Probing quantum gravity at all scales

Triangular Conference on Cosmological Frontiers in Fundamental Physics 2024,

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- Quantum gravity is necessary to answer profound questions about our universe

- Challenging to test proposed answers: expected scale of quantum gravity is Planck scale

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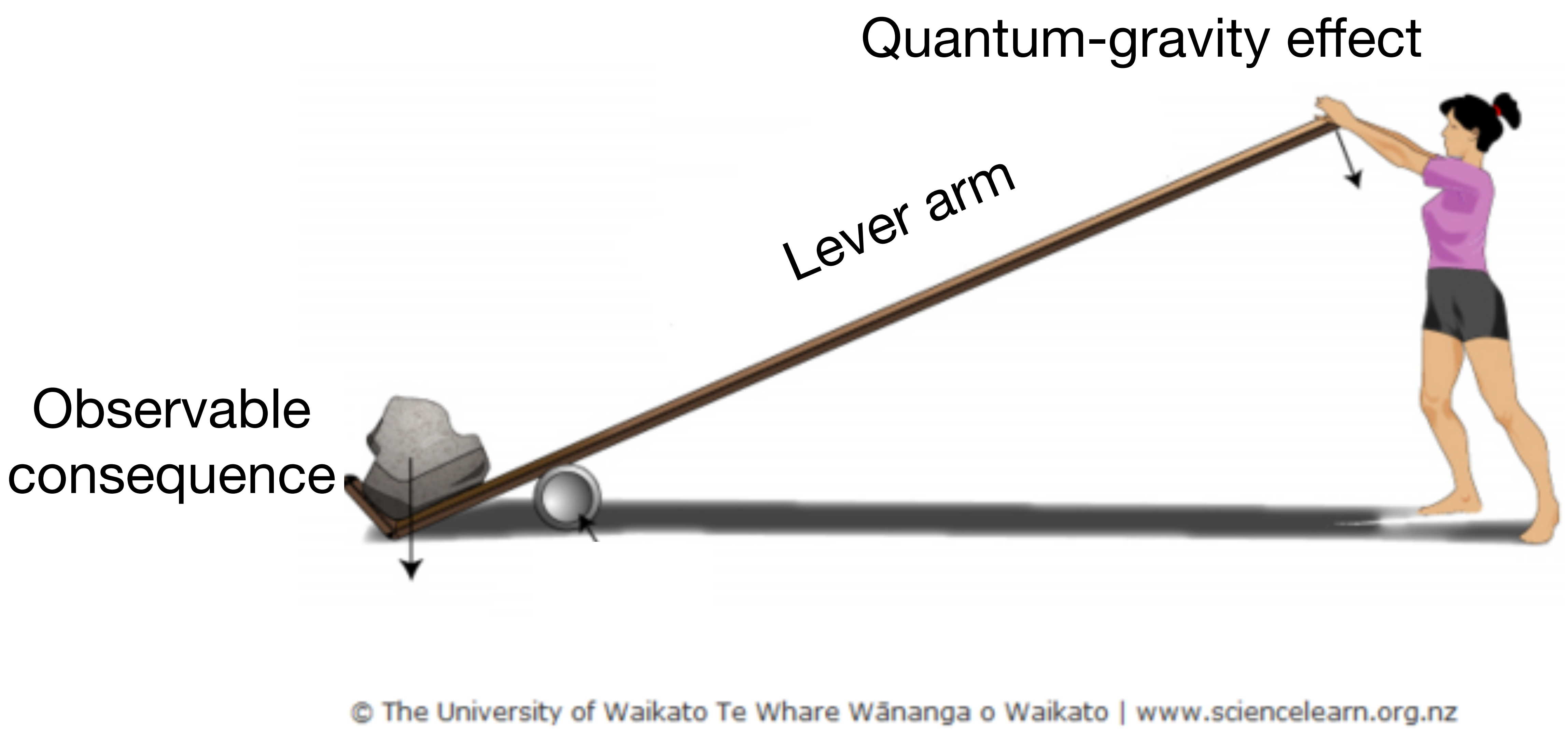
  Lever arm translates effect at Planck scale into effect at observationally accessible scale



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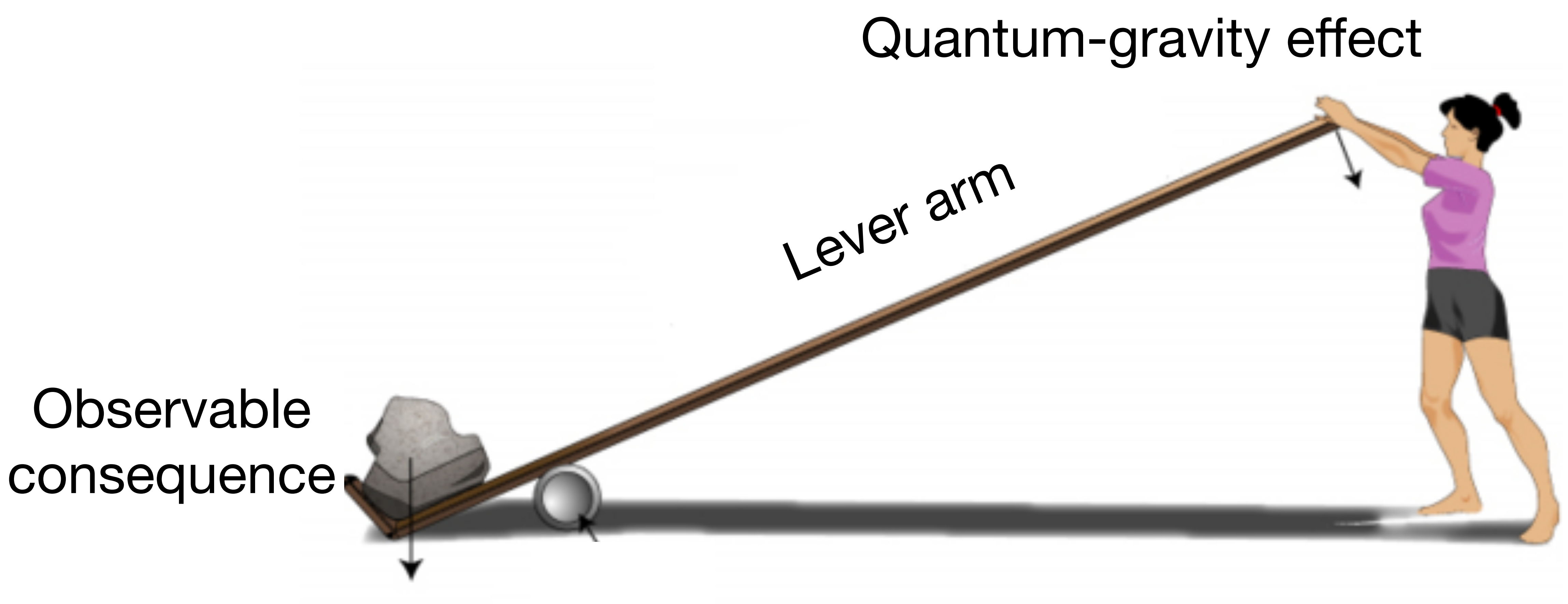
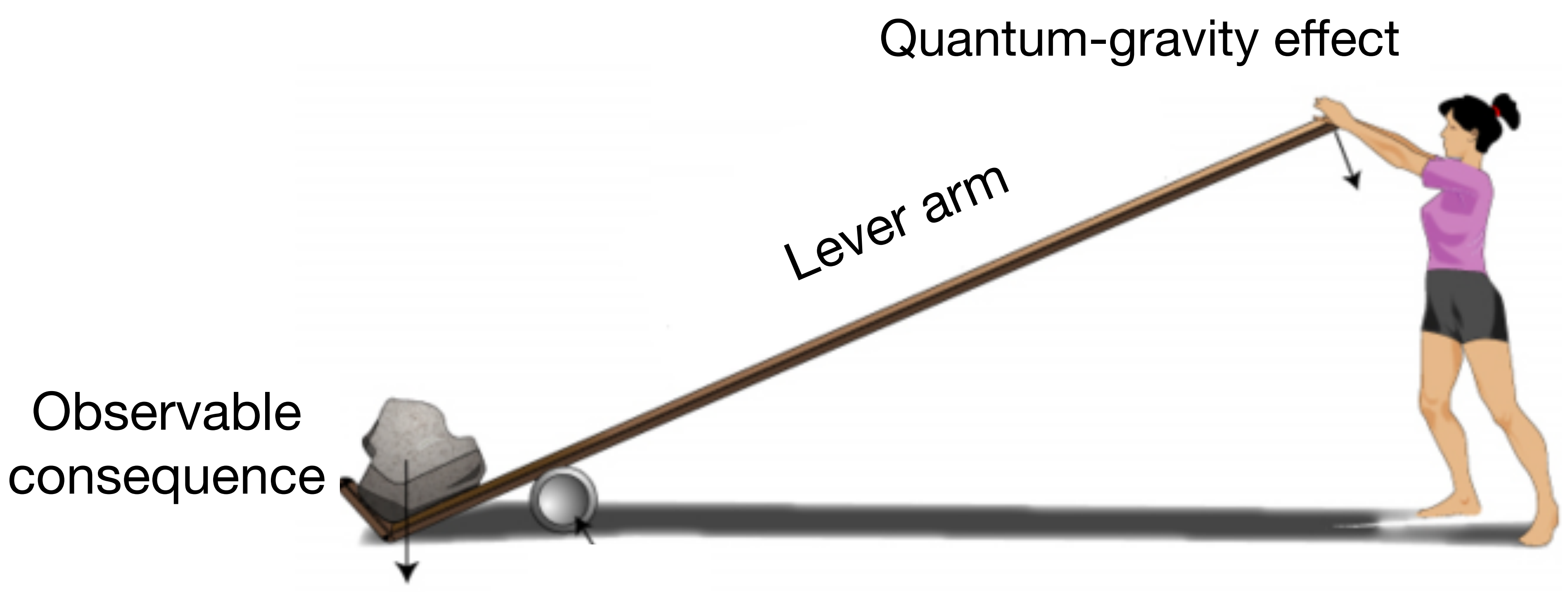
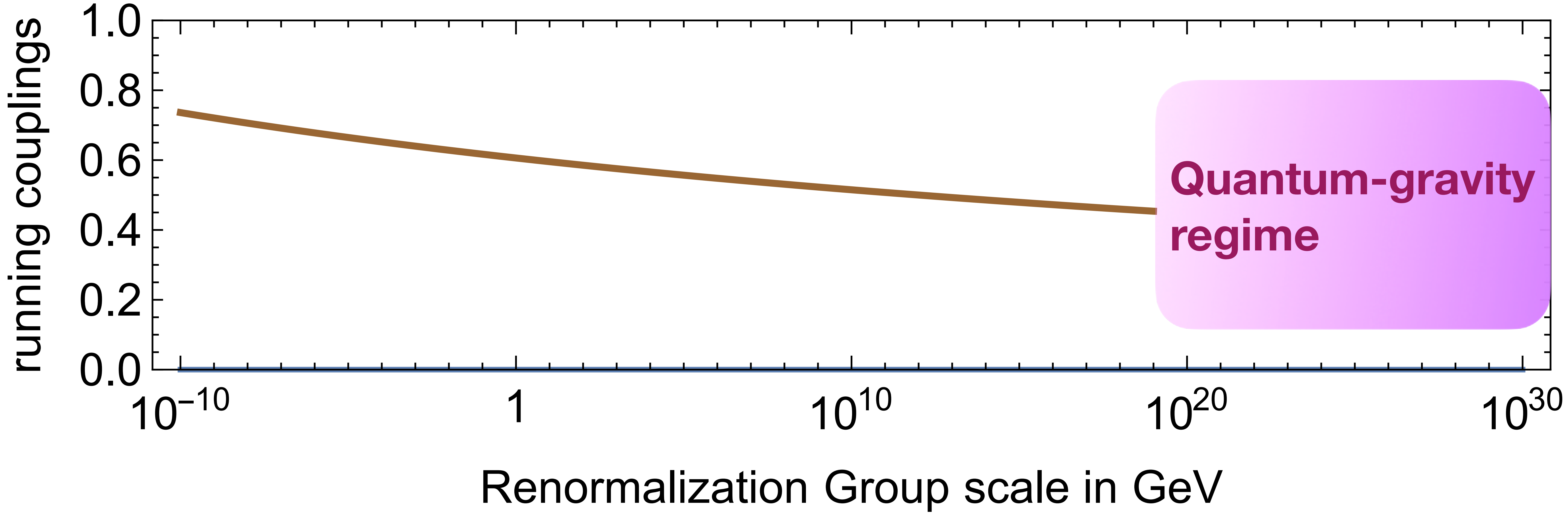


Examples:

- Accumulation of Lorentz-Invariance-Violation over astrophysical distances of photons from GRBs
  [Amelino-Camelia, Ellis, Mavromatos Nanopoulos, Sakar '97]
- Large extra dimensions
  [Arkani-Hamed, Dimopoulos, Dvali '98]
- this talk:
  Renormalization Group flow of couplings

Renormalization Group flow as a lever arm





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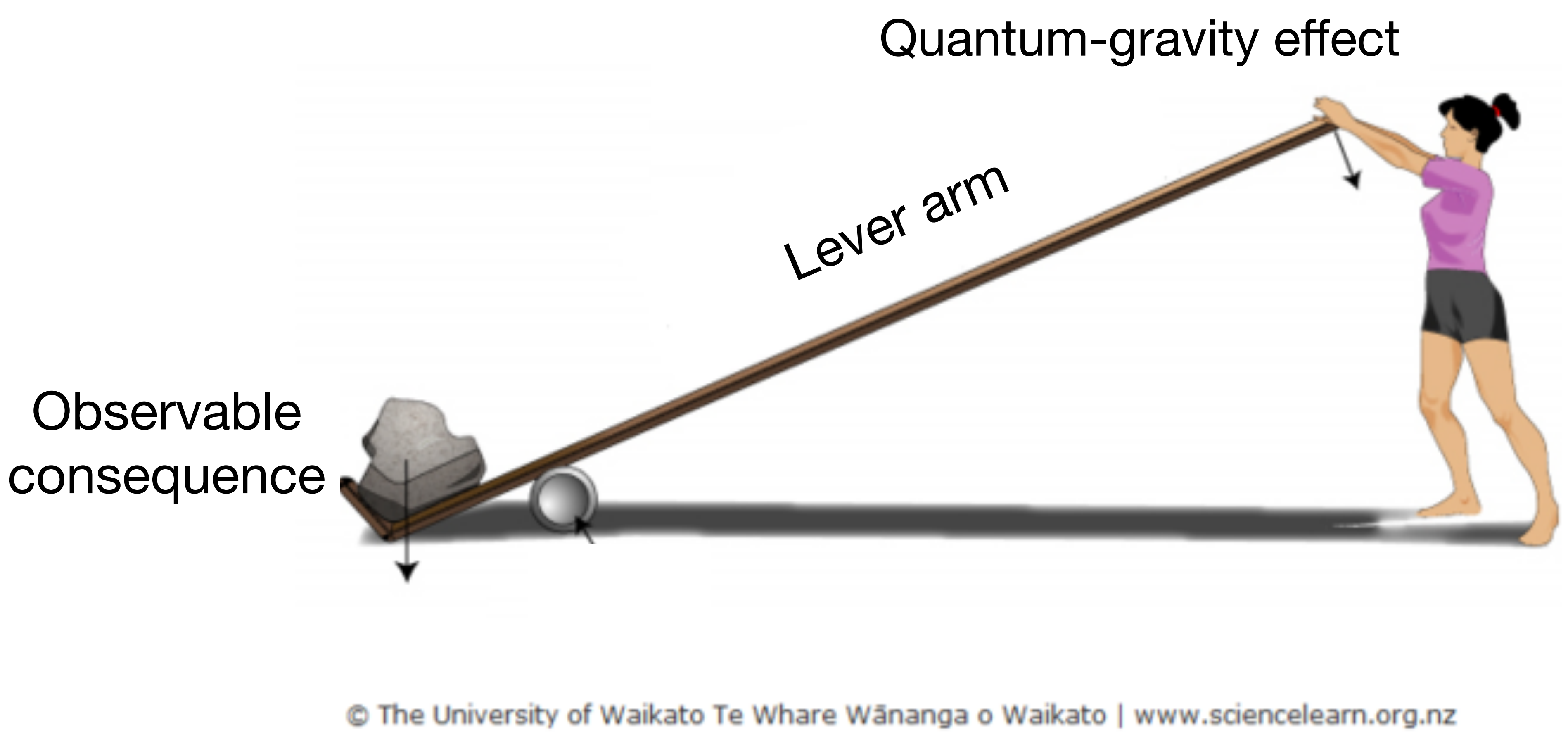
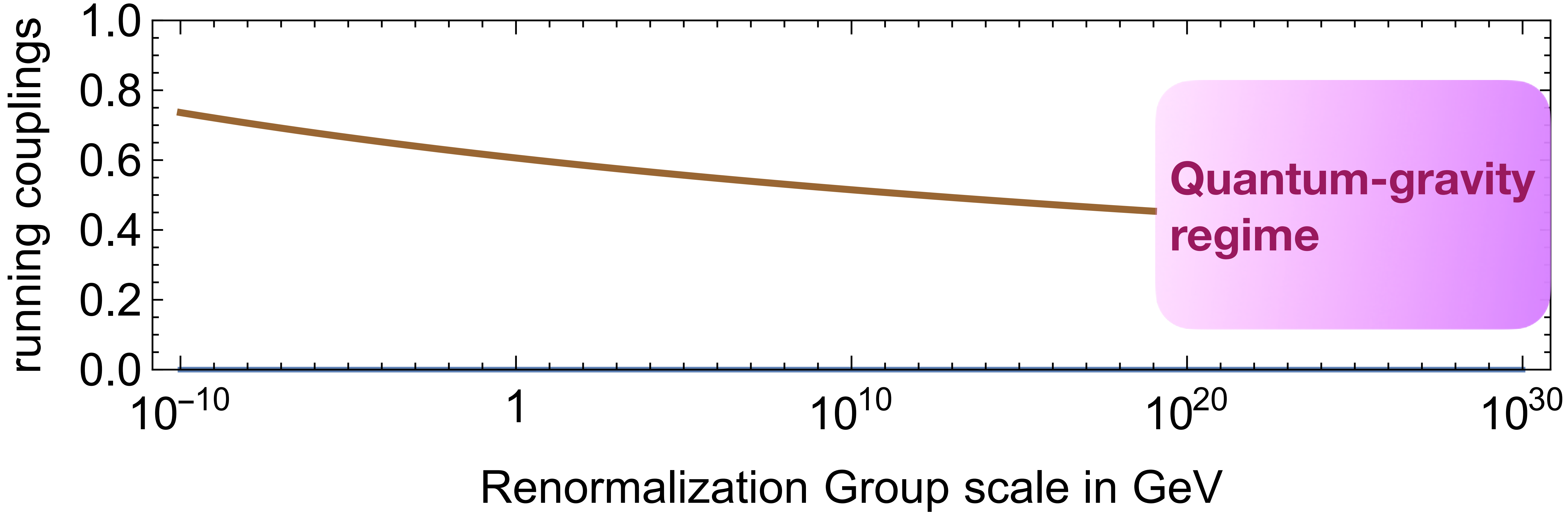


Setting: Effective field theory for degrees of freedom below the Planck scale (SMEFT-like)

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{i}^{N_{d=6}} \bar{g}_i \mathcal{O}^i + \dots$$



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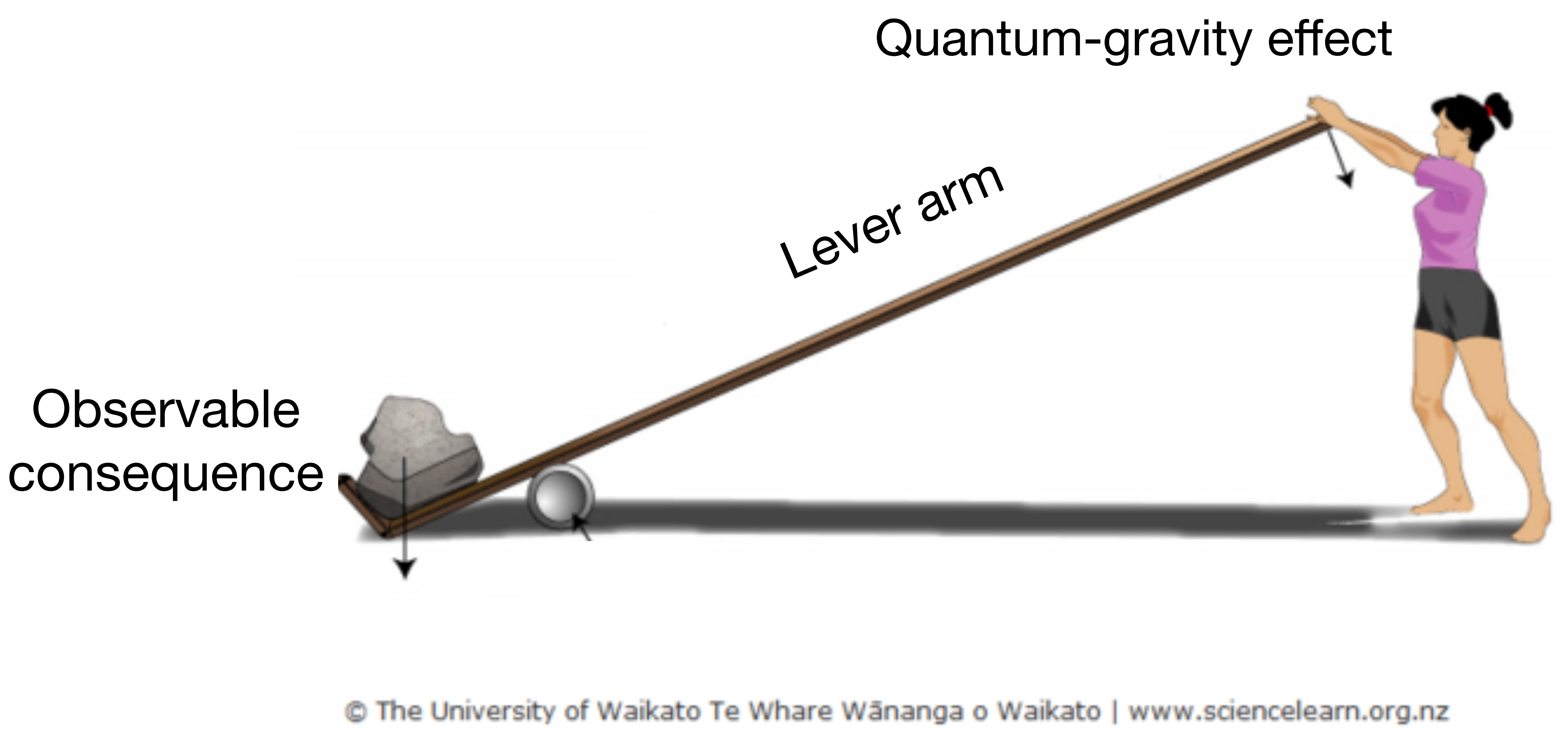

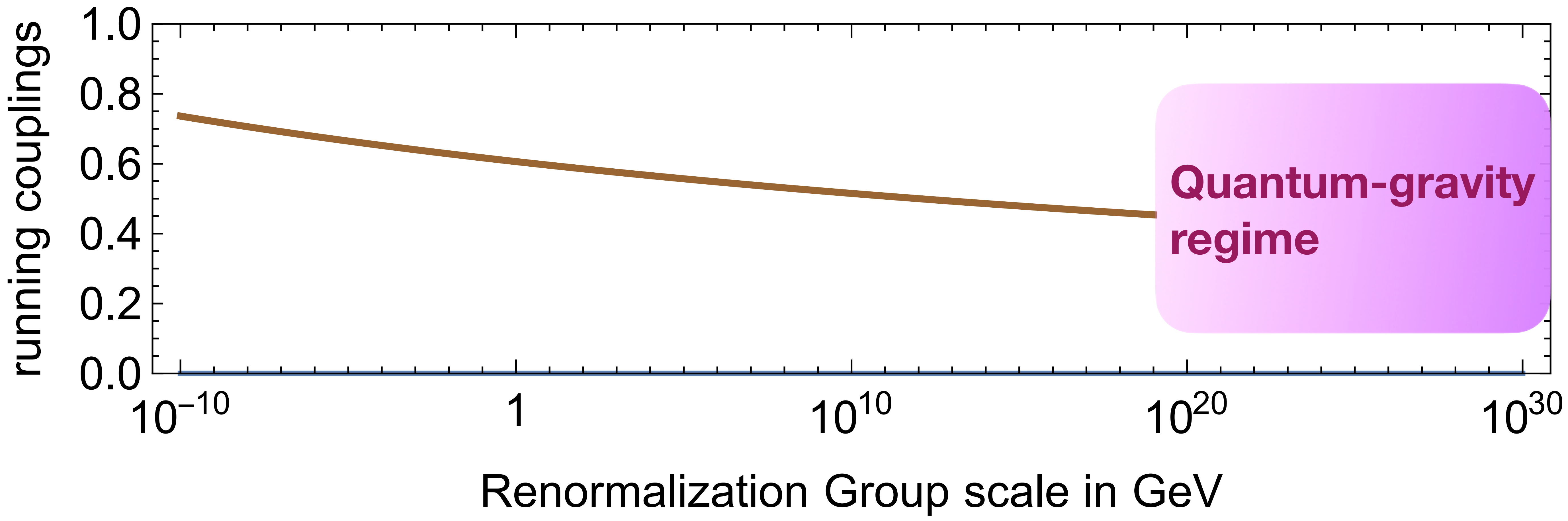

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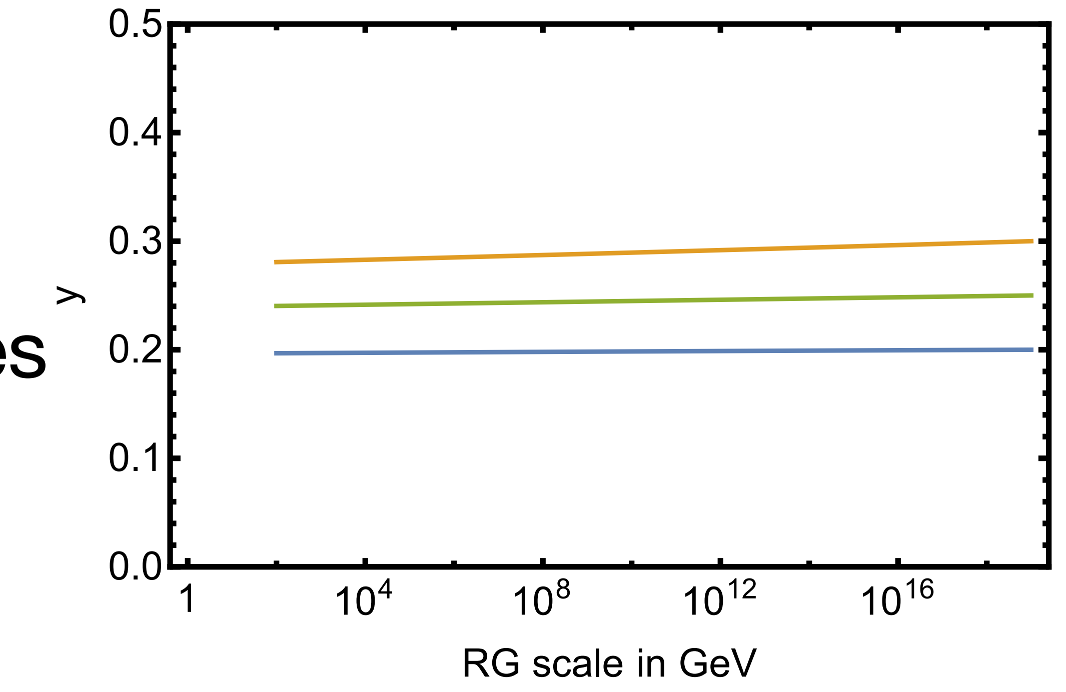
Marginal couplings:

- Logarithmic scale dependence preserves ``memory" of initial conditions at the Planck scale



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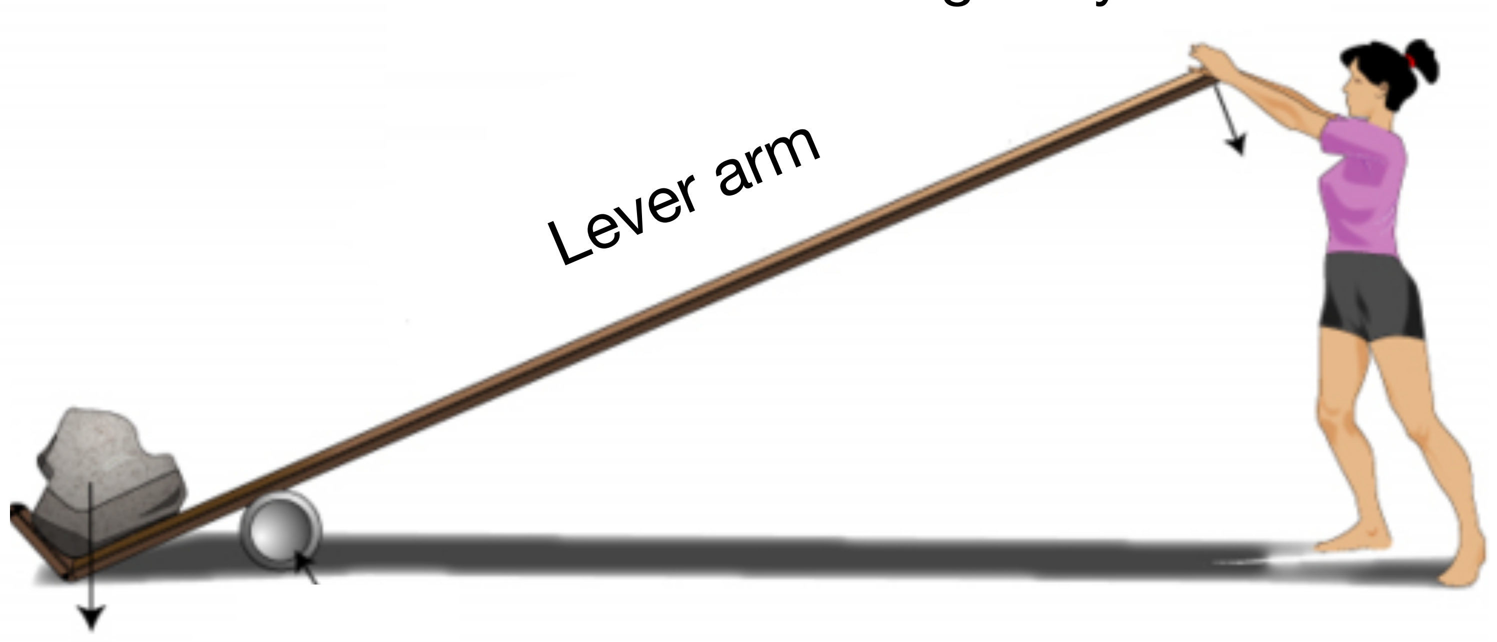

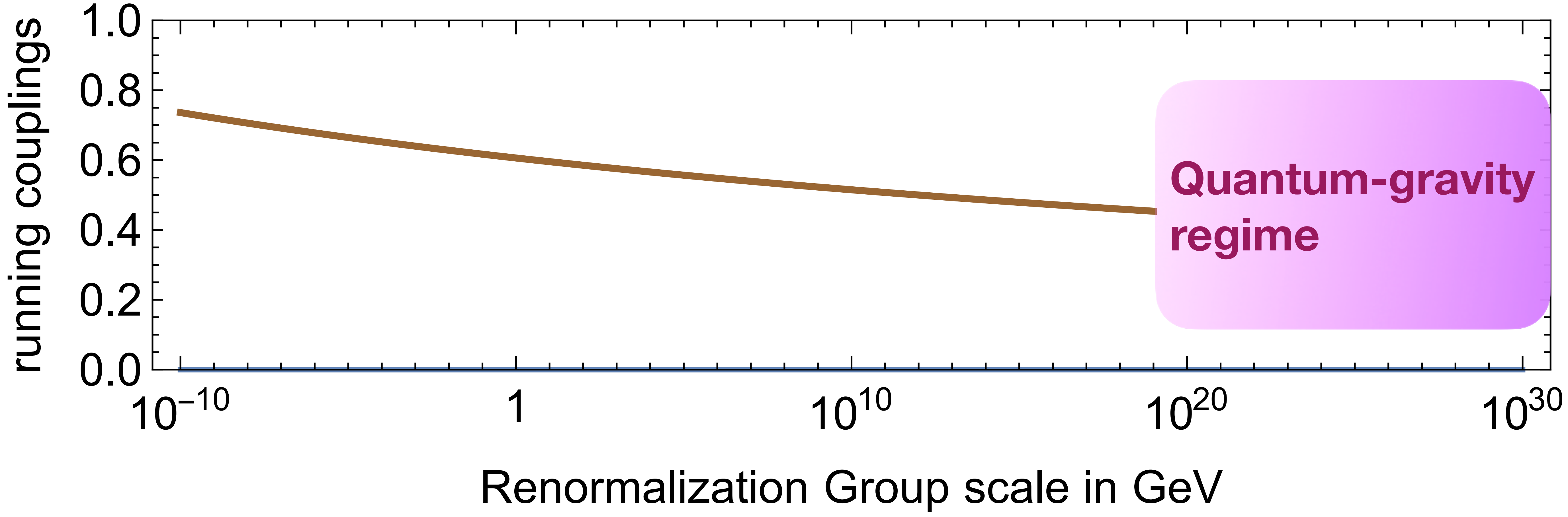

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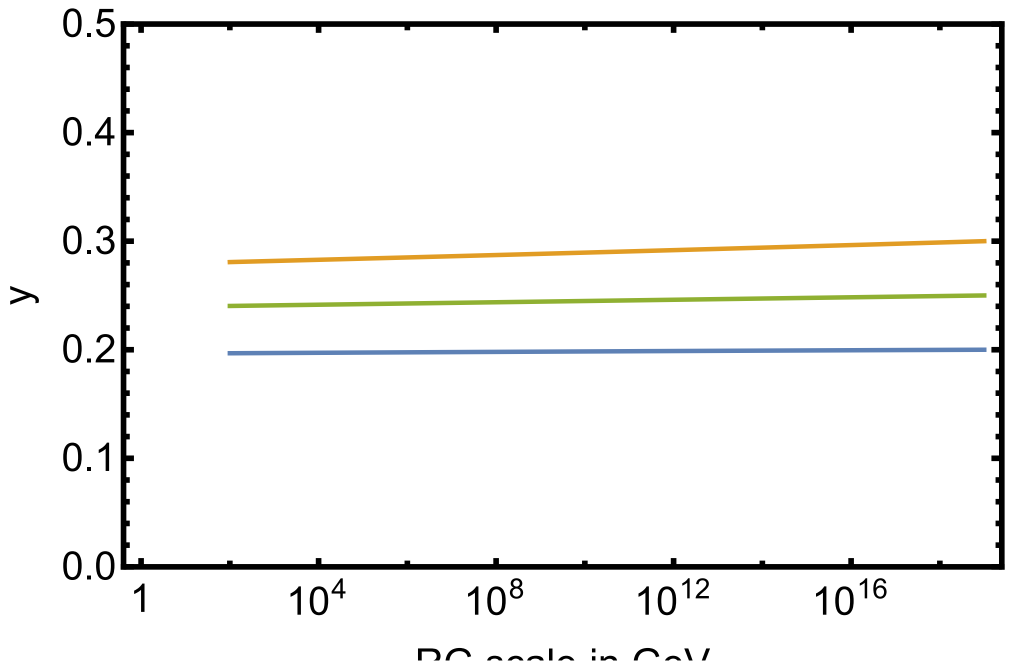
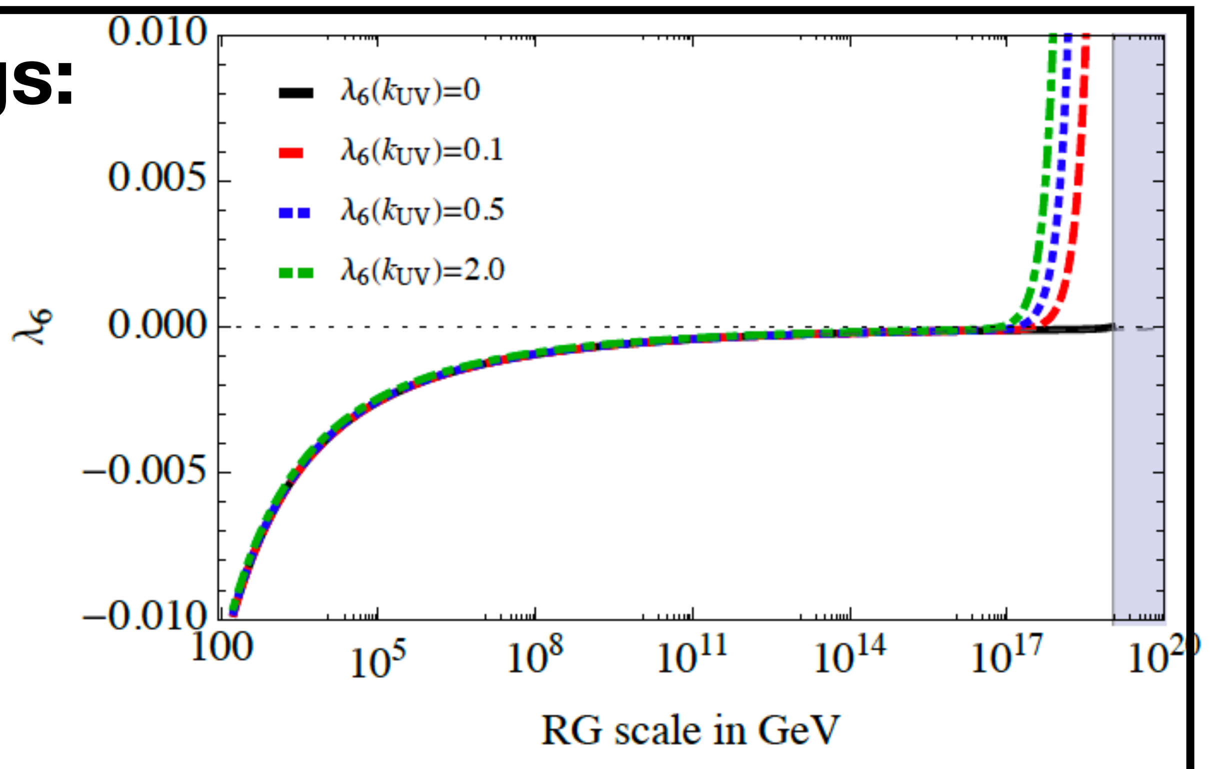


Higher-order couplings:

- Generic expectation: universality



- Positivity bounds
- Some may be phenomenologically important (examples: axion-photon-coupling; Horndeski gravity)

Quantum-gravity approaches with predictions for values of the couplings at the Planck scale

- String theory (see also stringy swampland conjectures)

  [Vafa, Valenzuela, Montero, Ooguri, Palti, Heidenreich, McNamara, Rudelius, Shiu…]

  [swampland conjectures in asymptotic safety: [de Alwis, AE, Held, Pawlowski, Schiffer, Versteegen ’19; Basile, Platania ’21]]

- Asymptotically safe gravity

  [AE, de Brito, Held, Pawlowski, Percacci, Reichert, Saueressig, Shaposhnikov, Schiffer, Wetterich, Yamada…]

  review: AE, Schiffer ‘22

- Causal sets: constraint on quartic coupling in scalar field theory

  [de Brito, AE, Fausten ’23]

- …an opportunity for other quantum-gravity approaches!

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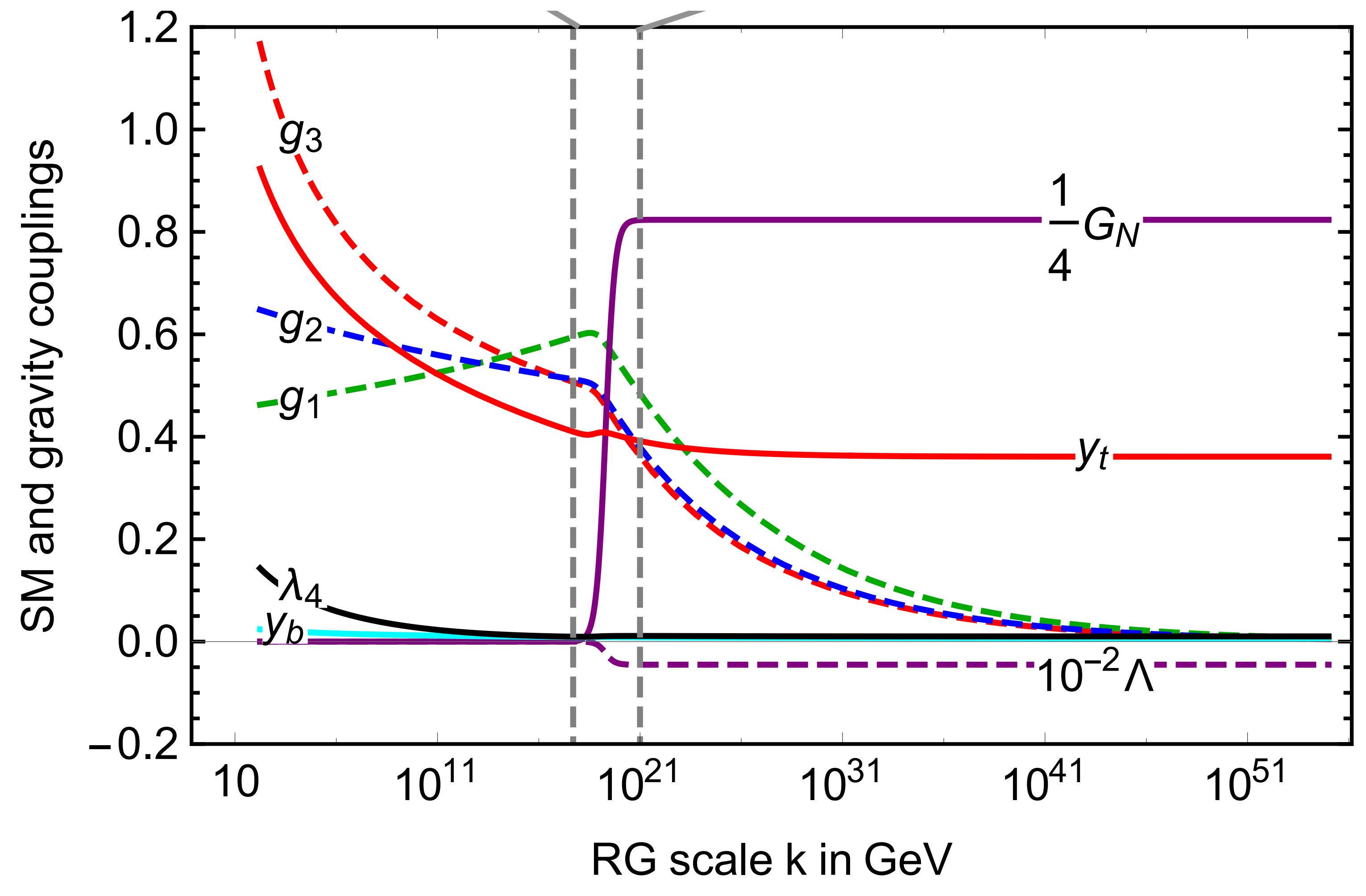
Lightning review of asymptotic safety & its predictive power

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]



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Origin of predictions at the Planck scale

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

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

$\rightarrow$ $e(k)$ decreases as k is lowered

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

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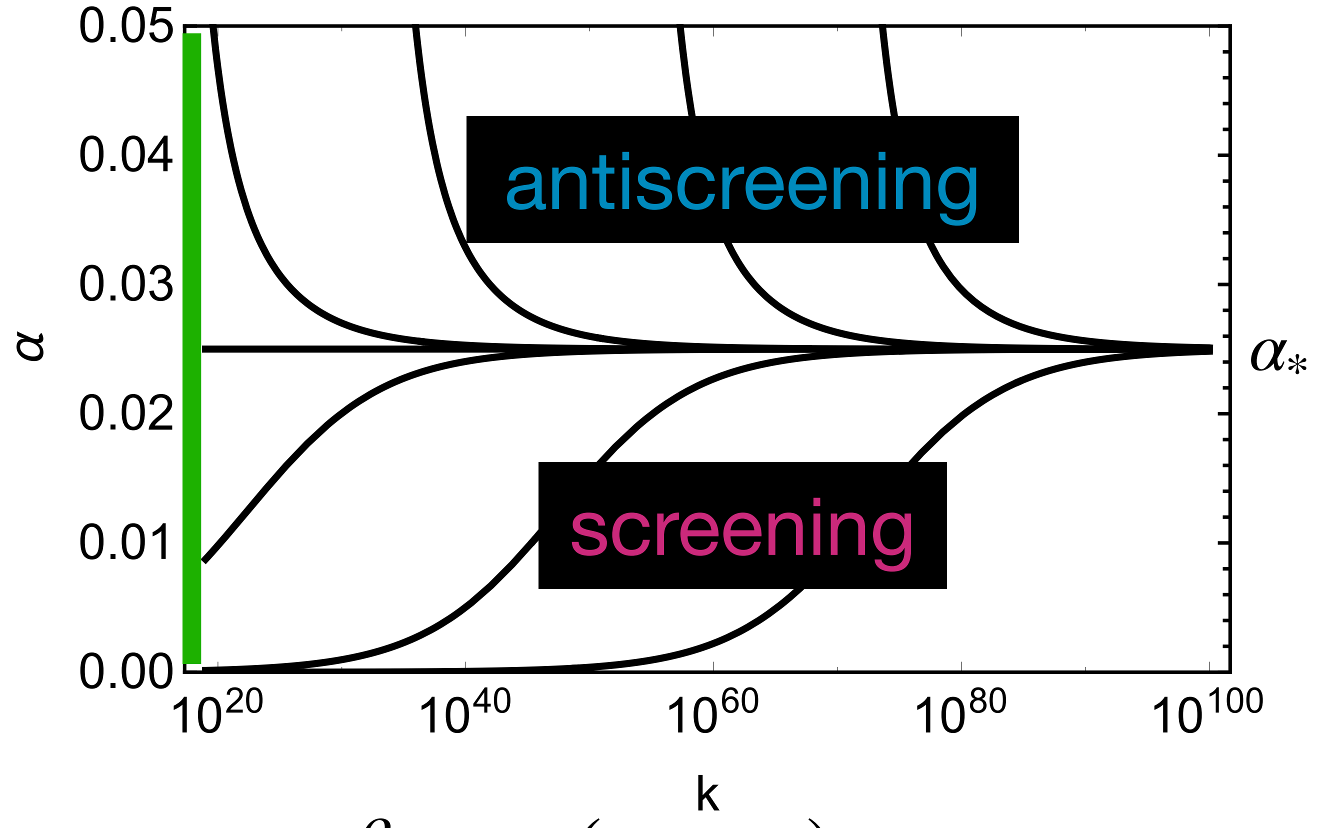

$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

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

$\rightarrow$ a range of coupling values achievable at the Planck scale

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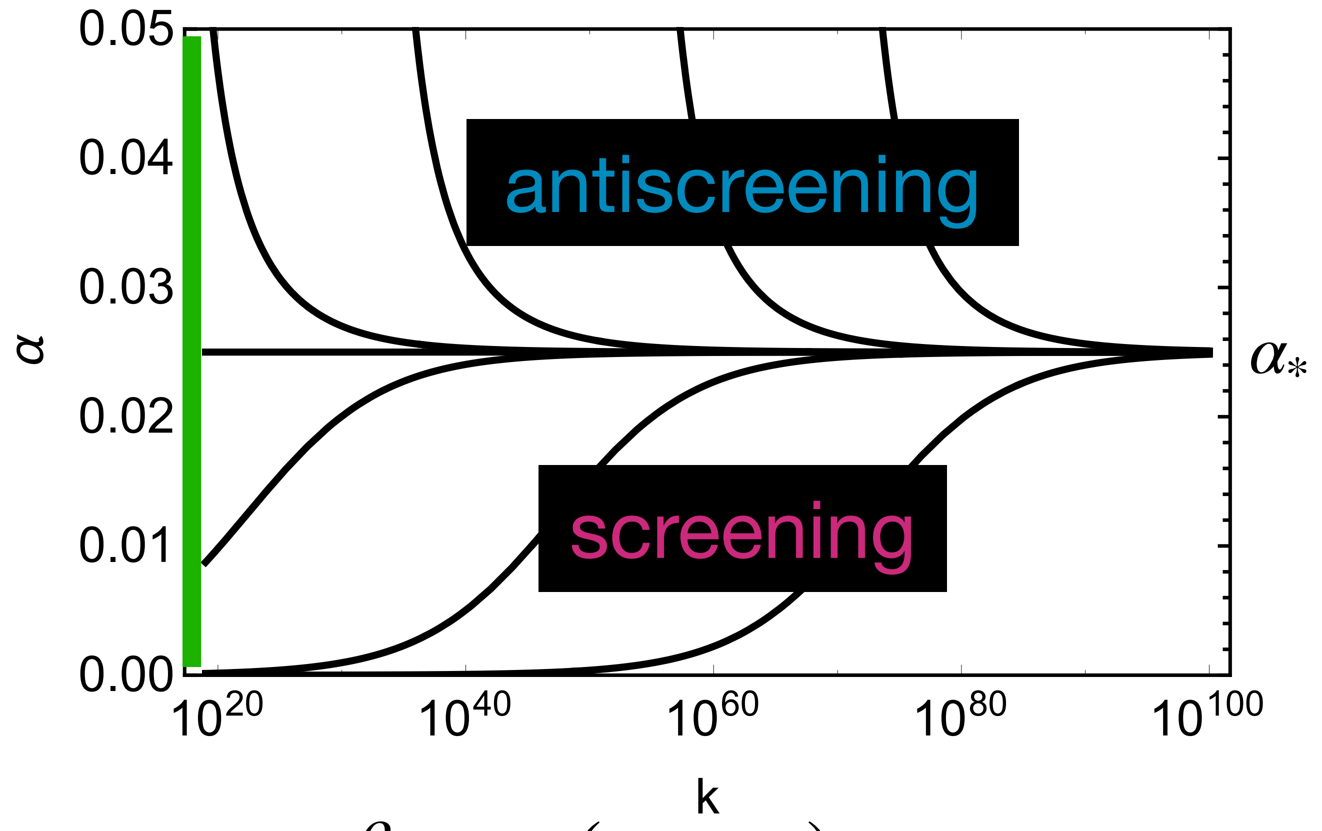

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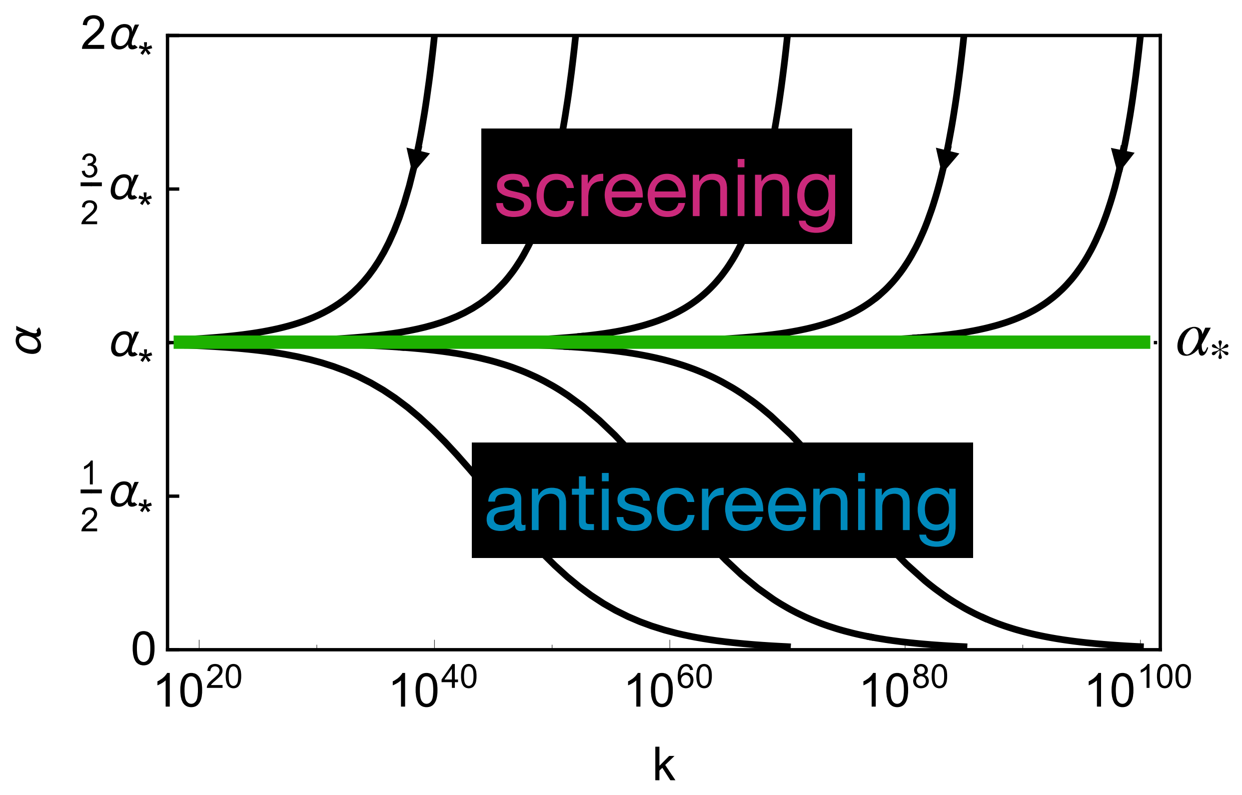

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quantum fluctuations drive coupling **towards** scale symmetry

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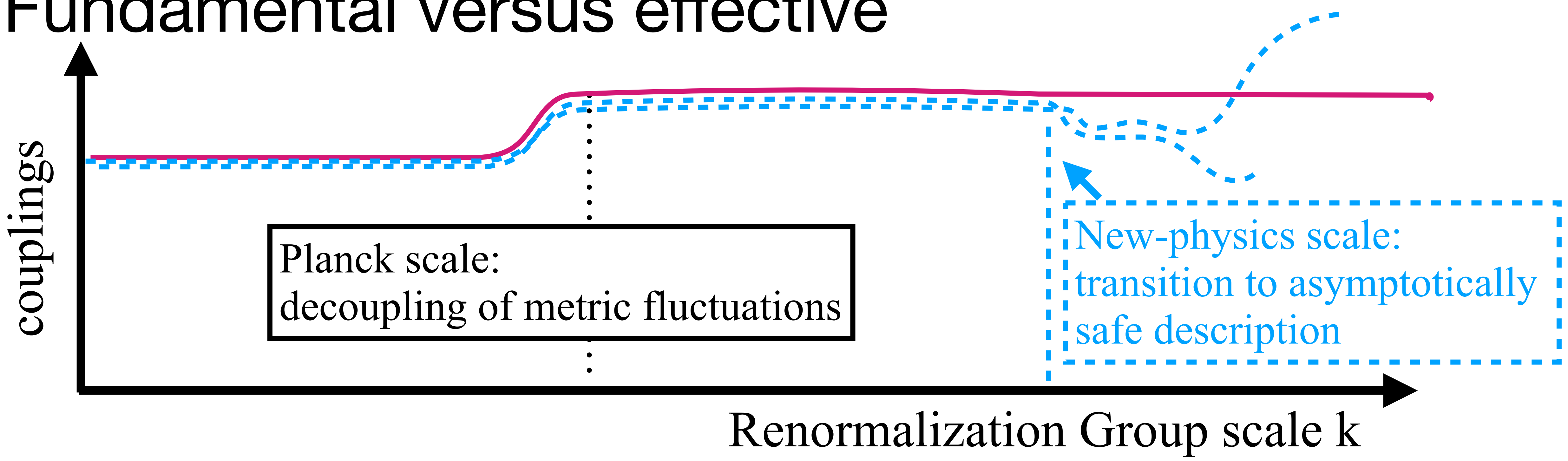
Fundamental versus effective



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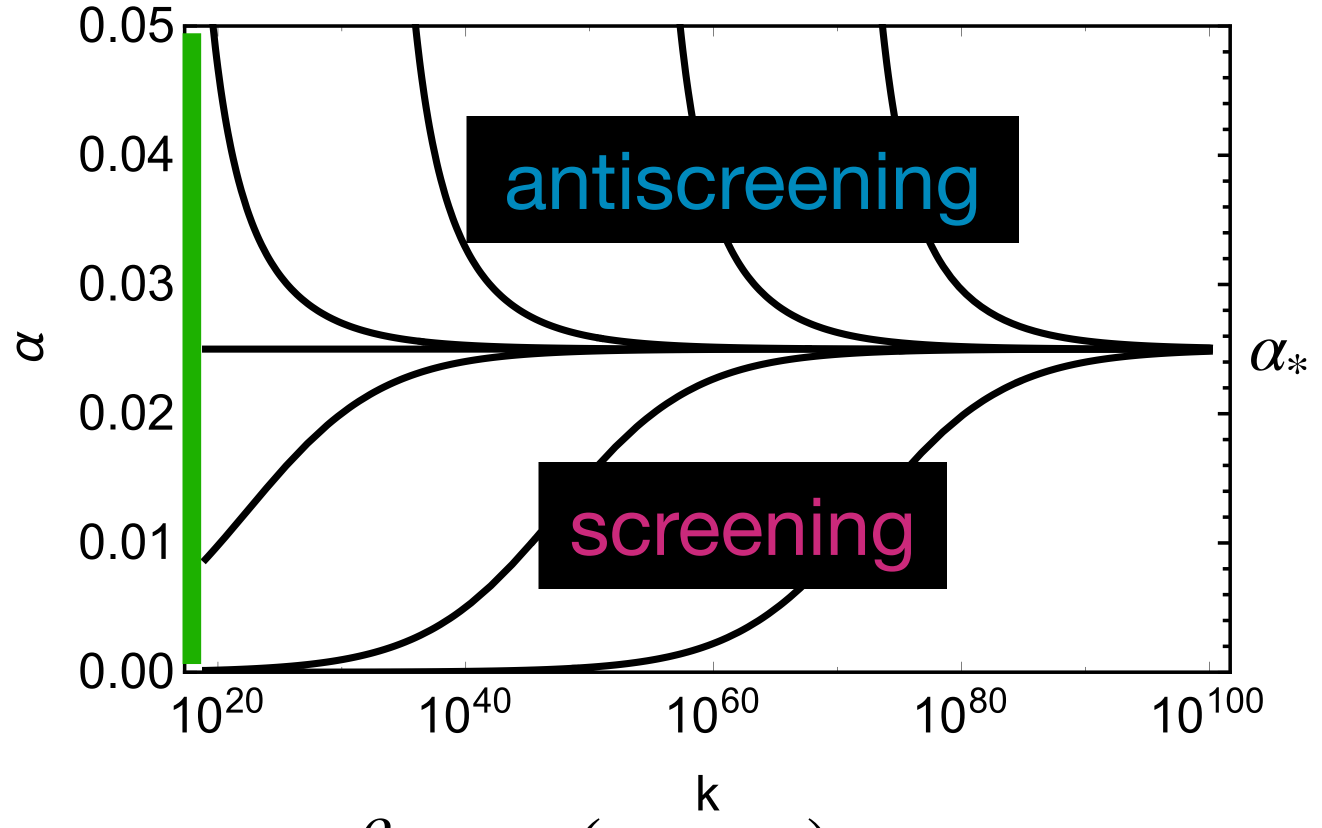

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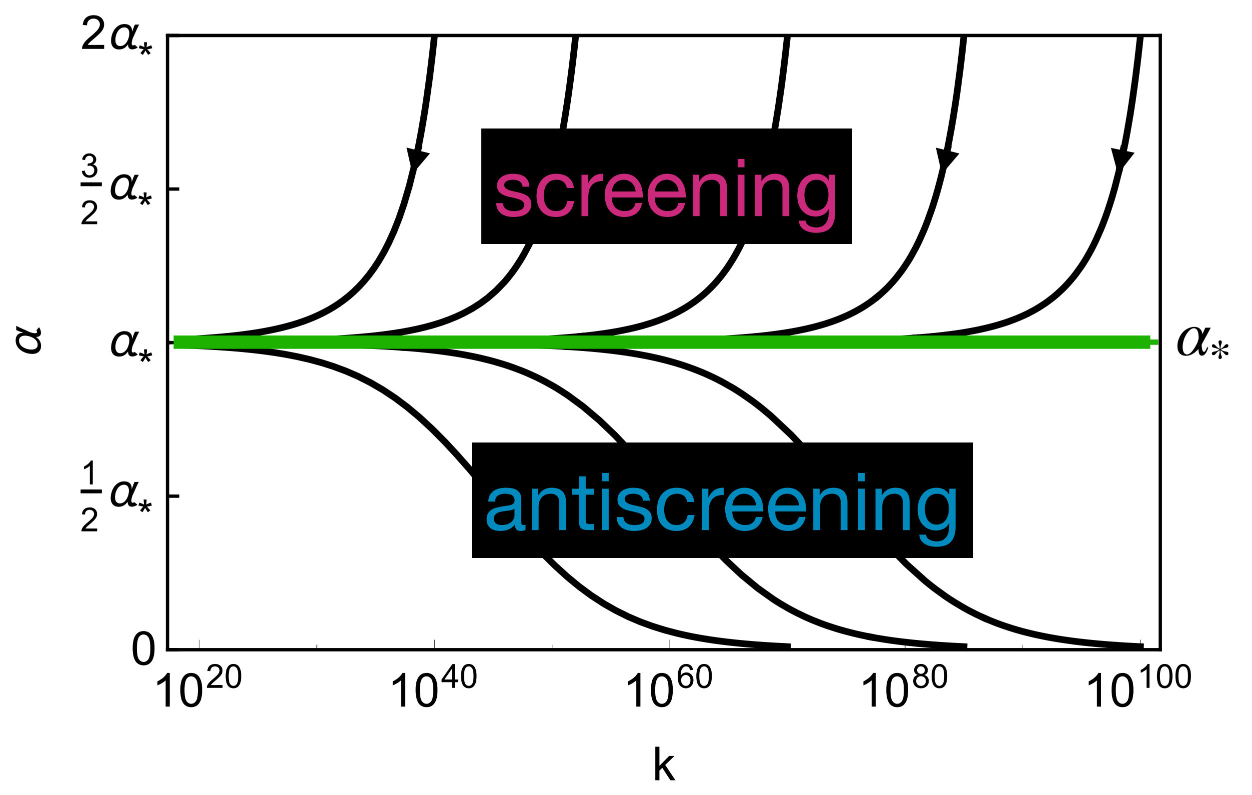

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Method & key assumptions

Functional Renormalization Group: based on Euclidean path integral

Γ_k: analog of classical action, but with quantum fluctuations above k included

$$k\,\partial_k\,\Gamma_k = \frac{1}{2}\mathrm{Tr}\left[\left(\Gamma_k^{(2)} + R_k\right)^{-1} k\,\partial_k R_k\right] \qquad \to \beta_g = k\partial_k\, g(k)$$

[Wetterich ’93; Reuter ‘96]

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Quantitative precision achievable

Example: Fixed point in the Ising model, derivative expansion

derivative expansion	ν	η
$s = 0$ (LPA)	0.651(1)	0
$s = 2$	0.6278(3)	0.0449 (6)
$s = 4$	0.63039(18)	0.0343(7)
$s = 6$	0.63012(5)	0.0361 (3)
$s \to \infty$	0.6300(2)	0.0358(6)
conformal bootstrap	0.629971(4)	0.0362978(20)

[Balog, Chaté, Delamotte, Marohnić, Wschebor '19]

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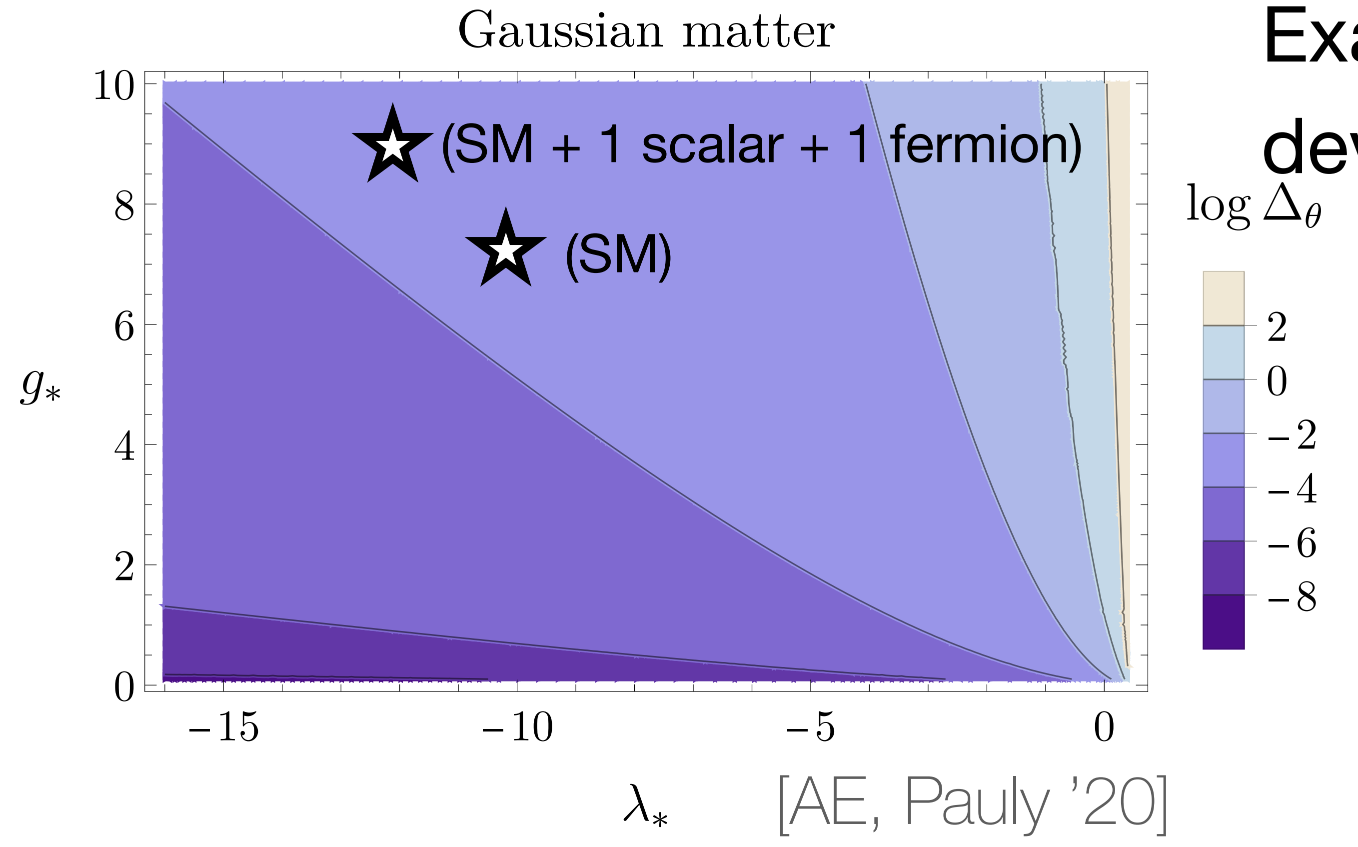
Truncation scheme for matter-gravity: near-perturbativity as a bootstrap

- assume near-perturbativity:
  quantum corrections are subleading compared to canonical scaling
- use canonical power-counting to set up truncations
- check that near-perturbativity holds at fixed point in truncation



[AE, Pauly '20]

Example (SM & BSM Yukawa sector):
deviation from perturbative scaling:

$$\Delta_\theta = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\theta_i - d_{\bar{g}_i}\right)^2}$$

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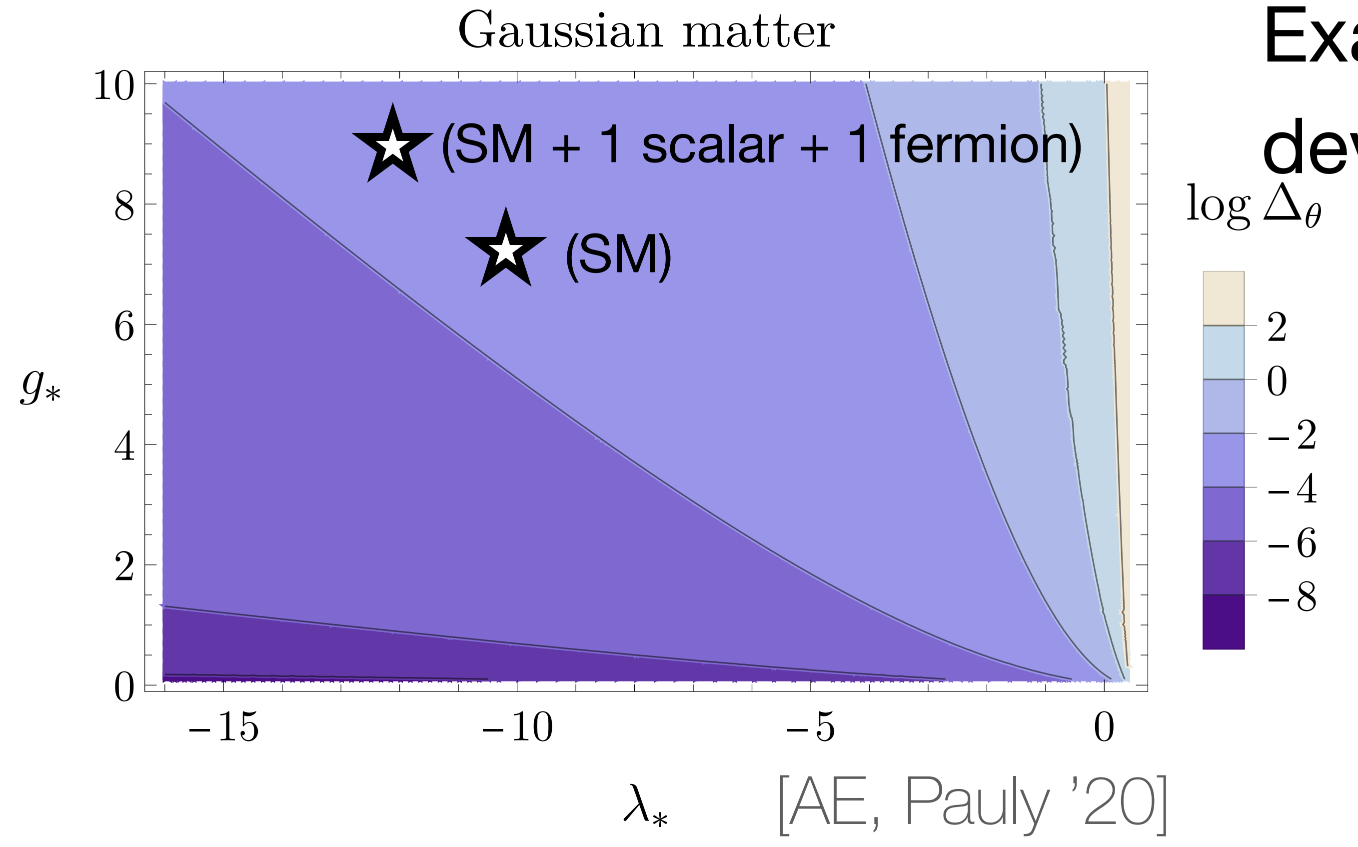

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Key assumption: Euclidean vs. Lorentzian signature

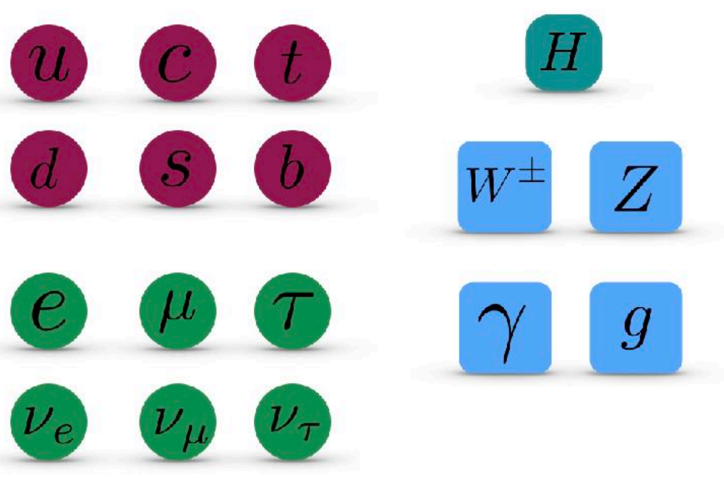
First hints of Lorentzian asymptotic safety

- impact of foliation on fixed-point structure small
  [Biemans, Platania, Saueressig '16 '17; Saueressig, Wang '23]
- calculation in Einstein-Hilbert truncation in Lorentzian signature yields fixed point
  [Fehre, Litim, Pawlowski, Reichert '21]

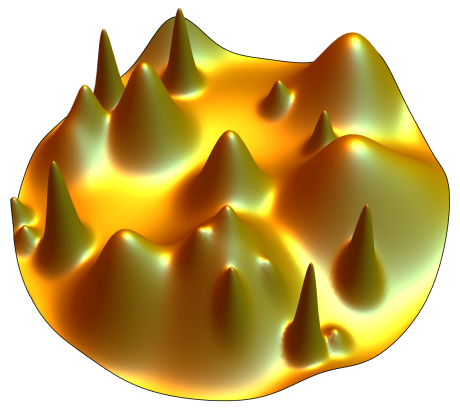
Probing quantum gravity at all scales

Theory

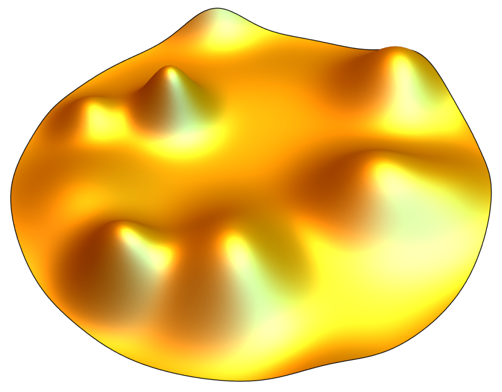
Observational tests



Known particles



Transplanckian scales



Planck scale

Particle physics scales

distance scale

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Step 1: Consistency tests:

- Positivity bounds
- Measurements of SM couplings

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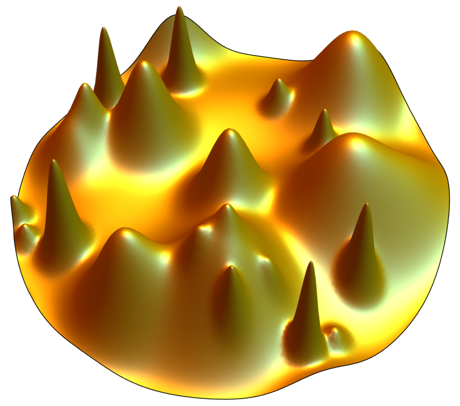
u c t d s b e μ τ ν_e ν_μ ν_τ H $W^\pm$ Z γ g

Known particles

?? ?? Dark matter



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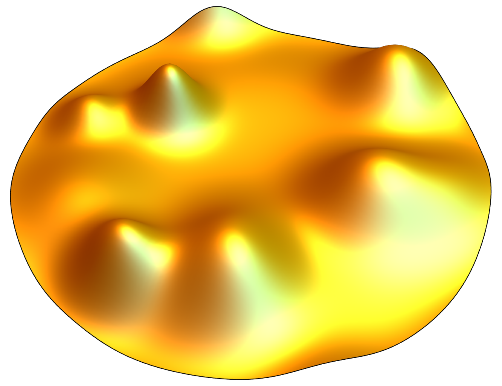

Planck scale

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distance scale

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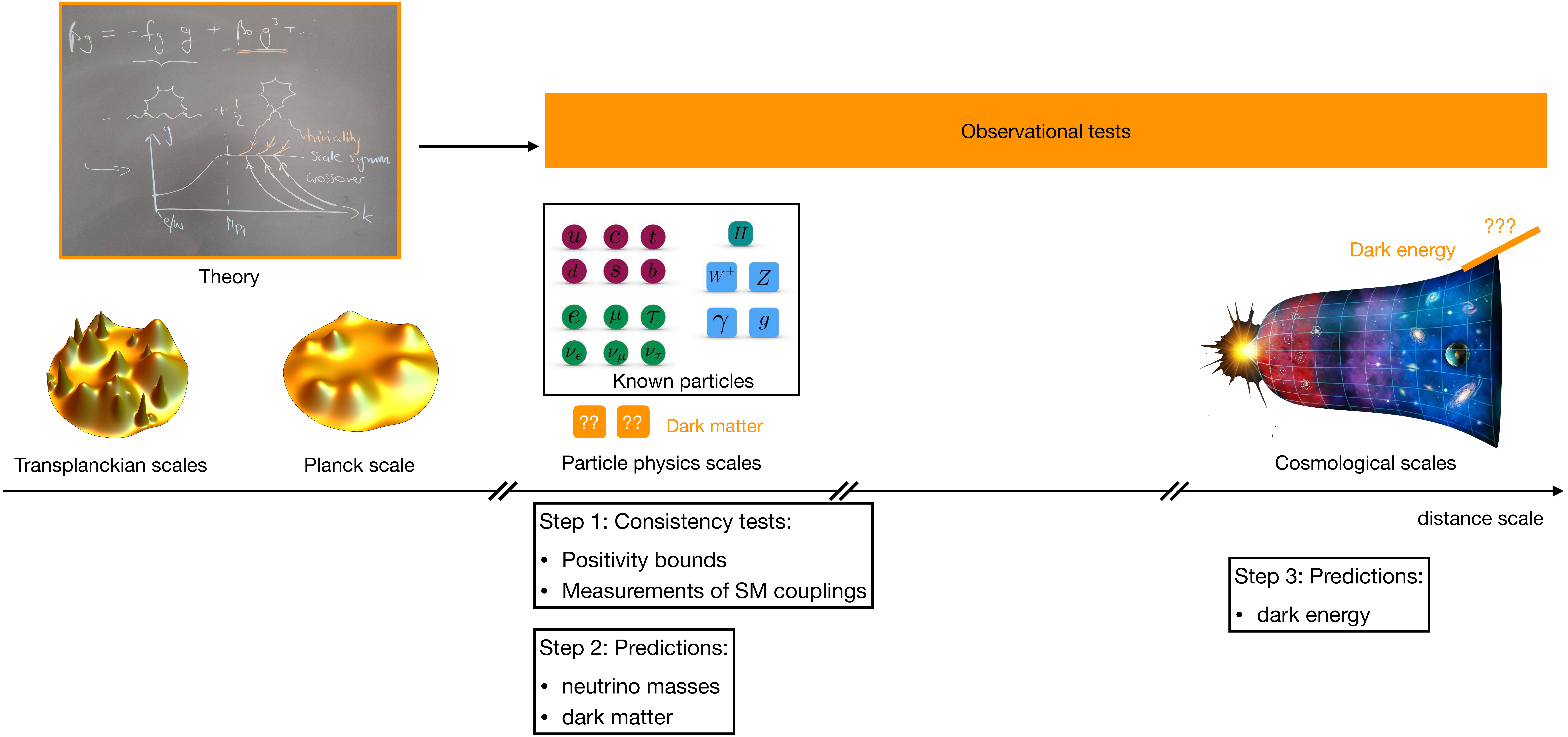
Step 2: Predictions:

- neutrino masses
- dark matter

Probing quantum gravity at all scales



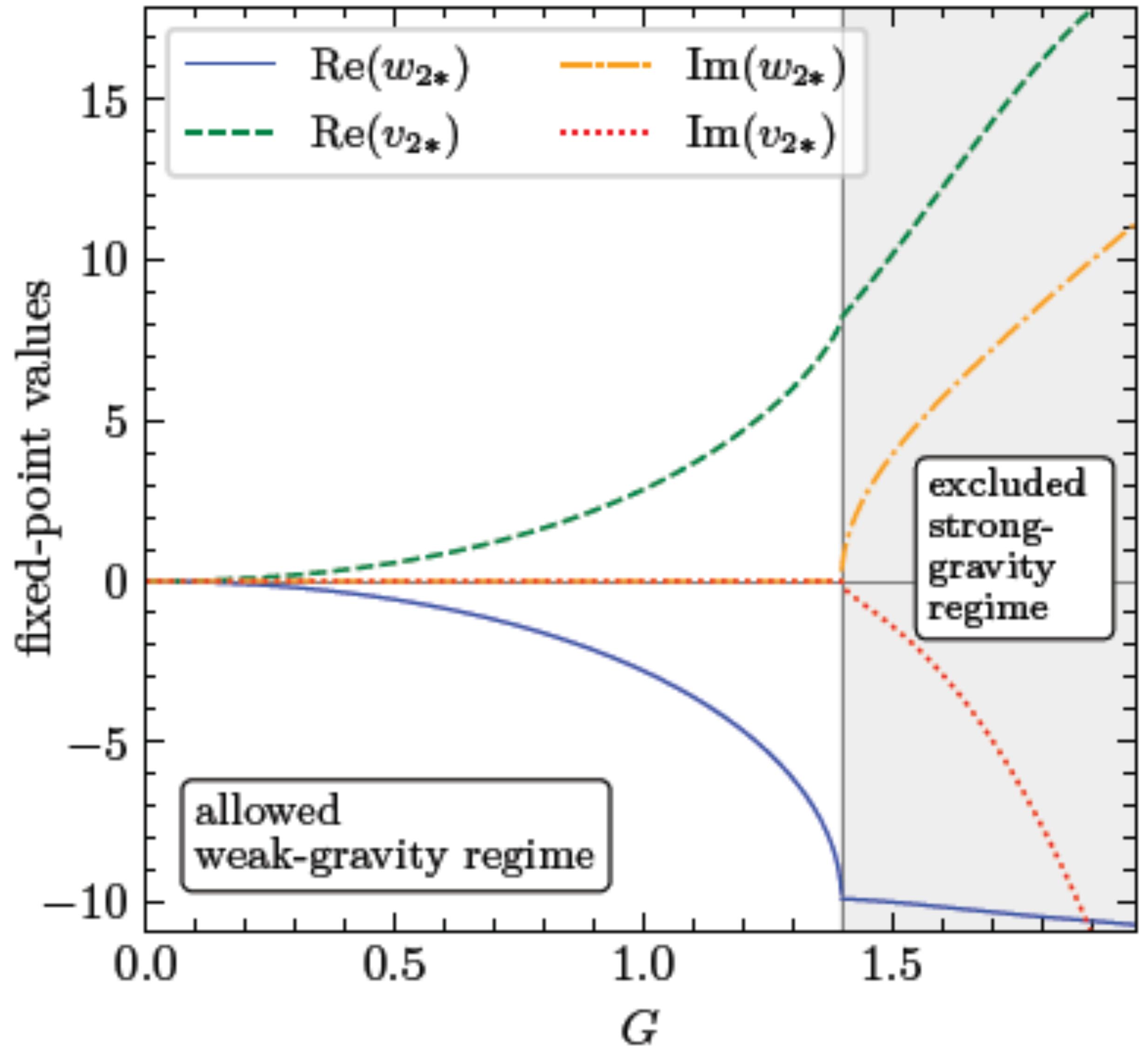
Higher-order couplings in gravity-matter systems

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]



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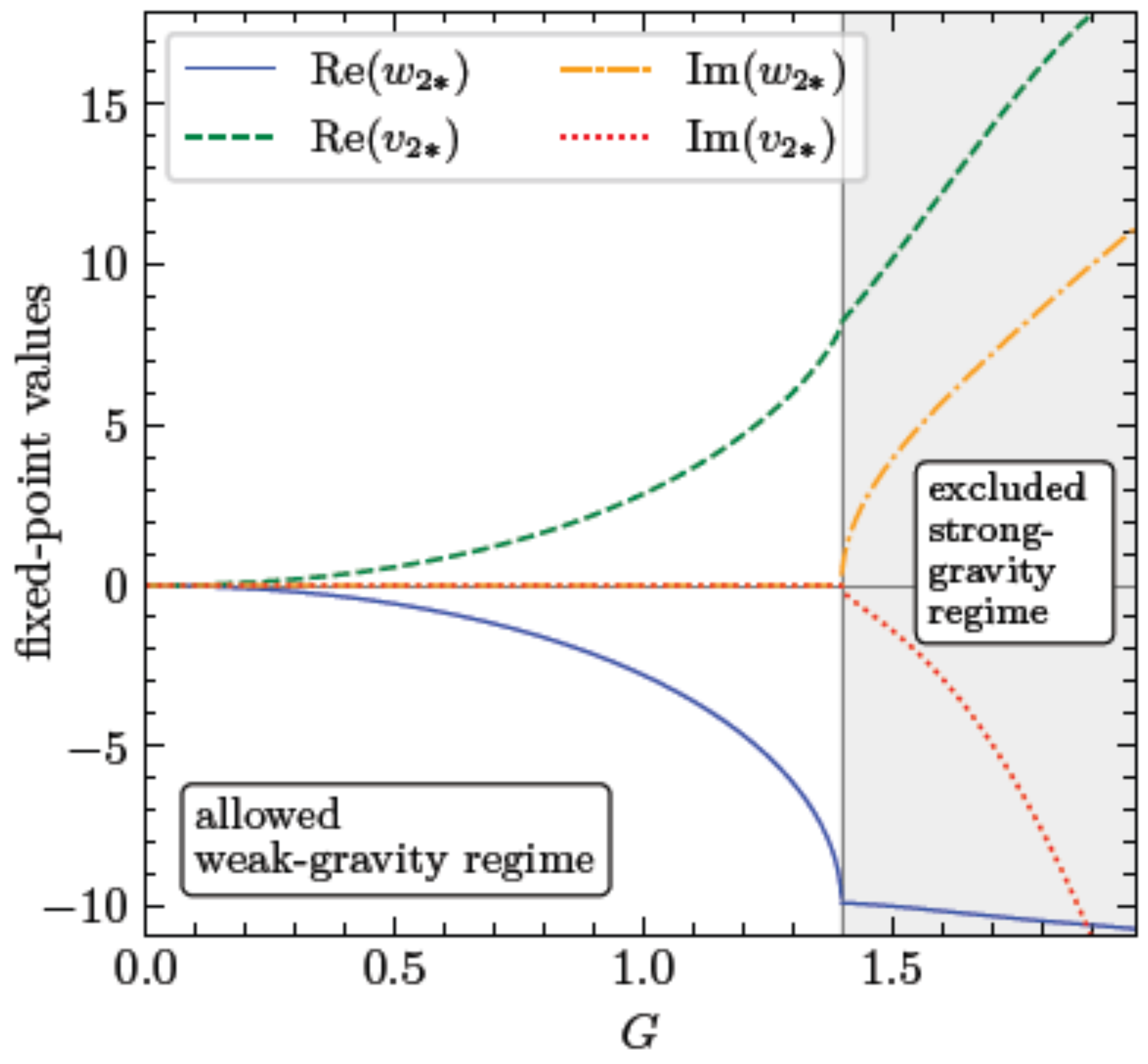

Preliminary results: Positivity bounds in asymptotically safe gravity

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]

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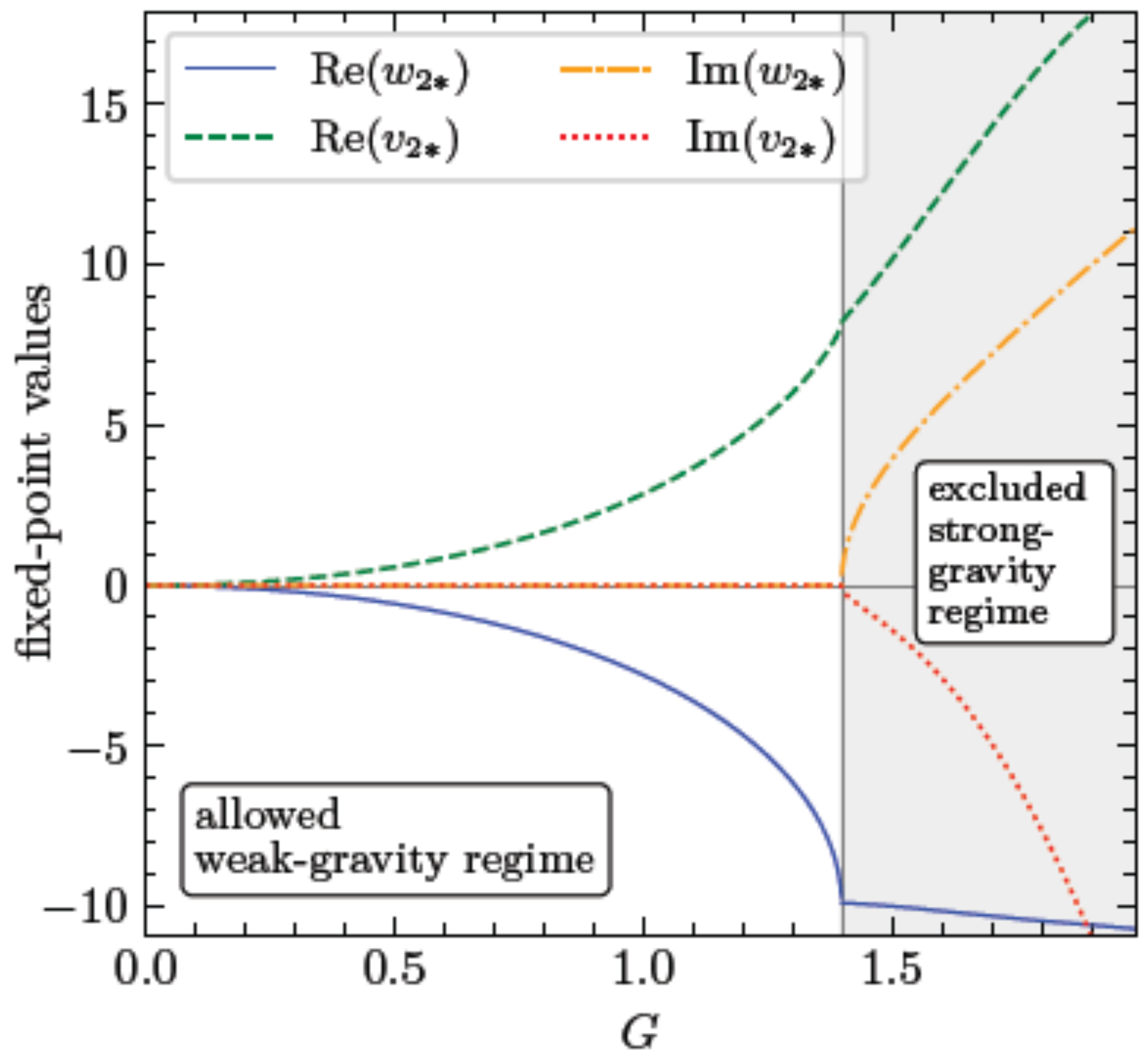

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Apply to photons in asymptotically safe gravity:

- assume that can Wick-rotate action
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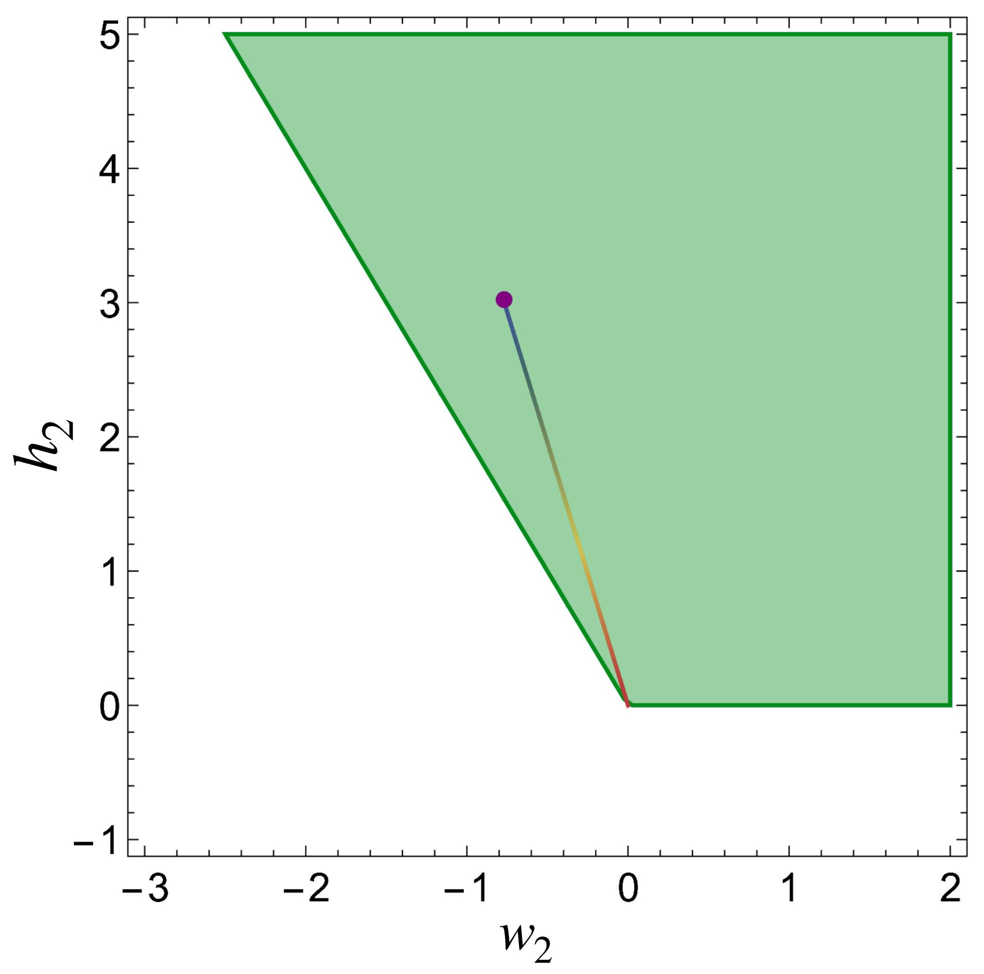
[work in progress with Oodgard Pedersen and Schiffer]



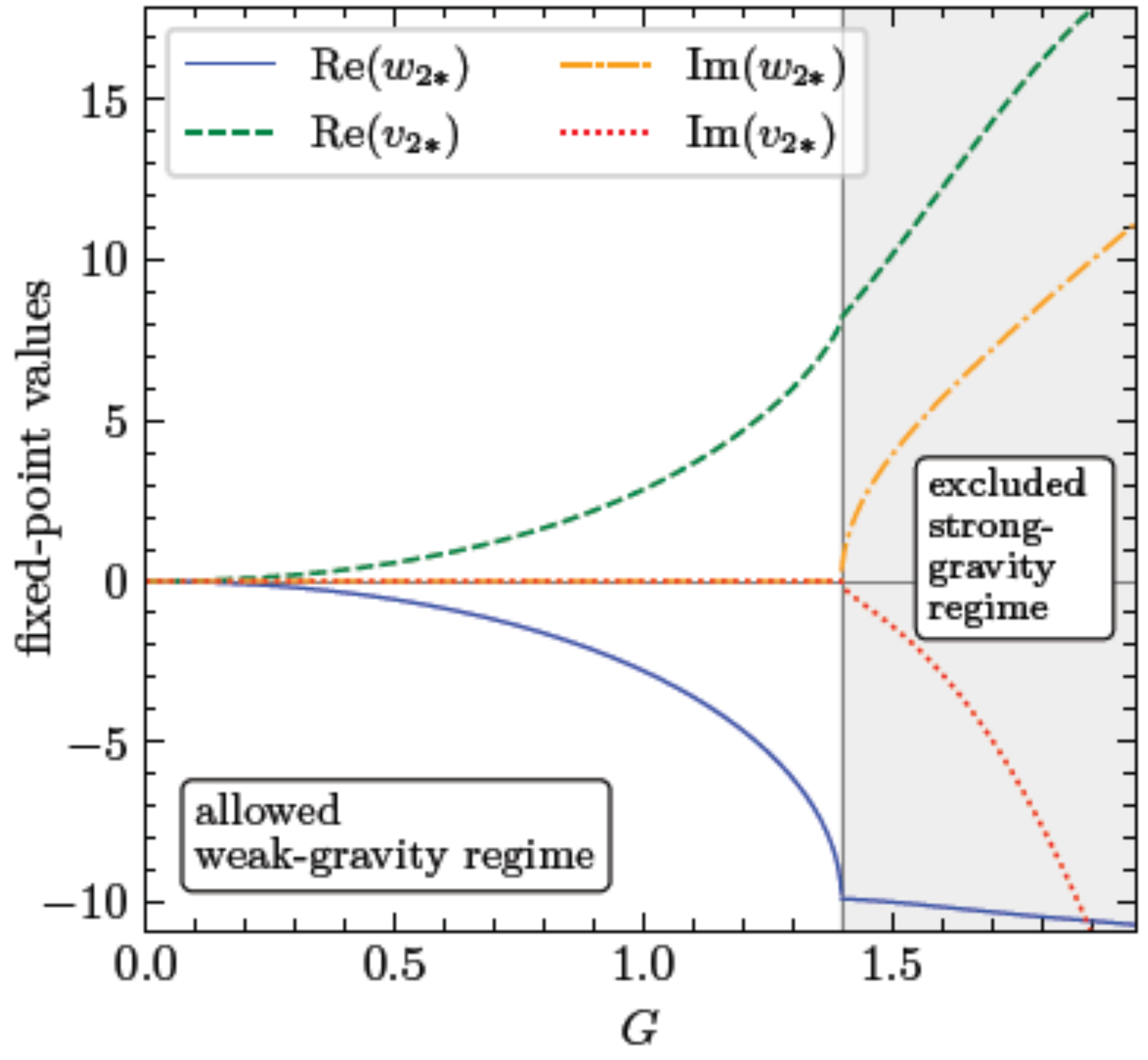
Higher-order couplings in gravity-matter systems

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]



Preliminary results: Positivity bounds in asymptotically safe gravity

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]

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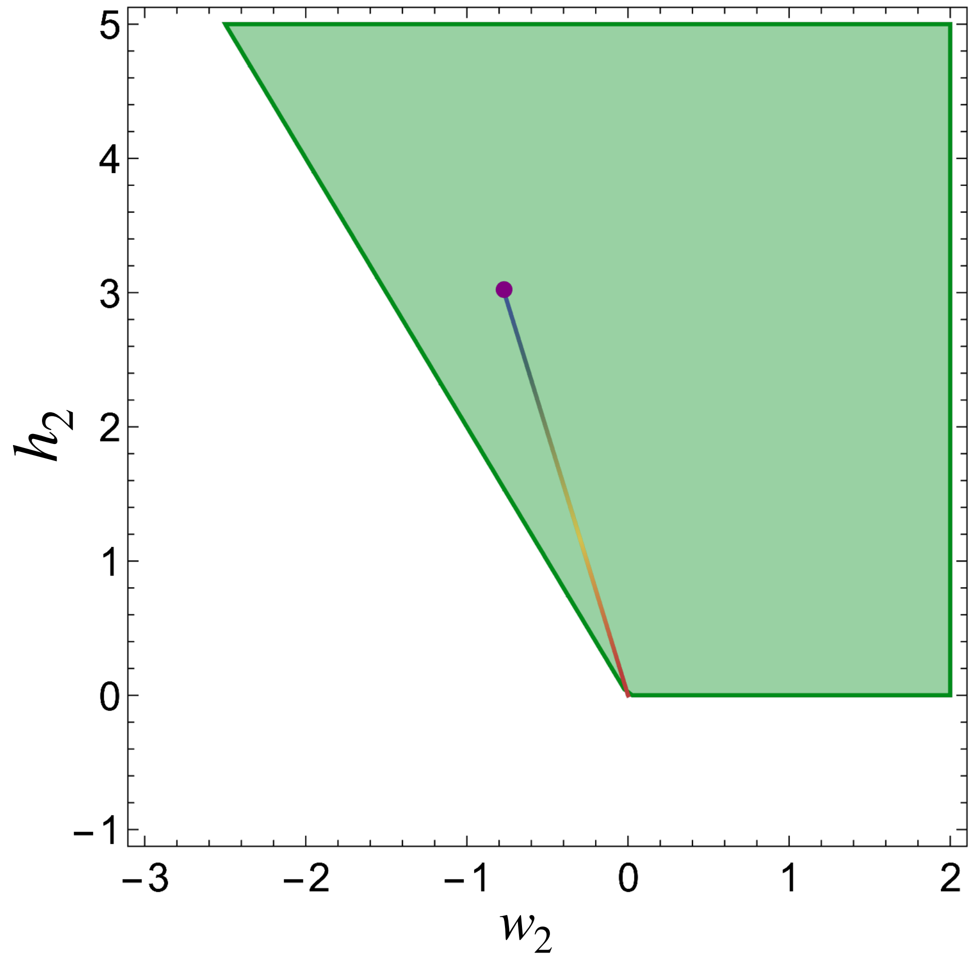

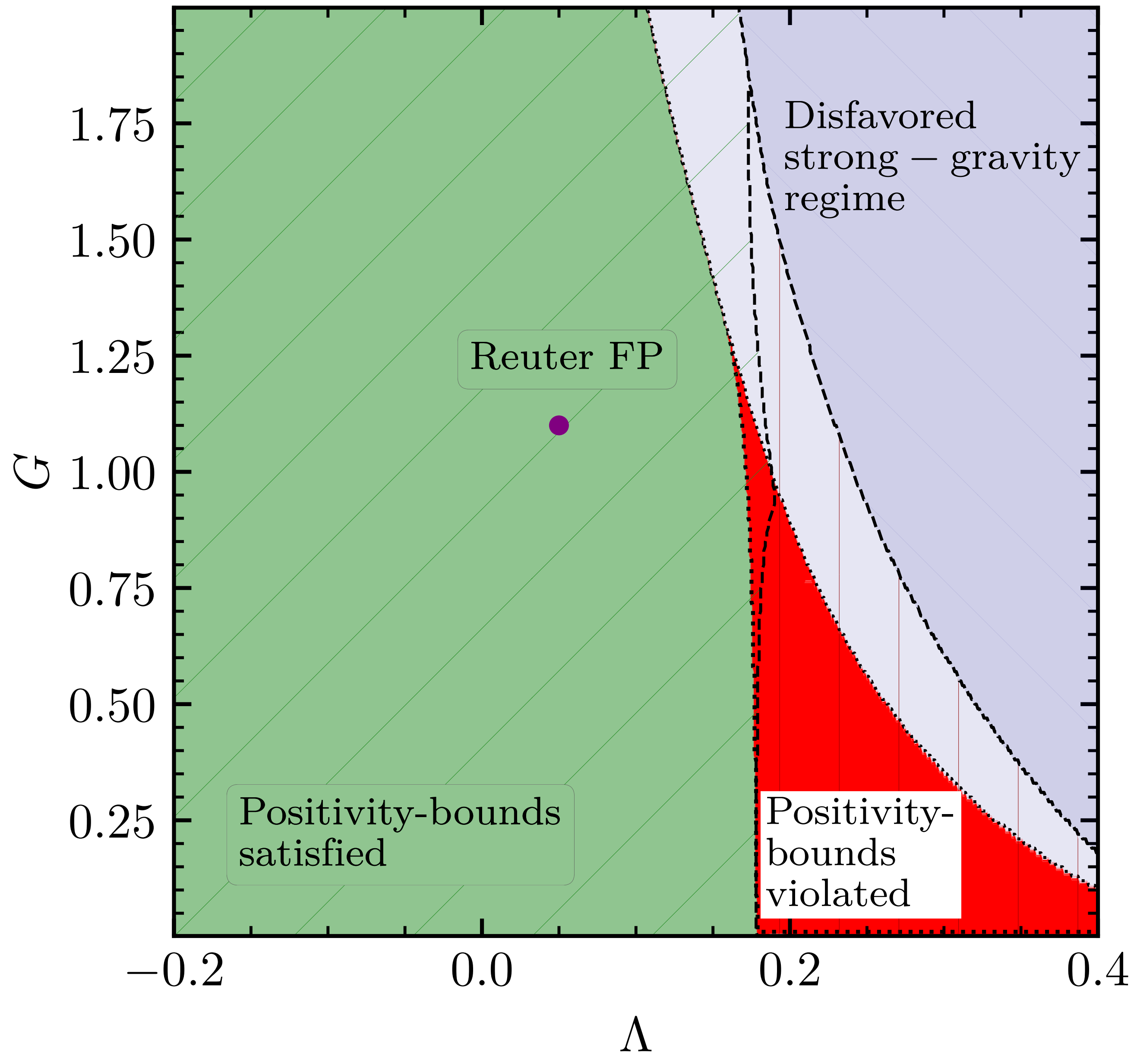

Marginally irrelevant couplings:
UV complete and bounded from above

Gravitational contribution to beta functions of marginal couplings:

→ linear in the Standard-Model couplings
(because gravity couples to the energy-momentum tensor)

→ only present beyond the Planck scale
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→ effects are the same for all gauge groups/all flavors
(because gravity is "blind" to internal symmetries/charges)

$$\beta_{g_i} = -f_{g_i}\, g_i + \beta_{i,0} g_i^3 + \dots$$

with $f_{g_i} = \mathrm{const}$, above M_{Planck}

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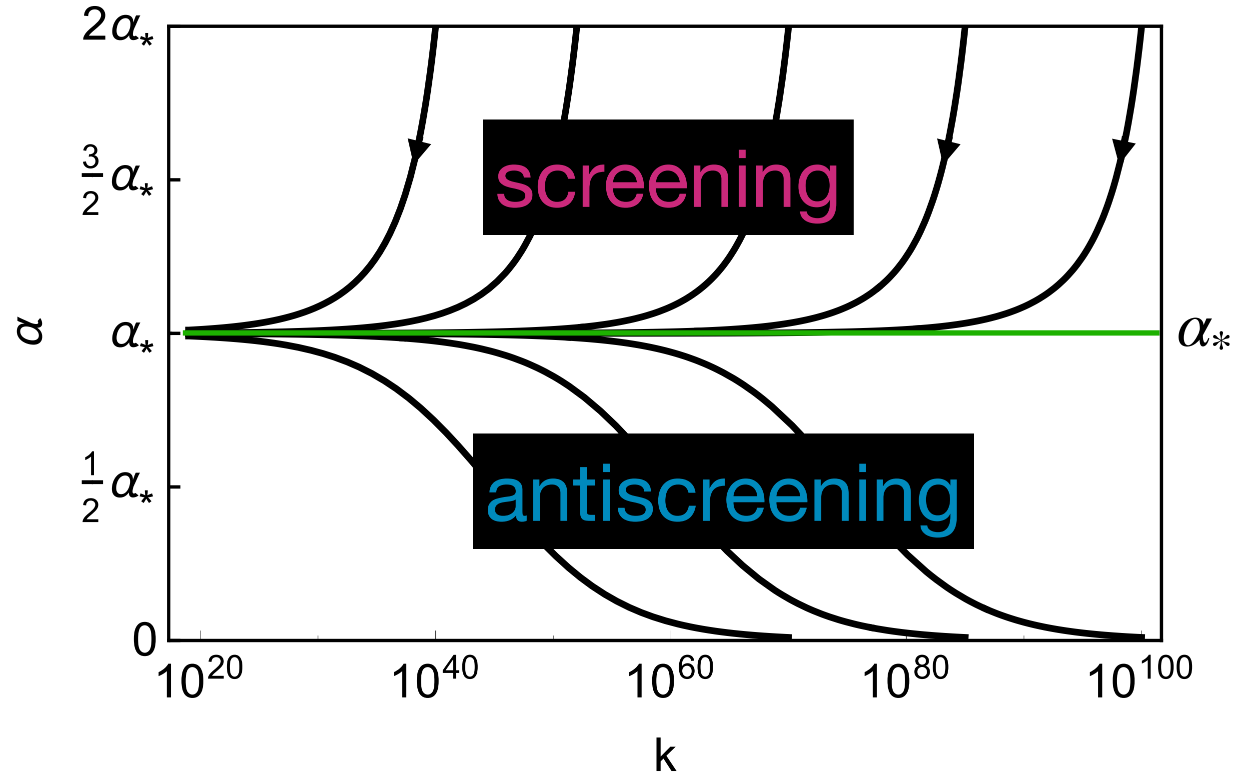

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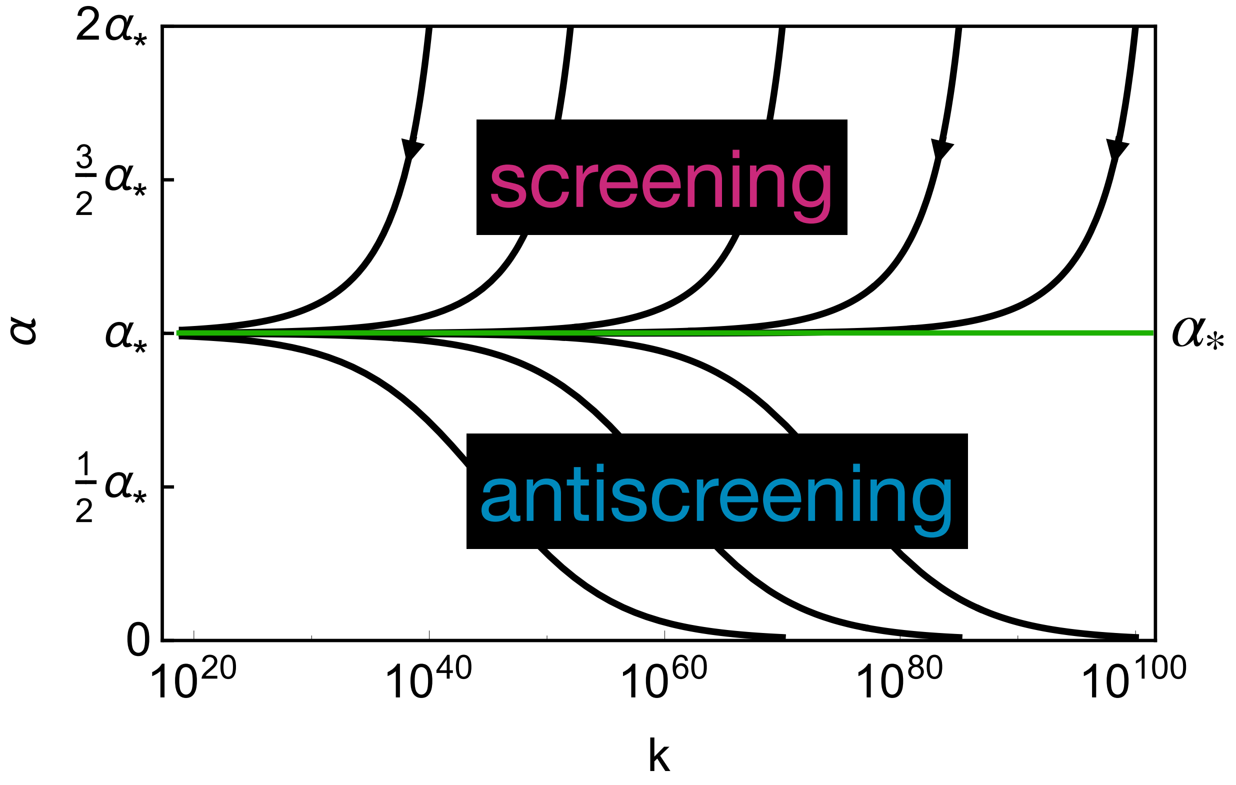

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Examples:

[Daum, Harst, Reuter '09, Harst Reuter '11 Folkerts, Litim, Pawlowski '11, Christiansen, AE, '17 AE, Versteegen '17, de Brito, AE, Pereira '19 AE, Schiffer '19, AE, Kwapisz, Schiffer '21]

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[Oda, Yamada '16; AE, Held, Pawlowski '16, AE, Held '17]

Extension to higher order [AE, Held '17; Christiansen, AE '17; de Brito, AE, Pereira '19, AE, Schiffer '19; AE, Kwapisz, Schiffer '21]

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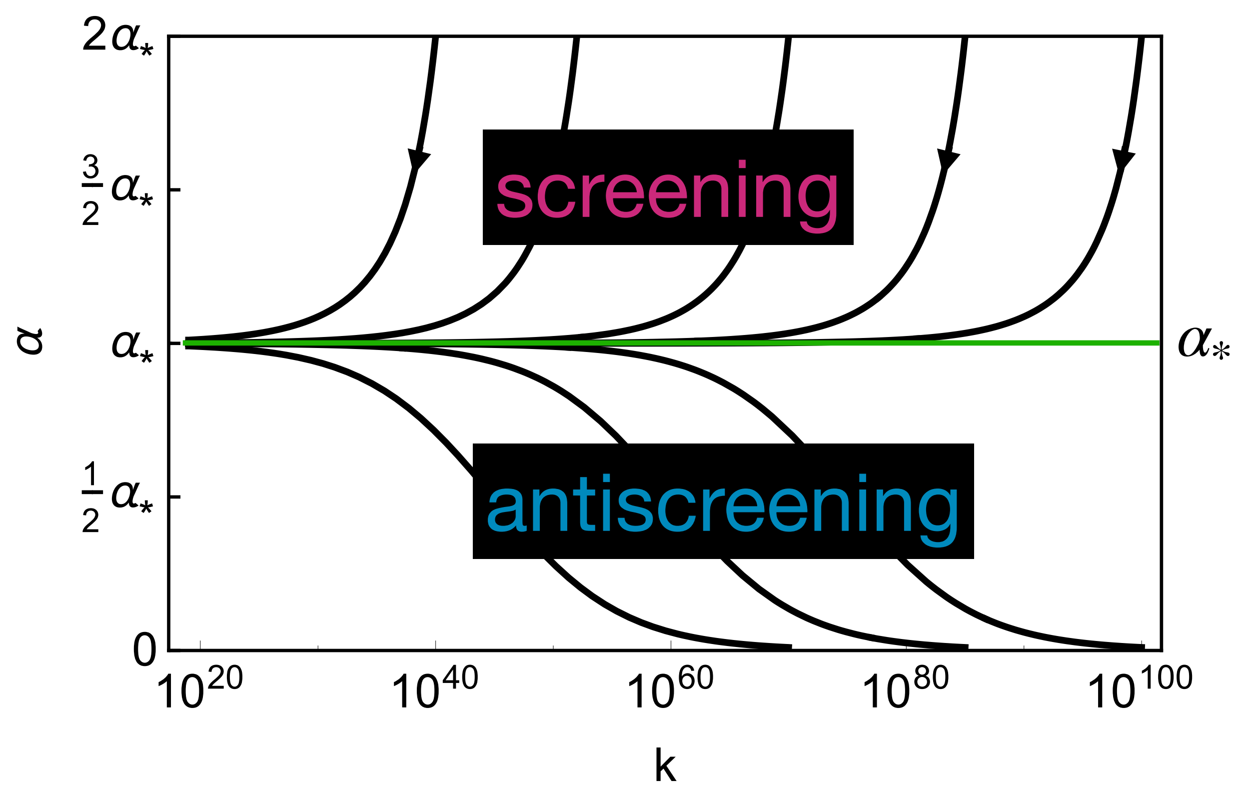

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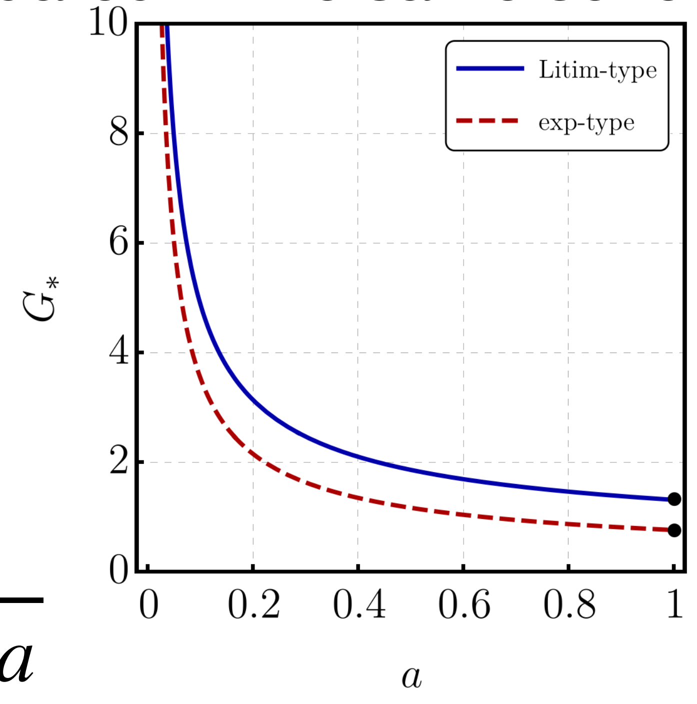
Universality and connection to perturbative results:

f_g not universal and vanishes in some schemes (e.g., dimensional regularization), if gravity coupling is treated as fixed external parameter

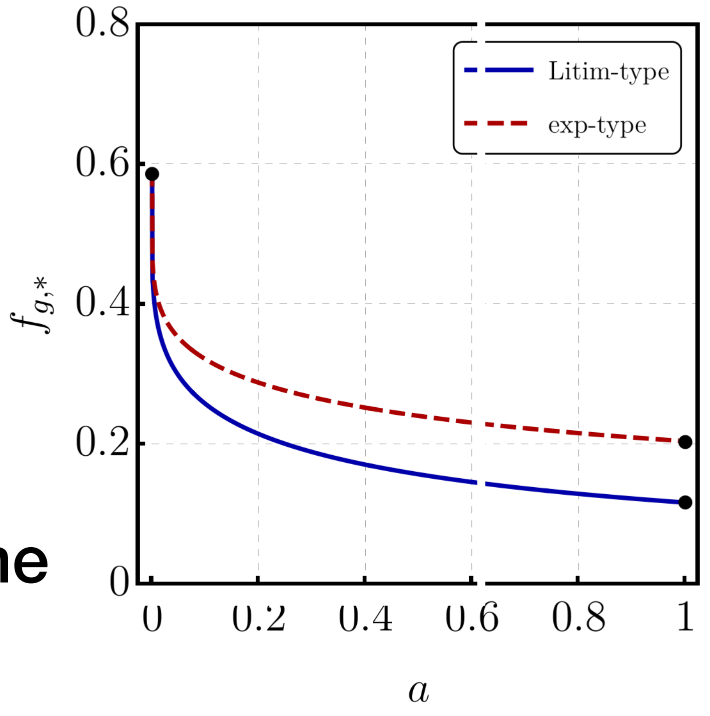
[Robinson, Wilczek '06; Toms '07; Ebert, Plefka, Rodigast '07; Anber, Donoghue, El-Houssieny '11; Ellis, Mavromatos '12…]

subtlety: $f_g > 0$ if fixed-point value for gravity evaluated in the same scheme [de Brito, AE '22]

$$f_g = -\frac{10}{6\pi}\left(\frac{2\,a}{(1-a)^2} + \frac{a\,(a+1)\,\log(a)}{(1-a)^3}\right) G_*$$
$$\sim a\log(a)$$



but $$G_*(a) = \frac{12\pi\,(1-a)^2}{(23a-34)\,a\,\log(a) - 11\,(1-a)\,a} \sim \frac{1}{a\log(a)}$$



a: parameter in regulator, characterizes scheme

[Baldazzi, Percacci, Zambelli '21]

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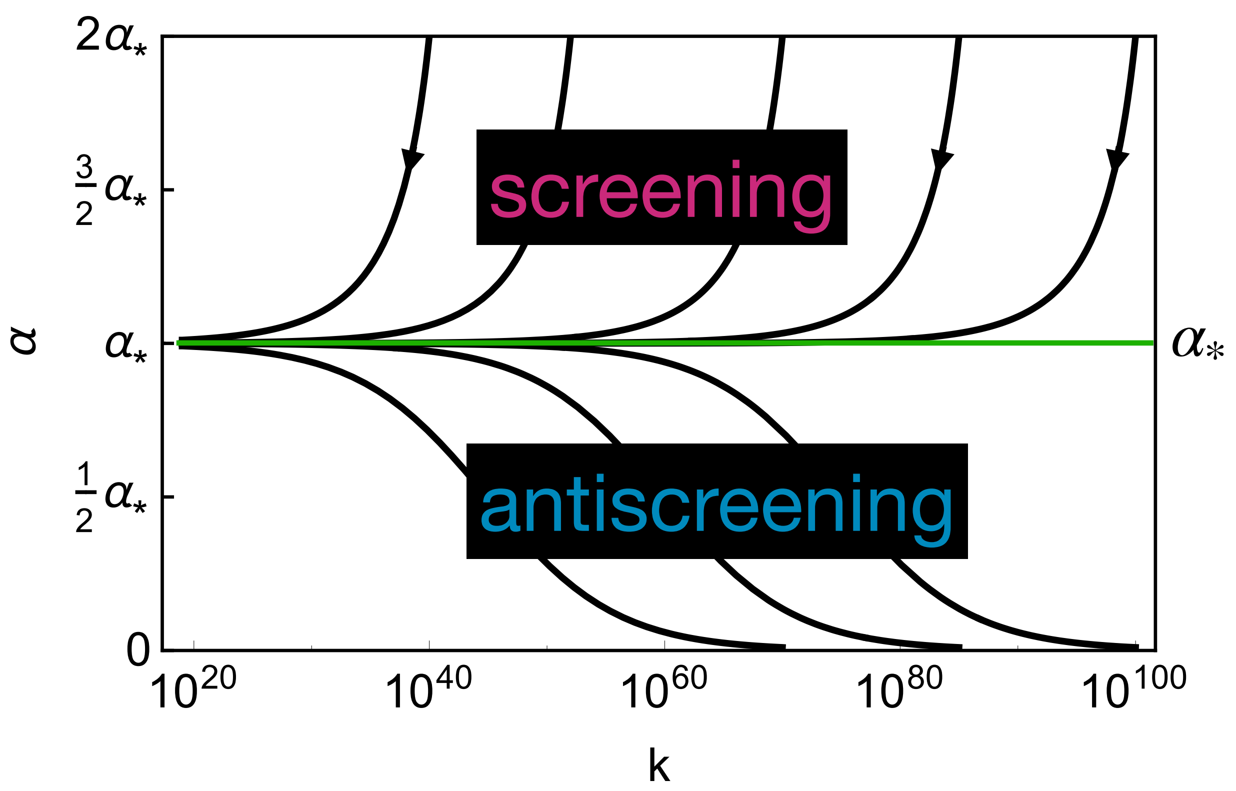

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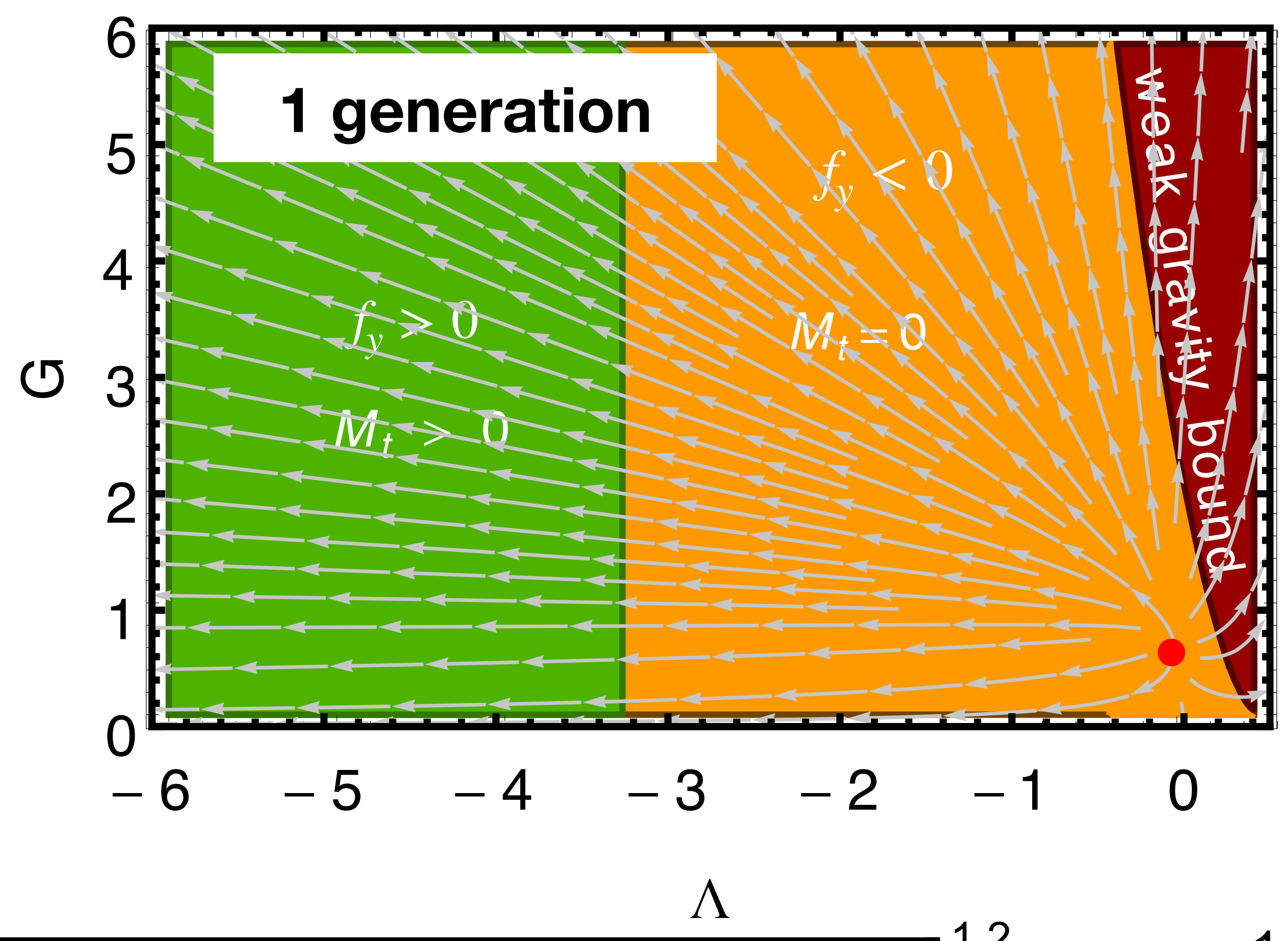
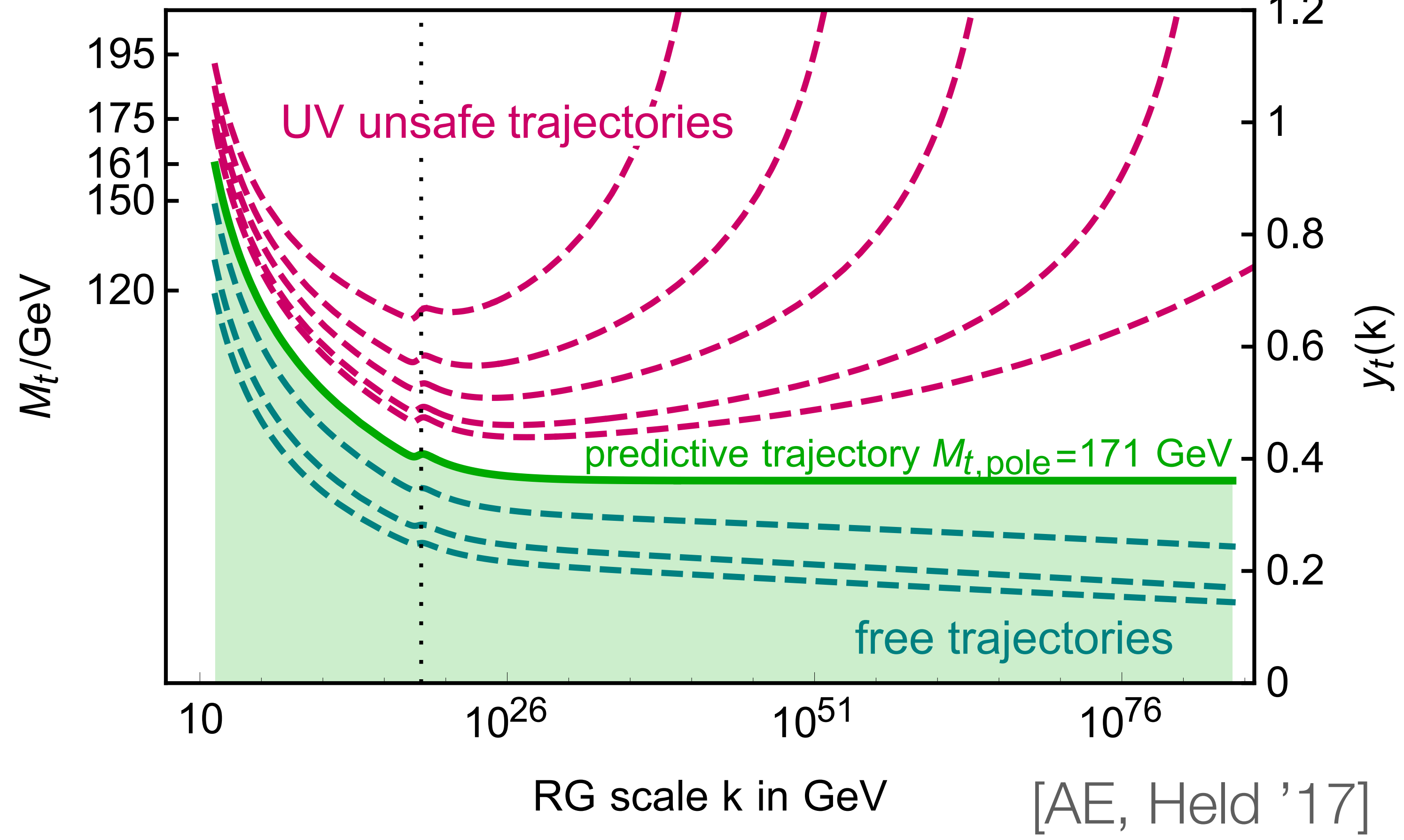


gravitational fixed-point values depend on matter
("matter matters")
[Dona, AE, Percacci '13]



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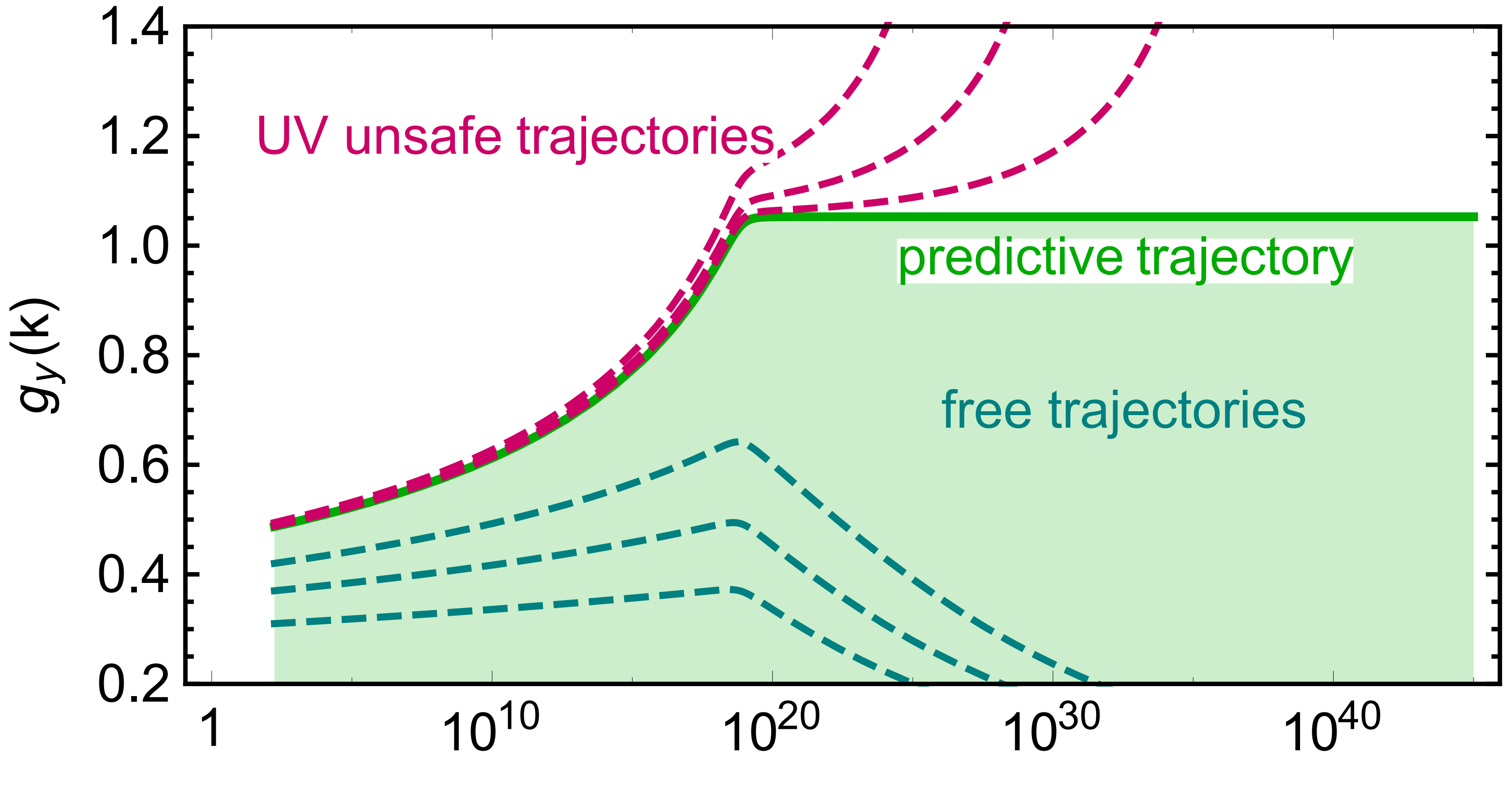

RG scale k in GeV [AE, Versteegen '17]

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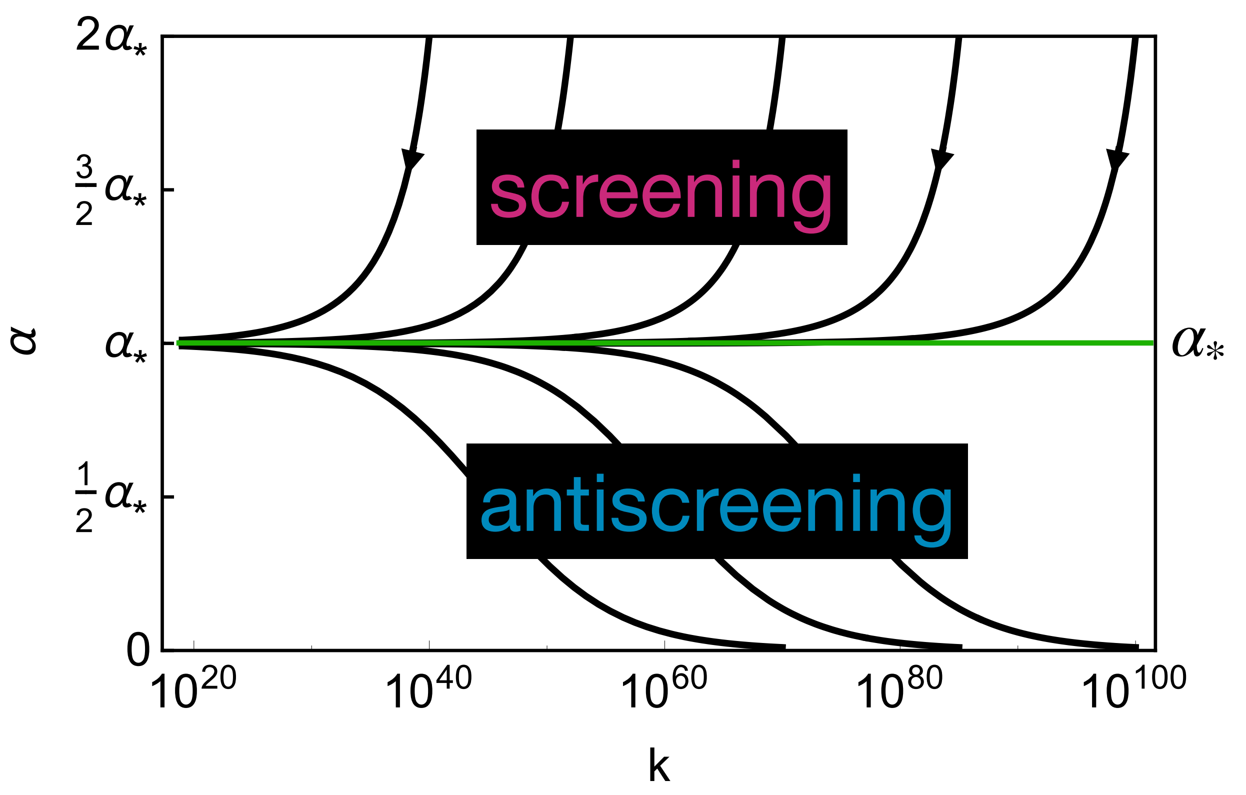

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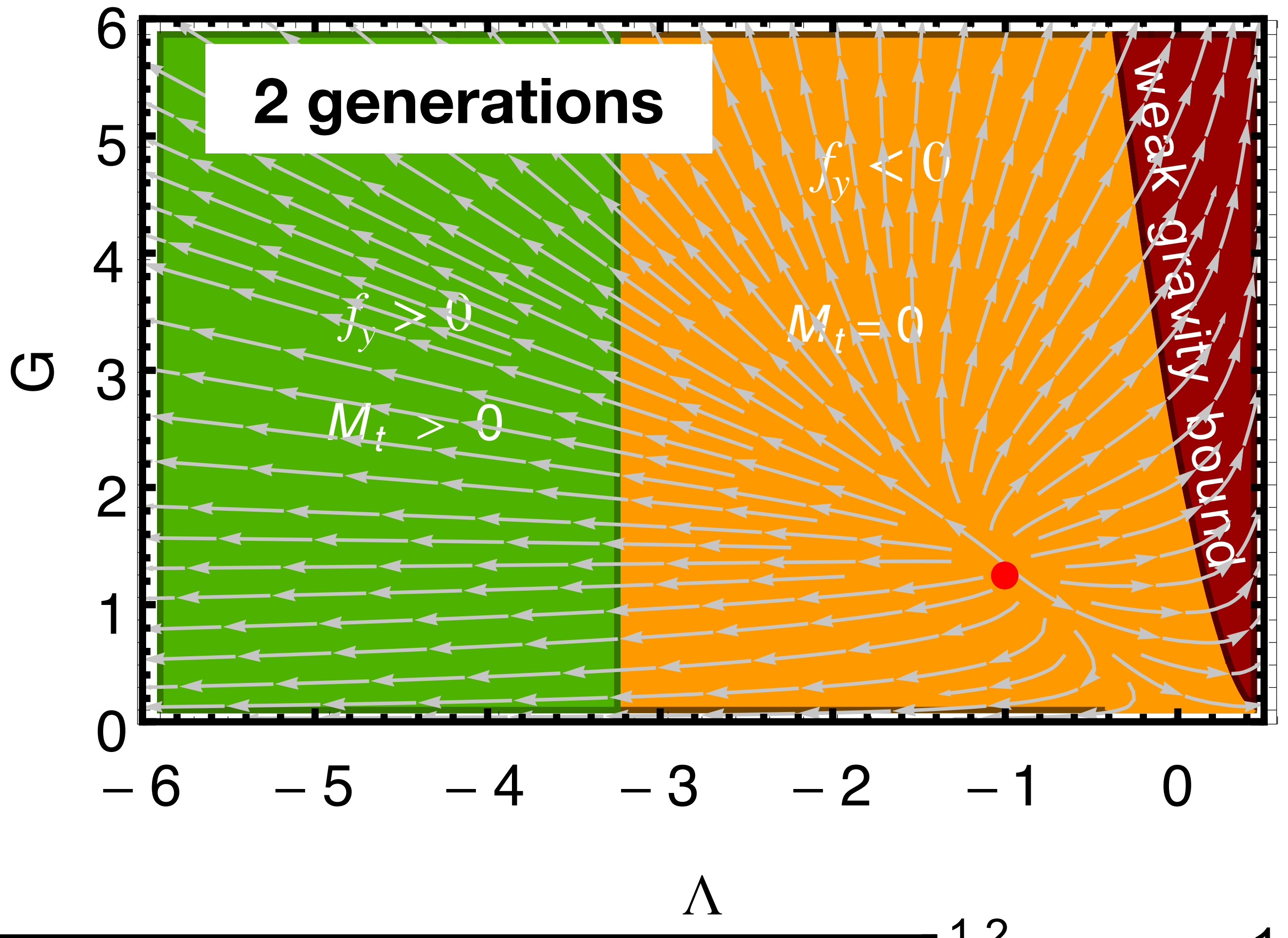

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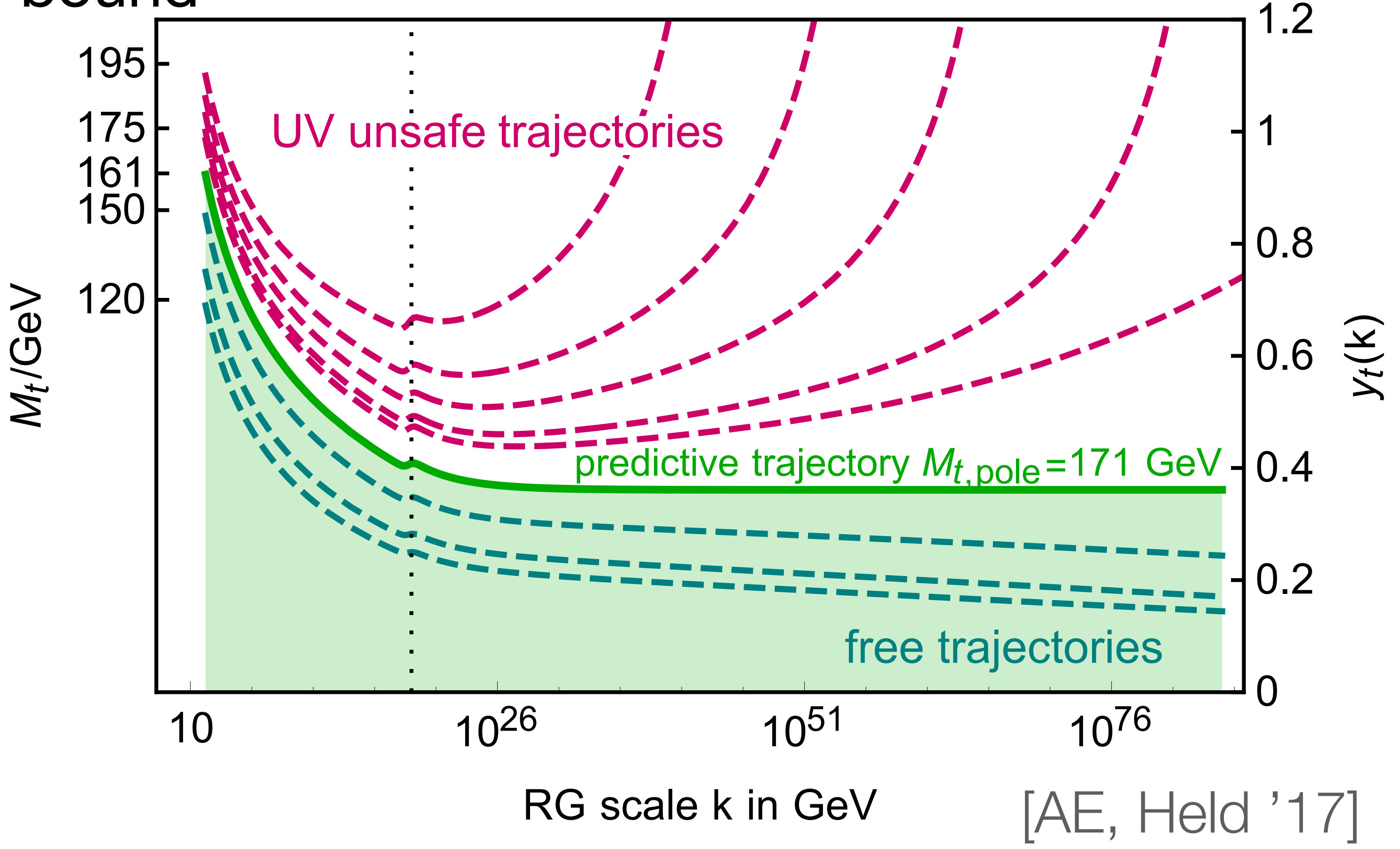

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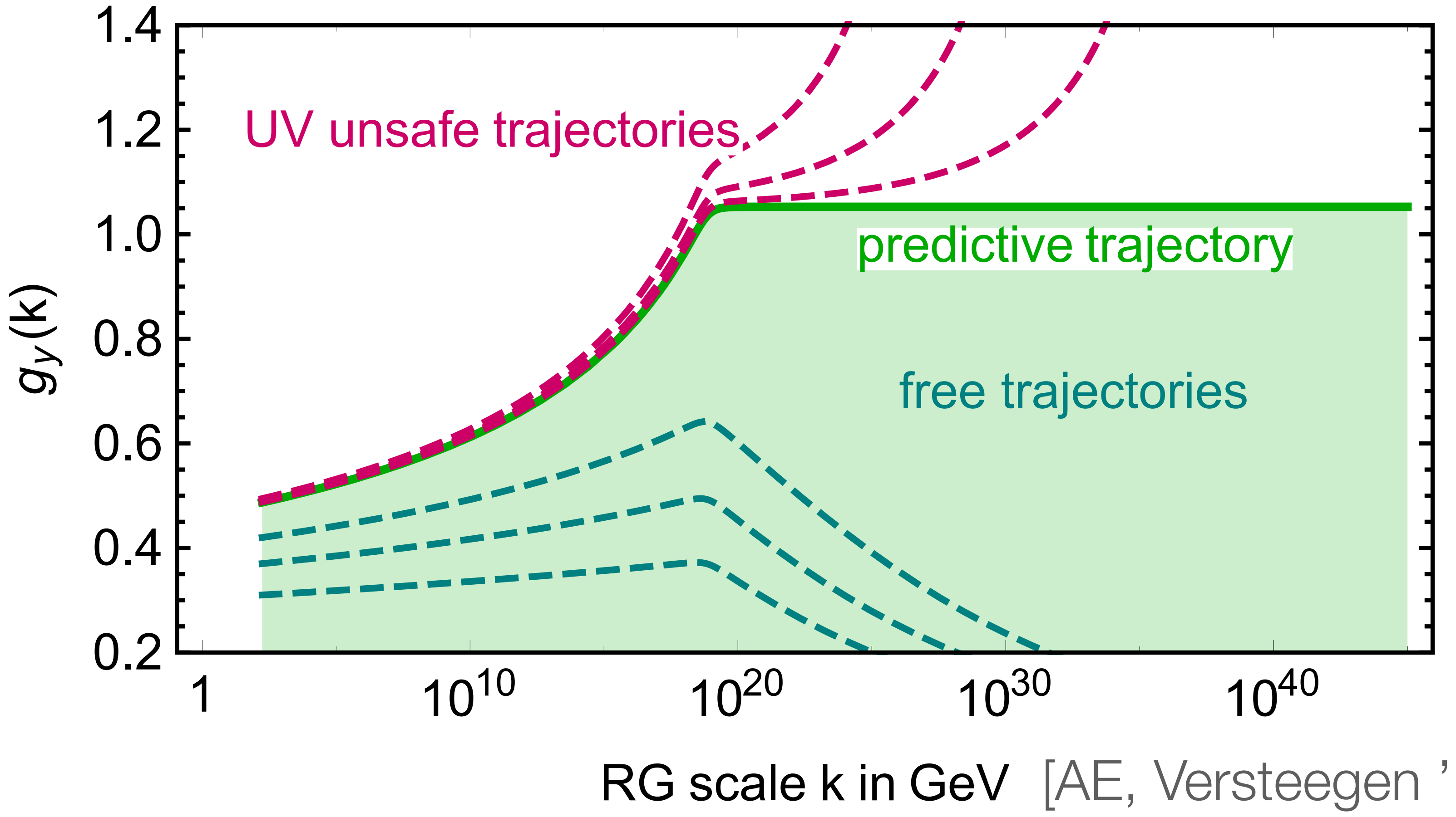

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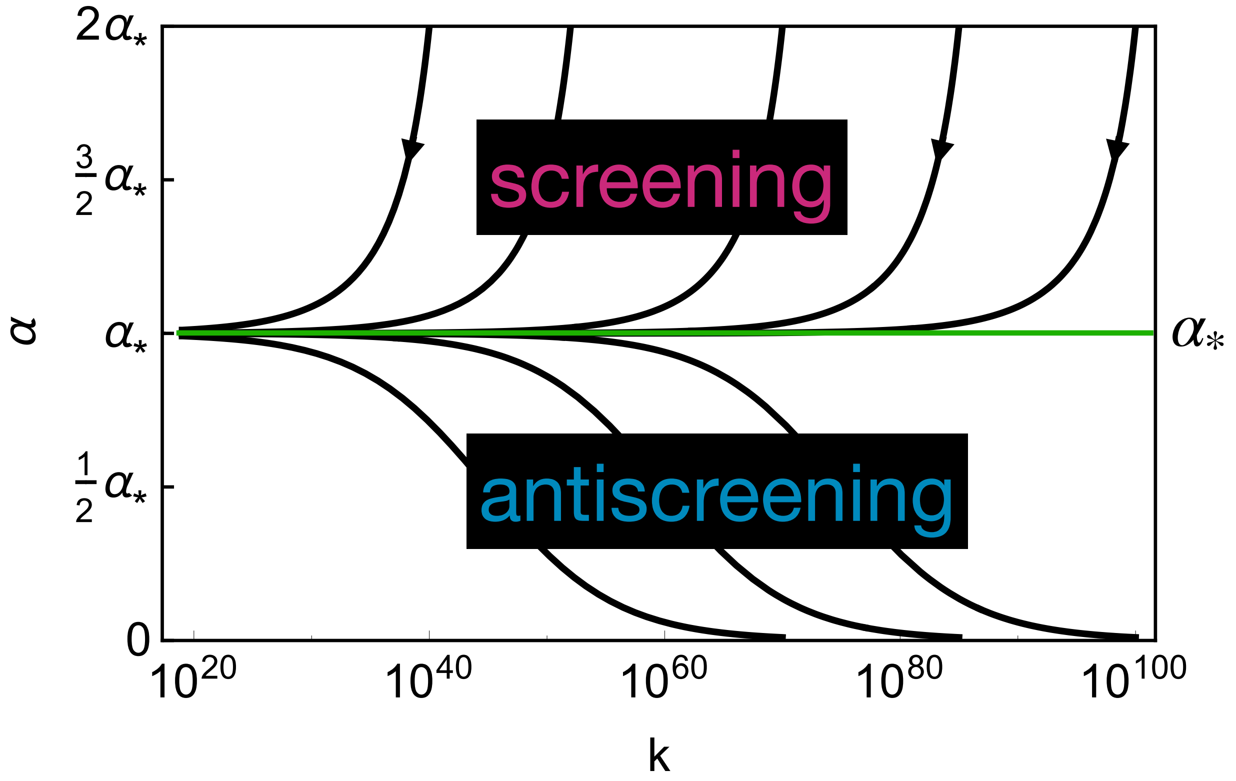

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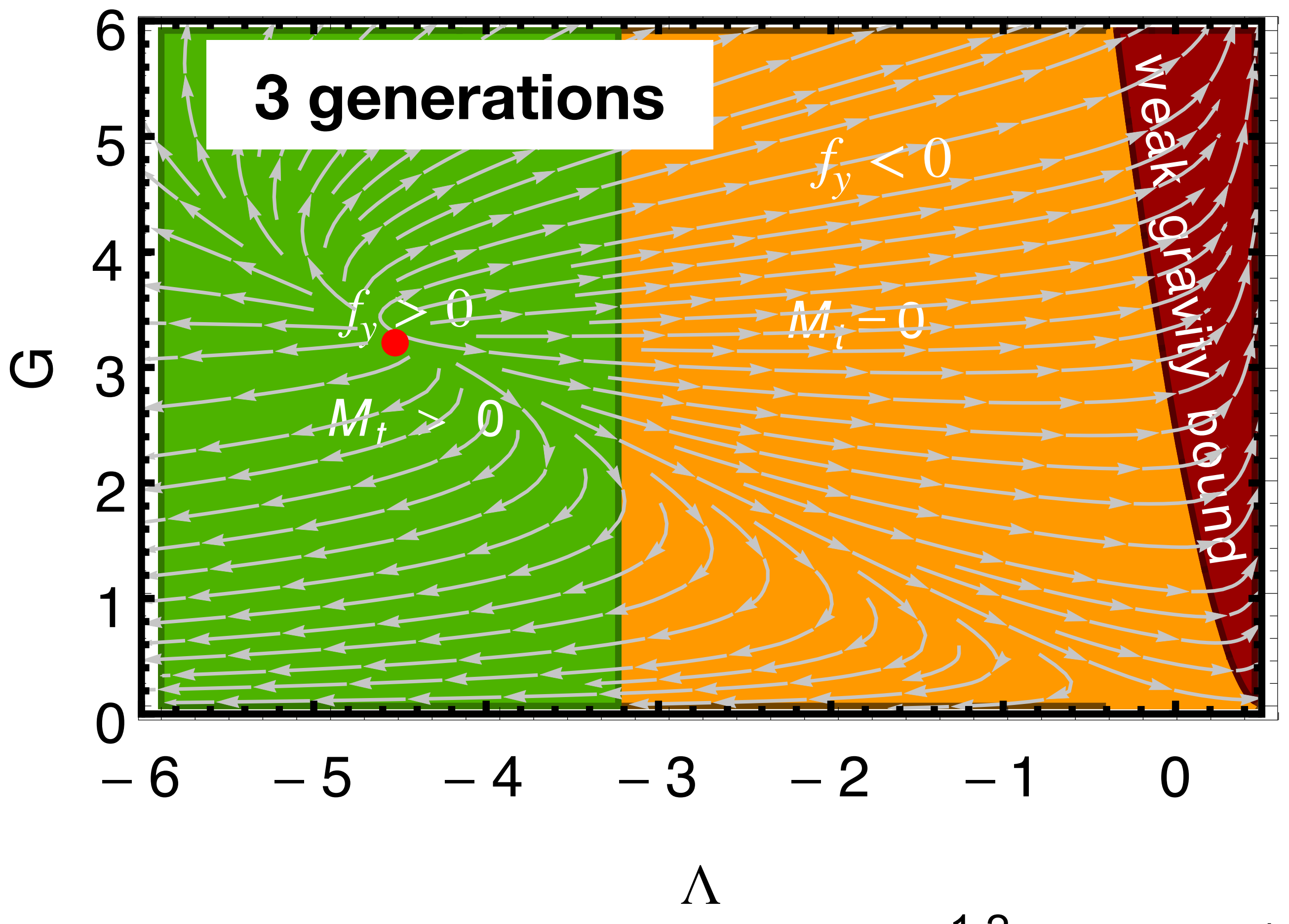

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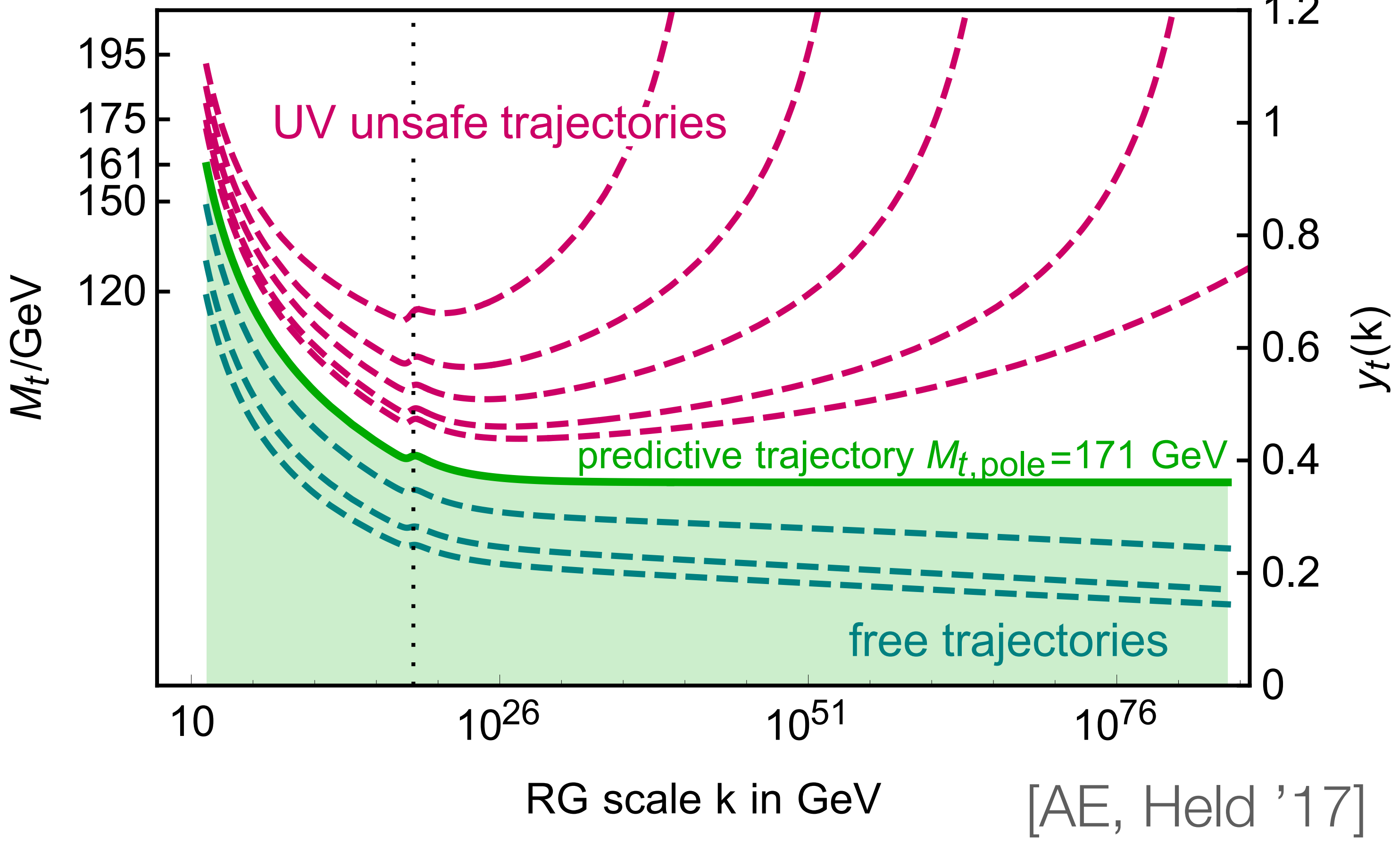

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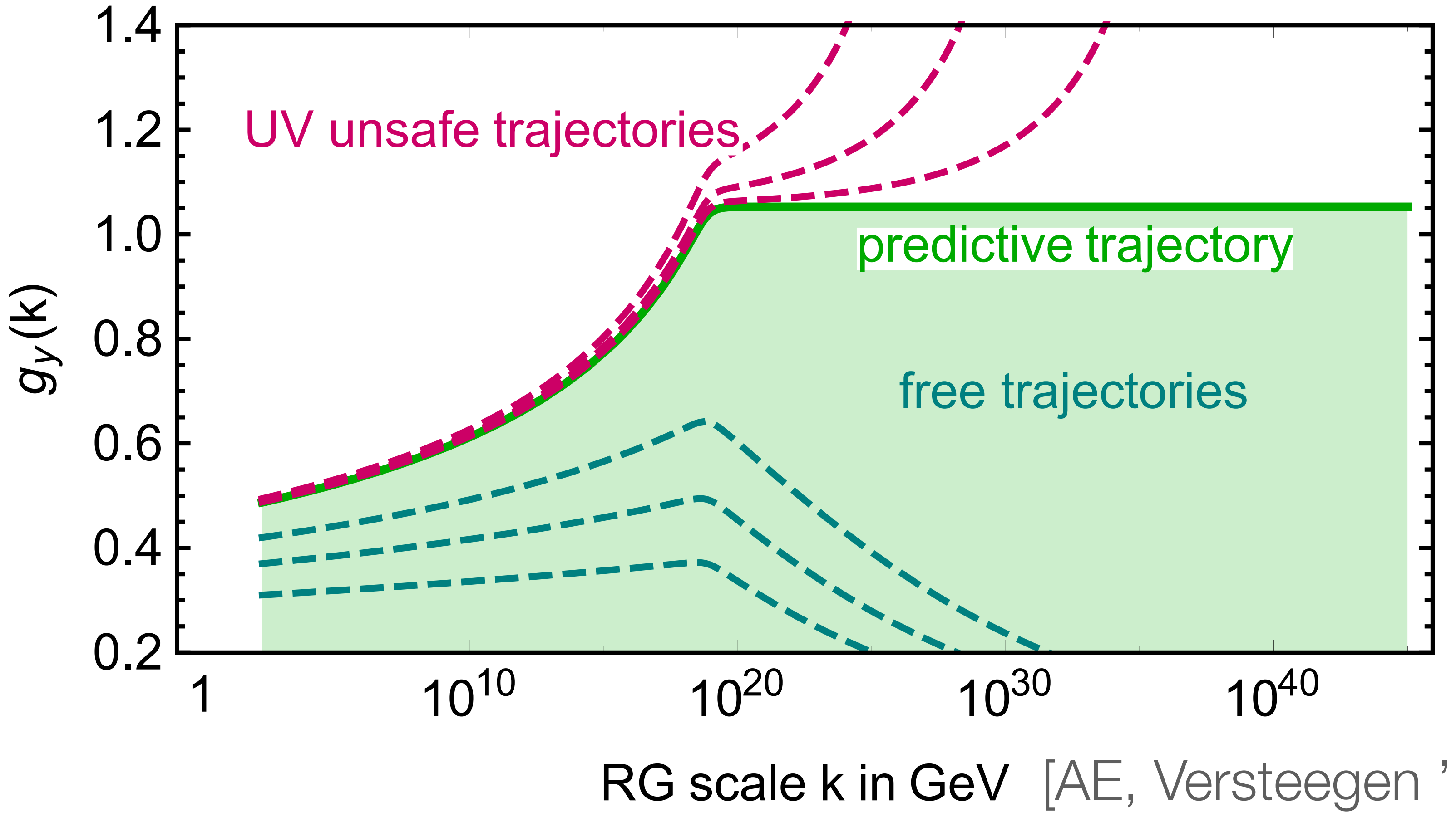

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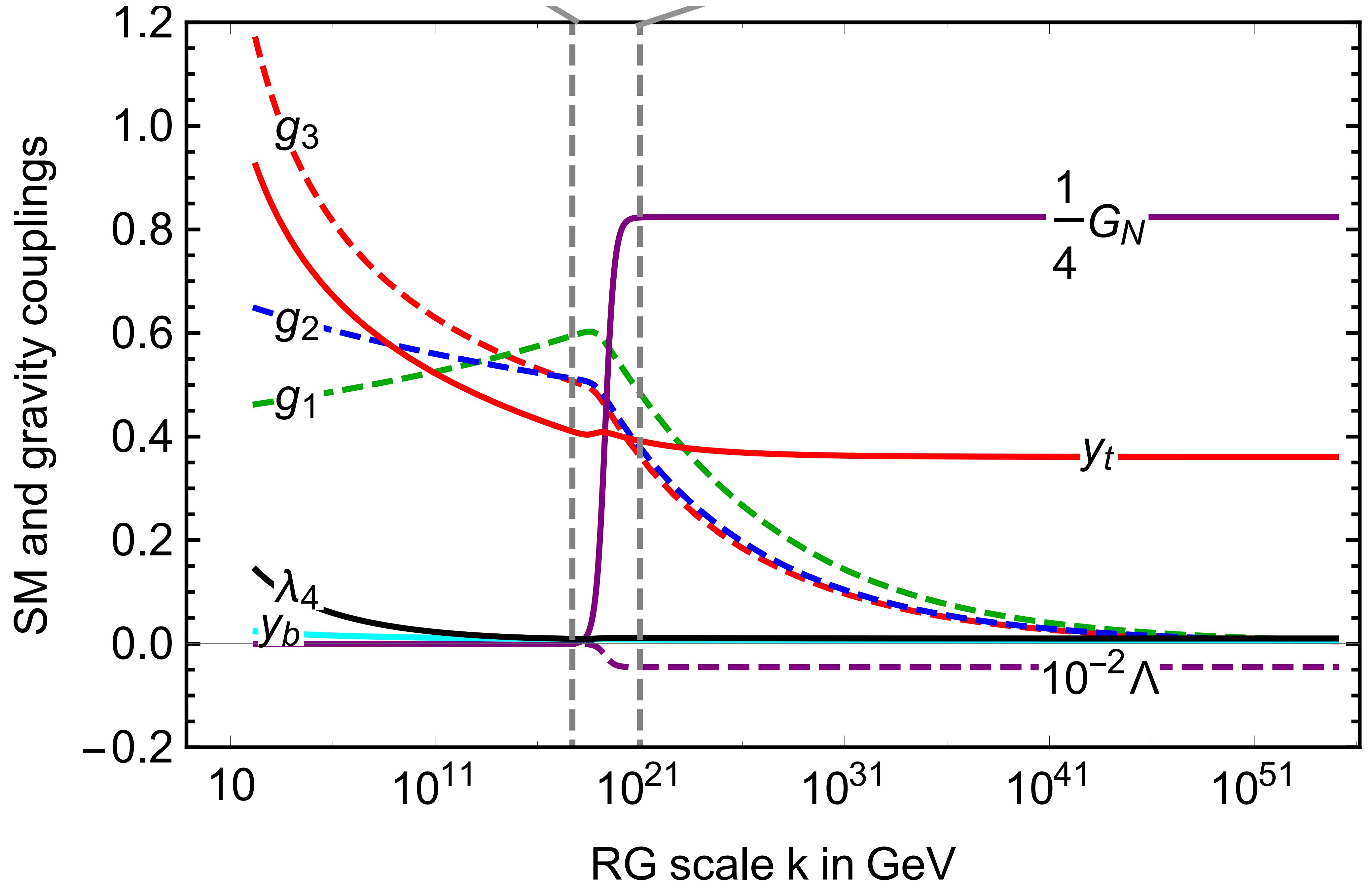
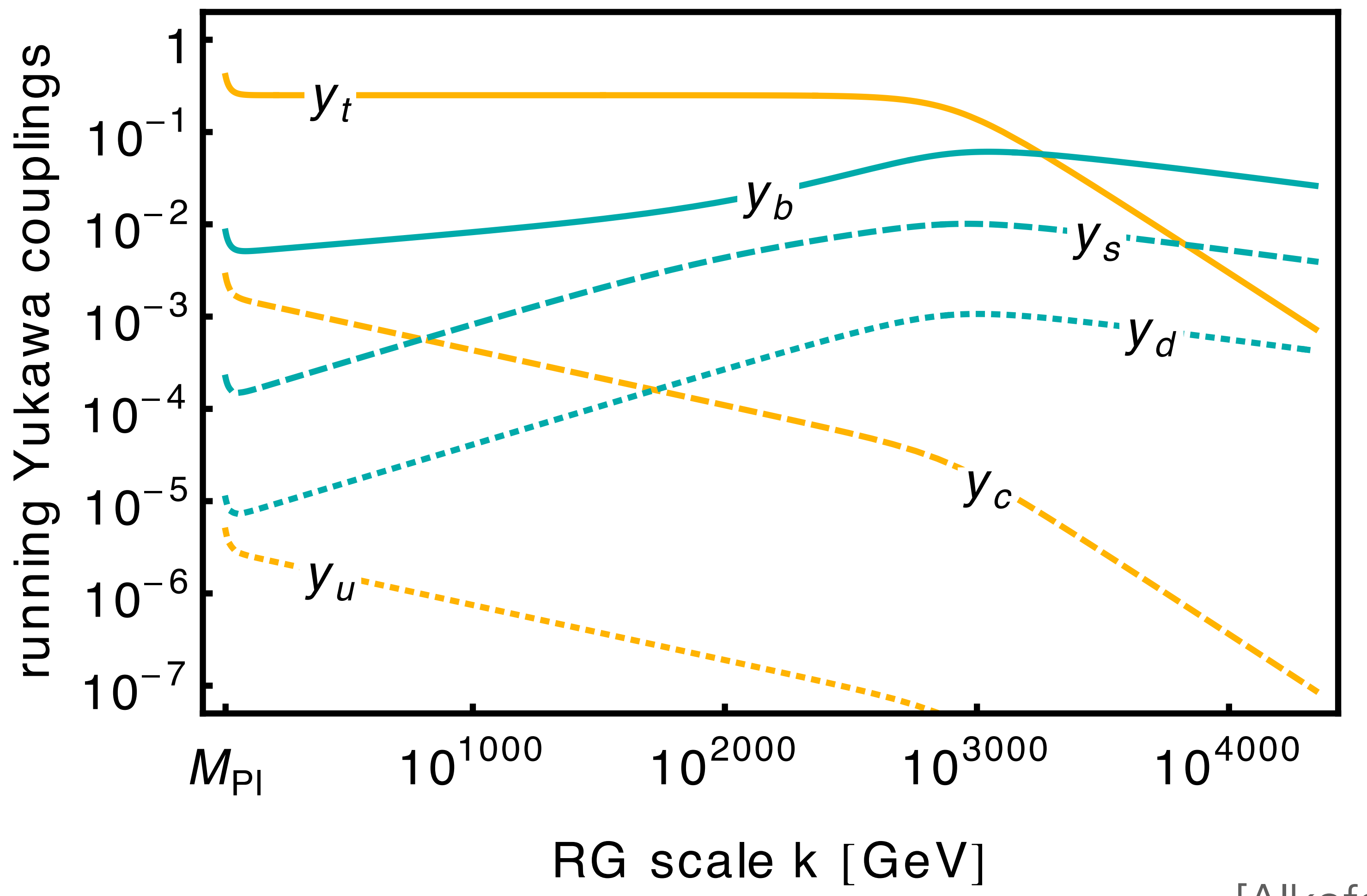
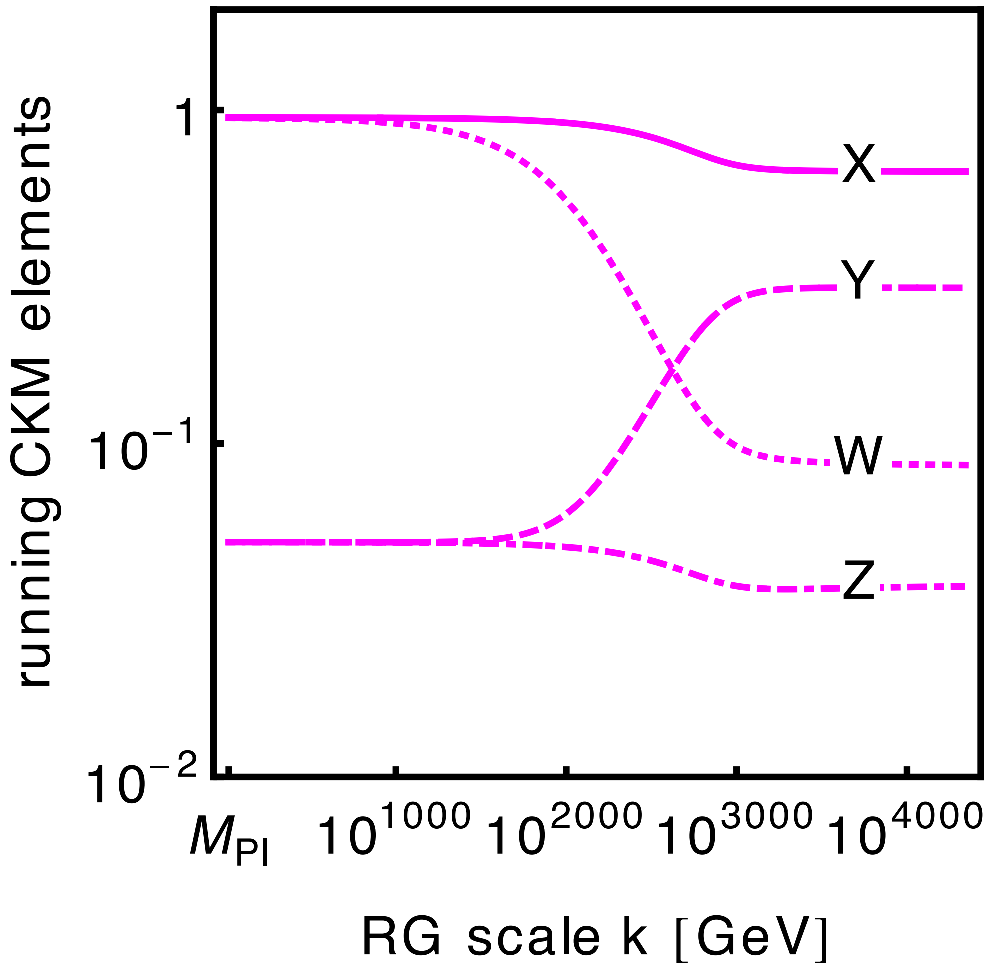
Asymptotically safe Standard Model with gravity



[AE, Held '17,
Alkofer, AE, Held, Percacci, Nieto, Schröfl '19;
Kowalska, Sessolo '19;
Pastor-Guiterrez, Pawlowski, Reichert '22]

Flavor sector:





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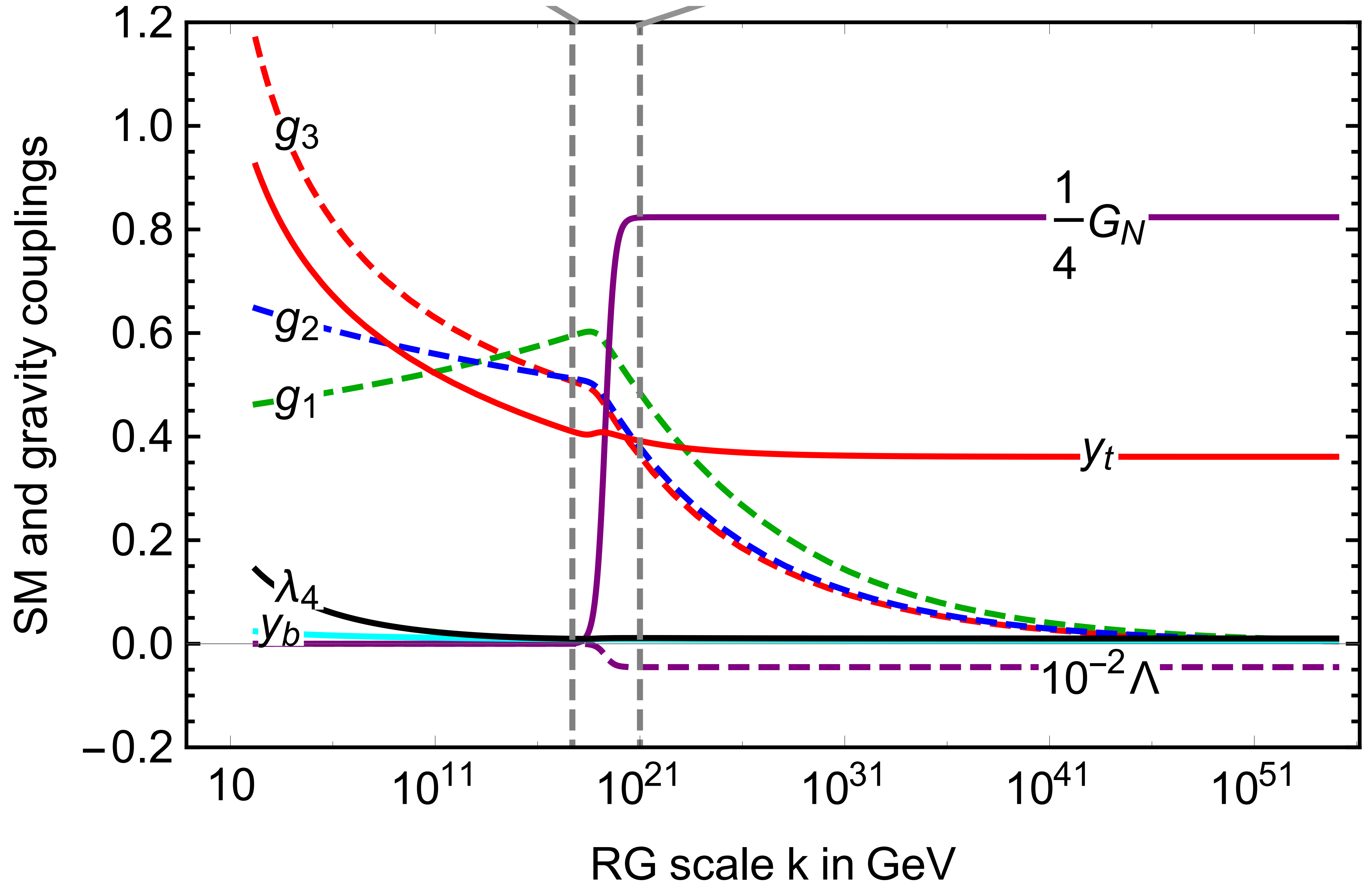

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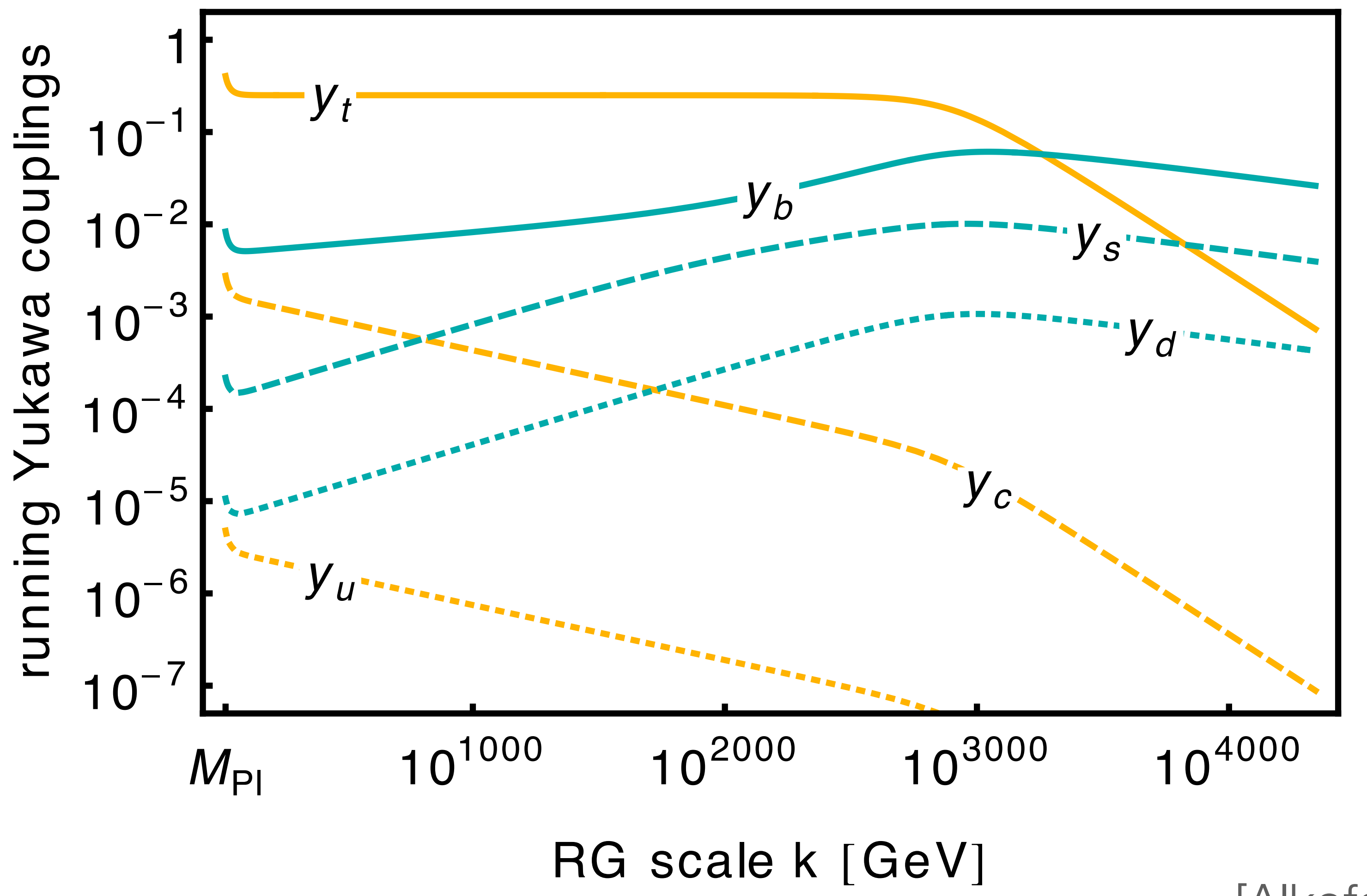

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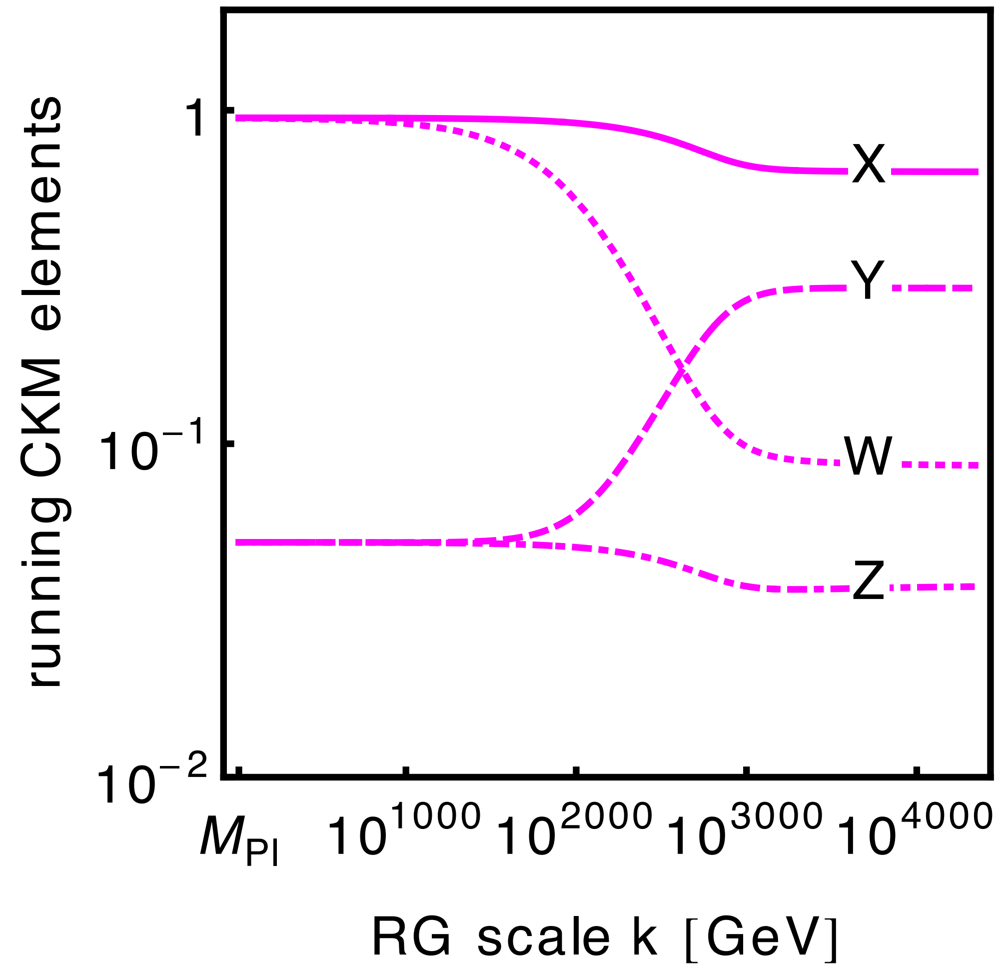
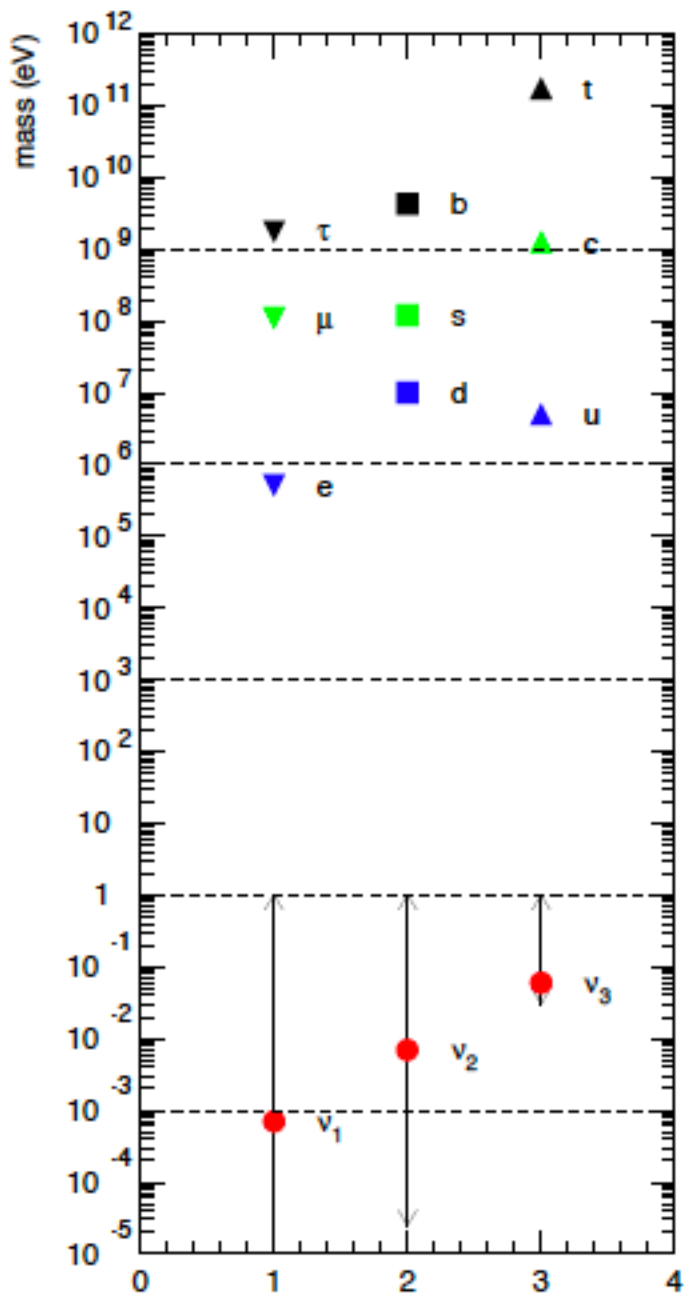


Open questions:

- Higgs mass & stability (note dependence on top quark mass!)
- Neutrino masses

Neutrino masses

Standard Model fermion masses



- Option 1:

  neutrino masses arise through a different mechanism than the other fermion masses:

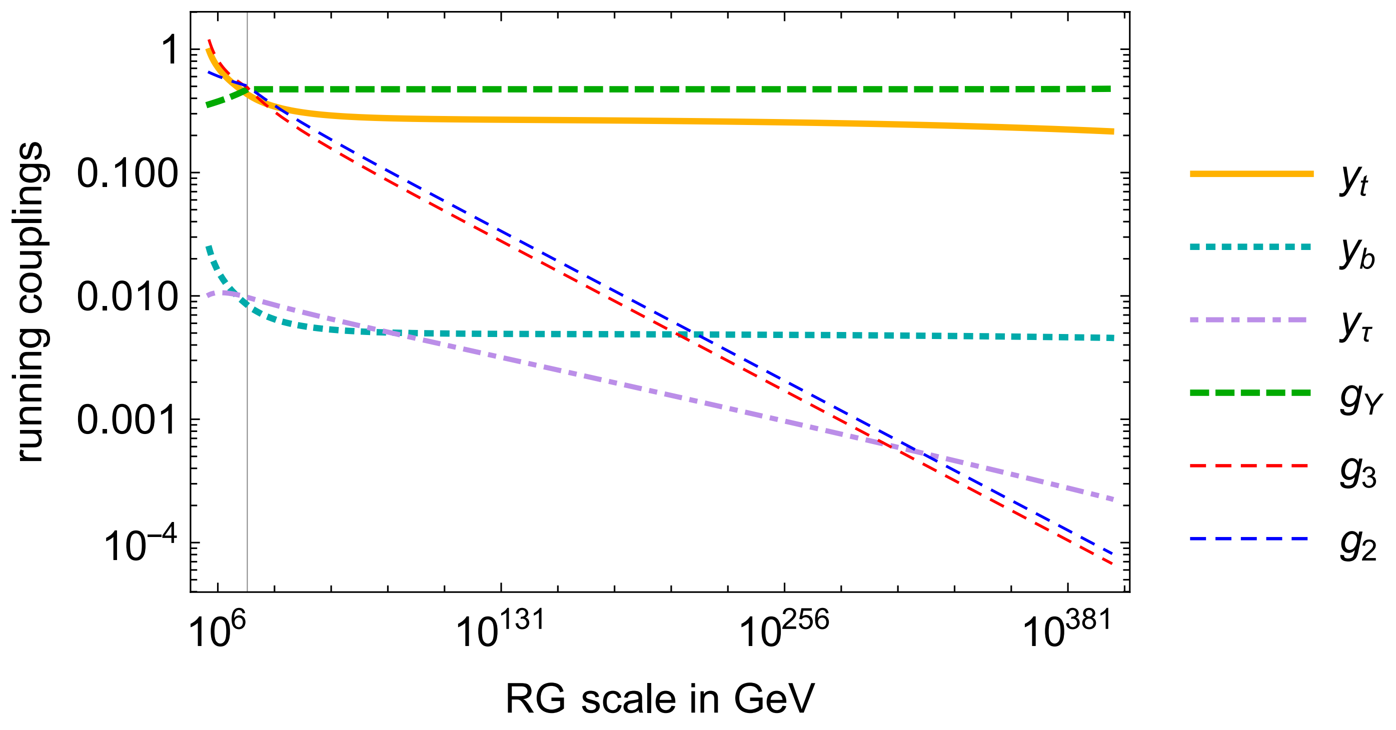
  Weinberg operator is zero and irrelevant; Seesaw-scale (type I) is bounded from above

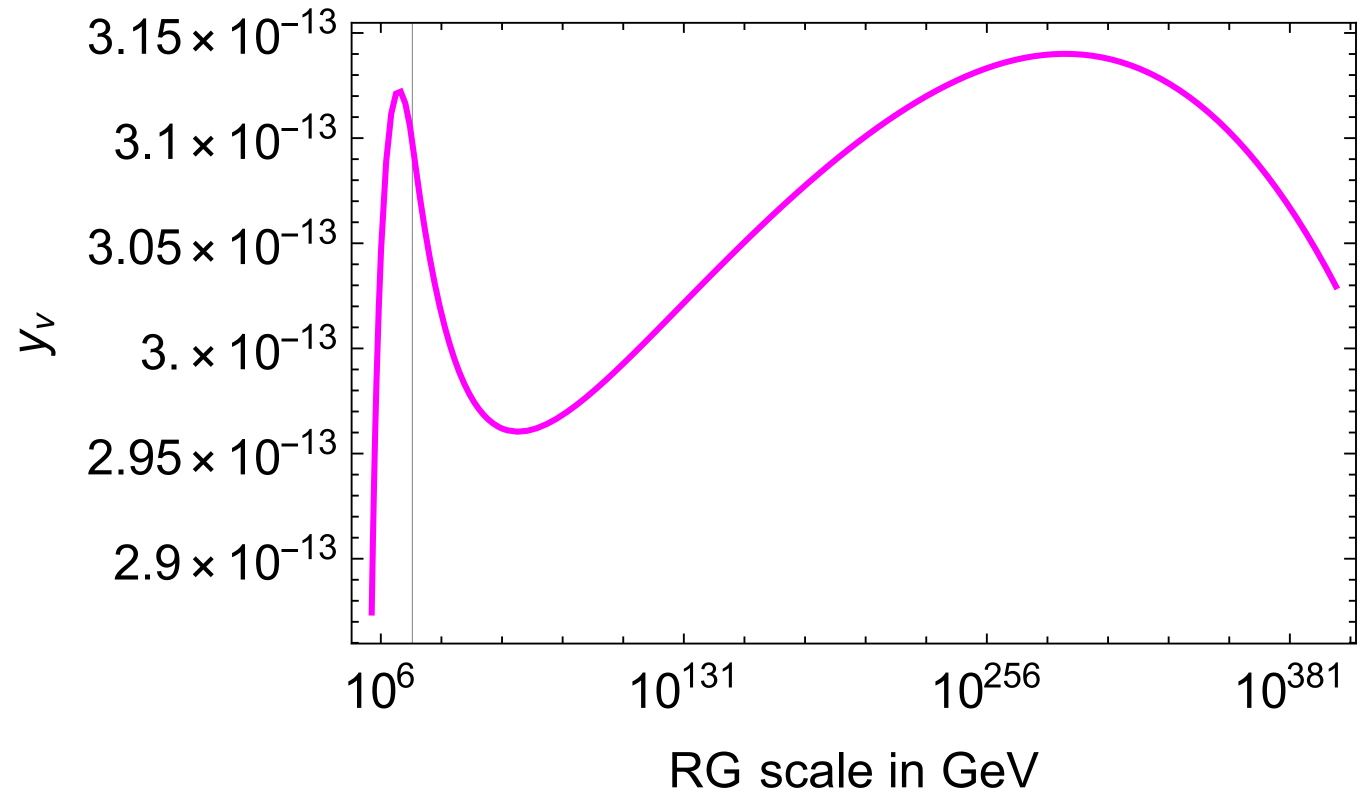
  [work in progress with de Brito, Pereira, Yamada]

- Option 2:

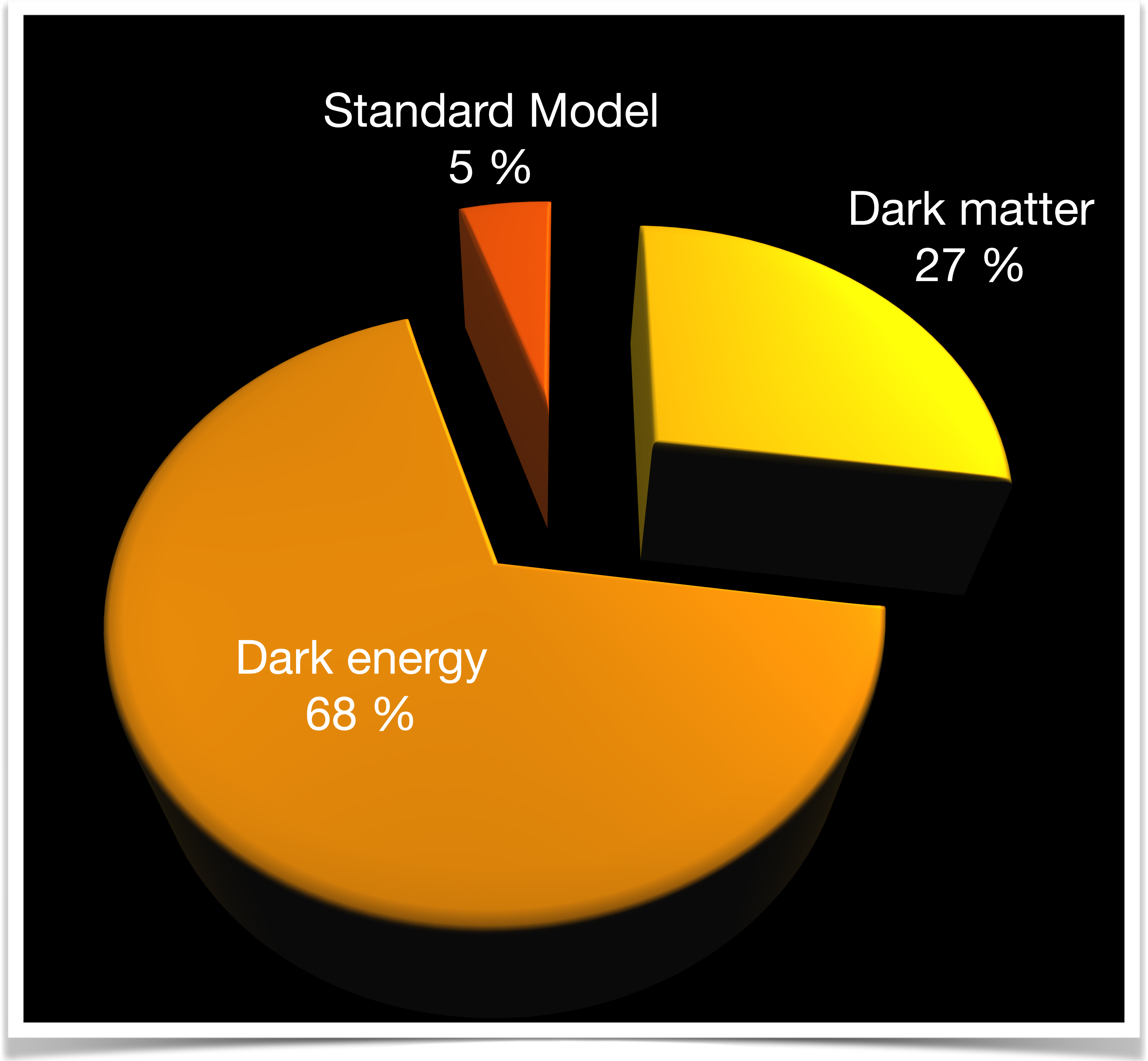
  neutrino masses arise through the Higgs mechanism with a very small Yukawa coupling

  [Held ’19; Kowalska, Sessolo ’22; AE, Held ’22]





Asymptotic safety and the dark universe



General idea: Use predictive power of asymptotic safety to constrain models of the dark sector

→ to make quantum gravity testable

→ to make dark sector predictive

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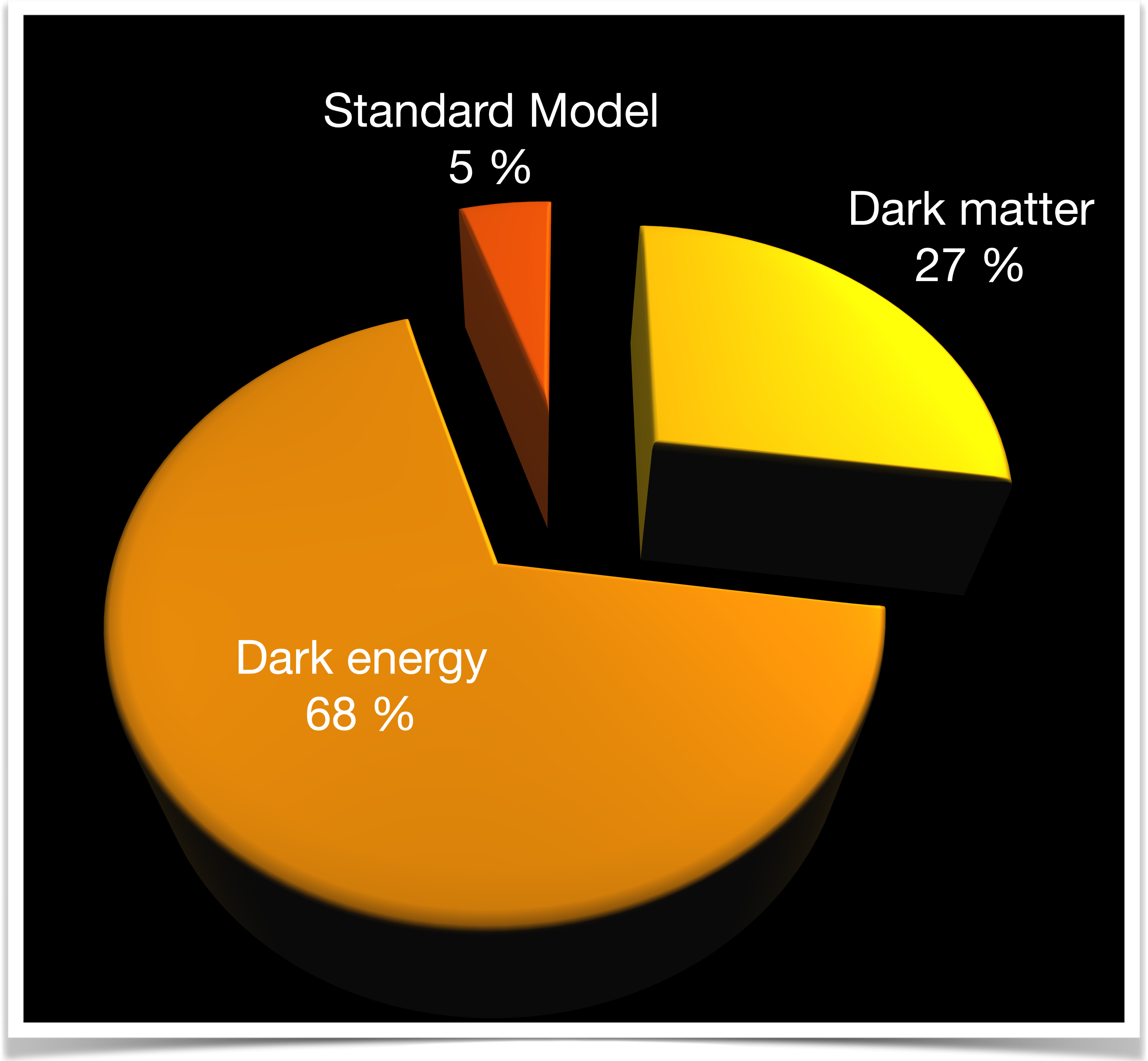

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Example: simplest Horndeski theory of dark energy

combine phenomenological constraints and asymptotic-safety-condition

$$\mathscr{L}_2 = -G_2(\phi,\chi), \quad \mathscr{L}_3 = G_3(\phi,\chi)D^2\phi,$$

$$\mathscr{L}_4 = -G_4(\phi,\chi)R + G_{4,\chi}\left(\left(D^2\phi\right)^2 - D_\mu D_\nu\phi D^\mu D^\nu\phi\right)$$

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[Horndeski ’74]

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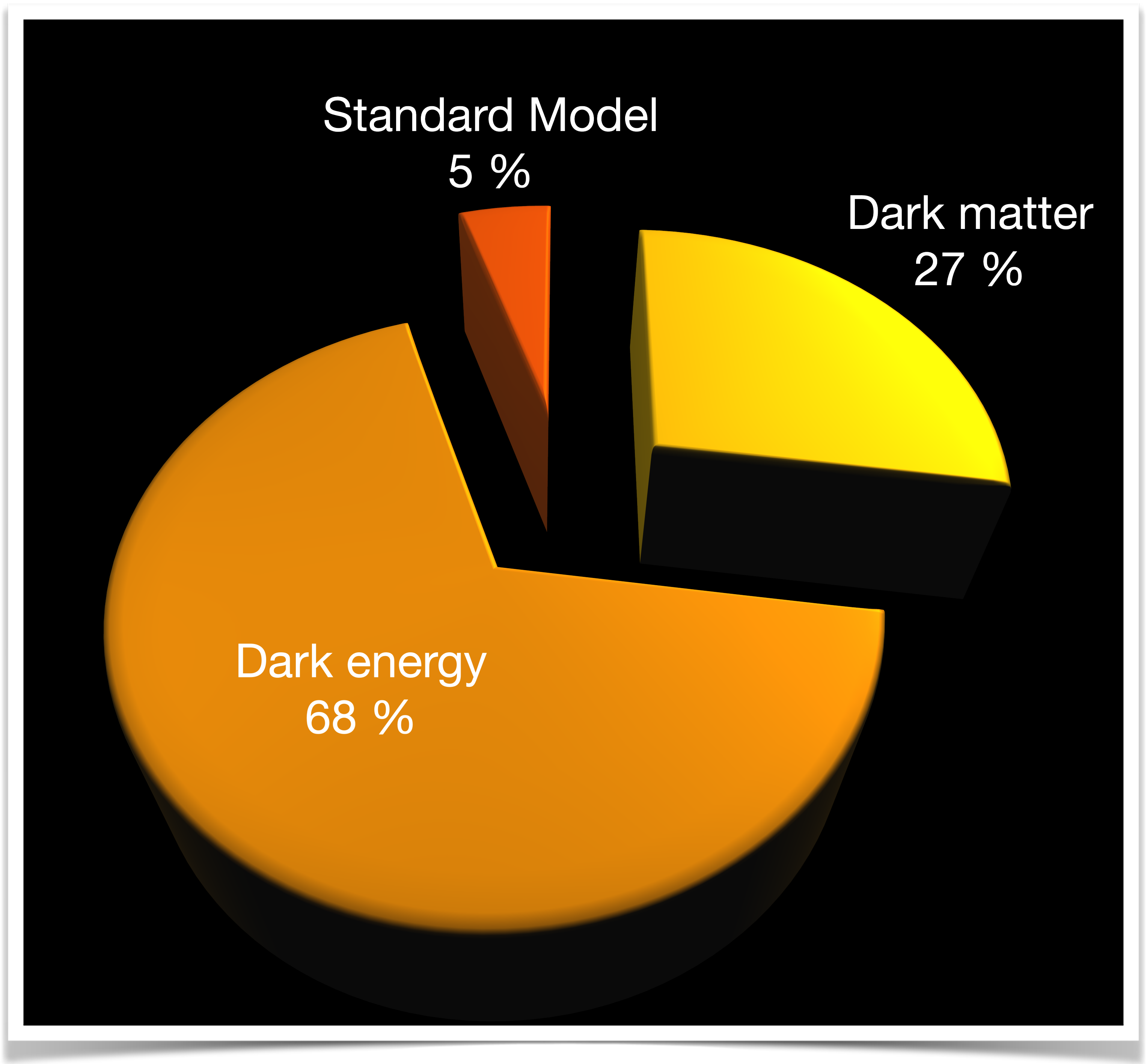

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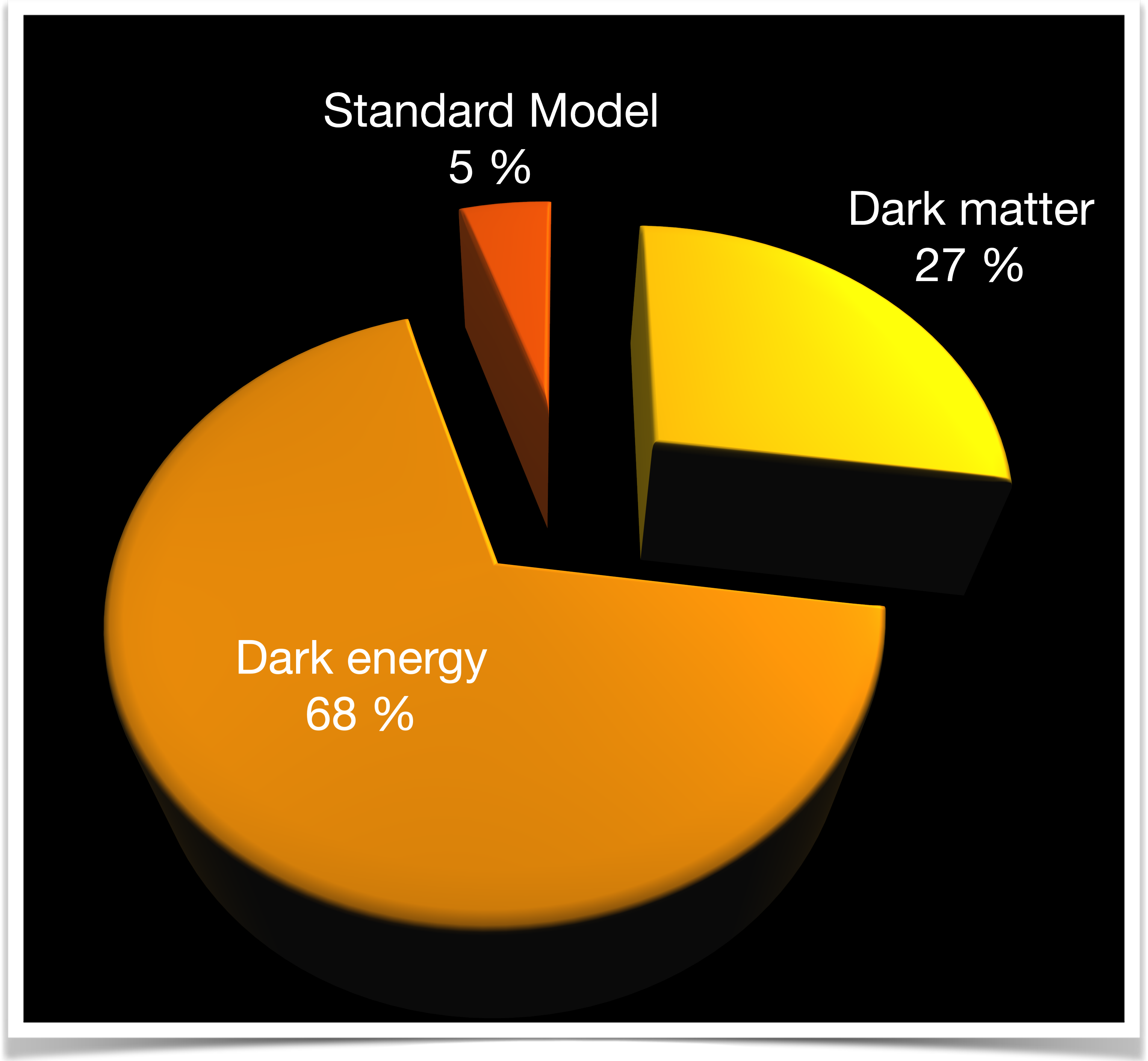
nearly excluded by GW170817
[Creminelli, Vernizzi ’17;
Ezquiaga, Zumalacárregui ’17;
Sakstein, Jain ’17;
Baker et al. ’17…]

[Horndeski ’74]

Asymptotic safety and the dark universe



General idea: Use predictive power of asymptotic safety to constrain models of the dark sector

→ to make quantum gravity testable

→ to make dark sector predictive

Example: simplest Horndeski theory of dark energy

combine phenomenological constraints and asymptotic-safety-condition

$$\mathscr{L}_2 = -G_2(\phi,\chi), \quad \mathscr{L}_3 = G_3(\phi,\chi)D^2\phi,$$

$$\mathscr{L}_4 = -G_4(\phi,\chi)R + G_{4,\chi}\left((D^2\phi)^2 - D_\mu D_\nu\phi D^\mu D^\nu\phi\right)$$

$$\mathscr{L}_5 = G_5(\phi,\chi)G_{\mu\nu}D^\mu D^\nu\phi - \frac{G_{5,\chi}}{6}\left[(D^2\phi)^3 - 3D^2\phi D_\mu D_\nu\phi D^\mu D^\nu\phi + 2D_\mu D_\nu\phi D^\nu D^\rho\phi D_\rho D^\mu\phi\right]$$

$$\chi = -D_\mu\phi D^\mu\phi/2$$

nearly excluded by GW170817
[Creminelli, Vernizzi '17;
Ezquiaga, Zumalacárregui '17;
Sakstein, Jain '17;
Baker et al. '17…]

[Horndeski '74]

$$\Gamma_k = \int d^4x\sqrt{\det g_{\mu\nu}}\left[-\frac{1}{16\pi\bar{G}}\left(R - 2\bar{\Lambda}\right) - Z_\phi\chi - \bar{h}\chi D^2\phi + \bar{g}\chi^2\right]$$

asymptotic-safety condition: $h(k) \to 0$ at all k

[AE, Rafael R. Lino dos Santos, Fabian Wagner '23]

Asymptotic safety and dark matter

dark matter mass

10^{-21} eV · peV · meV · eV · TeV · M_{Pl} · $10 M_\odot$

fuzzy dm · axion/ALP · thermal WIMP · Planckian · primordial bh

sterile ν

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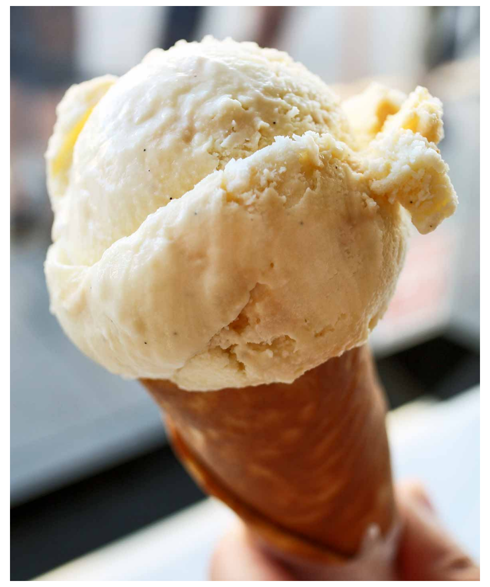


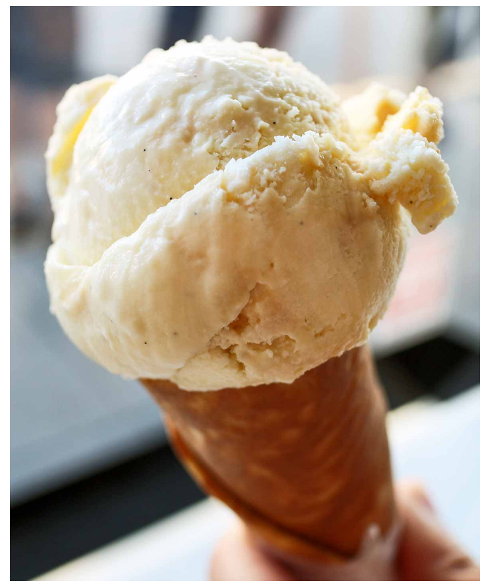
Thermal WIMP: Dark scalar with Higgs portal

$$\lambda_H \, H^\dagger H \, \phi^2$$

→ production in the early universe

→ experimental searches (e.g. LHC, XENON)

Asymptotic safety and dark matter



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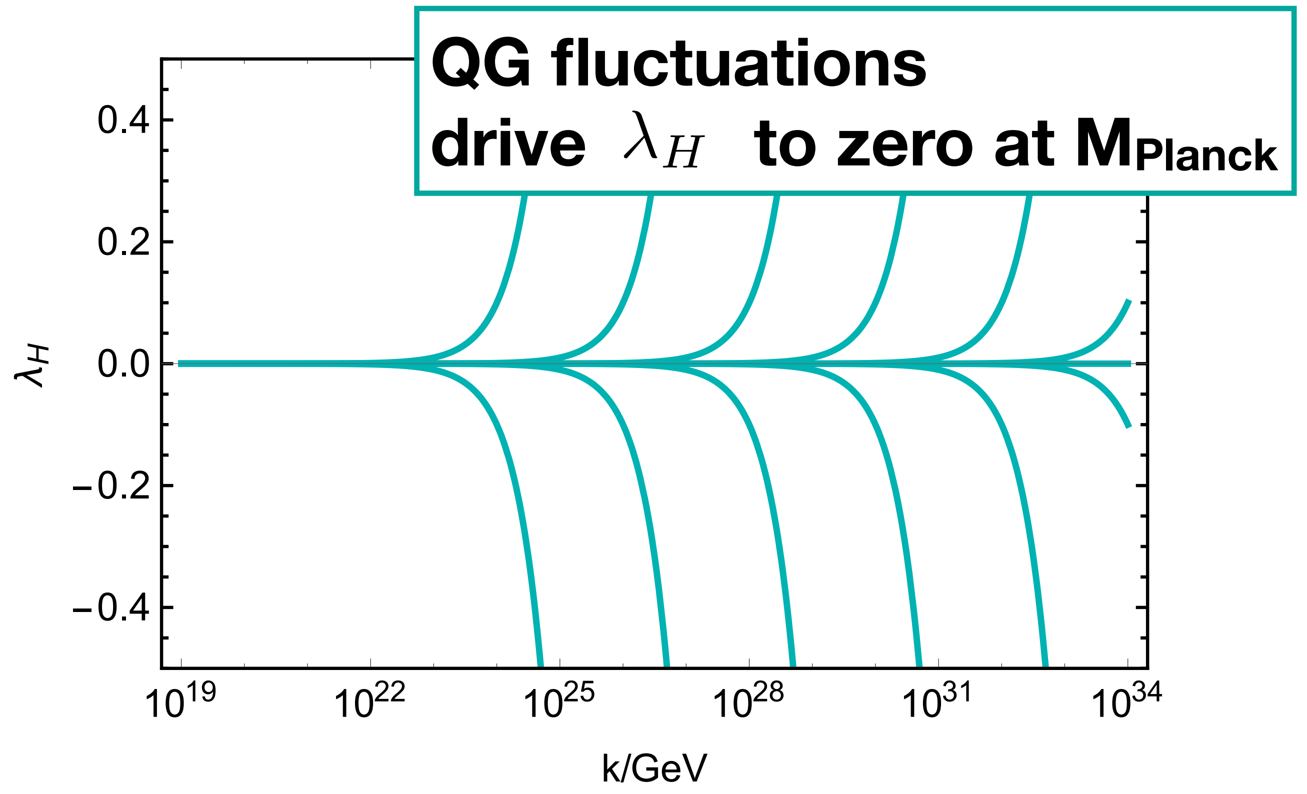

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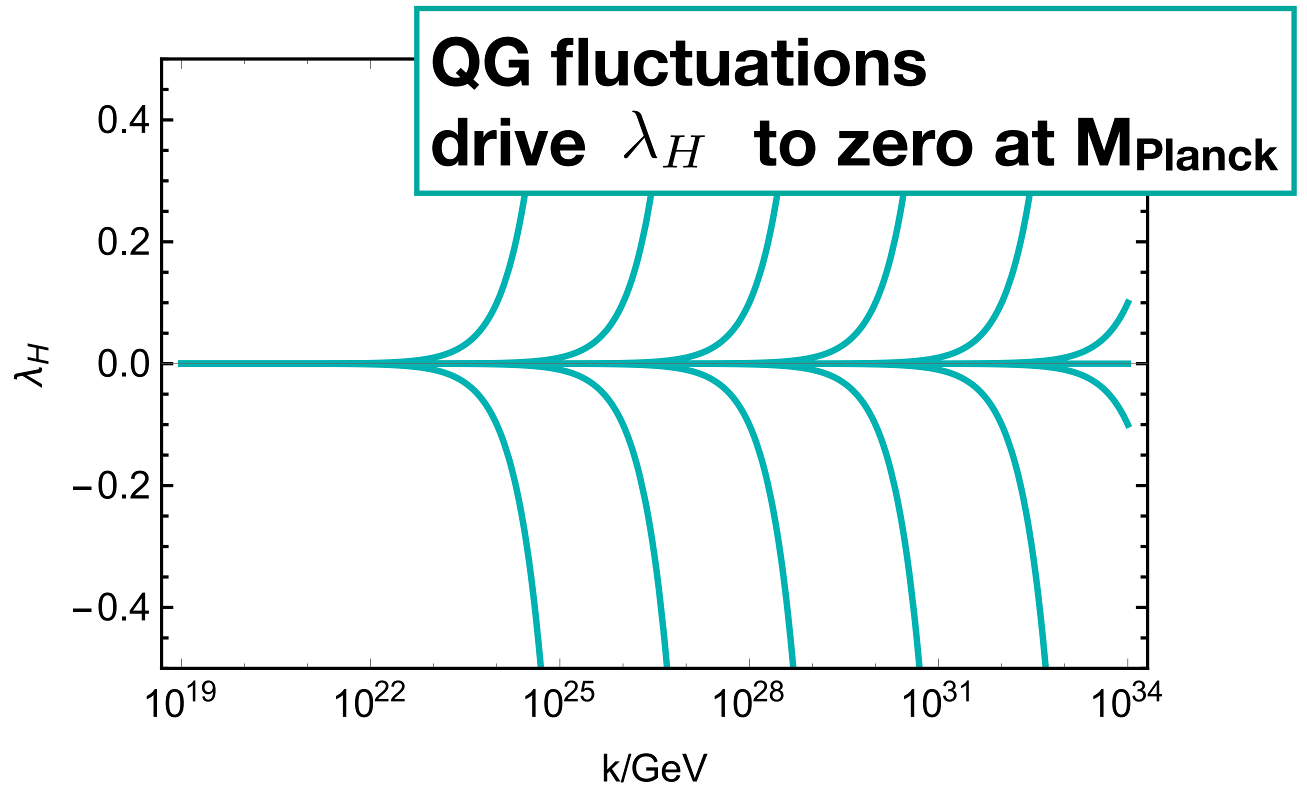

→ single dark scalar decouples in asymptotic safety

[AE, Hamada, Lumma, Yamada ‘17]

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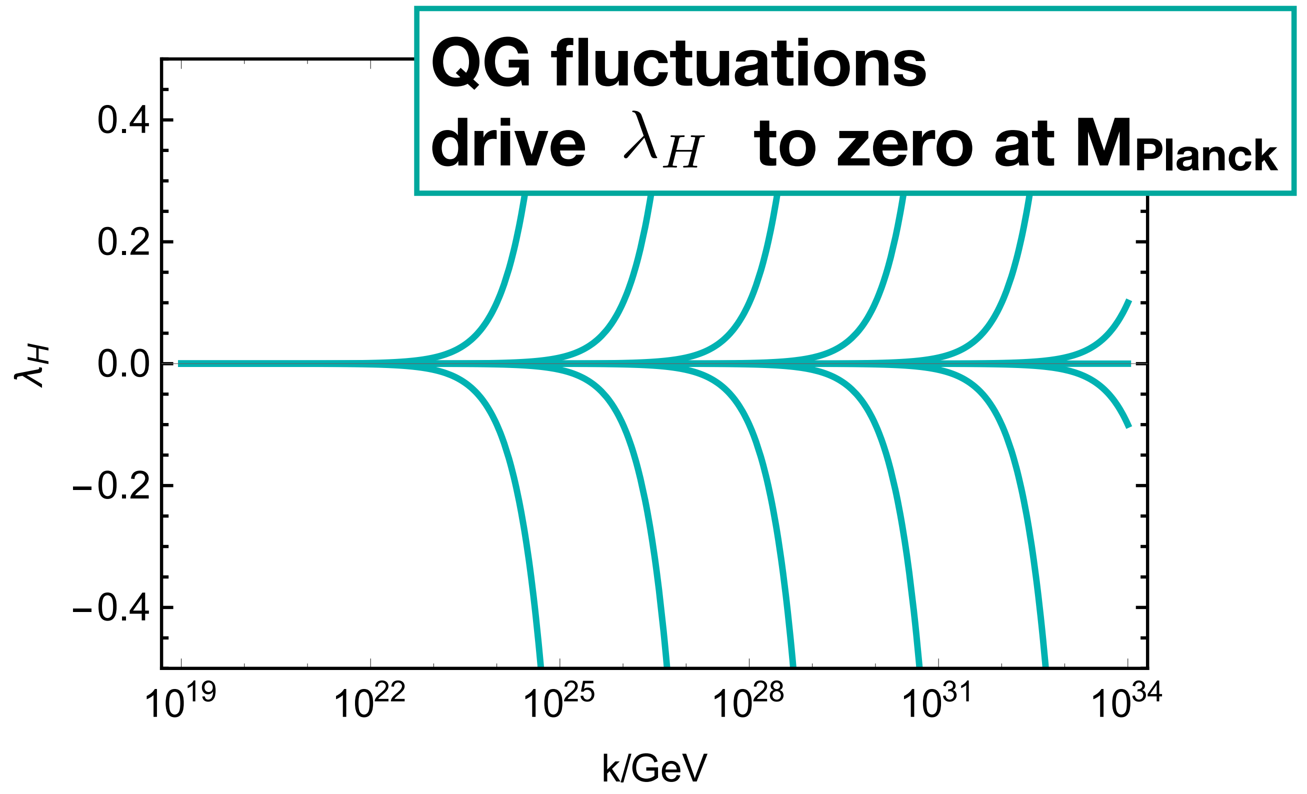

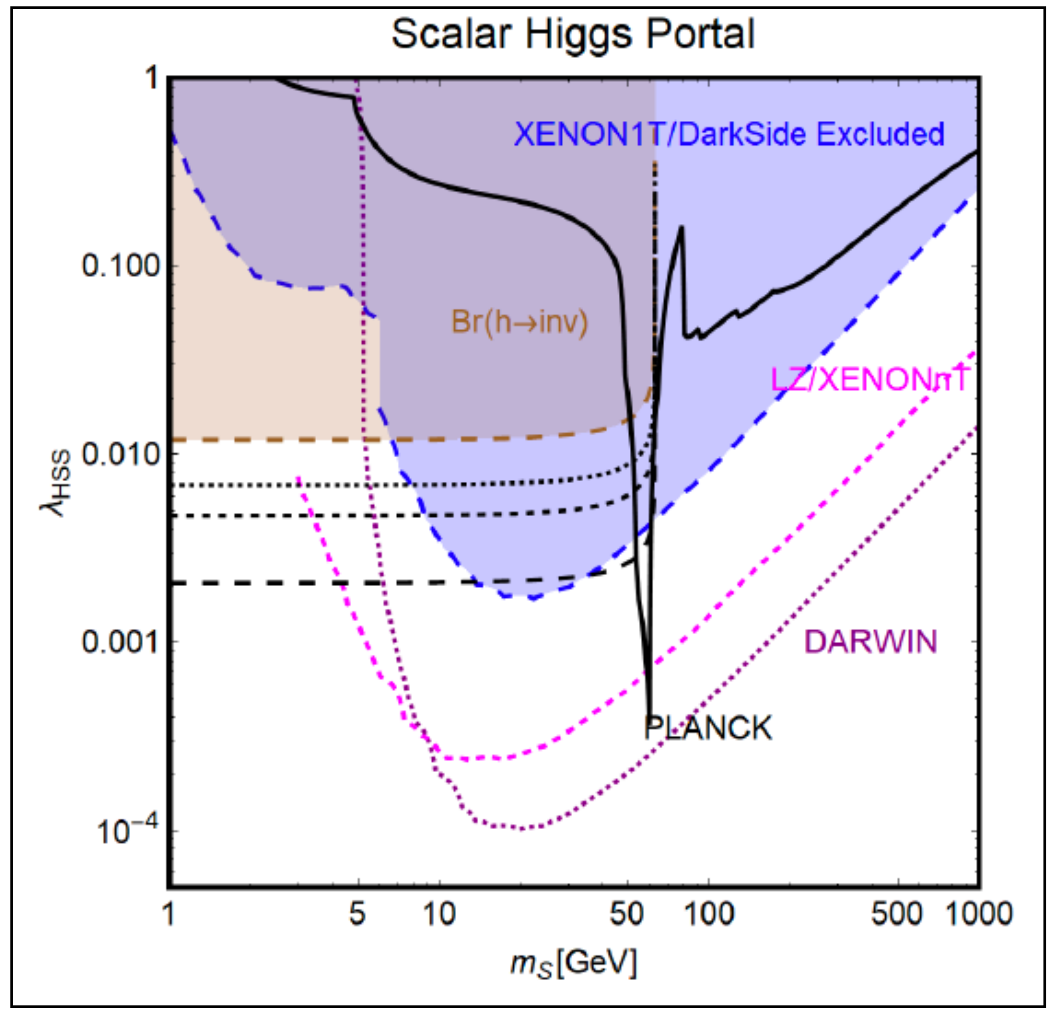

[Arcadi et al ’19]

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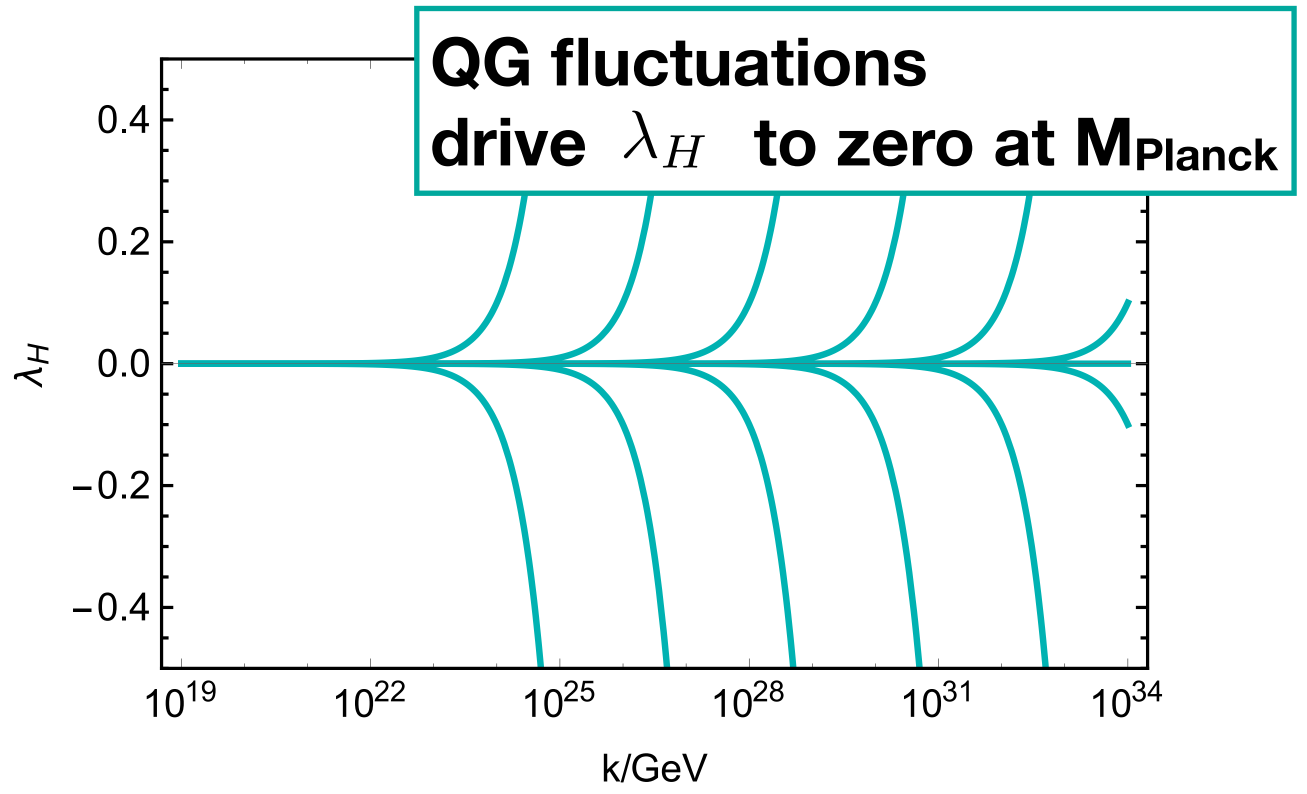

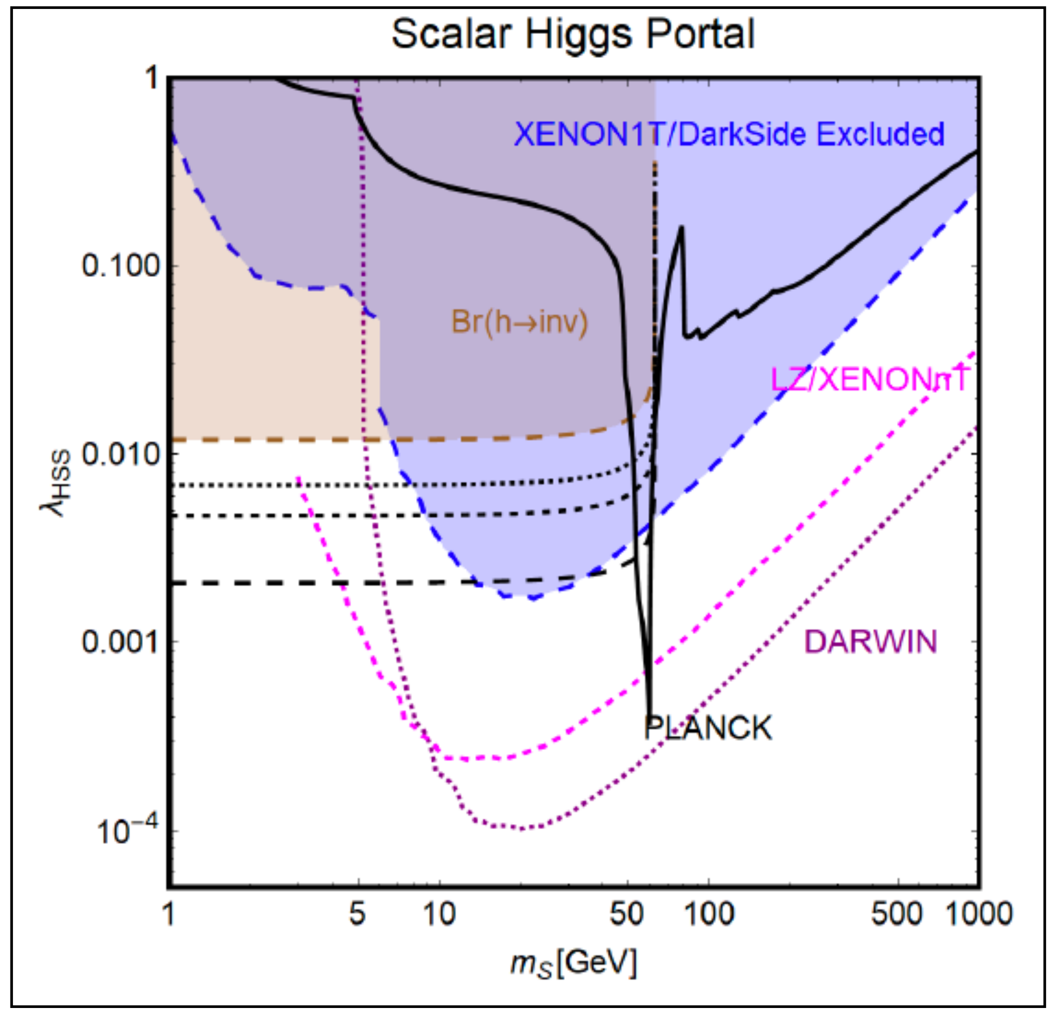

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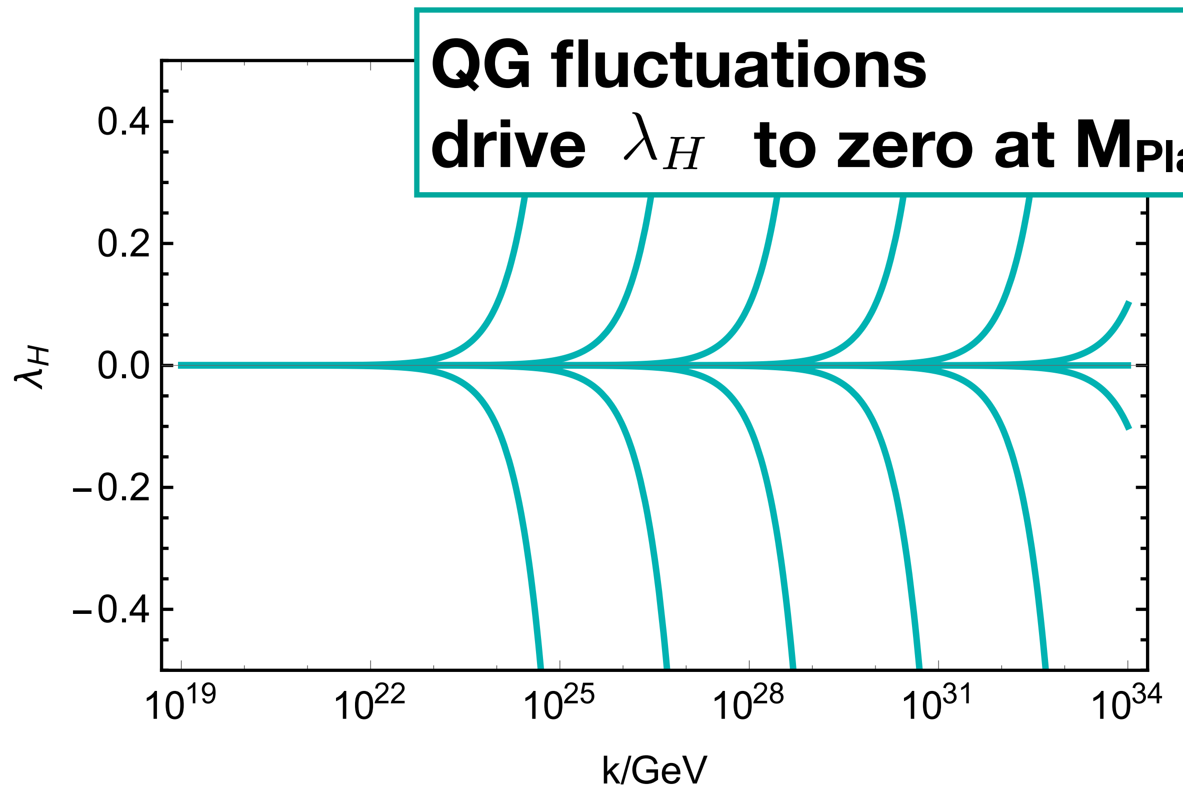
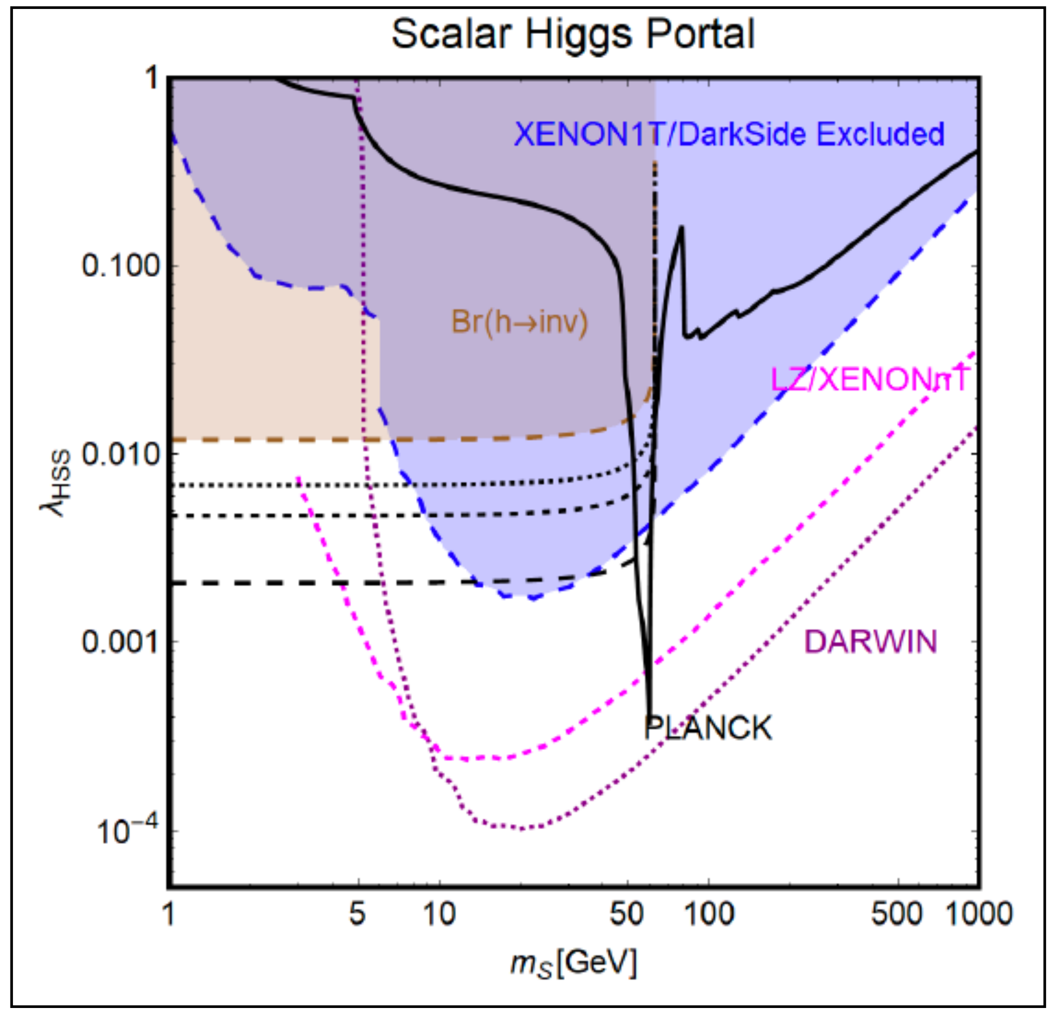
QG fluctuations drive λ_H to zero at M_{Planck}





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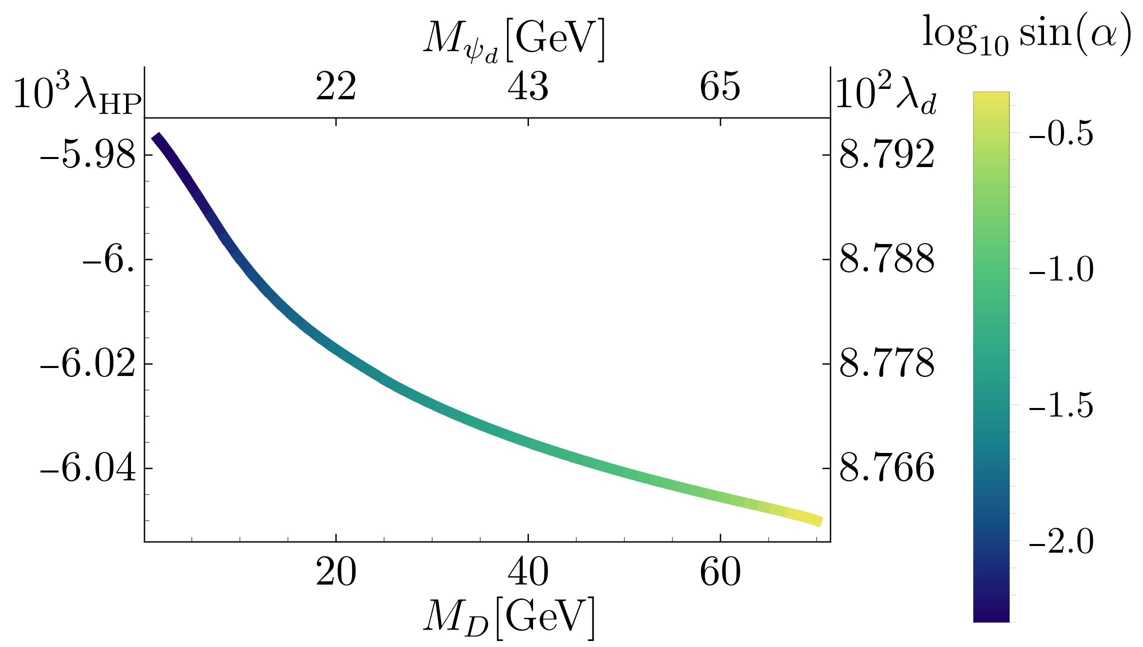
→ **single dark scalar decouples in asymptotic safety**

[AE, Hamada, Lumma, Yamada '17]

Extended thermal WIMP sectors with Higgs-portal

- add dark fermions and Yukawa interactions:
  EFT: 9 dimensional parameter space
  AS: 1-dimensional parameter space



[AE, Pauly '21, AE, Pauly, Ray '21]

- add dark U(1) with kinetic mixing and dark fermions with Yukawa interactions:
  upper bounds on couplings
  [Reichert, Smirnov '19; Hamada, Yamada '20]

- make dark scalar $U(1)_{\text{dark}}$-symmetric and add dark vectors:
  EFT: phenomenological constraints on couplings
  AS: model ruled out due to negative quartic coupling

[de Brito, AE, Frandsen, Rosenlyst, Thing, Vieira '23]

Asymptotic safety and dark matter

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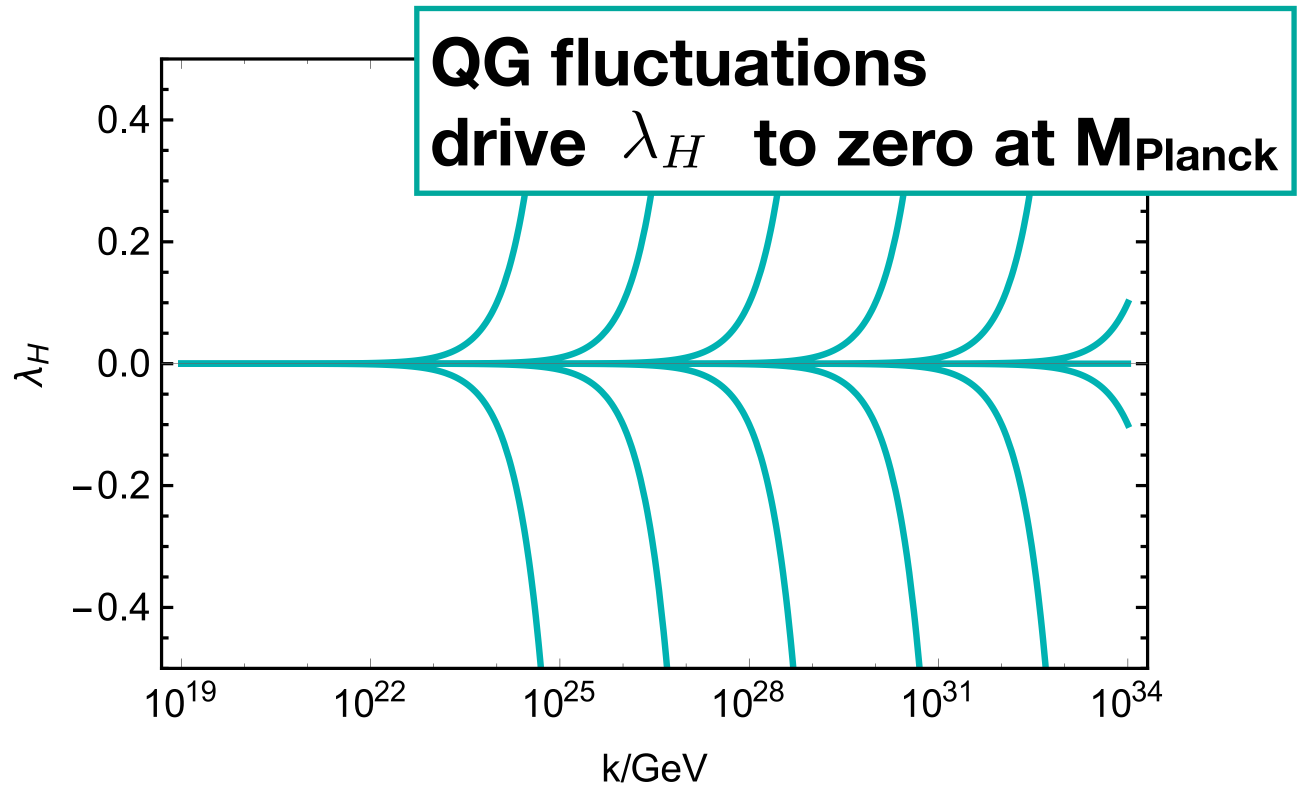

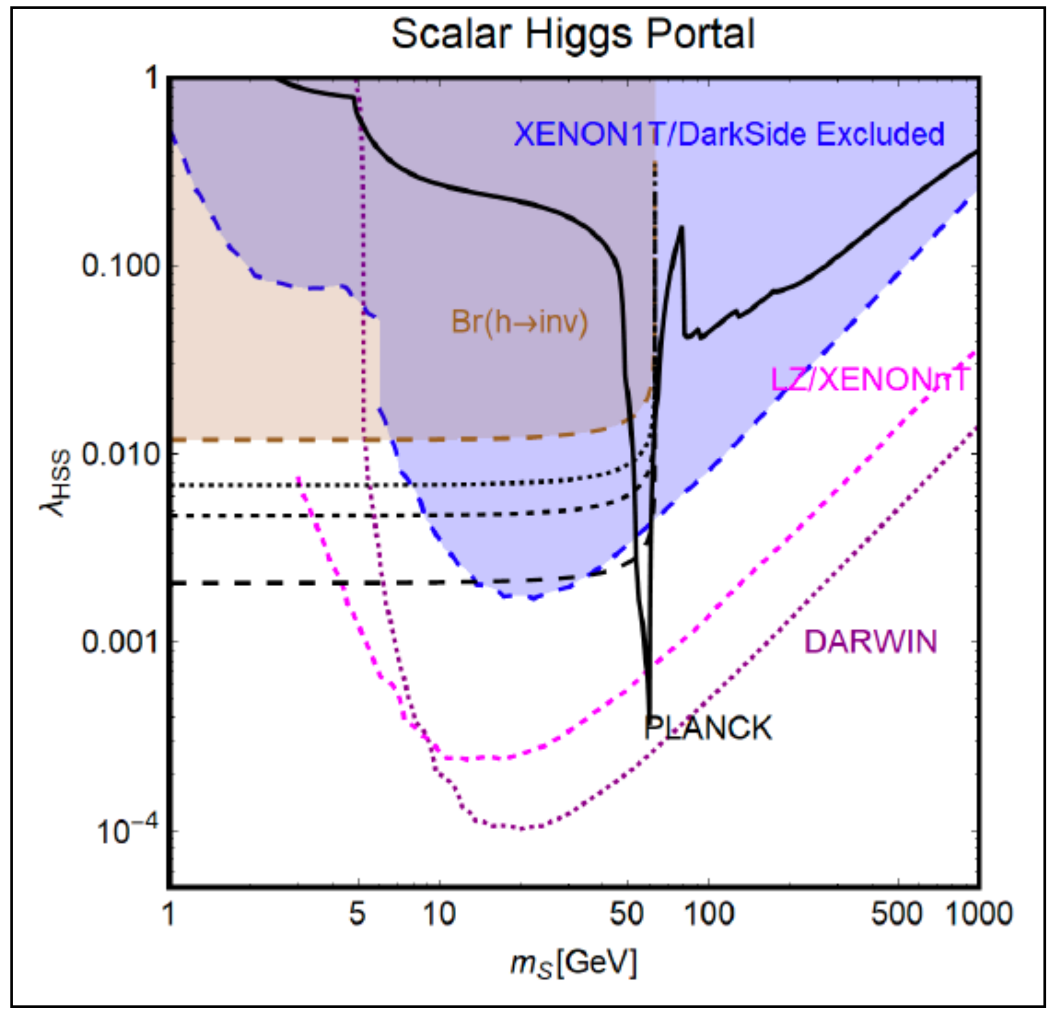

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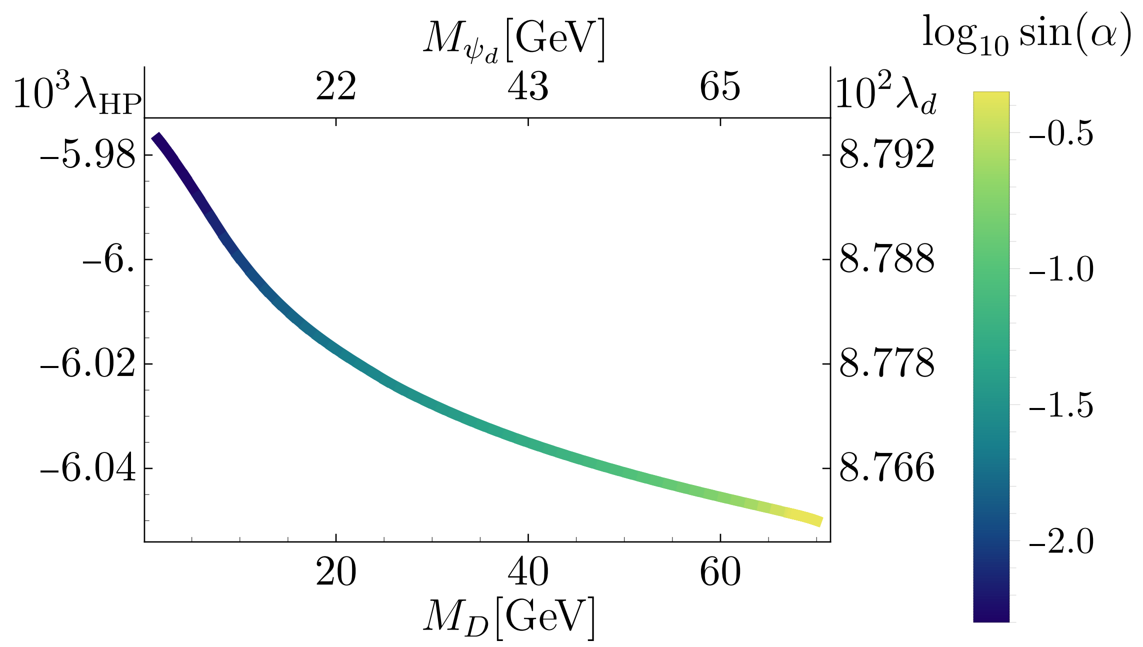

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→ extended WIMP sectors strongly constrained or ruled out

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fuzzy dm | axion/ALP | thermal WIMP | sterile ν | Planckian | primordial bh

ALPs: generically present in stringy settings

Is there a difference to asymptotic safety?
(Can axion-searches inform us about quantum gravity??)

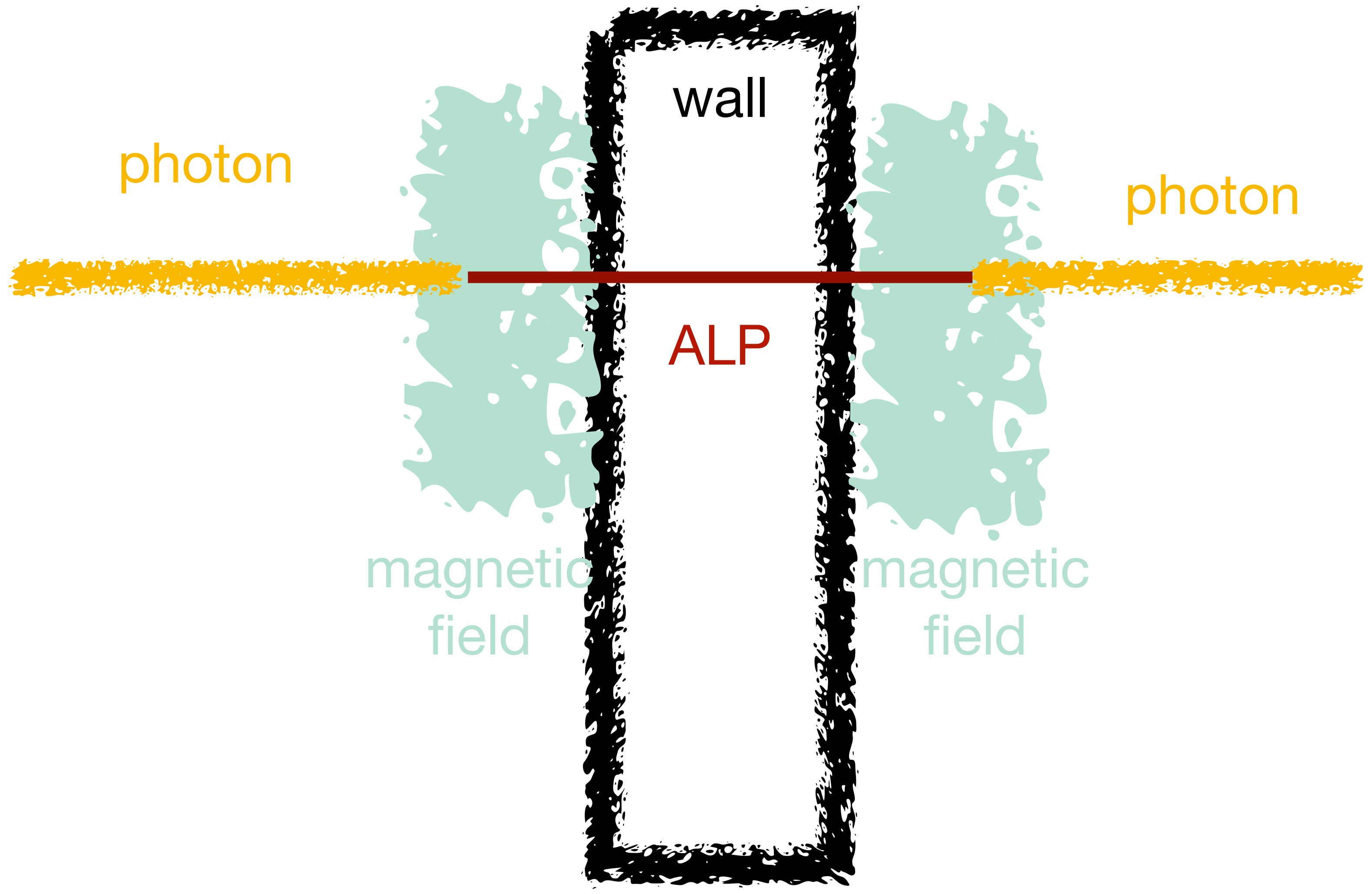
ALPs in asymptotically safe gravity

ALPS: axion-like particles with dimension-5-operator:

$$\bar{g}_a\, a(x)\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

phenomenology:

- ultralight (sub-eV) dark-matter candidate
- experimental searches: light-shining-through-wall



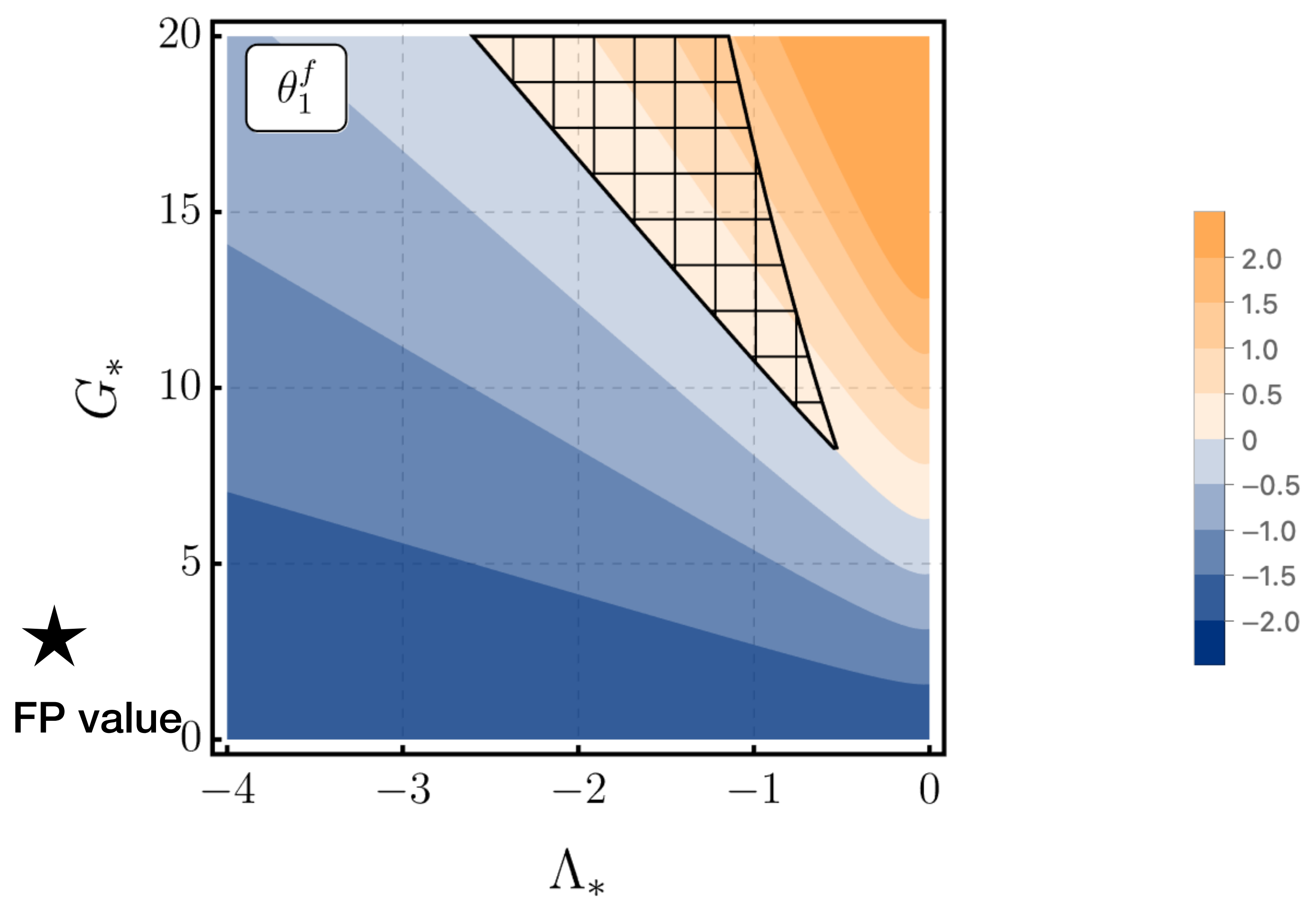
without gravity: $$\beta_{g_a^2} = 2g_a^2 + \frac{7}{48\pi^2}g_a^4 + \dots$$

→irrelevant at Gaussian fixed point:
vanishes if UV completion without extra fields demanded

with asymptotically safe gravity: $$\beta_{g_a^2} = 2g_a^2 - f_{g_a}g_a^2 + \frac{7}{48\pi^2}g_a^4 + \dots$$

[de Brito, AE, Lino dos Santos '21]

$g^2_{a\,*} = 0$ unless $f_{g\,a} > 2$ (strongly-coupled quantum gravity)



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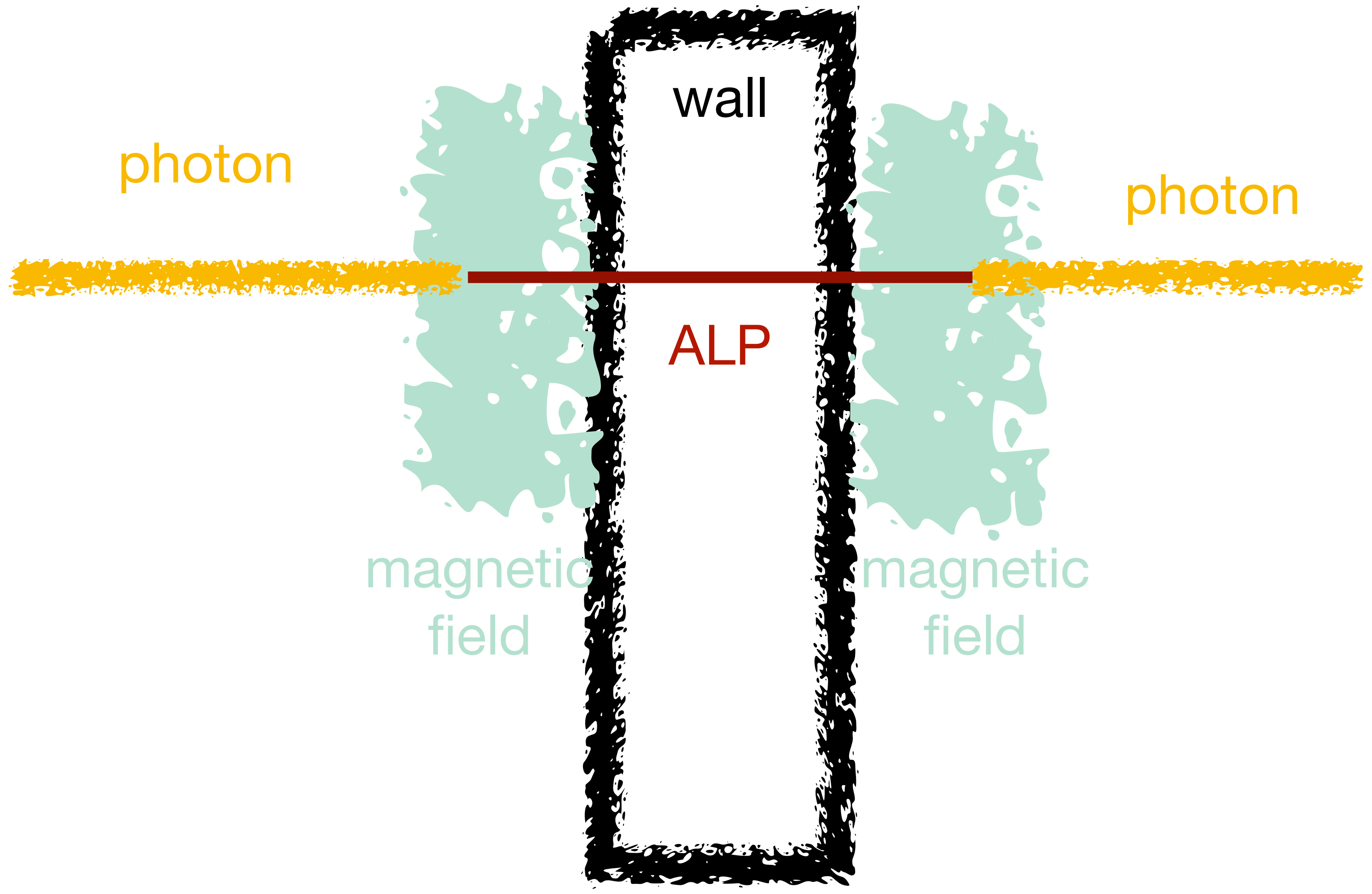

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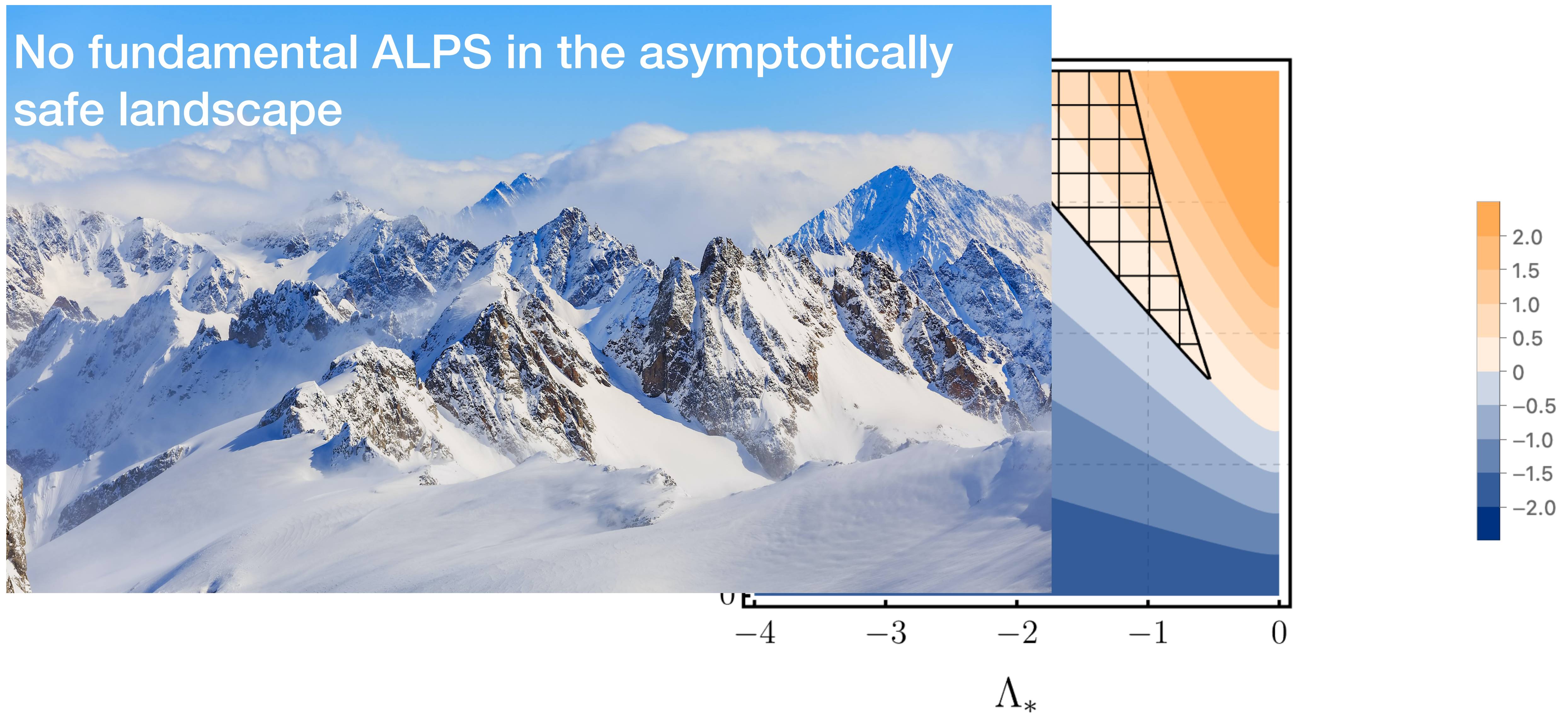
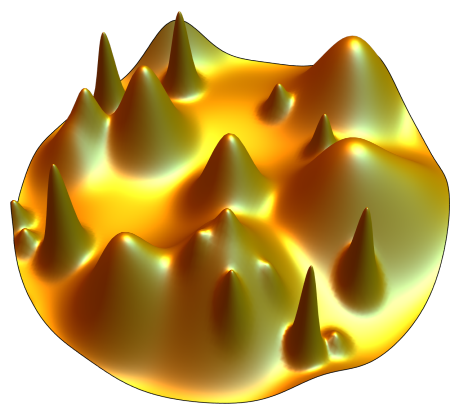


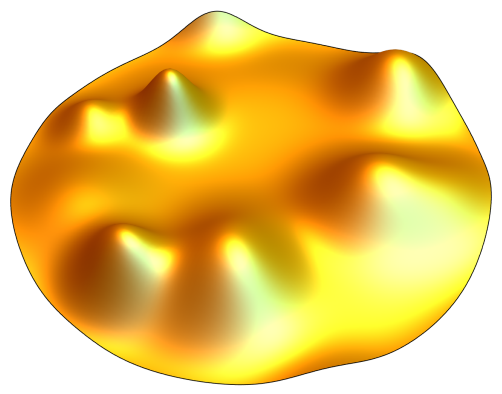
Summary and outlook

Theory

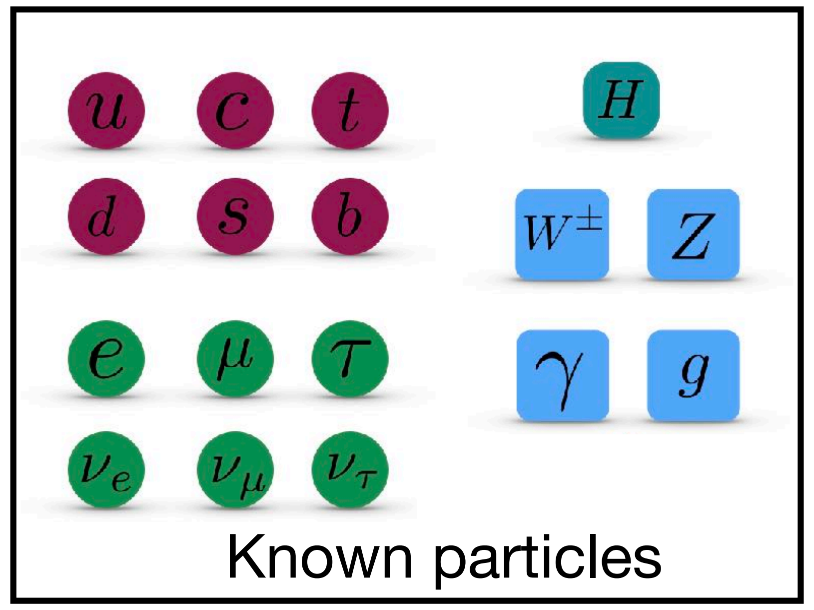
Observational tests



Transplanckian scales

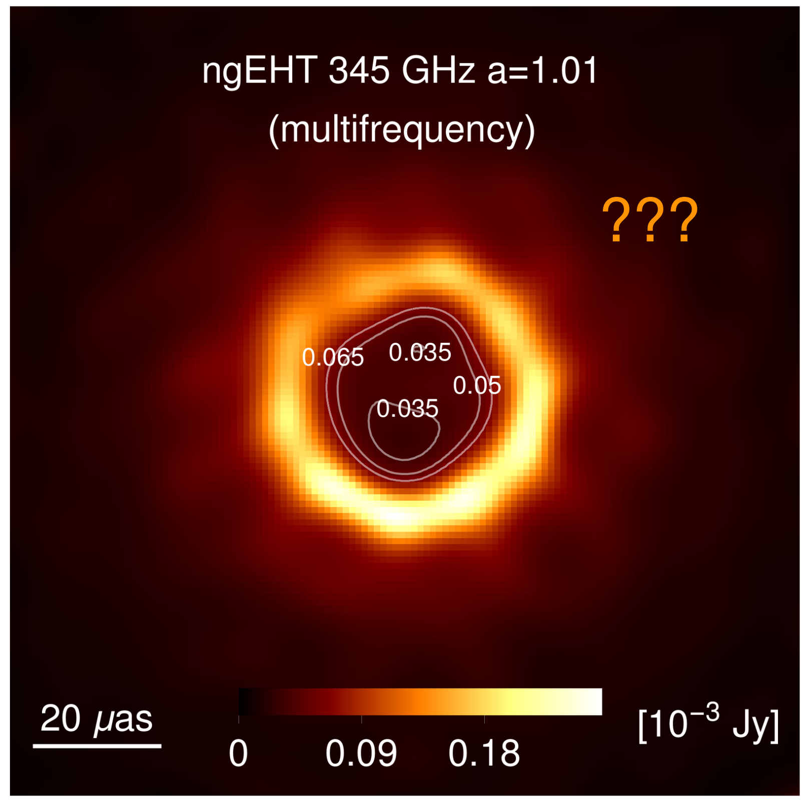


Planck scale



?? ?? Dark matter

Particle physics scales



Black-hole scales

Cosmological scales

distance scale

- Ensure quantitative control over truncations
- Work in Lorentzian signature
- understand relation to other approaches

- dark matter
- neutrino masses
- matter-antimatter asymmetry

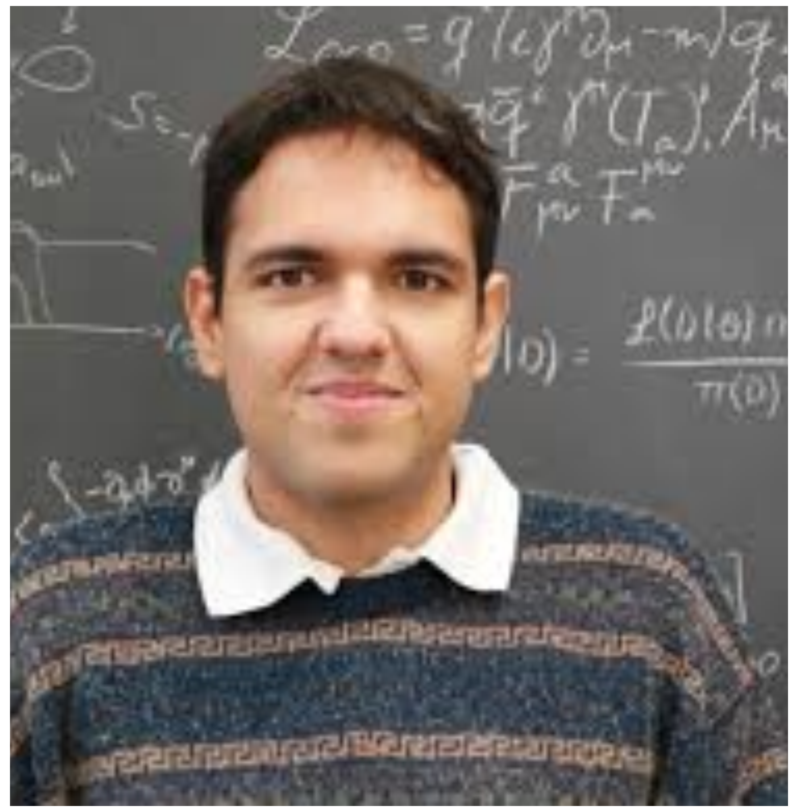
- dark energy

Thanks to

Current and former group members involved in this program:

Aaron Held, now ENS Paris

Marc Schiffer, now PI

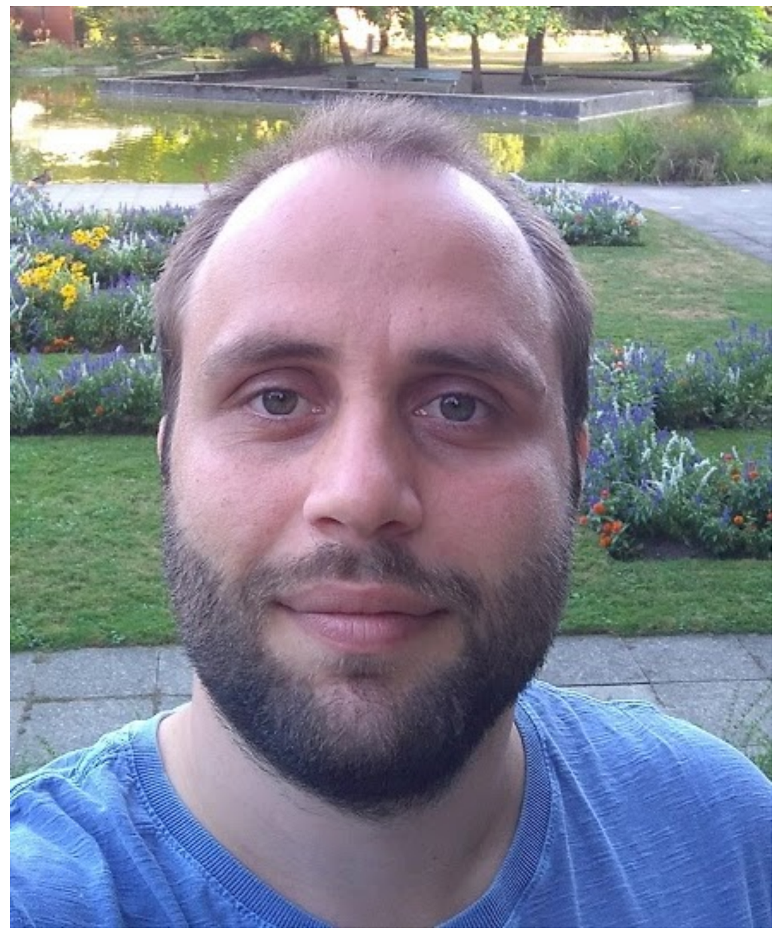


Rafael R. Lino dos Santos,
now Warsaw University

Fabian Wagner
soon Heidelberg Univ.

Fleur Versteegen,
now ASML

Martin Pauly,
now exnaton



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Manuel Reichert
Mads Frandsen
Martin Rosenlyst
Masatoshi Yamada