Title: The universal swampland

Speakers: Astrid Eichhorn

Collection/Series: Emmy Noether Workshop: Quantum Space Time

Subject: Quantum Gravity

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Abstract:

The swampland is the space of those effective field theories that cannot be ultraviolet completed in quantum gravity. Understanding the swampland is relevant for phenomenological model-building and for observational tests of quantum gravity.
This talk will have three parts:
First, I will introduce the notion relative swamplands, to distinguish the swamplands of different quantum-gravity approaches. Their intersection forms the absolute swampland.
Second, I will discuss a subset of swampland conjectures in the light of asymptotically safe gravity.
Third, I will explain how asymptotic safety can provide a mechanism to generate universality, when it is realized within an intermediate regime between a non-quantum-field-theoretic quantum regime of gravity and the standard effective field theory regime below the Planck scale.

The universal swampland

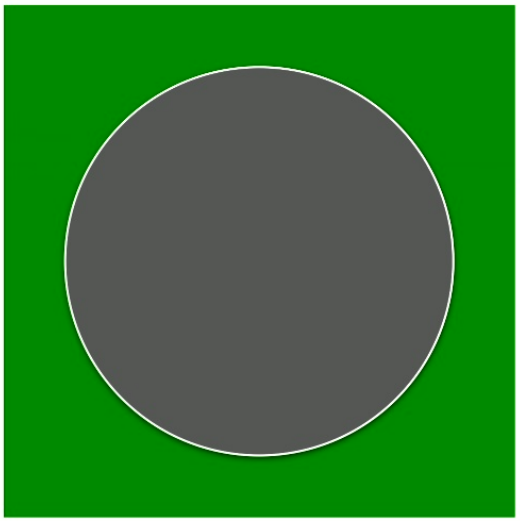
Emmy Noether Workshop on Quantum Space Time

Perimeter Institute, March 13, 2025

Astrid Eichhorn, Heidelberg University

The swampland

Space of all
effective field theories of gravity and matter
(e.g., GR+Standard Model,
Beyond Standard Model,
dark-energy models…)



Landscape
effective field theories that are
ultraviolet completed by quantum gravity

Swampland
field theories that are **not**
ultraviolet completed by quantum gravity

Why is this relevant?

- phenomenological model building (e.g., dark matter, neutrino masses, modified gravity…):
  UV completion with quantum gravity as a selection principle

- observational tests of quantum gravity: swampland properties testable at $\ell \gg \ell_{\rm Planck}$ ($E \ll M_{\rm Planck}$)

The swampland

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effective field theories of gravity and matter
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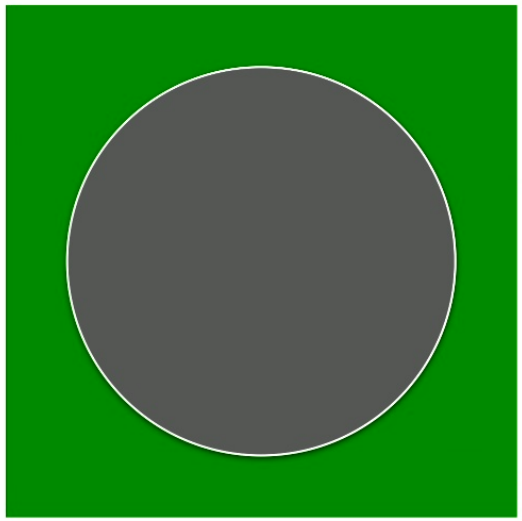

Landscape
effective field theories that are
ultraviolet completed by quantum gravity

Swampland
field theories that are **not**
ultraviolet completed by quantum gravity

may depend on quantum theory of gravity
(assume several internally consistent, distinct theories)

Why is this relevant?

- phenomenological model building (e.g., dark matter, neutrino masses, modified gravity…):
  UV completion with quantum gravity as a selection principle

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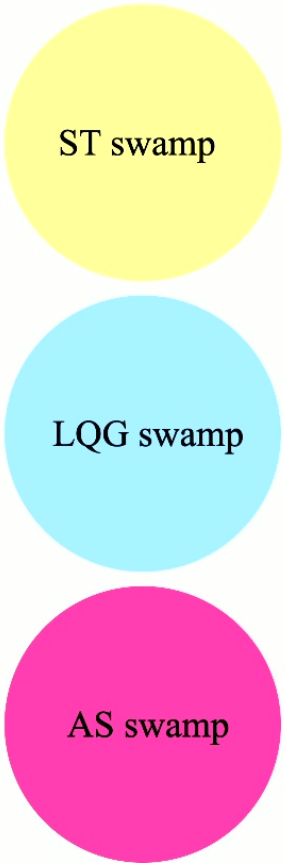
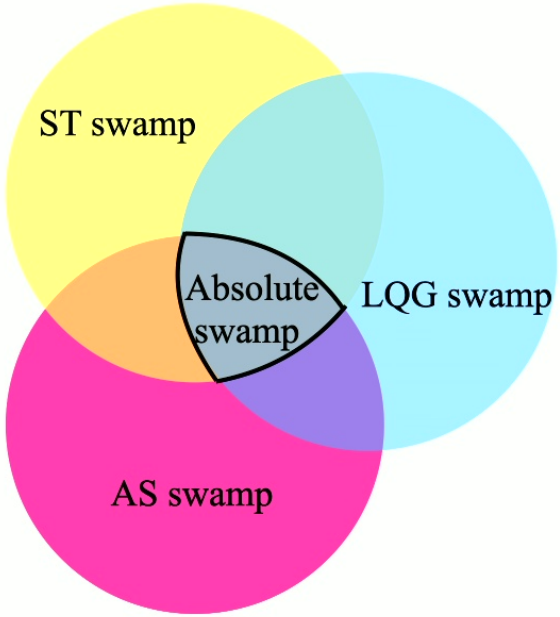
Refined picture: relative, absolute and universal swamp

Relative swamp of given QG theory:
Swamp specific to that theory

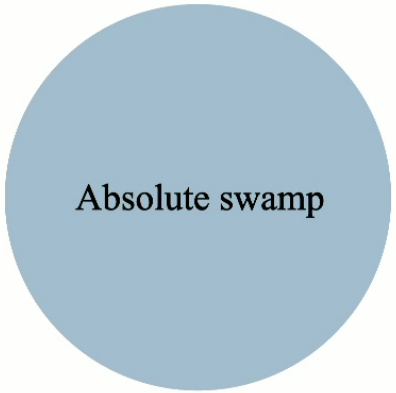


Absolute swamp:
intersection of all swamps



Is there an absolute swamp?

Universal swamp:
intersection of all swamps
= union of all swamps



Is the swamp universal?

[AE, Hebecker, Pawlowski, Walcher '24]

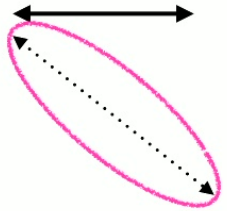
What is known about the swamp?

Absolute swamp
(conjectural)

Relative swamps

String-inspired swampland conjectures
[Vafa '05; Ooguri, Vafa '07…]

reviews: Brennan, Carta, Vafa '17;
Palti '19;
Van Beest, Calderon-Infante, Mirfendereski,
Valenzuela '22;
Graña, Herraez '21;
Agmon, Bedroya, Kang, Vafa '22



Concrete effective field theories in specific string-theory settings

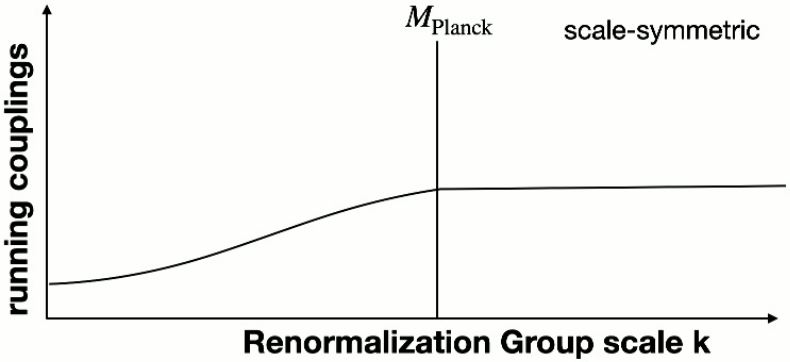
Concrete effective field theories in asymptotic safety

Few hints about properties of matter in LQG, causal sets, EDTs…

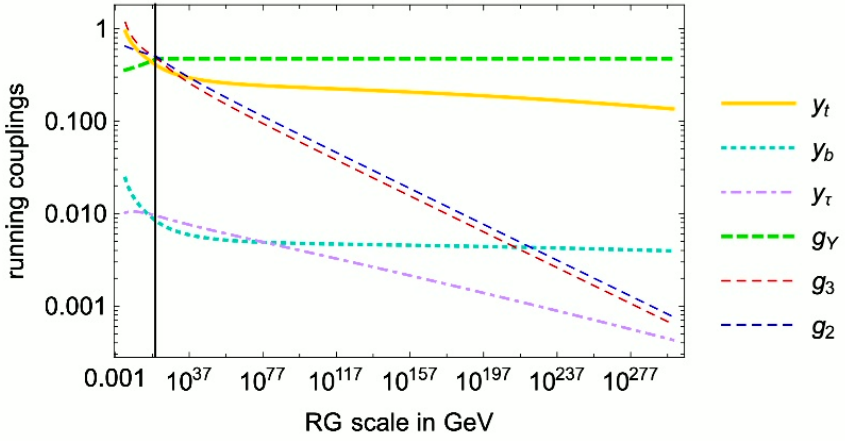
Lightning review of asymptotic safety & its predictive power

Asymptotic safety in gravity-matter systems

- Scale symmetry at (trans-) Planckian scales
- Compelling evidence with Standard Model-like matter sectors
  [review of current status: AE, Schiffer '22]
- Open questions: Lorentzian signature, unitarity under investigation
  [e.g., Fehre, Litim, Pawlowski, Reichert '21; Platania '22; Saueressig, Wang '23]



Predictions for effective field theories at the Planck scale: Example: Standard Model



top Yukawa coupling bound from above [AE, Held '17]

bottom Yukawa coupling bound from above [AE, Held '18]

hypercharge coupling bound from above [AE, Versteegen '17]

Higgs quartic coupling predicted ($M_{\text{Higgs}} \approx 12\text{X GeV}$)
[Shaposhnikov, Wetterich '09]

Neutrino Yukawa couplings driven towards small values
[Held PhD thesis '19; Kowalska et al '22; AE, Held '22]

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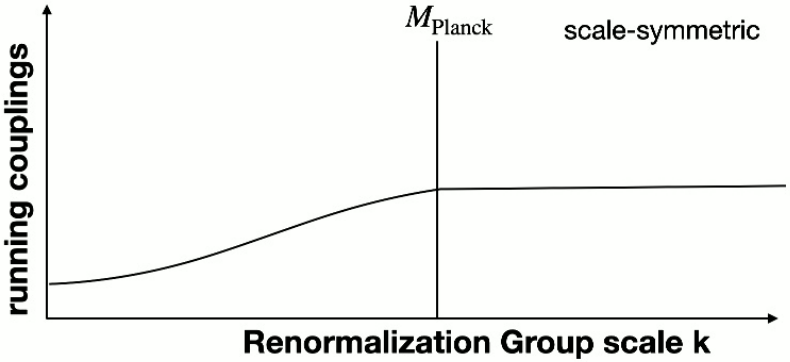


Origin of predictions at the Planck scale

Quantum fluctuations
screen or antiscreen interactions, e.g.,

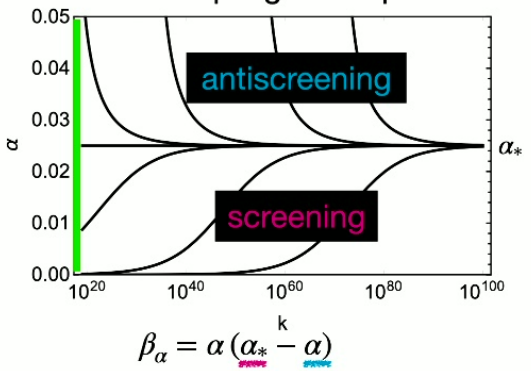
QED: $\beta_e = k\,\partial_k\, e(k) = \frac{1}{12\pi^2} e^3 + \ldots$

→ $e(k)$ decreases as k is lowered

QCD: $\beta_g = k\,\partial_k\, g(k) = -\frac{7}{16\pi^2} g^3 + \ldots$

→ $g(k)$ increases as k is lowered

relevant coupling = free parameter

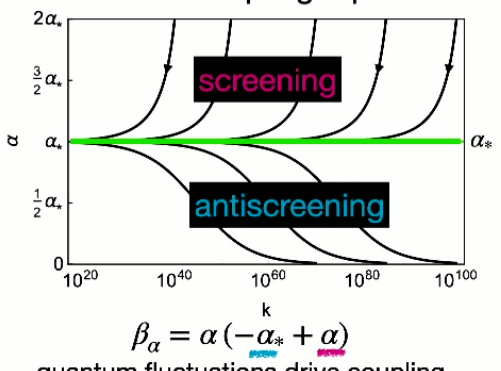


$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

quantum fluctuations drive coupling **away from** scale symmetry

→ a range of coupling values achievable at the Planck scale

irrelevant coupling = prediction



$\beta_\alpha = \alpha\,(-\alpha_* + \alpha)$

quantum fluctuations drive coupling **towards** scale symmetry

→ a unique coupling value achievable at the Planck scale

Lightning review of asymptotic safety & its predictive power

How non-perturbative is the fixed point?

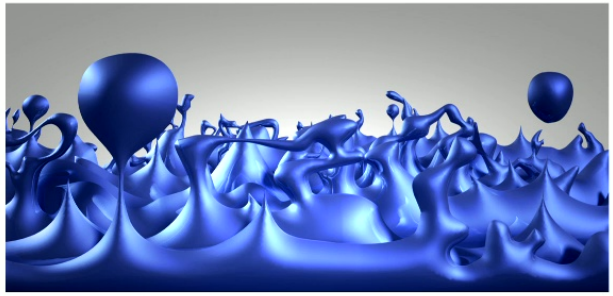


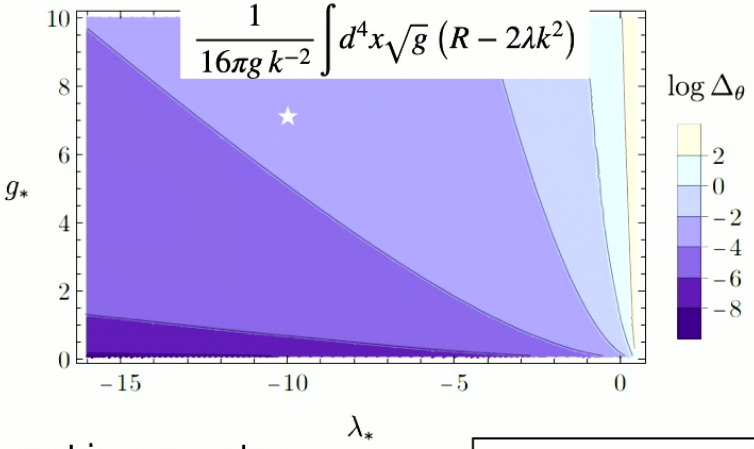
Image Credit: NASA/CXC/M.Weiss

or

?

Key property: near-perturbative

- free parameters ≃ dimension-4-interactions
- similar set as free parameters at perturbative (Gaussian) fixed point

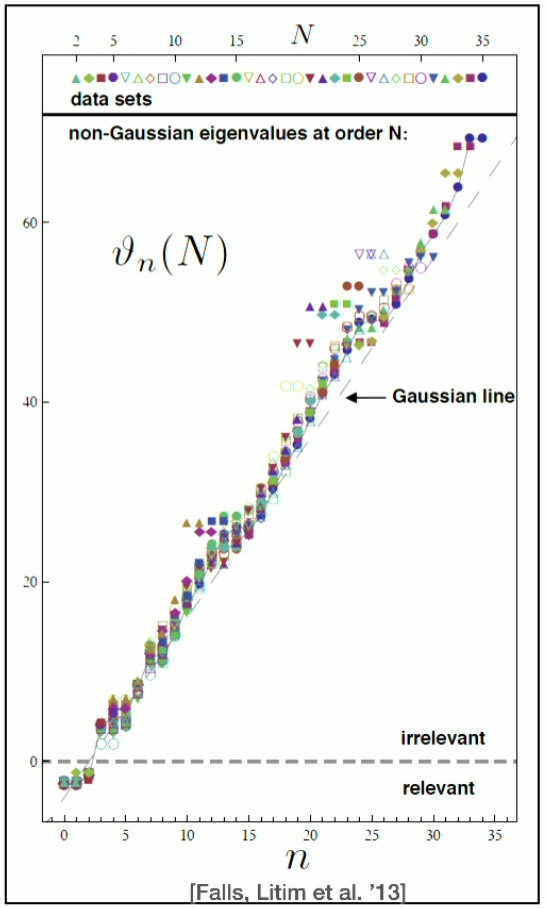


metric propagator:

$$\frac{g_*}{1 - 2\lambda_* + \ldots}$$

$$\Delta_\theta = \sqrt{\frac{\sum_i \left(\mathrm{Re}(\theta^{(i)}) - \theta_{\mathrm{Gauss}}\right)^2}{\sum_i}}$$

[AE, Pauly '18]



[Falls, Litim et al. '13]

String-inspired swampland conjectures in the light of asymptotic safety

no global symmetries

weak gravity

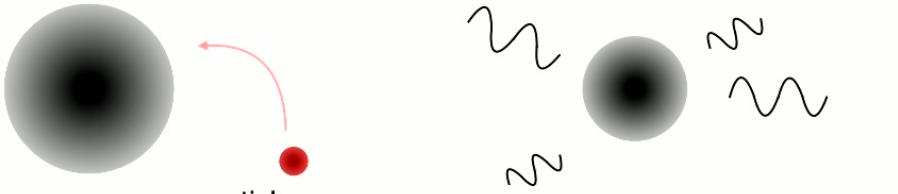
de Sitter

Global symmetries

No-global symmetries conjecture:

[Banks, Dixon '88; Giddings, Strominger '88; Abbott, Wise '89; Kallosh, Linde, Linde, Susskind '95….]

1) Black-hole spacetimes violate conservation of global charges



black hole

particle w. global charge

black hole undergoes complete Hawking evaporation (no remnants)

with Hawking entropy

2) Gravity-matter path integral contains black-hole configurations

⇒ effective theory for matter has no conserved global charges

But: explicit calculations in asymptotic safety:

No interactions are generated by gravity which violate global symmetries of matter fields

[AE '12; AE, Held '17; de Brito, AE, Lino dos Santos '20, Laporte, Pereira, Saueressig, Wang '21,… (full list in review AE, Schiffer '22]

What gives?

Possibility 1: black-hole configurations not adequately accounted for in functional RG (due to Euclidean signature?)

(can numerical approaches to the PI help?)

Possibility 2: black holes in asymptotic safety work differently

Asymptotic safety or standard black-hole thermodynamics?

[Basile, Knorr, Platania, Schiffer '25]

Possibility 2a: remnants
asymptotic-safety inspired black holes have vanishing temperature at Planckian mass [Bonanno, Reuter '06]

Global symmetries

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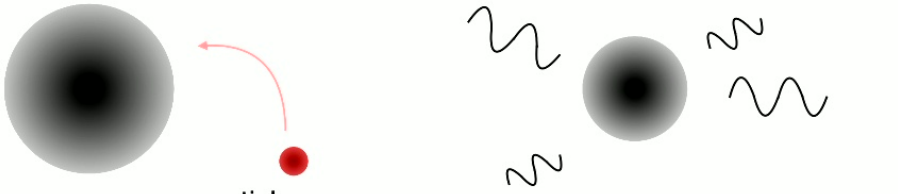

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[Basile, Knorr, Platania, Schiffer '25]

Possibility 2b: black holes dynamically suppressed in path integral

$\int \mathscr{D} g_{\mu\nu} e^{iS}$: destructive interference for configurations with $S \to \infty$

Weyl tensor

$$S = \ldots + \int d^4x \sqrt{g} C^2 \to \infty \text{ for singular black holes}$$

[Borissova, AE '20; Borisssova '23]

$$S = \ldots + \int d^4x \sqrt{-g} \frac{(C^2)^8}{4C^2(\nabla_\mu C)^2 - (\nabla_\mu C^2)^2} \to \infty \text{ at the horizon}$$

Borissova, AE, Ray '24

Global symmetries

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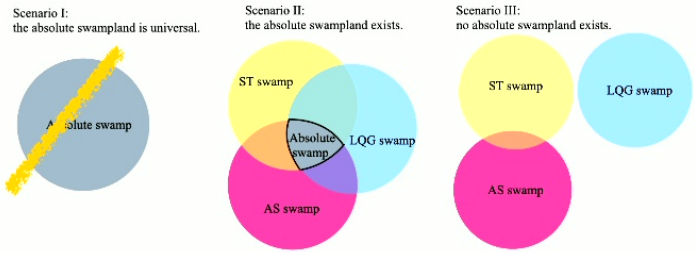


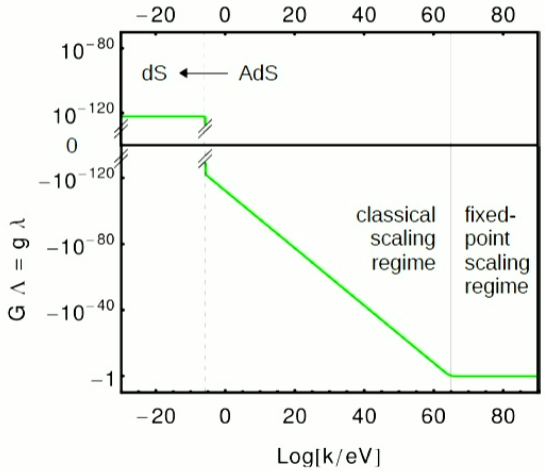
[AE, Hebecker, Pawlowski, Walcher '24]

de Sitter conjecture

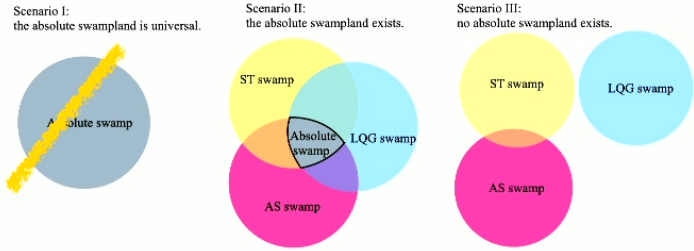
De Sitter spacetime is not compatible with quantum gravity and any scalar potential V must not be too flat: $|\nabla V| \geq \frac{c}{M_{\text{Planck}}} V$

[Ooguri, Palti, Shiu, Vafa '18]

Asymptotic safety: fixed point connected to positive cosmological constant at large scales

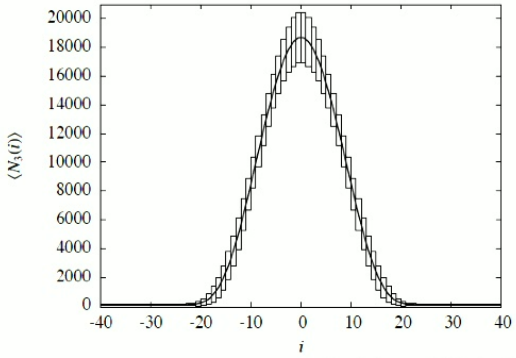


[de Alwis, AE, Held, Pawlowski, Schiffer, Versteegen '19]



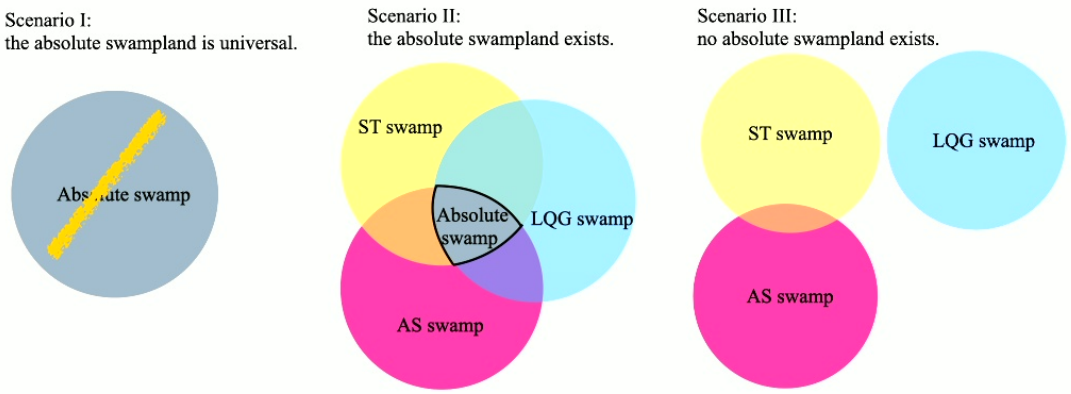
[AE, Hebecker, Pawlowski, Walcher '24]

Causal Dynamical Triangulations:



[Ambjørn, Görlich, Jurkiewicz, Loll '08]

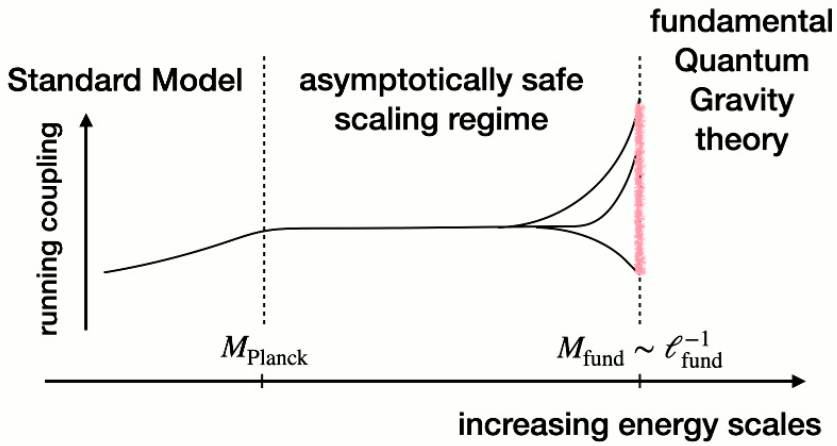
So is there no absolute swamp that is shared between distinct approaches?



[AE, Hebecker, Pawlowski, Walcher '24]

Asymptotic safety generates a universal corner of the swampland

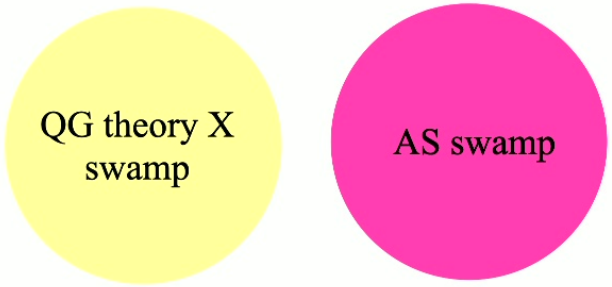
Main idea: Asymptotic safety in an intermediate regime
(*effective asymptotic safety*)



[de Alwis, AE, Held, Pawlowski, Schiffer, Versteegen '19]

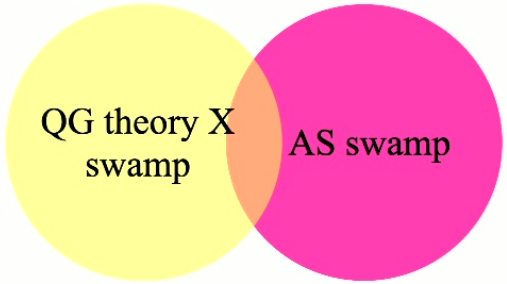
Swamplands without effective asymptotic safety

$M_{\text{Planck}} \approx \ell_{\text{fund}}^{-1}$



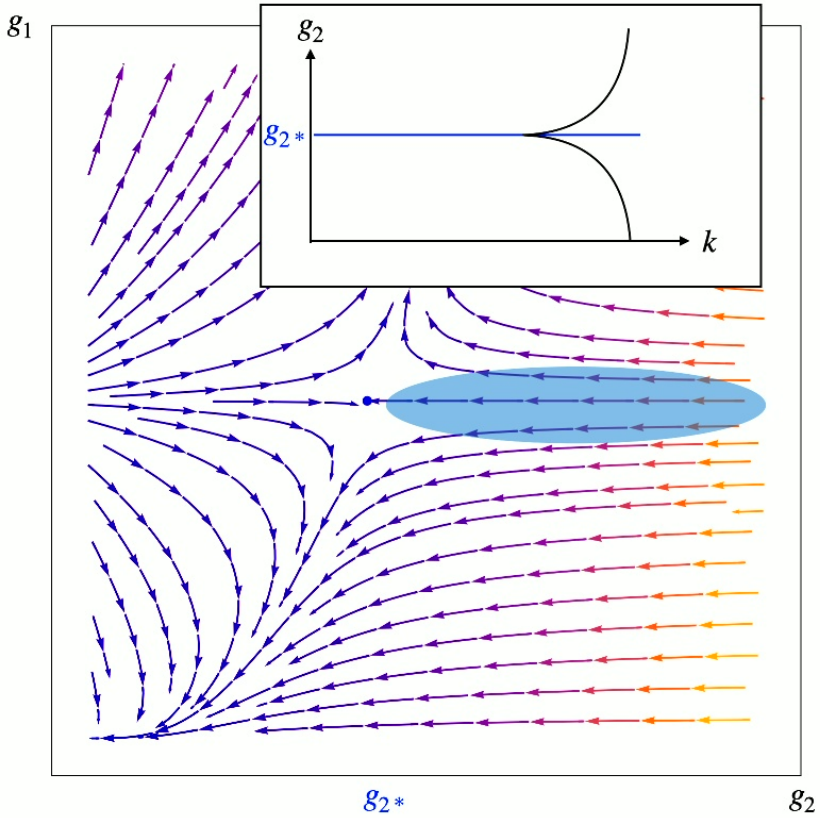
Swamplands with effective asymptotic safety

$M_{\text{Planck}} \ll \ell_{\text{fund}}^{-1}$



$\ell_{\text{fund}}^{-1} = 10^x M_{\text{Planck}},\ x > 0$

Universality from effective asymptotic safety: mechanism



Renormalization Group flow:
arrows point towards decreasing energy scales

Universality:

Different initial conditions for infrared attractive couplings are mapped to ~ fixed-point value

$$g_2(k) = g_{2,*} + c\,\left(k \cdot \ell_{\text{fund}}\right)^{-\theta}$$

critical exponent
$\theta < 0$ for infrared attractive couplings

free parameter
(initial condition at $g_2(\ell_{\text{fund}}^{-1})$)

To delineate universal part of the swamp:

→ which interactions correspond to infrared attractive couplings?

→ what are their fixed-point values?

Universality from effective asymptotic safety: mechanism in more detail

$$g_2(k) = g_{2,*} + c\,\left(k \cdot \ell_{\text{fund}}\right)^{-\theta}$$

free parameter
(initial condition at $g_2(\ell_{\text{fund}}^{-1})$)

To delineate universal part of the swamp:

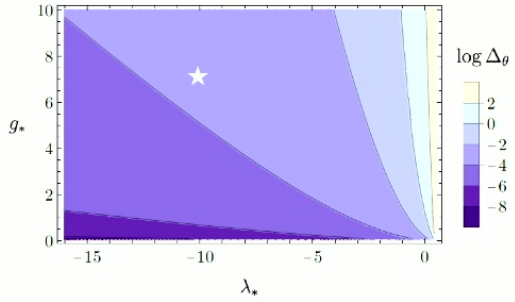
→ which interactions correspond to infrared attractive couplings?

→ what are their fixed-point values?

(Tentative) fixed-point properties:

→ near-perturbative: dimension $\gtrsim 5$ interactions,

because $\theta \approx \theta_{\text{Gauss}} + \delta\theta$



$$\Delta_\theta = \sqrt{\frac{\sum_i \left(\text{Re}(\theta^{(i)}) - \theta_{\text{Gauss}}\right)^2}{\sum_i}}$$

Universality from effective asymptotic safety: Examples

$$g_2(k) = \cancel{g_{2,*}} + c\,\left(k \cdot \ell_{\rm fund}\right)^{-\theta}$$

vanishes if interaction protected by global symmetry

free parameter (initial condition at $g_2(\ell_{\rm fund}^{-1})$)

critical exponent $\theta < 0$: for couplings belonging to dimension-$\gtrsim$ 5- interactions

Examples:

- **Proton decay**

  quark-lepton interactions

An intermediate, approximately asymptotically safe regime*

- **extends the lifetime of the proton**
- **decouples dark scalars from the Higgs field**
- **decouples axion-like-particles from the photon**
- **...**

*** within the systematic uncertainties of our calculations**

with $\theta_{qqql} = -2 - \frac{29}{15\pi} G_* + \ldots$

[AE, Ray '23]

- **Higgs portal to dark scala**

  $\lambda_H H^\dagger H \phi^2$ **with Higgs fiel**

$$-\frac{55}{18\pi} G_*$$

[AE, Hamada, Lumma, Yamada '18]

s

- **Axion-like-particle coupling to photon**

  $g_a\, a \cdot F_{\mu\nu}\tilde{F}^{\mu\nu}$ **with axion-like particle** a **and electromagnetic field strength** $F_{\mu\nu}$: $g_a = \cancel{g_{a*}} + c\,\left(k \cdot \ell_{\rm fund}\right)^{-\theta_{g_a}}$ **with** $\theta_{g_a} = -2 + \frac{G}{\pi}$

  protected by shift symmetry $a \to a + s$

de Brito, AE, Lino dos Santos '21]

Summary

- Goal: understand the swampland as part of an effort to develop phenomenology of quantum gravity
- Question: is there an absolute swampland (shared between QG approaches) or is the swampland even universal (i.e., no relative swampland outside the absolute swampland)?
- Status: string-inspired swampland may (in part) differ from relative swampland of asymptotic safety (no-global symmetries conjecture, weak-gravity conjecture, de Sitter conjecture)
- universality in the swampland may be generated by asymptotic safety as intermediate regime (proton lifetime extended, Higgs portal coupling switched off, axion-like-particle- photon coupling driven to zero)
- …more to come