Impact of quantum gravity on the UV sensitivity of extremal black holes

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2509.07058 w/ F. Del Porro, A. Platania

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The Niels Bohr International Academy

THE CENTER OF GRAVITY

Perturbatively nonrenormalizable

Quantum Gravity

Gravity as a consistent QFT at every scale

Perturbatively nonrenormalizable

Asymptotically Safe Quantum Gravity

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non-perturbatively renormalizable

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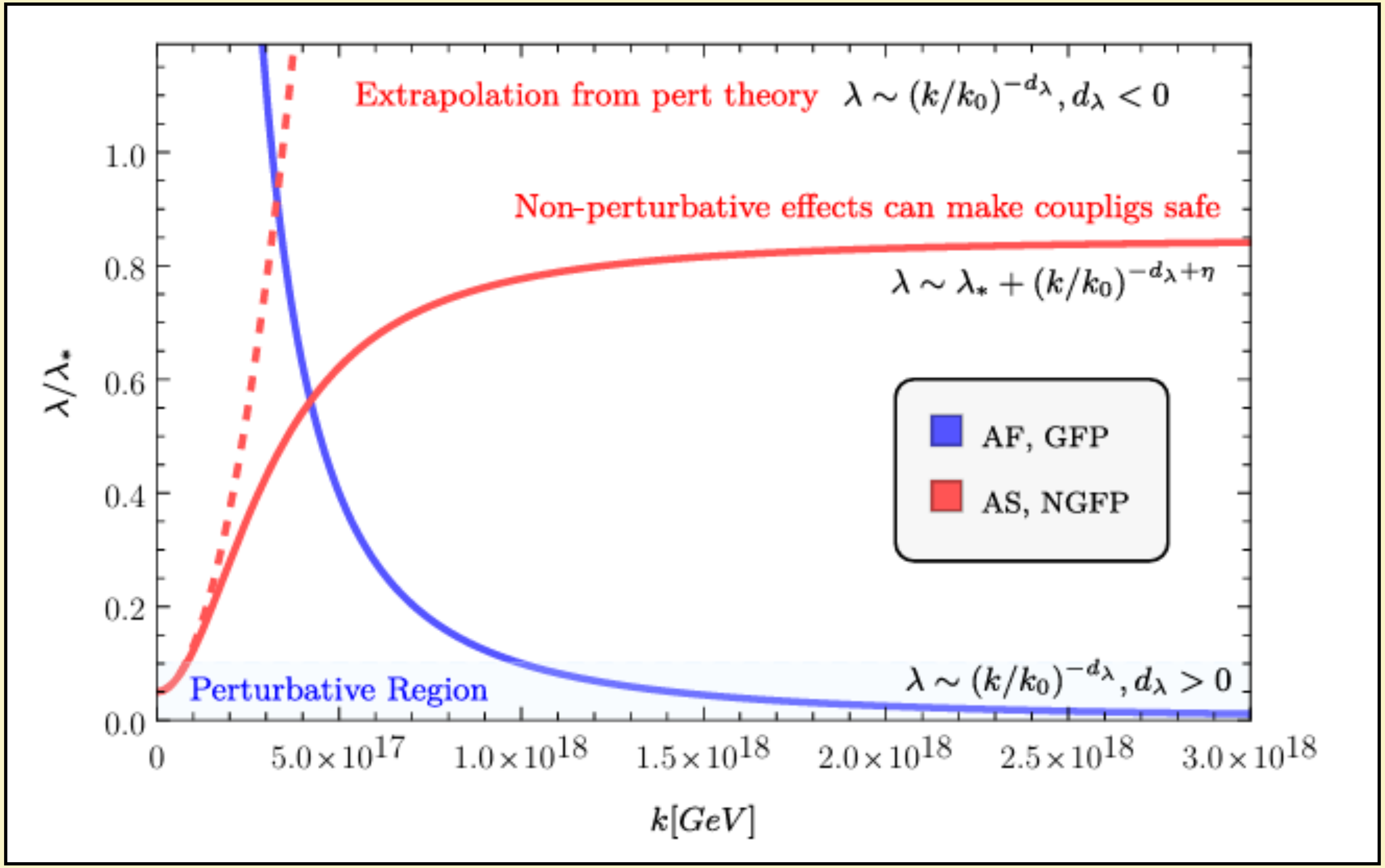
Wilsonian Renormalization Group

UV controlled by an interacting fixed point

Generalizing Asymptotic Freedom: zeros of the beta functions at non-vanishing values of the couplings



[Basile, Buoninfante, Di Filippo, Knorr, Platania, Tokareva, '25]

Asymptotically Safe Quantum Gravity

UV complete and predictive: finitely many couplings are relevant (fixed by experiments)
Irrelevant couplings are fixed by the theory!

The relevant couplings span the landscape of all EFTs from AS

[Weinberg, '76]

non-perturbative
renormalizability

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[Eichhorn, Schiffer, '22]

Asymptotic Safety w/ matter
top-to-Higgs mass ratio & other
SM parameters

(Effective?) Asymptotically Safe Quantum Gravity

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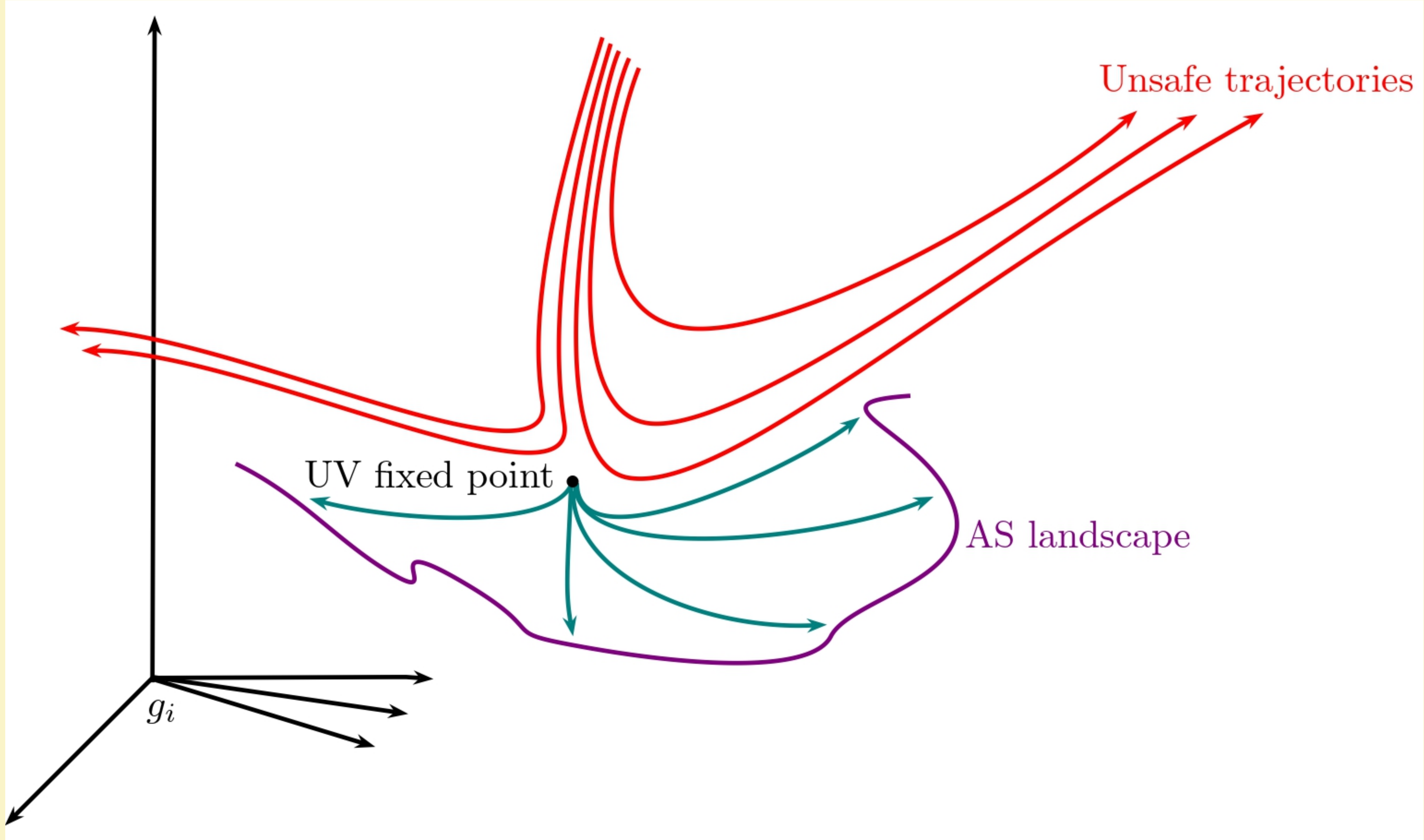
Renormalization group and asymptotic safety landscapes



〔Knorr, Platania, '24〕

Clear recipe for computing
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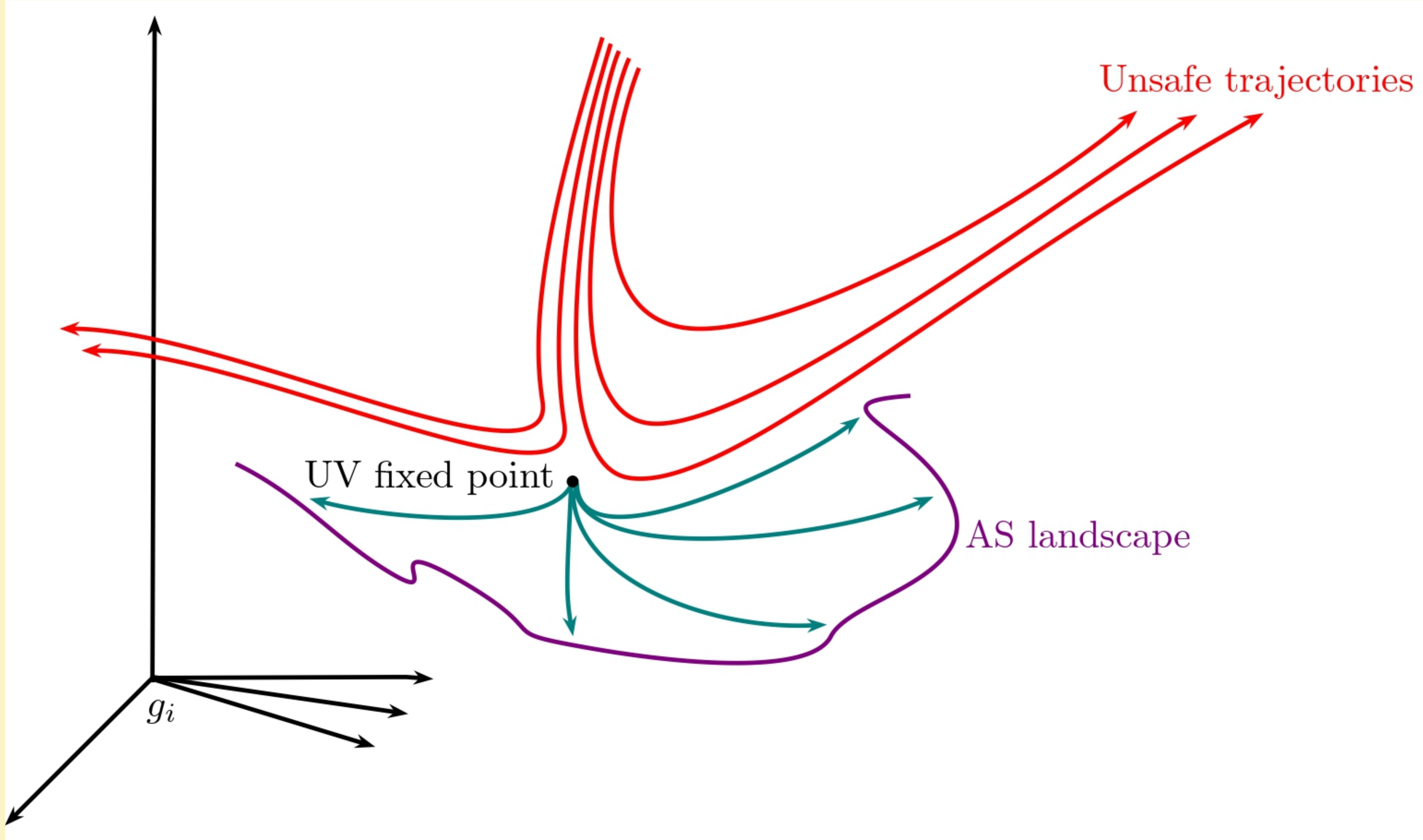
Renormalization group and asymptotic safety landscapes



Clear recipe for computing **Wilson coefficients**

Follow the flow stemming from the UV of all asymptotically safe trajectories

Identify the Wilson coefficients with the **IR limits** of the FRG running couplings

[Knorr, Platania, '24]

[Basile, Platania, '21]

PHYSICAL REVIEW LETTERS **131**, 091402 (2023)

Editors' Suggestion | Featured in Physics

Extremal Kerr Black Holes as Amplifiers of New Physics

Gary T. Horowitz,[1] Maciej Kolanowski,[2] Grant N. Remmen,[1,3] and Jorge E. Santos[4]

We show that extremal Kerr black holes are sensitive probes of new physics. Stringy or quantum corrections to general relativity are expected to generate higher-curvature terms in the gravitational action. We show that in the presence of these terms, asymptotically flat extremal rotating black holes have curvature singularities on their horizon. Furthermore, near-extremal black holes can have large yet finite tidal forces for infalling observers. In addition, we consider five-dimensional extremal charged black holes and show that higher-curvature terms can have a large effect on the horizon geometry.

Einstein Hilbert + **higher-derivative terms**

Maximally rotating solution to Einstein equations exhibit

divergent tidal forces on the horizon

Goroff-Sagnotti counterterm

$$\mathcal{L} = \frac{1}{2\kappa^2}\left(R + \eta\kappa^4 R_{\mu\nu}{}^{\rho\sigma} R_{\rho\sigma}{}^{\lambda\tau} R_{\lambda\tau}{}^{\mu\nu}\right)$$

Goroff-Sagnotti counterterm

Wilson coefficient

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Power-law behavior

$$C_{\rho a \rho b} \propto \rho^{\gamma-2} \qquad \gamma = 2 + \eta\gamma^{(6)}$$

$\rho \to 0$ to the horizon

Extremal Kerr horizon is smooth

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$\rho \to 0$ to the horizon

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Divergence if $\eta < 0$

Scalar curvature invariants remain finite

The horizon is uniquely sensitive to UV physics

Predicting η within ASQG

Extremal Kerr solution

$$\mathcal{L} = \frac{1}{2\kappa^2}\left(R + \eta\kappa^4 R_{\mu\nu}{}^{\rho\sigma} R_{\rho\sigma}{}^{\lambda\tau} R_{\lambda\tau}{}^{\mu\nu}\right)$$

$\longrightarrow$

Equivalent basis

$$\mathcal{L} = -\frac{R}{2\kappa^2} + G_{\mathcal{C}^3} C_{\mu\nu}{}^{\rho\sigma} C_{\rho\sigma}{}^{\lambda\tau} C_{\lambda\tau}{}^{\mu\nu}$$

The two corrections can be mapped via local field redefinitions, leaving the e.o.m. unaffected. **Divergence for $\mathbf{G}_{\mathcal{C}^3} < 0$**

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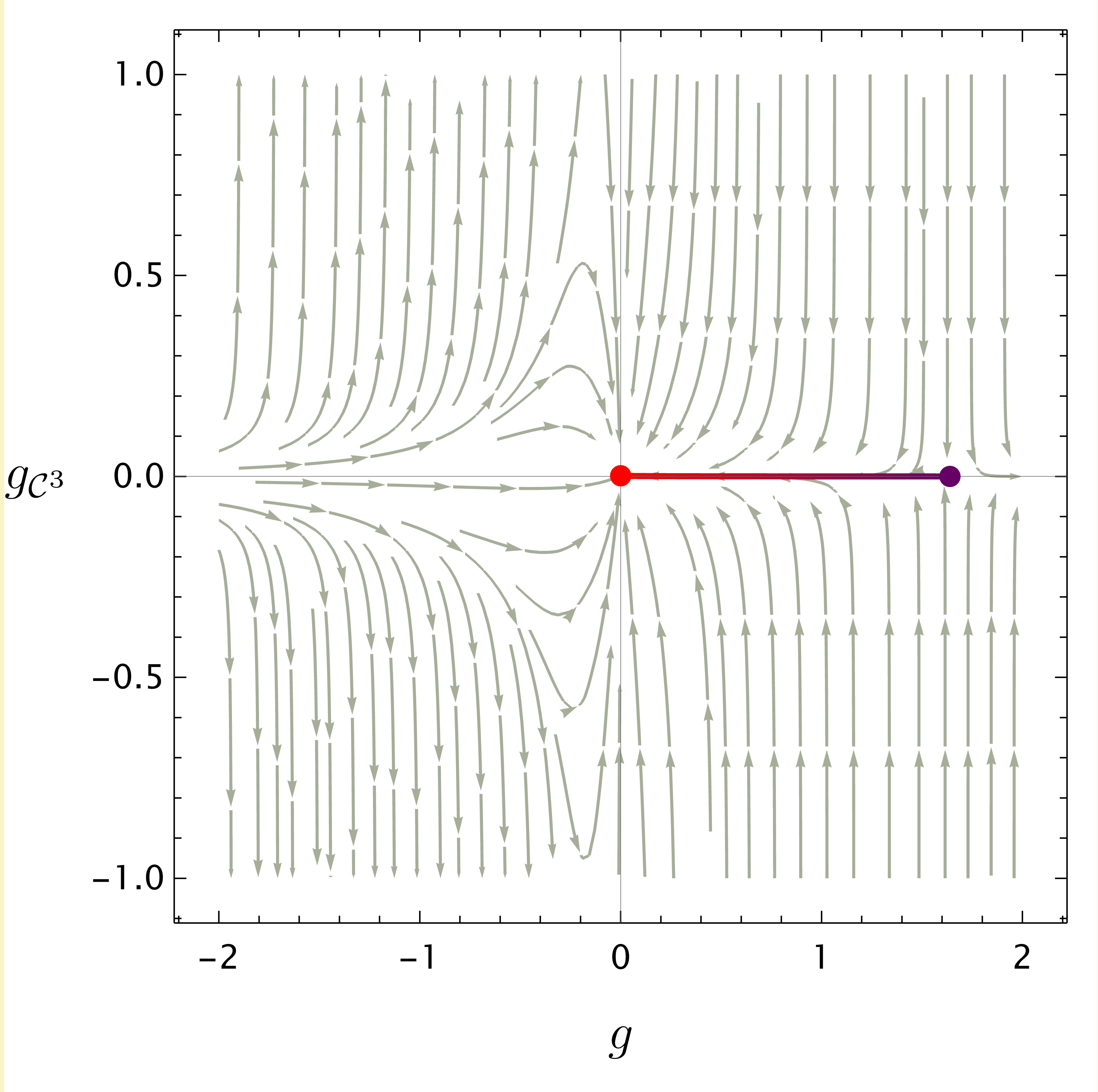
Defining the Wilson coefficients:

1. Beta functions [Baldazzi, Falls, Kluth, Knorr, '23]
2. Solve RG flow and identify the $k \to 0$ limit of all asymptotically safe trajectories

Predicting η within ASQG

[Del Porro, Ferrarin, Platania, '25]



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Flow of the dimensionless couplings

$$g_{\mathcal{C}^3}(k) = k^2 G_{\mathcal{C}^3}(k)$$
$$g(k) = k^2 G_{\mathrm{N}}(k)$$

Only one relevant direction

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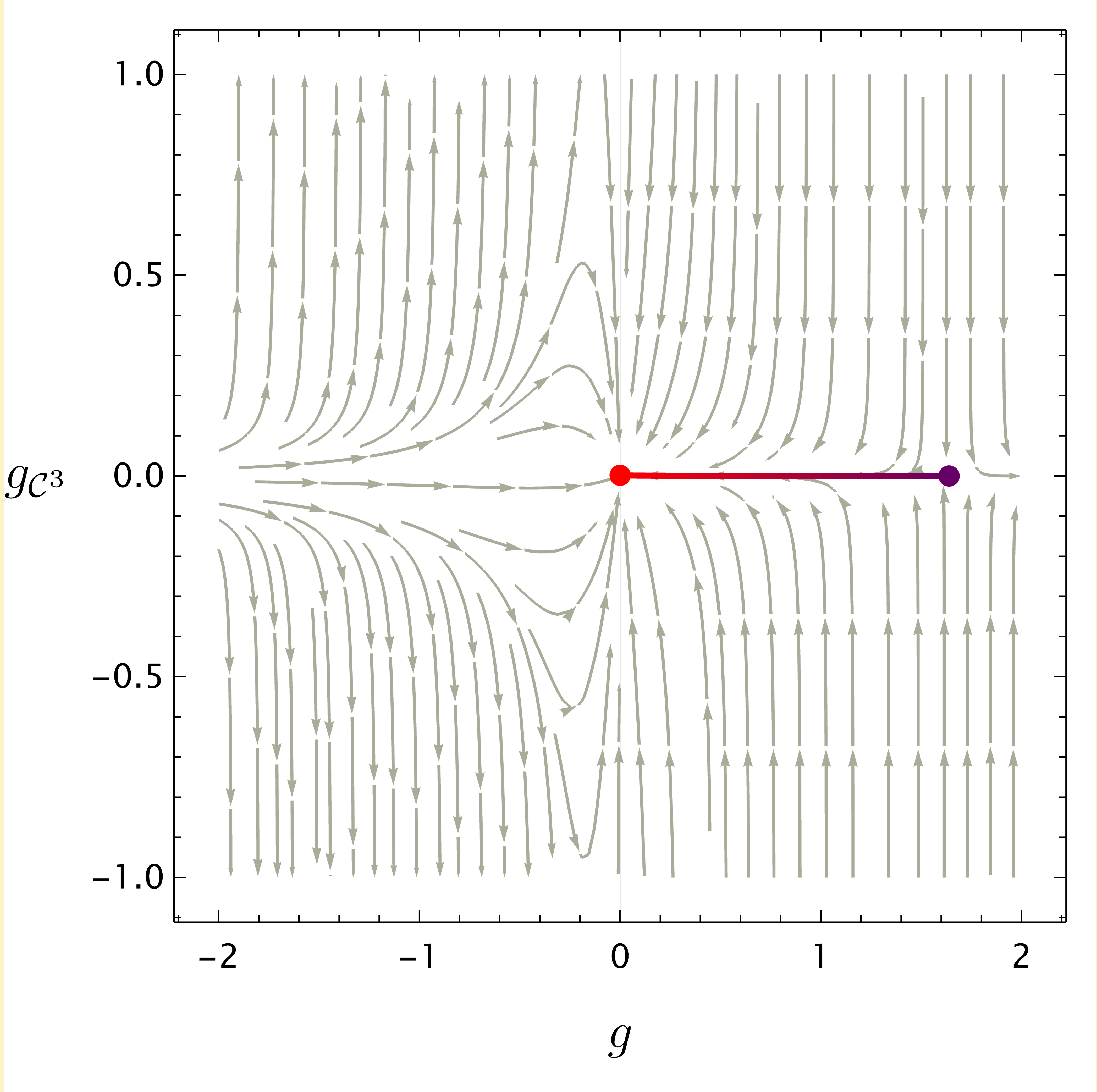

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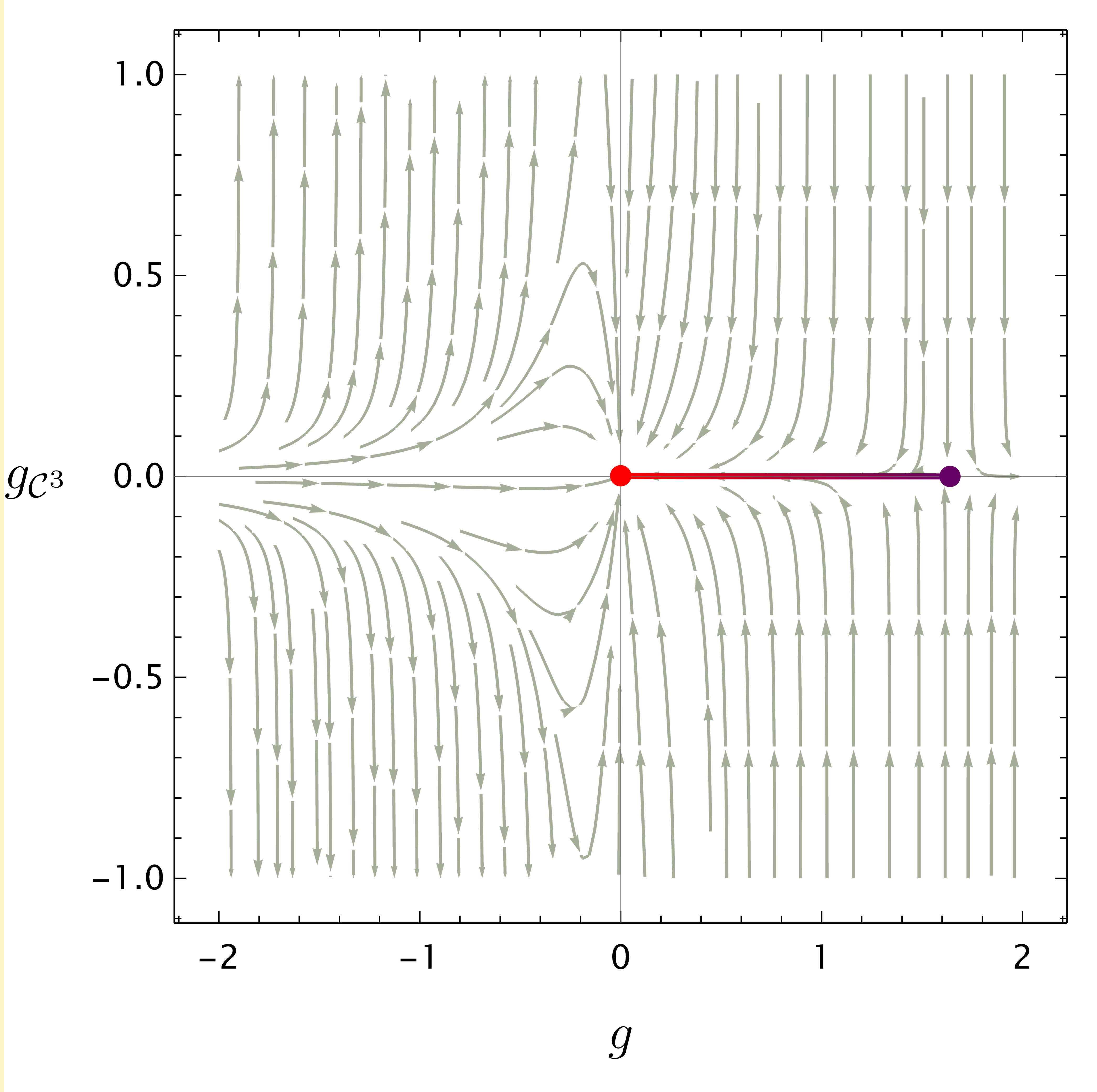
No free parameters after fixing the scale

Predicting η within ASQG

[Del Porro, Ferrarin, Platania, '25]



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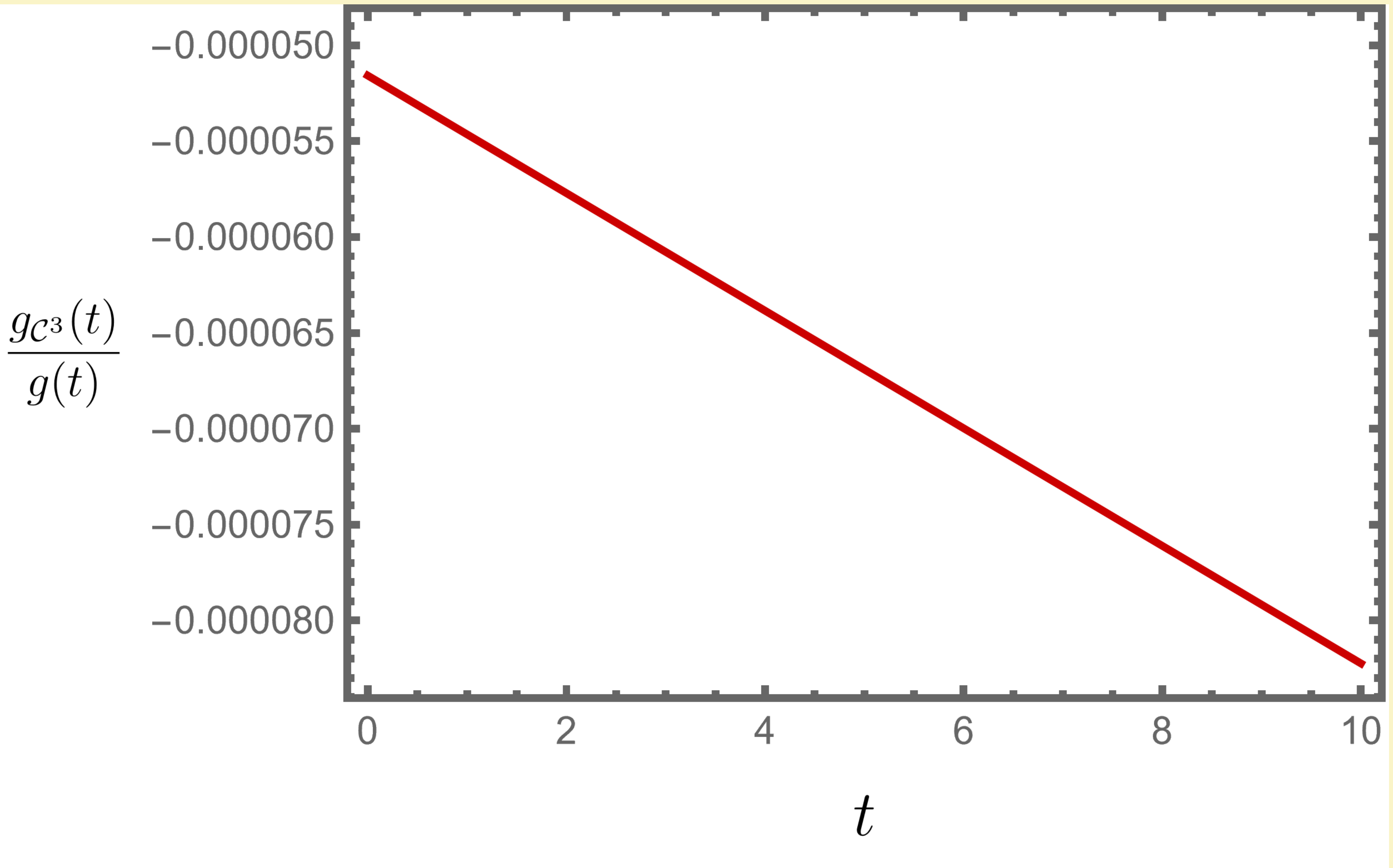
Identifying the Wilson coefficients as the IR limit of the FRG running couplings

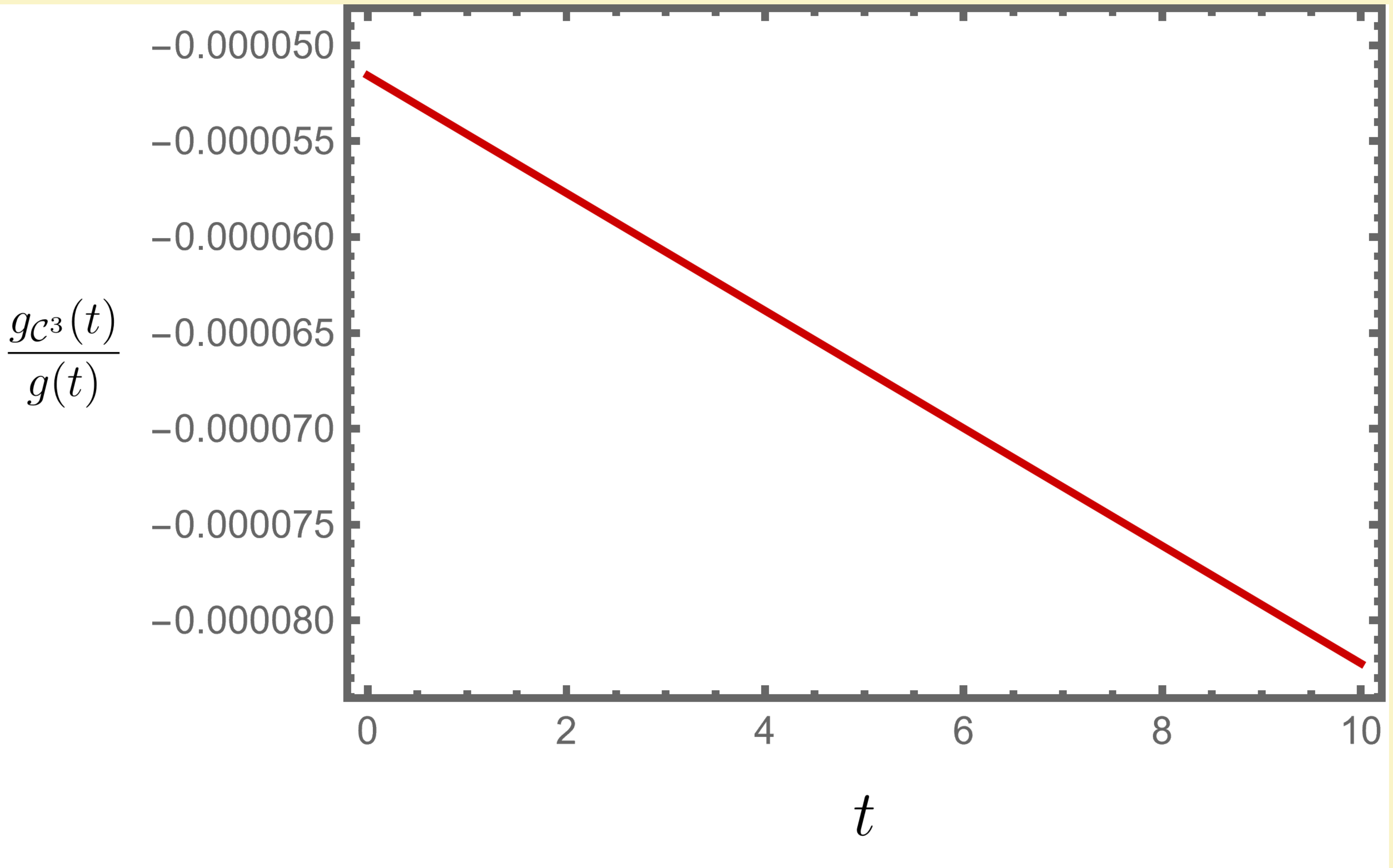
$$\boxed{\frac{G_{\mathcal{C}^3}}{G_{\mathrm{N}}} = \lim_{k\to 0} \frac{G_{\mathcal{C}^3}(k)}{G_{\mathrm{N}}(k)} = \lim_{k\to 0} \frac{g_{\mathcal{C}^3}(k)}{g(k)}}$$



$$g_{\mathcal{C}^3}(k) = g_{\mathcal{C}^3,\mathrm{IR}} \left(\frac{k}{k_0}\right)^2 \left[1 + b \log\left(\frac{k}{k_0}\right)\right]$$

$$g(k) = g_{\mathrm{IR}} \left(\frac{k}{k_0}\right)^2$$

Logarithmic running of the Goroff-Sagnotti coupling



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Logarithmic running of the Goroff-Sagnotti coupling

Integration of **massless fluctuations**

Logarithmic form factors in the quantum effective action $\boxed{\log\left(\Box/\Lambda^2_{\mathrm{QG}}\right)}$

transition scale to the QG regime

$$\boxed{g_{\mathcal{C}^3}(k) = g_{\mathcal{C}^3,\mathrm{IR}} \left(\frac{k}{k_0}\right)^2 \left[1 + b \log\left(\frac{k}{k_0}\right)\right]}$$

$$\mathcal{L} = \frac{1}{2\kappa^2}\left(R + \eta\kappa^4 R_{\mu\nu}{}^{\rho\sigma} R_{\rho\sigma}{}^{\lambda\tau} R_{\lambda\tau}{}^{\mu\nu}\right)$$

Local EFT, no logarithmic form factors

Open problem in EFT: ambiguity in the definition of Wilson coefficients in the presence of massless fluctuations

[Alberte, de Rahm, Jaitly, Tolley '20]
[Herrero-Valea, Santos-Garcia, Tokareva '22]

<u>Decouple logarithmic running to identify constant part</u>

[Basile, Platania, '21]
[Knorr, Platania, '24]

Introduce an ambiguity in determining the IR limit. **Need to fix the transition scale**

$$\boxed{g_{\mathcal{C}^3}(k) = g_{\mathcal{C}^3,\mathrm{IR}}\left(\frac{k}{k_0}\right)^2\left[1 + b\,\log\left(\frac{k}{k_0}\right)\right]}$$

Fundamental realization of ASQG: the **Planck mass** is the only scale naturally appearing

Remove the logarithmic running

$$\frac{G_{\mathcal{C}^3}|_{k_0=M_{\mathrm{Pl}}}}{G_{\mathrm{N}}} = \frac{g_{\mathcal{C}^3}(k)}{g(k)} - g_{\mathcal{C}^3,\mathrm{IR}}\, b\log\left(\frac{k}{M_{\mathrm{Pl}}}\right)$$

$$C_{\rho a \rho b} \propto \rho^{\gamma-2} \qquad \gamma = 2 + \eta\gamma^{(6)}$$

$$\frac{G_{\mathcal{C}^3}|_{k_0=M_{\rm Pl}}}{G_{\rm N}} > 0$$

A fundamental realization of ASQG yields the right sign to **avoid the divergence of tidal forces**

What in a scenario of Effective ASQG?

Departing from the Planck mass

Consider $\boxed{\mathbf{k_0 = \xi M_{Pl}}}$

When eliminating the logarithmic running

$$\frac{G_{\mathcal{C}^3}\big|_{k_0=M_{\rm Pl}}}{G_{\rm N}} = \frac{g_{\mathcal{C}^3}(k)}{g(k)} - g_{\mathcal{C}^3,\rm IR}\, b\log\left(\frac{k}{M_{\rm Pl}}\right)$$

$$g_{\mathcal{C}^3}\big|_{k_0} = g_{\mathcal{C}^3}\big|_{M_{\rm Pl}} + g_{\mathcal{C}^3,\rm IR}\, b\log(\xi)$$

Consider $\mathbf{k_0} = \xi \mathbf{M_{Pl}}$

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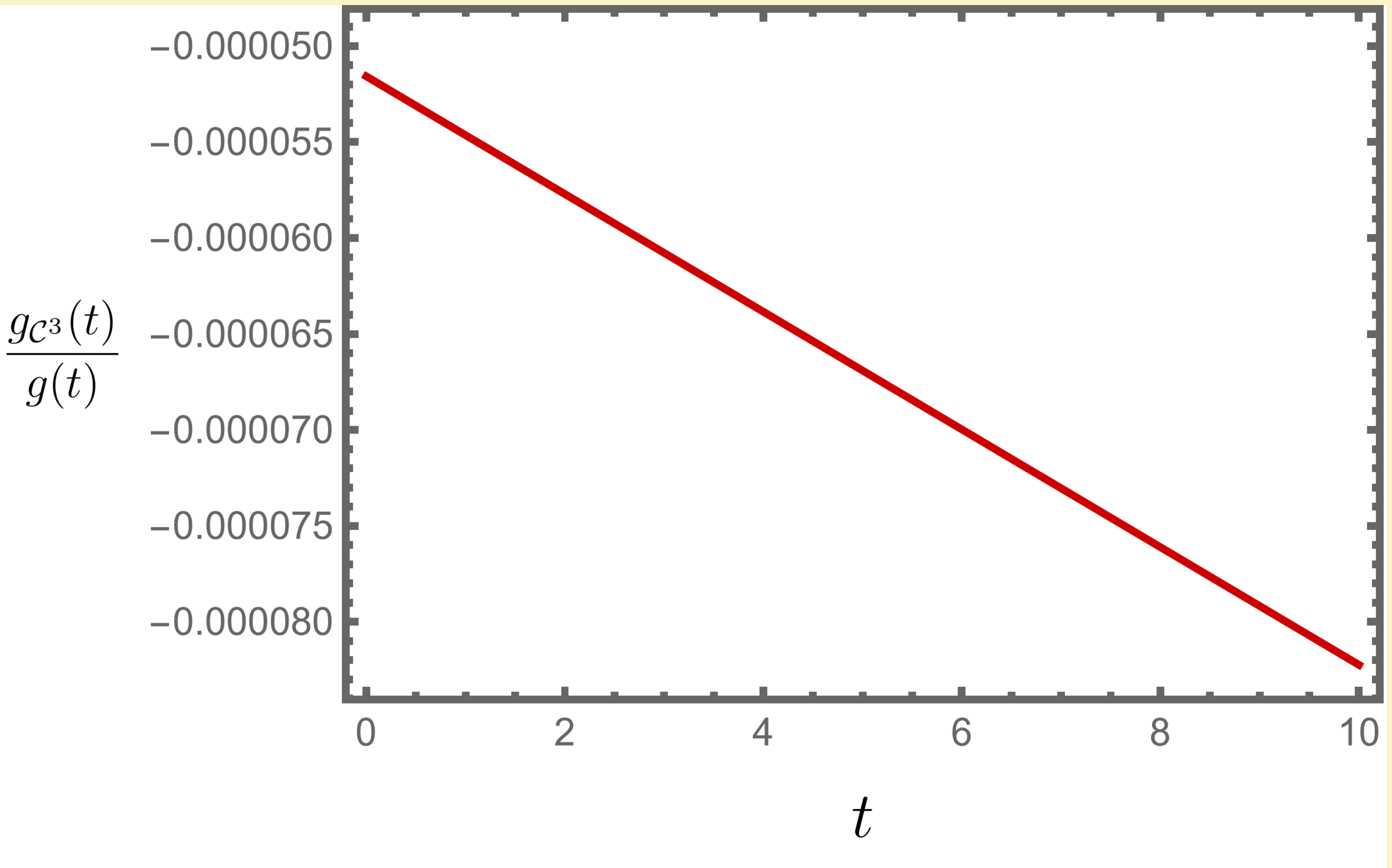
$$\frac{G_{\mathcal{C}^3}|_{k_0=M_{\rm Pl}}}{G_{\rm N}} = \frac{g_{\mathcal{C}^3}(k)}{g(k)} - g_{\mathcal{C}^3,\rm IR}\, b \log\left(\frac{k}{M_{\rm Pl}}\right)$$



<0

$$g_{\mathcal{C}^3}|_{k_0} = g_{\mathcal{C}^3}|_{M_{\rm Pl}} + g_{\mathcal{C}^3,\rm IR}\, b \log(\xi)$$

Demanding regularity on the horizon is equivalent to setting a **lower bound on the transition scale**

$$\boxed{k_0 \gtrsim \mathcal{O}(10^{-1}) M_{\mathrm{Pl}}}$$

Expected in a fundamental realization of ASQG

If a low-energy realization of String Theory, its characteristic transition scale would need to lie **below the string scale**

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Expected in a fundamental realization of ASQG

If a low-energy realization of String Theory, its characteristic transition scale would need to lie **below the string scale**

Sub-Planckian

Divergence of tidal forces on the horizon!

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A fundamental realization of ASQG predicts regular tidal forces on the horizon

Regularity of tidal forces imposes a lower bound on the QG scale. Within an effective realization of ASQG, tidal divergences may reappear

On the log running: repeating the analysis w/ logarithmic form factors in the QEA

Thank you for your attention

2509.07058 w/ F. Del Porro, A. Platania

Wick rotation: from Euclidean to Lorentzian

The RG is performed in Euclidean signature

$$\boxed{g^{(t)}_{\mu\nu} = g_{(L)\mu\nu} + 2tX_\mu X_\nu}$$

Wick rotation revisited: ~~analytical continuation of time~~

analytical continuation of the metric

- The EH term flips sign for how the metric determinant and the analytic continuation combine together (with the requirement that the action densities yield the same weight)

- The Goroff-Sagnotti term keeps the same sign because the internal contractions cancel all minus signs

On the fixed point scale

Recast the gravitational beta functs allowing for generic FP values

$$\beta_g = 2g\left(1 - \frac{g}{g_*}\right) \qquad \beta_\lambda = -2\lambda + 4\frac{g\lambda_*}{g_*} - 2\frac{g\lambda}{g_*}$$

Extract approx solutions for the running gravitational cps

$$\boxed{g(k) = \frac{G_{N,0}k^2}{1 + g_*^{-1}G_{N,0}k^2}}$$

Identify the scale at which g(k) enters the FP regime

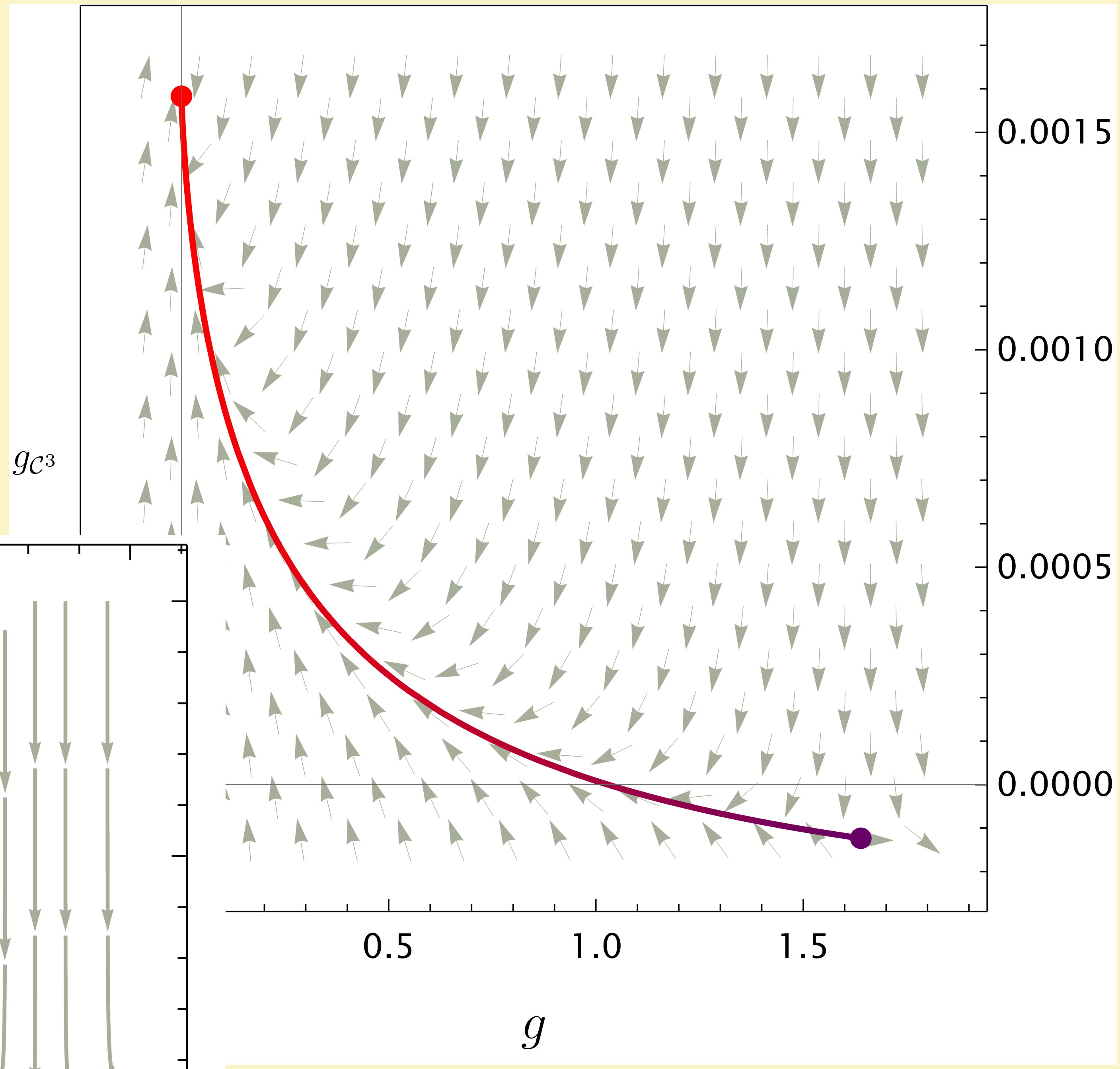
$$\boxed{k_{\rm FP} = \sqrt{g_*}M_{\rm Pl}}$$

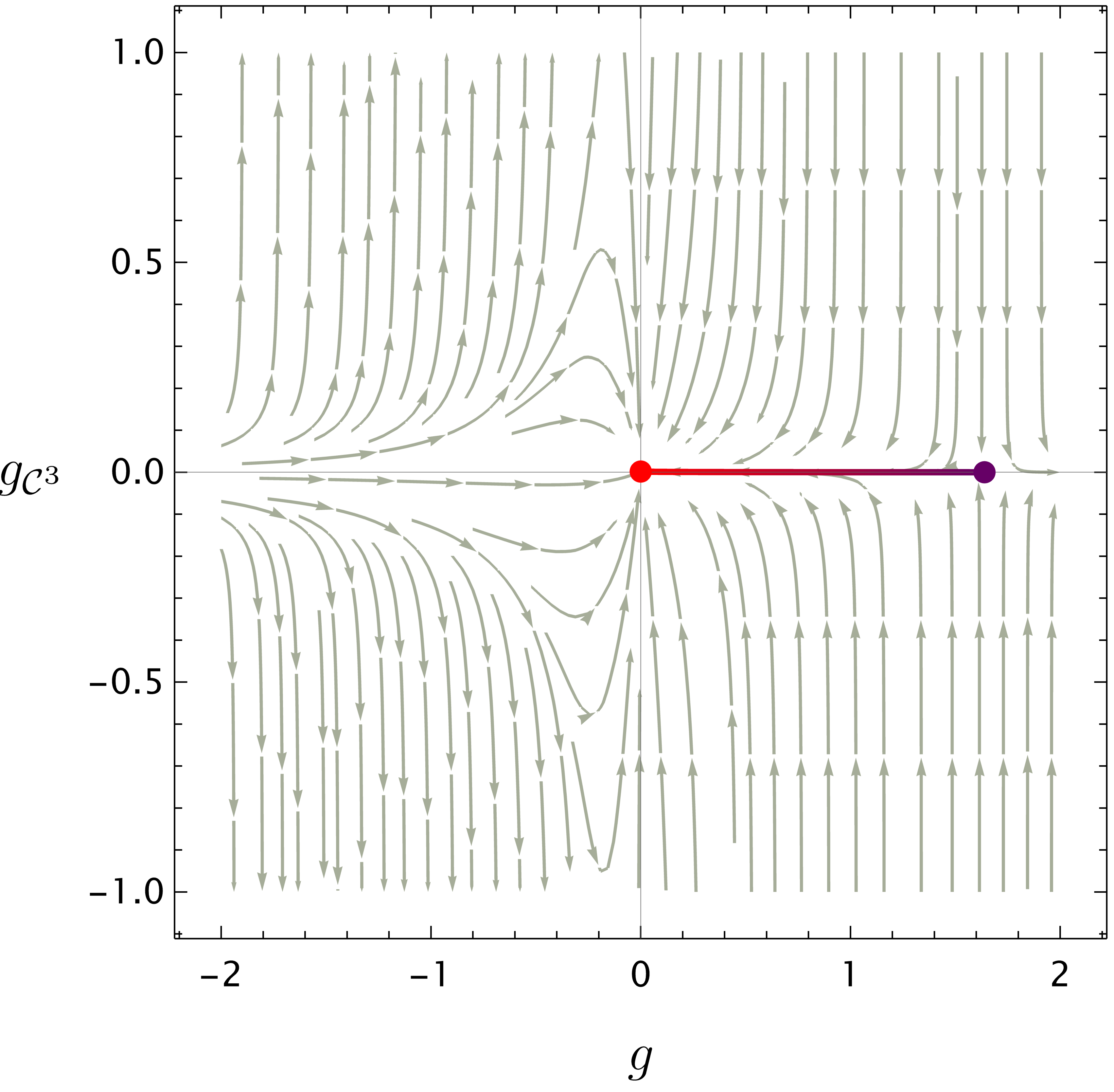
The transition scale to the FP is universal: also for the cc!

$$g(k_{\rm FP}) = \tfrac{1}{2}g_*$$

Different regularization scheme

Shifted Gaussian fixed point





Considering the ratio of the **deviations from the FP values**

$$\frac{G_{\mathcal{C}^3}|_{k_0=M_{\rm Pl}}}{G_{\rm N}} = \boxed{\frac{g_{\mathcal{C}^3}(k) - g_{\mathcal{C}^3,0}}{g(k)}} - g_{\mathcal{C}^3,\rm IR}\, b \log\left(\frac{k}{M_{\rm Pl}}\right)$$

Same qualitative behavior since the two flows share the same UV physics

$$\frac{G_{\mathcal{C}^3}|_{k_0=M_{\rm Pl}}}{G_{\rm N}} > 0$$

$$k_0 \gtrsim \mathcal{O}(10^{-1}) M_{\rm Pl}$$

Beyond pure gravity

With a U(1) additional field

Tidal divergences are unavoidable for D≥5

Same argument as before, from **WGC** and BH thermodynamics considerations

In ASQG, the WGC is mildly violated

Remarks on the sign of η

One loop contributions from massive states are not enough, need a UV completion of gravity & matter

k-running *vs* p-running

Within the FRG flow, k is an auxiliary coarse-graining scale. It orders how you integrate out fluctuations.

The physical momentum dependence is encapsulated in the form factors of the full EAA

The whole machinery reads off the Wilson coefficients by going to the k->0 limit, and $\Gamma_{k\to 0}$ reduces to the ordinary effective action. **It encodes all the physical p-dependence**

Caveat with truncations…

Transition scale in ST and species scale

In order to achieve weak coupling, the species scale needs to be below the Planck mass

$$M_{\mathrm{Pl}}/\sqrt{N_{\mathrm{sp}}}$$

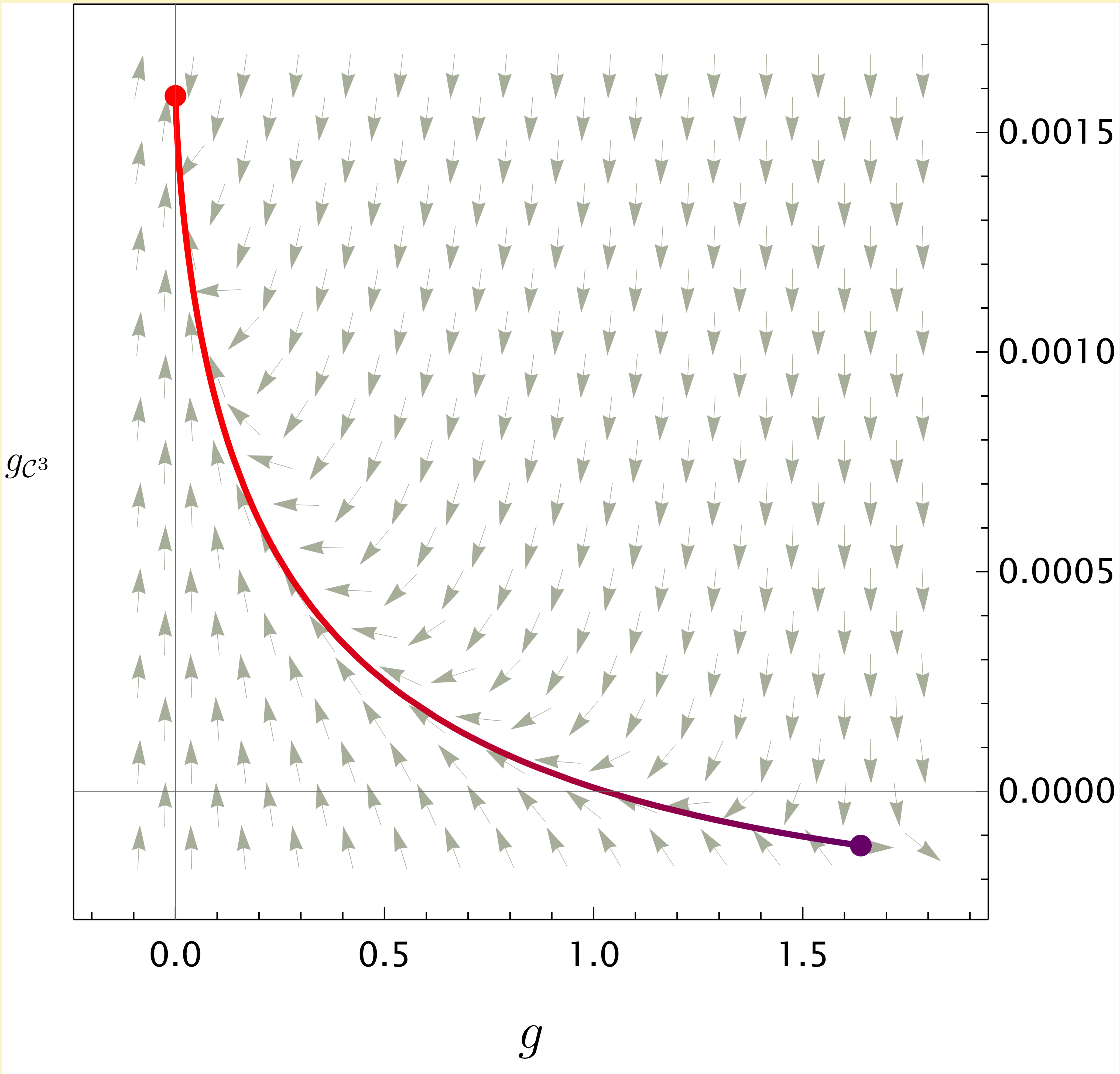
Number of species interacting w/ gravity

If the QG scale is above the Planck mass, the theory is inherently nonperturbative

Classicalization effects? Formation of BHs for energies above -> Observables beyond Planck

Shifted Gaussian Fixed Point

[Del Porro, Ferrarin, Platania, '25]



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Canonical mass-dimension scaling but the GFP is **shifted**

Ansatz for the behavior of the couplings in the IR limit

$$g_{\mathcal{C}^3}(k) = \boxed{g_{\mathcal{C}^3,0}} + g_{\mathcal{C}^3,\mathrm{IR}} \left(\frac{k}{k_0}\right)^2 \left[1 + b \log\left(\frac{k}{k_0}\right)\right]$$

$$g(k) = g_{\mathrm{IR}} \left(\frac{k}{k_0}\right)^2$$

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Since the GFP is shifted, the ratio displays a $1/k^2$ behavior

On the $1/k^2$ behavior: **physical or unphysical?**

Approximating k-running with p-running: IR non-localities of the $1/\Box$-type? [Knorr, Saueressig '18]

If there are IR non-localities: observational bounds? [Maggiore '16]

Divergence in the entropy of BHs? If not highly fine-tuned [Platania, Redondo-Yuste '23]

Loophole favoring thermodynamic interpretation of BHs in QFTs [Basile, Knorr, Platania, Schiffer '25]

After discussion with B. Knorr: **tracing it to the regularization?** in [Baldazzi, Falls, Kluth, Knorr, '23]

If the divergence is unphysical

Possible prescription: **subtract the divergent part by hand**

$$\boxed{\frac{g_{C^3}(k) - g_{C^3,0}}{g(k)}}$$

Alternatively: adopt a **regularization with "natural" endomorphisms** [Knorr, '21]

Provided a modified version of the beta functions of [Baldazzi, Falls, Kluth, Knorr, '23]

The GFP is not shifted