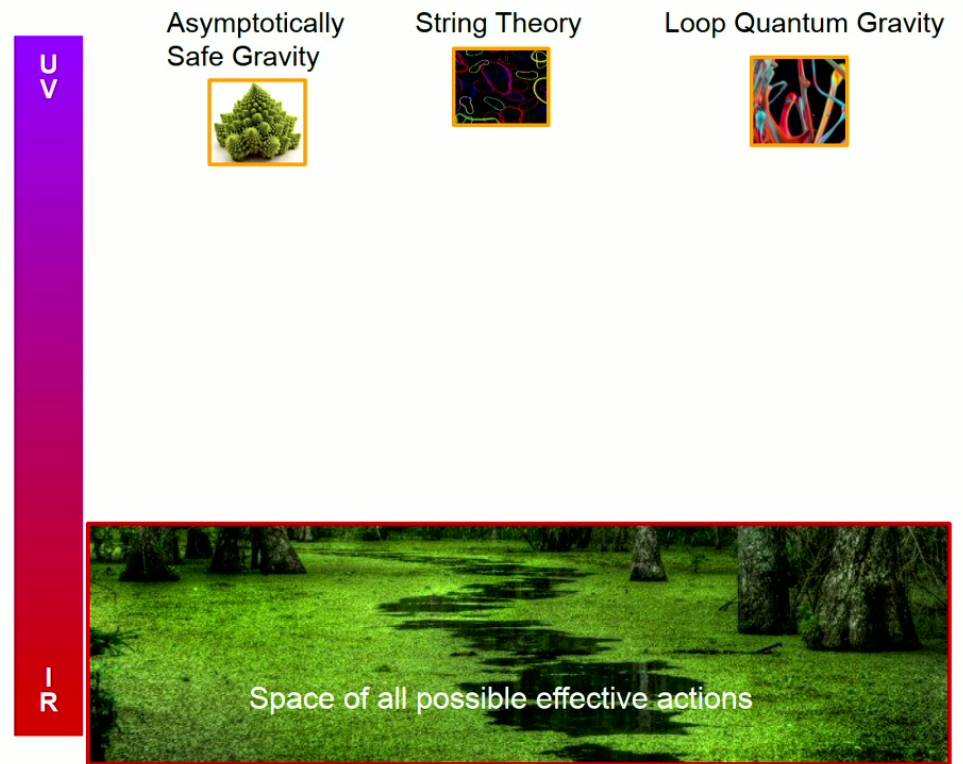


- **Task:** define map connecting UV and IR
- **Expectation:** not everything goes, QG is predictive



Quantum gravity through the lens of effective field theory

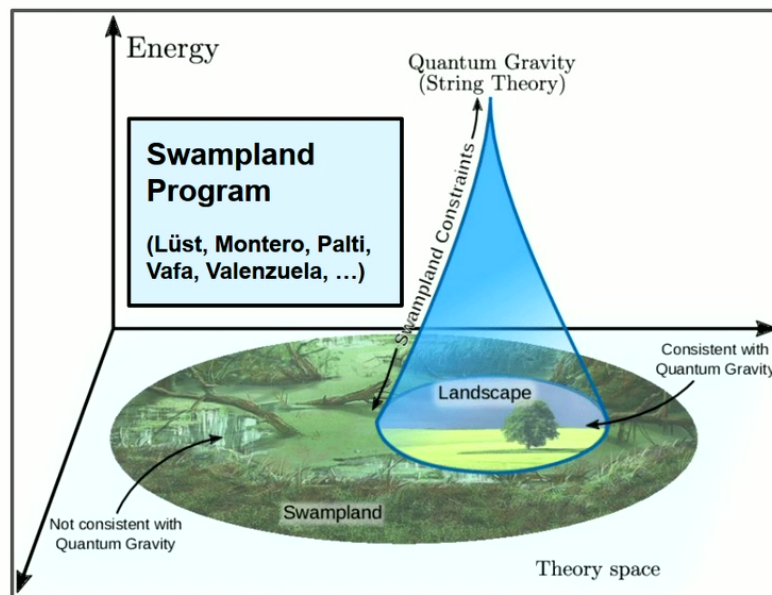
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Quantum gravity through the lens of effective field theory

One attempt within String Theory: the “swampland program”

- Find criteria that select consistent EFTs (that come from UV-complete QG+matter)
- Criteria inspired by universal patterns in string constructions or derived from EFT/BH arguments



Asymptotically Safe Gravity



String Theory



Loop Quantum Gravity



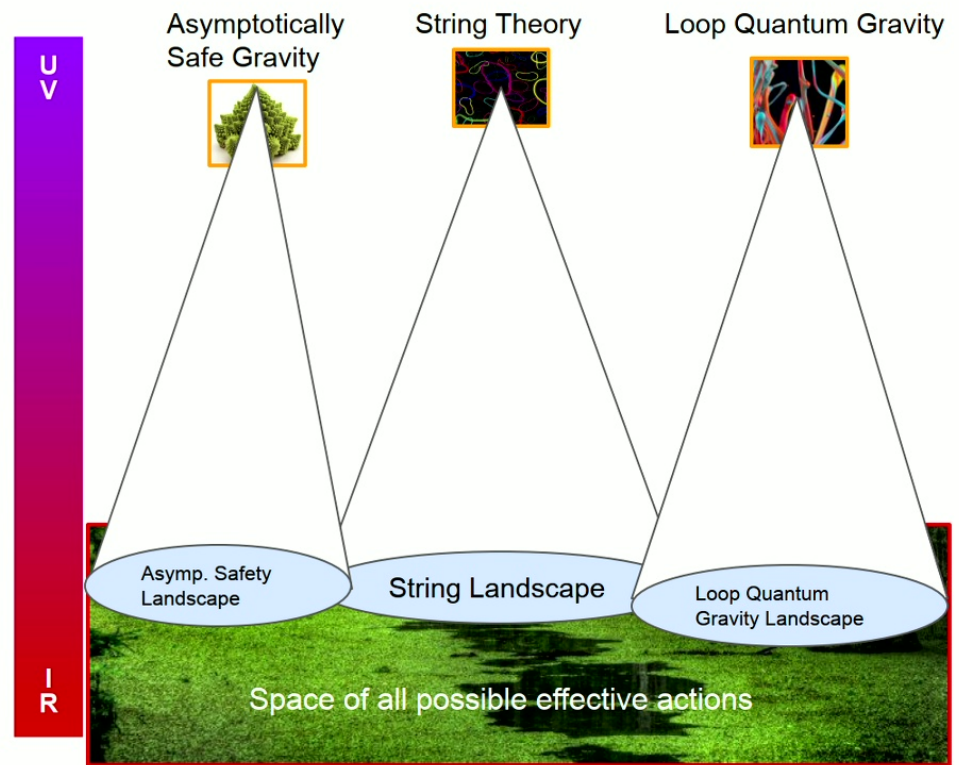
Quantum gravity through the lens of effective field theory

Can the “big picture” of the swampland program be generalized?

[Basile, AP, '21]

[Eichhorn, Hebecker, Pawłowski, Walcher, '24]

(see also talk by Astrid!)

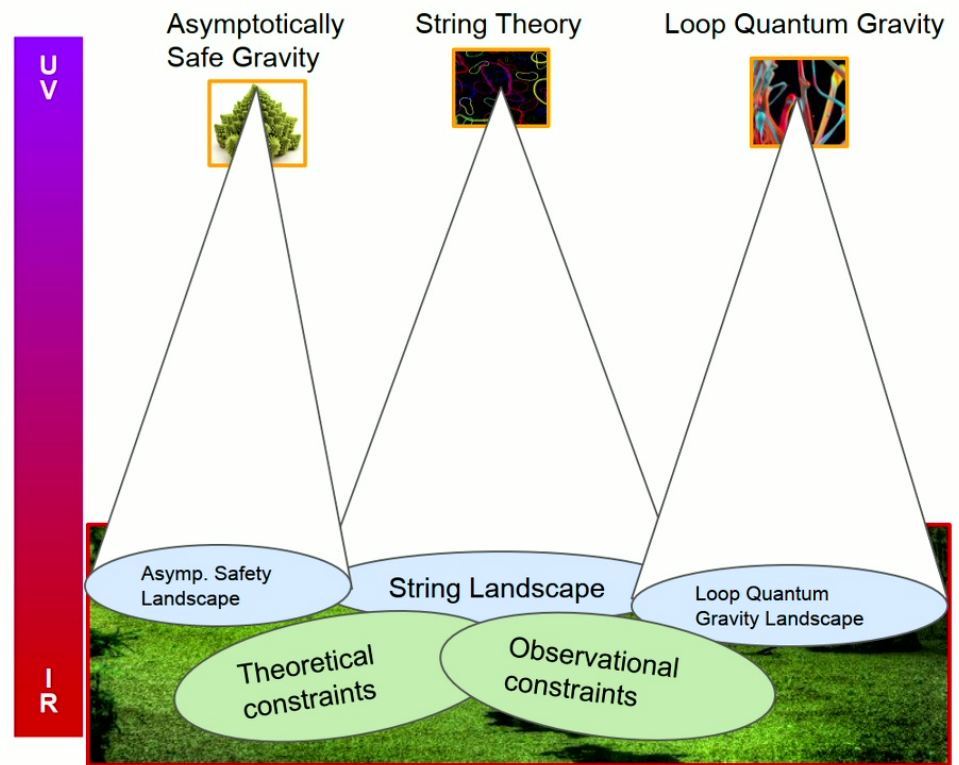


Quantum gravity through the lens of effective field theory

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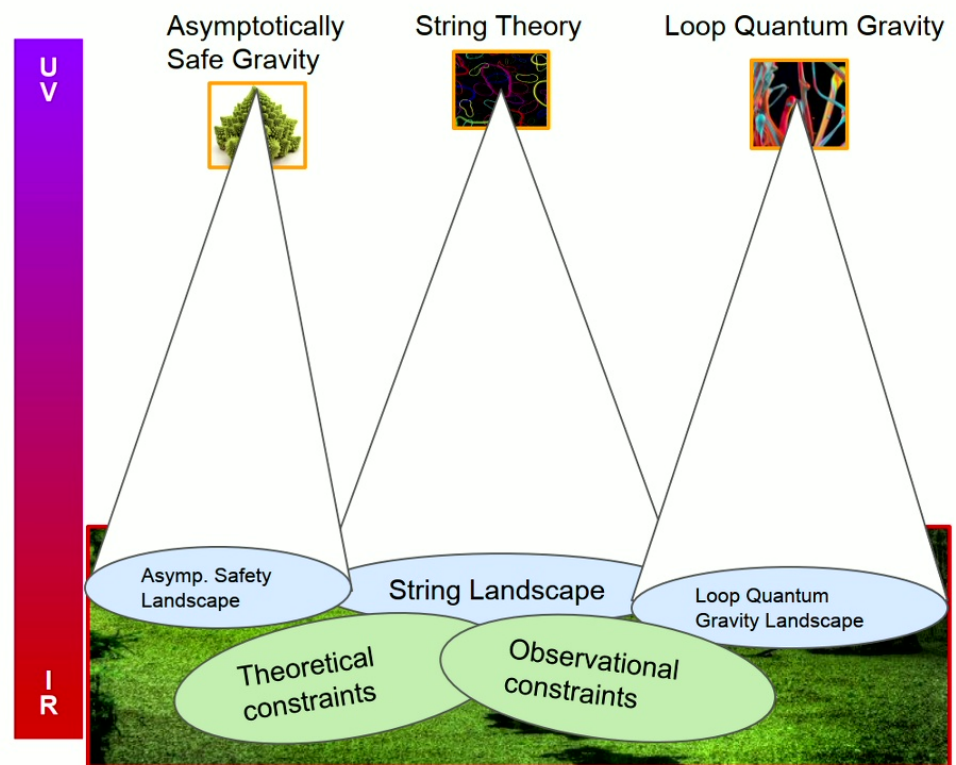
Quantum gravity through the lens of effective field theory

Several interesting questions at the intersections:

- **Consistency**, e.g., compatibility of QG predictions with positivity bounds (unitarity, causality, stability)
- **Tests of Swampland Constraints & string “universality”**: are they all general? Do they apply to all (consistent) QG or they only identify EFTs stemming from ST?

c.f. **String Lamppost Principle** [Montero, Vafa, '21]:
“All consistent quantum gravity theories are part of the string landscape”

- Comparison between **predictions of different QG approaches**? Connections between approaches?
- Comparison with bounds from **observations**?



Let us go deeper:

- **EFT parametrize and constrain.** (e.g. Wilson coefficients, amplitudes)
- **QG computes.** (ideally as many parameters as possible: predictivity!) (e.g., via renormalization group, simulations, amplitude techniques)

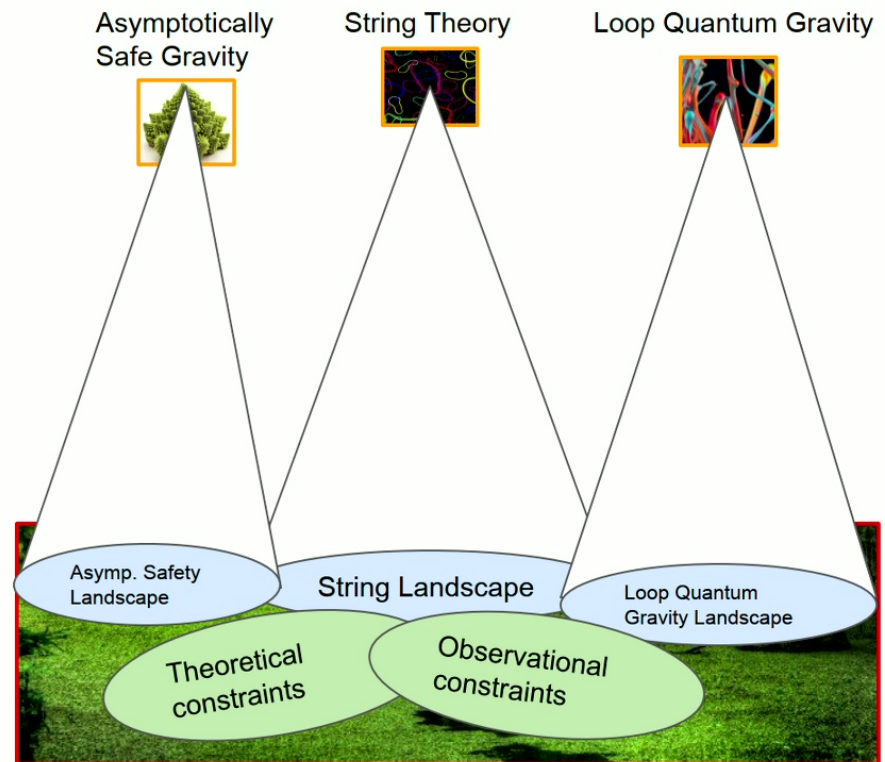
Concretely, in terms of effective actions (can be mapped onto amplitudes):

$$\Gamma_{\text{eff}} = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} + \mathcal{L}_{\text{HD}} \right)$$

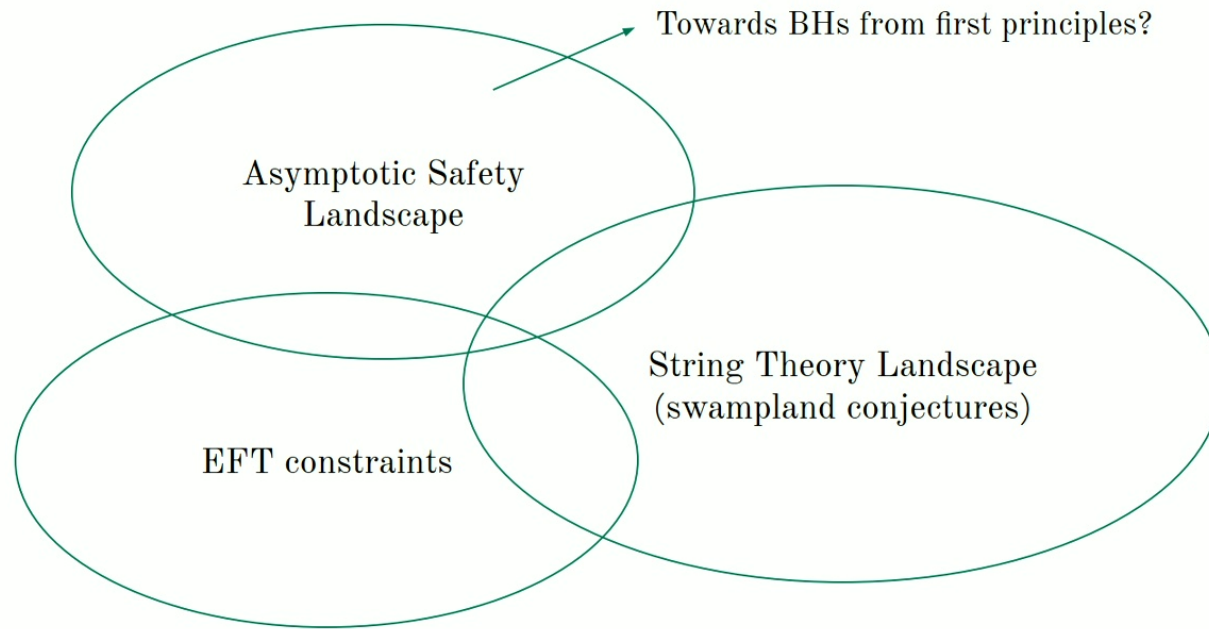
$$\mathcal{L}_{\text{HD}} = \frac{1}{16\pi G} (R\mathcal{F}_1(\square)R + R_{\mu\nu}\mathcal{F}_2(\square)R^{\mu\nu} + R_{\mu\nu\rho\sigma}\mathcal{F}_3(\square)R^{\mu\nu\rho\sigma} + \mathcal{O}(R^3))$$

From a given **UV completion**, one may map a *specific* set of Wilson coefficients. This is one way to define a **landscape**.

Then **compare**, extract **physical results**

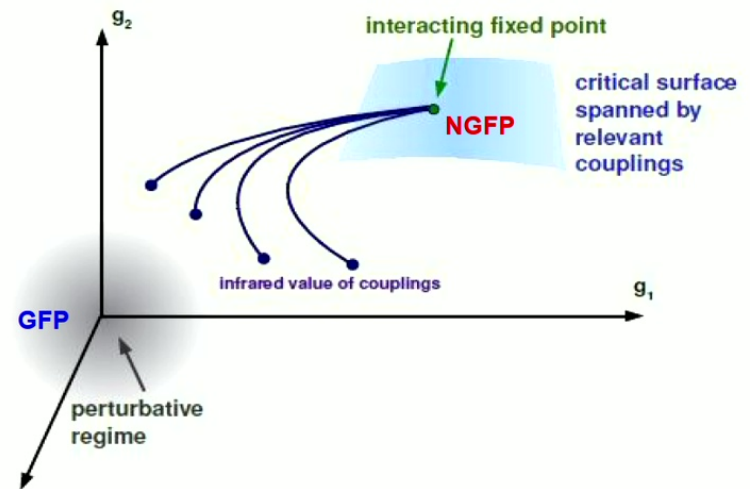
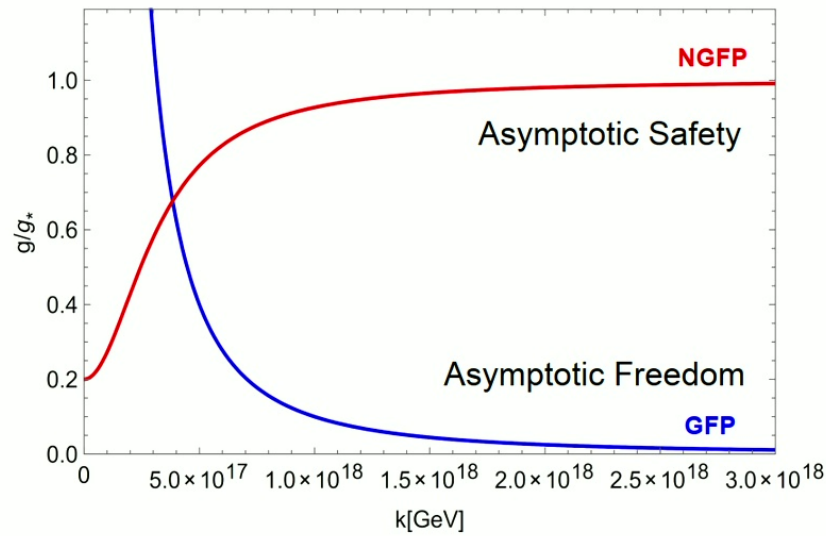


This talk's focus



Asymptotic Safety in a Nutshell

Let us start conservative: can we have a consistent QG theory fully within QFT?

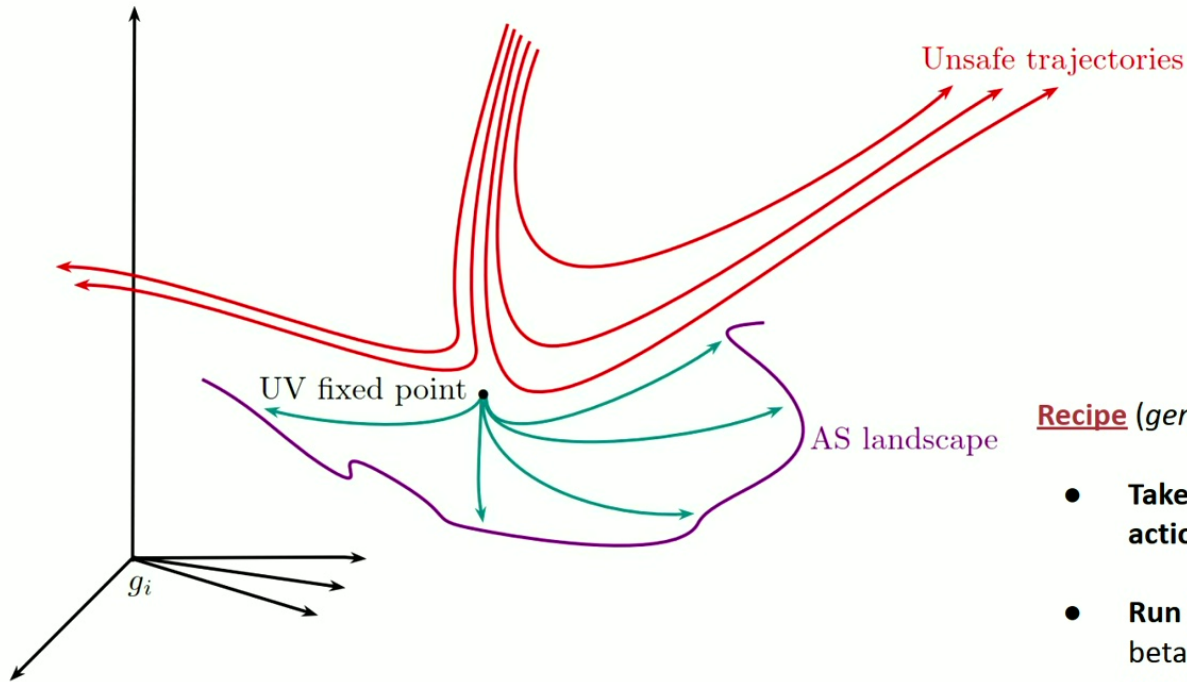


Idea: gravity non-perturbatively renormalizable, interacting UV-completion

(Weinberg, '76)

Predictivity: number of free parameters = number of relevant directions minus one fixing the scale

Defining the asymptotic safety landscape



Recipe (generalizable to other approaches?)

- Take a model of AS (truncation of the action)
- Run (functional) RG machinery: compute beta functions, solve beta functions for a sample of UV-complete trajectories
- Identify the "AS landscape" in terms of **dimensionless Wilson coefficients in the effective action** [some caveats in the def]

Lessons from the intersections



**AS landscapes
vs
Swampland Constraints**

- **AS toy model:** one-loop quadratic gravity

$$\mathcal{L} = \frac{2\Lambda - R}{16\pi G} + \frac{1}{2\lambda} C^2 - \frac{\omega}{3\lambda} R^2 + \frac{\theta}{\lambda} E$$

- **Three dimensionless Wilson coefficients** (+ gauss-bonnet, but decoupled)
One dimensionful coupling sets the mass unit scale!

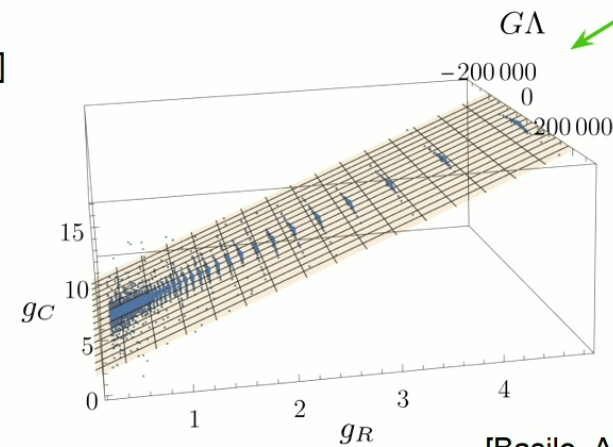
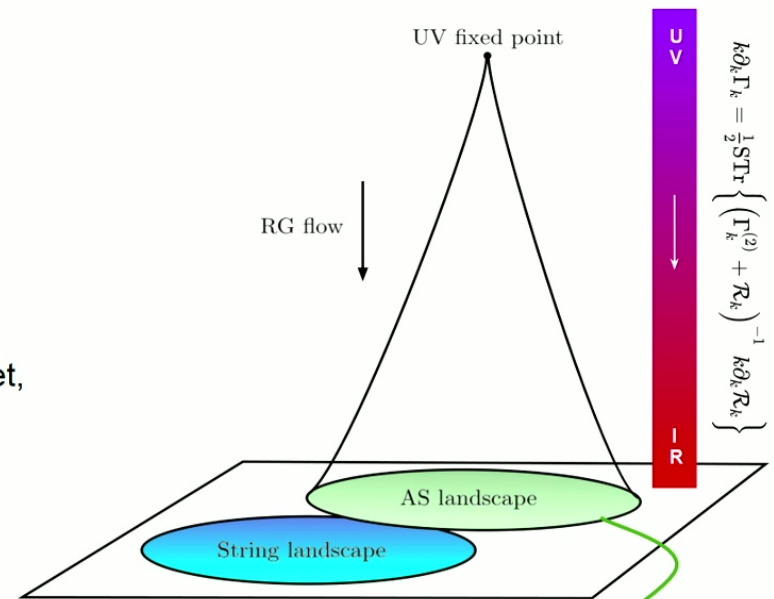
$$G\Lambda, \quad g_R = -\frac{\omega}{3\lambda}, \quad g_C = \frac{1}{2\lambda}$$

- Beta function and fixed points [(Codello, Percacci, 2006)]

The Wilson coefficients stemming from an AS fixed point lie on a plane

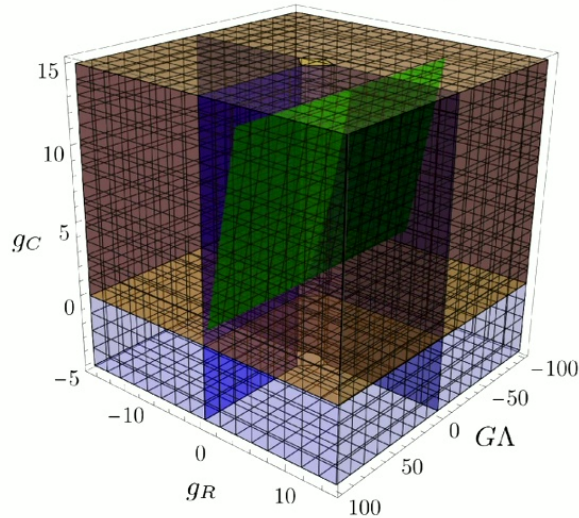
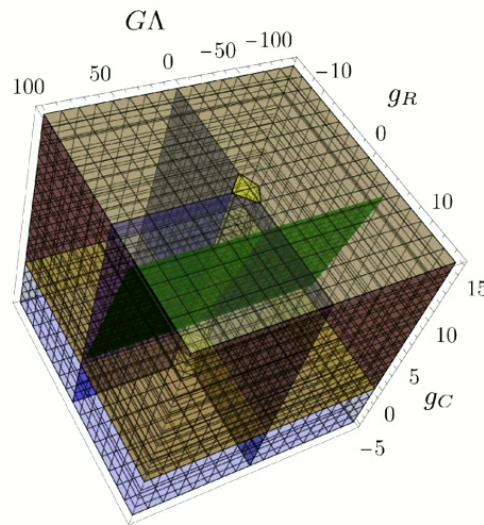
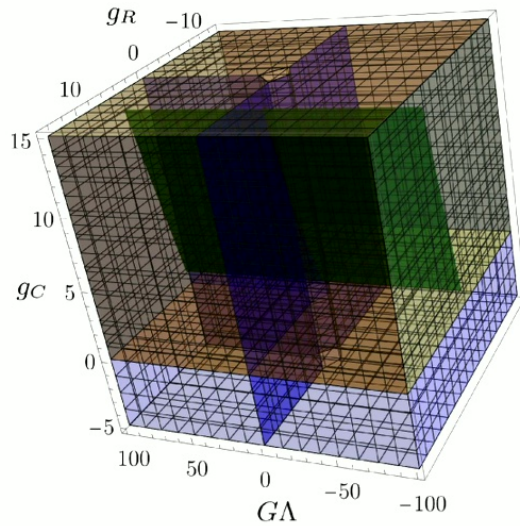
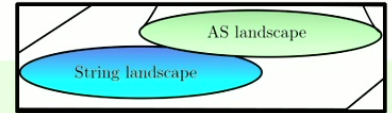
$$\text{EFT}_{\text{AS}} \approx \left\{ g_R = -0.74655 - \frac{2}{3} \omega - g_C \right\}$$

$$g_C > 0$$



Result from
 $\sim 10^7$ num
integrations
of RG eqs.

[Basile, AP. 2107.06897]



Green plane:

AS landscape [one-loop quadratic approx]

$$EFT_{AS} \approx \left\{ g_R = -0.74655 - \frac{2}{3} \omega_- g_C \right\} \quad g_C > 0$$

Blue hyperplane:

Stringy “no de Sitter” conjecture

[~ no positive cosmological constant]

Yellow hyperplane:

Weak gravity conjecture

[~ gravity is the weakest force]

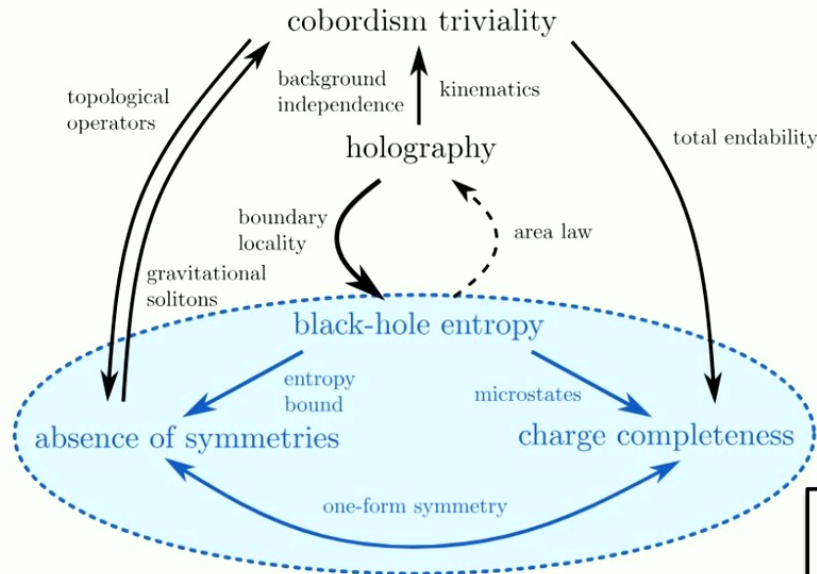
Within this simple model of AS, and only some swampland conjectures

⇒ non-trivial intersection (partial compatibility?)

[Basile, AP. 2107.06897]

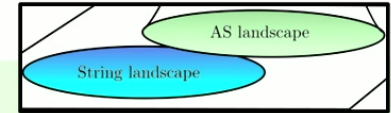
Not all swampland conjectures need to hold in all approaches (more in Astrid's talk).

Their principles are interrelated:



...but assuming standard EFT expansion and principles, topology change is key to satisfy the most solid swampland conjectures!

[Basile, Knorr, AP, Schiffer, '25]



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AS landscape [one-loop quadratic approx]

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**AS landscapes
vs
EFT constraints:
Positivity Bounds**

- **AS model: photon-graviton** systems at quadratic order, only **essential couplings** included

$$\mathcal{L} = -\frac{R}{16\pi G_N} + \Theta_E E + \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + G_2 (F^{\mu\nu} F_{\mu\nu})^2 + G_4 F^\mu{}_\nu F^\nu{}_\rho F^\rho{}_\sigma F^\sigma{}_\mu + G_{CFF} C^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

- **Three dimensionless Wilson coefficients** (redefined for convenience; only one log-presc. ambiguity)

$$w_+ = \frac{1}{2} \frac{G_2 + G_4}{(16\pi G_N)^2}, \quad w_- = \frac{1}{2} \frac{G_2 - G_4}{(16\pi G_N)^2} + b \ln[16\pi G_N k^2], \quad w_C = \frac{G_{CFF}}{16\pi G_N}$$

- **IR: positivity bounds and weak gravity conjecture**

Positivity bounds:

$$w_+ > w_-, \quad 3w_+ - w_- - 2|w_C| > 0$$

[Carrillo González, de Rham, Jaitly, Pozsgay, Tokareva, '23]

Electric WGC in the presence of higher derivatives

$$3w_+ - w_- + 2w_C > 0$$

[Cheung, Liu, Remmen, '18]

- **Ambiguity in removing the logs**
- **Positivity bounds typically identified in theories with massive DOF that are integrated out, not in the presence of massless poles**
- **EXPECTATION: Standard positivity bounds may be violated in the presence of gravity**

$$c > 0 \quad \rightarrow \quad c > -\mathcal{O}(1) M^{-2} M_{Pl}^{-2}$$



[Alberte, de Rham, Jaitly, Tolley, '20+'21)]

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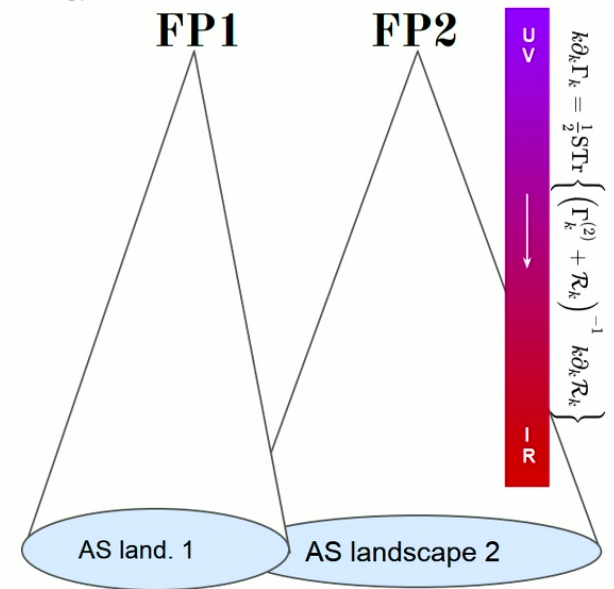
- **Two UV fixed points:**

FP1: one relevant direction (most predictive!)

⇒ once the QG scale is fixed, this is a zero-parameter theory = 1 point in the space of dimensionless Wilson coefficients

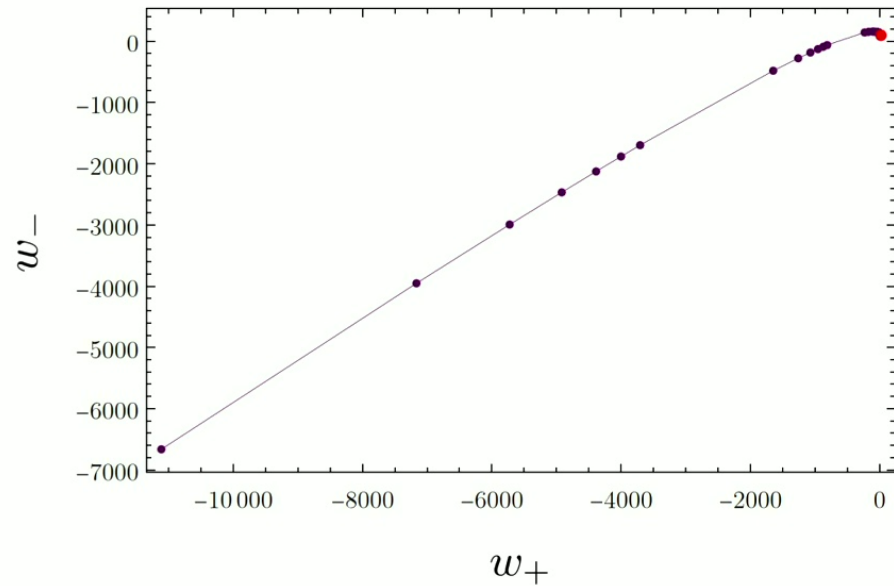
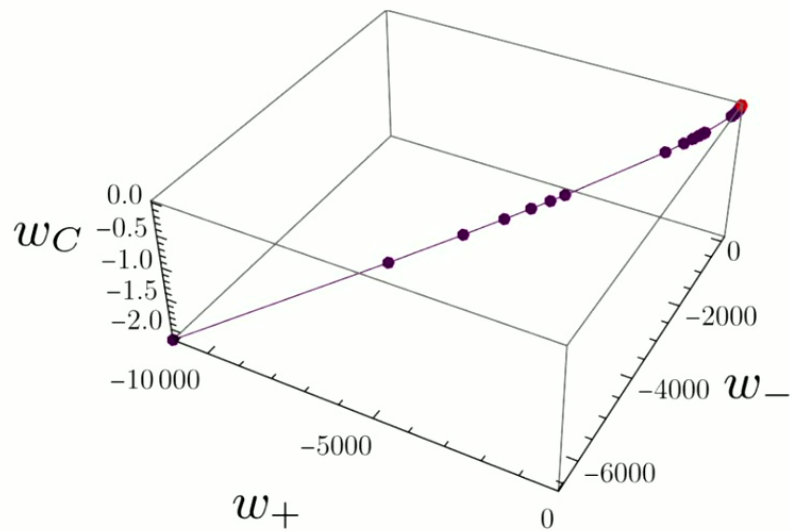
FP2: two relevant directions

⇒ effective action parametrized by 1 dimensionless parameter (line of EFTs)



Asymptotic Safety Landscapes

[Knorr, AP, 2405.08860]

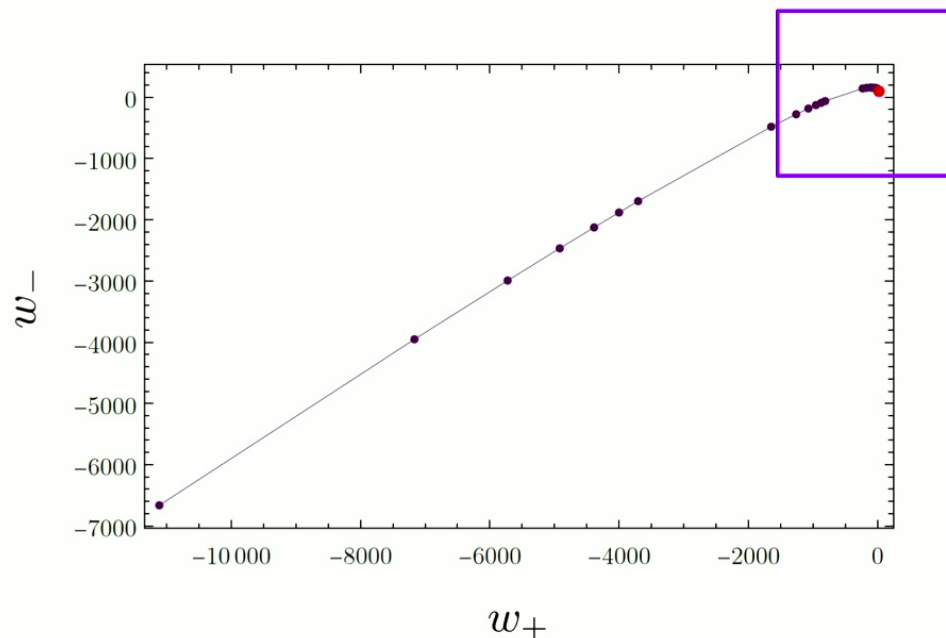
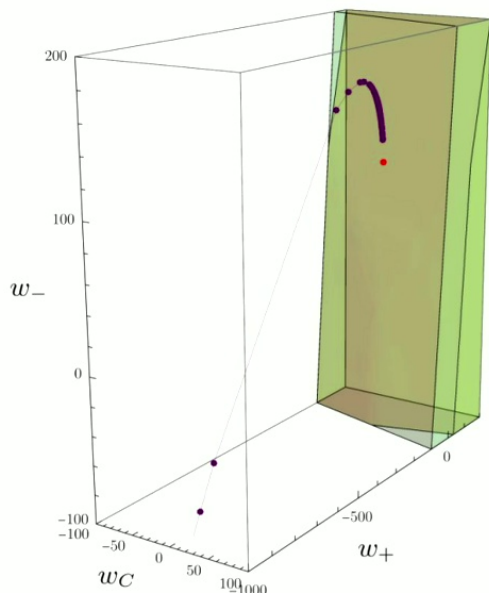


AS landscape from FP1: 1 single point

AS landscape from FP2: almost straight line

Asymptotic Safety Landscapes

[Knorr, AP, 2405.08860]



Planck-scale suppressed violations of WGC and positivity bounds [B. Knorr, AP, '24]

Compatible with expectations/conjectures from EFT in the presence of massless poles:
[Alberte, de Rham, Jaitly, Tolley, '20]

$$c > -\mathcal{O}(1) M^{-2} M_{Pl}^{-2}$$

See also [Eichhorn, Schiffer, '24]

AS landscape from FP1: 1 single point

AS landscape from FP2: almost straight line

+ small "candy cane" regime which connects the two

AS landscapes and Black Hole Mimickers



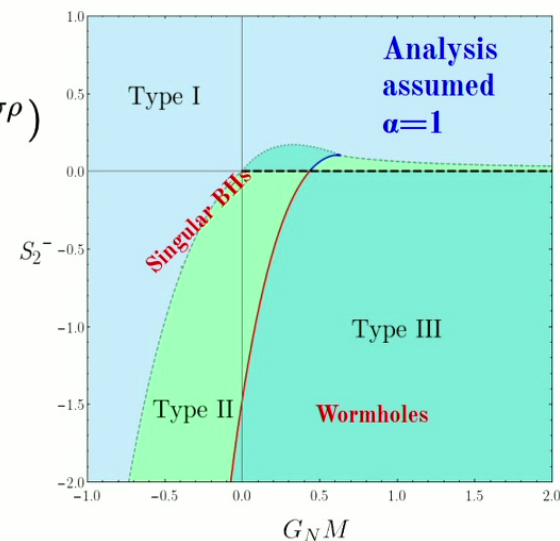
Towards Black Holes from First Principles

- Several phenomenological models, unclear relation to fundamental physics
- Some progress in charting “black hole phase diagrams”: mapping solutions for certain actions as function of Wilson coefficients and integration constants [Bonanno, Silveravalle, Zuccotti...]
- Quantum gravity can predict Wilson coefficients
- **Idea:** connect the to worlds. **Compute Wilson coefficients from given UV completion of QG and associate specific black hole phase diagram**

Simple example: **Asymptotically Safe Einstein-Weyl gravity**

$$L = \frac{1}{16\pi G} (R + C^2 C_{\mu\nu\sigma\rho} C^{\mu\nu\sigma\rho})$$

**Only one dimensionless
Wilson coefficient:
 $\alpha = C^2/G$**

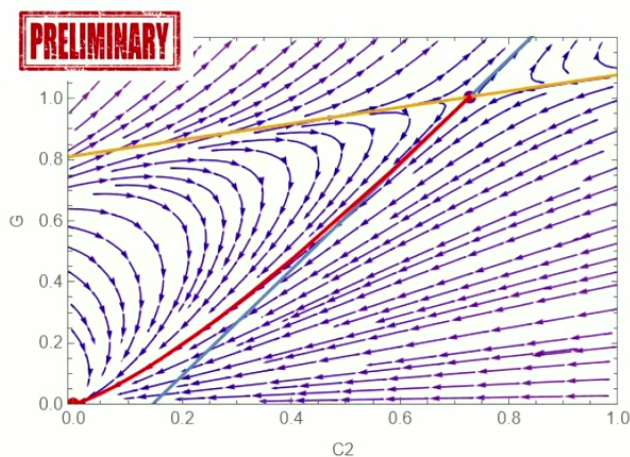


[Silveravalle, Zuccotti, '22]

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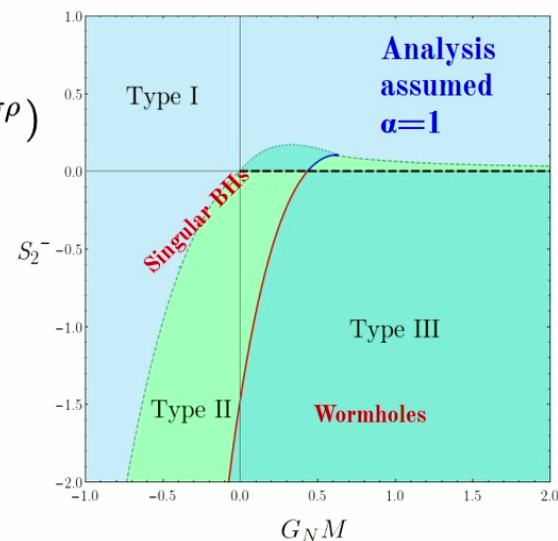
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**UV complete trajectory gives $\alpha = 0.509249$
 \Rightarrow complete BH phase diagram from UV complete model (truncation)!
 [WIP with F. Del Porro, J. Pfeiffer, S. Silveravalle]**



[Silveravalle, Zuccotti, '22]

Summary

- A decoupling phenomenon in Quantum Gravity:
Formal QG communities mostly focus on UV; EFT and pheno community mostly focus on IR;
- One way to go: **Quantum Gravity through the lens of Effective Field Theory**
- *Computing QG landscapes: “killing N birds with one stone”*
Testing swampland conjectures in other approaches to quantum gravity, e.g., asymptotic safety
Testing consistency of QG predictions (from different approaches): positivity bounds
ST vs AS landscape (vs others?): comparing predictions
String Lamppost Principle: do swampland conjectures identify the string landscape or are more general?
- **Very clear recipe in asymptotic safety:**
 - Start from UV fixed point, integrate the FRG flow down to the IR, switch to AS landscape
 - Find intersections: swampland constraints, positivity bounds, other QG landscapes
 - Quantum spacetimes from effective action
- **Exciting research directions opening up:**
String and Asymptotic Safety Landscapes: non-trivial intersection?
Positivity and causality bounds: satisfied by the landscape?
Emerging feature: flatness of the Asymptotic Safety Landscape?
Quantum black holes from first principles?

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