The universal swampland

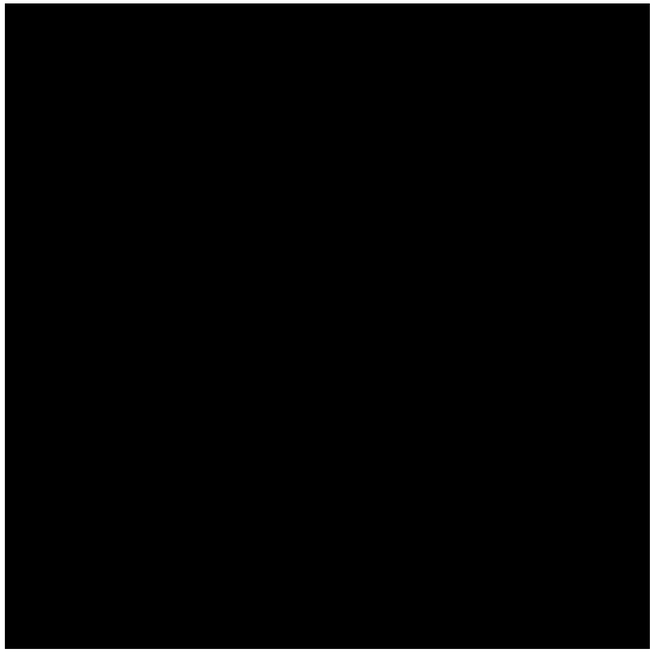
Workshop on quantum gravity across all scales

Erlangen, May 20, 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…)



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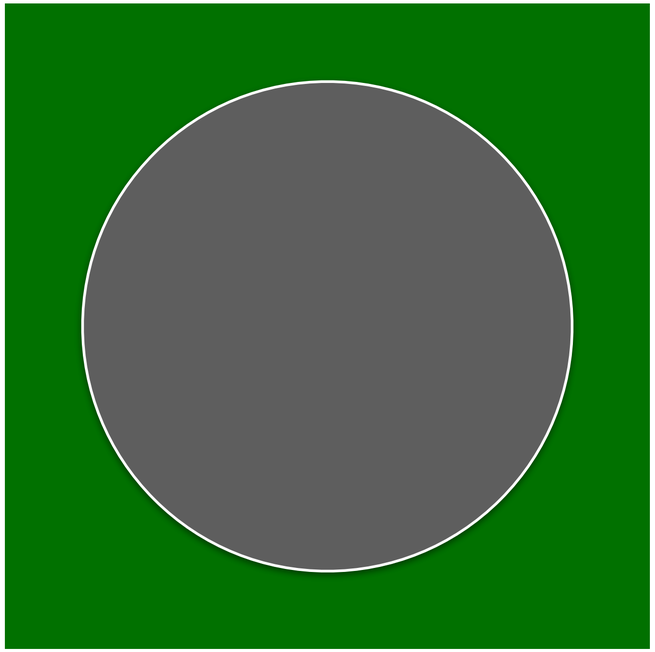

Landscape
effective field theories that are
ultraviolet completed by quantum gravity

Swampland
field theories that are **not**
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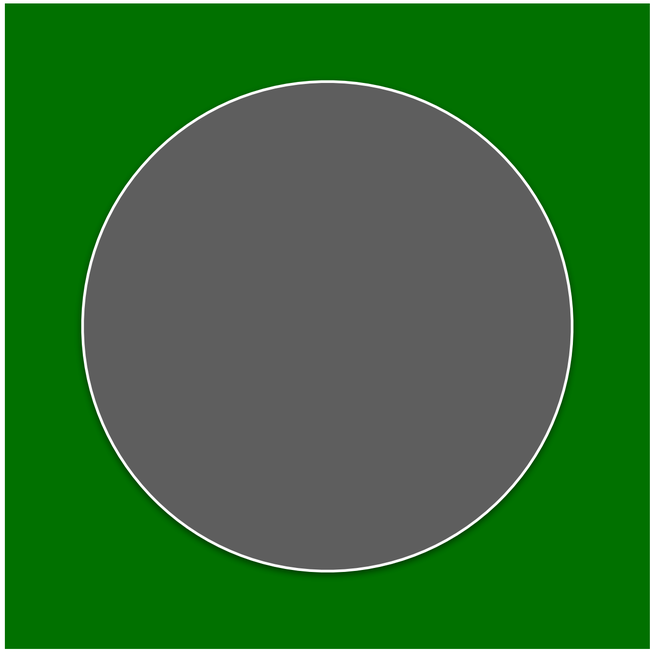

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Why is this relevant?

- 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 $\ell \gg \ell_{\rm Planck}$ ($E \ll M_{\rm Planck}$)

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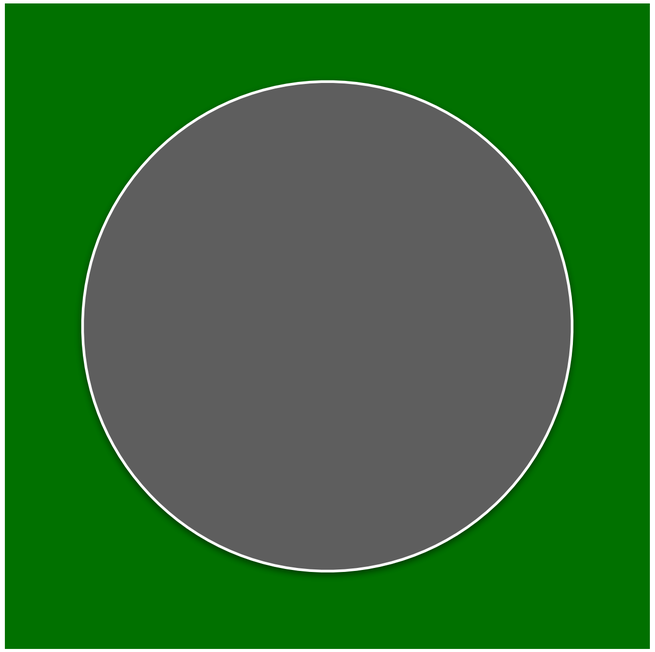

Landscape
effective field theories that are
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Swampland
field theories that are **not**
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may depend on quantum theory of gravity
(assume several internally consistent, distinct theories)

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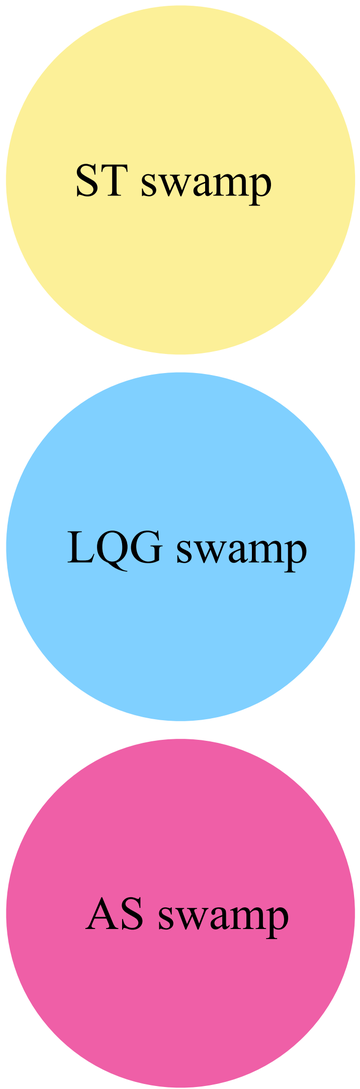
Refined picture: relative, absolute and universal swamp

[AE, Hebecker, Pawlowski, Walcher ’24]

Refined picture: relative, absolute and universal swamp

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



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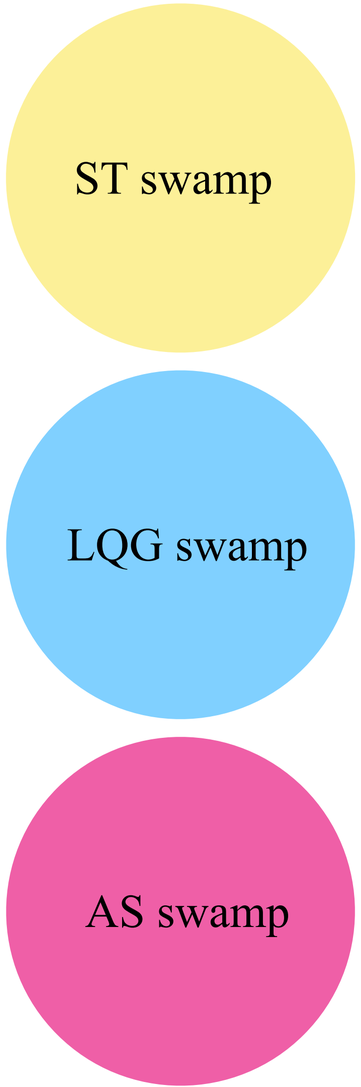
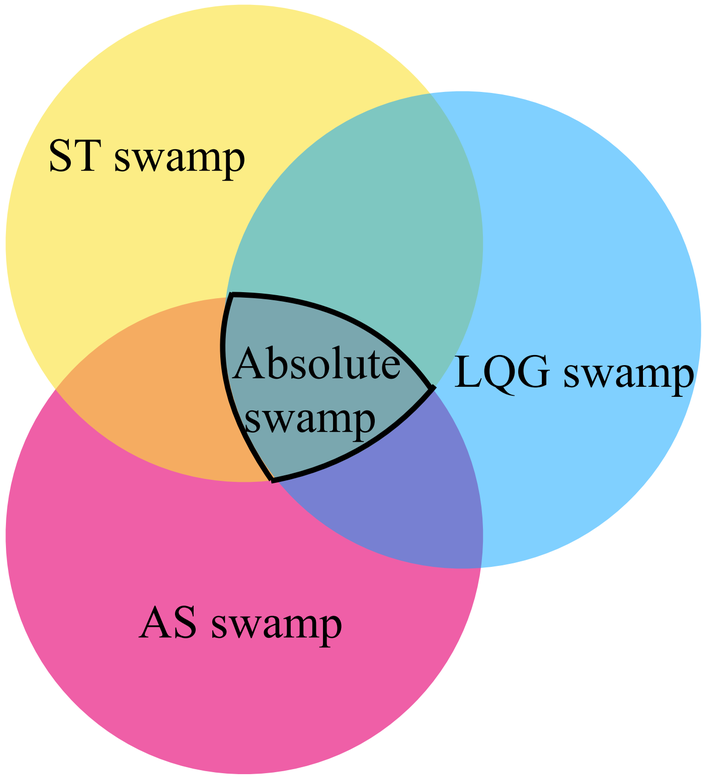


Absolute swamp:
intersection of all swamps



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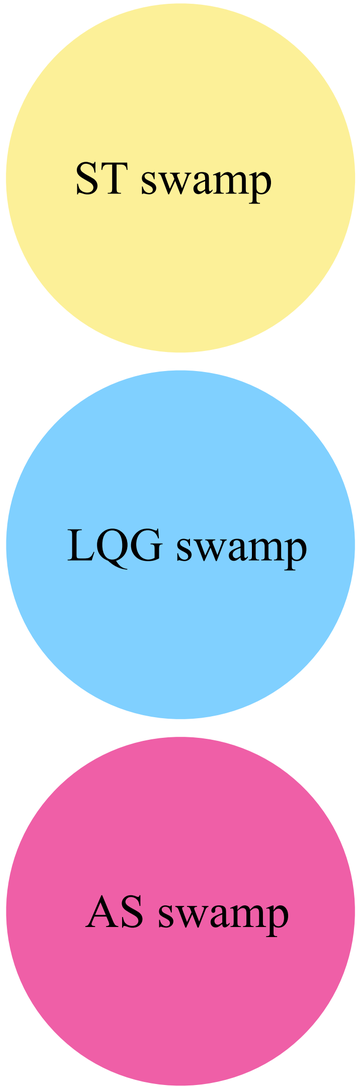

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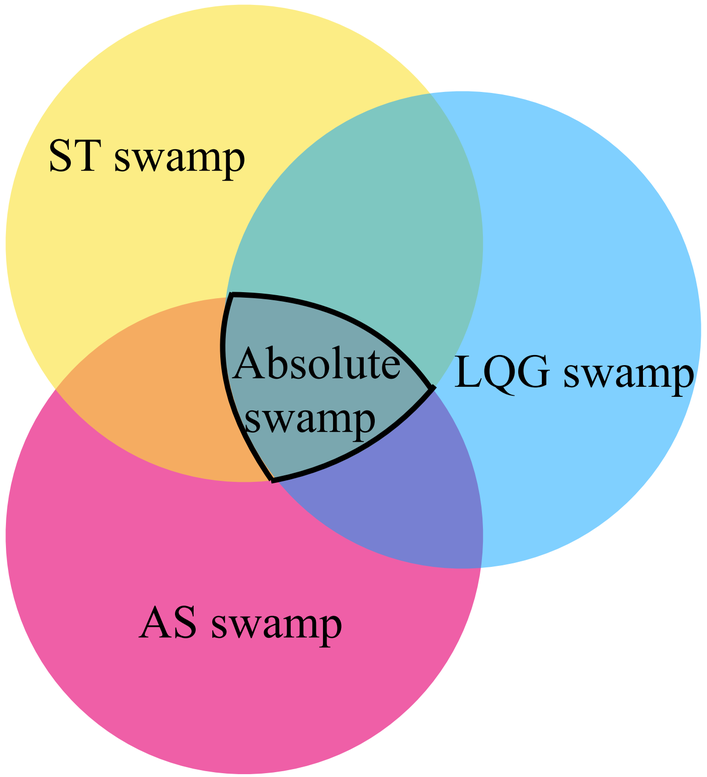

Is there an absolute swamp?

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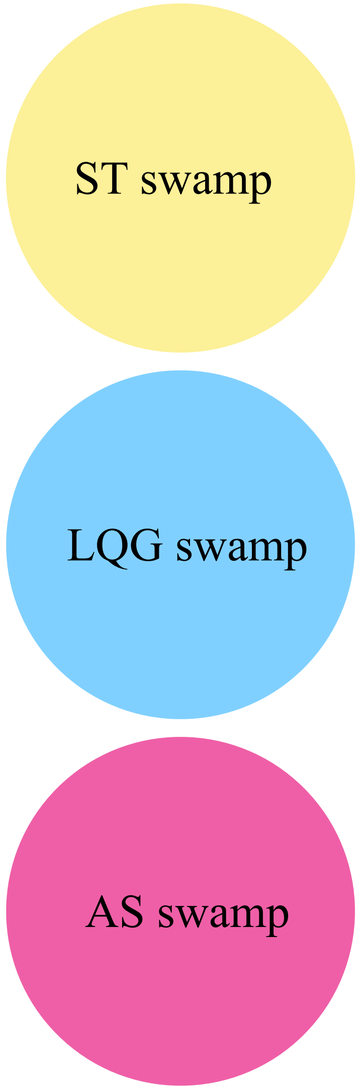

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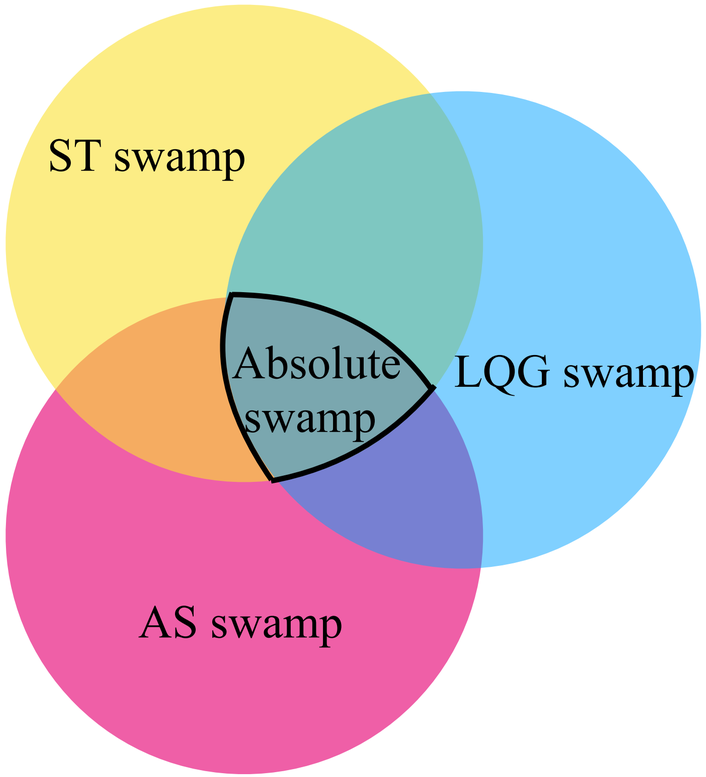

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Universal swamp:
intersection of all swamps
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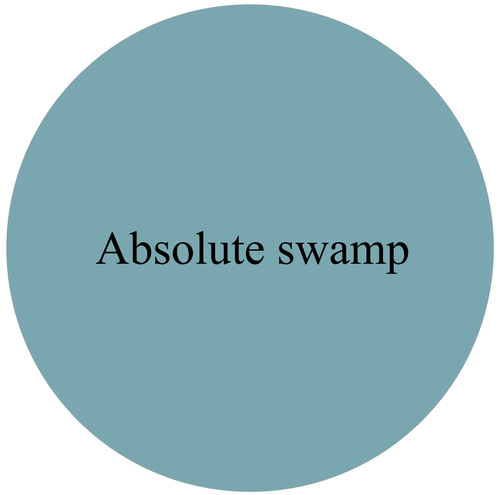

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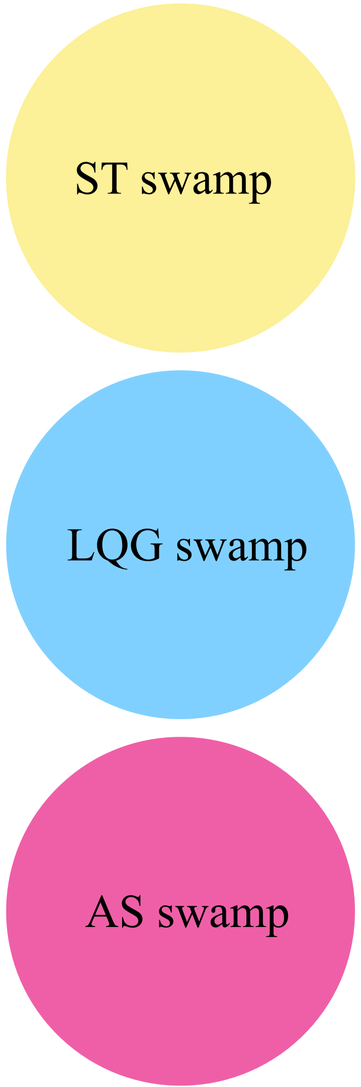

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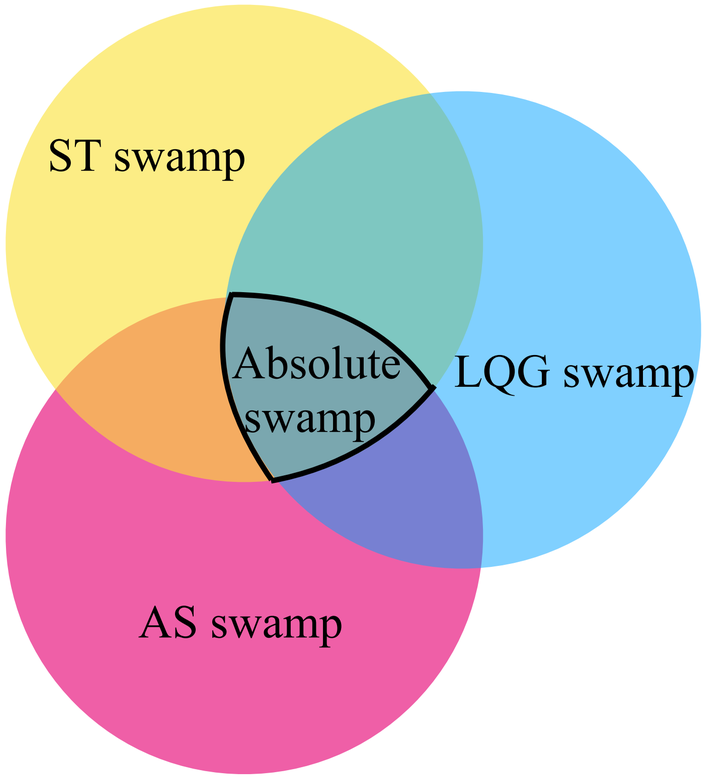

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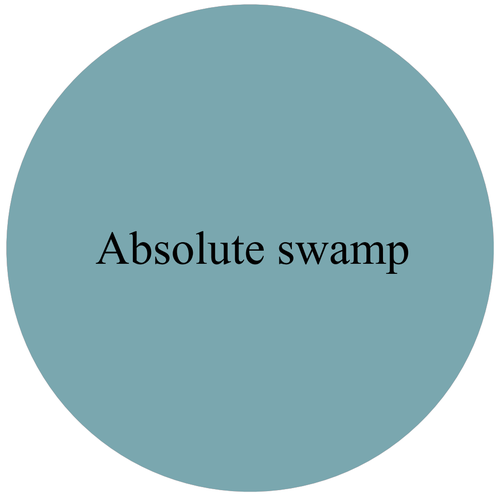

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What is known about the swamp?

Absolute swamp
(conjectural)

Relative swamps

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

reviews: Brennan, Carta, Vafa ’17;
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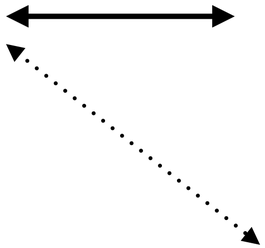

Concrete effective field theories in specific string-theory settings

Concrete effective field theories in asymptotic safety

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

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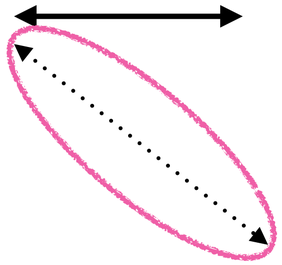

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String-inspired swampland conjectures in the light of asymptotic safety

Lightning review of asymptotic safety & its predictive power

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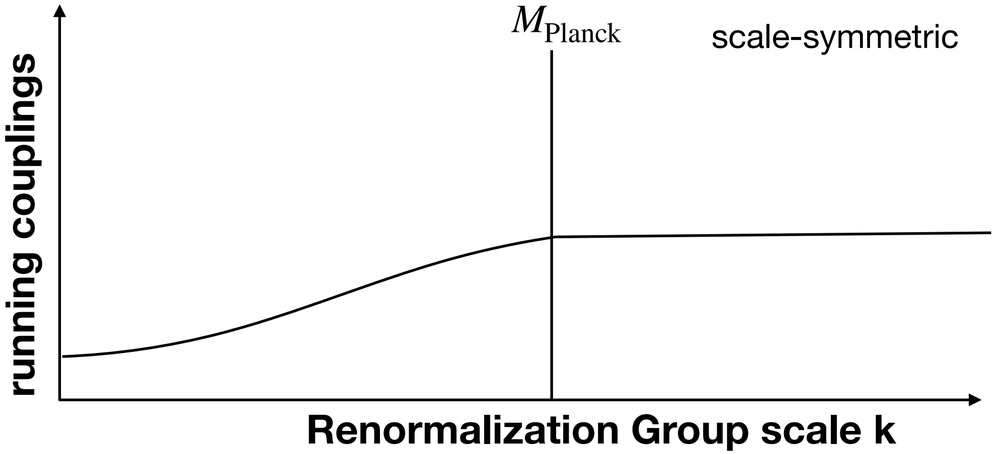
Asymptotic safety in gravity-matter systems

- 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]



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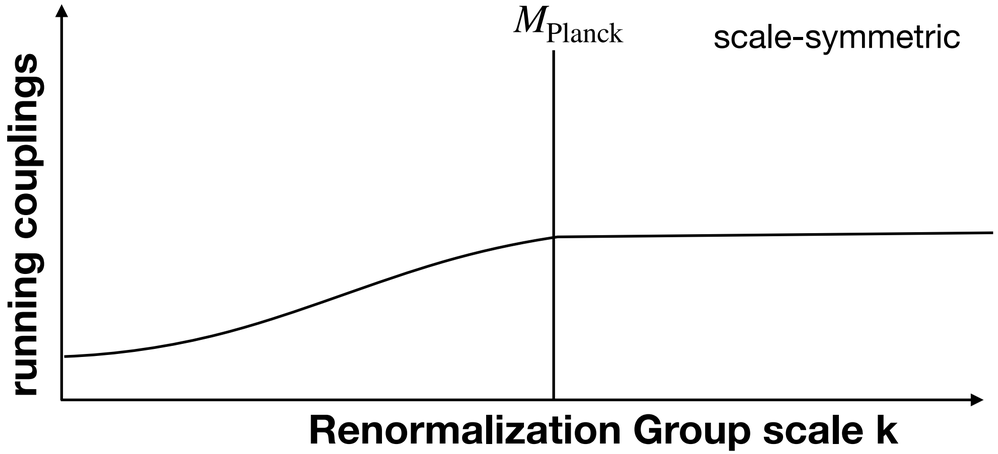
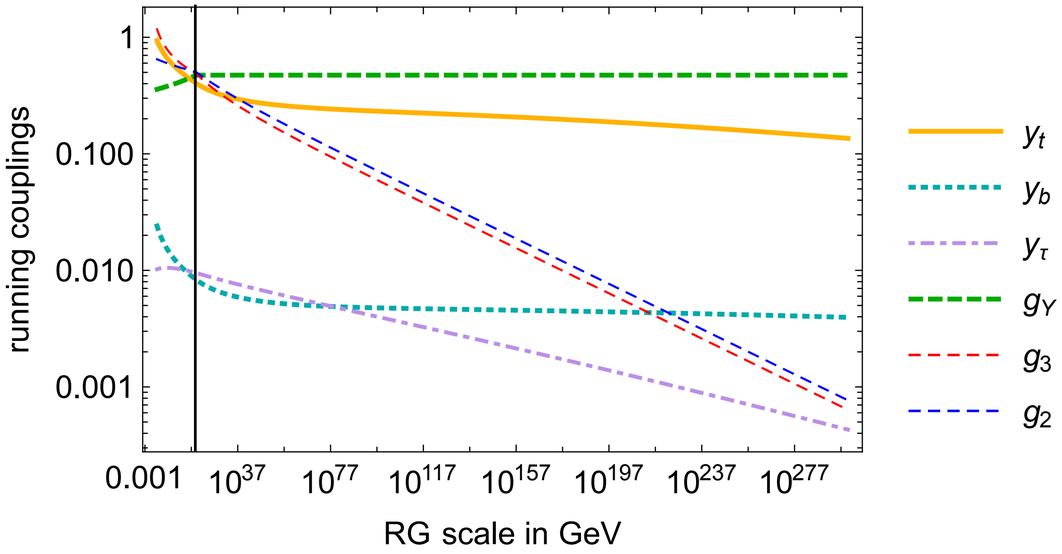


Predictions for effective field theories at the Planck scale: Example: Standard Model



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]

in $d \approx 4$ dimensions [AE, Schiffer ’19]

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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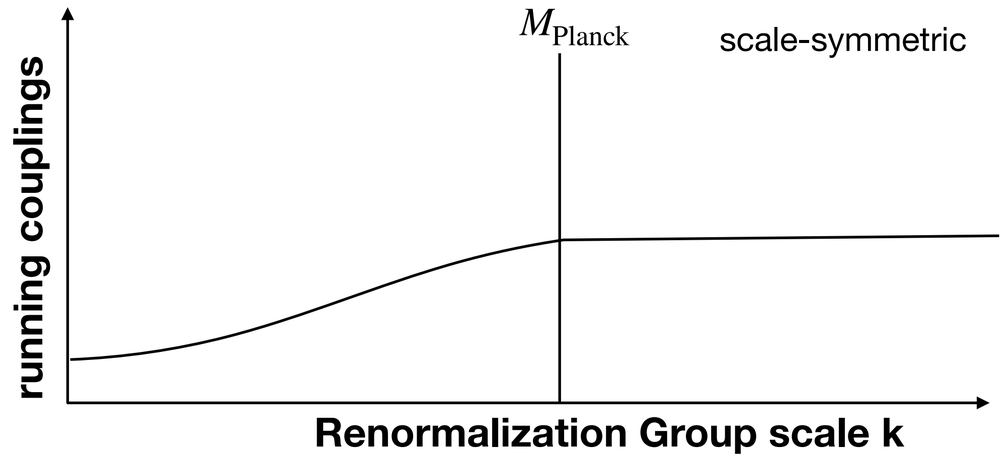

Origin of predictions at the Planck scale

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

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

→ $e(k)$ decreases as k is lowered

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

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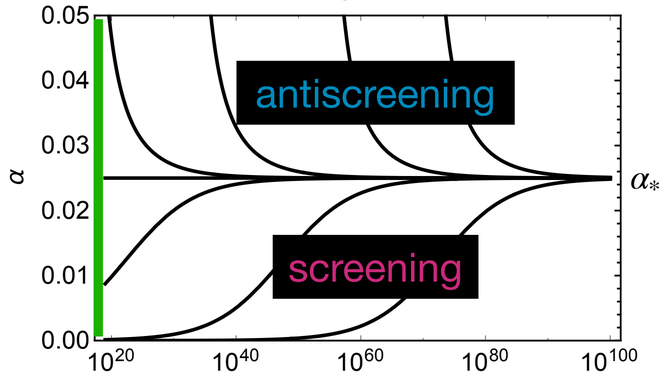
relevant coupling = free parameter



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

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

→ a range of coupling values achievable at the Planck scale

Lightning review of asymptotic safety & its predictive power

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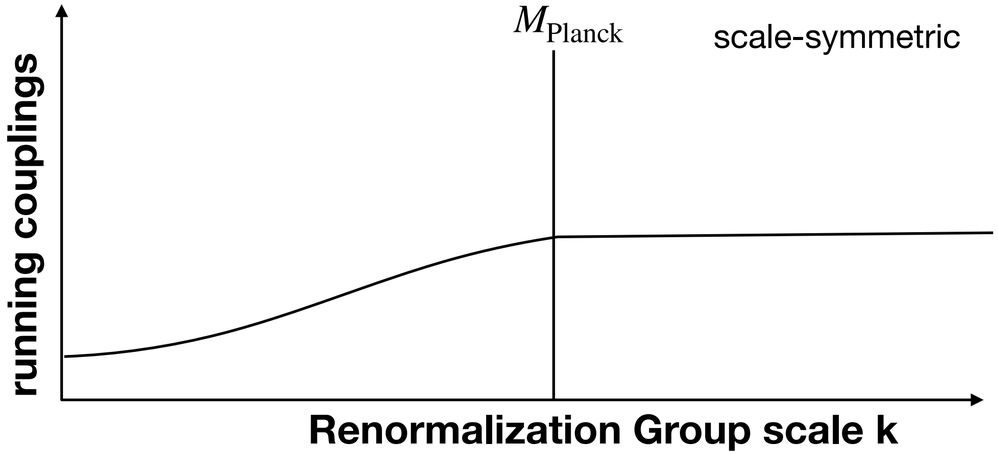

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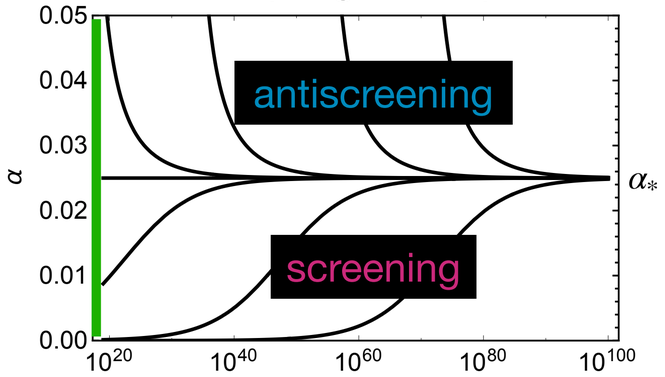

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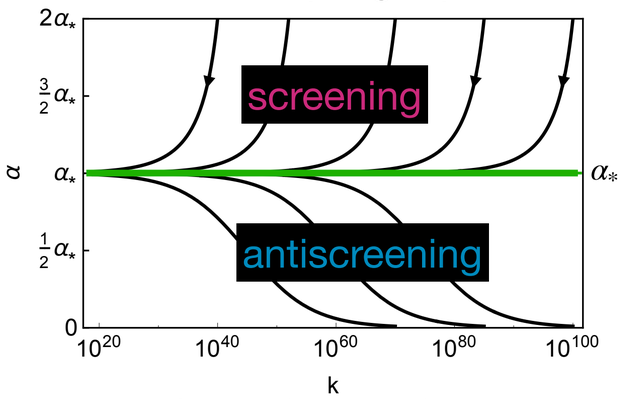
irrelevant coupling = prediction



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

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?

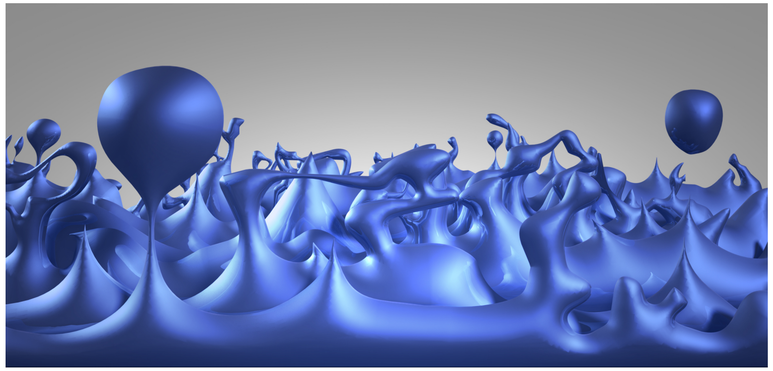
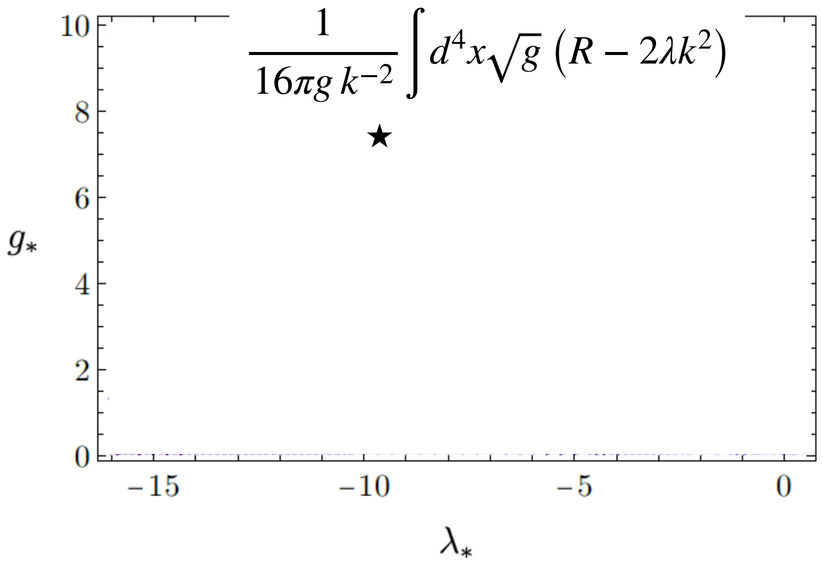


Image Credit: NASA/CXC/M.Weiss

or

?



Lightning review of asymptotic safety & its predictive power

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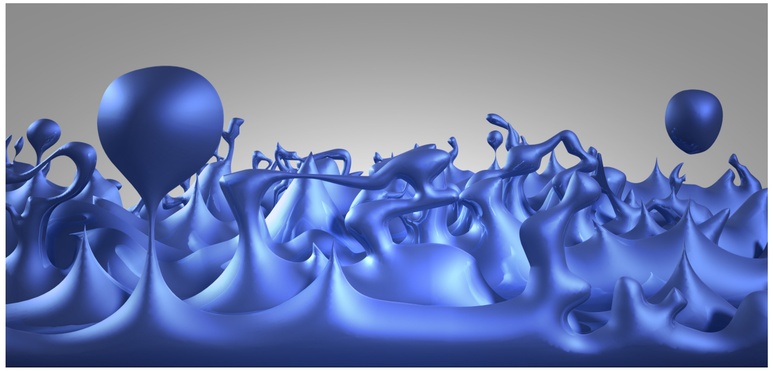

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or

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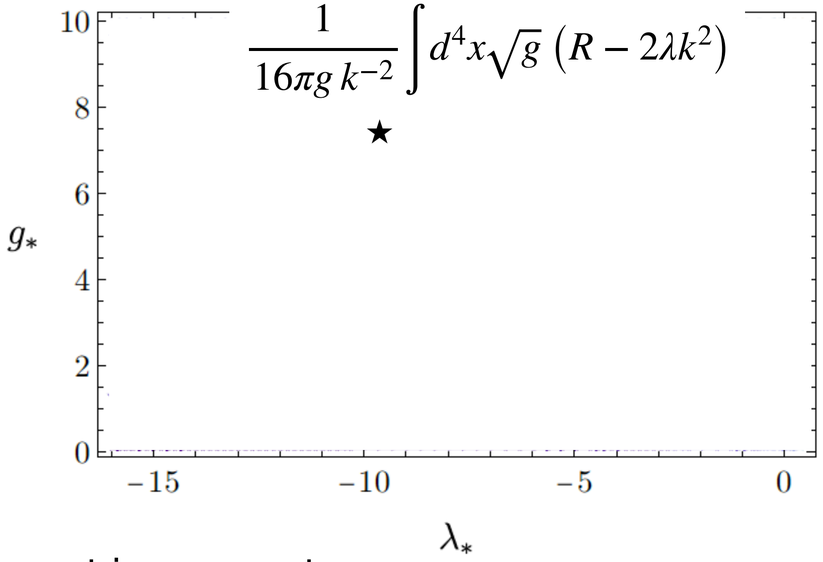
$$\frac{1}{16\pi g\, k^{-2}} \int d^4x \sqrt{g}\, \left(R - 2\lambda k^2\right)$$



metric propagator:

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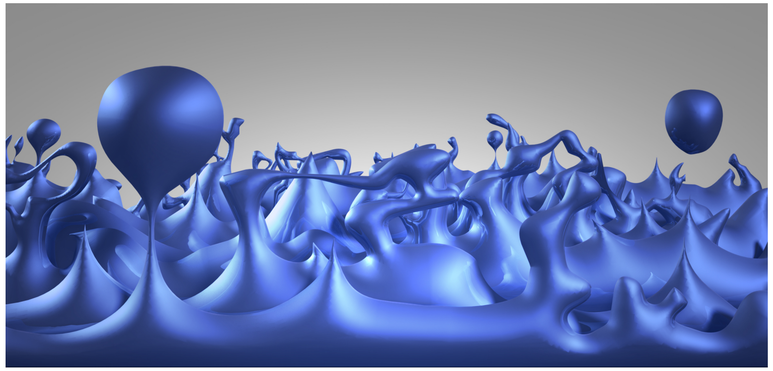

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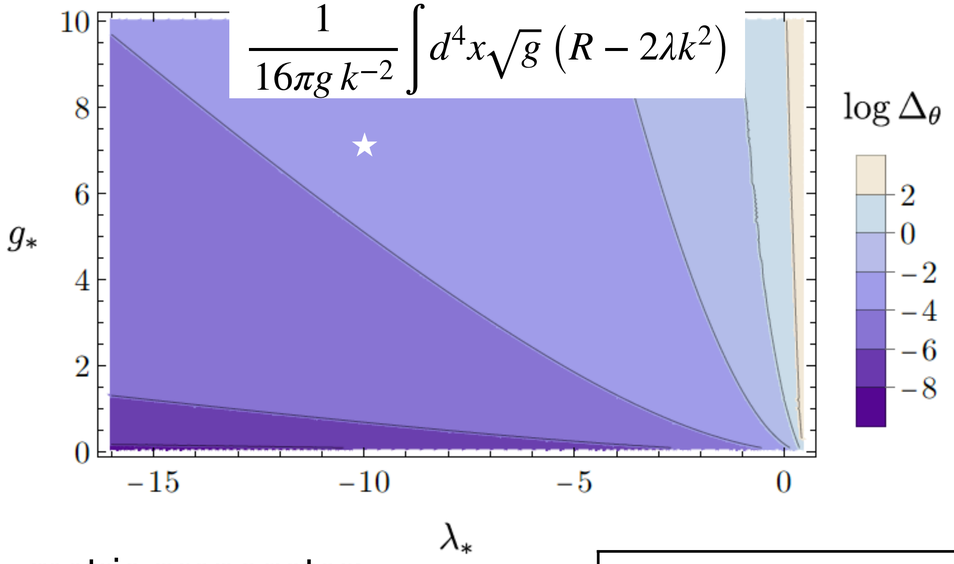
Key property: near-perturbative

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



metric propagator:

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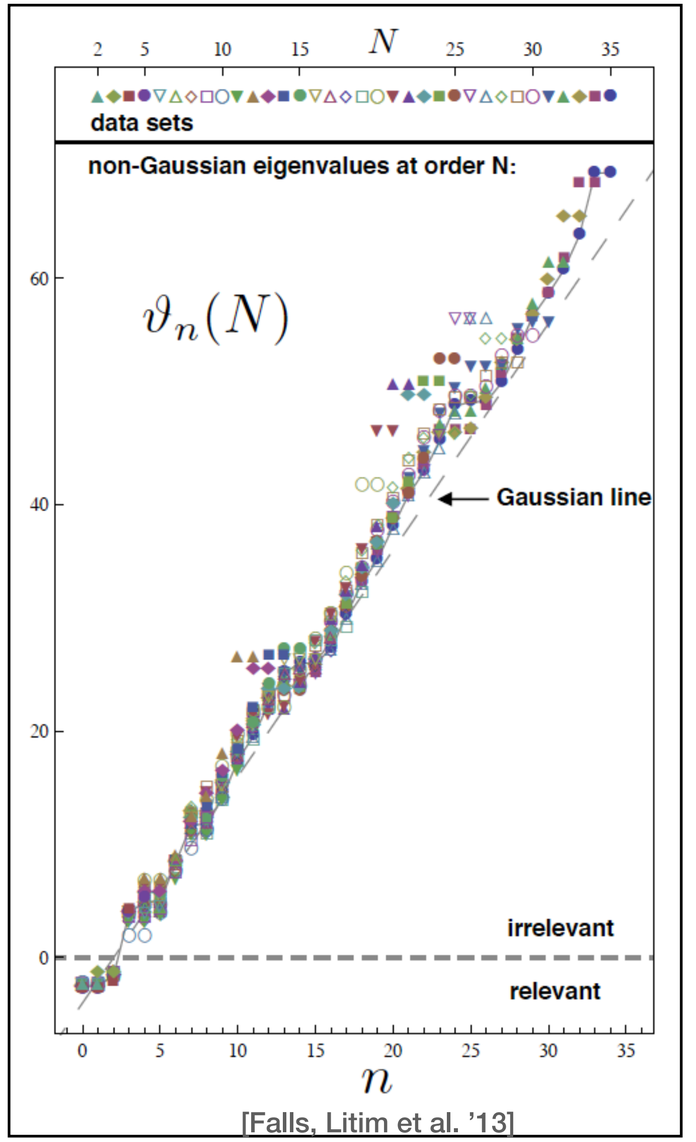
$$\Delta_\theta = \sqrt{\frac{\sum_i \left(\mathrm{Re}(\theta^{(i)}) - \theta_{\mathrm{Gauss}}\right)^2}{\sum_i}}$$

[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….]

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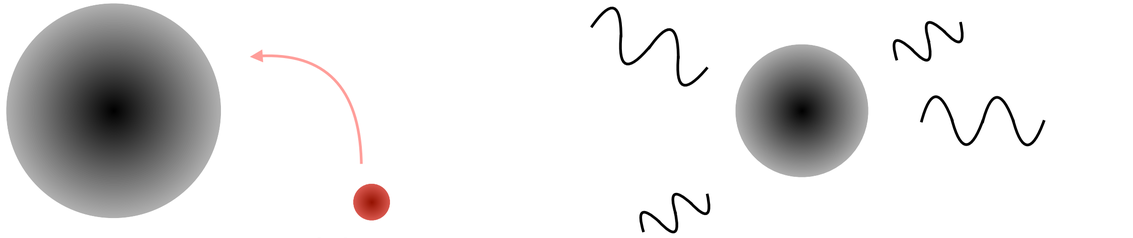
1) Black-hole spacetimes violate conservation of global charges



black hole

particle w.
global charge

black hole undergoes complete
Hawking evaporation (no remnants)

with Hawking entropy

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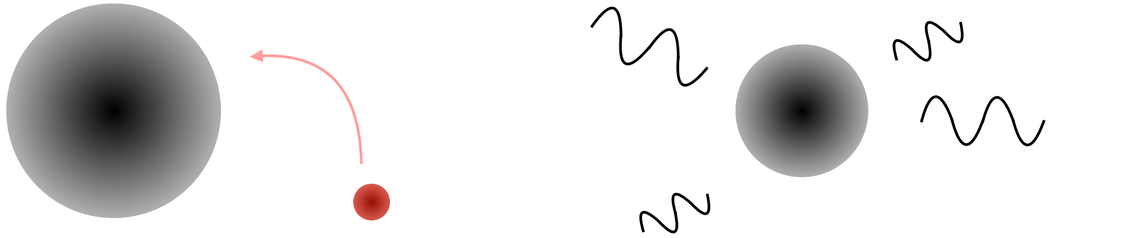

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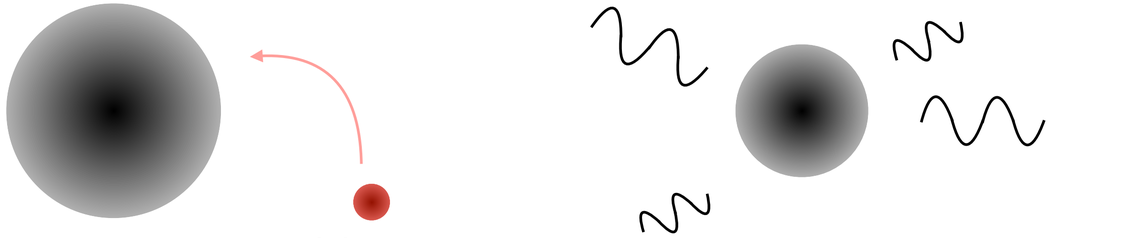

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But: explicit calculations in asymptotic safety:

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,
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(full list in review AE, Schiffer ’22]

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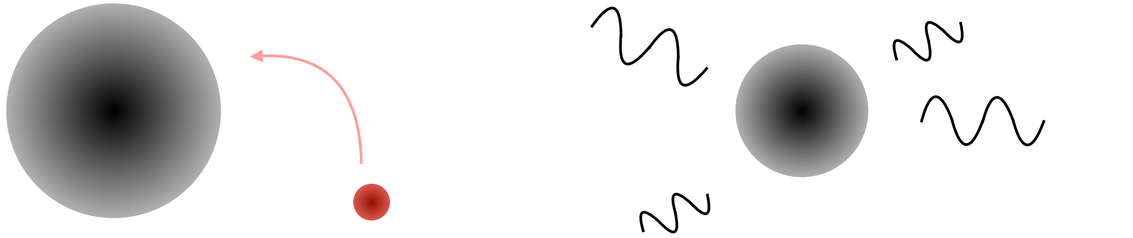

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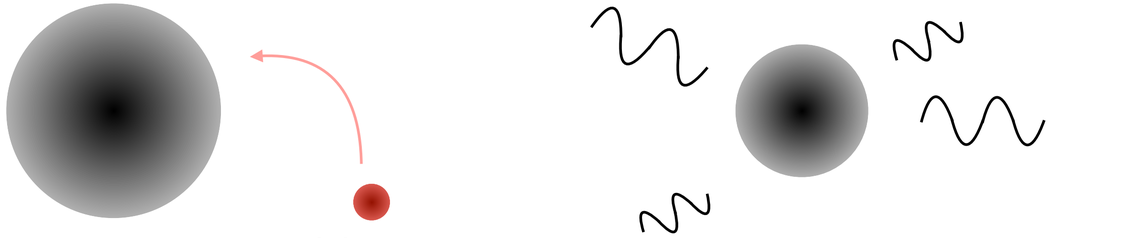

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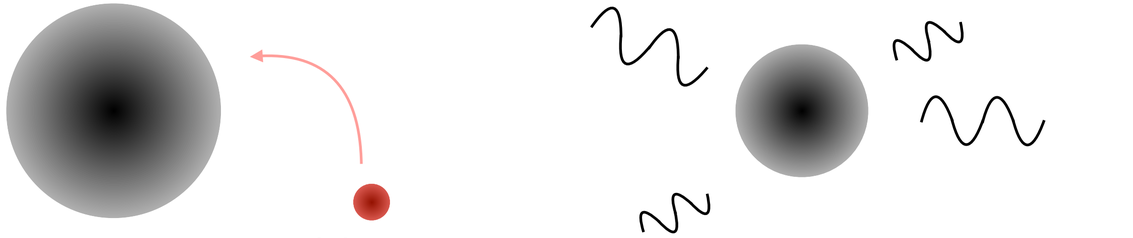

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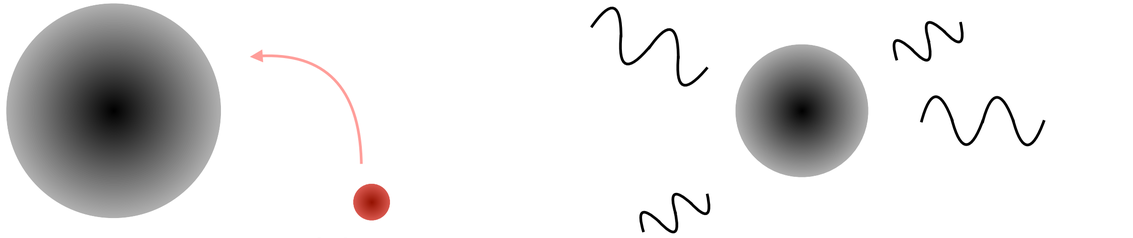

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Possibility 2a: remnants
asymptotic-safety inspired black holes have vanishing temperature at Planckian mass [Bonanno, Reuter ’06]

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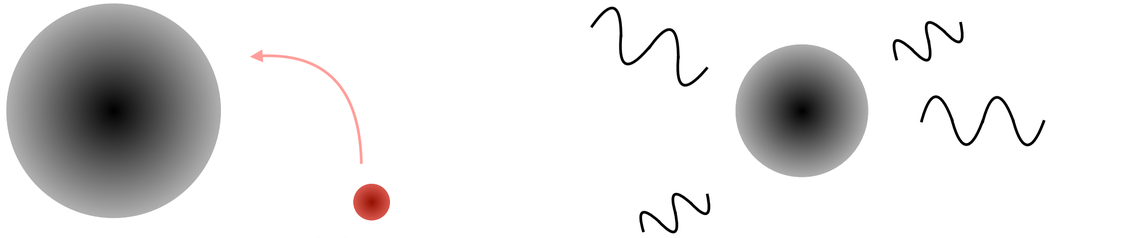

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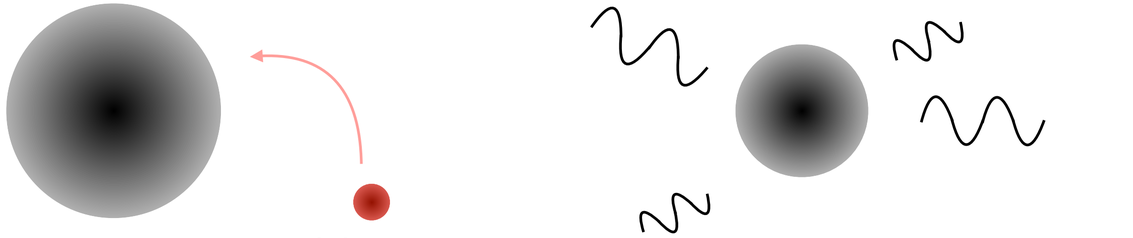

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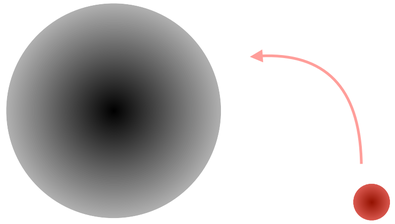

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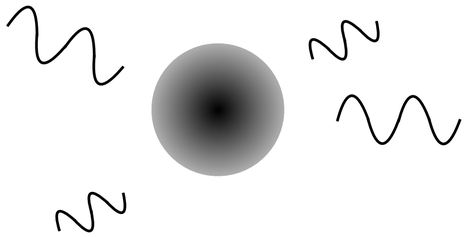

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$$S = \ldots + \int d^4x \sqrt{-g} \frac{(C^2)^8}{4C^2(\nabla_\mu C)^2 - (\nabla_\mu C^2)^2} \to \infty$$ at the horizon

Borissova, AE, Ray ‘24

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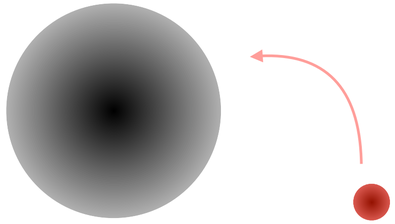

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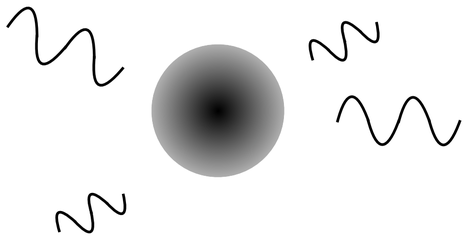

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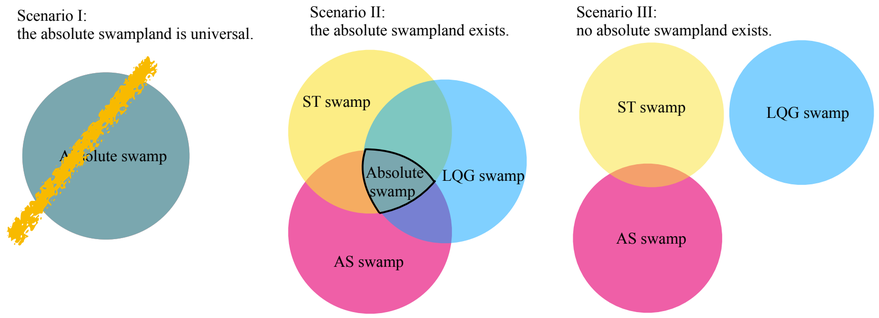

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Gravity as the weakest force

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Weak-gravity conjecture: $\dfrac{m}{M_{\text{Planck}}} \leq e\,q\sqrt{2}$ [Arkani-Hamed, Motl, Nicolis, Vafa '07]

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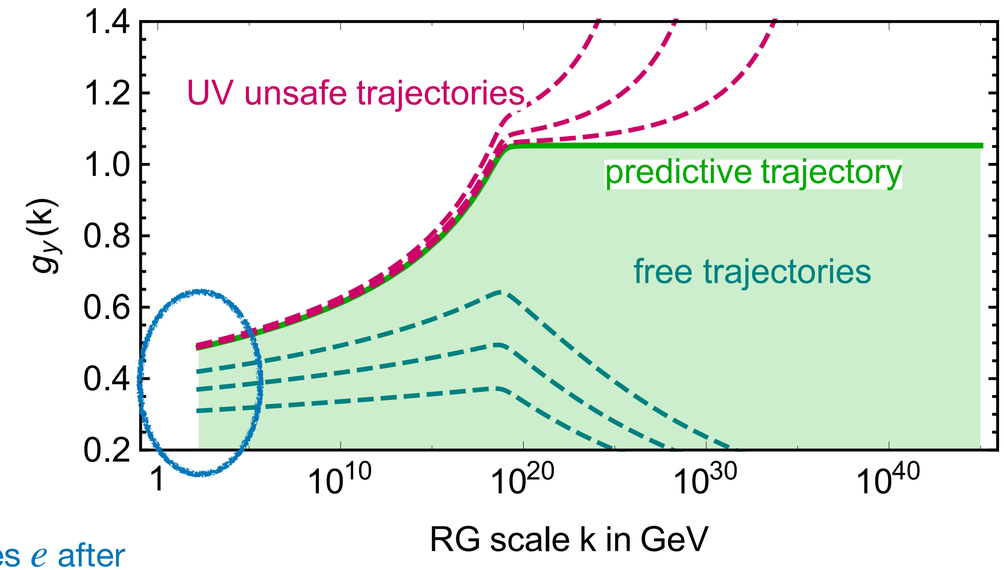
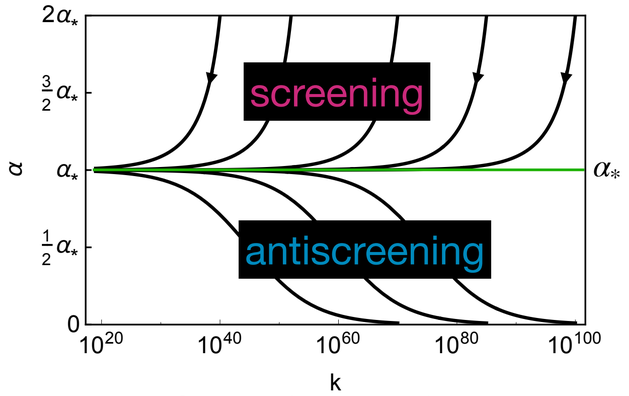


g_y becomes e after electroweak symmetry breaking



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

quantum fluctuations drive coupling **towards** scale symmetry

$f_g \geq 0$ for $k \geq M_{\text{Planck}}$

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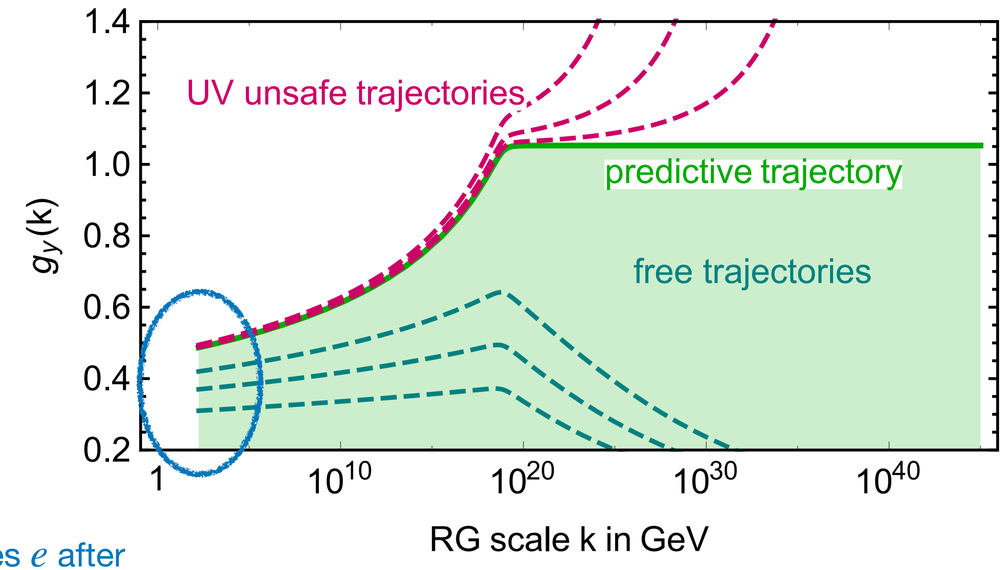

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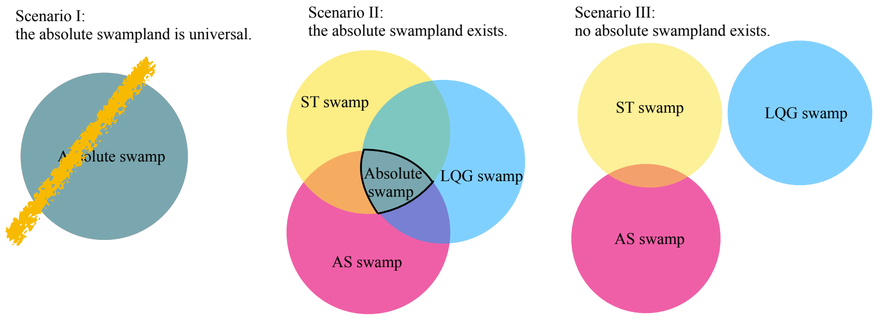

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De Sitter spacetime is not compatible with quantum gravity and any scalar potential V must not be too flat: $|\nabla V| \geq \frac{c}{M_{\text{Planck}}} V$

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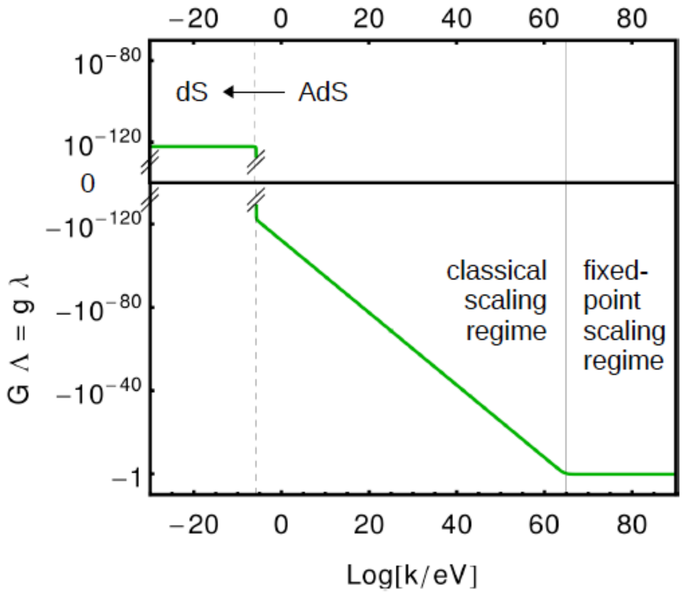

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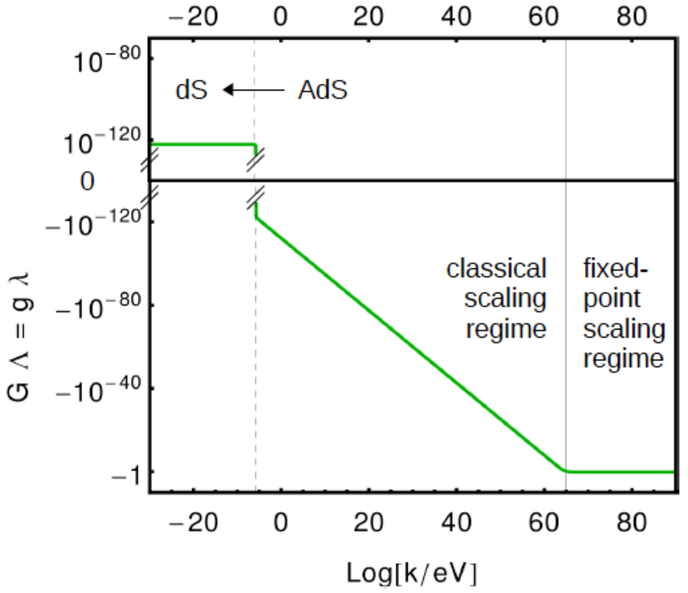

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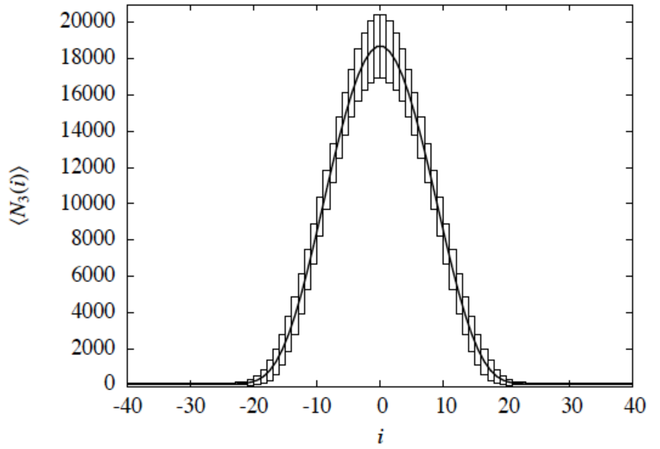

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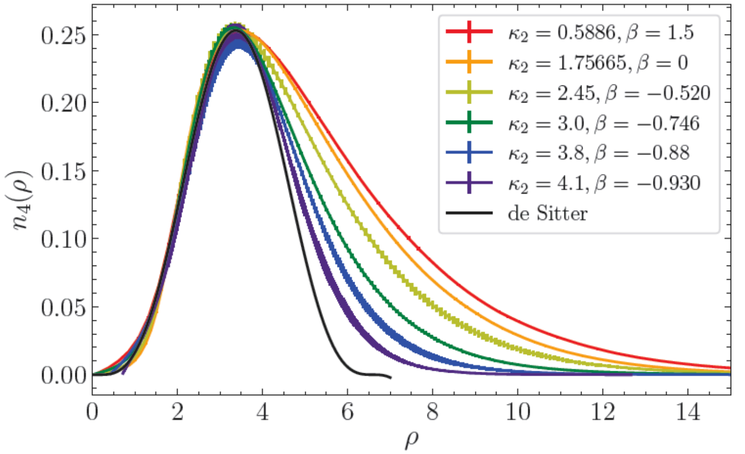

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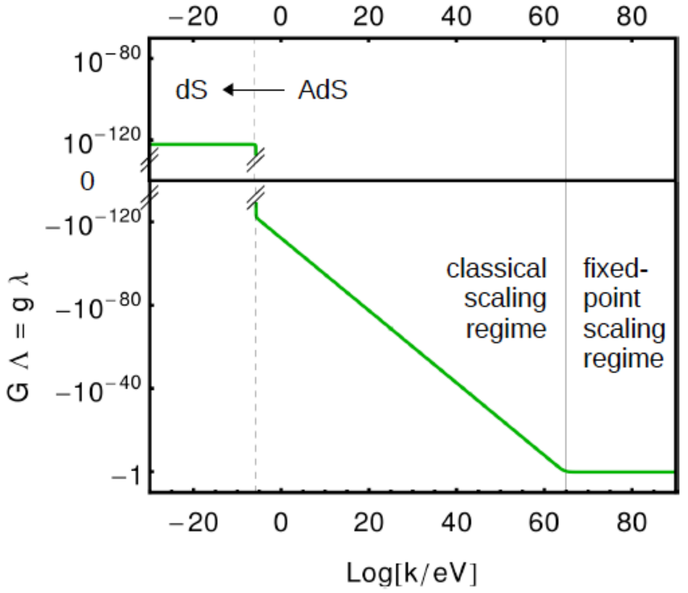

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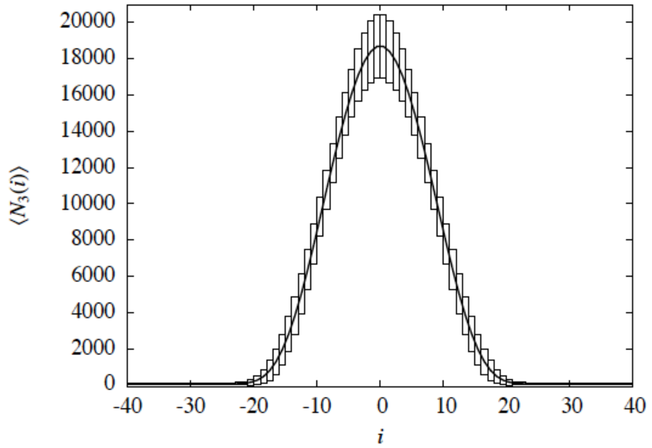

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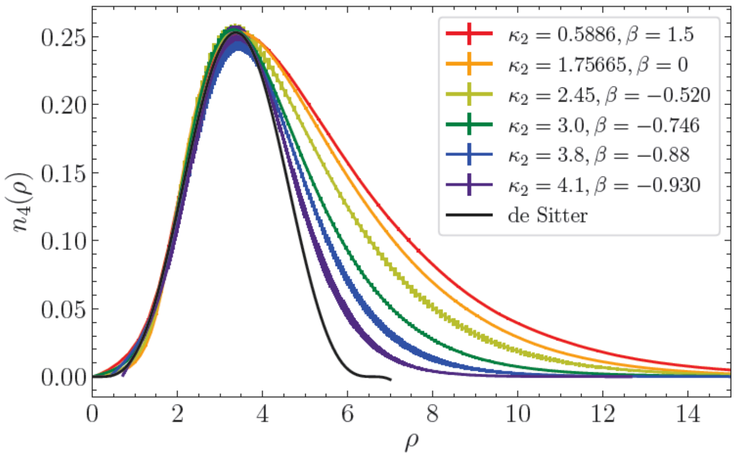

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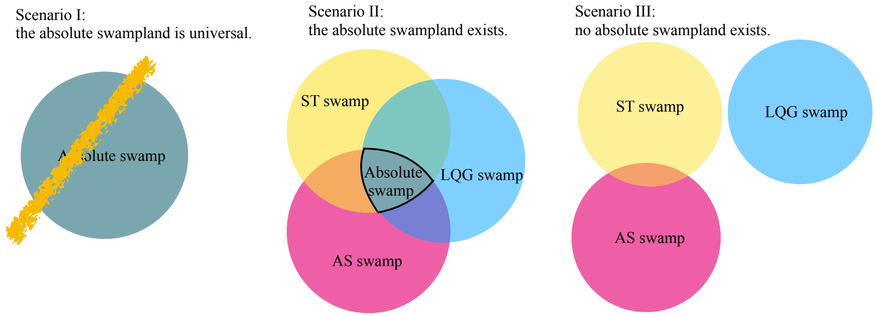

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So is there no absolute swamp that is shared between distinct approaches?

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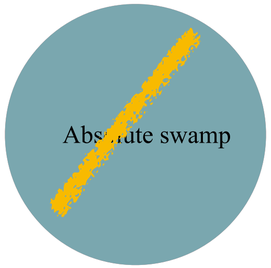
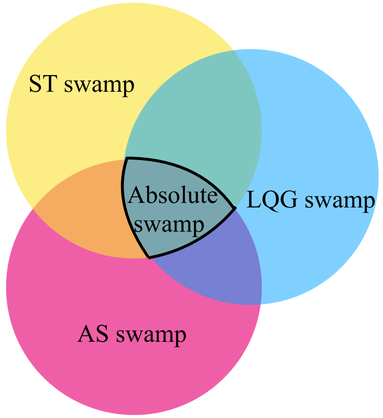
the absolute swampland is universal.



Scenario II:
the absolute swampland exists.



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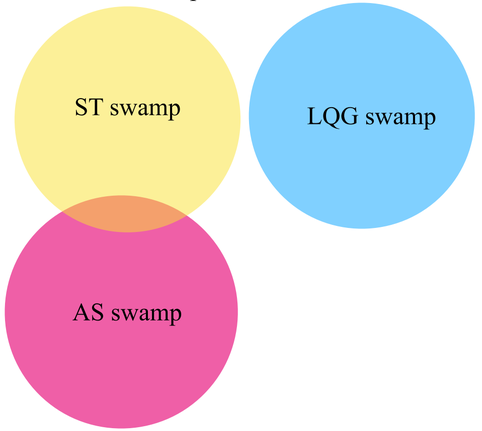

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Asymptotic safety generates a universal corner of the swampland

Main idea: Asymptotic safety in an intermediate regime
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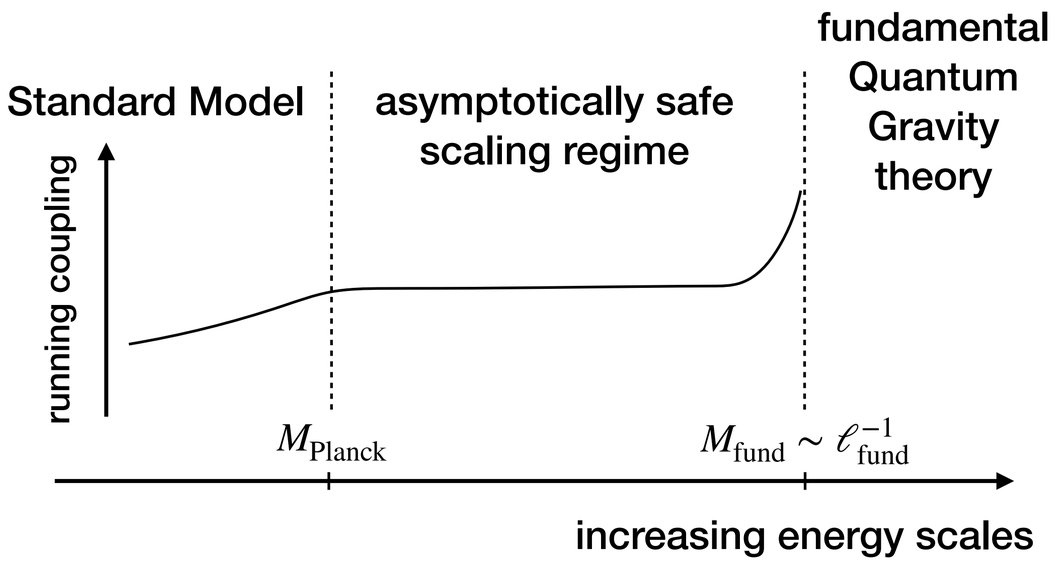

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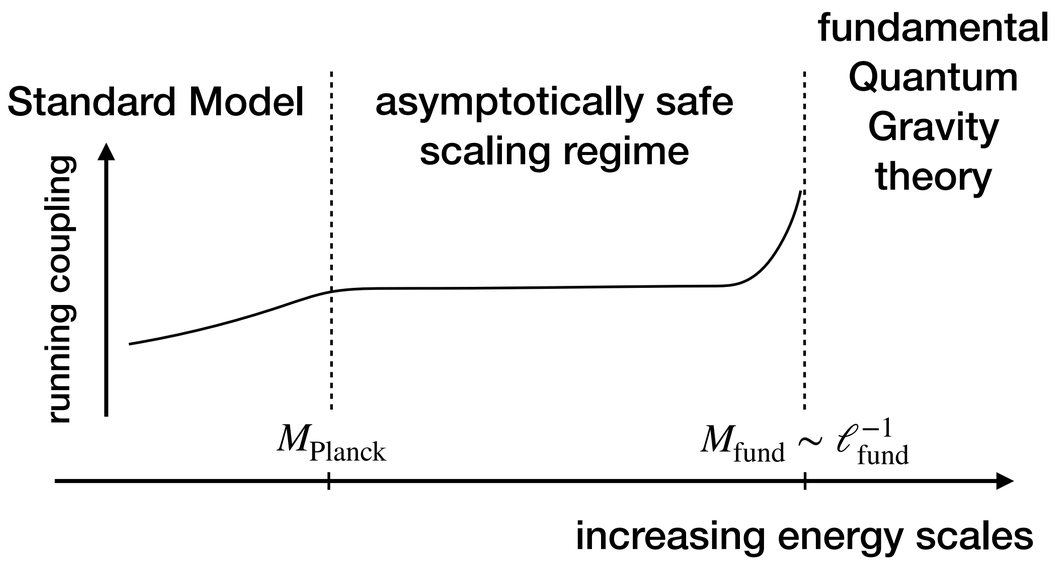

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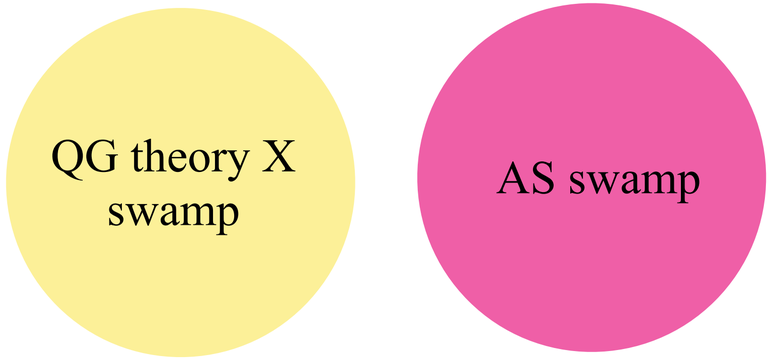
Swamplands without effective asymptotic safety

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



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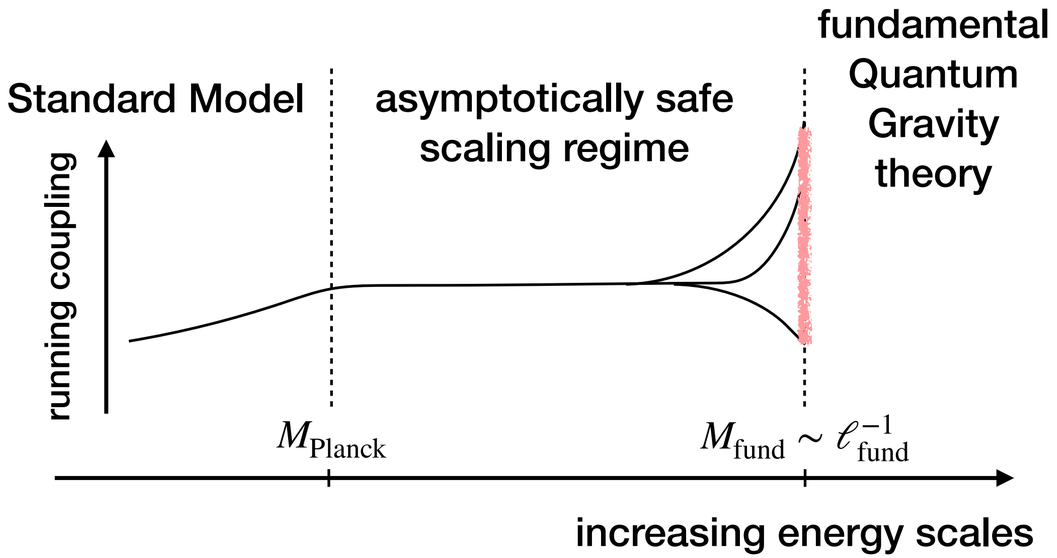

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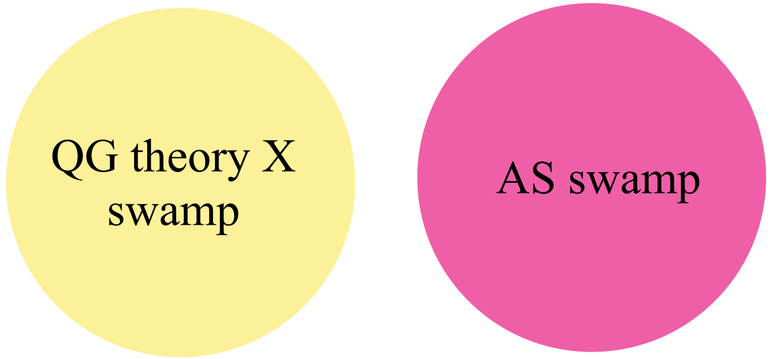

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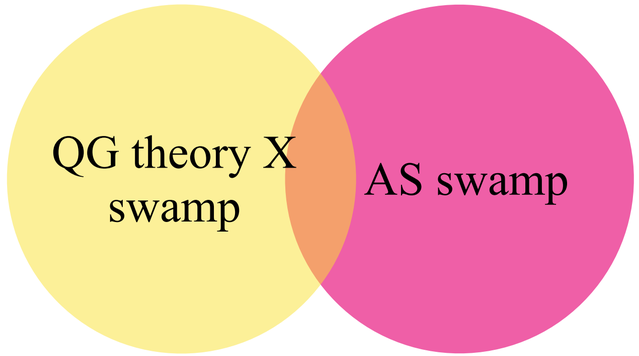

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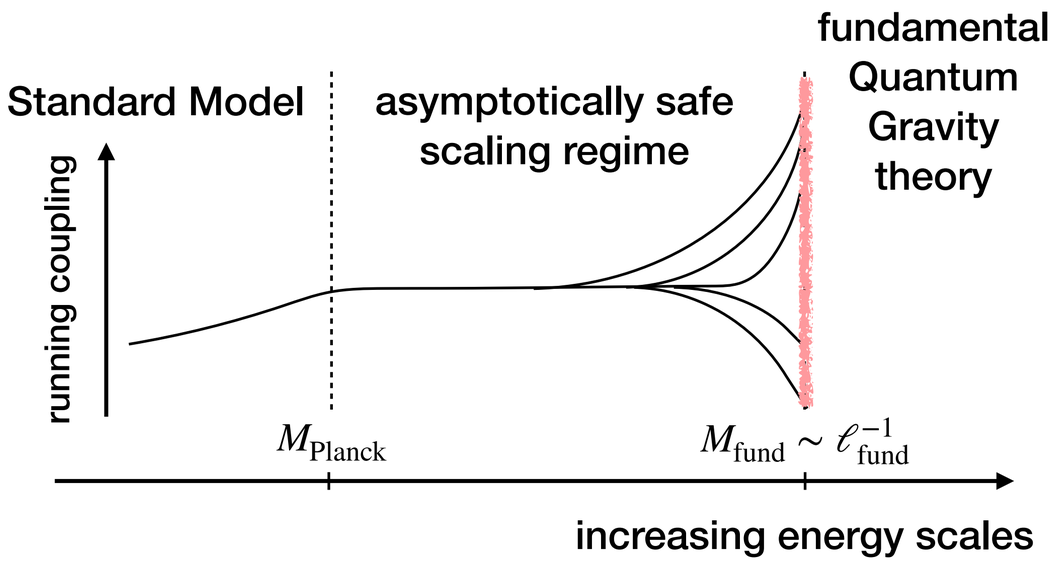

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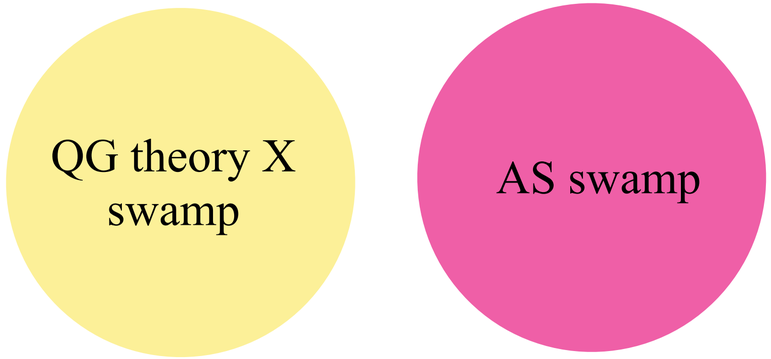

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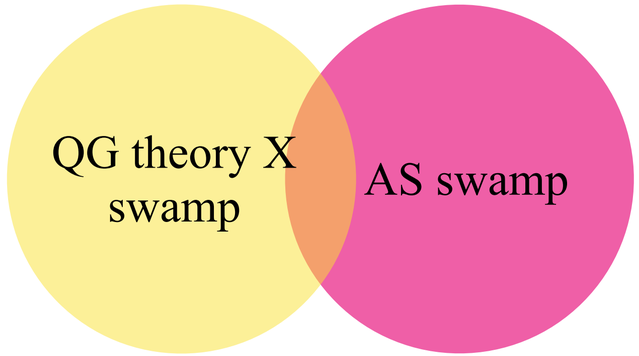
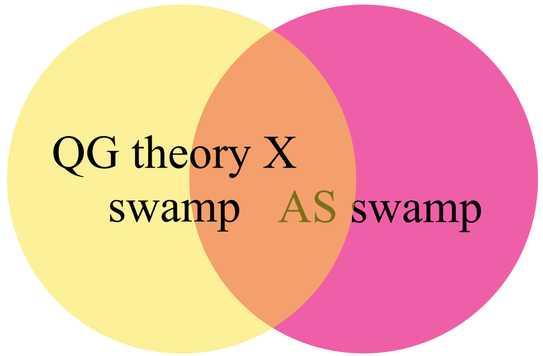
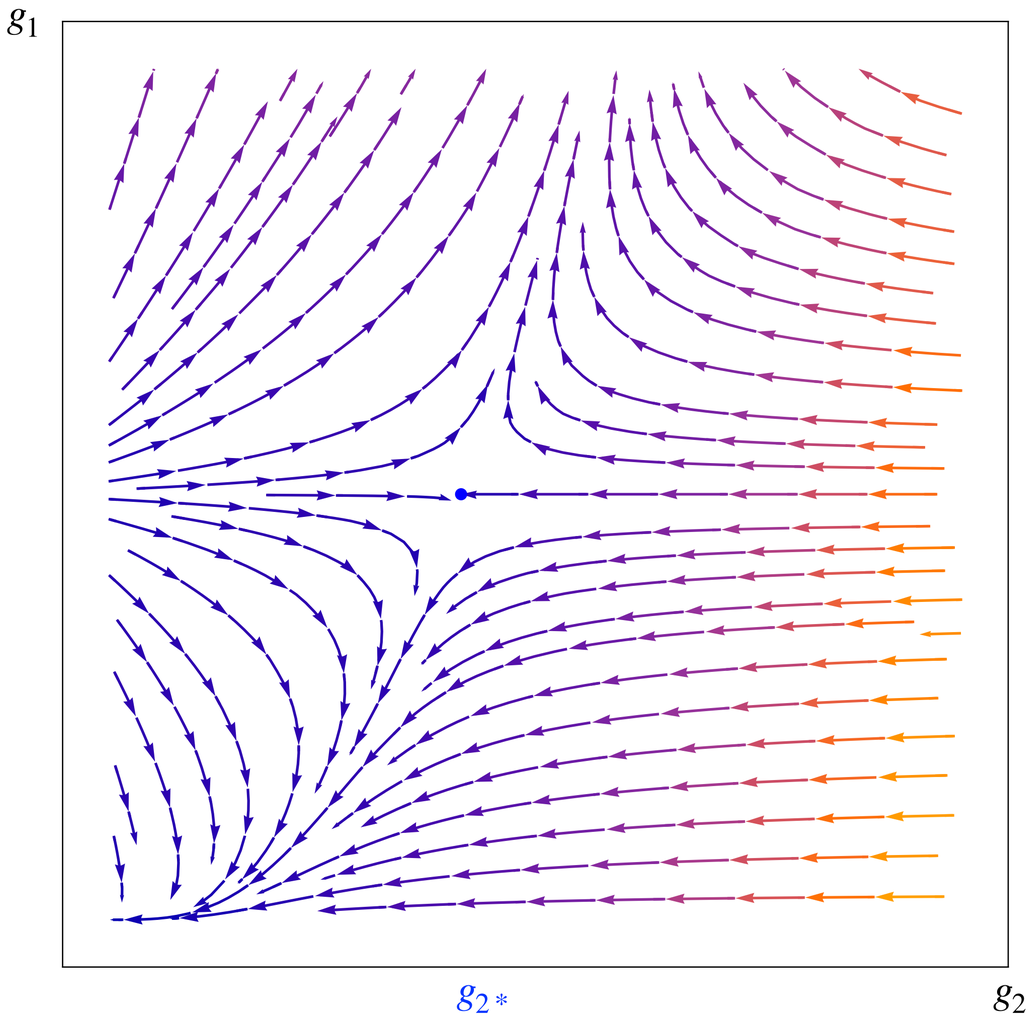


$\ell_{\text{fund}}^{-1} = 10^{x} M_{\text{Planck}},\ x > 0$



$\ell_{\text{fund}}^{-1} = 10^{n \cdot x} M_{\text{Planck}},\ x > 0, n \in \mathbb{N}$

Universality from effective asymptotic safety: mechanism



Renormalization Group flow:
arrows point towards decreasing energy scales

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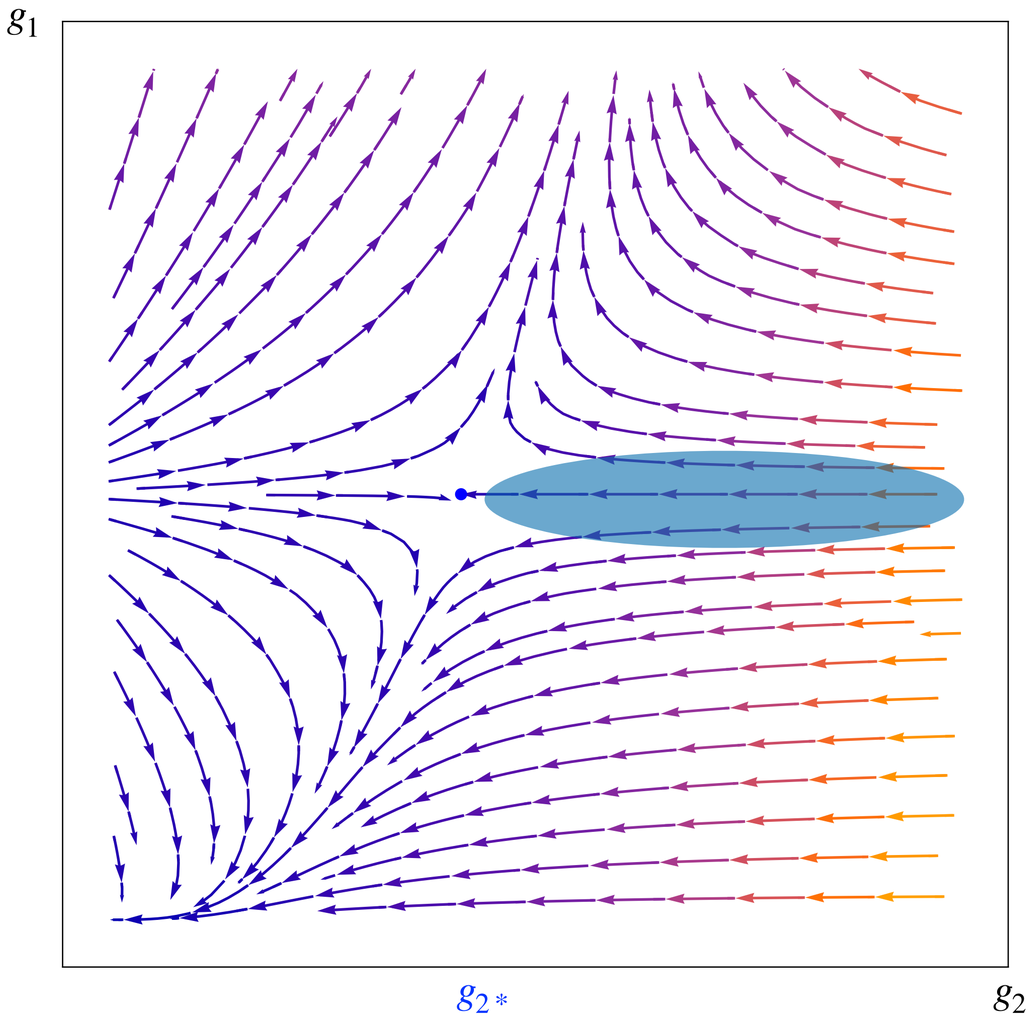

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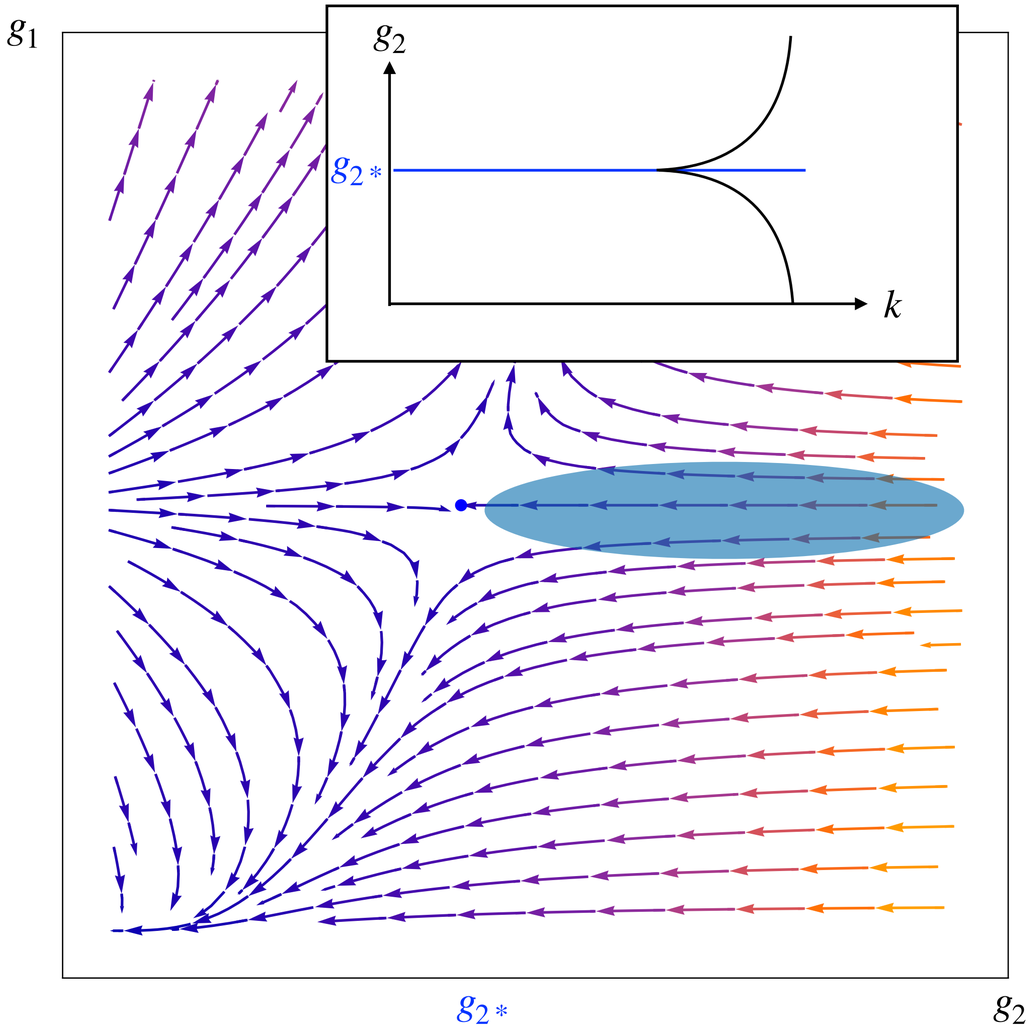

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Universality:

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
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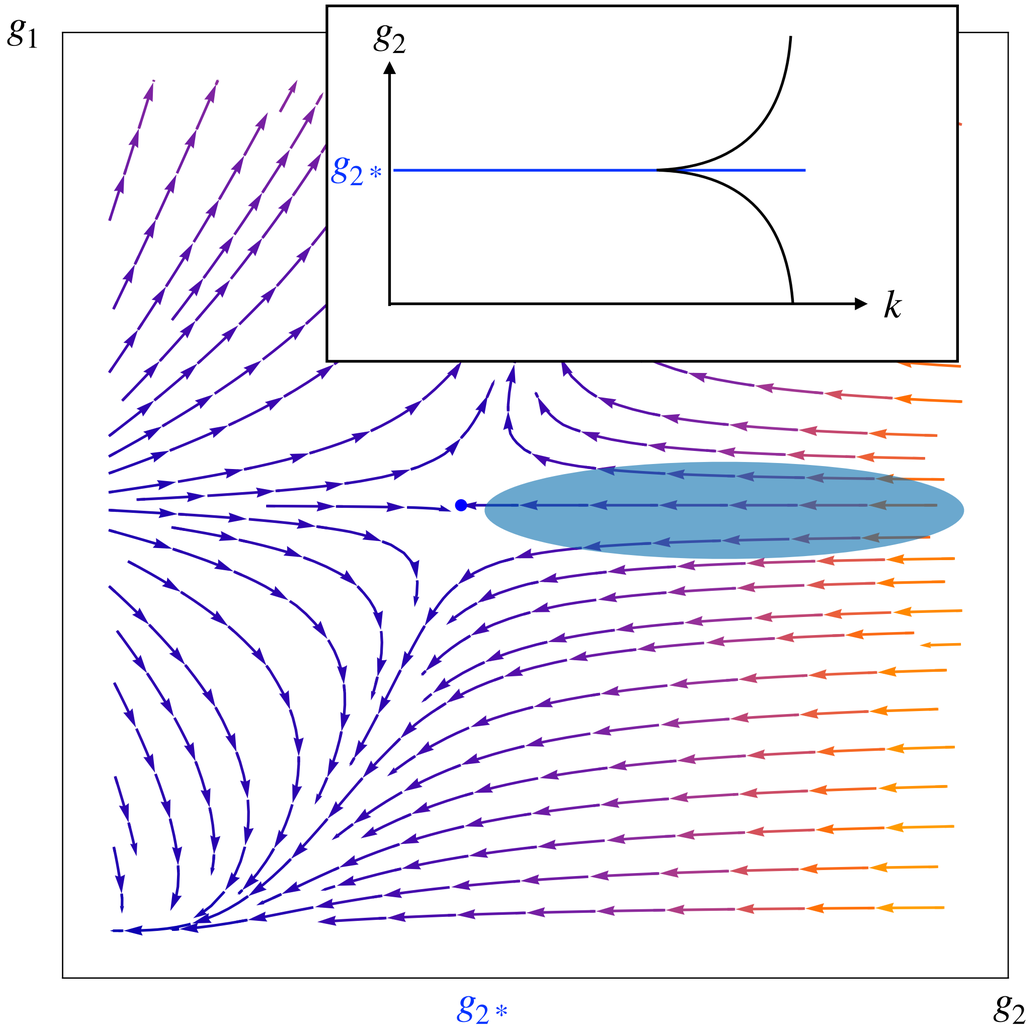

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To delineate universal part of the swamp:

→ **which interactions correspond to infrared attractive couplings?**

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Universality from effective asymptotic safety: mechanism in more detail

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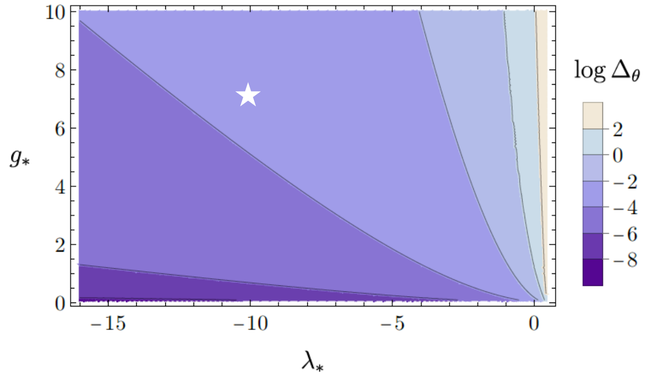
(Tentative) fixed-point properties:

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

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



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

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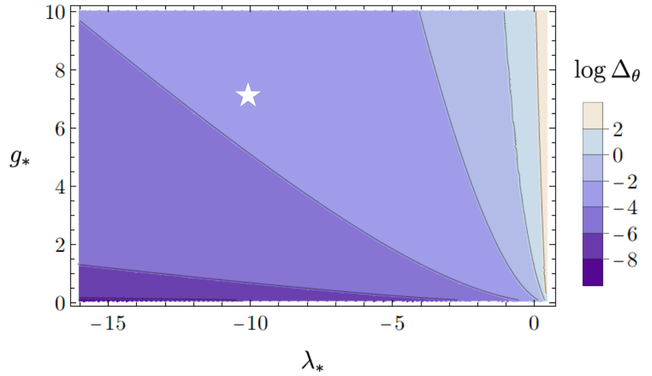

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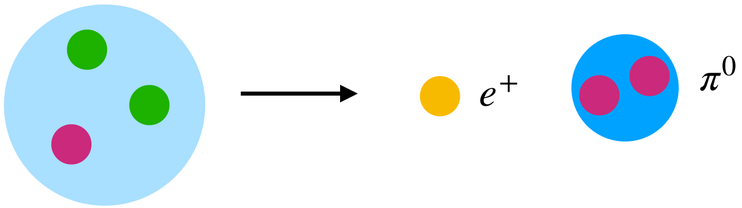
Examples:

- **Proton decay**



quark-lepton interactions that mediate proton decay: $g_{qqql} \sim \cancel{g_{qqql\,*}} + c\,\left(k \cdot \ell_{\rm fund}\right)^{-\theta_{qqql}}$ **with** $\theta_{qqql} = -2 - \frac{29}{15\pi} G_* + \ldots$

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[AE, Ray '23]

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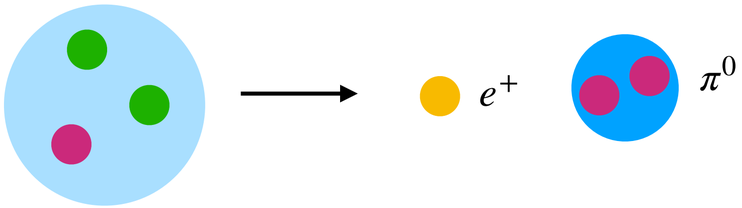

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$\lambda_H\, H^\dagger H\, \phi^2$ **with Higgs field** H **and dark scalar** ϕ**:** $\lambda_H = \cancel{\lambda_{H\,*}} + c\,\left(k \cdot \ell_{\rm fund}\right)^{-\theta_{\lambda_H}}$ **with** $\theta_{\lambda_H} = -\frac{55}{18\pi} G_*$

[AE, Hamada, Lumma, Yamada '18]

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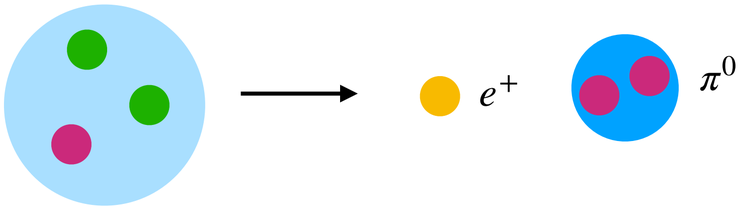

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An intermediate, approximately asymptotically safe regime*

- **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**

Effective-Field-Theory consistency and the asymptotically safe swampland

Asymptotically safe gravity induces higher-order interactions

[AE, Gies ’11; AE, 12]

Example: (Abelian vector fields) $\mathscr{L}_k = \frac{Z_k}{4}F^2 + \frac{w_2}{k^4}\left(F^2\right)^2 + \frac{h_2}{k^4}F^4$

in the presence of gravity: $w_2 \neq 0, h_2 \neq 0$ [Christiansen, AE 17; AE, Schiffer ’19; AE, Kwapisz, Schiffer ‘21]

Causality bounds

Causality bounds (no detectable propagation outside the light cone)

$$\frac{w_2}{h_2} > -\frac{3}{4}, \quad \frac{4w_2 + 3h_2}{|4w_2 + h_2|} > 1$$

[Carillo Gonzalez, de Rham, Jaitly, Pozsgay, Tokareva ‘23]

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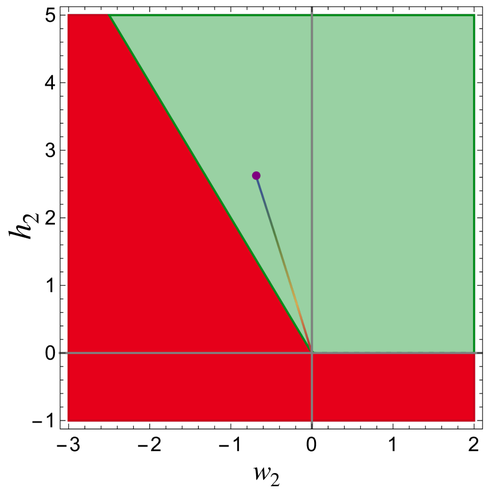
Apply to photons in asymptotically safe gravity:

- assume that can Wick-rotate action
- start at interacting fixed point and integrate to low k:
  use that $w_2(k), h_2(k)$ are irrelevant and thus calculable
- gravity fluctuations decouple dynamically at Planck scale

[AE, Oodgard Pedersen, Schiffer '24; see also Knorr, Platania '24]



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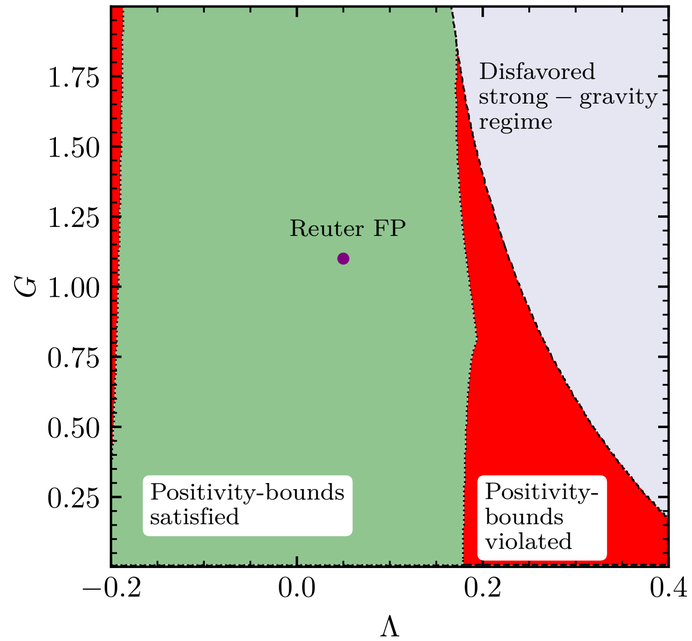

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