SMEFT meets quantum gravity

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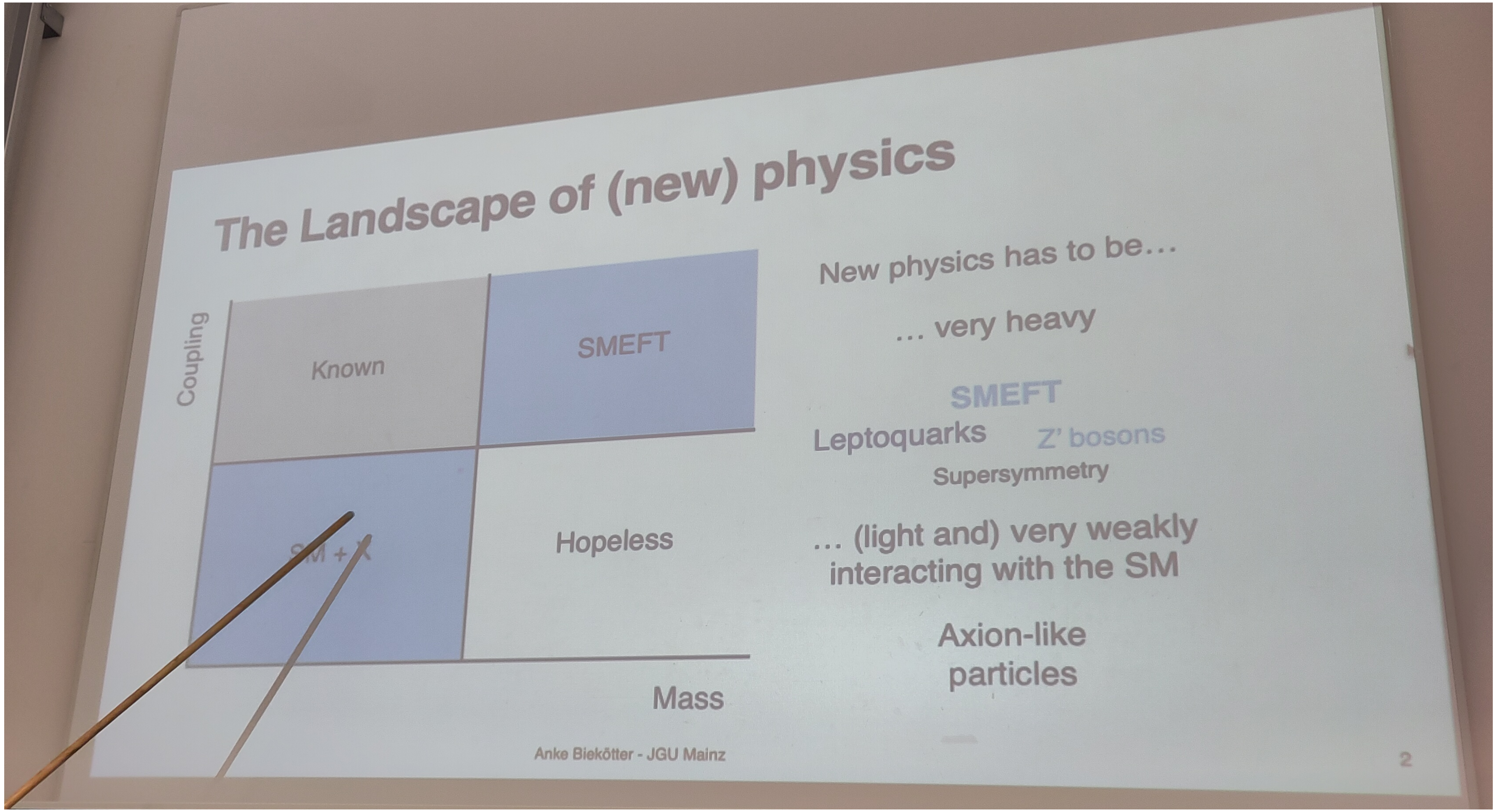
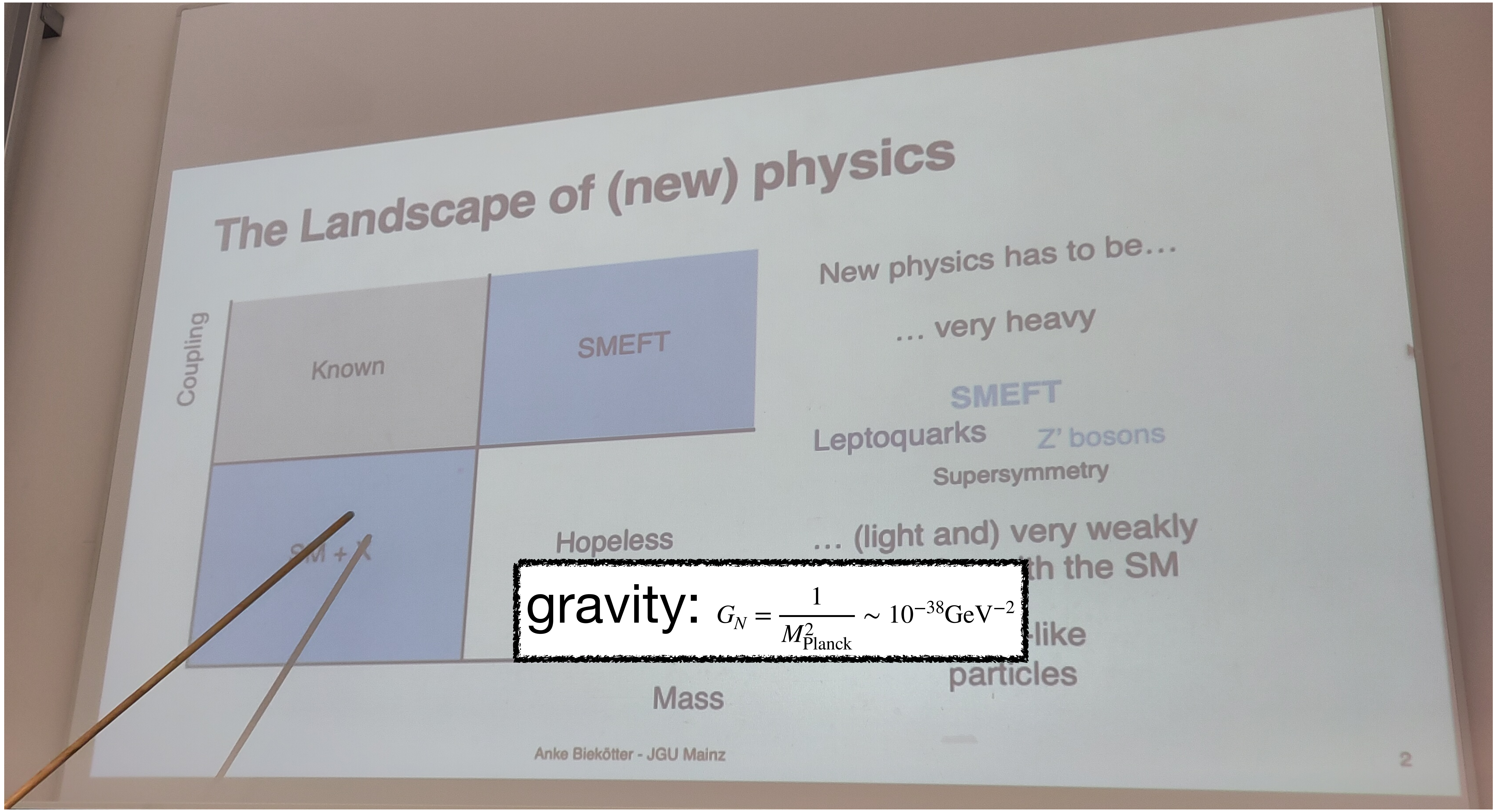
8th General Meeting of the LHC EFT working group, December 3, 2024

New physics


The Landscape of (new) physics
Coupling
Known
SMEFT
SM + X
Hopeless
Mass
New physics has to be…
… very heavy
SMEFT
Leptoquarks
Z' bosons
Supersymmetry
… (light and) very weakly interacting with the SM
Axion-like particles
Anke Biekötter - JGU Mainz
2

New physics



gravity: $G_N = \frac{1}{M_{\text{Planck}}^2} \sim 10^{-38}\text{GeV}^{-2}$

Asymptotic safety: Lightning introduction

- quantum field theory of the metric $\rightarrow$ quantize just like the other fundamental forces
- perturbative non-renormalizability: breakdown of predictivity
- asymptotic safety = quantum scale symmetry

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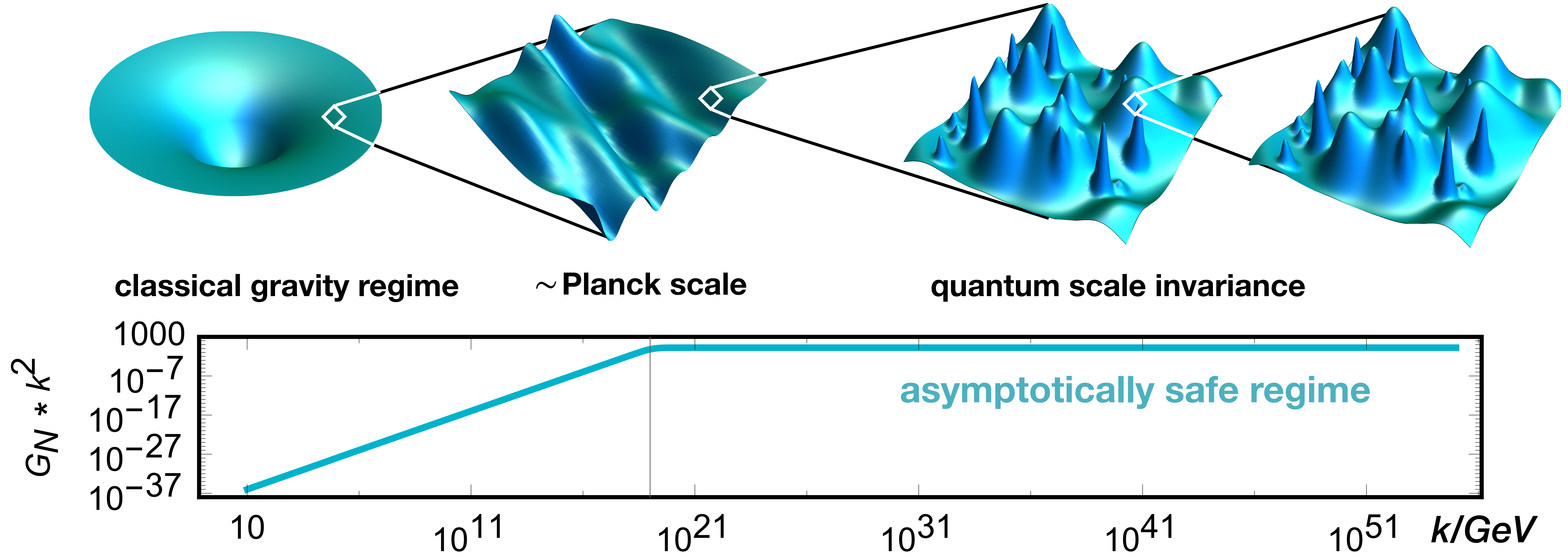

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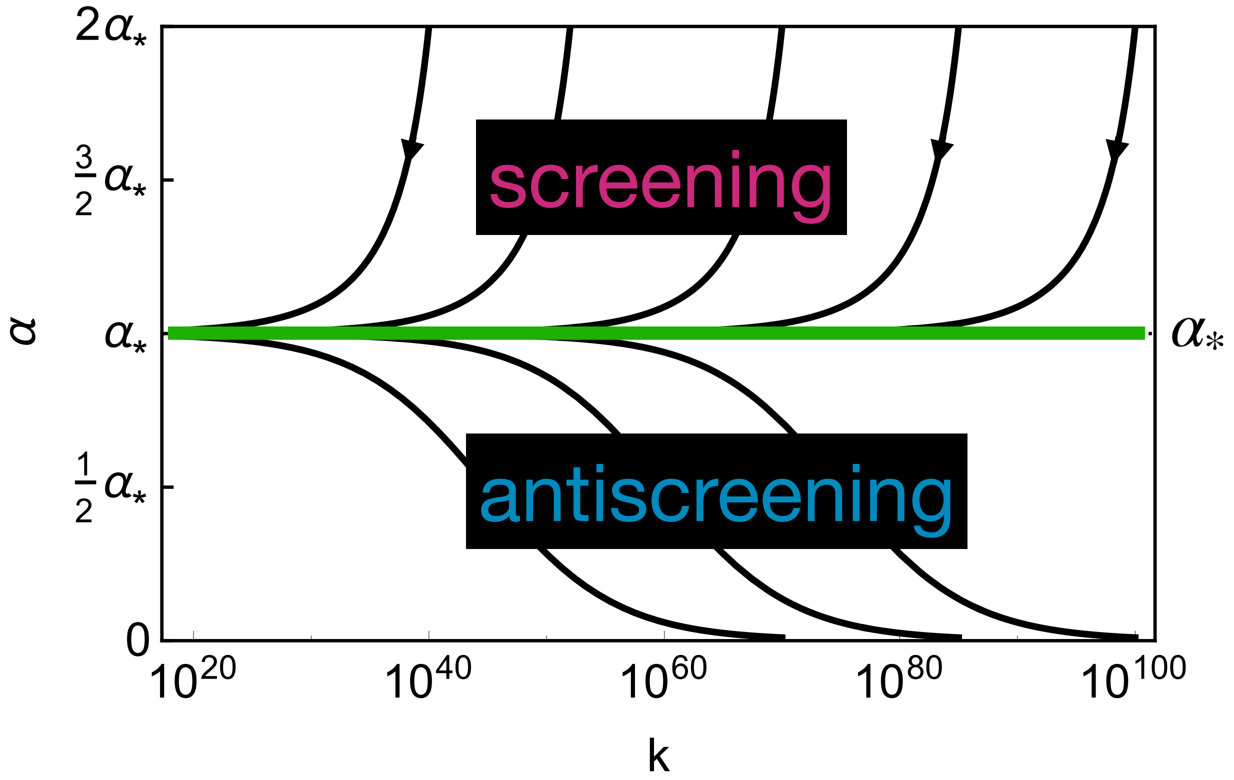
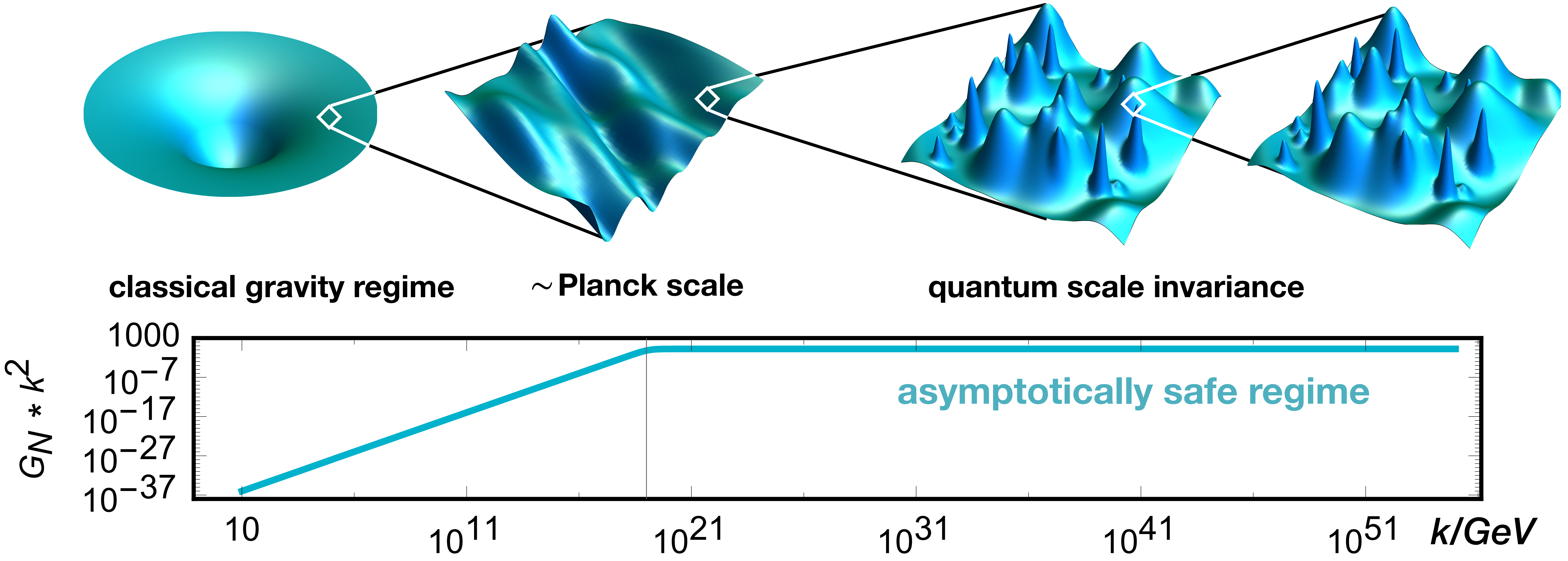
→ restore predictivity

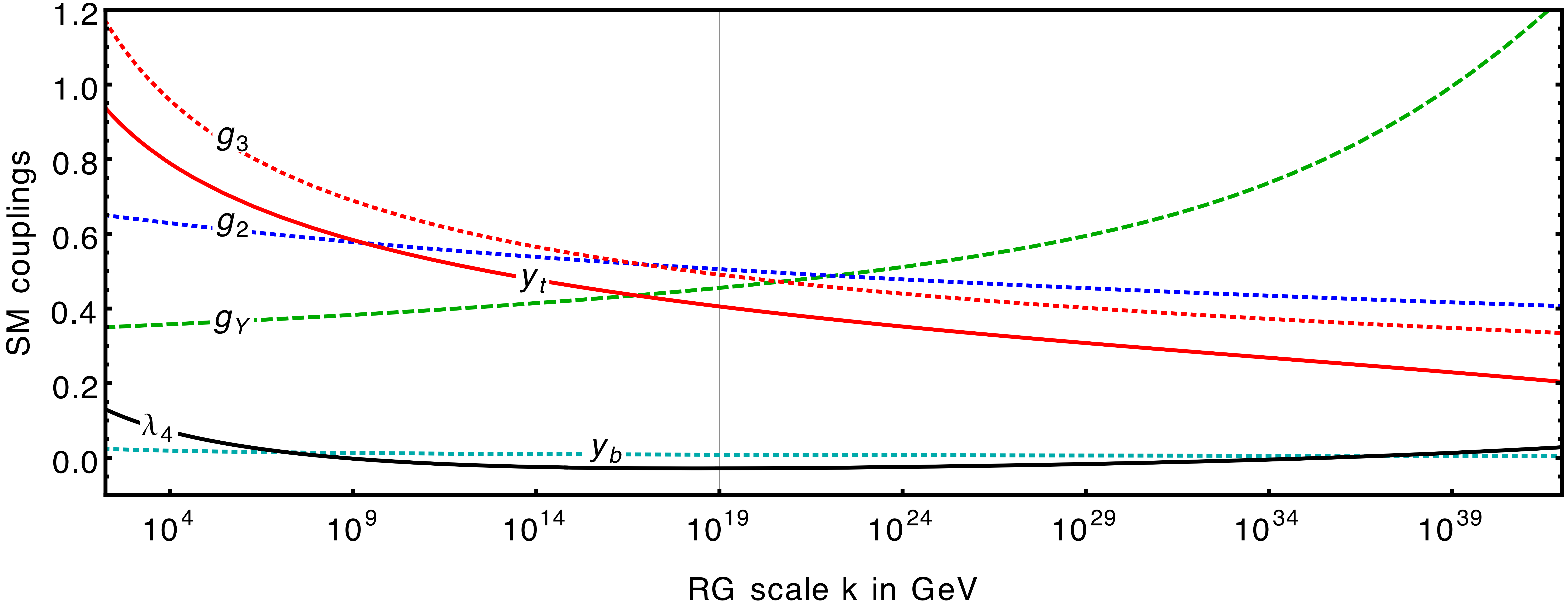


$$\beta_\alpha = \alpha\,(-\alpha_* + \alpha)$$

quantum fluctuations drive coupling **towards** scale symmetry



Asymptotically safe Standard Model



without gravity:

- not ultraviolet complete (Landau pole/triviality problem)
- measured values are free parameters

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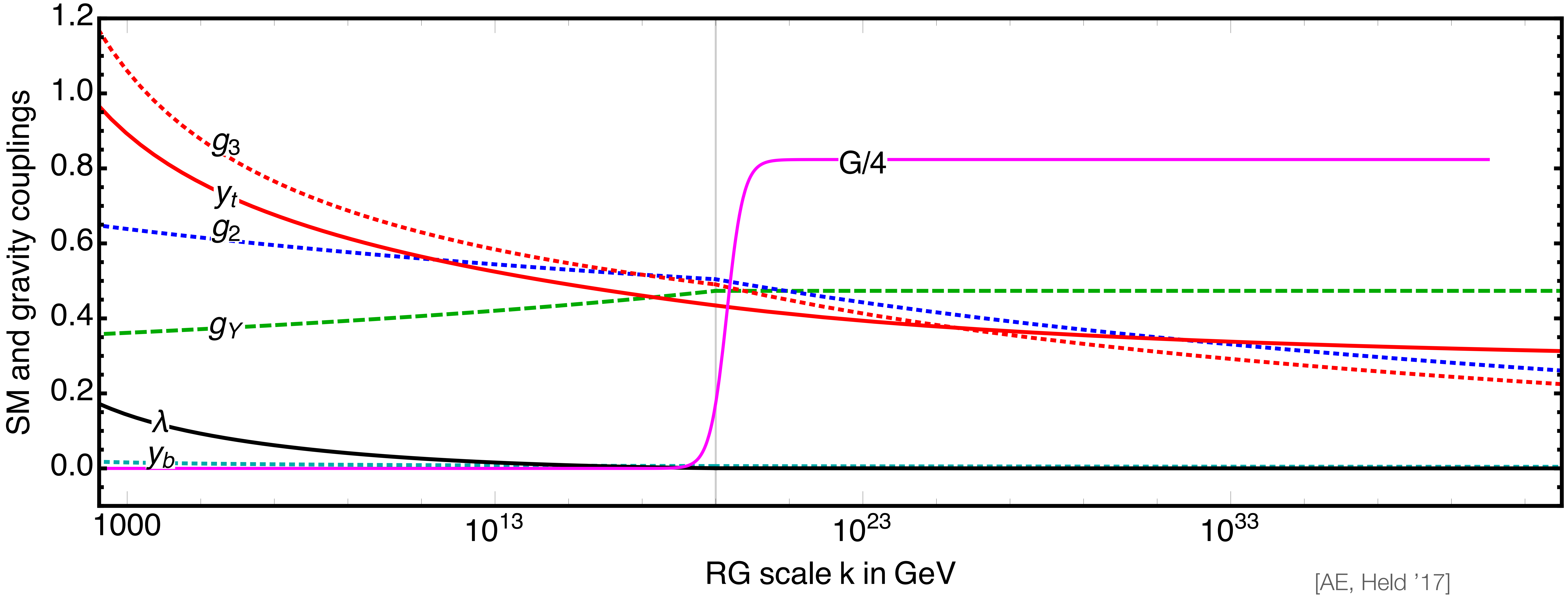

[AE, Held '17]

without gravity:
- not ultraviolet complete (Landau pole/triviality problem)
- measured values of couplings are free parameters

with gravity: indications that
- ultraviolet complete (no Landau poles)
- measured values of some (not all) couplings are predicted/bounded from above

work by many groups: de Brito, Gies, Held, Knorr, Kowalska, Litim, Percacci, Pereira, Reichert, Reuter, Saueressig, Wetterich, Yamada

reviews: AE '18; AE, Schiffer '22

Asymptotically safe gravity meets SMEFT

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Transplanckian scales:

- Asymptotically safe gravity unavoidably generates higher-order interactions that are part of the SMEFT
- Not all SMEFT interactions nonzero to first approximation (e.g., no B-violating interactions)

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- Positivity bounds provide nontrivial consistency-check for asymptotic safety

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    - scenario I: essentially zero at LHC scales
    - scenario II (speculative): non-zero due to intermediate fixed-point regime

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No “smoking gun” for gravity, but consistency tests

SMEFT interactions in asymptotic safety: transplanckian regime

- generation mechanism: [AE, Gies ’11; AE ’12; AE, Held ’17; Christiansen, AE ‘17]

  gravity cannot be decoupled.

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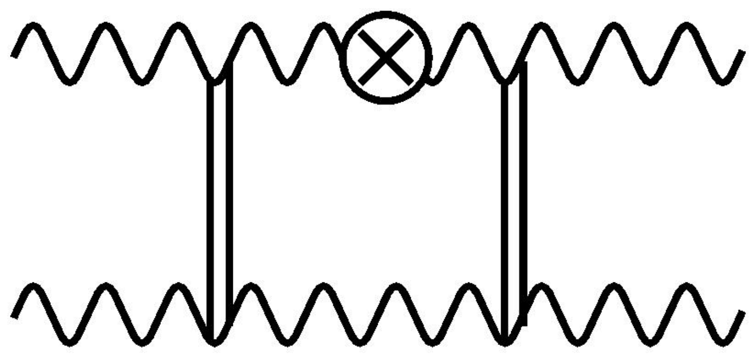
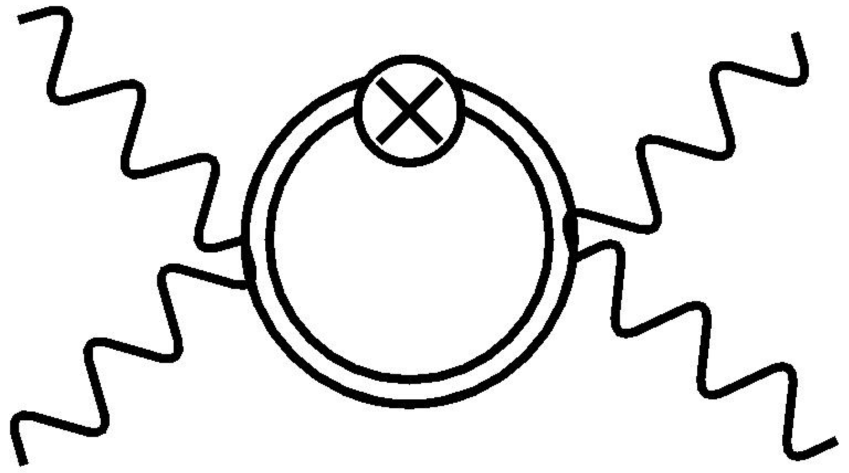
  example: gravity generates photon-interactions

$$\eta_{\mu\nu}\eta^{\kappa\lambda}F_{\mu\nu}F_{\nu\lambda} \to \sqrt{g}\,g^{\mu\nu}g^{\kappa\lambda}F_{\mu\kappa}F_{\nu\lambda}$$





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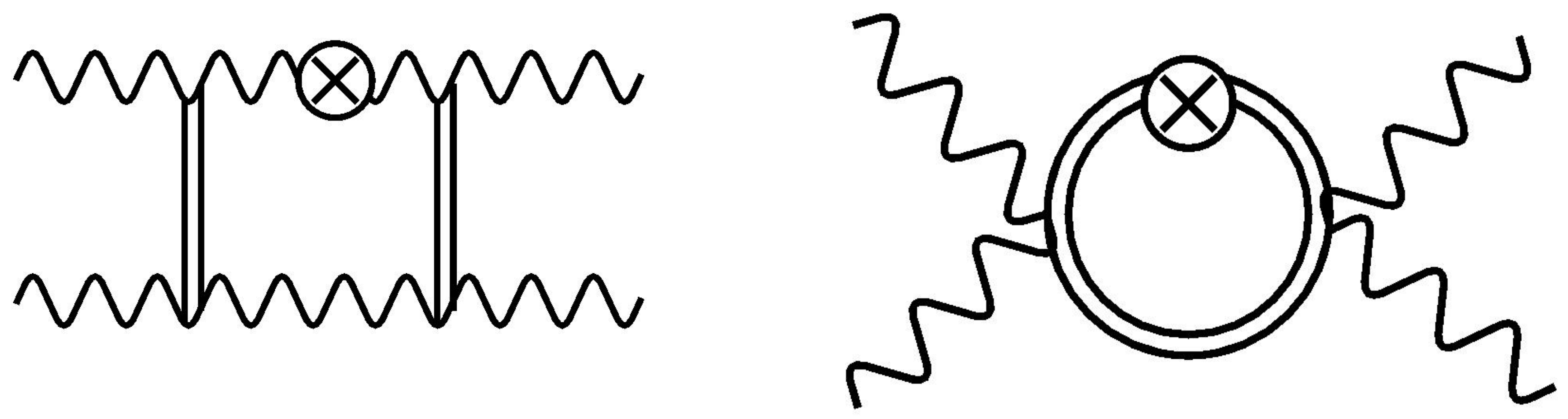
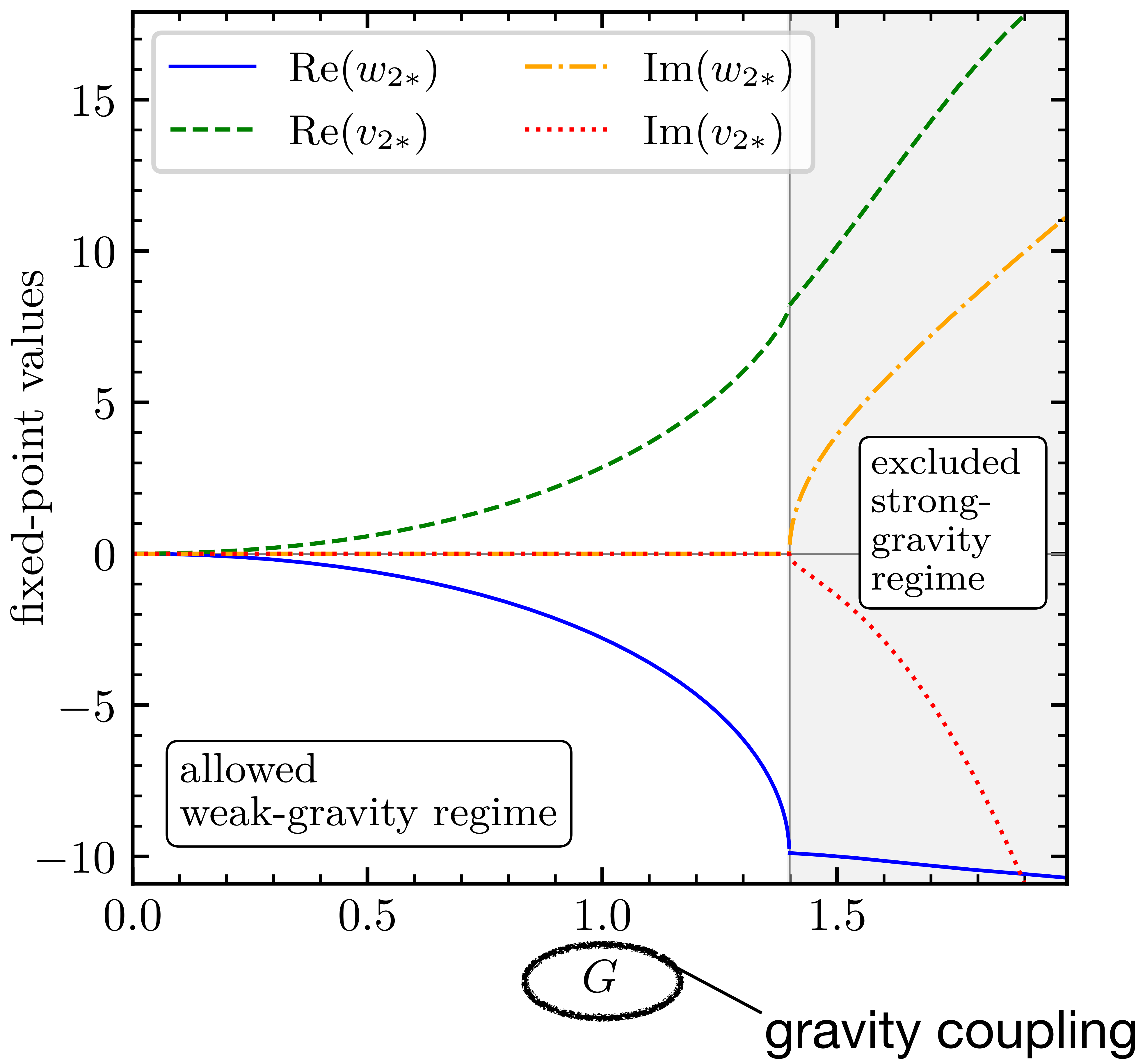


$\to w_2\left(F^2\right)^2$ with $w_2 \neq 0$



[AE, Kwapisz, Schiffer '21]

SMEFT interactions in asymptotic safety: transplanckian regime

Current status: no studies in full SMEFT, instead simplified studies (e.g. without flavor-structure)

operator dimension	Gauge sector	Scalar sector	Fermion sector	Mixed
dimension 5	-		no proton decay in asymptotic safety AE, Ray '23	
dimension 6	not generated in asymptotic safety	not generated in asymptotic safety	$\left(\bar{\psi}\gamma_\mu\psi\right)^2$ AE, Gies '11; Meibohm, Pawlowski '16; de Brito, AE, Schiffer '20; de Brito, AE, Ray '23	not generated in asymptotic safety
dimension 8	$\left(F_{\mu\nu}F^{\mu\nu}\right)^2, F_{\mu\nu}F^{\nu\kappa}F_{\kappa\lambda}F^{\mu\lambda}$ Christiansen, AE '17, AE, Schiffer (+) '19, '21, '24 Knorr, Platania '24	$\left(\partial_\mu\phi\partial^\mu\phi\right)^2$ AE '12; de Brito, AE, L. d. Santos '21, Laporte, Pereira, Saueressig, Wang '21, de Brito, Knorr, Schiffer '23		$\left(\bar{\psi}\gamma_\mu\nabla^\mu\psi\right)\left(\partial_\nu\phi\partial^\nu\phi\right)$ AE, Held '17
dimension 10 or higher	$\left(F_{\mu\nu}F^{\mu\nu}\right)^3$ AE, Schiffer '24	$\left(\partial_\mu\phi\partial^\mu\phi\right)^n$ de Brito, Knorr, Schiffer '23		

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Only those interactions which share the symmetries of the kinetic terms are induced

SMEFT interactions in asymptotic safety: transplanckian regime

SMEFT @ dim 6

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

no-global-symmetries conjecture:
no evidence in asymptotic safety

reviewed in: [AE, Schiffer '22
AE, Hebecker, Pawlowski, Walcher '24]

⇒ only interactions with the symmetries of kinetic terms are necessarily present

⇒ other terms to first approximation zero, unless quantum gravity changes scaling dimension from irrelevant to relevant; however: so far no evidence for this

SMEFT interactions in asymptotic safety: transplanckian regime

SMEFT @ dim 6: 4-fermion couplings

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

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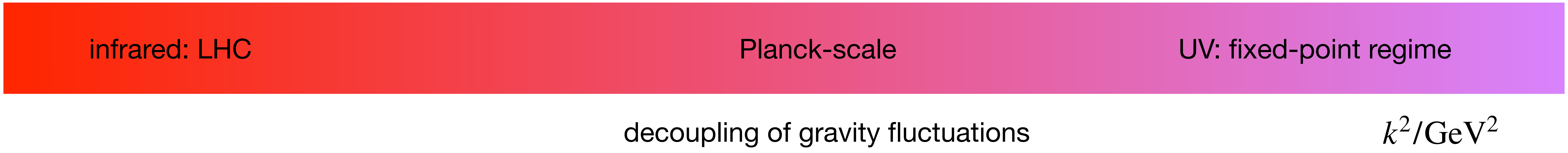
AE, Ray '23

Implications for Wilson coefficients at LHC energies

Functional Renormalization Group: k^2 sets infrared cutoff in Euclidean path integral



Implications for Wilson coefficients at LHC energies

Functional Renormalization Group: k^2 sets infrared cutoff in Euclidean path integral

infrared: LHC | Planck-scale | UV: fixed-point regime

decoupling of gravity fluctuations

k^2/GeV^2

$$\Gamma_k = \int d^4x \sum_i \bar{g}_i(k)\mathcal{O}_i^{(6)} + \dots \xrightarrow{k^2\to 0} \Gamma = \int d^4x \mathscr{L}_{\rm EFT}$$

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda_{\rm NP}^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda_{\rm NP}^4}\mathcal{O}_i^{(8)} + \dots$$

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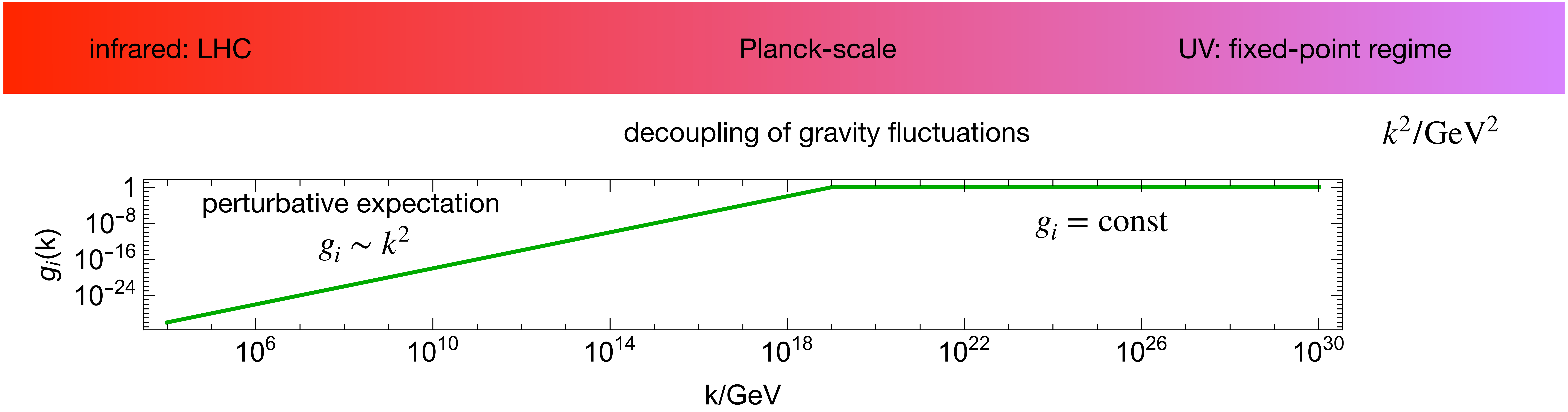

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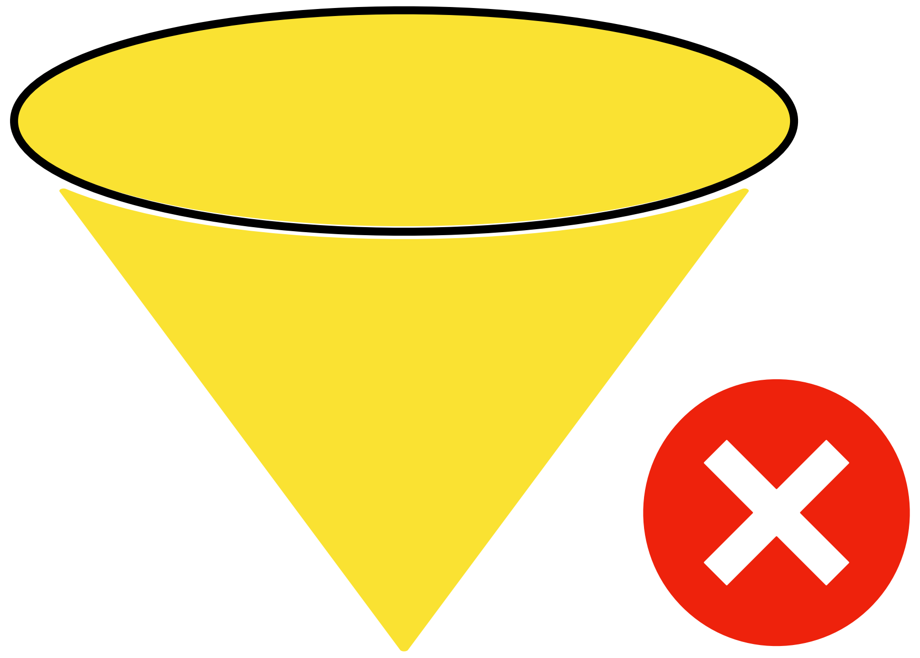
$$\bar{g}_i(k) = \frac{g_i(k)}{k^2} \xrightarrow{k^2 \to 0} \frac{c_i}{\Lambda_{\mathrm{NP}}^2} = \frac{g(M_{\mathrm{Planck}})}{M_{\mathrm{Planck}}^2}$$

SMEFT interactions in asymptotic safety: positivity bounds

$$\mathcal{L}_k = \frac{1}{4}F^2 + \frac{w_2}{k^4}\left(F^2\right)^2 + \frac{h_2}{k^4}F^4$$

Positivity bounds from causality in the IR

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



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

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

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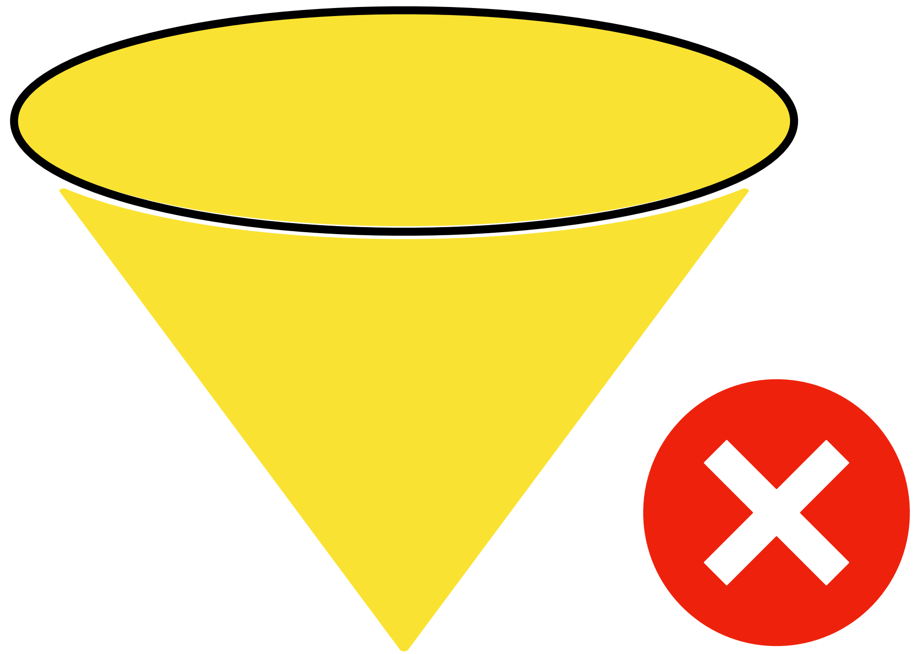

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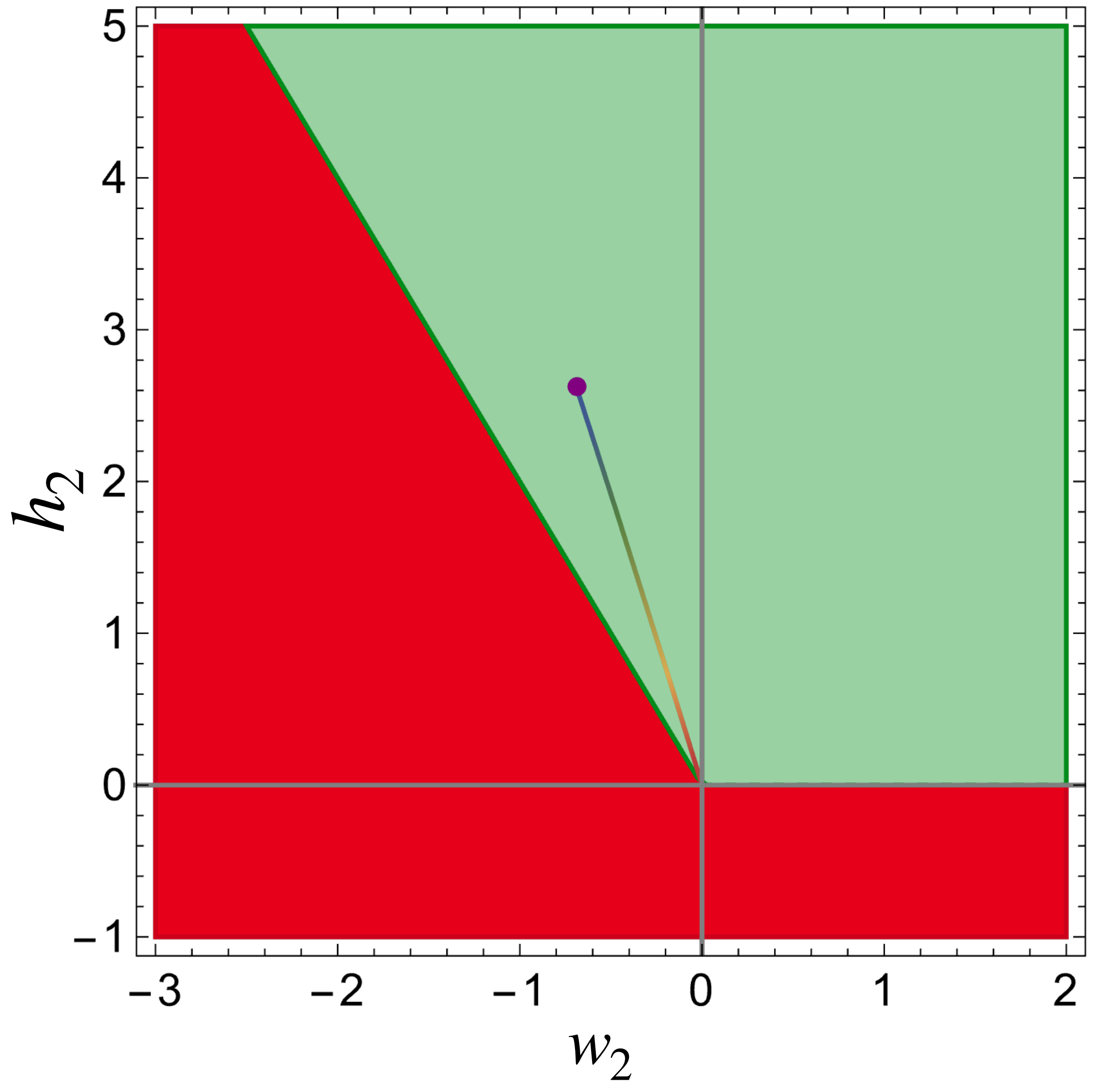

asymptotic safety avoids propagation outside the lightcone

[AE, Pedersen, Schiffer ’24;

see also
Knorr, Platania ’24]

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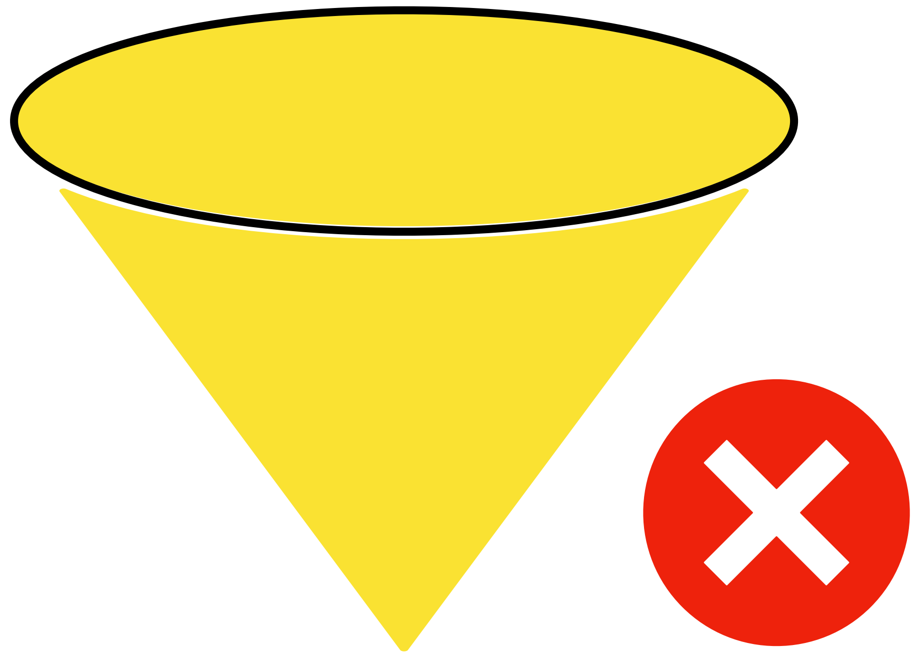

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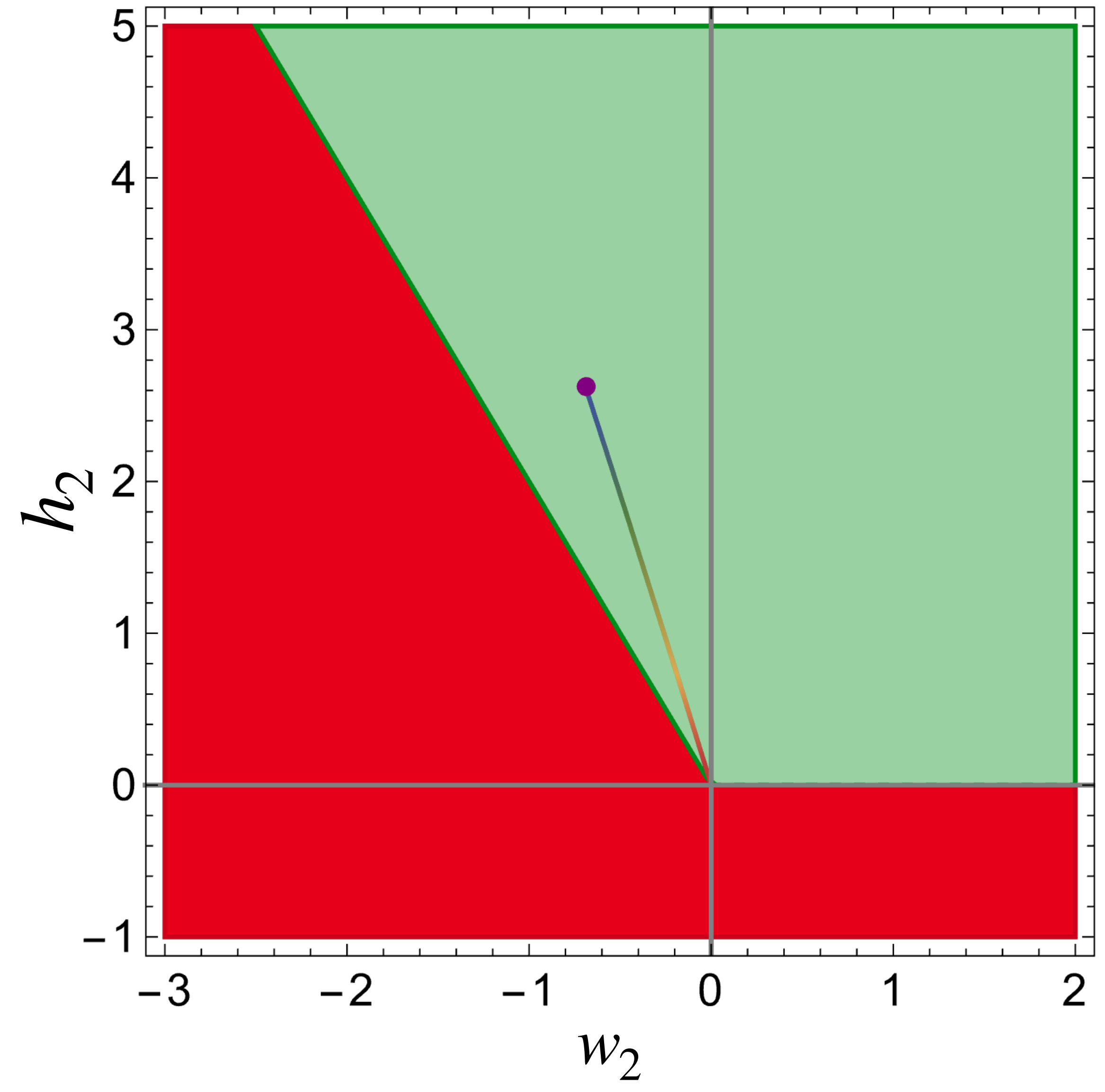

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see also
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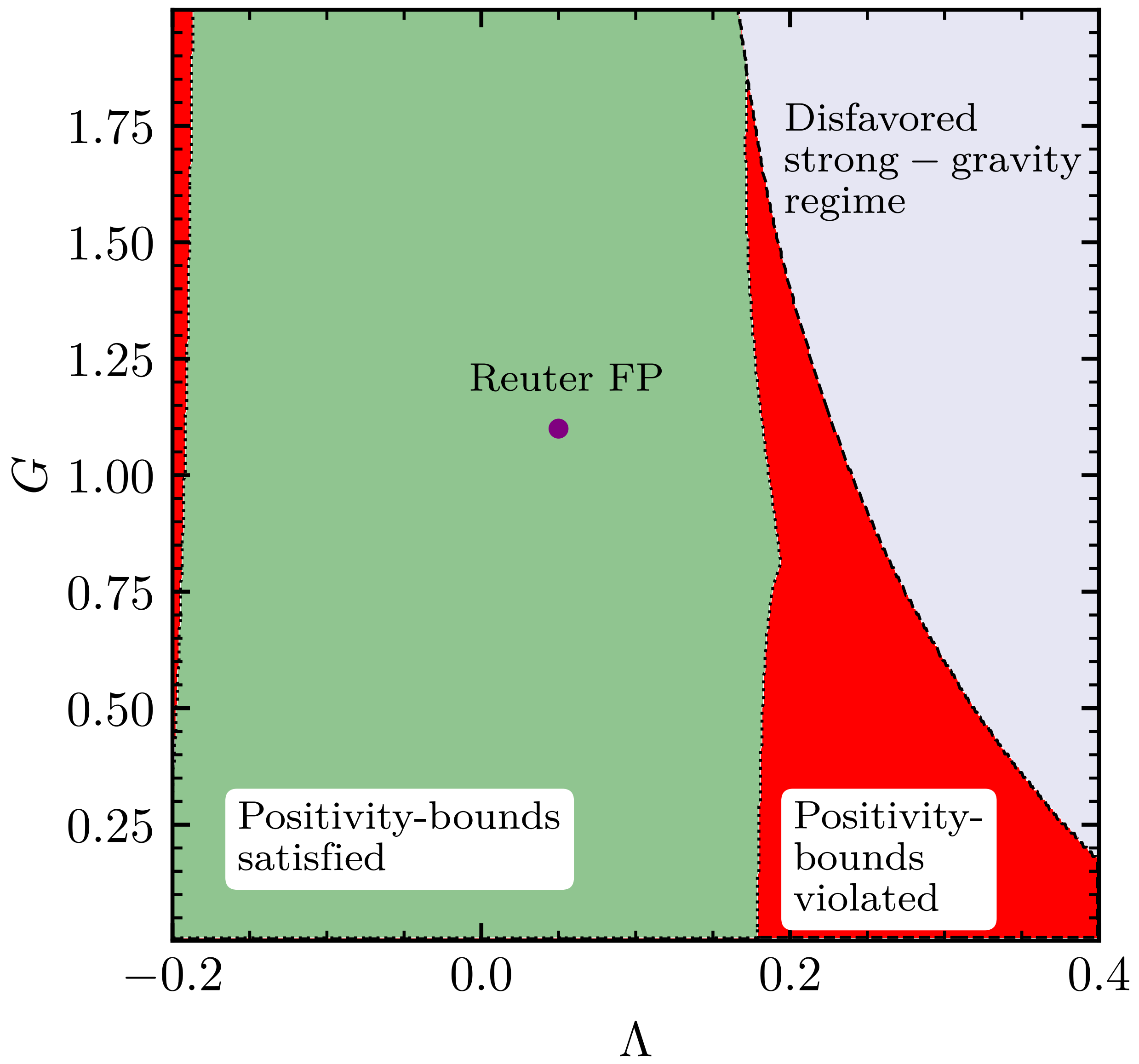
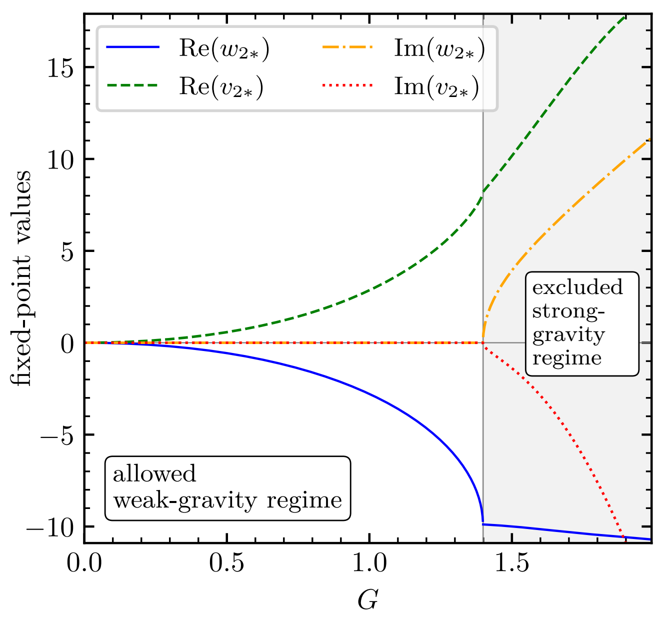


reminder:



SMEFT interactions in asymptotic safety: below-planckian regime

Four-fermion interactions

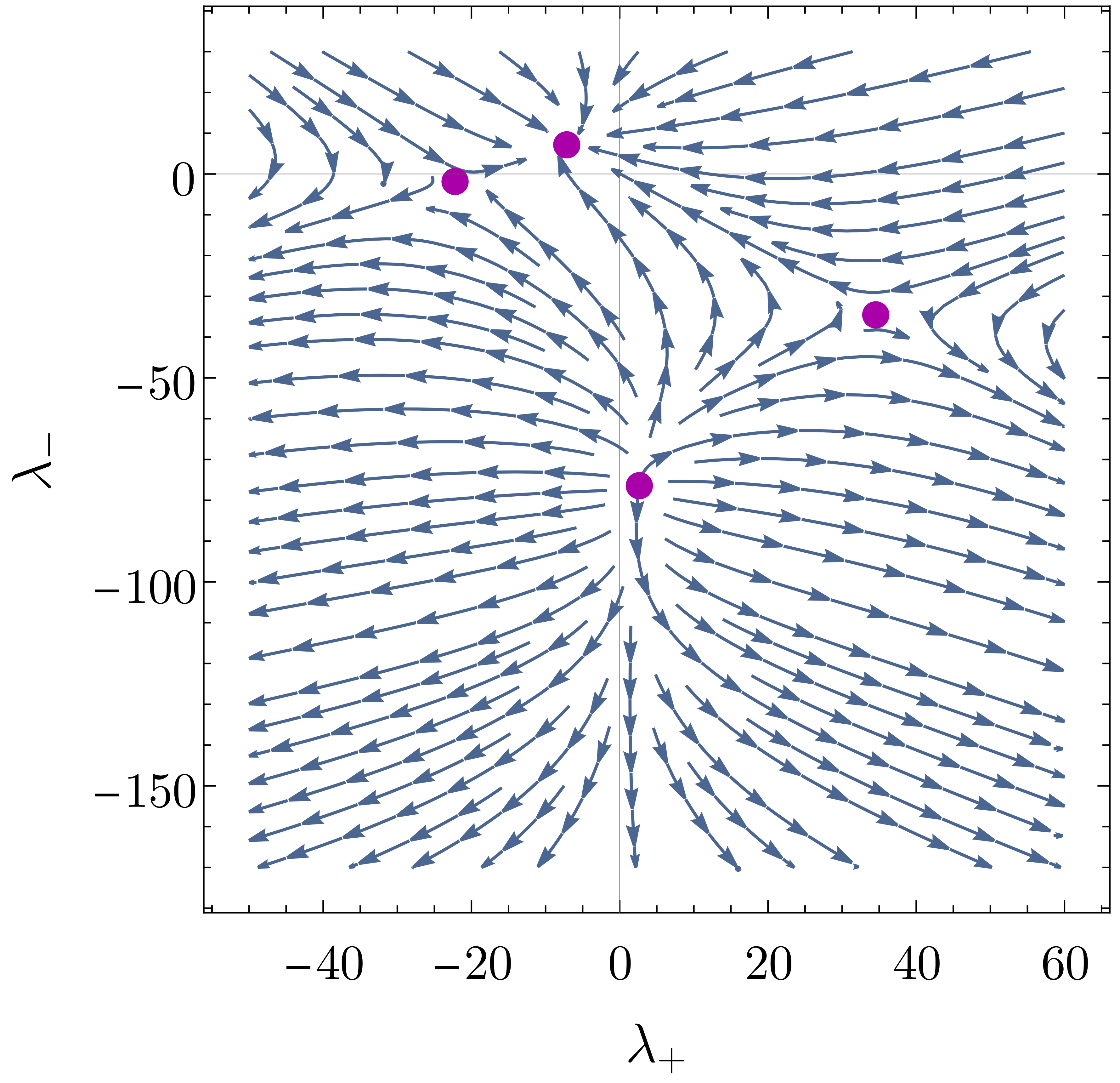
Toy model with two fermion species (no color, flavor, charge): $\bar{\lambda}_{\pm} = \dfrac{\lambda_{\pm}}{k^2} \rightarrow \dfrac{c_{4-f}}{\Lambda_{\rm NP}^2}$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Renormalization Group flow with gravity

[AE, Gies ’11; Meibohm, Pawlowski ’16;
de Brito, AE, Schiffer ’20; de Brito, AE, Ray ’23]



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Potential implications for SMEFT (assuming a "desert")

[Brenner, Chikkaballi, AE, Ray '24]

- Scenario I: $\lambda_{\pm} \sim k^2$ for $k^2 < M_{\rm Planck}^2$;
  thus $\Lambda_{\rm NP} \sim M_{\rm Planck}$

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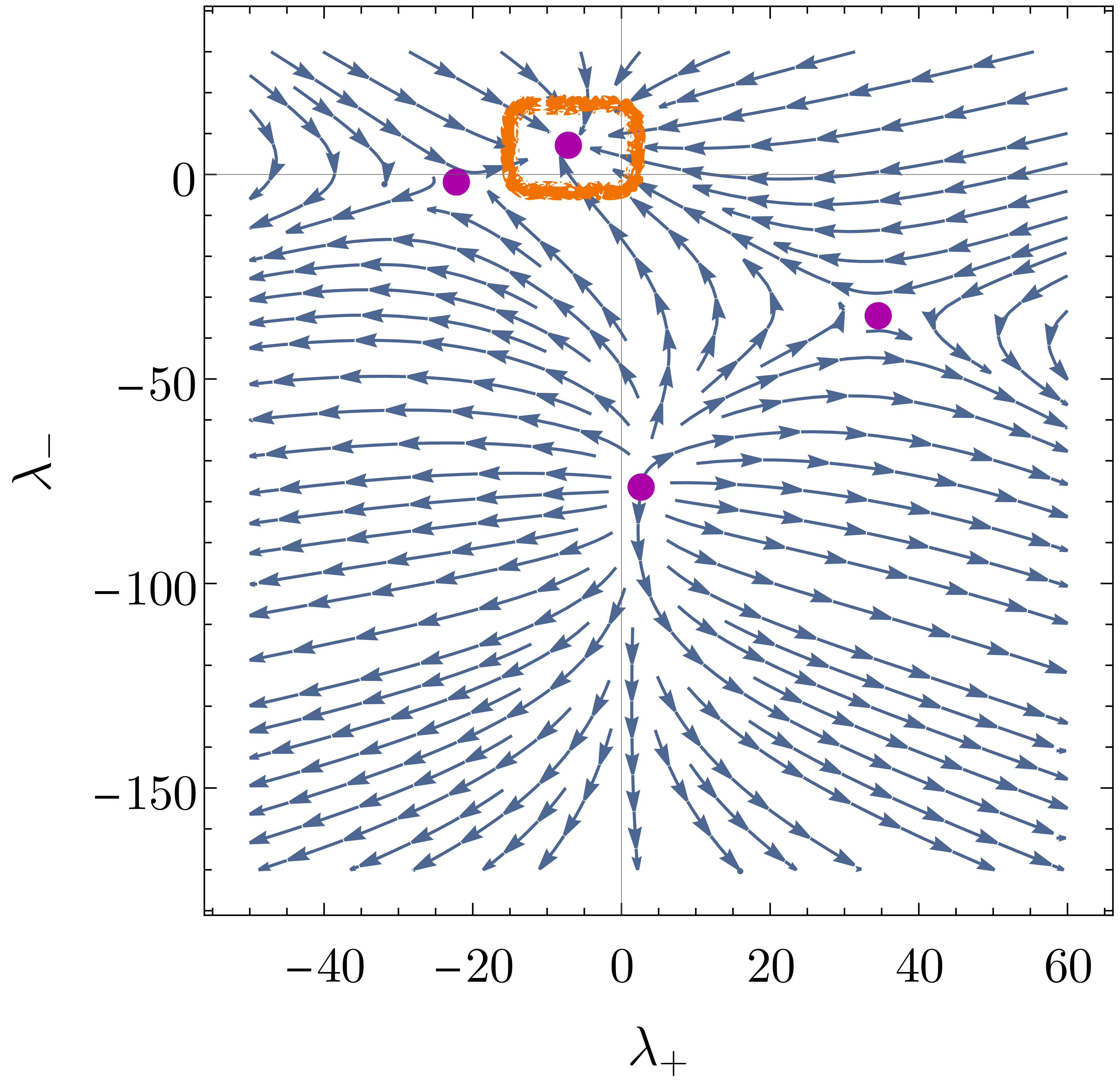

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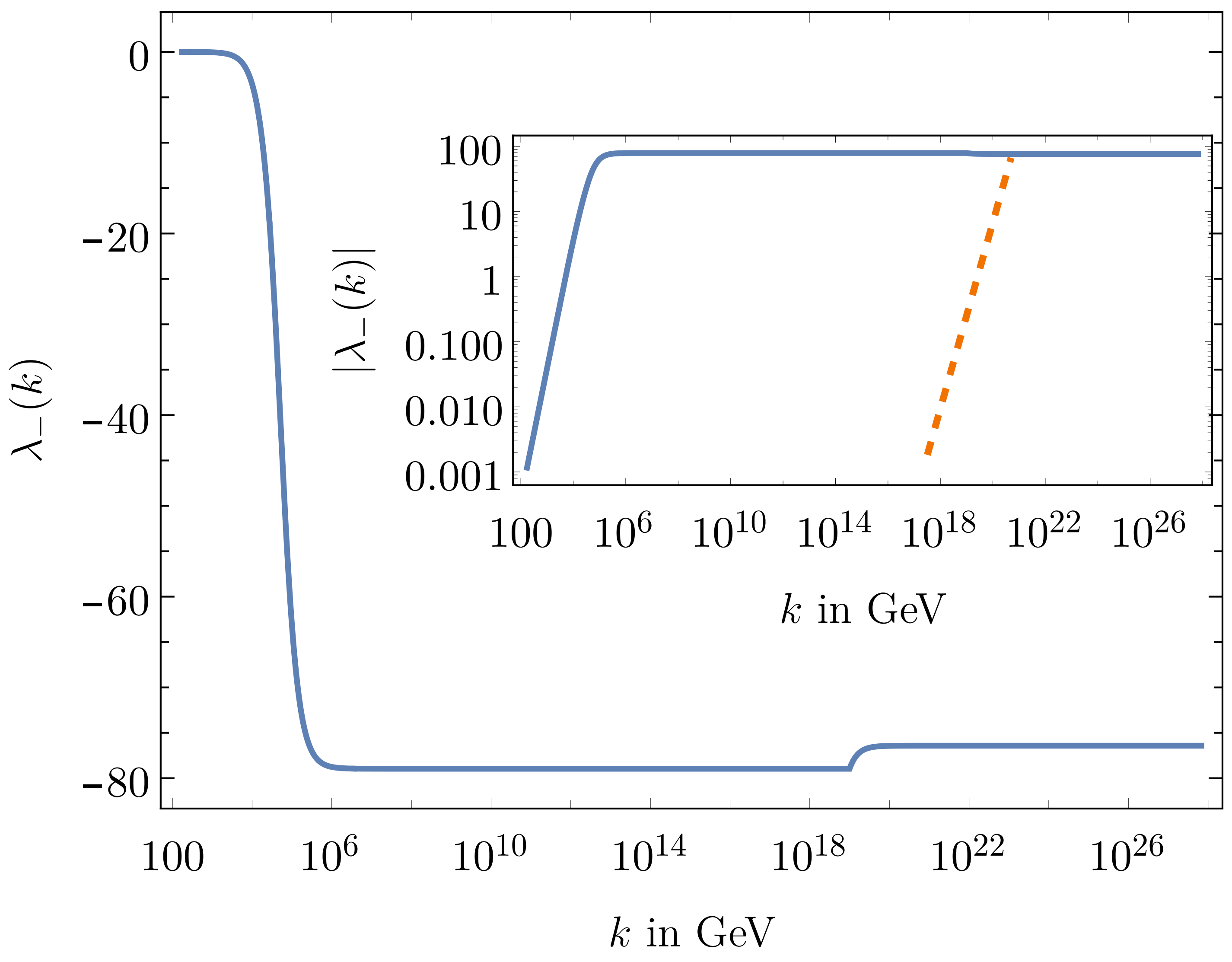
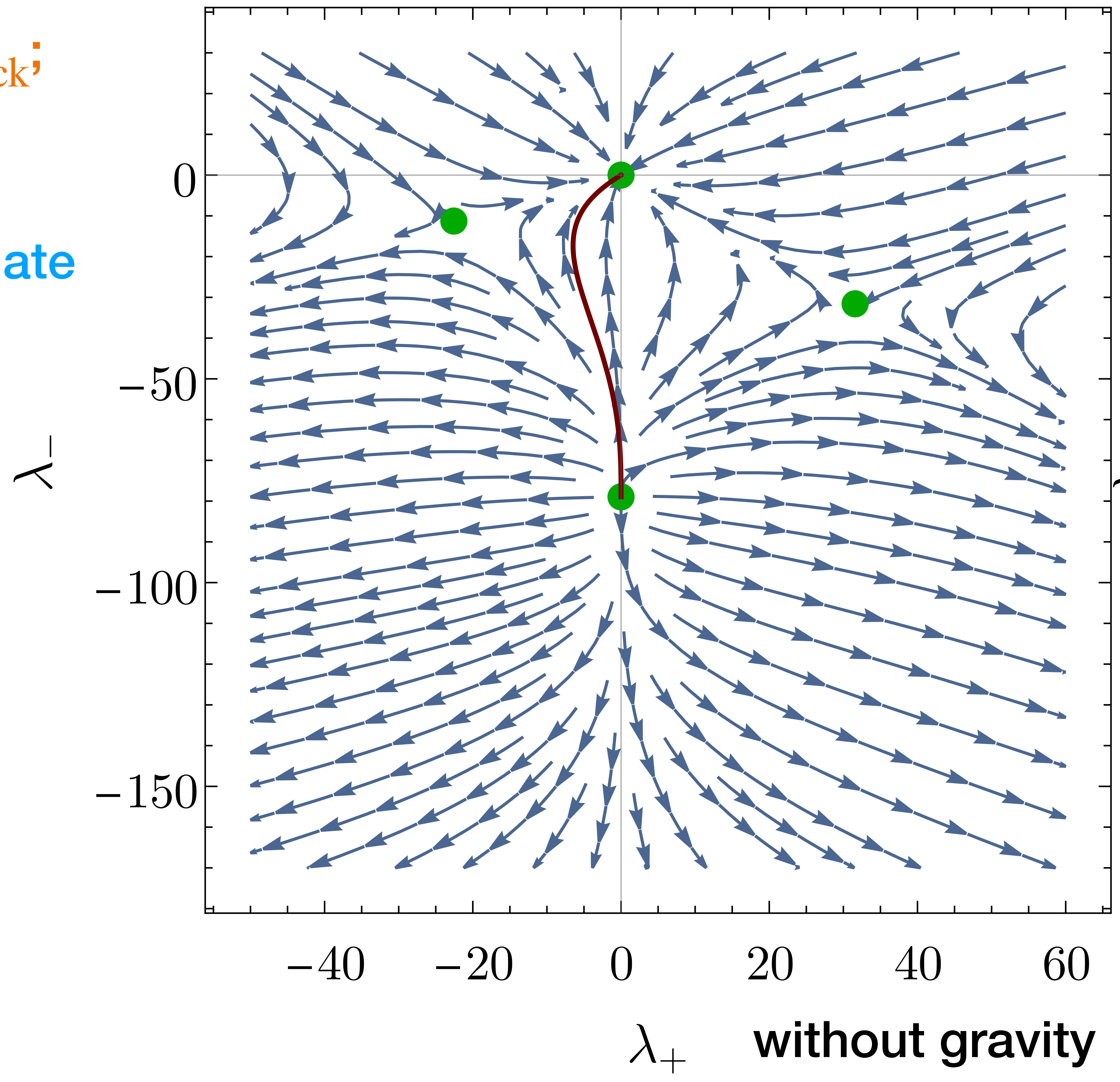
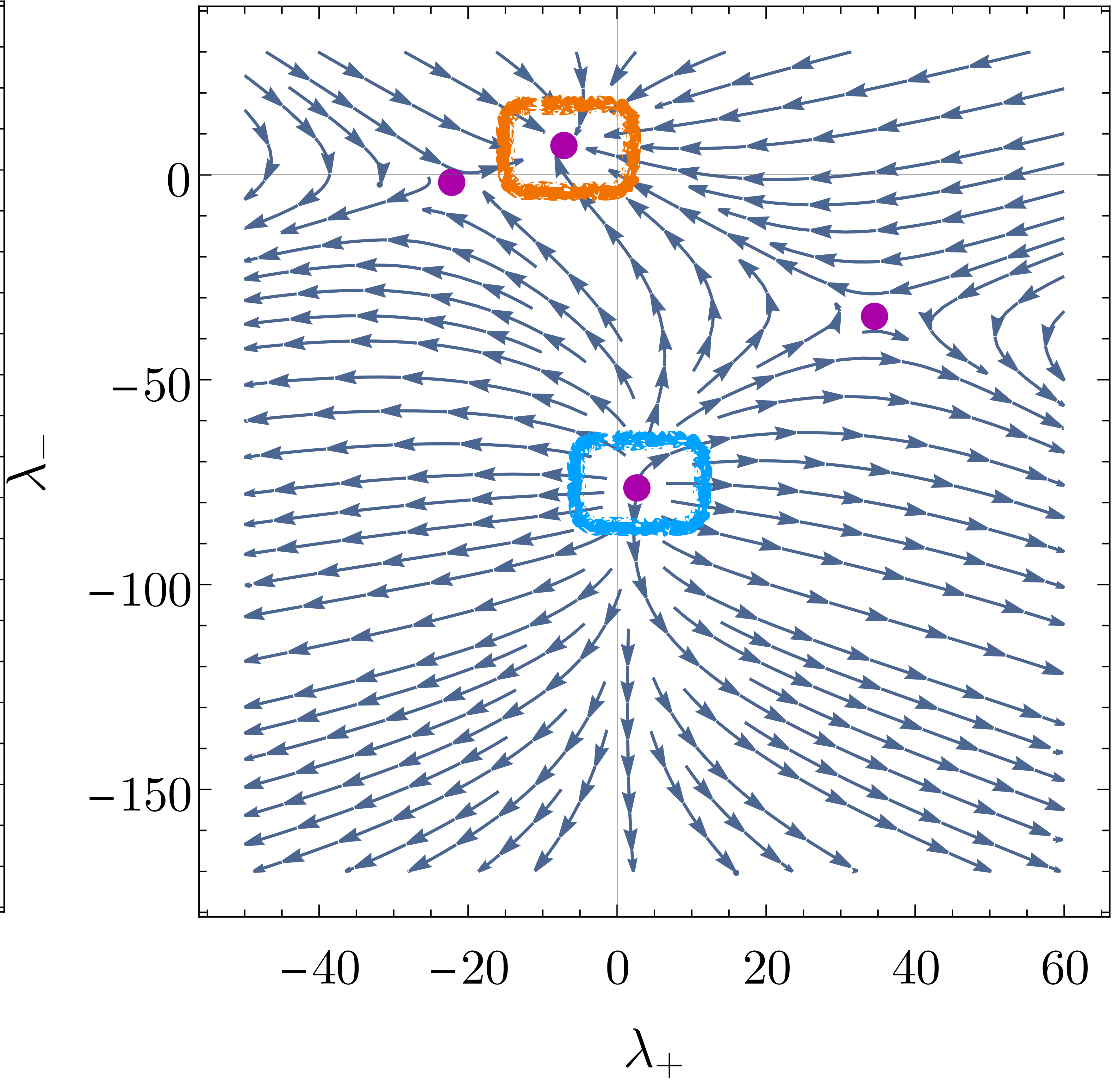
[Brenner, Chikkaballi, AE, Ray '24]

- Scenario I: $\lambda_\pm \sim k^2$ for $k^2 < M_{\rm Planck}^2$; thus $\Lambda_{NP} \sim M_{\rm Planck}$
- Scenario II: (speculative) intermediate anomalous scaling regime; thus $\Lambda_{NP} = \Lambda_{\rm eff\ NP} \ll M_{\rm Planck}$







Asymptotically safe gravity meets SMEFT

Key messages:

Transplanckian scales:

- Asymptotically safe gravity unavoidably generates higher-order interactions that are part of the SMEFT
- Not all SMEFT interactions nonzero to first approximation (e.g., no B-violating interactions)

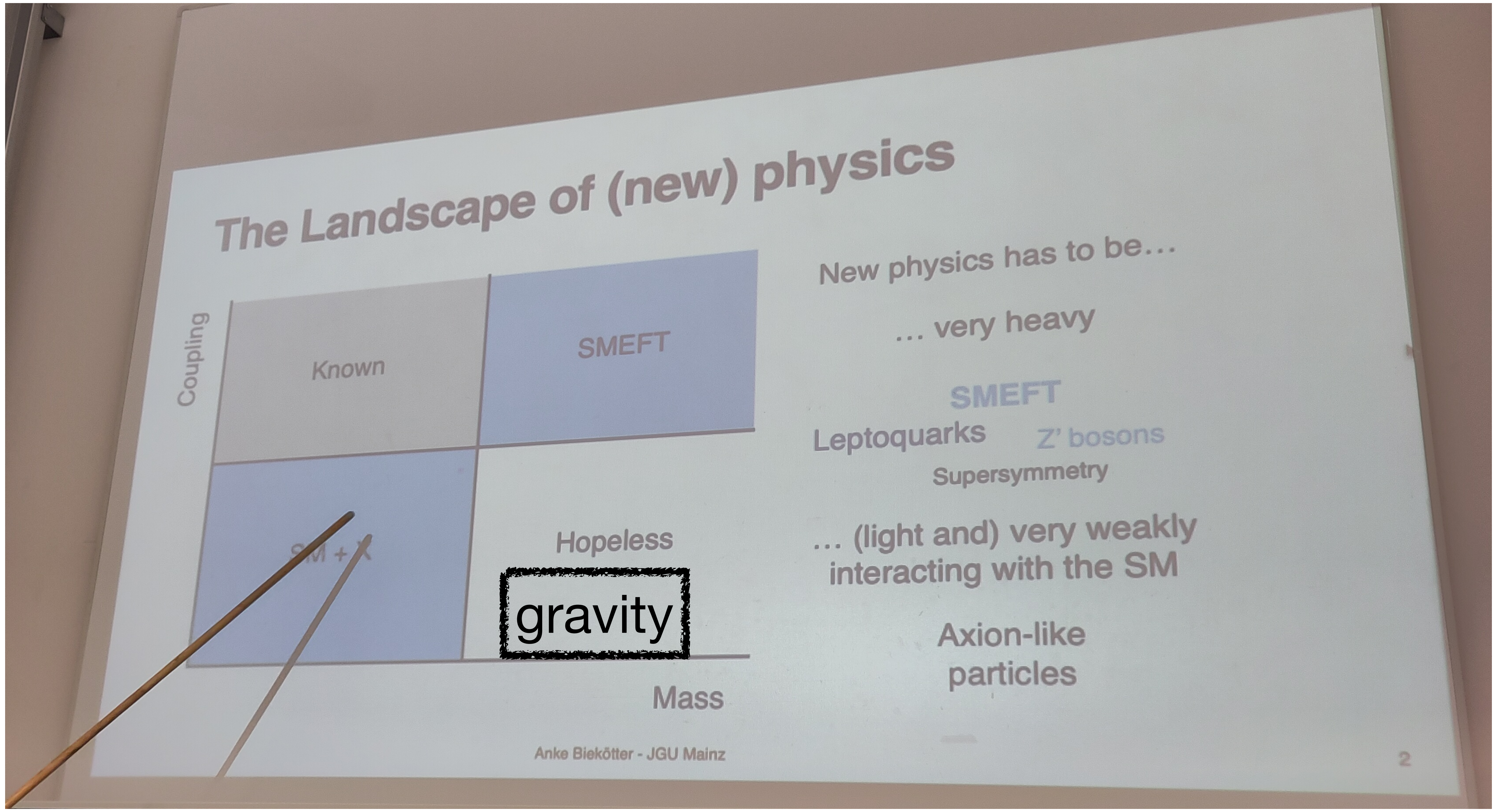
Below-planckian scales:

- Positivity bounds provide nontrivial consistency-check for asymptotic safety
- size of Wilson coefficients:
    - scenario I: essentially zero at LHC scales
    - scenario II (speculative): non-zero due to intermediate fixed-point regime

Outlook

- from toy models towards the SMEFT (add flavor structure)
- remove “desert” hypothesis:

constraints on Wilson coefficients from quantum gravity in presence of intermediate new physics



Outlook

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