Lecture 2:
Probing (asymptotically safe) quantum gravity at all scales

Motivation

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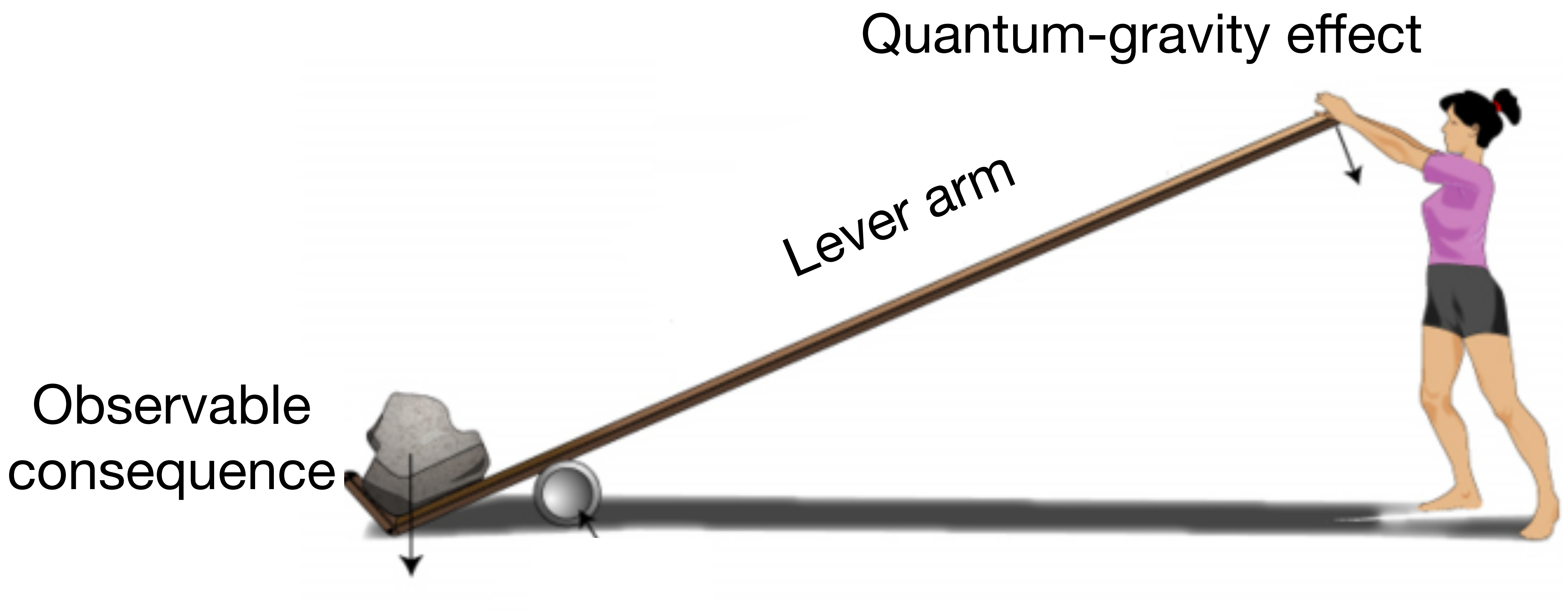
  Lever arm translates effect at Planck scale into effect at observationally accessible scale



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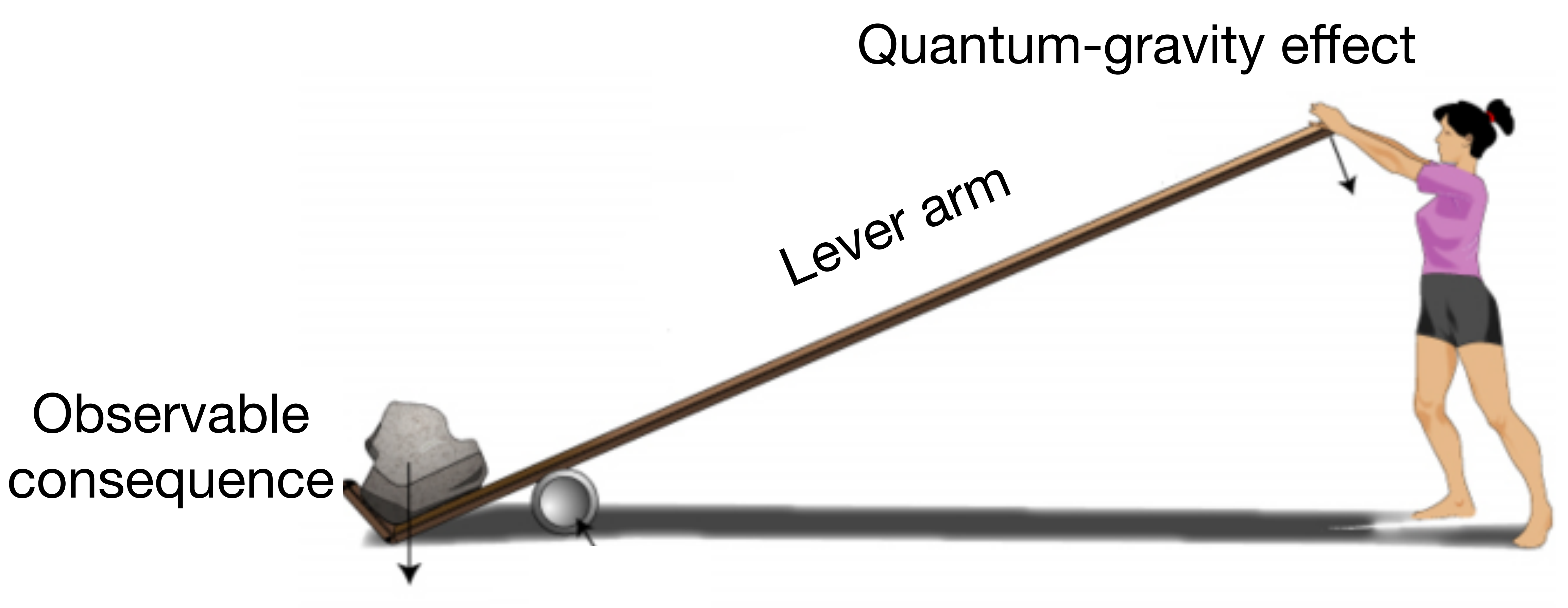
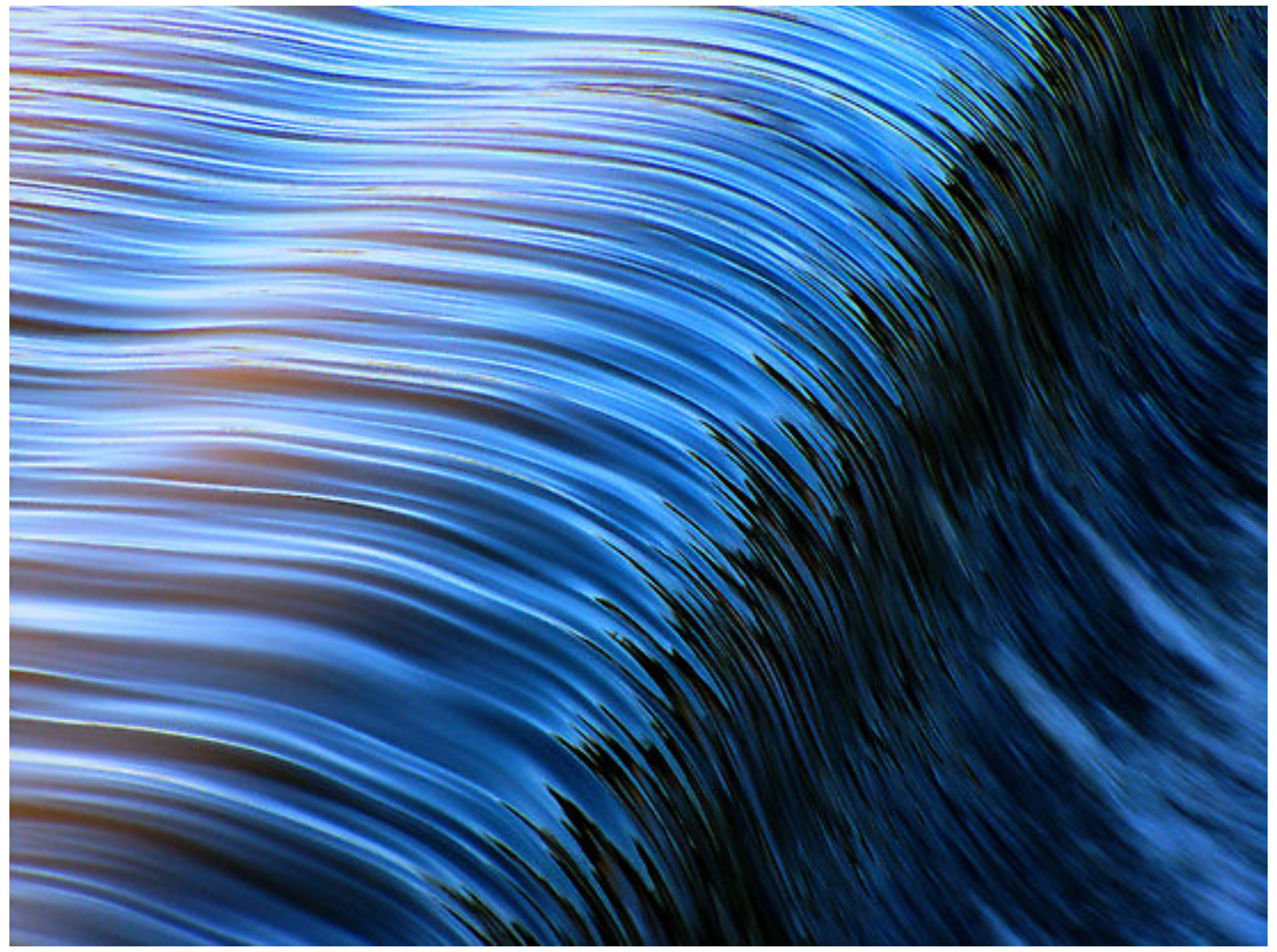


Examples:

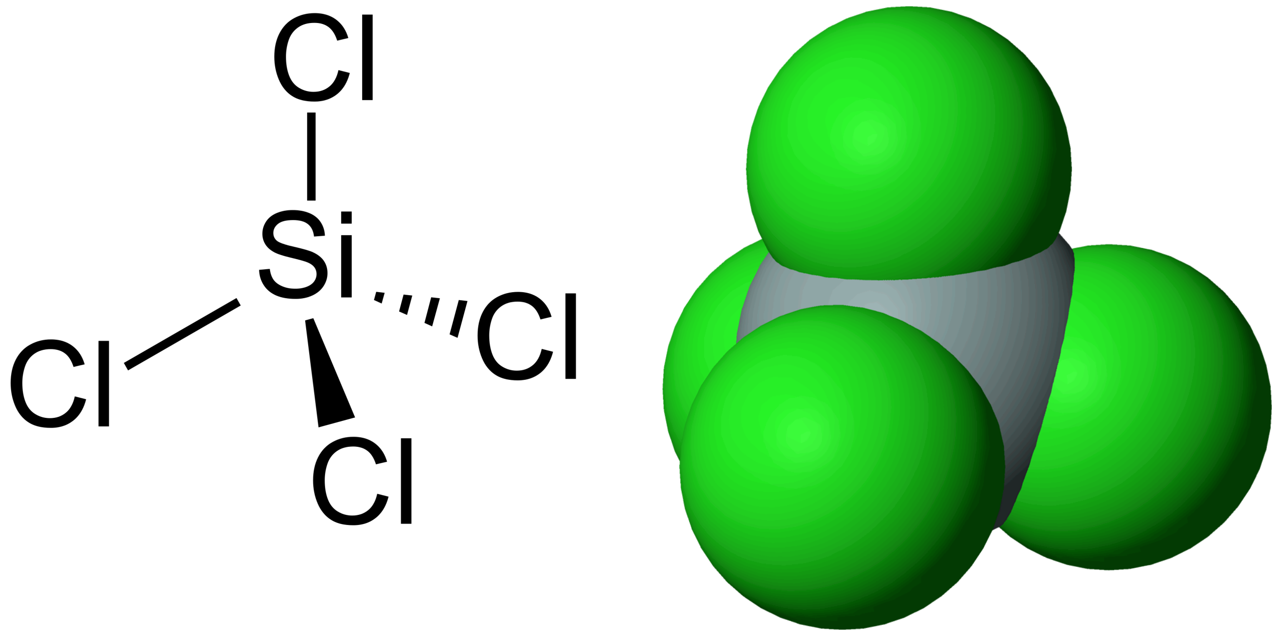
- Accumulation of Lorentz-Invariance-Violation over astrophysical distances of photons from GRBs
  [Amelino-Camelia, Ellis, Mavromatos Nanopoulos, Sakar '97]
- Large extra dimensions
  [Arkani-Hamed, Dimopoulos, Dvali '98]
- this talk:
  Renormalization Group flow of couplings

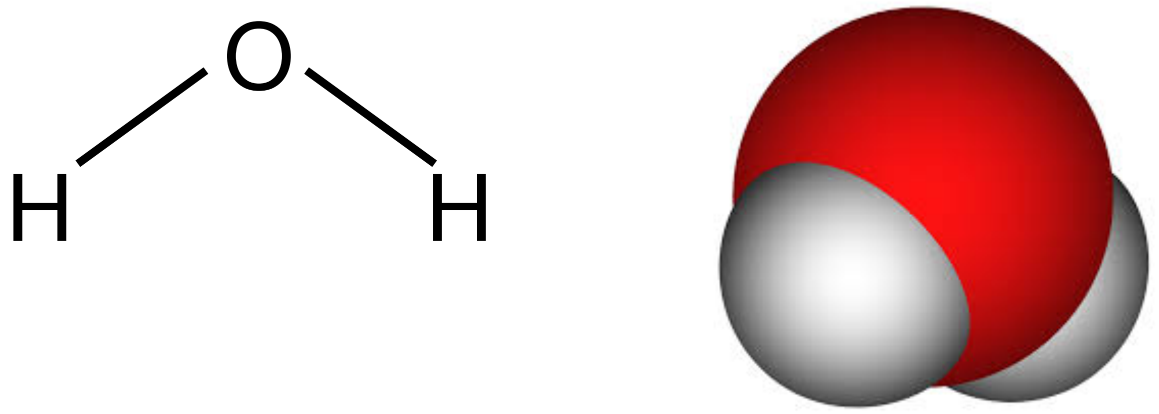
Imprints of microphysics in macroscopic quantities — an analogy



not so different at large scales?

zooming out:
microscopic information gets lost





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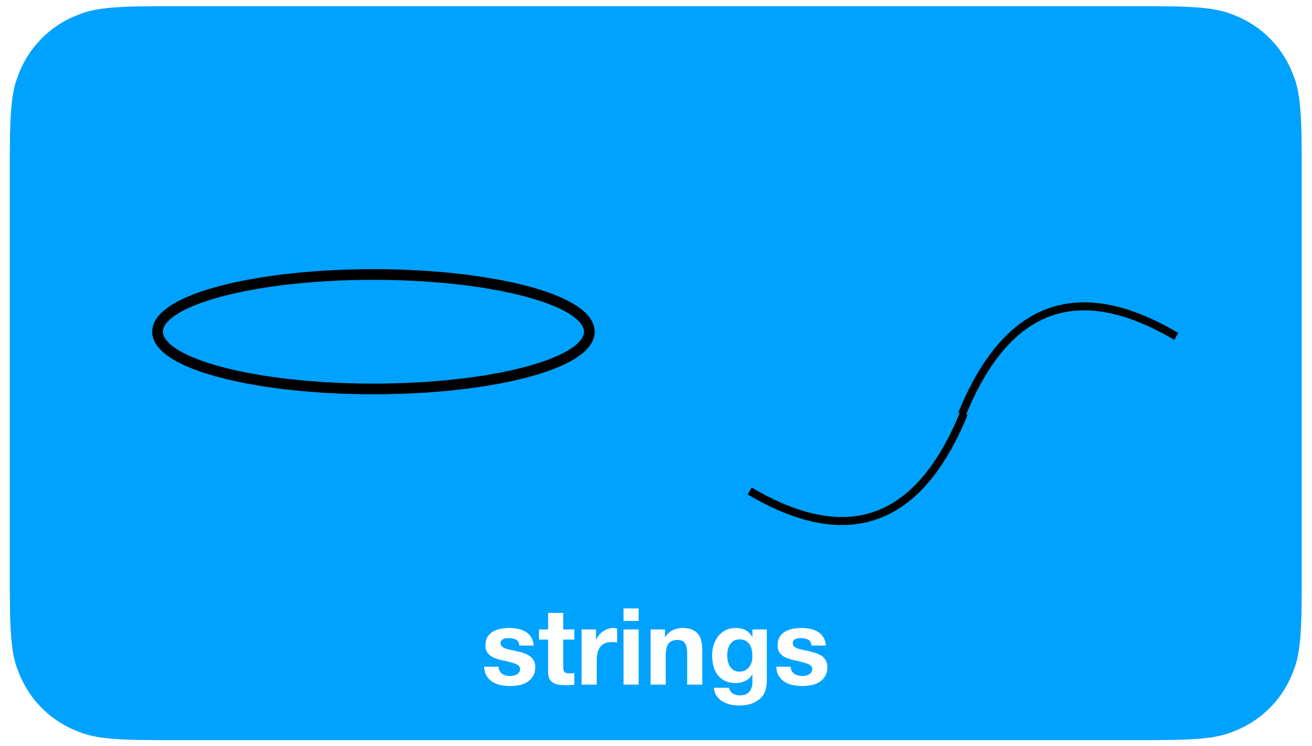

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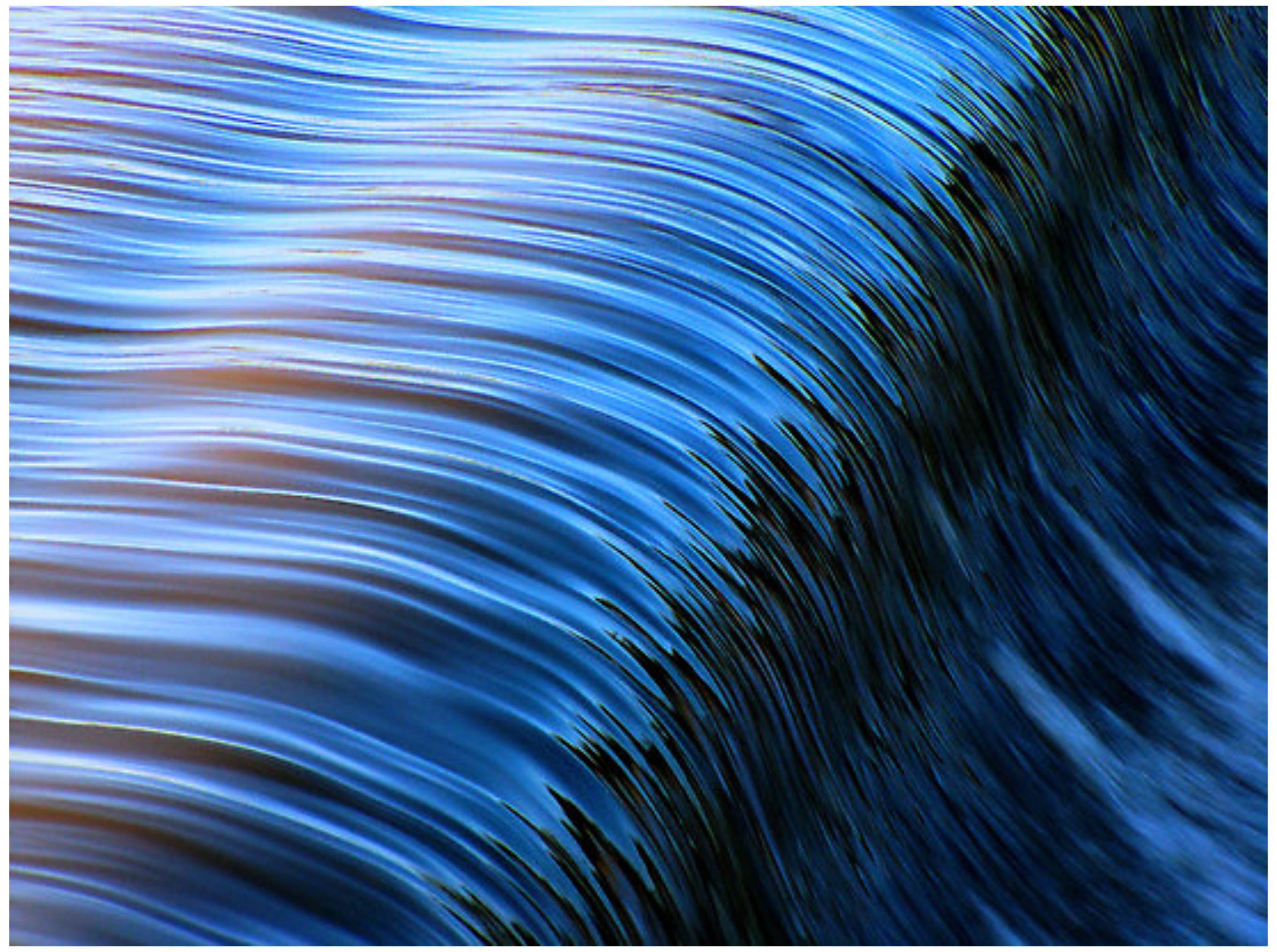

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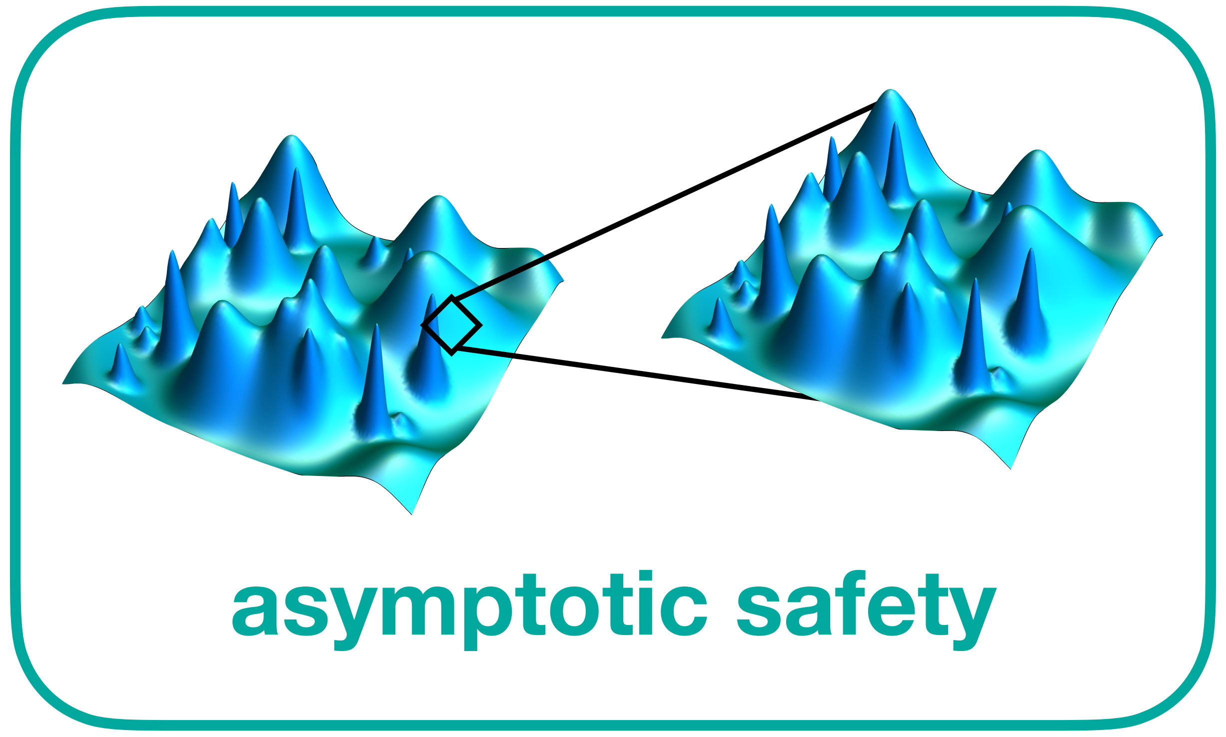

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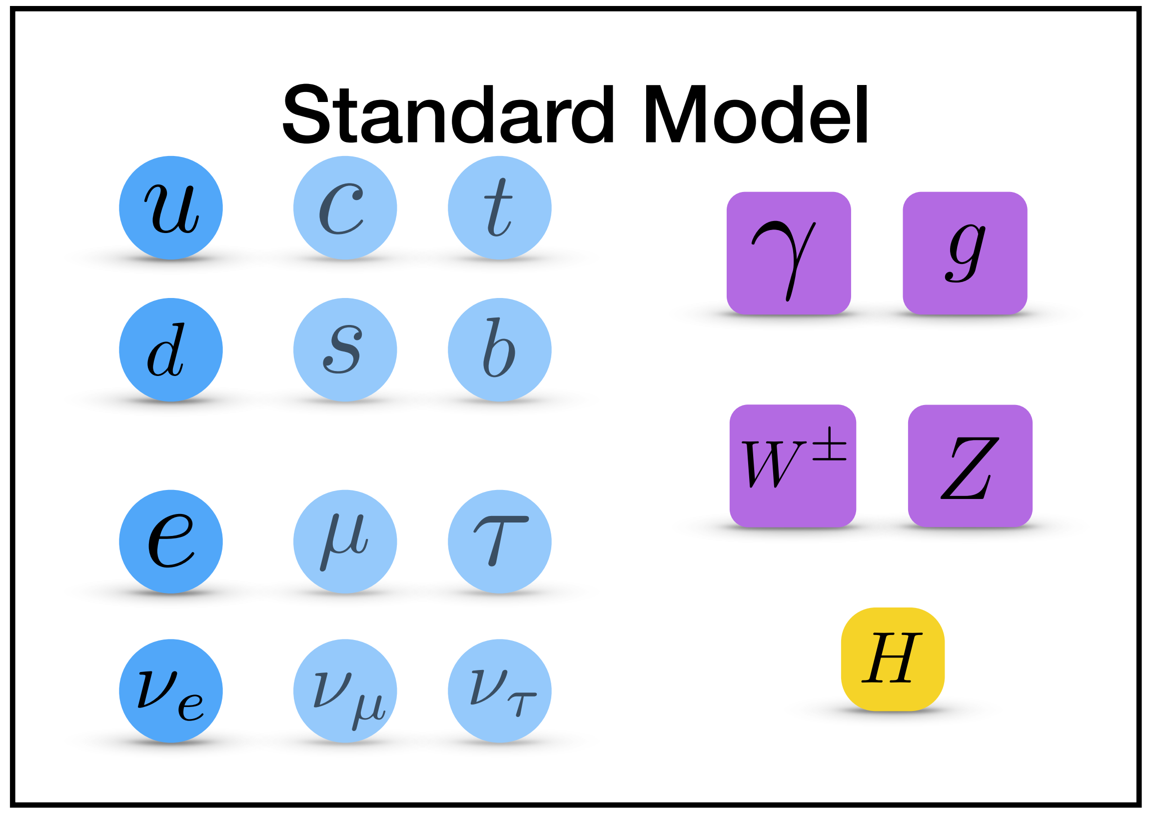

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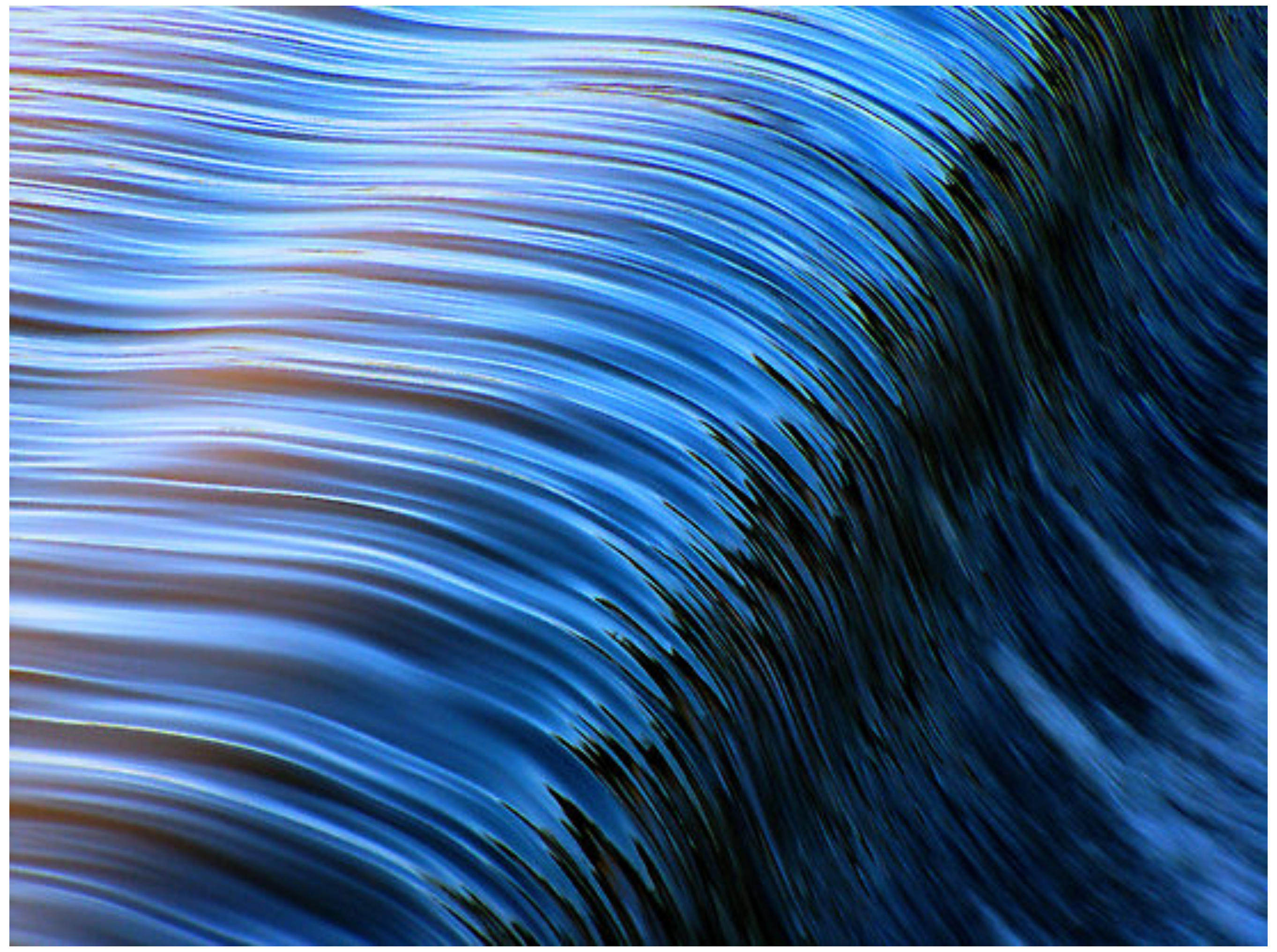

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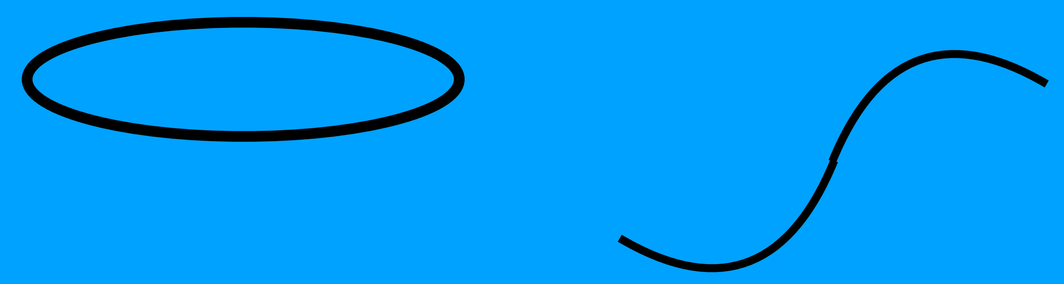
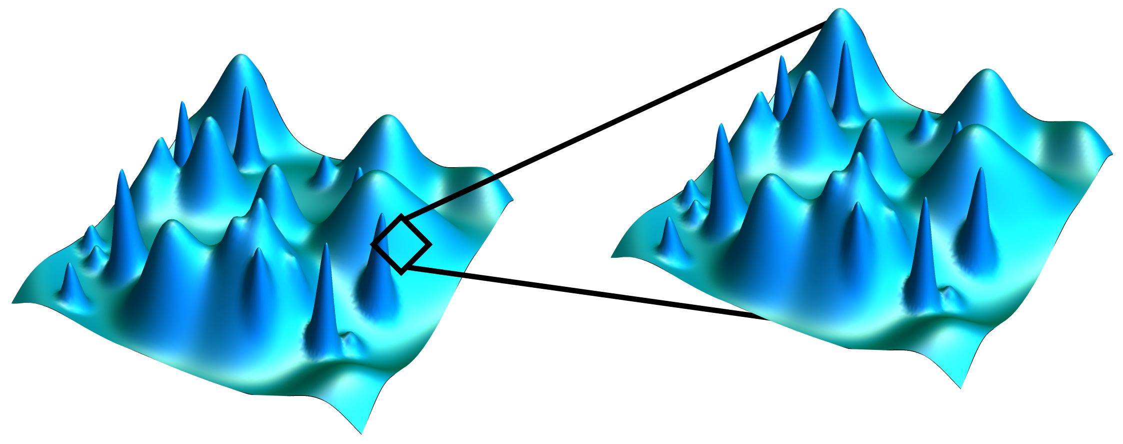


strings



asymptotic safety

different at small scales*

Standard Model

u c t γ g

d s b

e μ τ $W^{\pm}$ Z

ν_e ν_μ ν_τ H

10^{-18} m ← 10^{-35} m

* or are they? [de Alwis, AE, et al. 19; AE, Hebecker, Pawlowski, Walcher ‘24]

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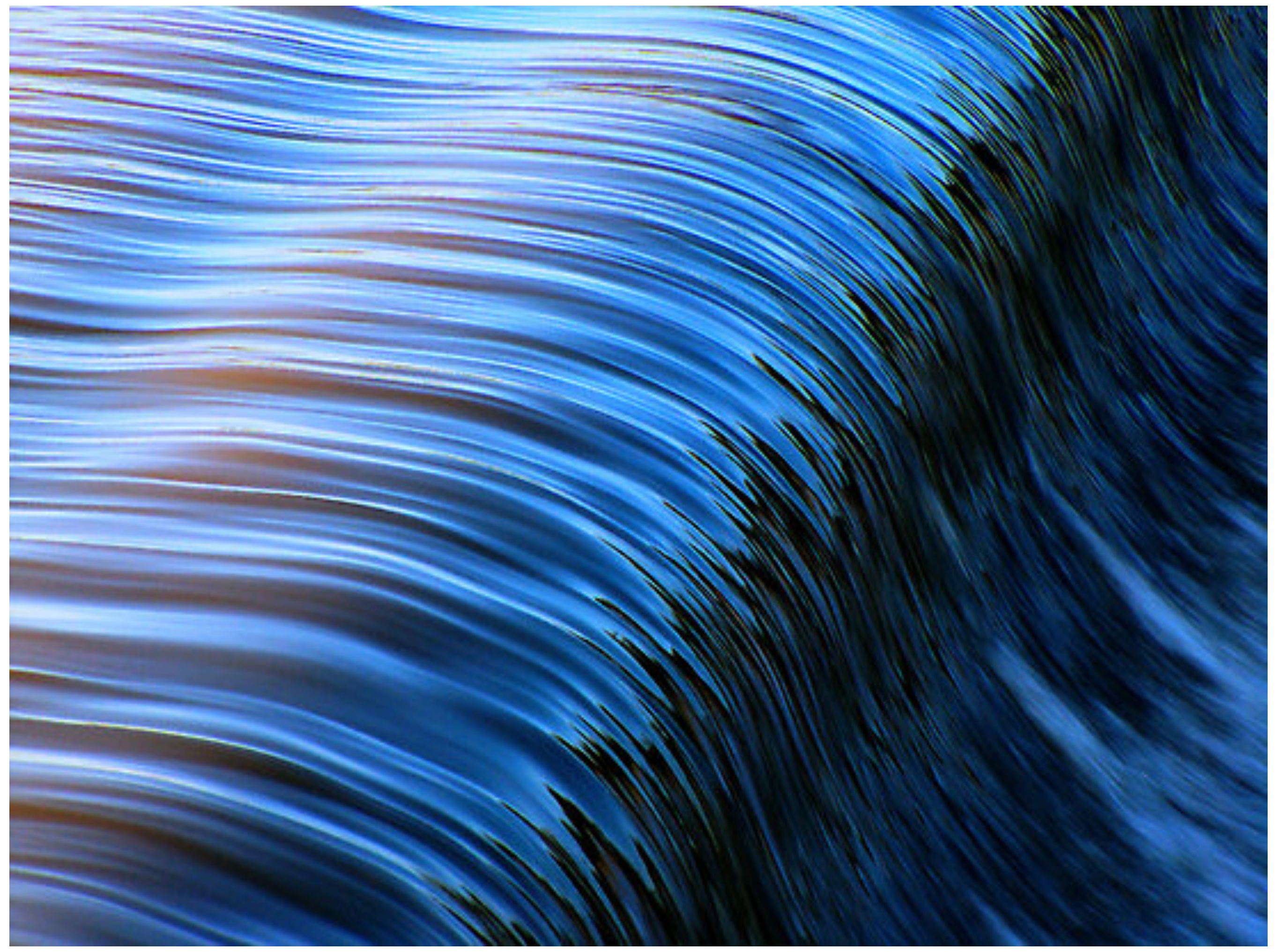
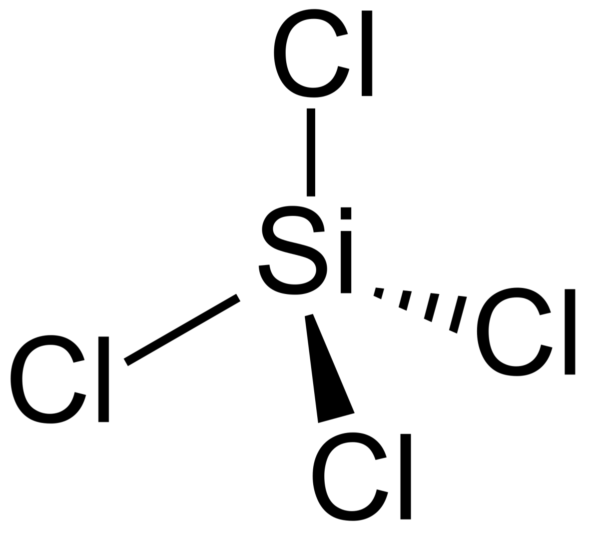
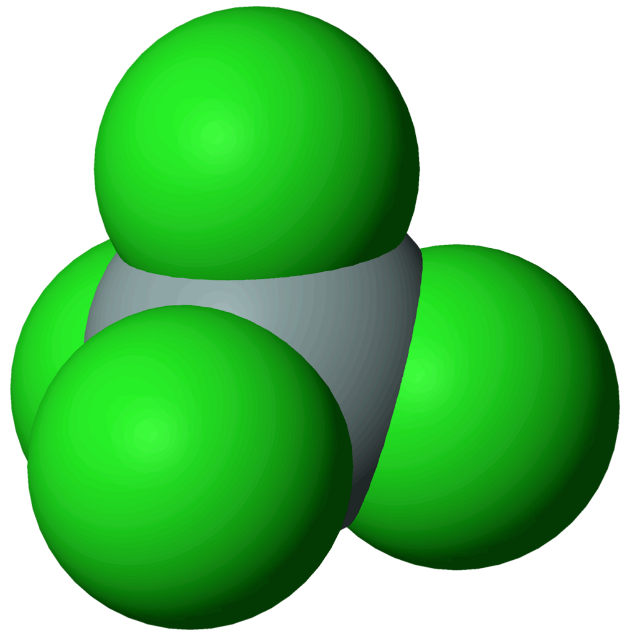


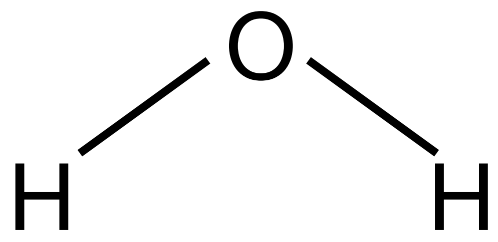
not so different at large scales?

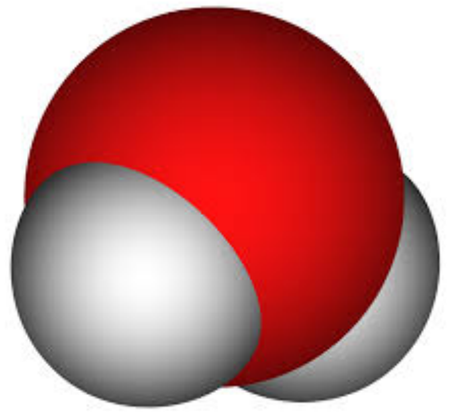
macroscopic variable:
viscosity differs

zooming out:
most microscopic information gets lost









different at small scales

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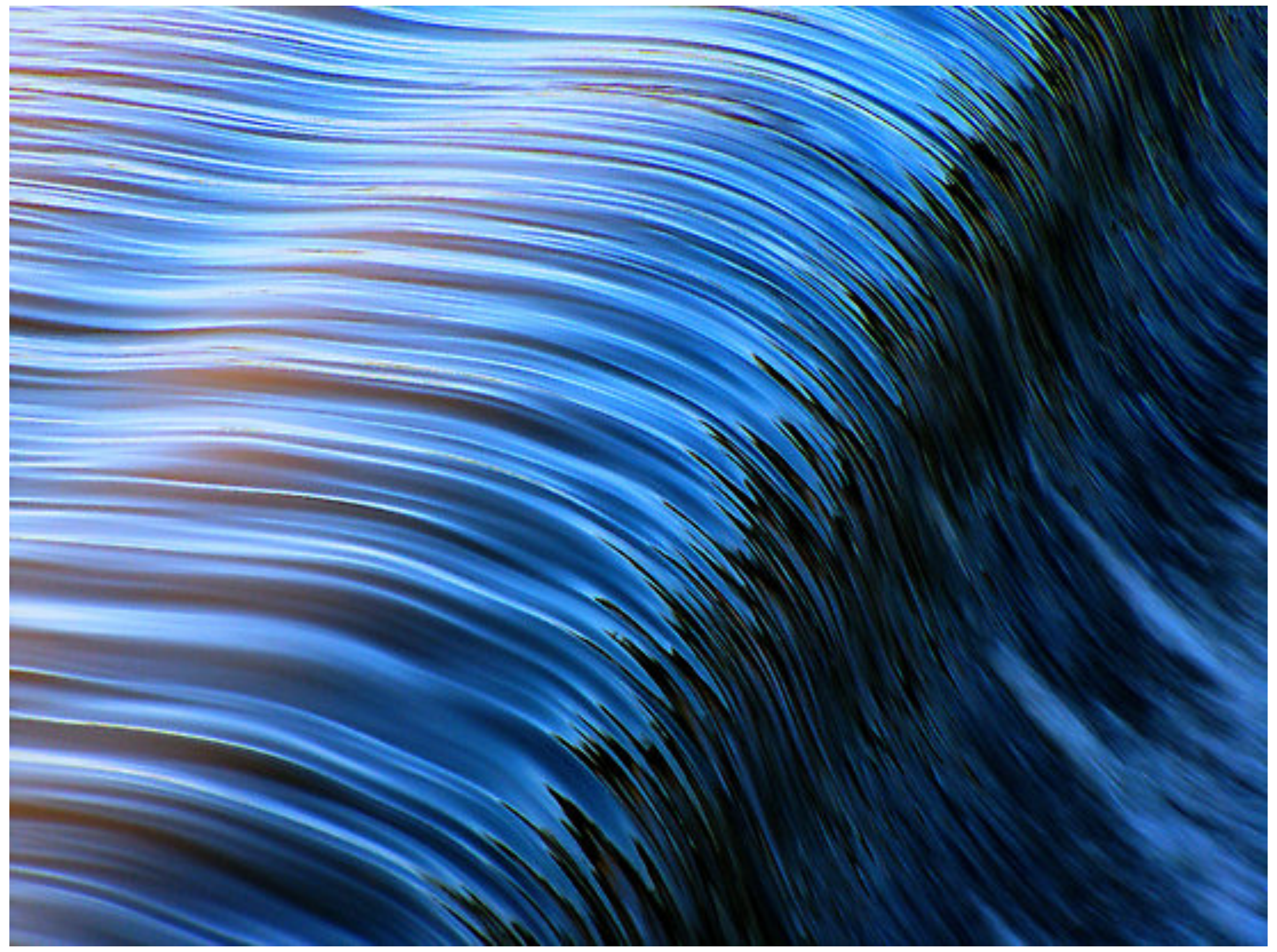

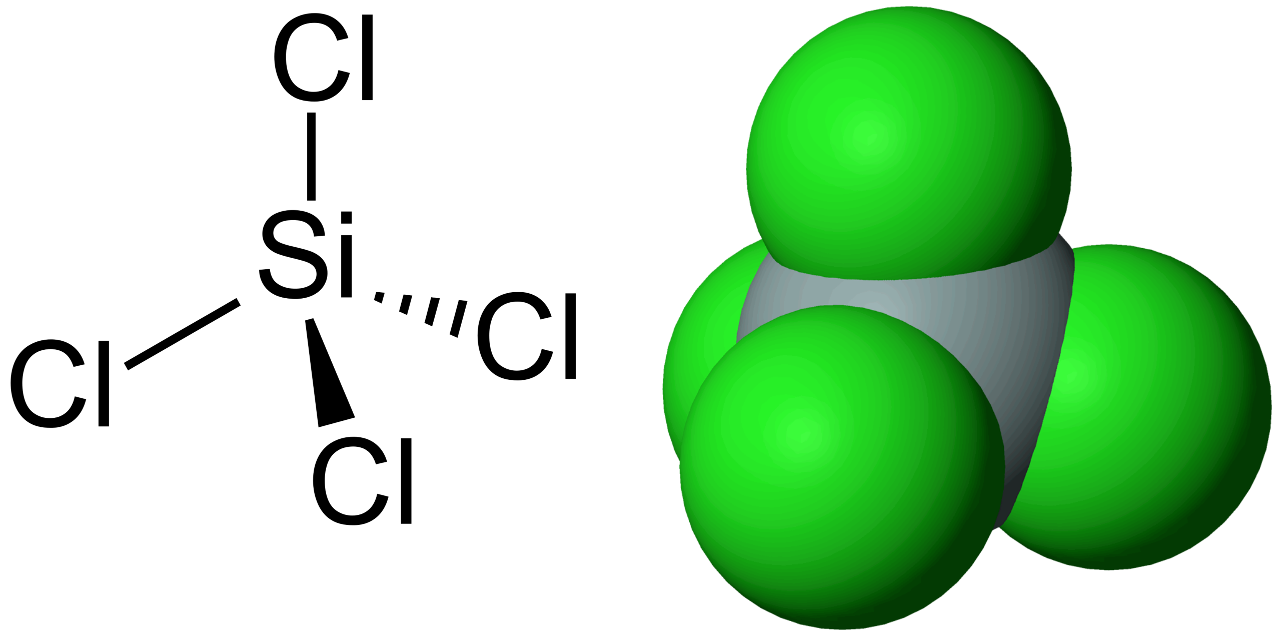

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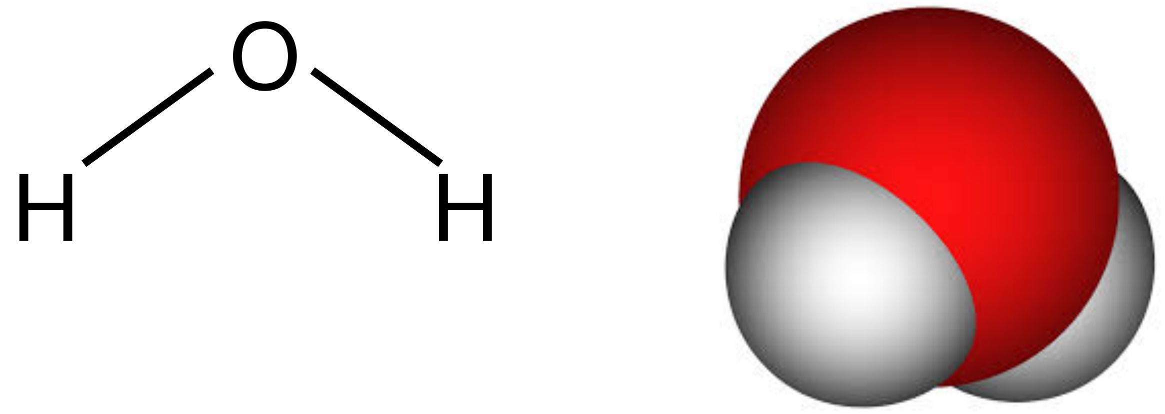
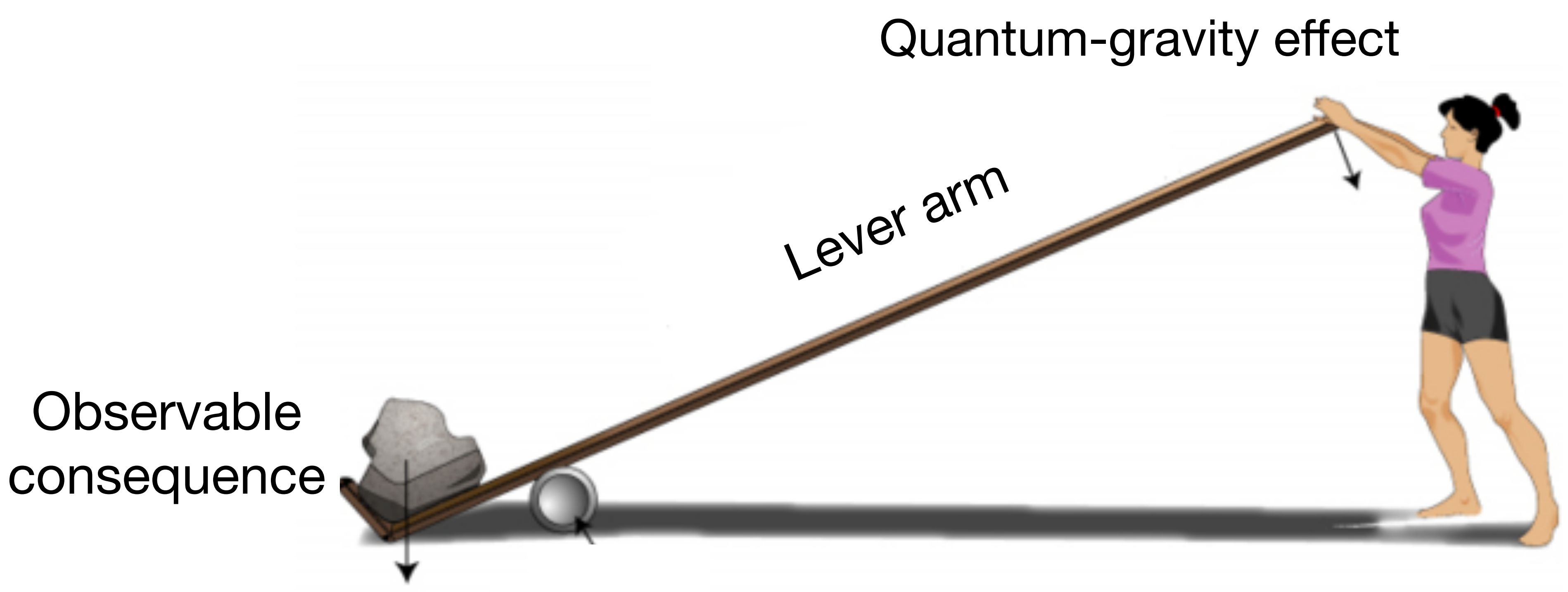
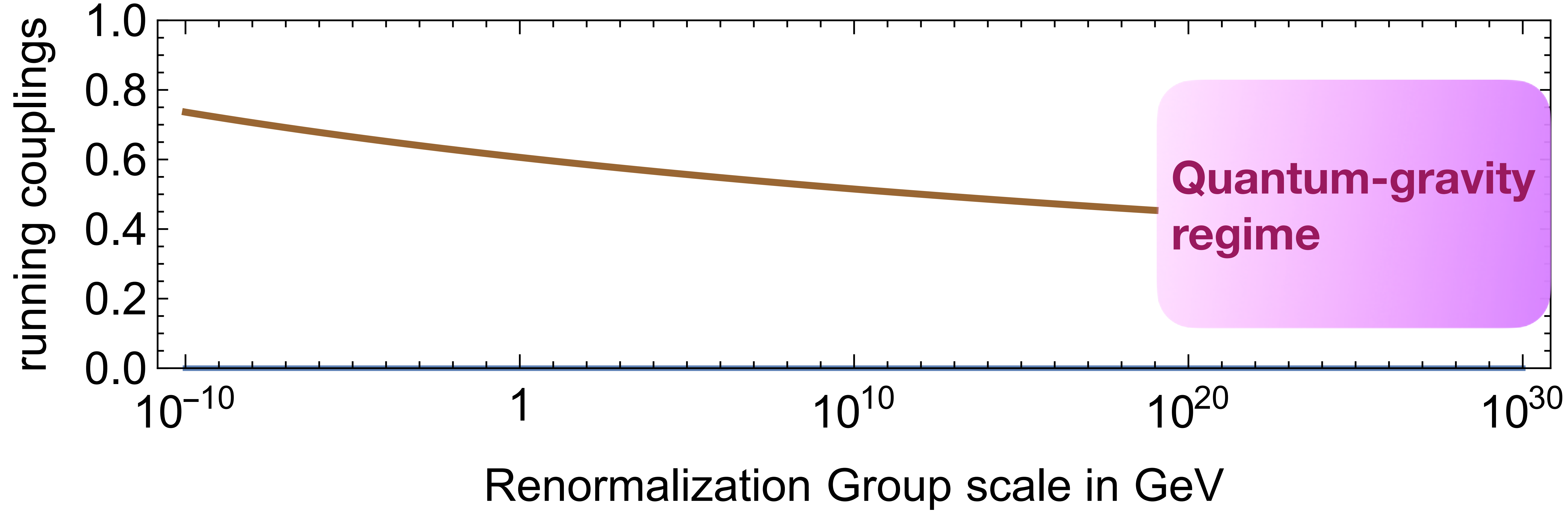


different at small scales

Renormalization Group: tools to translate physics between different scales

Renormalization Group flow as a lever arm





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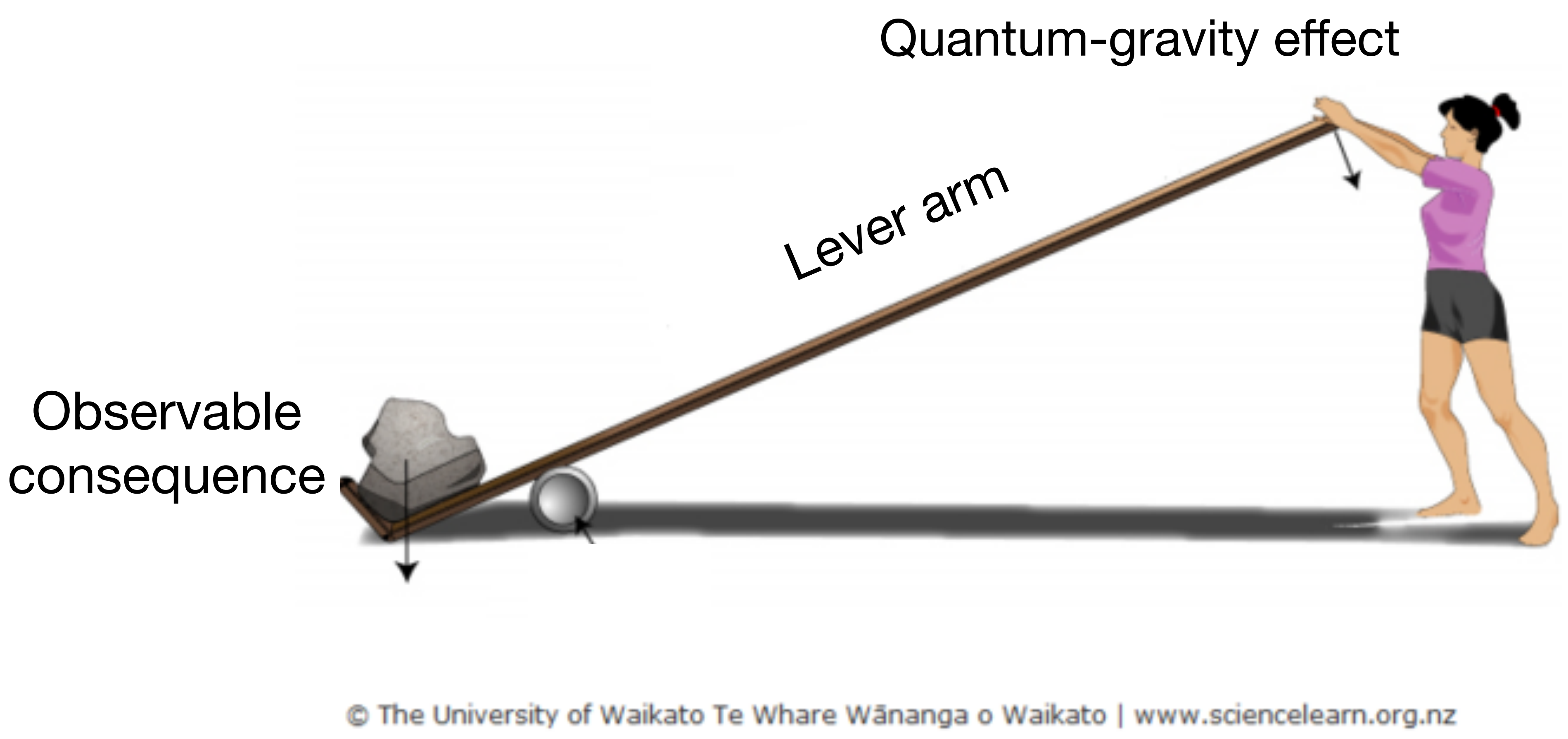

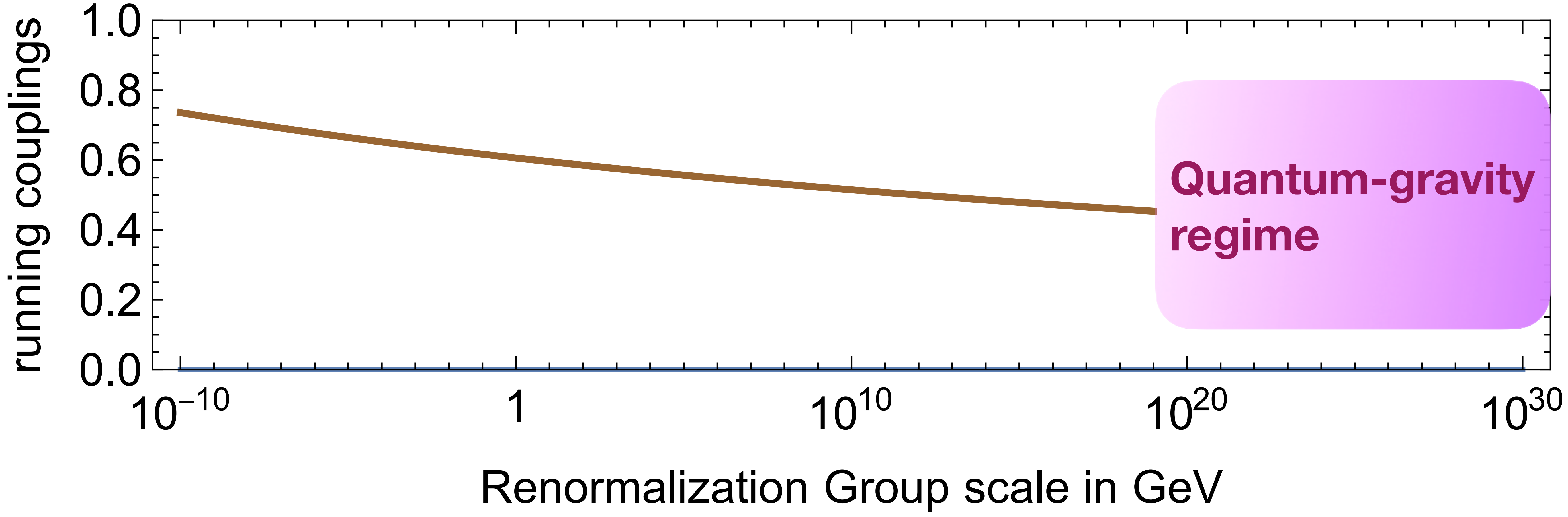

Setting: Effective field theory for degrees of freedom below the Planck scale (SMEFT-like)

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

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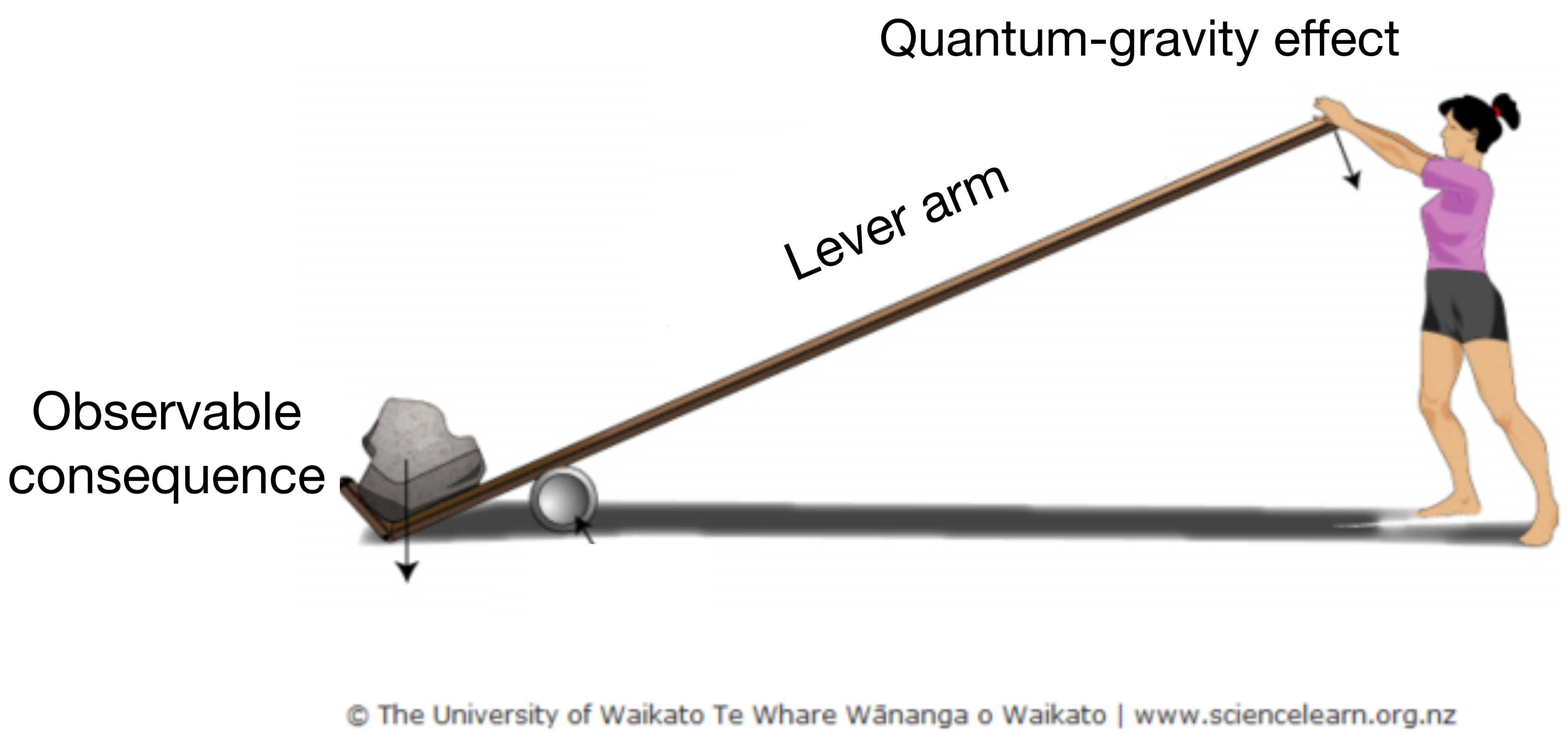

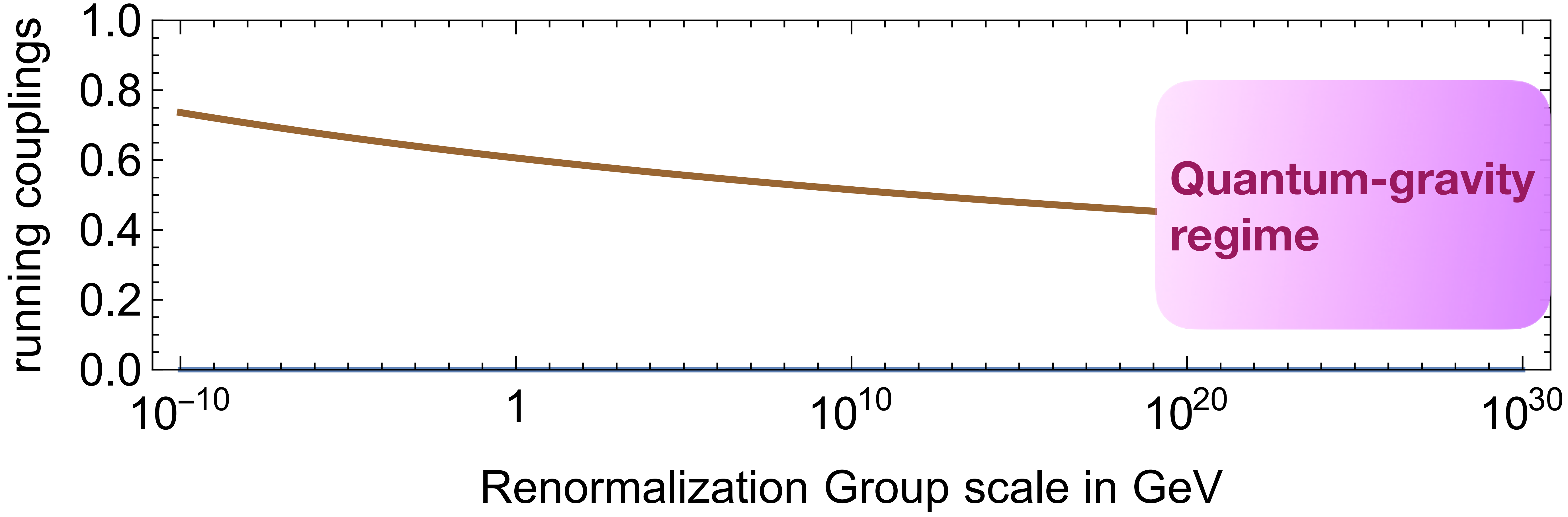

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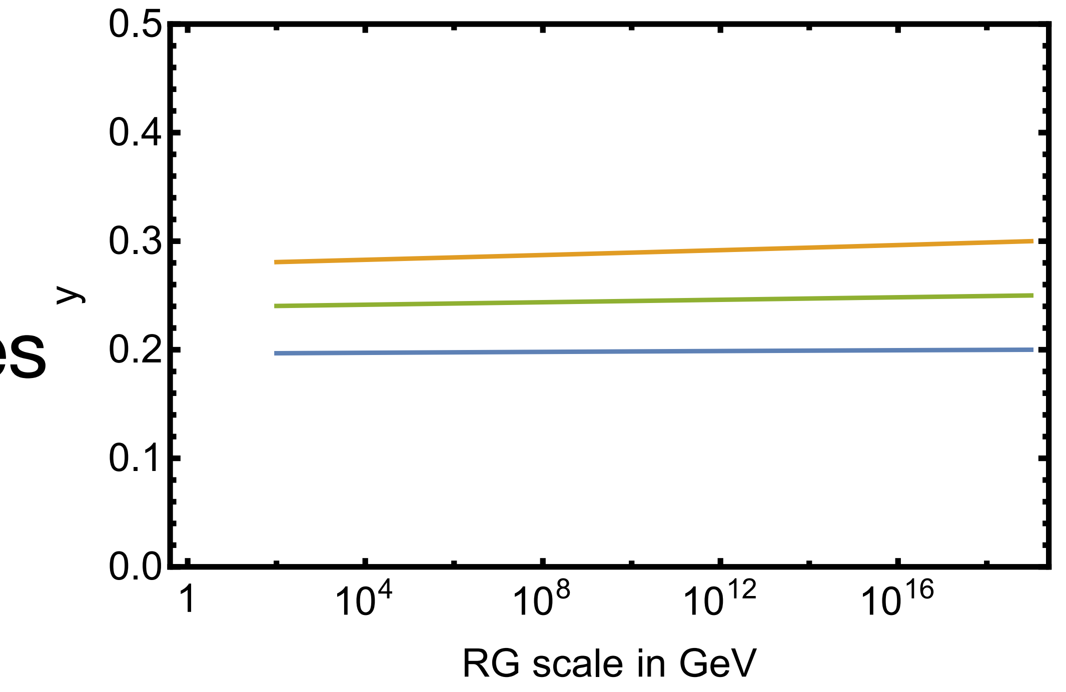
Marginal couplings:

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



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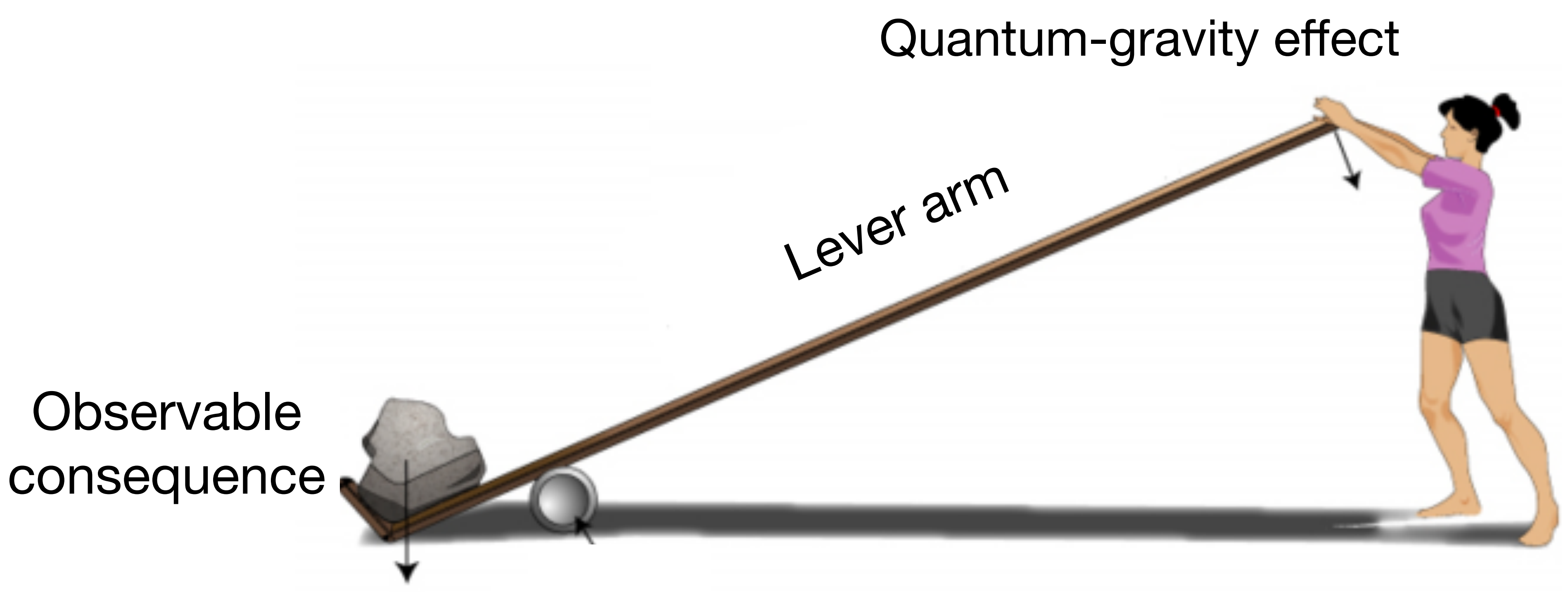

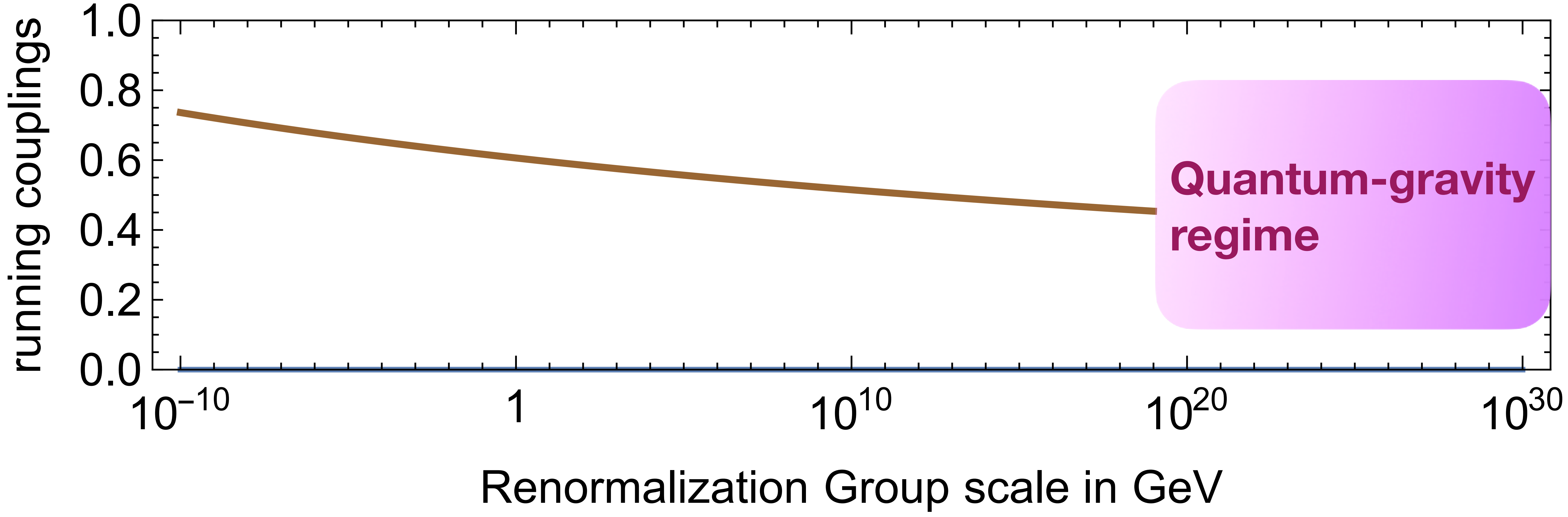

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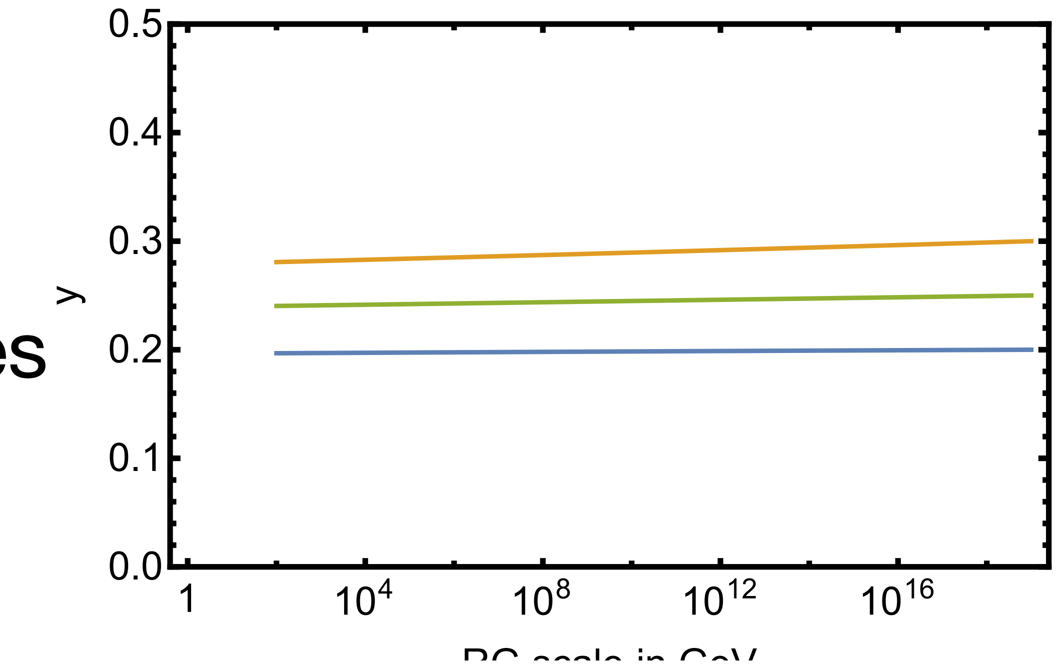
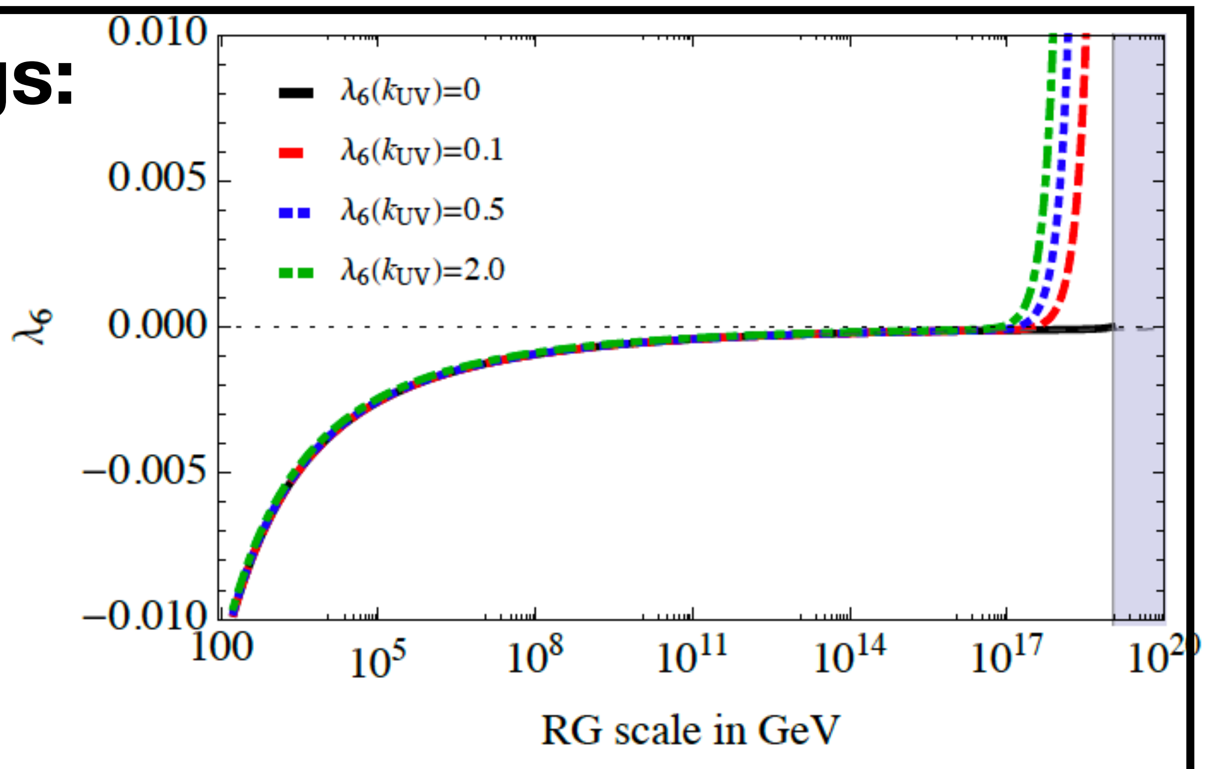


Higher-order couplings:

- 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

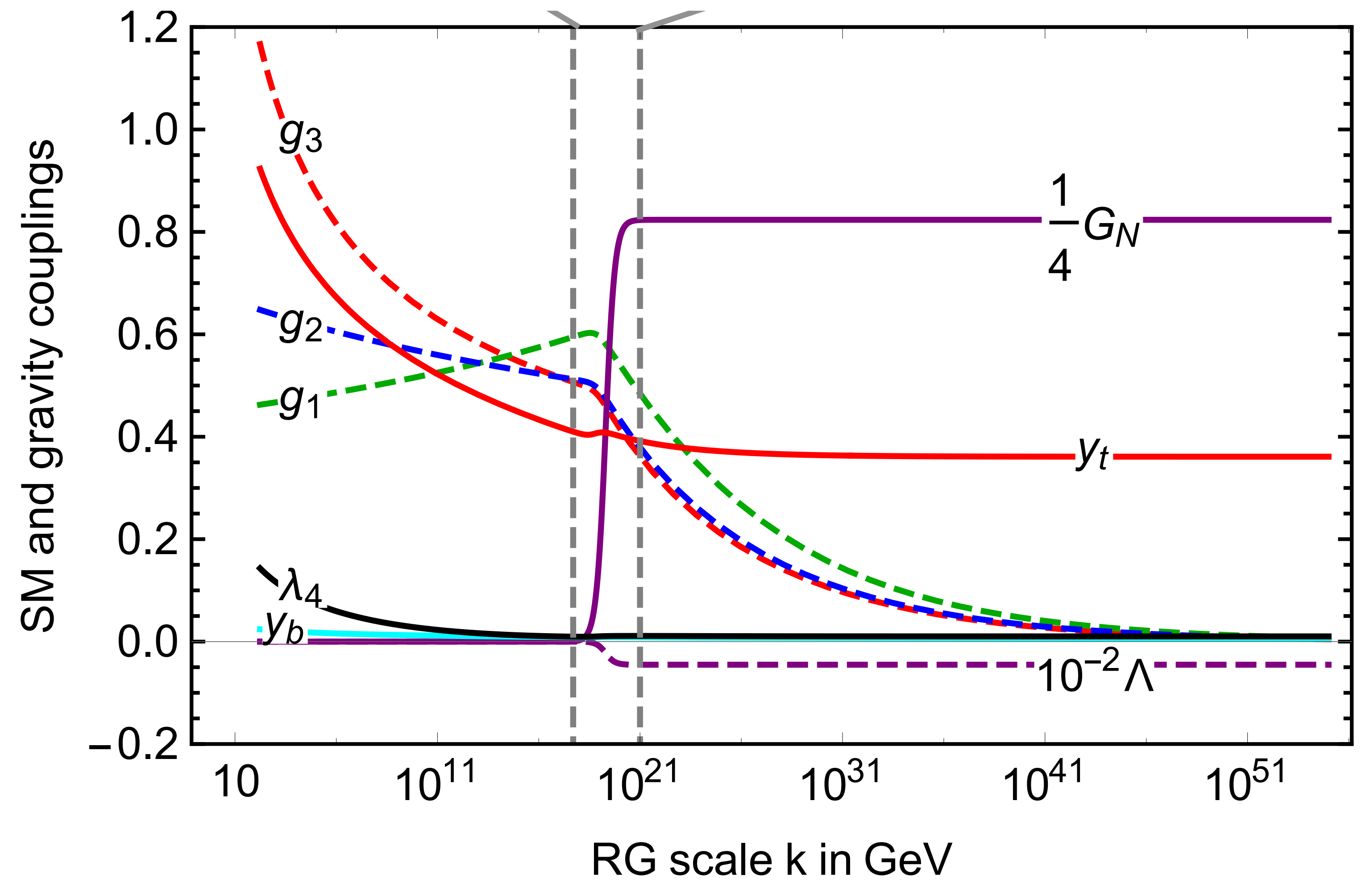
Asymptotic safety in gravity-matter systems

- 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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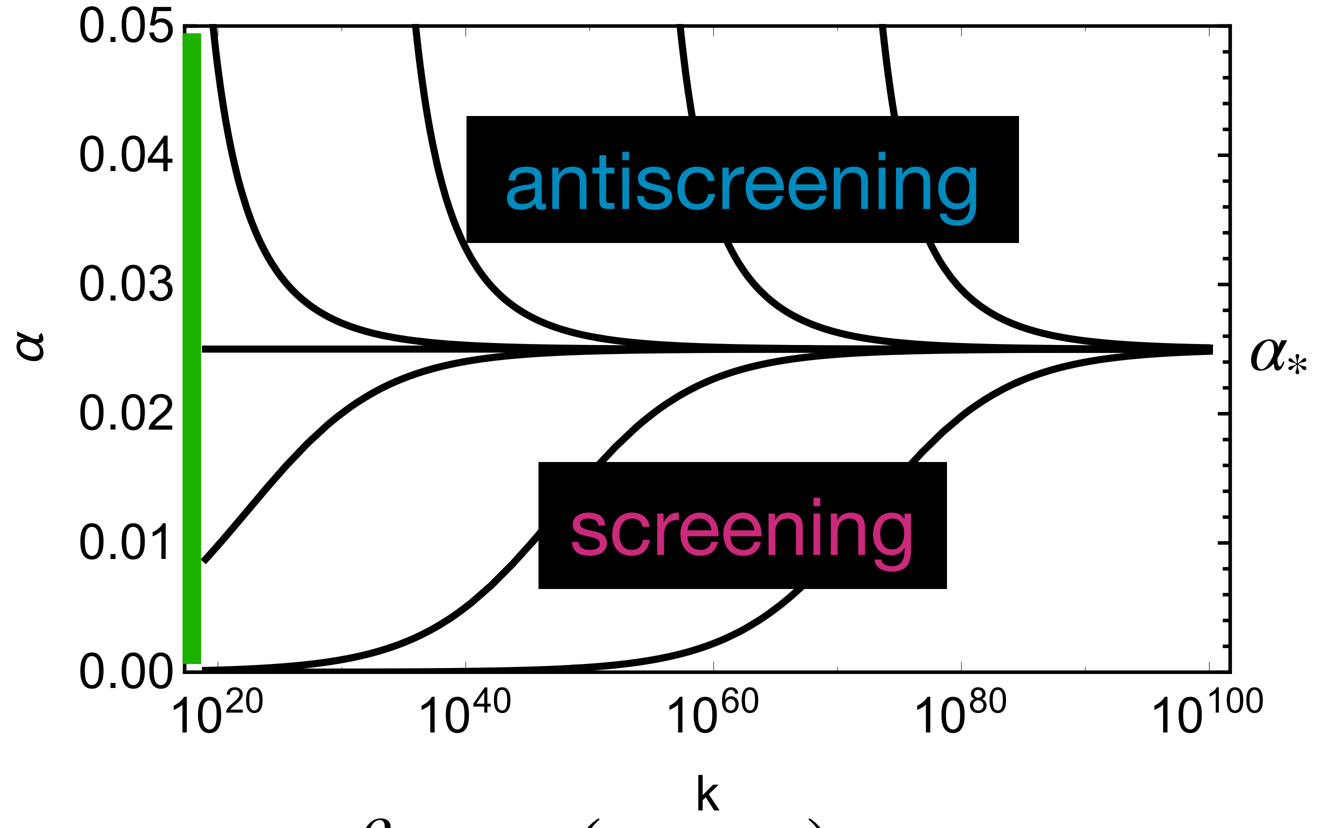
relevant coupling = free parameter



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

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

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

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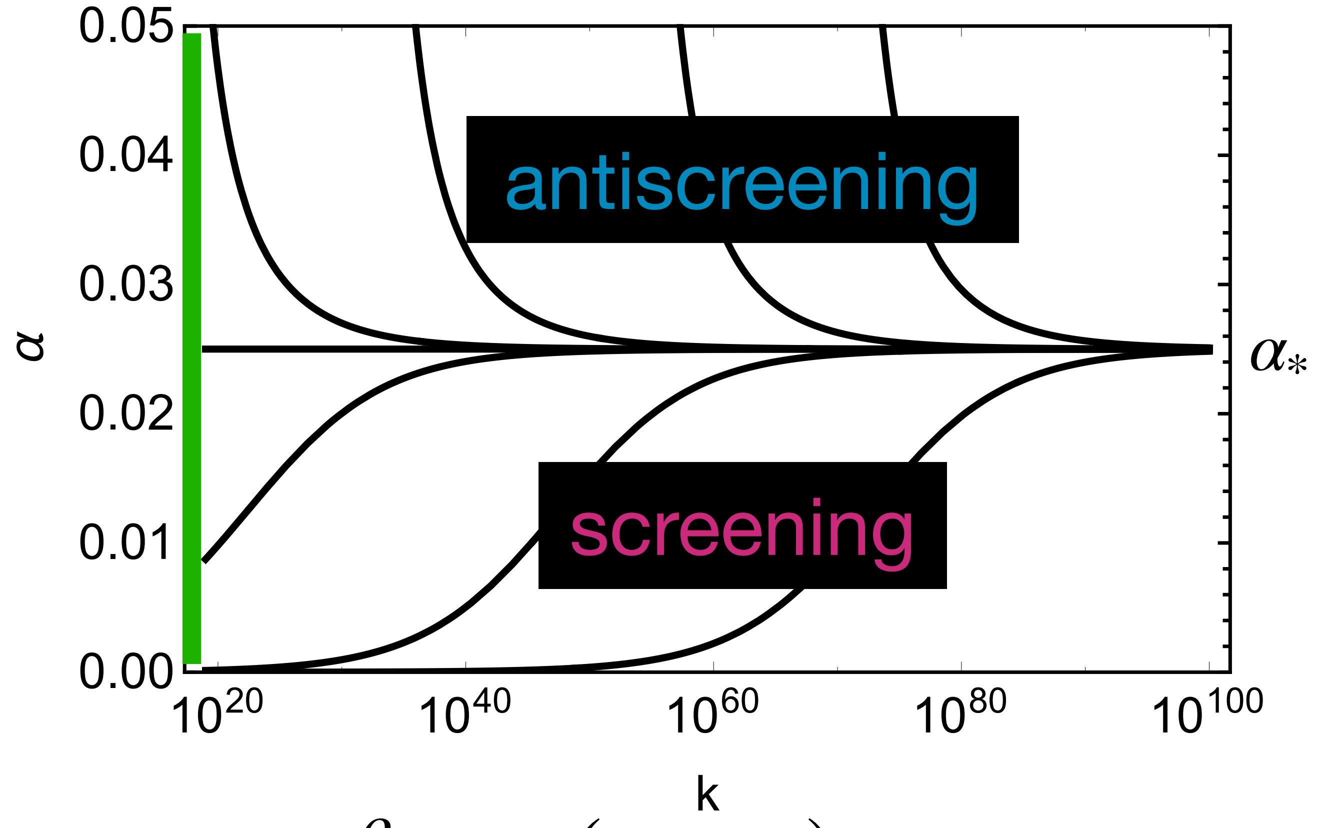
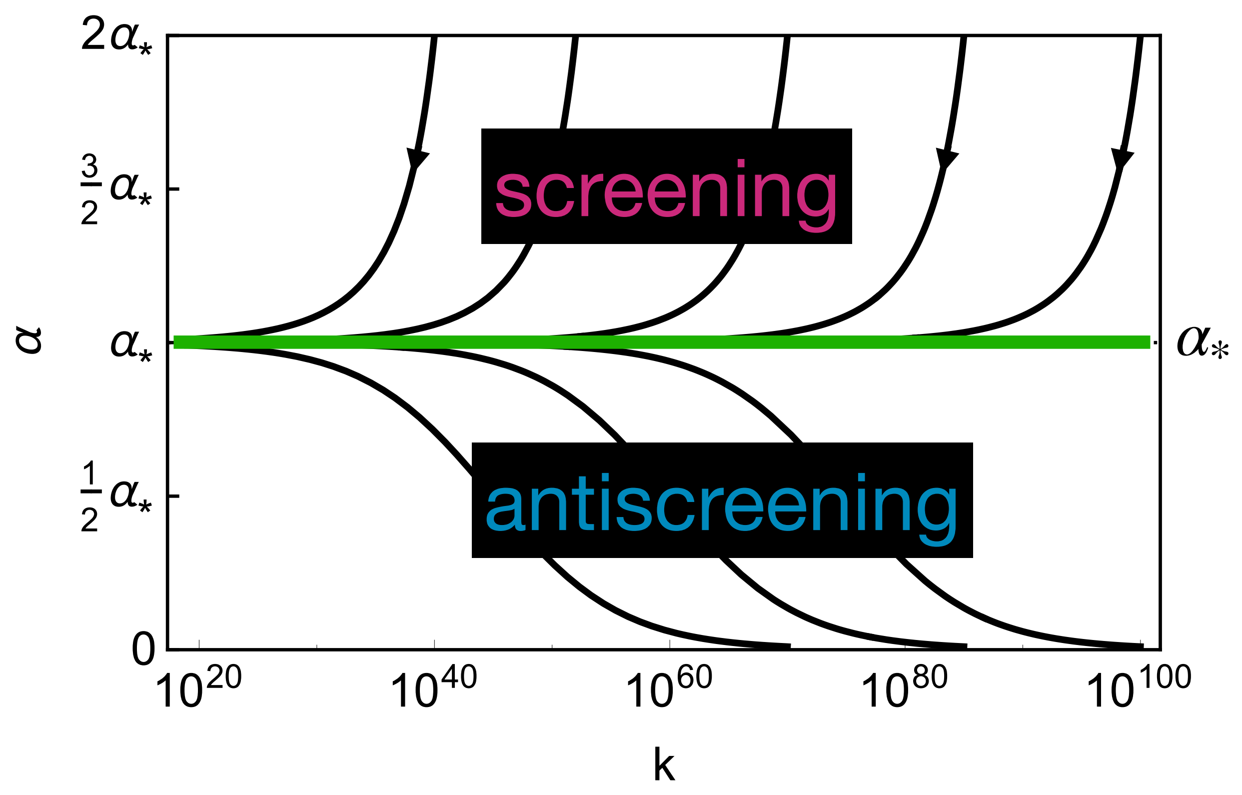


$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

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

→ a range of coupling values achievable at the Planck scale

irrelevant coupling = prediction



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

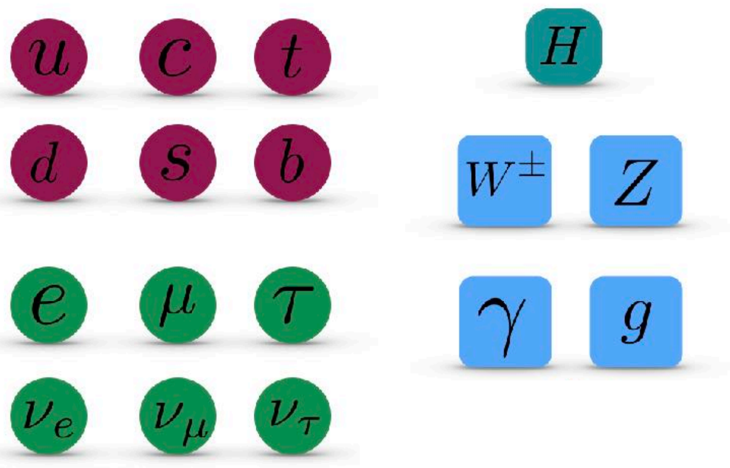
quantum fluctuations drive coupling **towards** scale symmetry

→ a unique coupling value achievable at the Planck scale

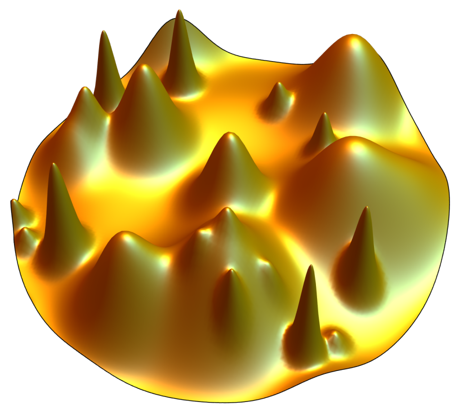
Probing quantum gravity at all scales

Theory

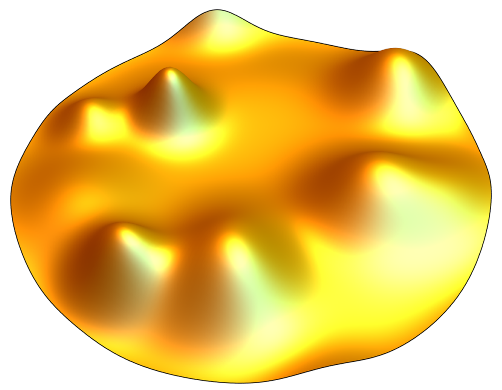
Observational tests



Known particles



Transplanckian scales



Planck scale

Particle physics scales

distance scale

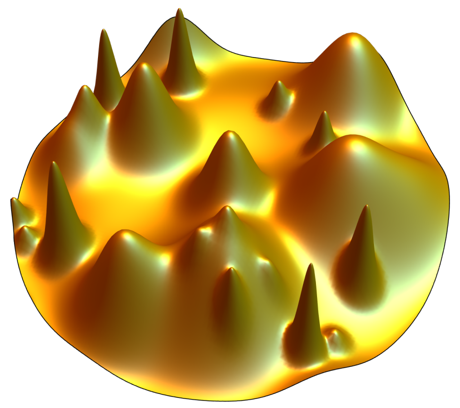
Step 1: Consistency tests:

- Positivity bounds
- Measurements of SM couplings

Probing quantum gravity at all scales

Theory

Observational tests



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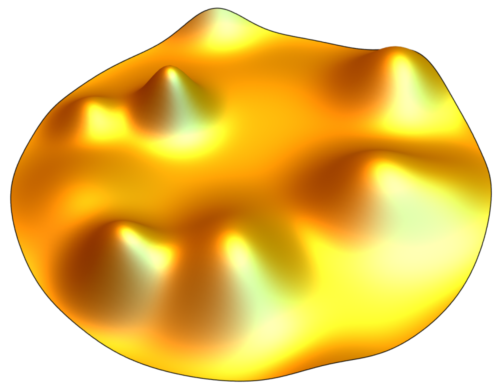
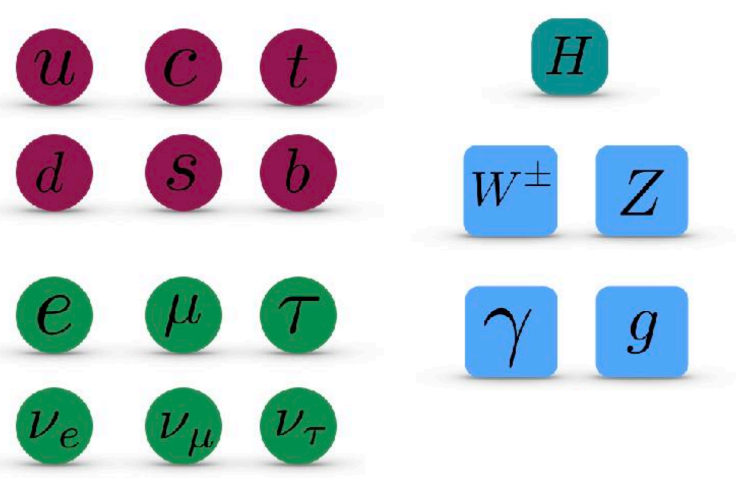


Planck scale



Known particles

?? ?? Dark matter

Particle physics scales

distance scale

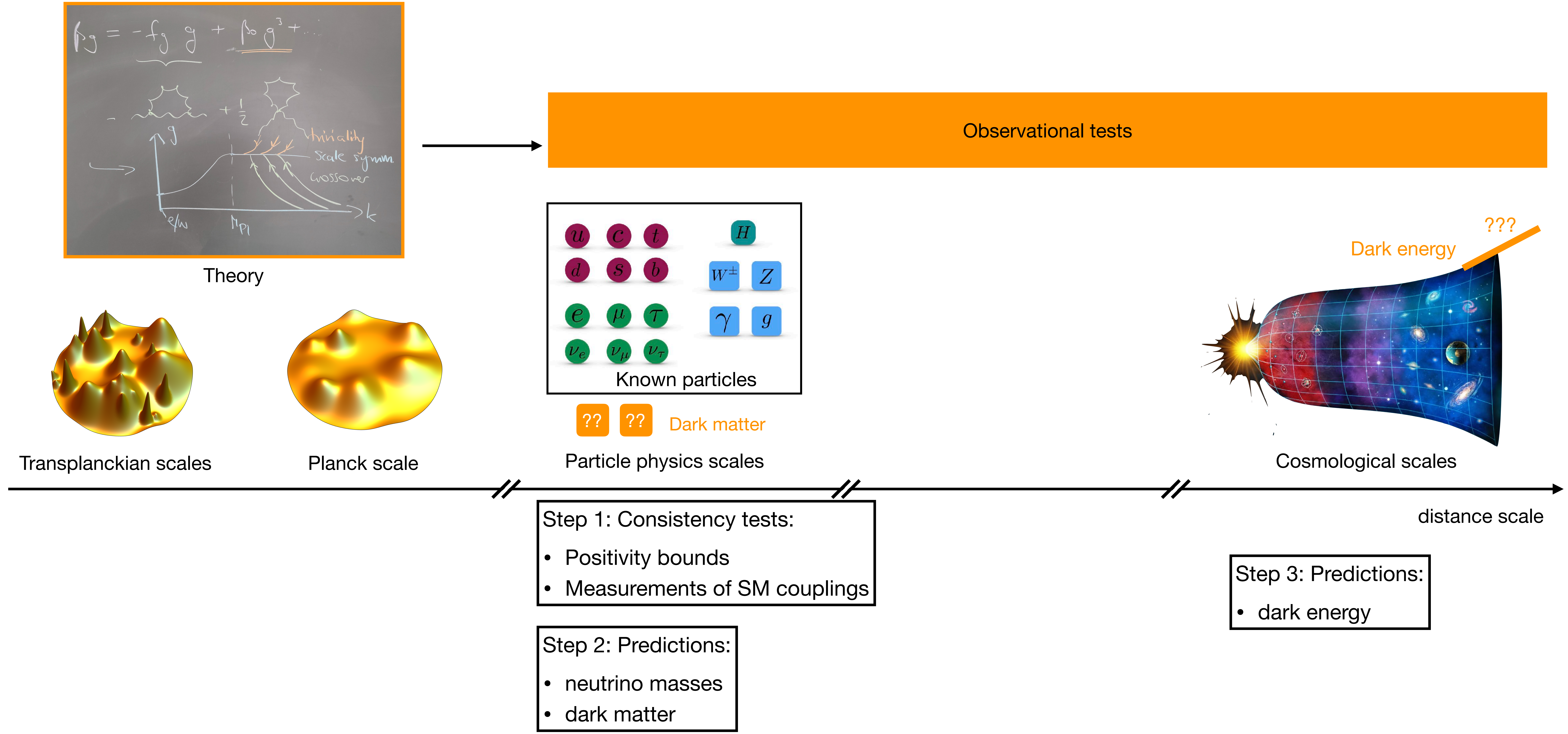
Step 1: Consistency tests:

- Positivity bounds
- Measurements of SM couplings

Step 2: Predictions:

- neutrino masses
- dark matter

Probing quantum gravity at all scales



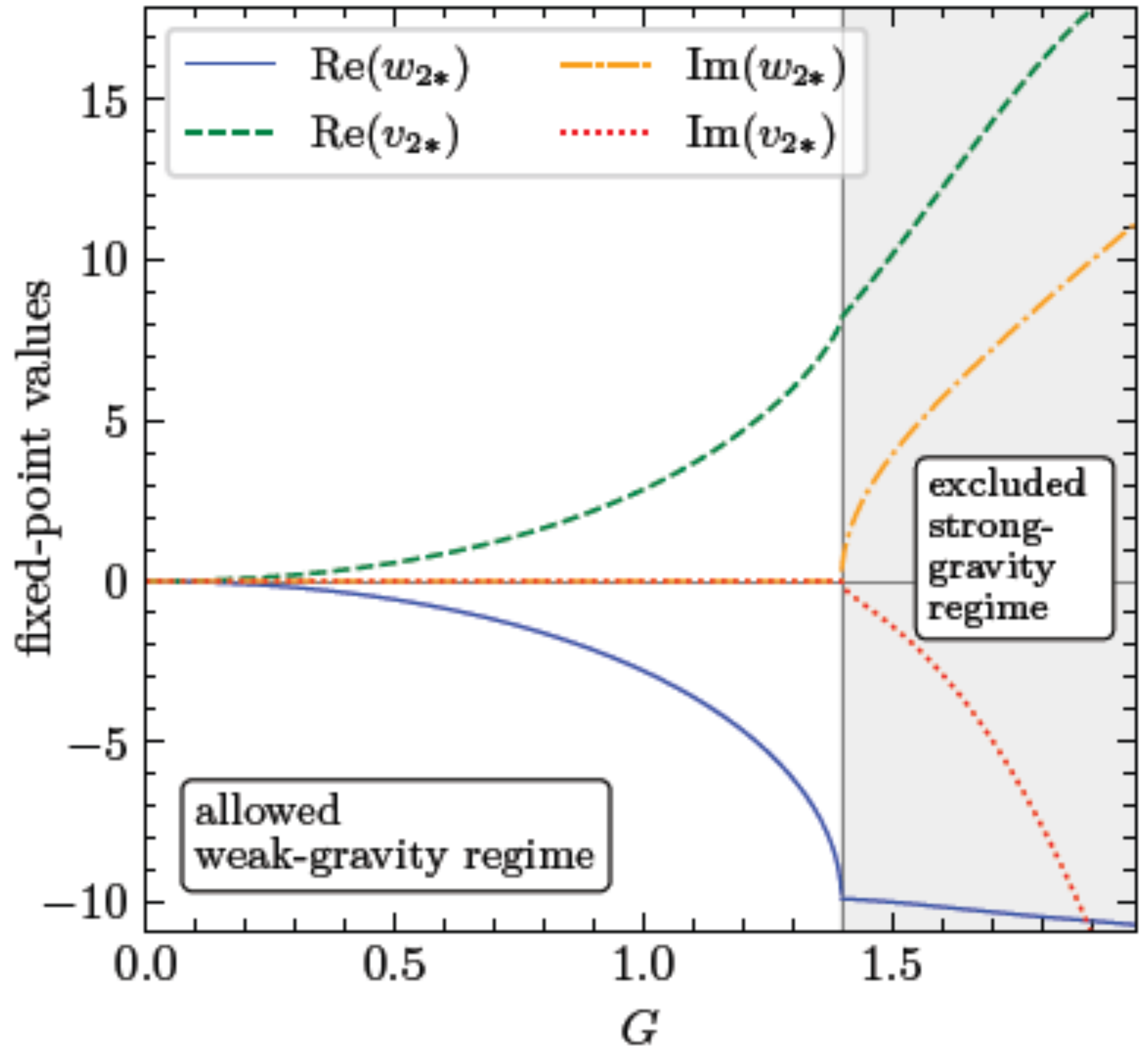
Higher-order couplings in gravity-matter systems

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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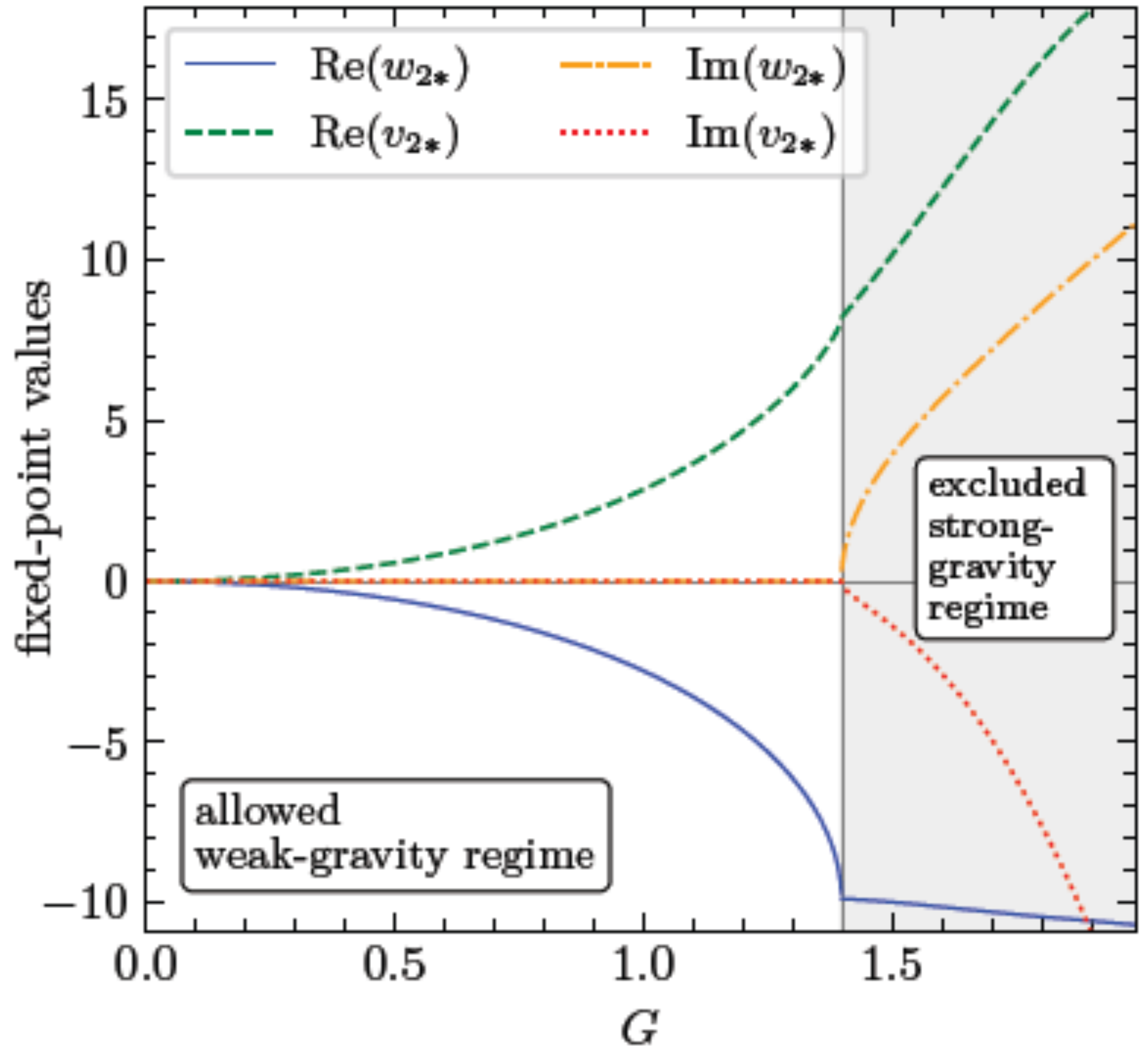


Positivity bounds in asymptotically safe gravity

Positivity bounds from causality in the IR

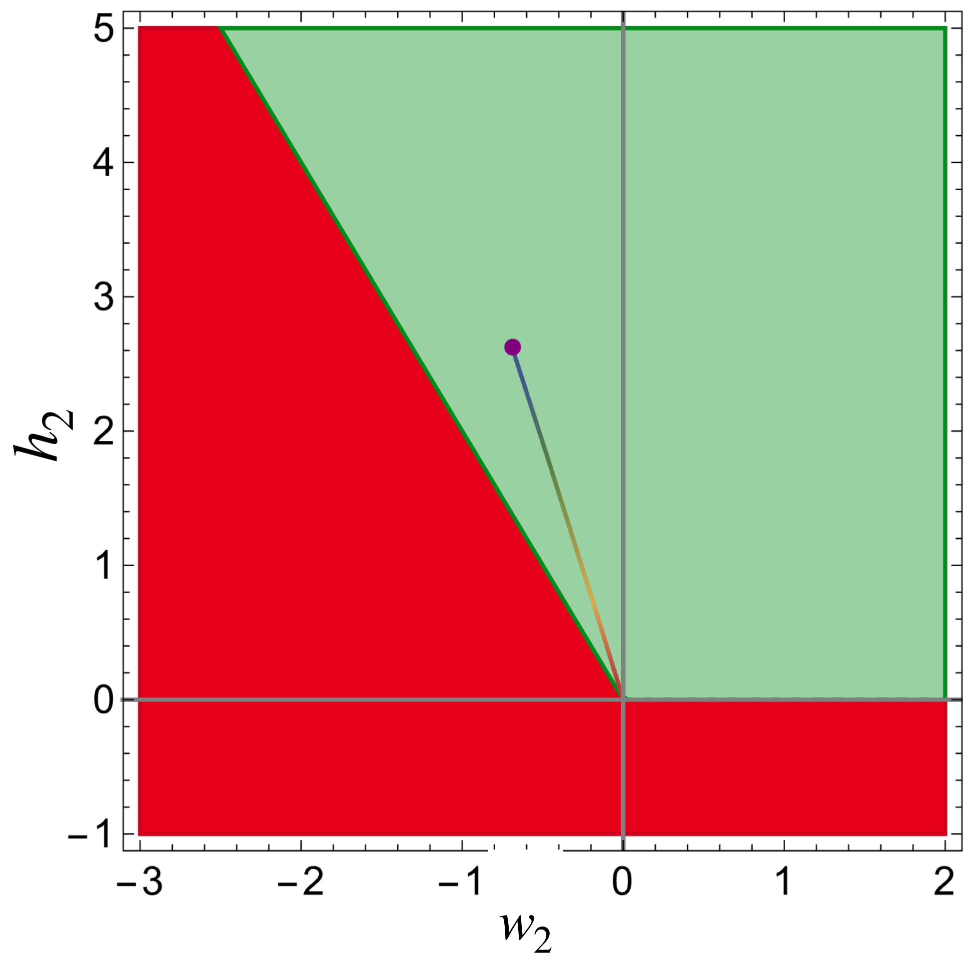
$$\frac{w_2}{h_2} > -\frac{3}{4}, \quad \frac{4w_2 + 3h_2}{|4w_2 + h_2|} > 1$$

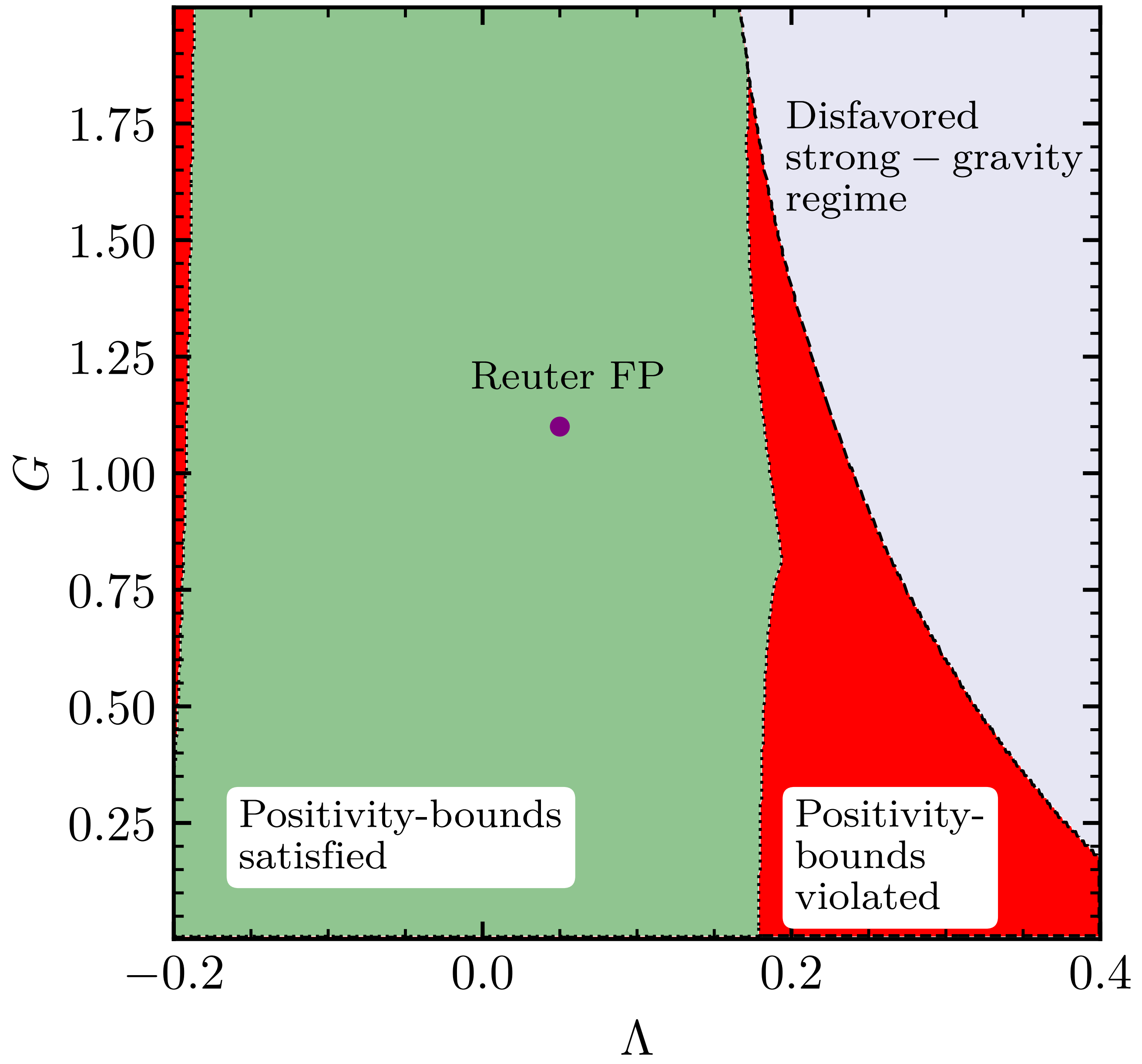
[Carillo Gonzalez, de Rham, Jaitly, Pozsgay, Tokareva ‘23]

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, Pedersen, Schiffer ’24]





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)

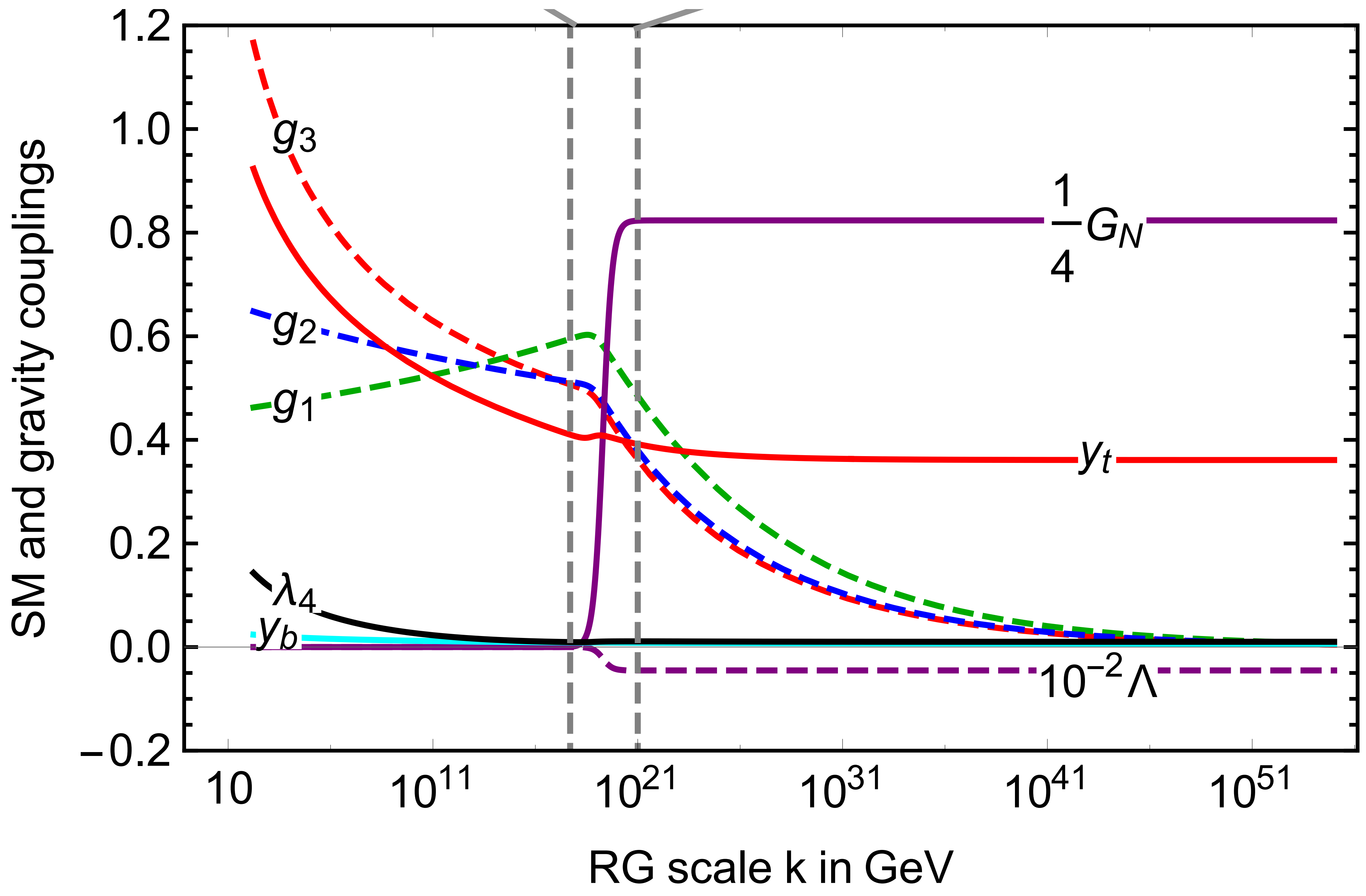
→ only present beyond the Planck scale
(because gravity coupling negligible below the Planck scale)

→ 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 $f_{g_i} = \text{const}$, above M_{Planck}

$f_{g_i} \to 0$, below M_{Planck}



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UV complete and bounded from above

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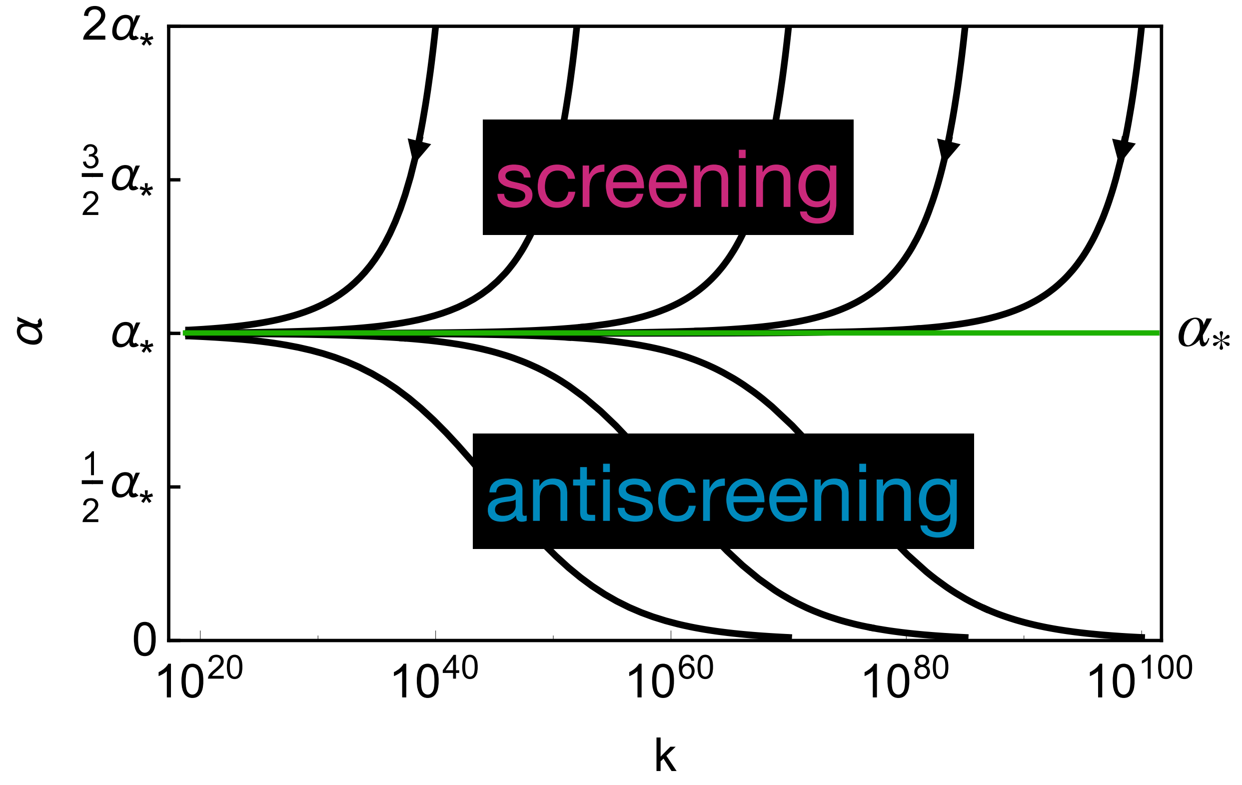

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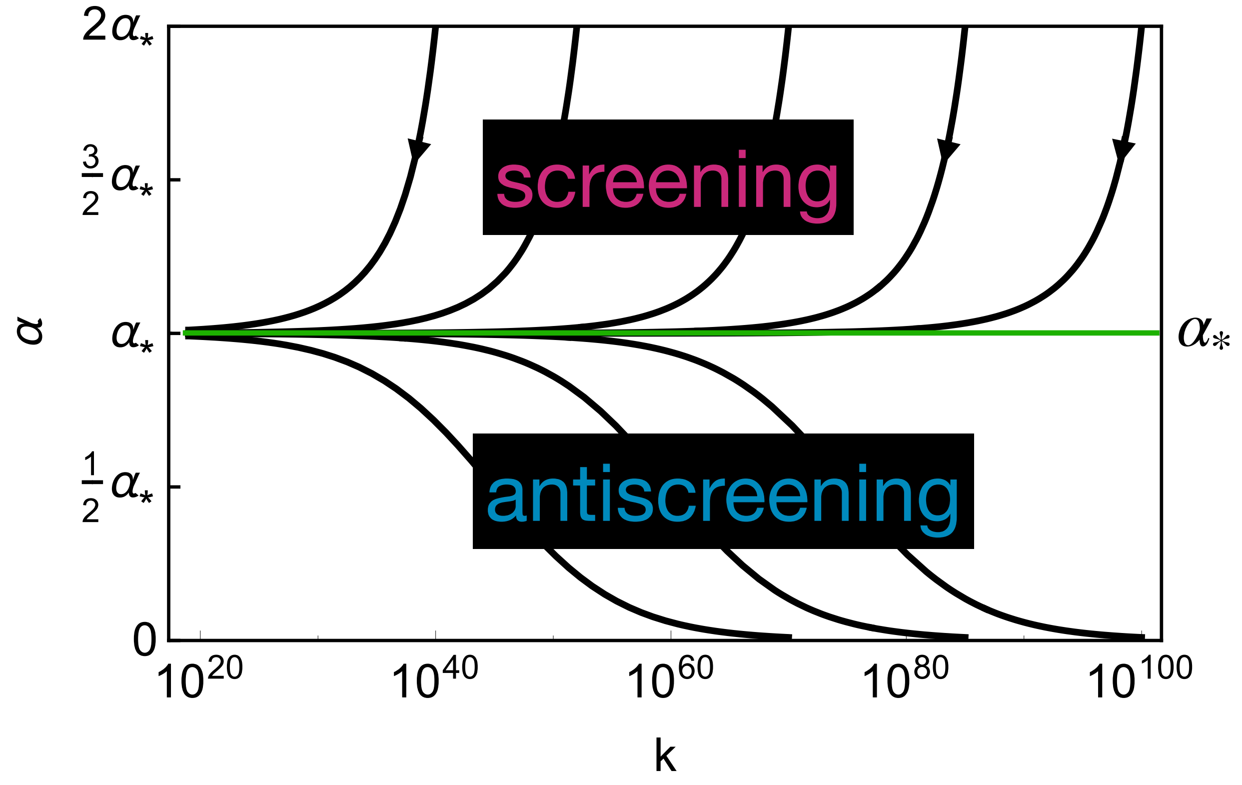

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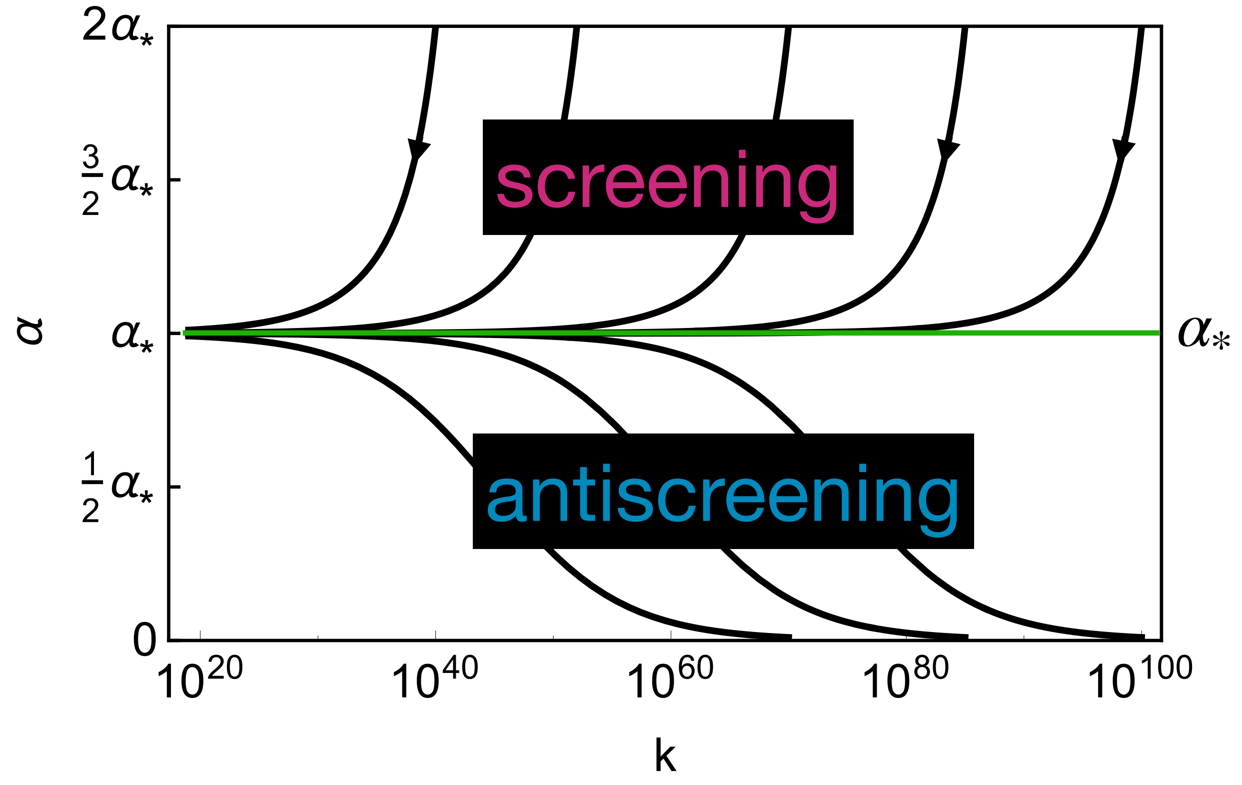

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Extension to higher order [AE, Held '17; Christiansen, AE '17; de Brito, AE, Pereira '19, AE, Schiffer '19; AE, Kwapisz, Schiffer '21]

Universality and connection to perturbative results:

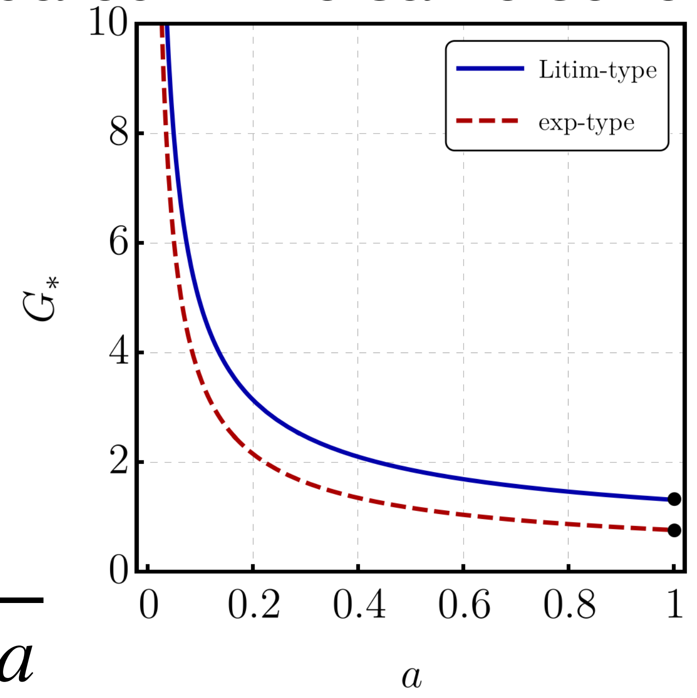
f_g not universal and vanishes in some schemes (e.g., dimensional regularization), if gravity coupling is treated as fixed external parameter

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

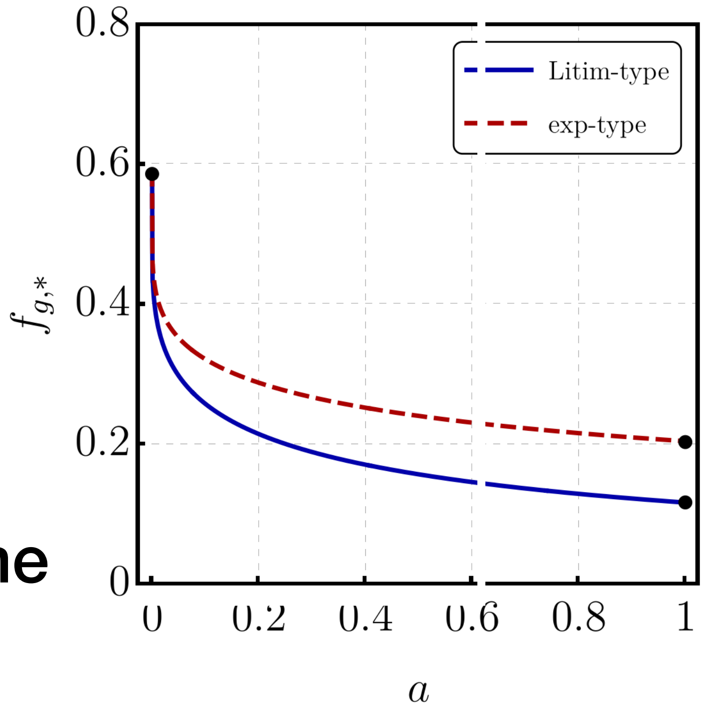
subtlety: $f_g > 0$ if fixed-point value for gravity evaluated in the same scheme [de Brito, AE '22]

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

$$\sim a\log(a)$$



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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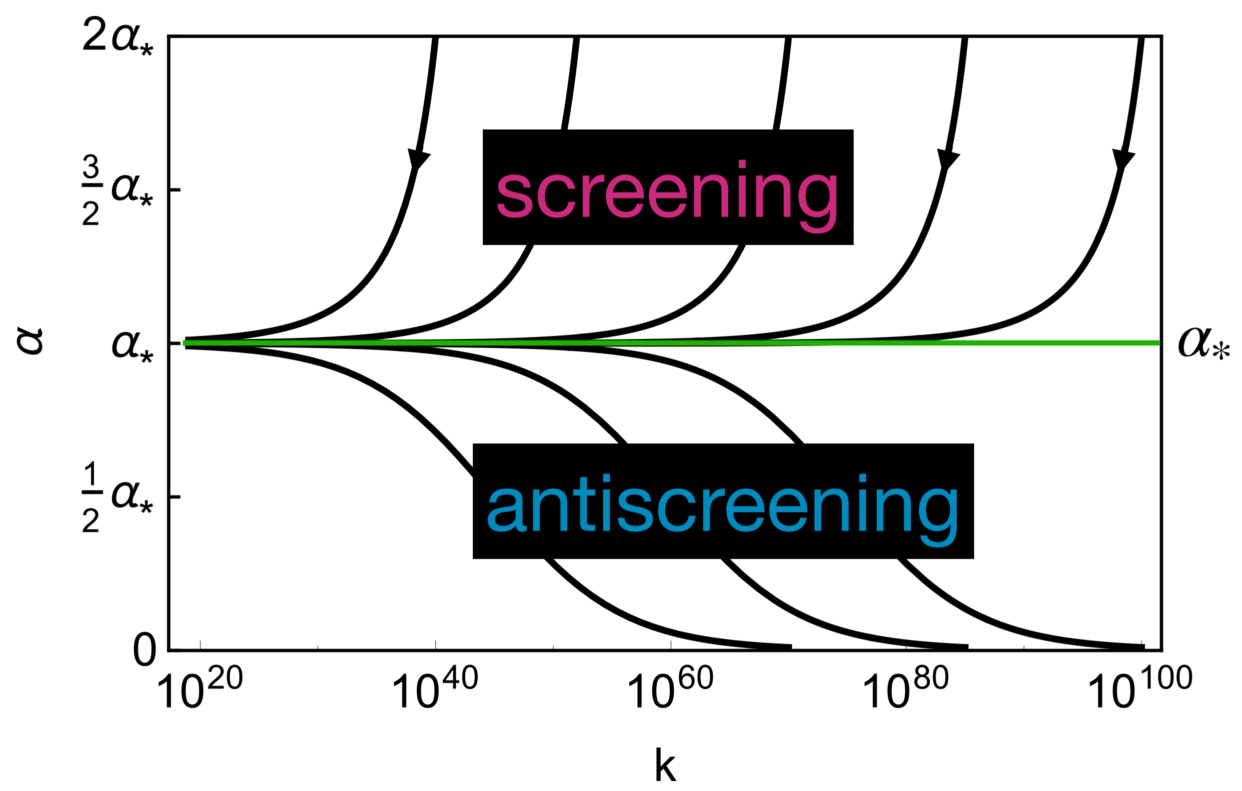

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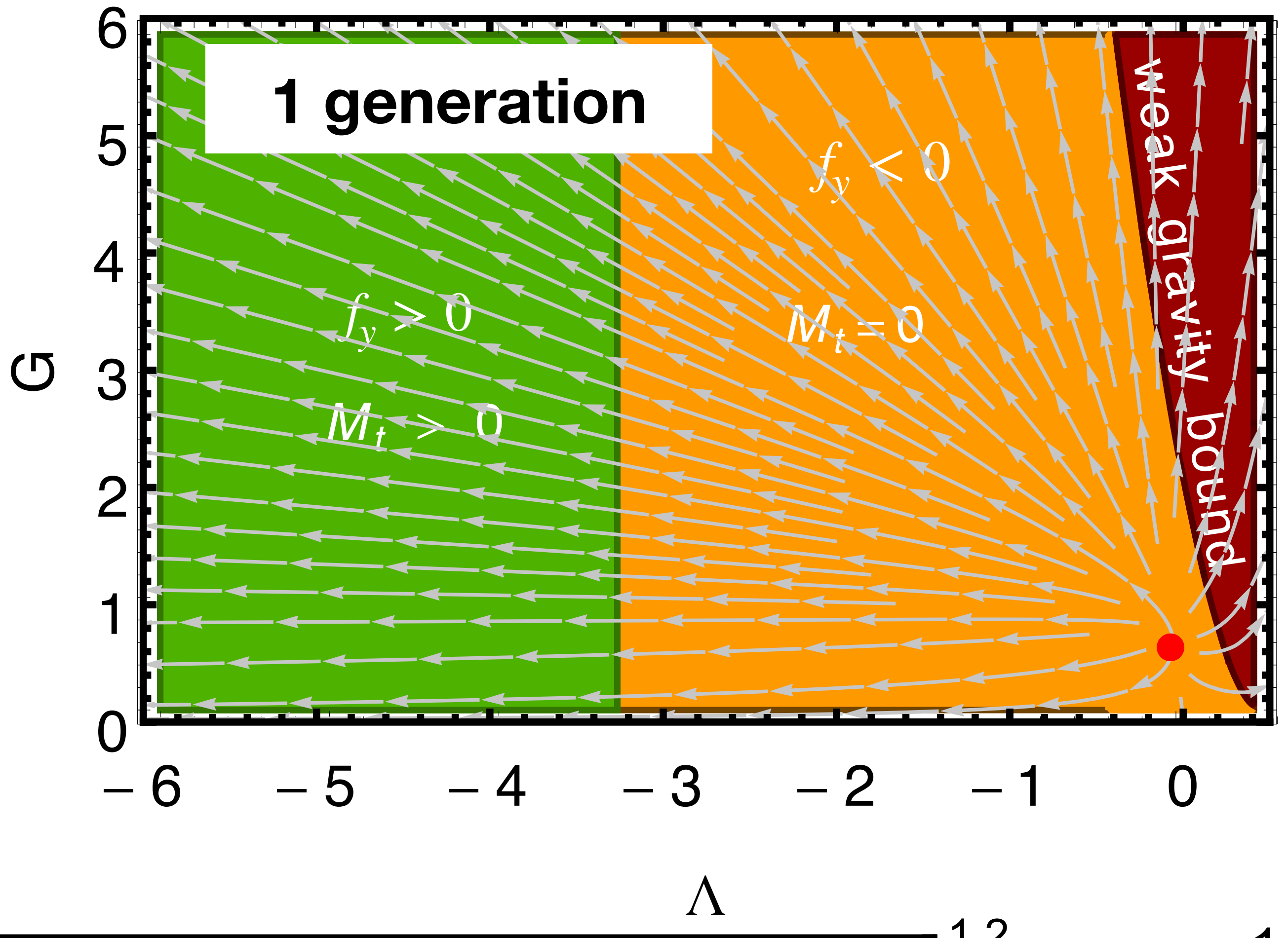

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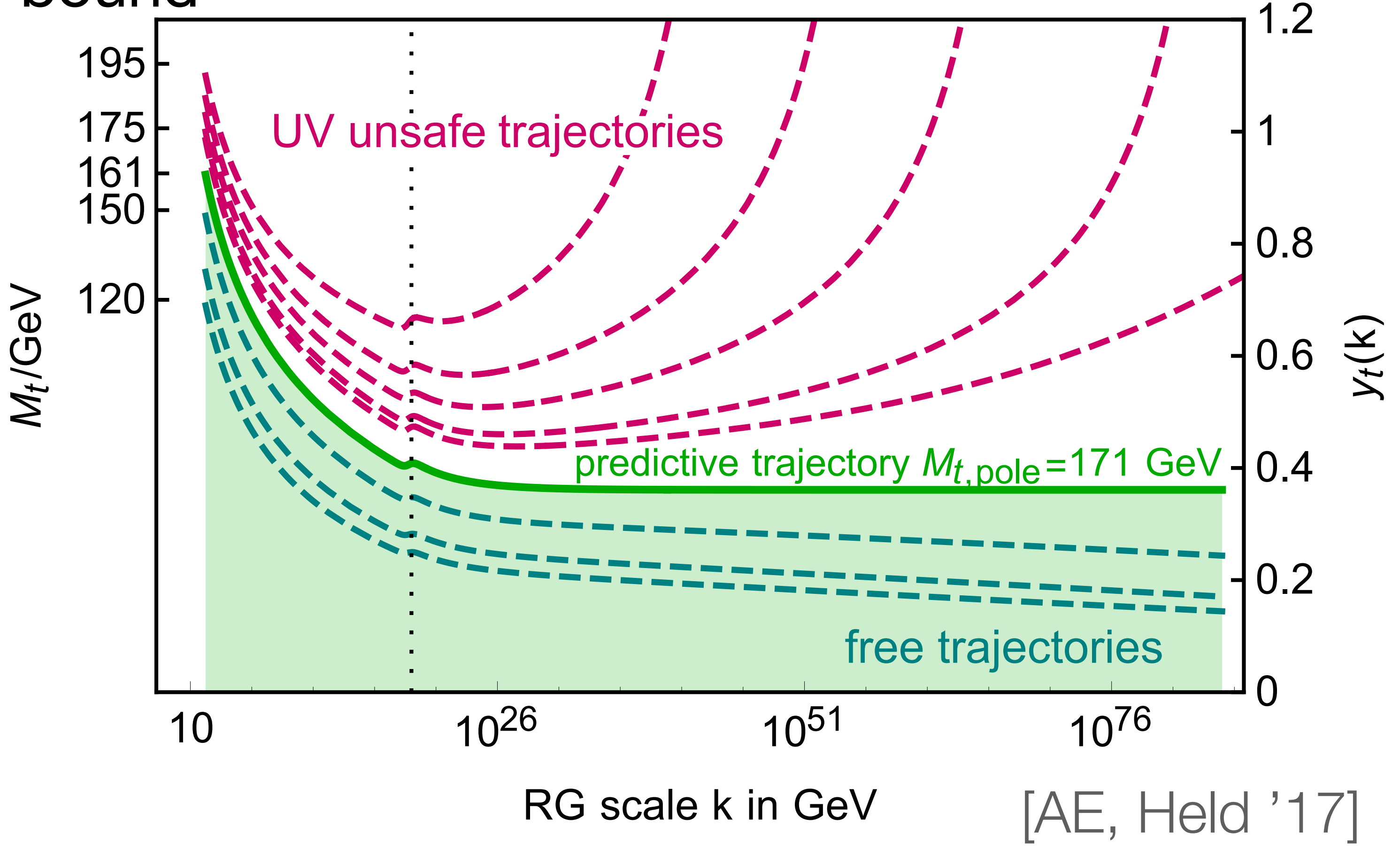
[Dona, AE, Percacci '13]



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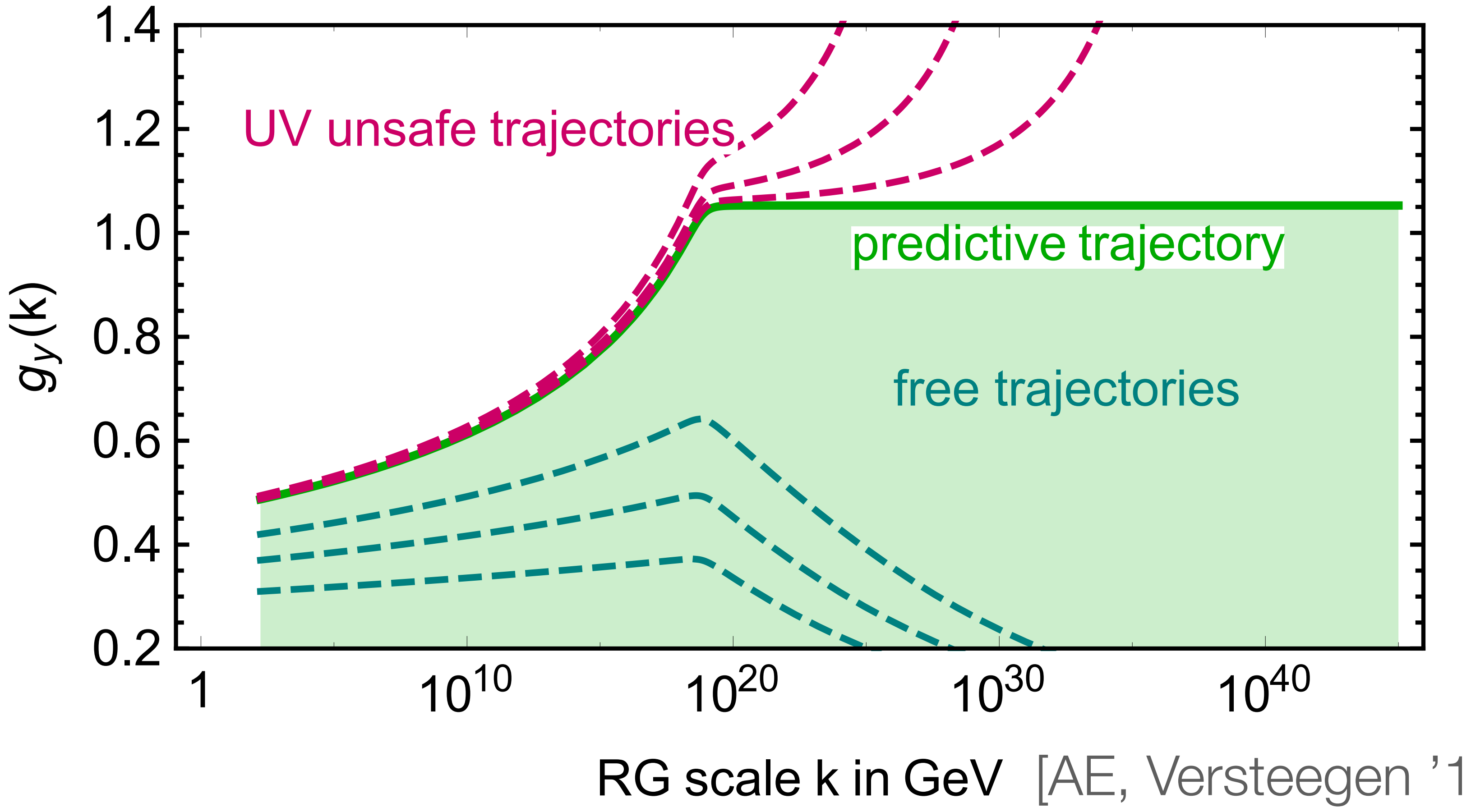

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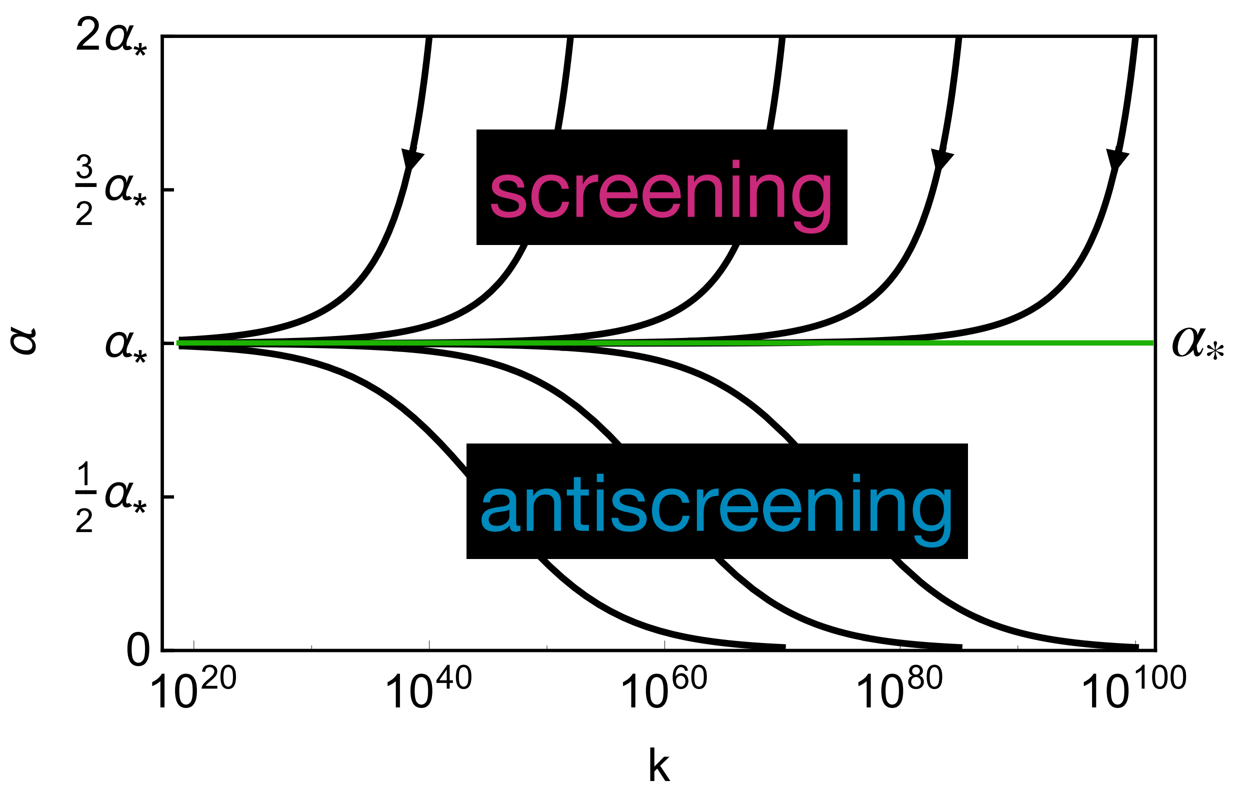

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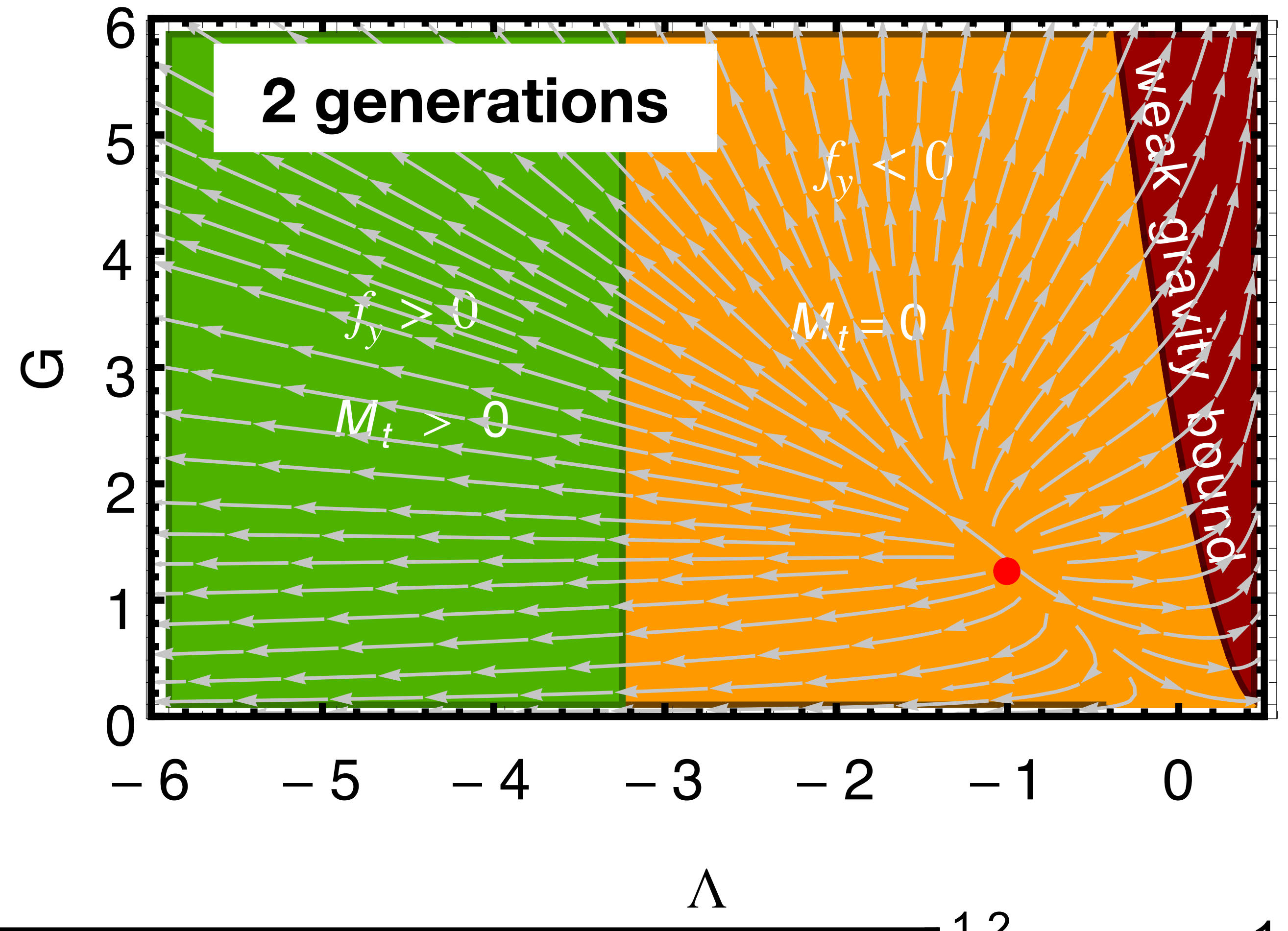

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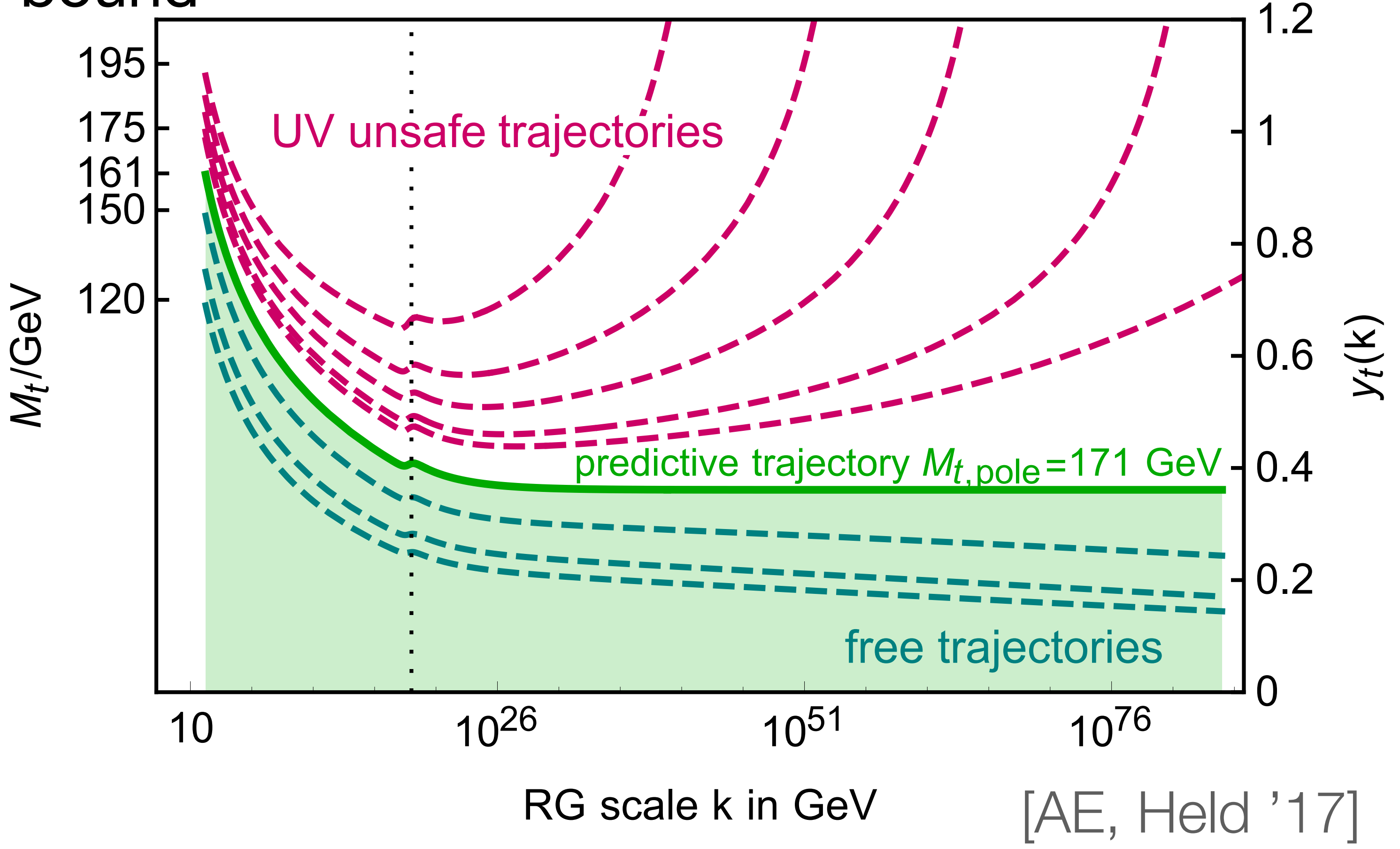

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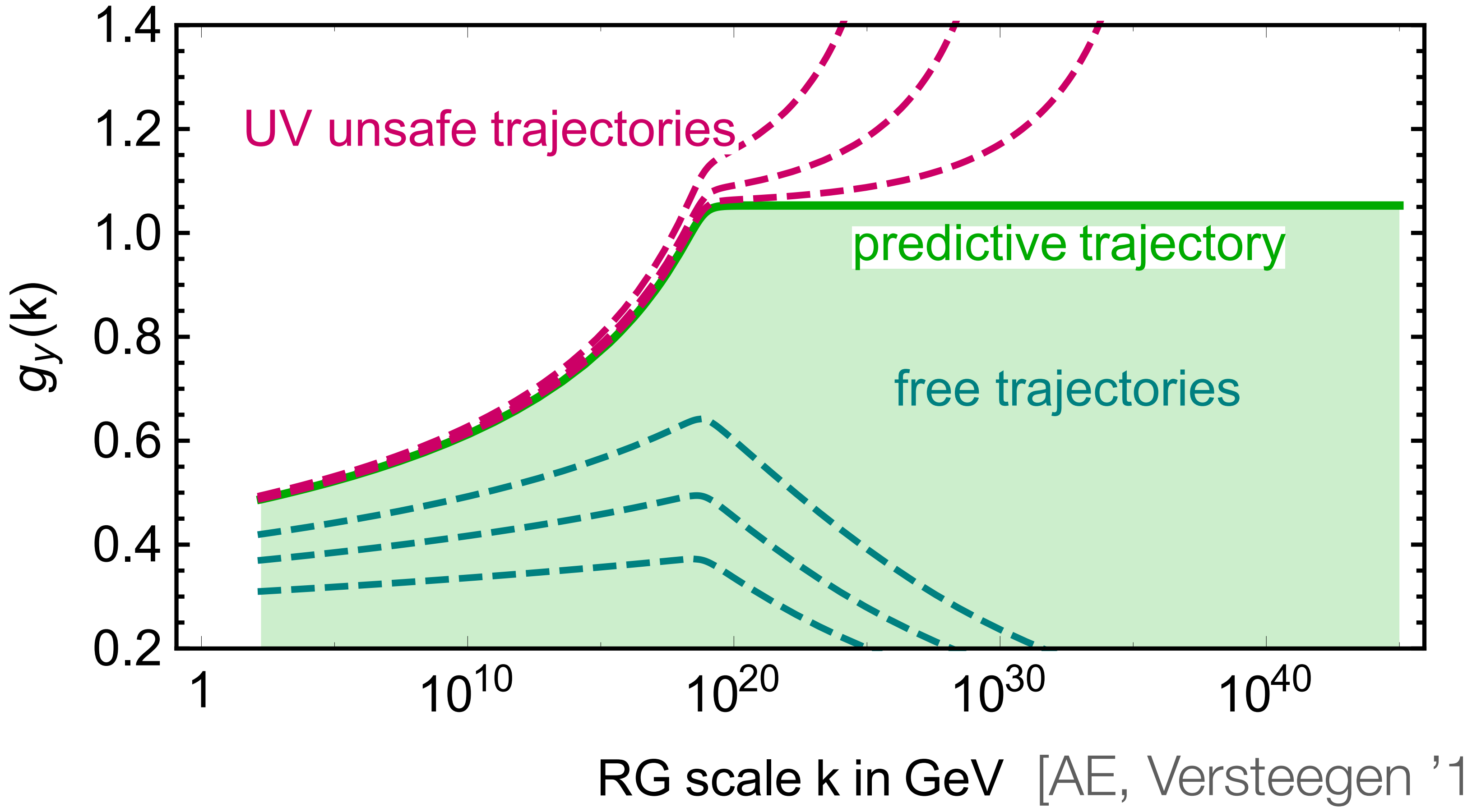

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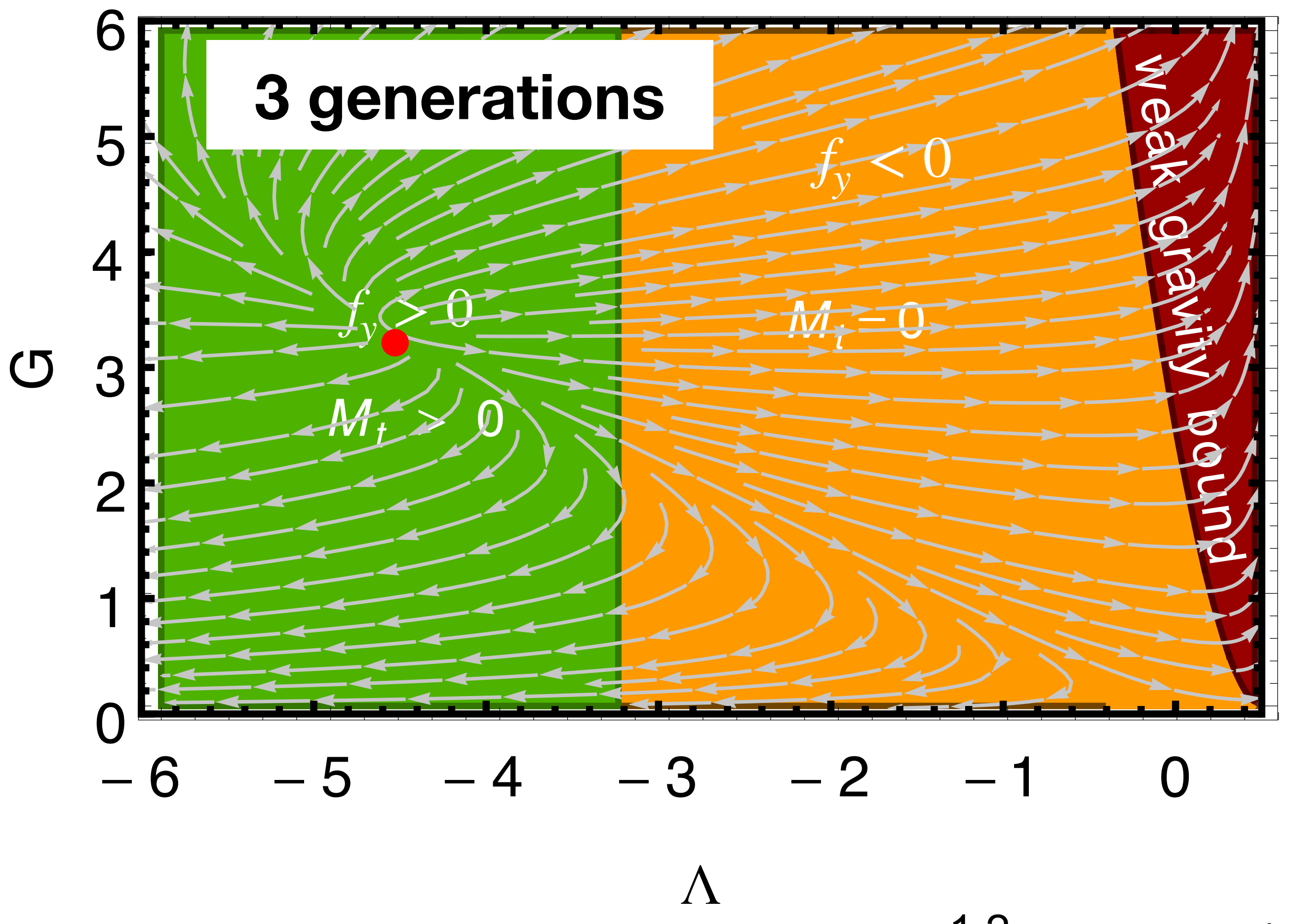

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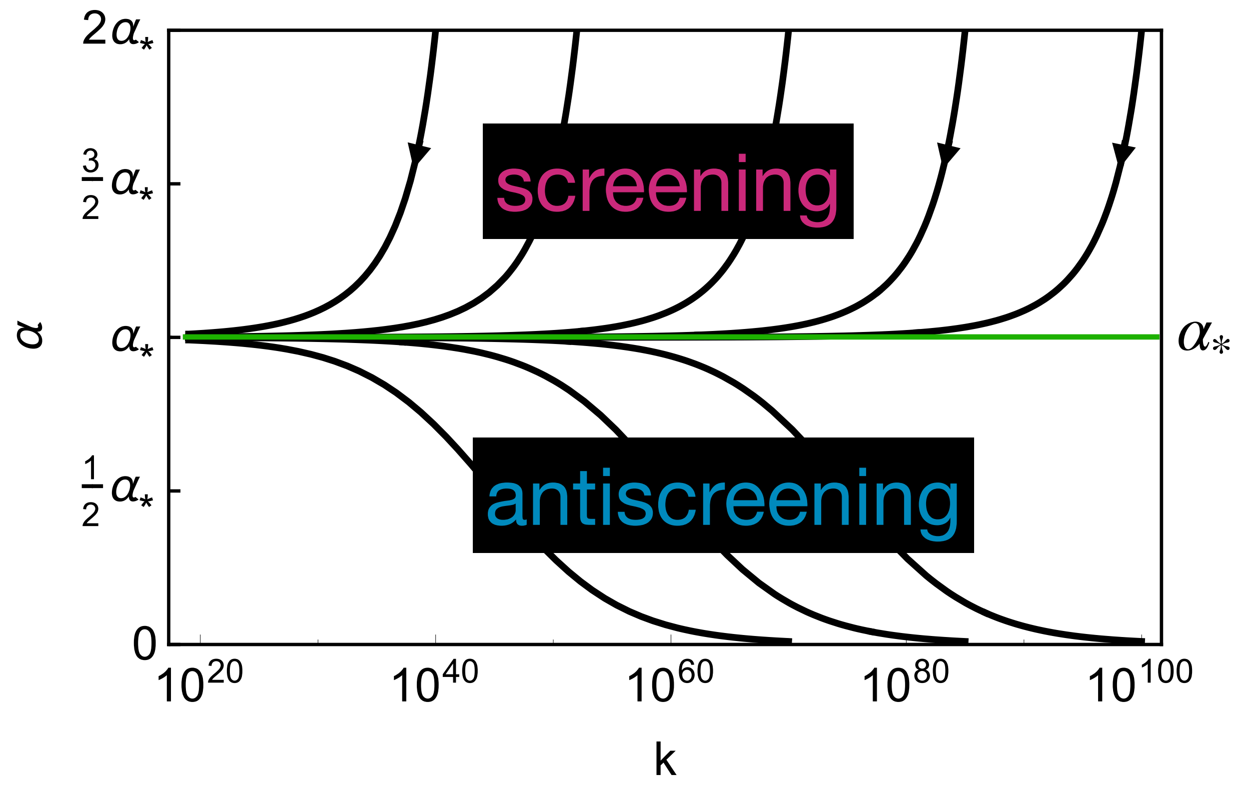

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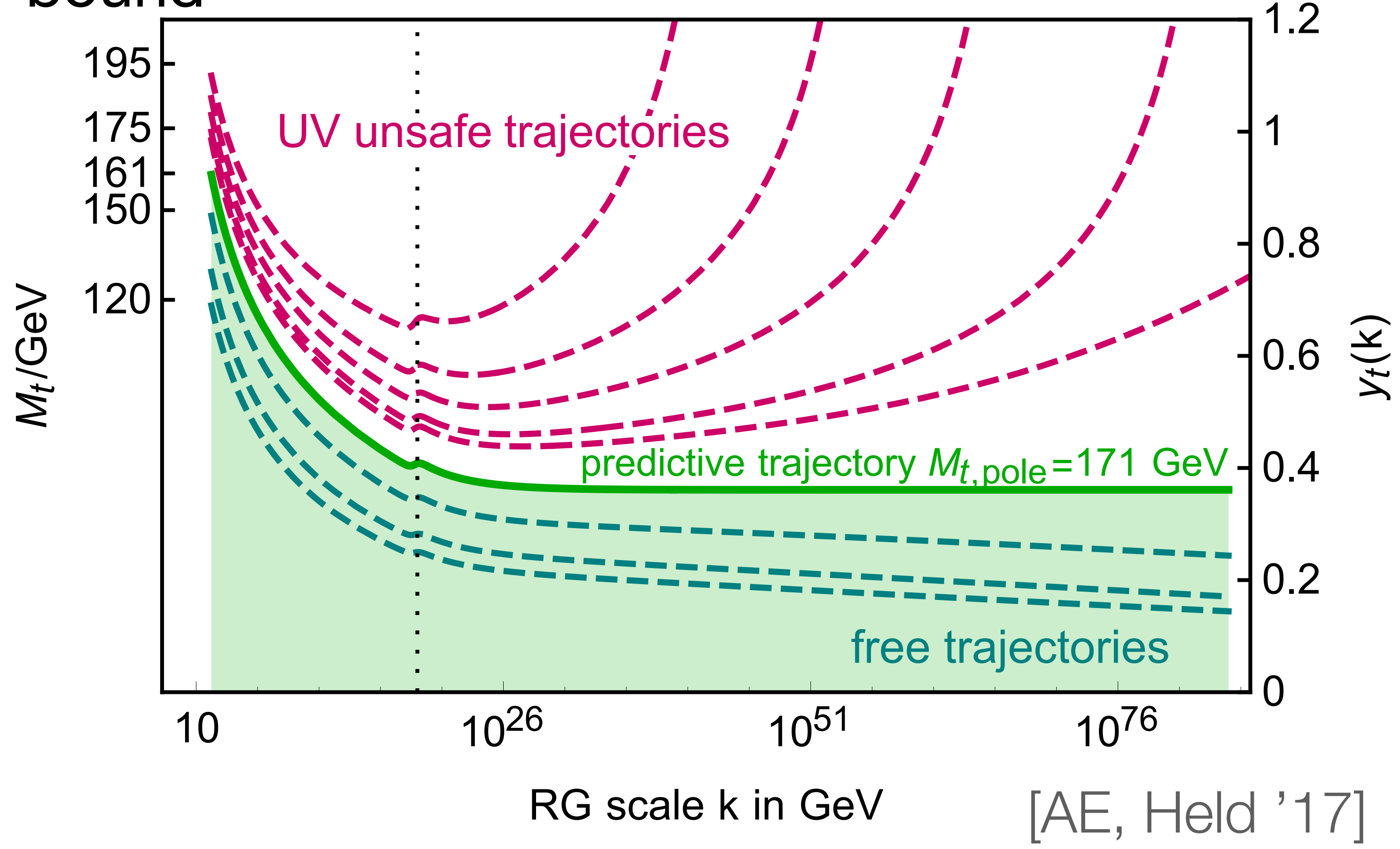

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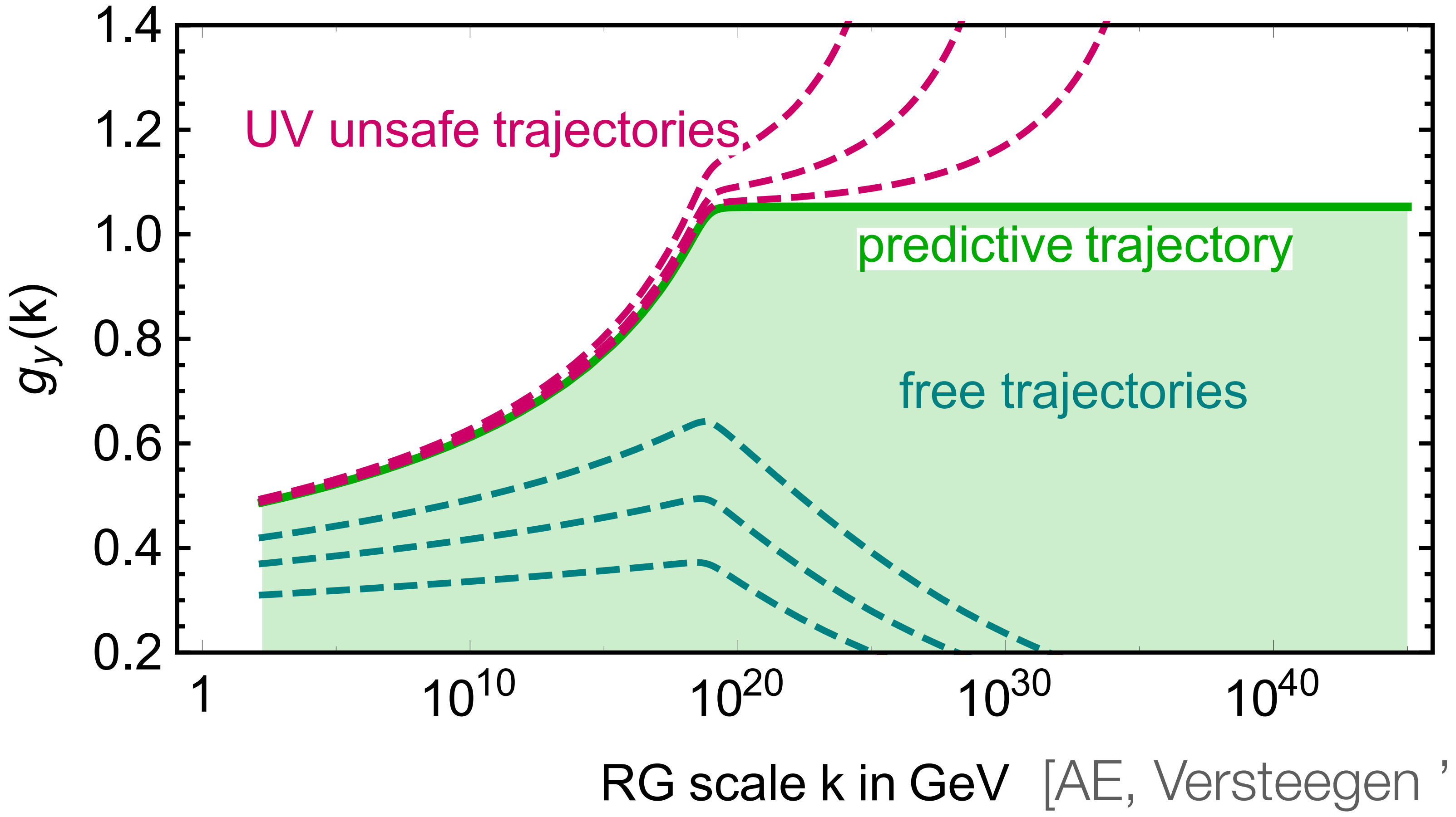

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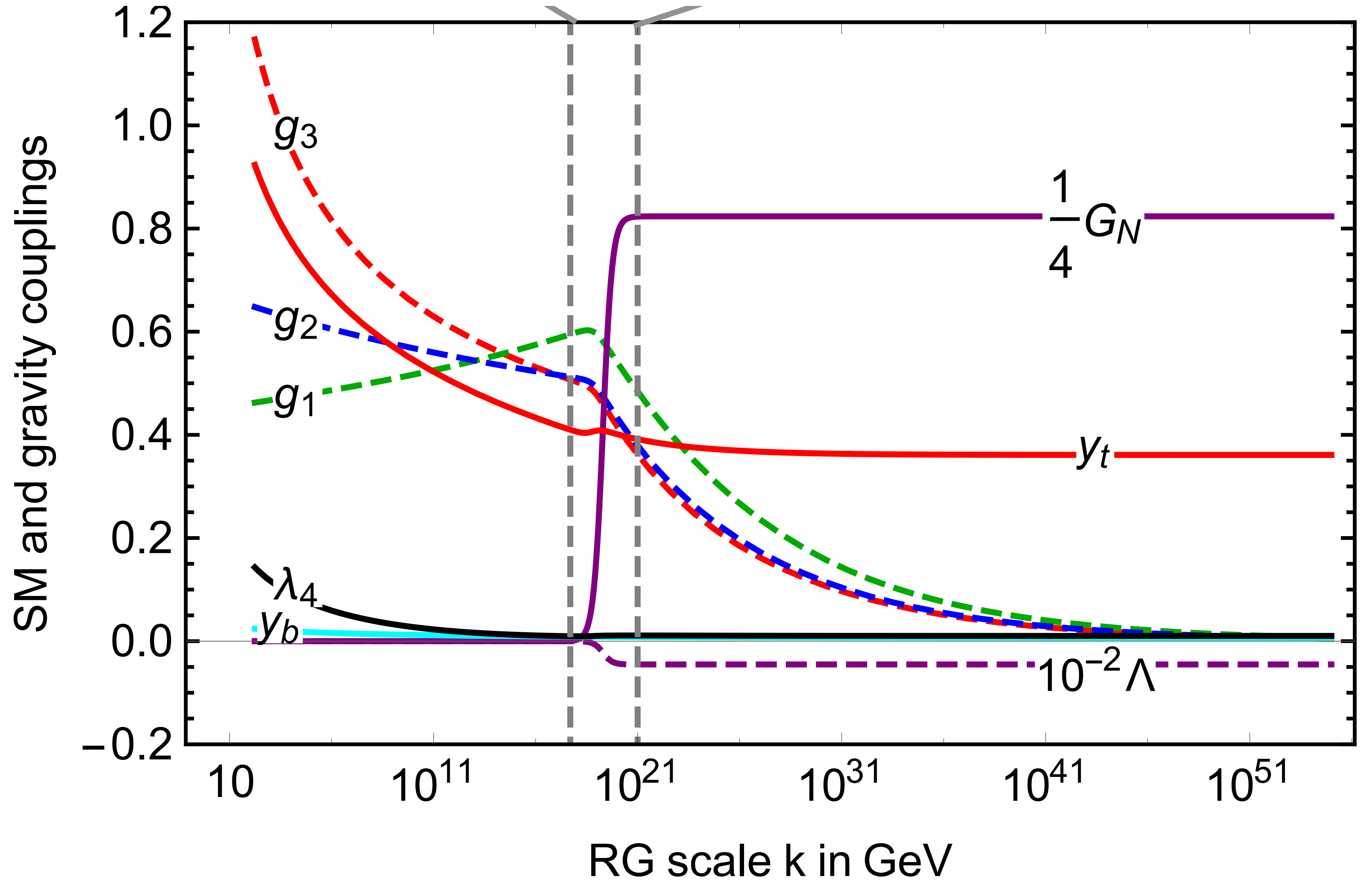
Asymptotically safe Standard Model with gravity



[AE, Held '17,
Alkofer, AE, Held, Percacci, Nieto, Schröfl '19;
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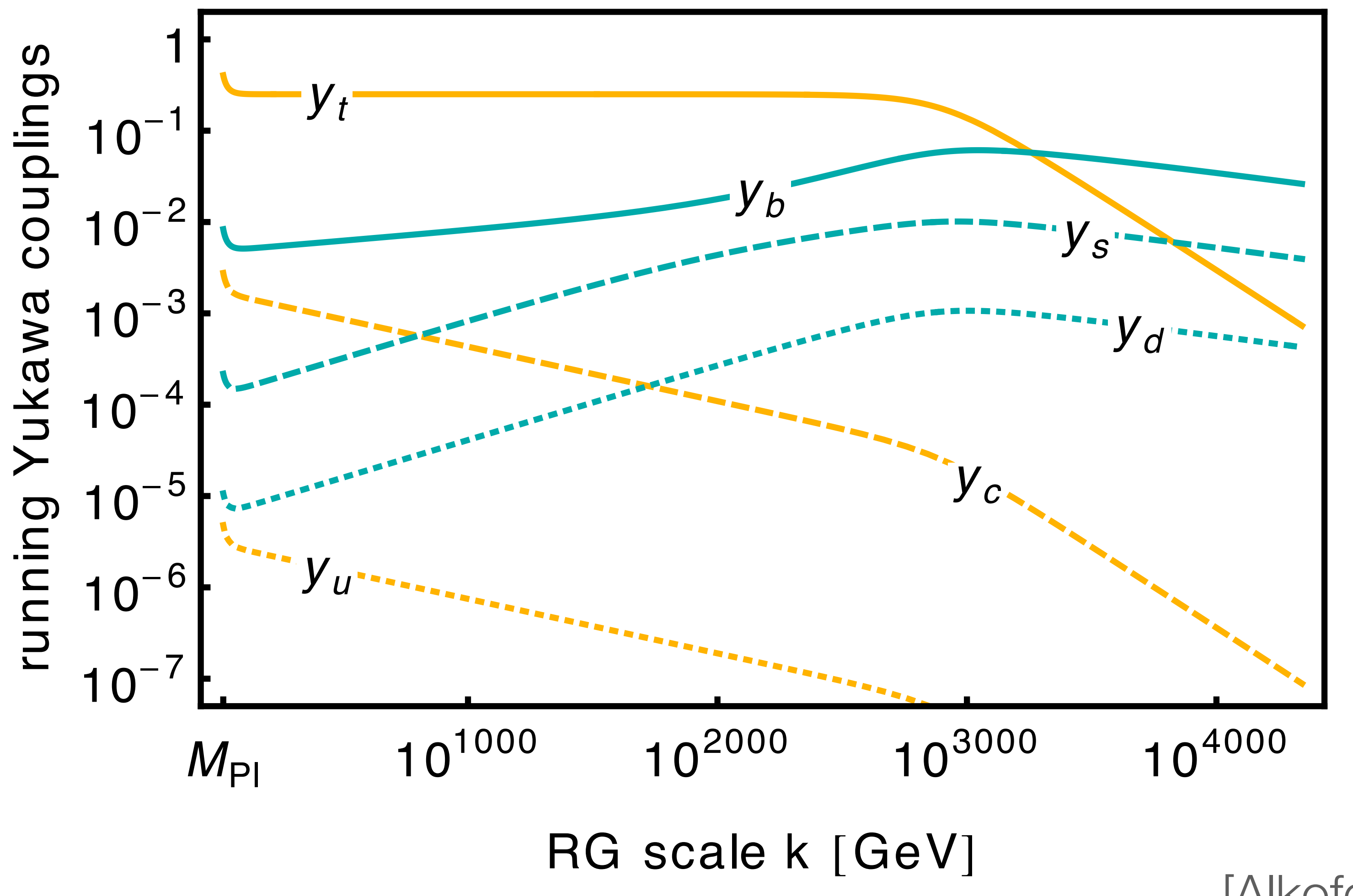

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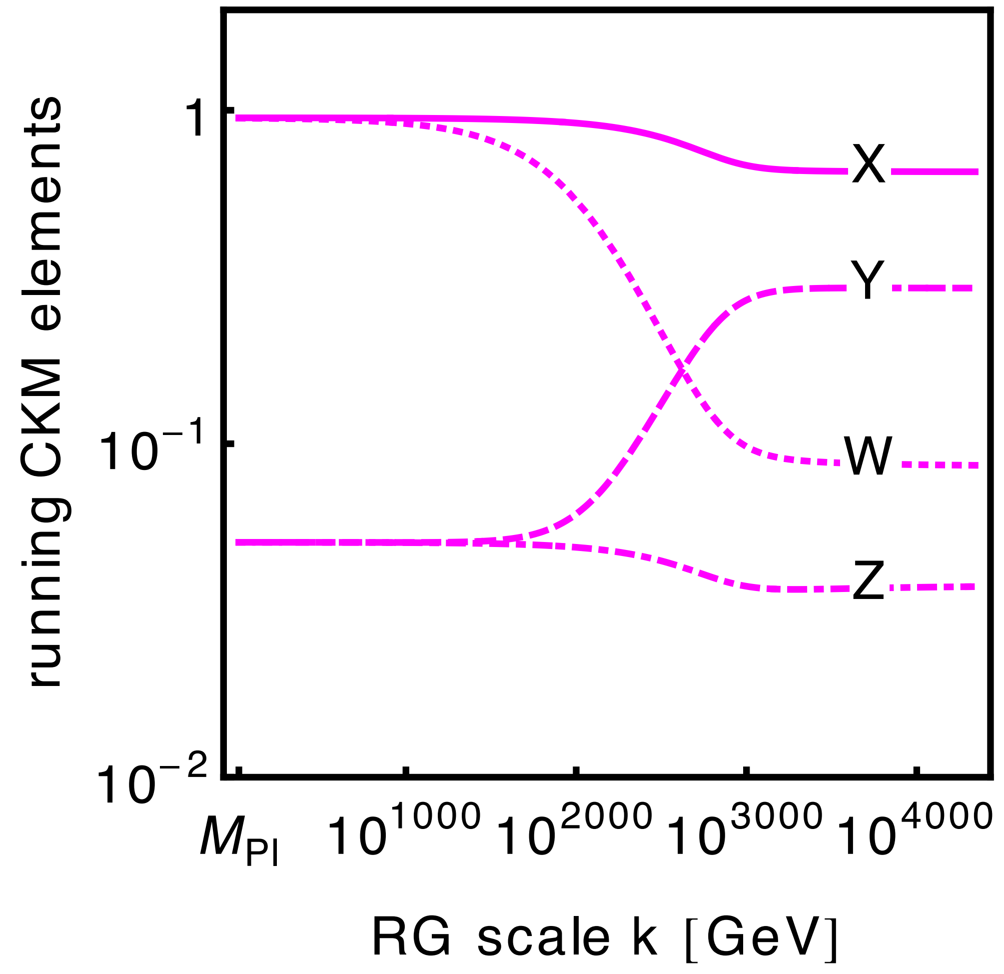

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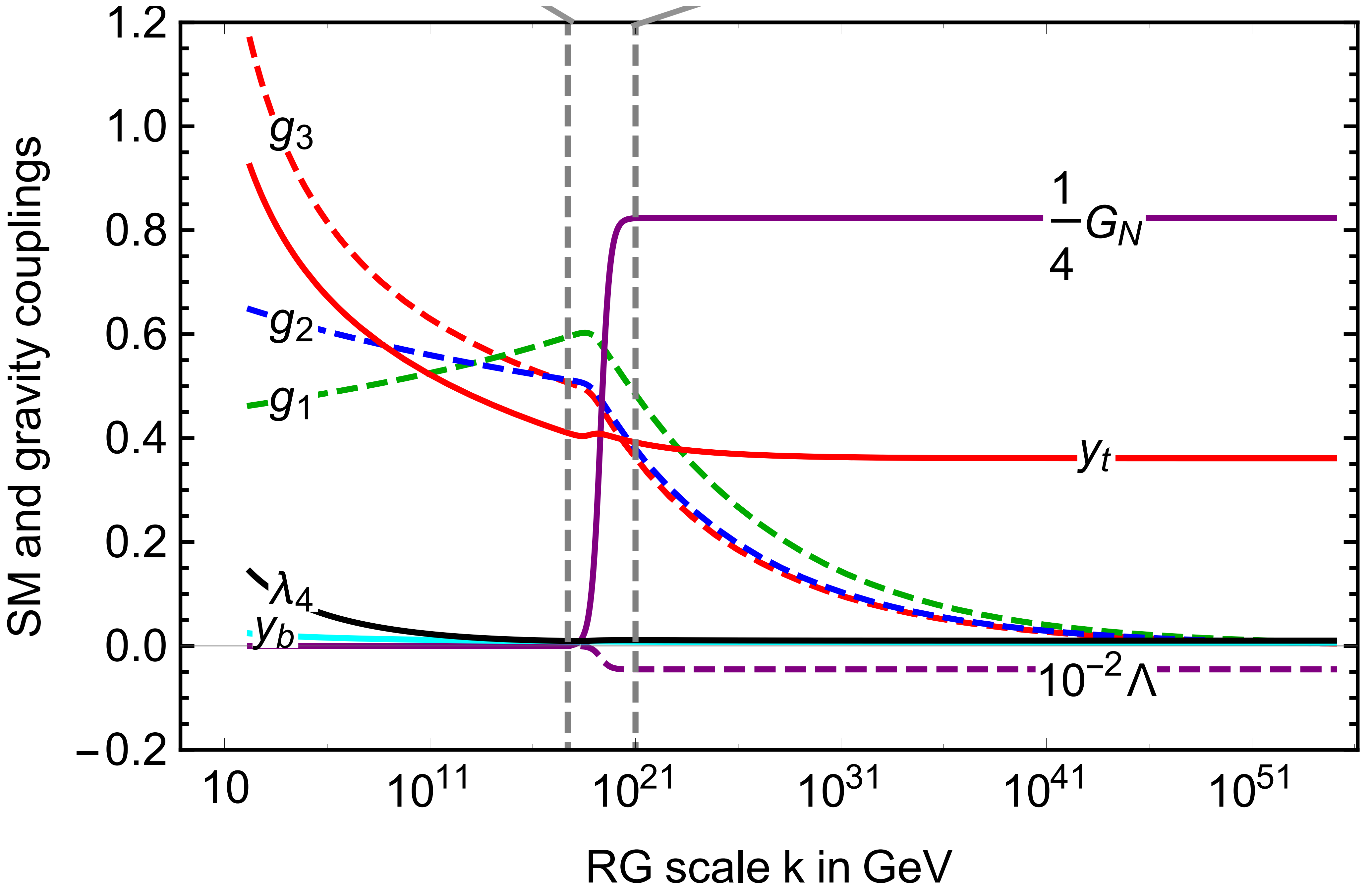

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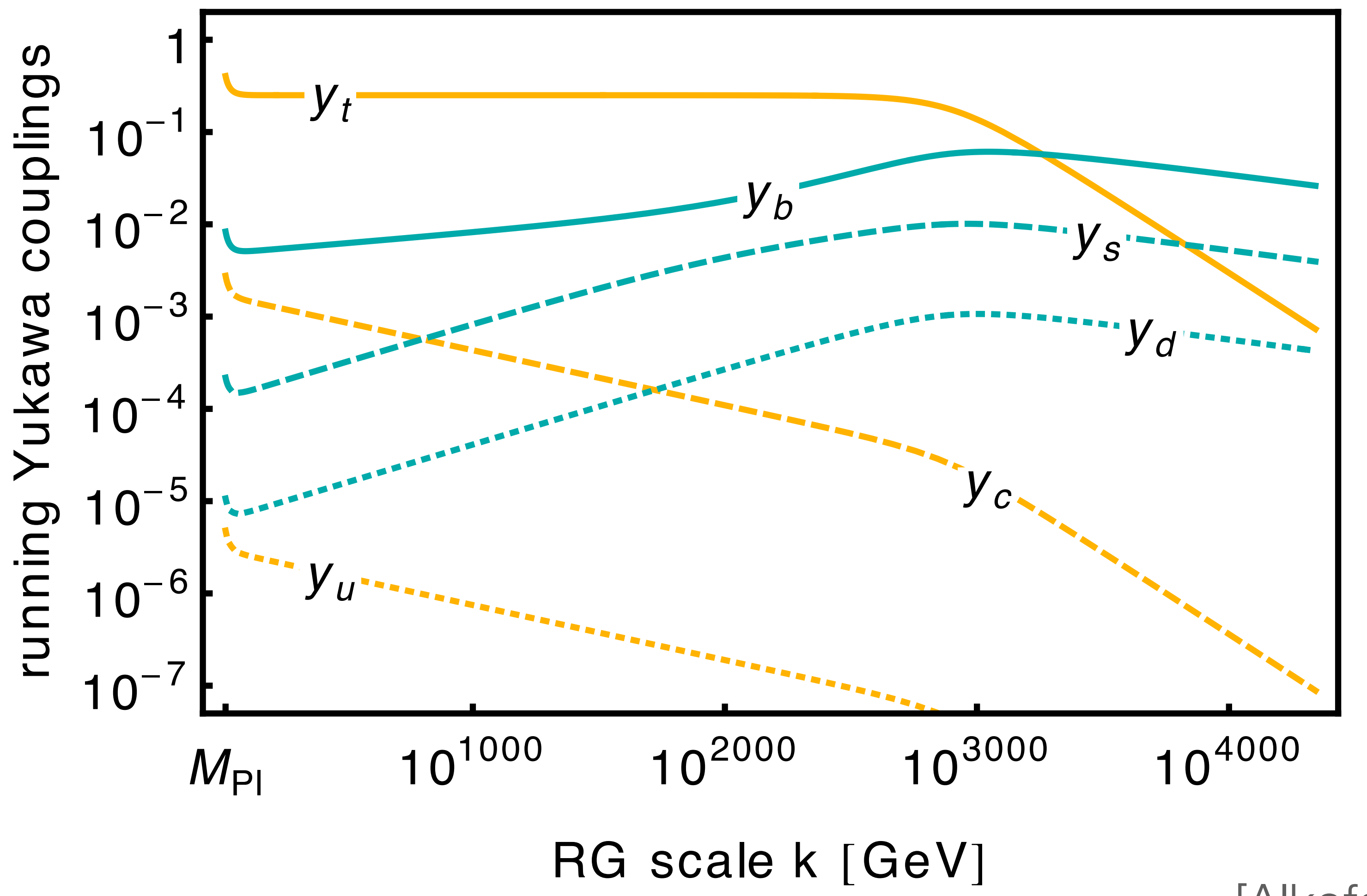

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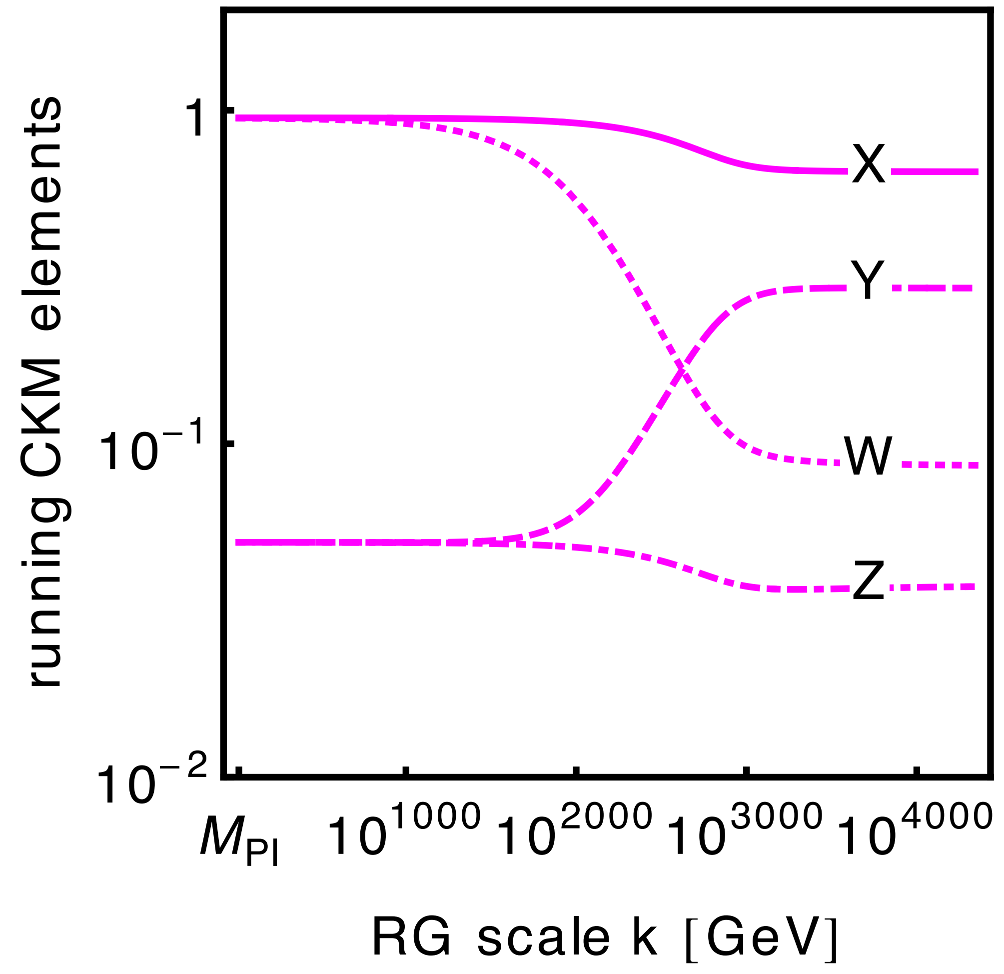
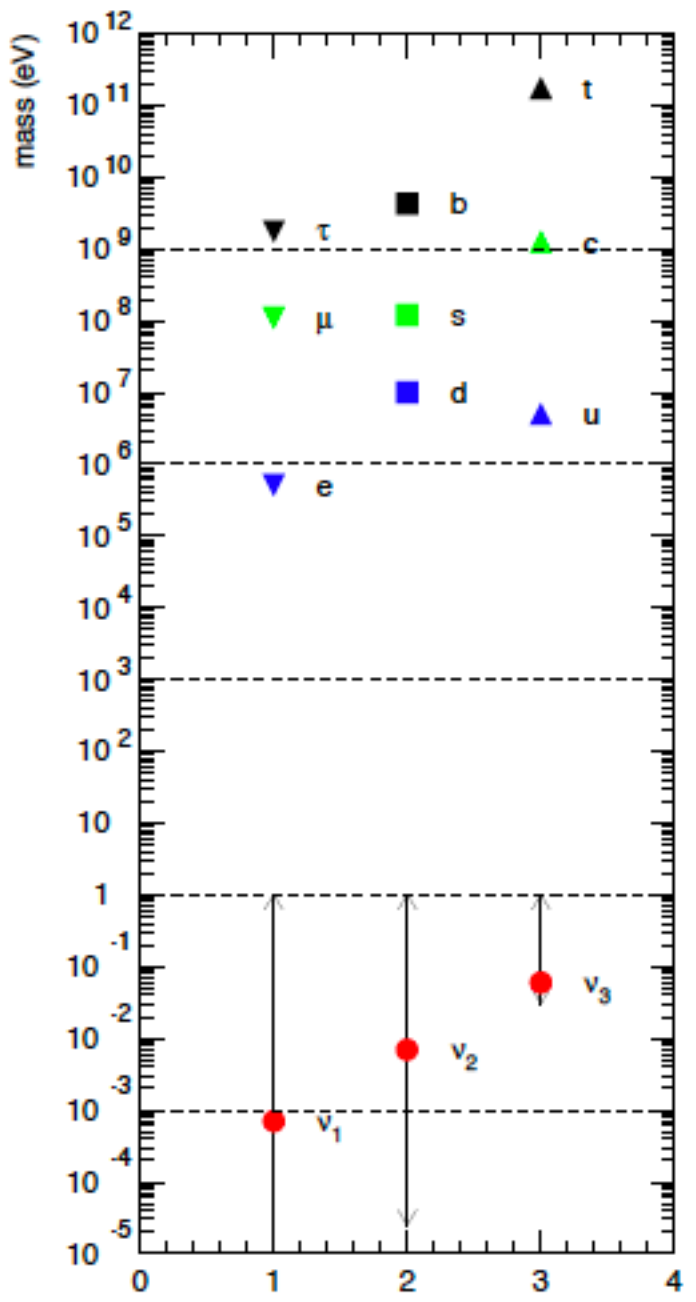


Open questions:

- 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:

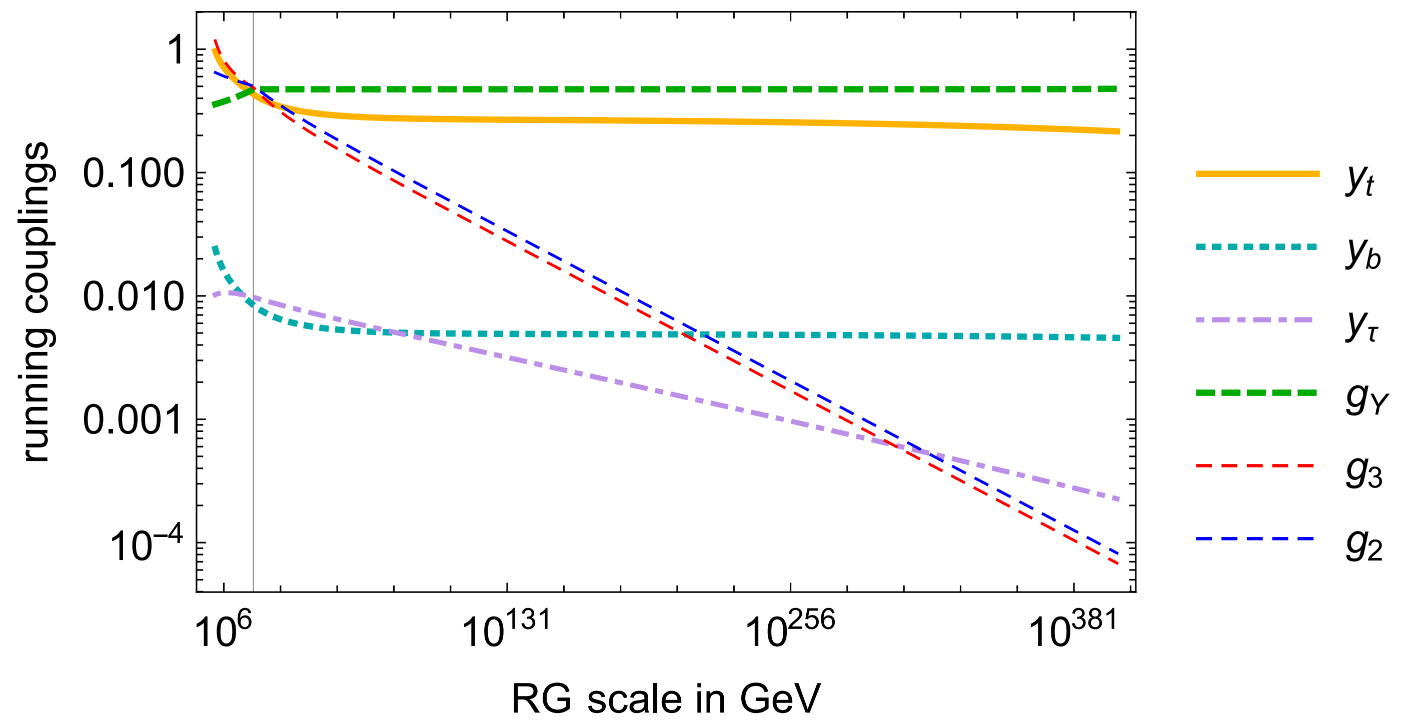
  Weinberg operator is zero and irrelevant; Seesaw-scale (type I) is bounded from above

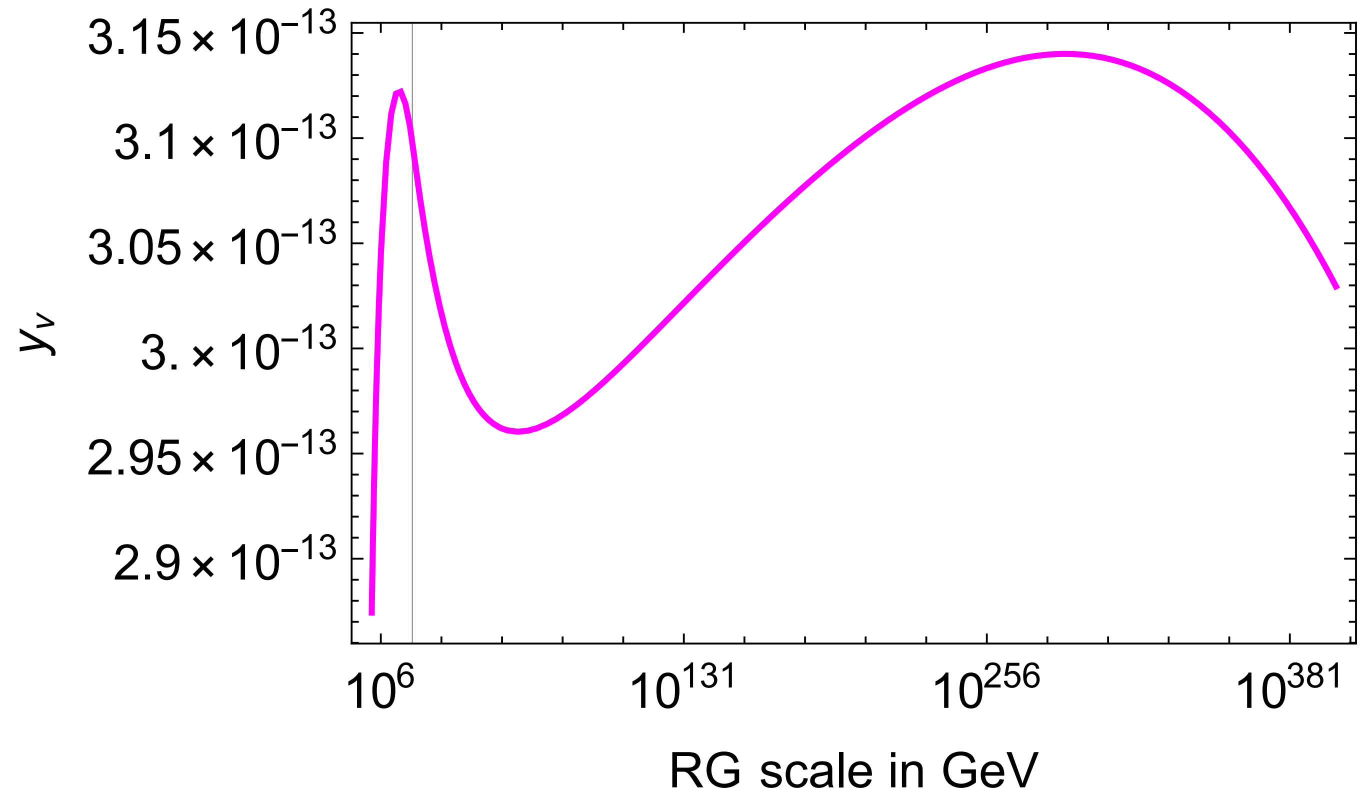
  [work in progress with de Brito, Pereira, Yamada]

- Option 2:

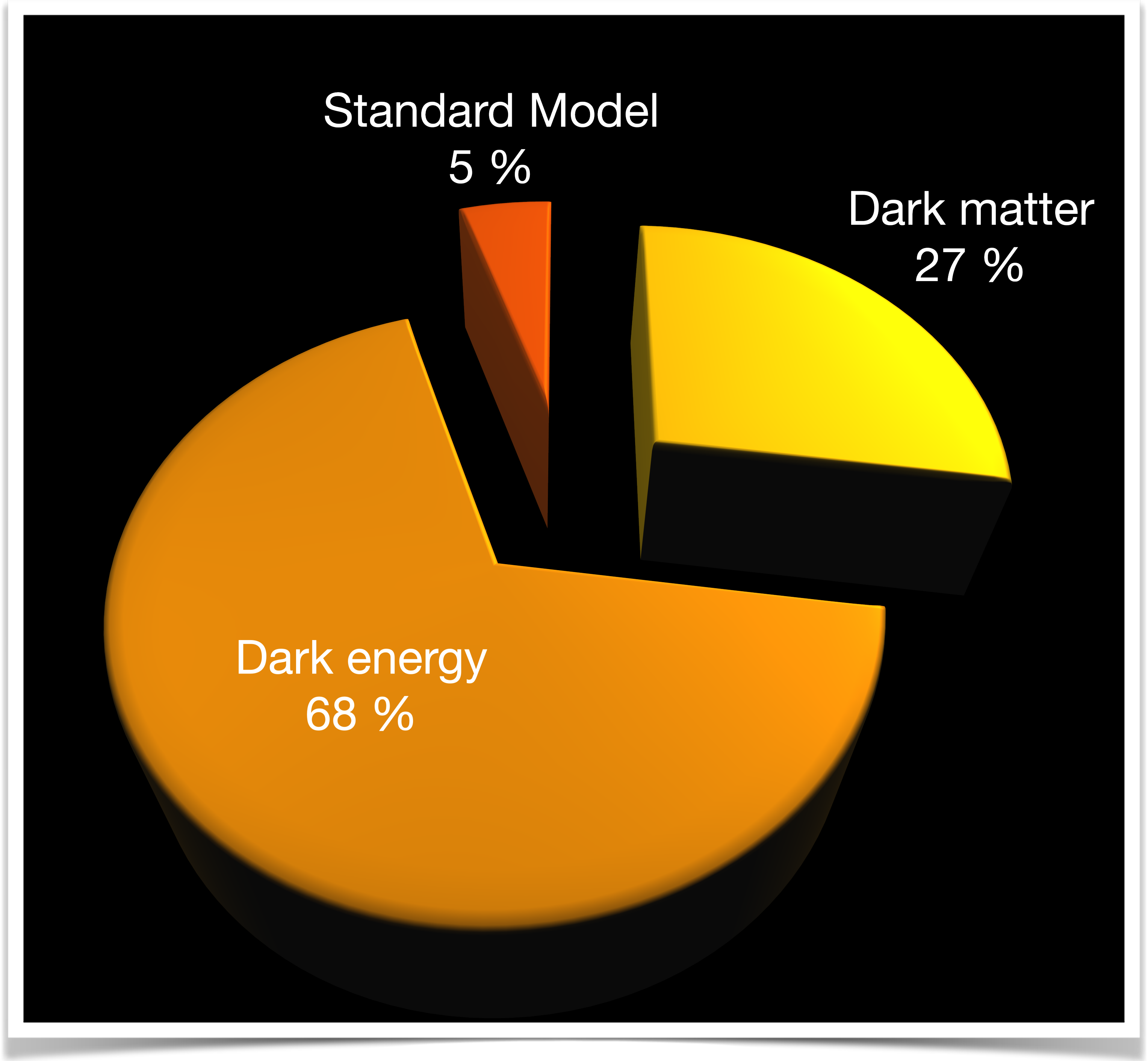
  neutrino masses arise through the Higgs mechanism with a very small Yukawa coupling

  [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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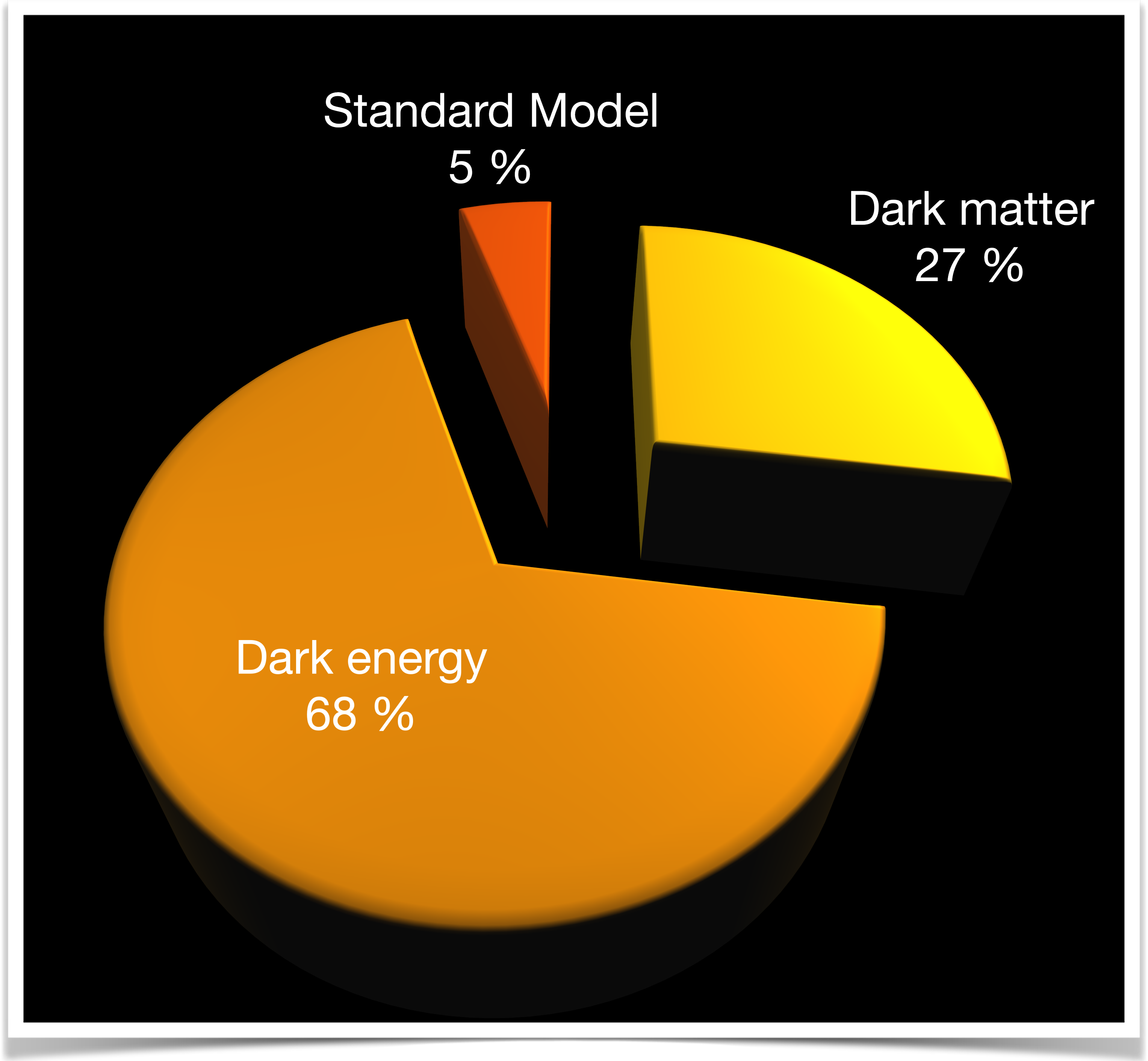

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Example: simplest Horndeski theory of dark energy

combine phenomenological constraints and asymptotic-safety-condition

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

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

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

[Horndeski '74]

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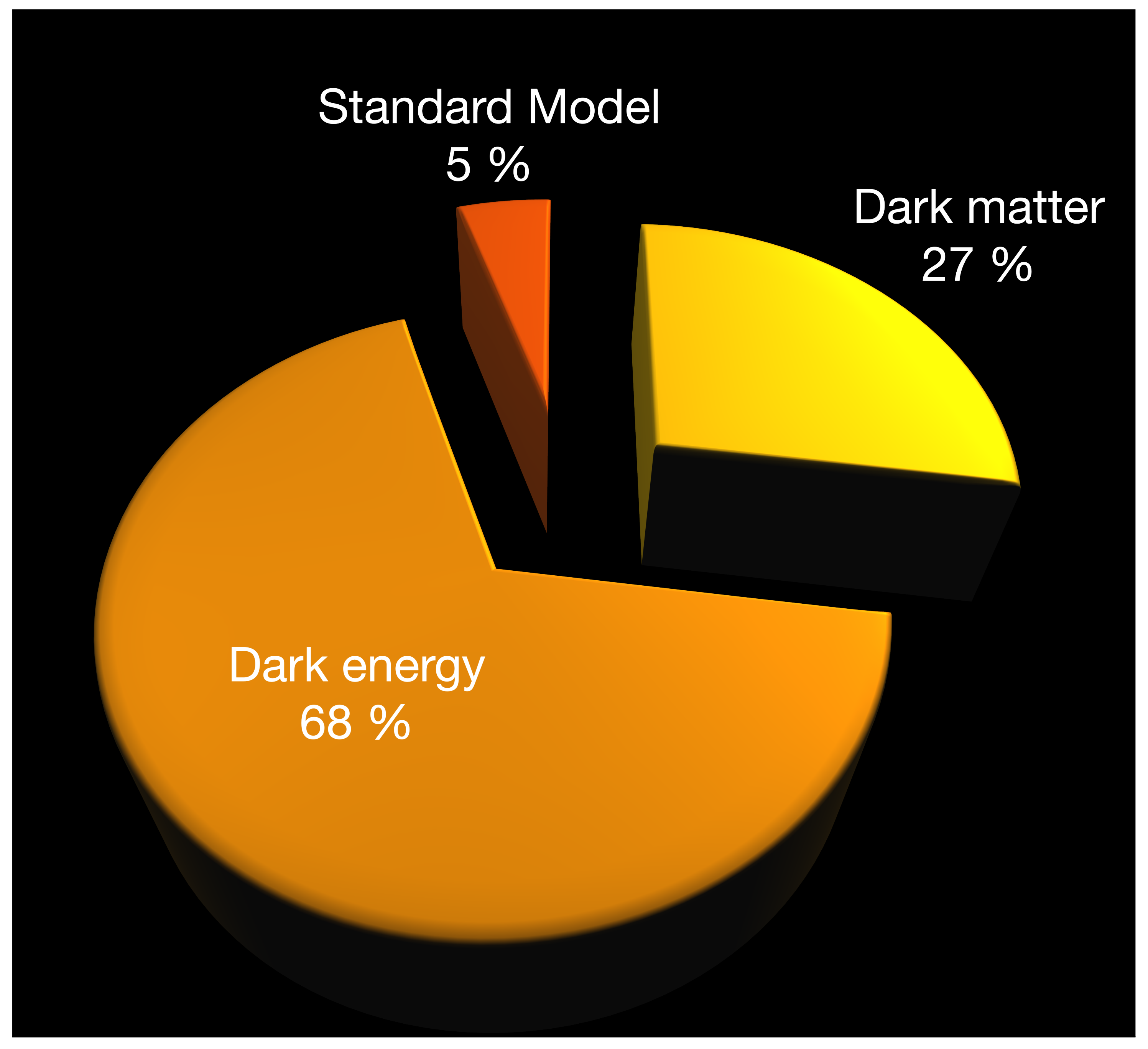

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nearly excluded by GW170817 [Creminelli, Vernizzi '17; Ezquiaga, Zumalacárregui '17; Sakstein, Jain '17; Baker et al. '17…]

[Horndeski '74]

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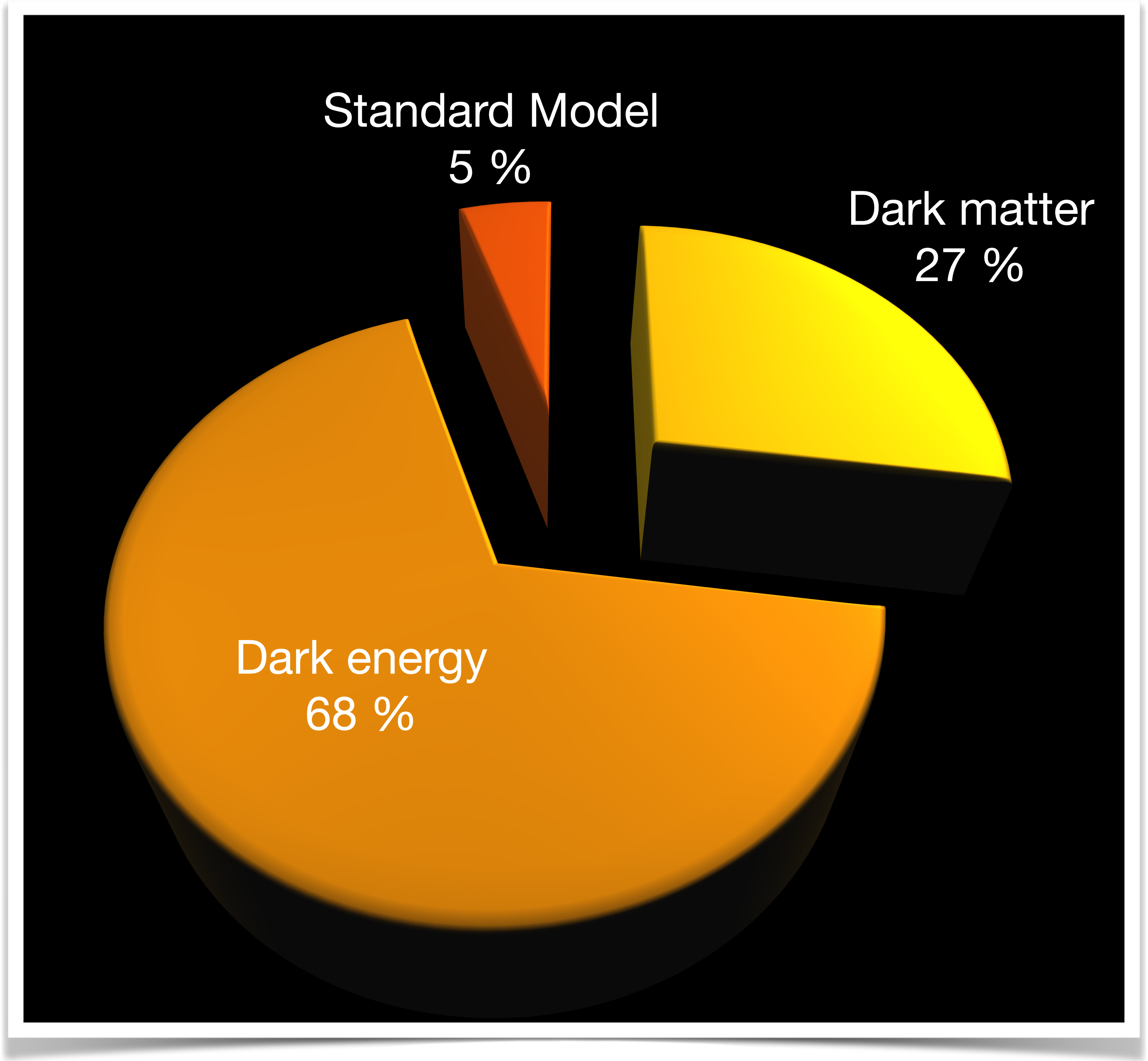

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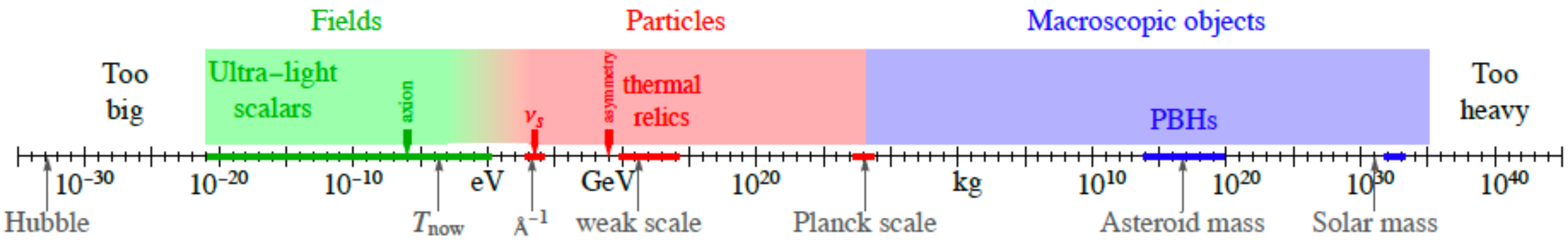
$$\Gamma_k = \int d^4x\sqrt{\det g_{\mu\nu}}\left[-\frac{1}{16\pi\bar{G}}\left(R - 2\bar{\Lambda}\right) - Z_\phi\chi - \bar{h}\chi D^2\phi + \bar{g}\chi^2\right]$$

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

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

Asymptotic safety and dark matter



[cf. lectures by Marco Cirelli]

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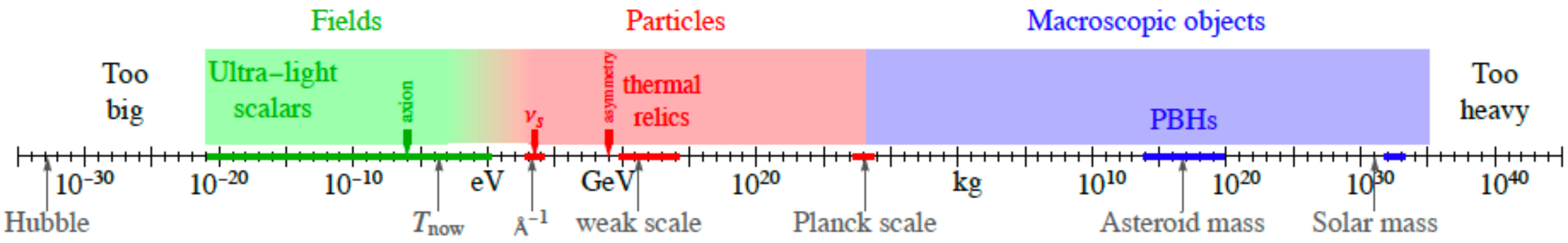

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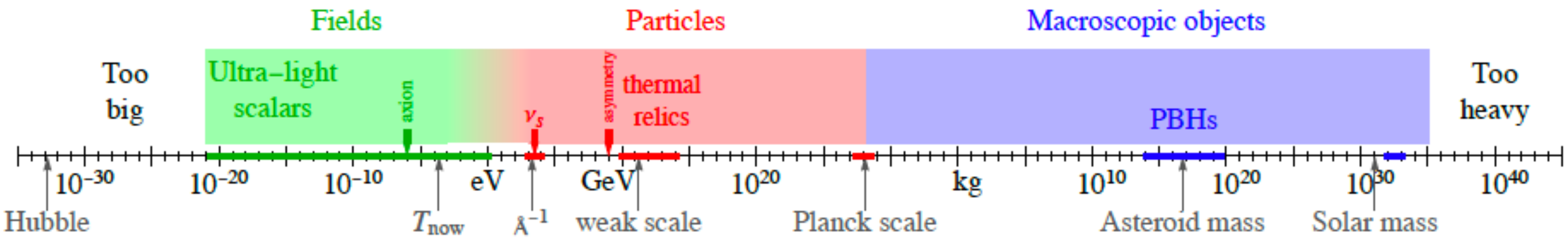
Asymptotic safety and dark matter



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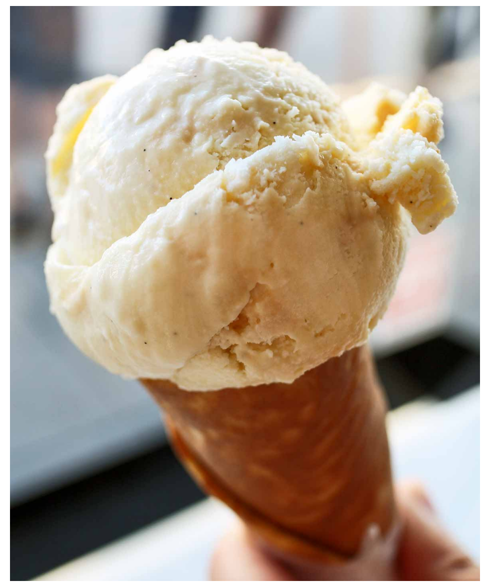


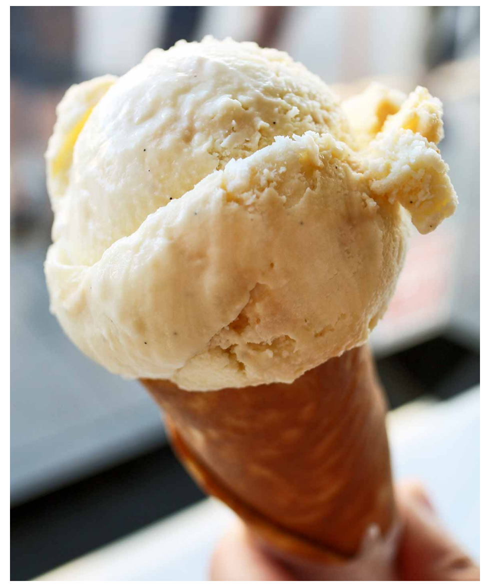
Thermal WIMP: Dark scalar with Higgs portal

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

→ production in the early universe

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

Asymptotic safety and dark matter



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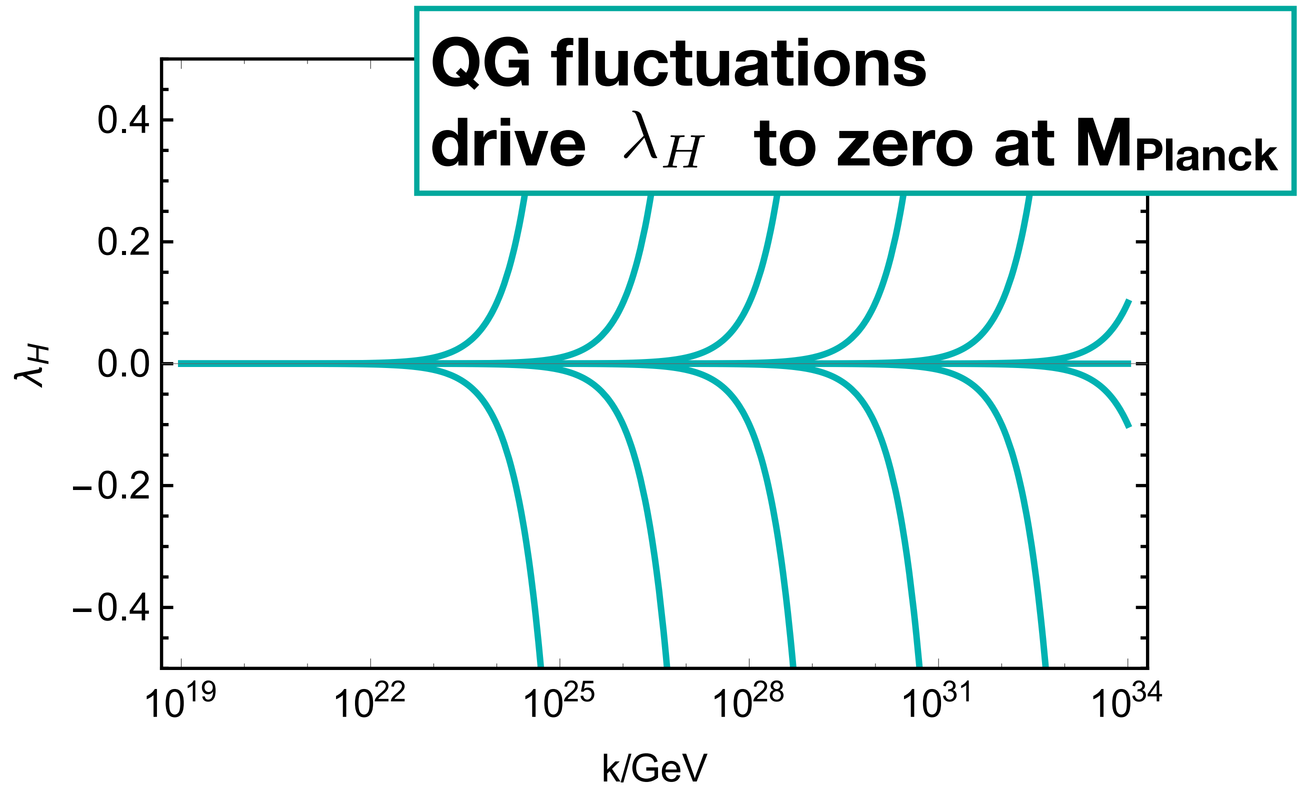

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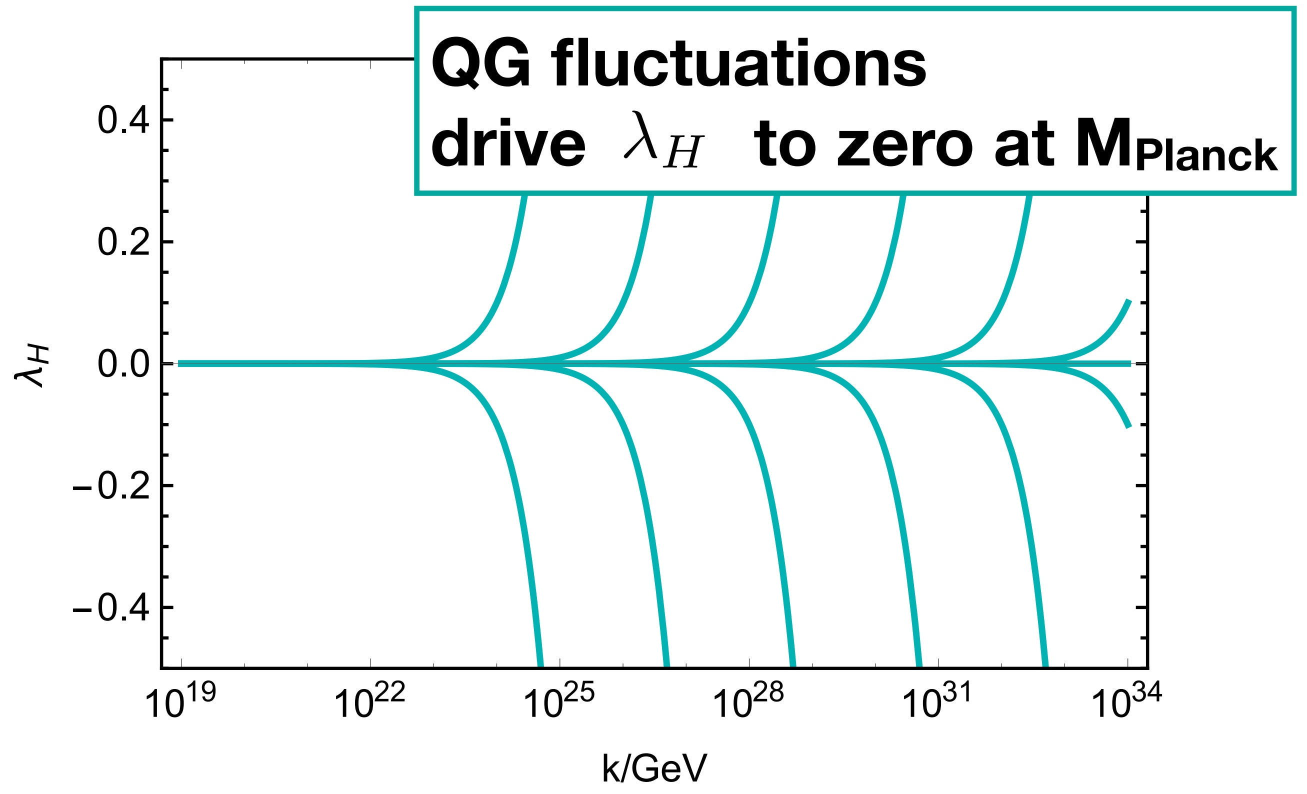

→ single dark scalar decouples in asymptotic safety

[AE, Hamada, Lumma, Yamada ‘17]

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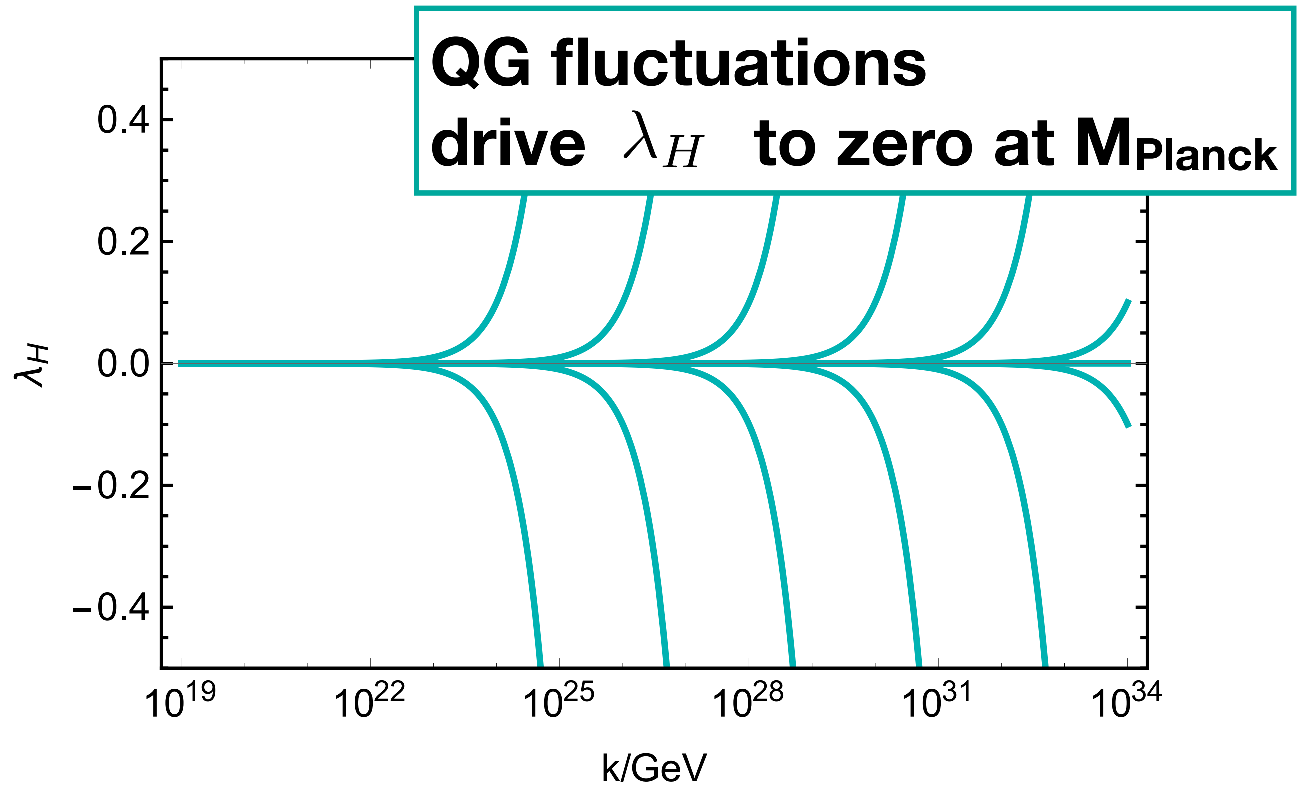

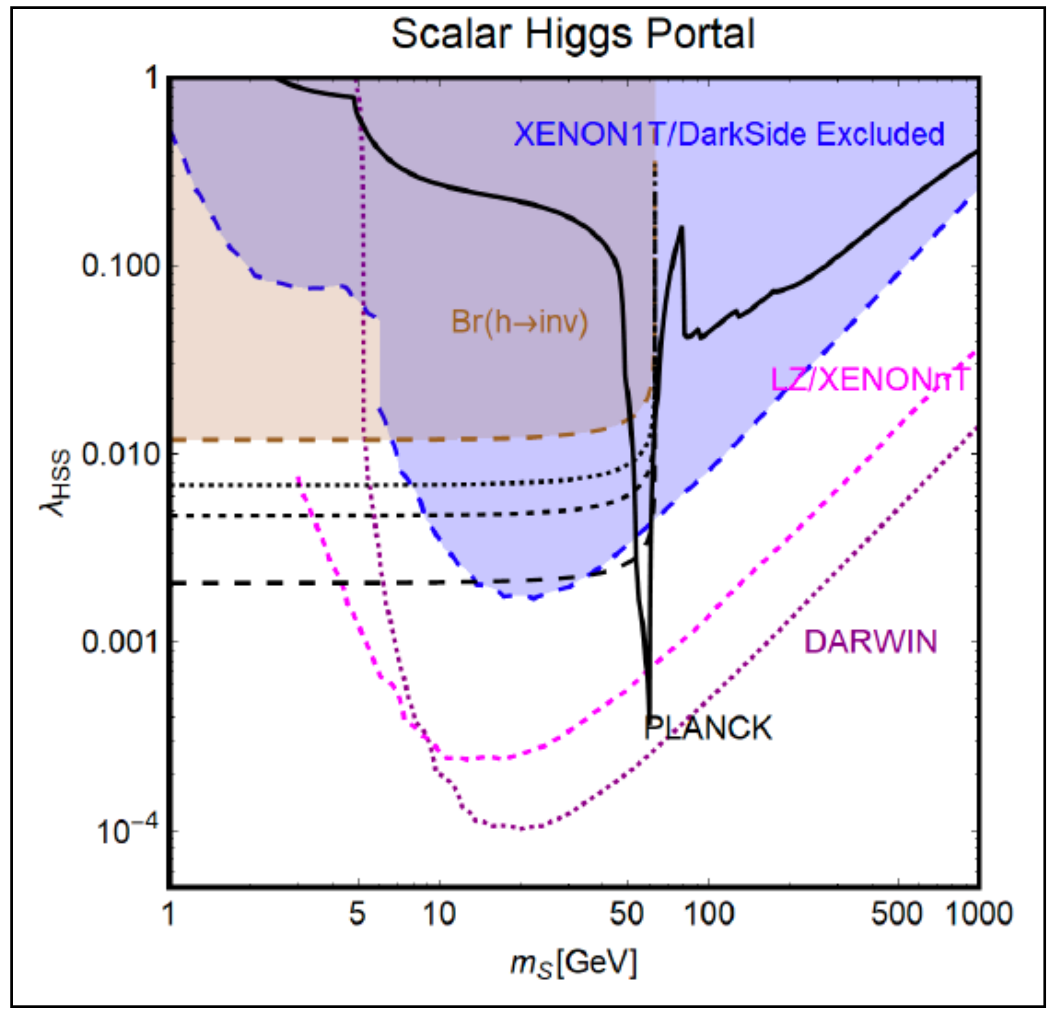

[Arcadi et al '19]

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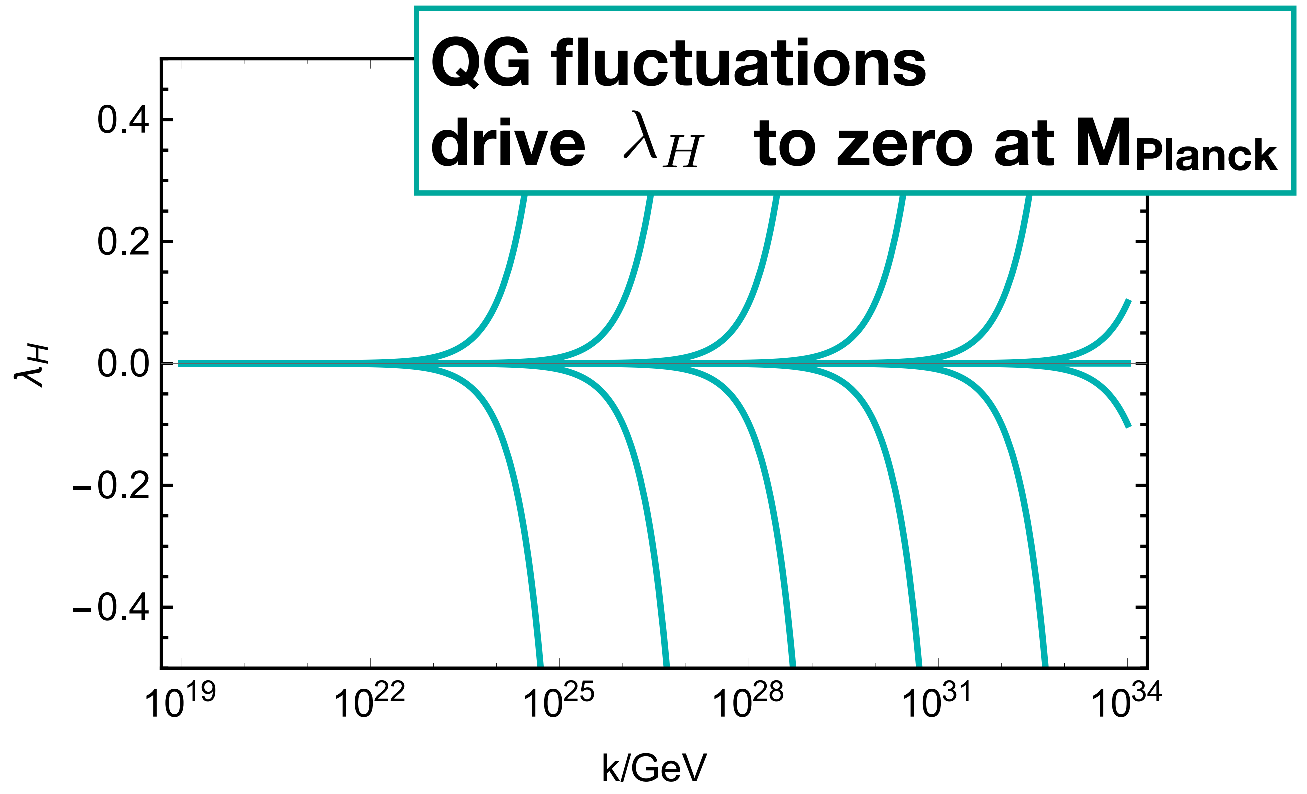

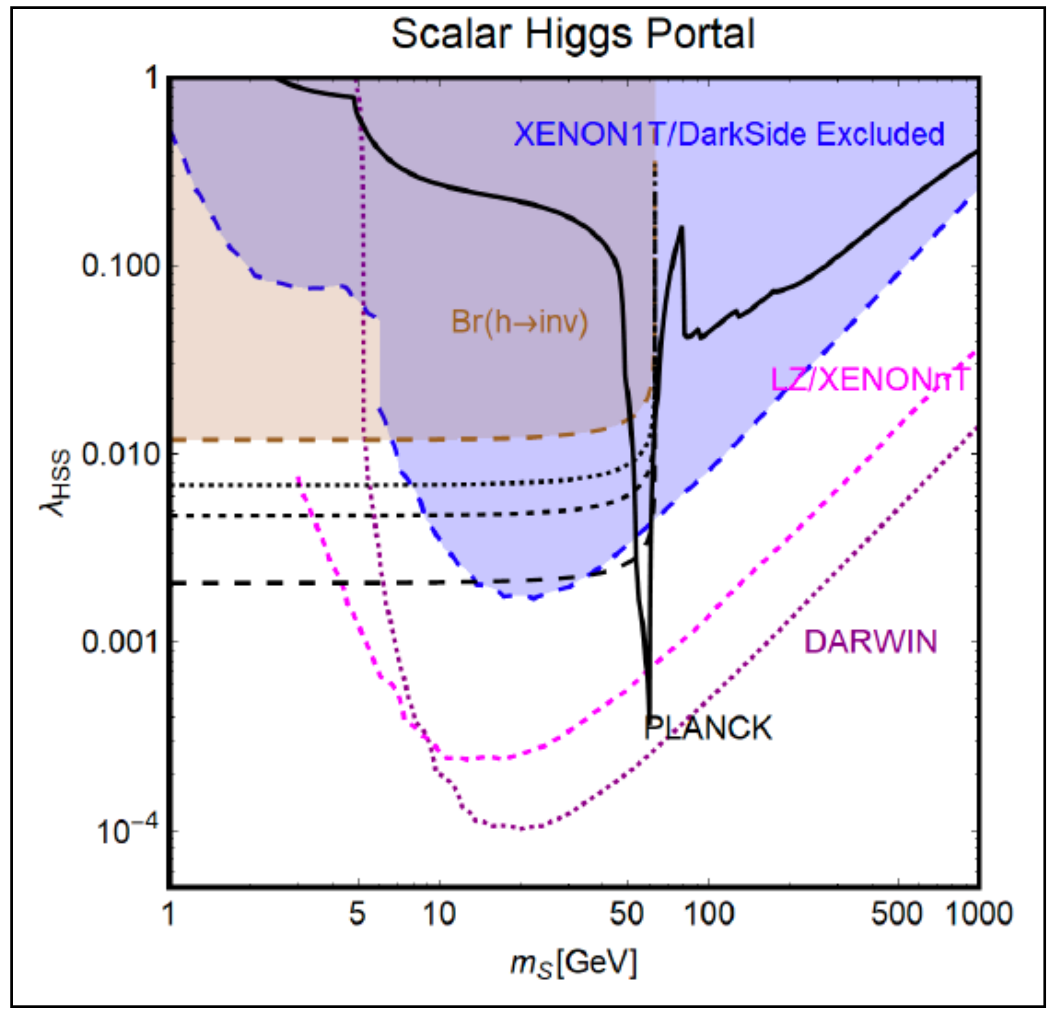

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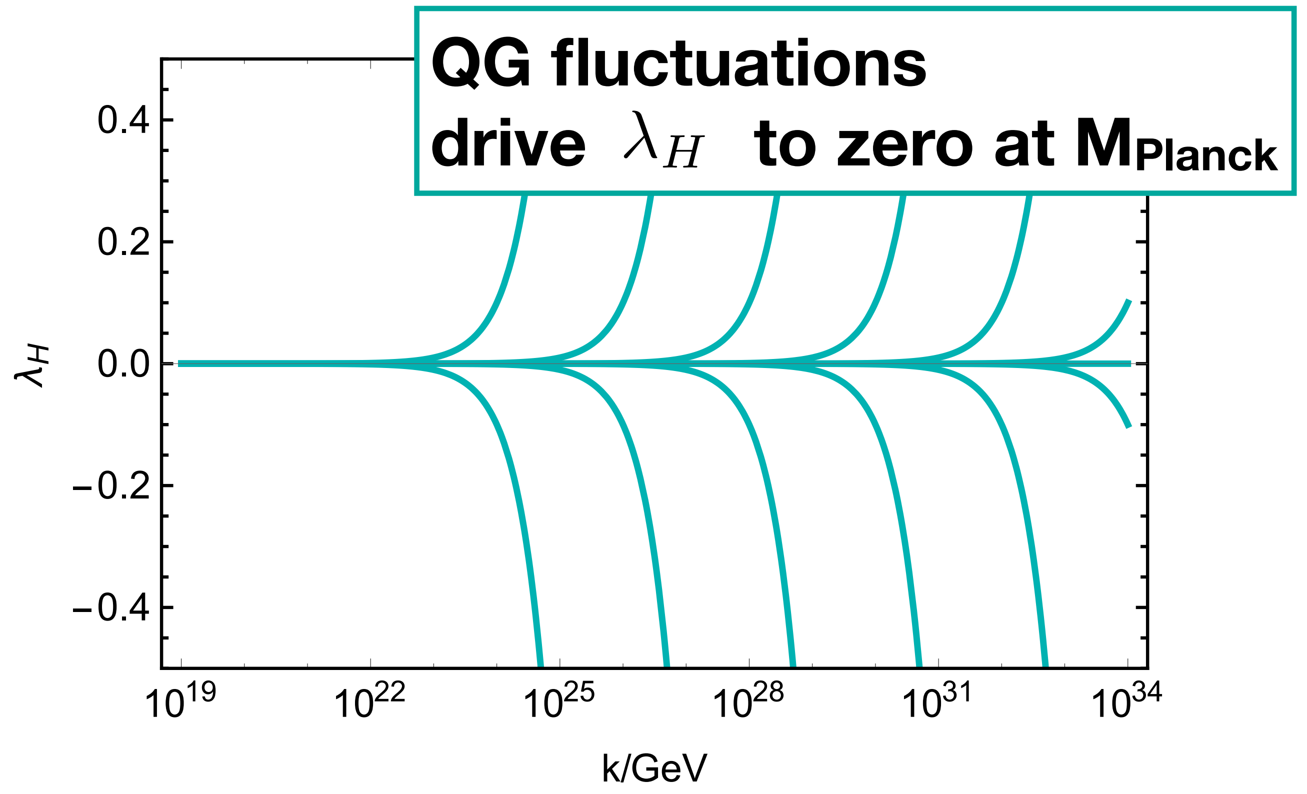

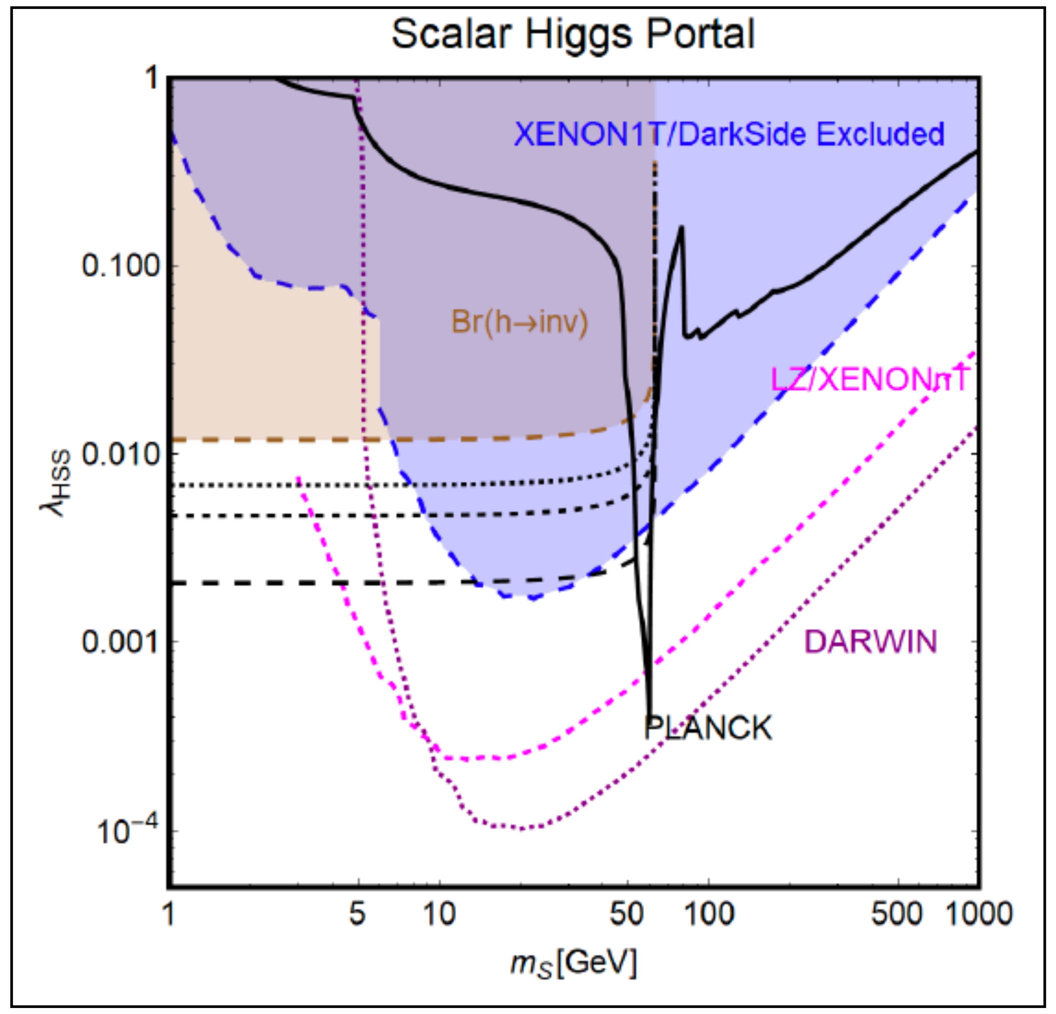

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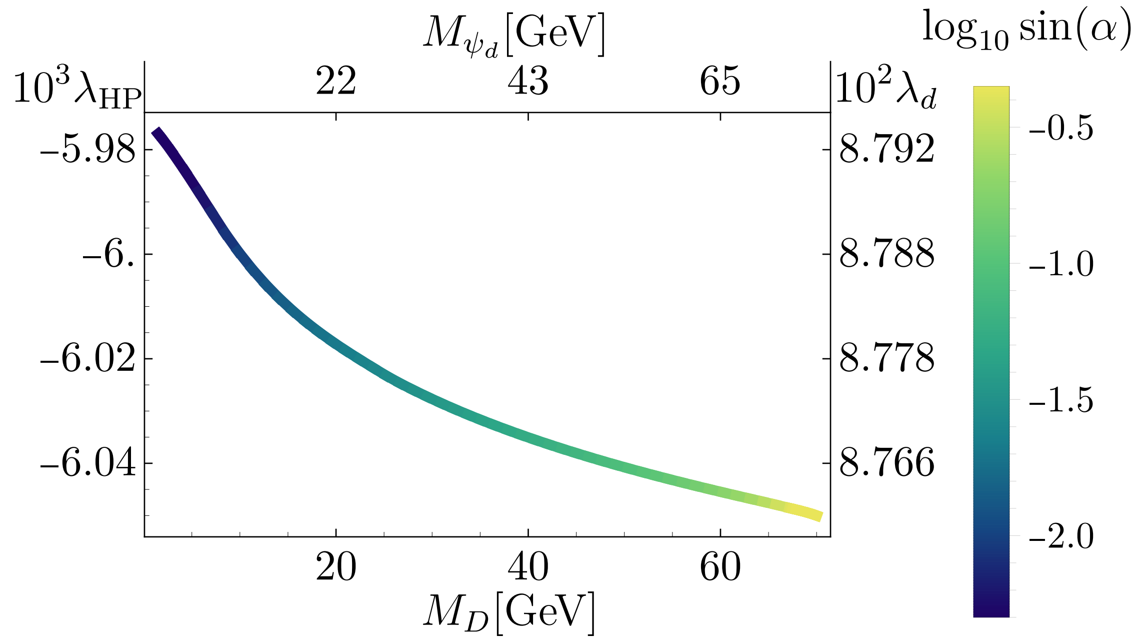
Extended thermal WIMP sectors with Higgs-portal

- 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 $U(1)_{\rm dark}$-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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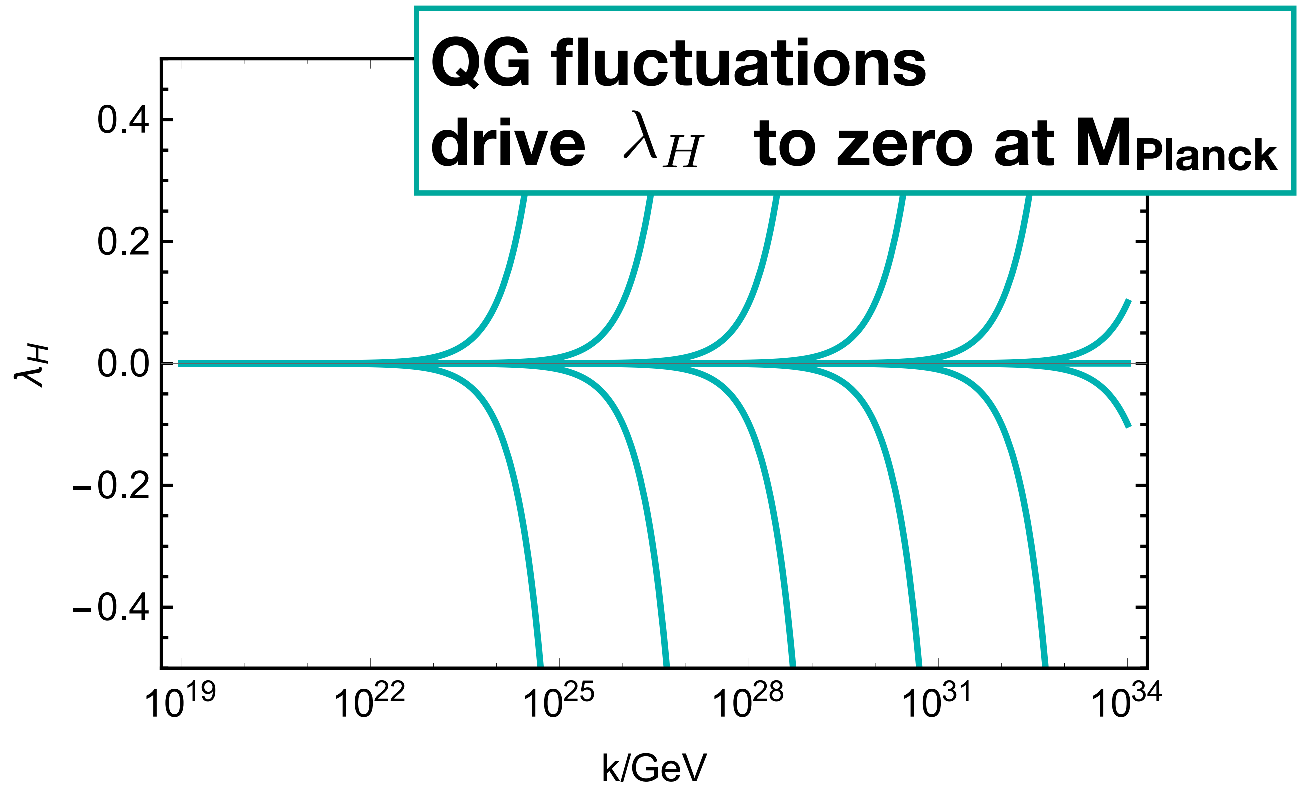

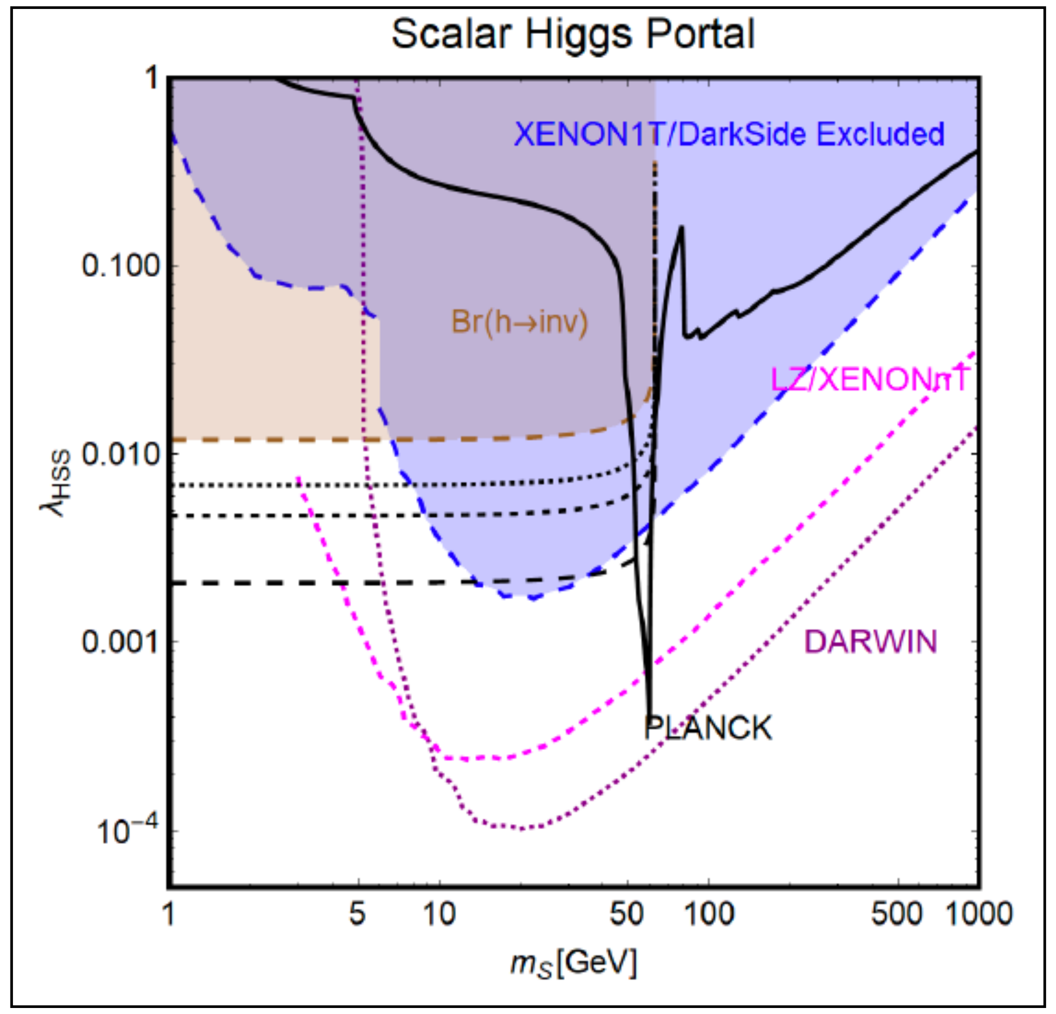

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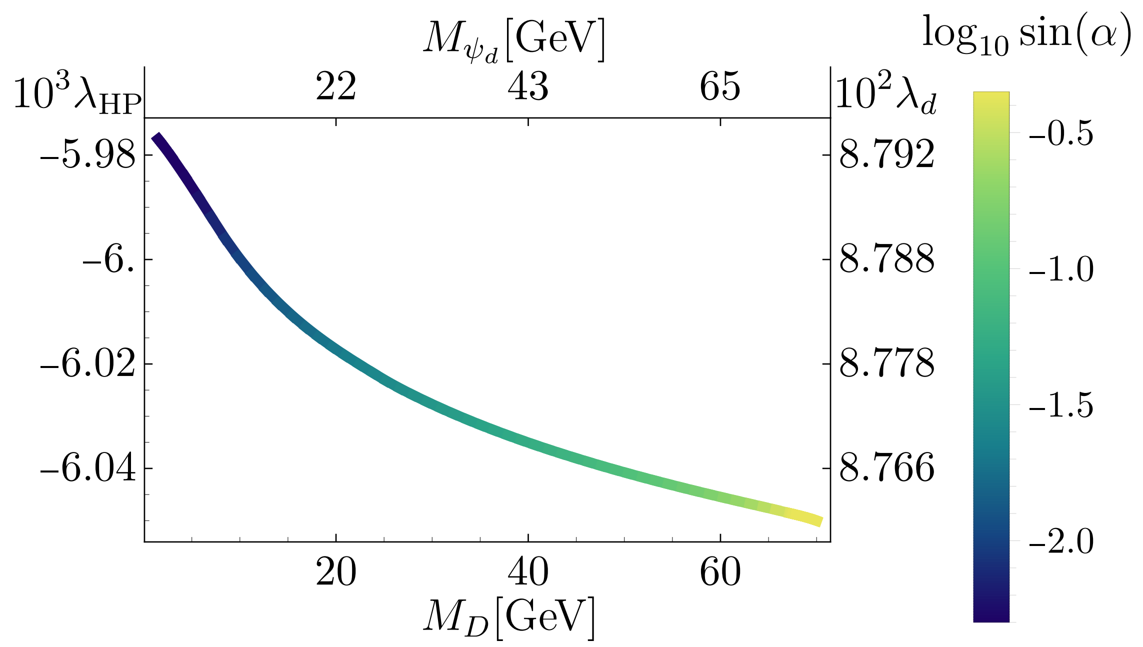

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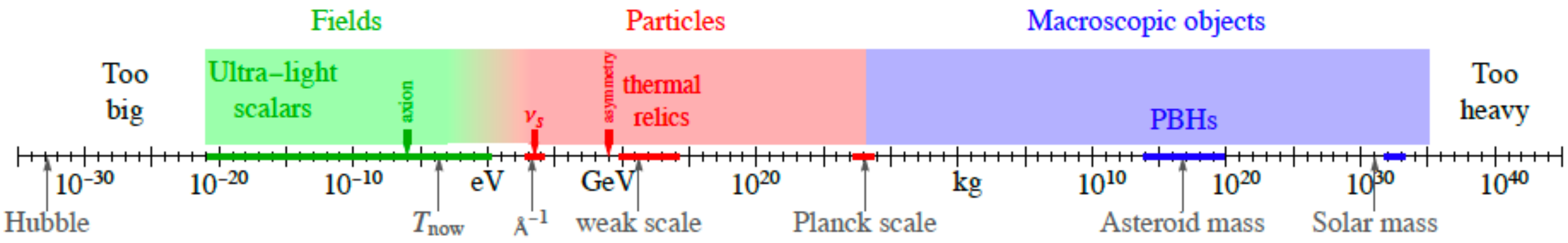
→ extended WIMP sectors strongly constrained or ruled out

Asymptotic safety and dark matter



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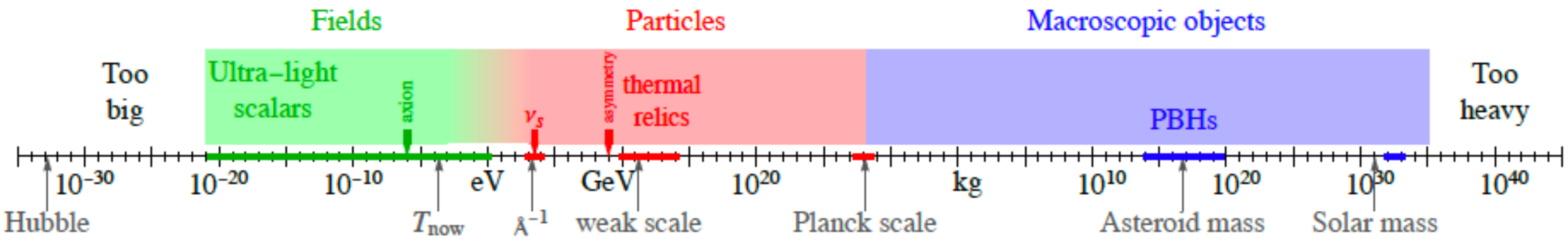
Asymptotic safety and dark matter



[cf. lectures by Marco Cirelli]

ALPs: generically present in stringy settings

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

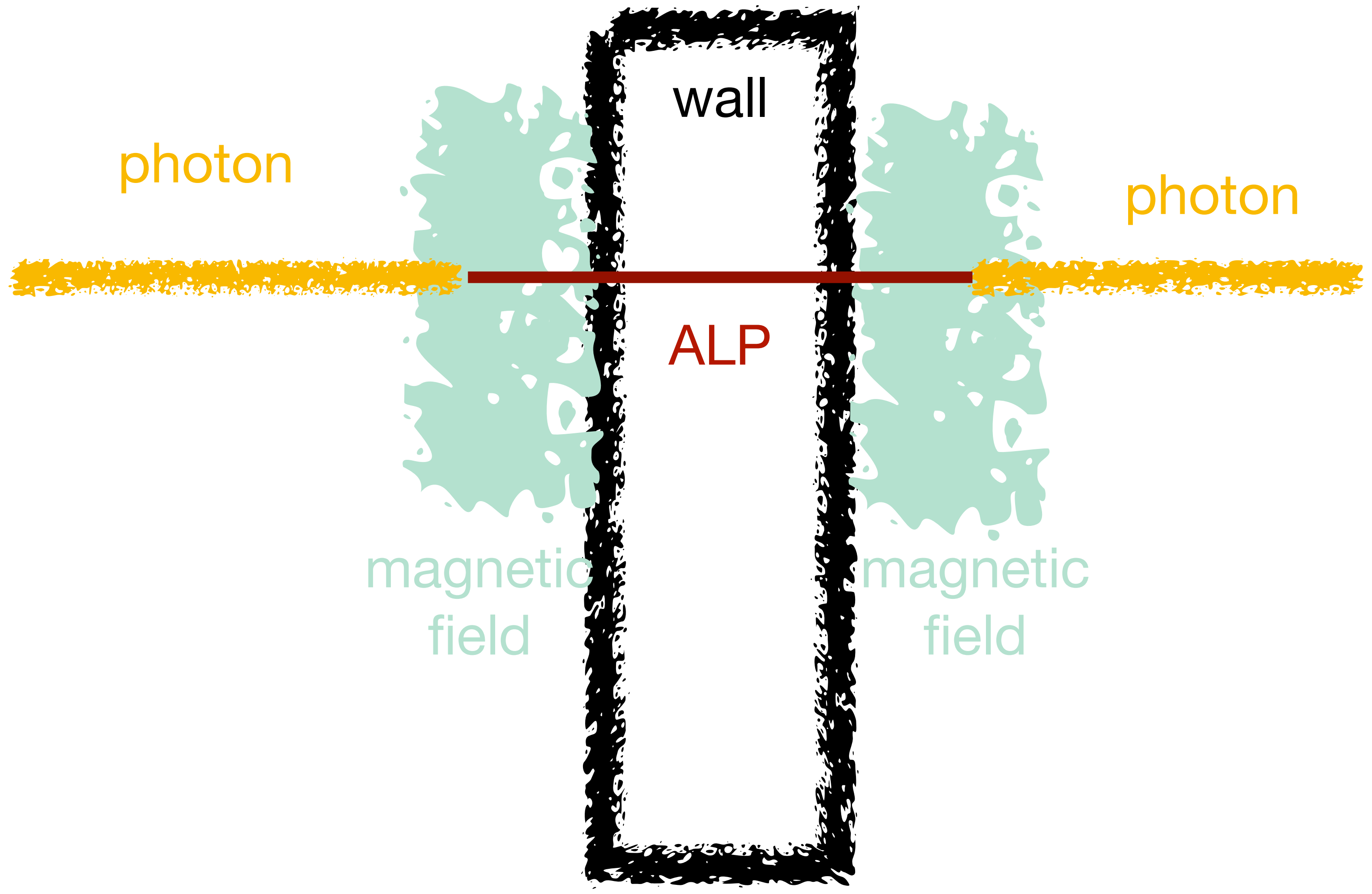
ALPs in asymptotically safe gravity

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



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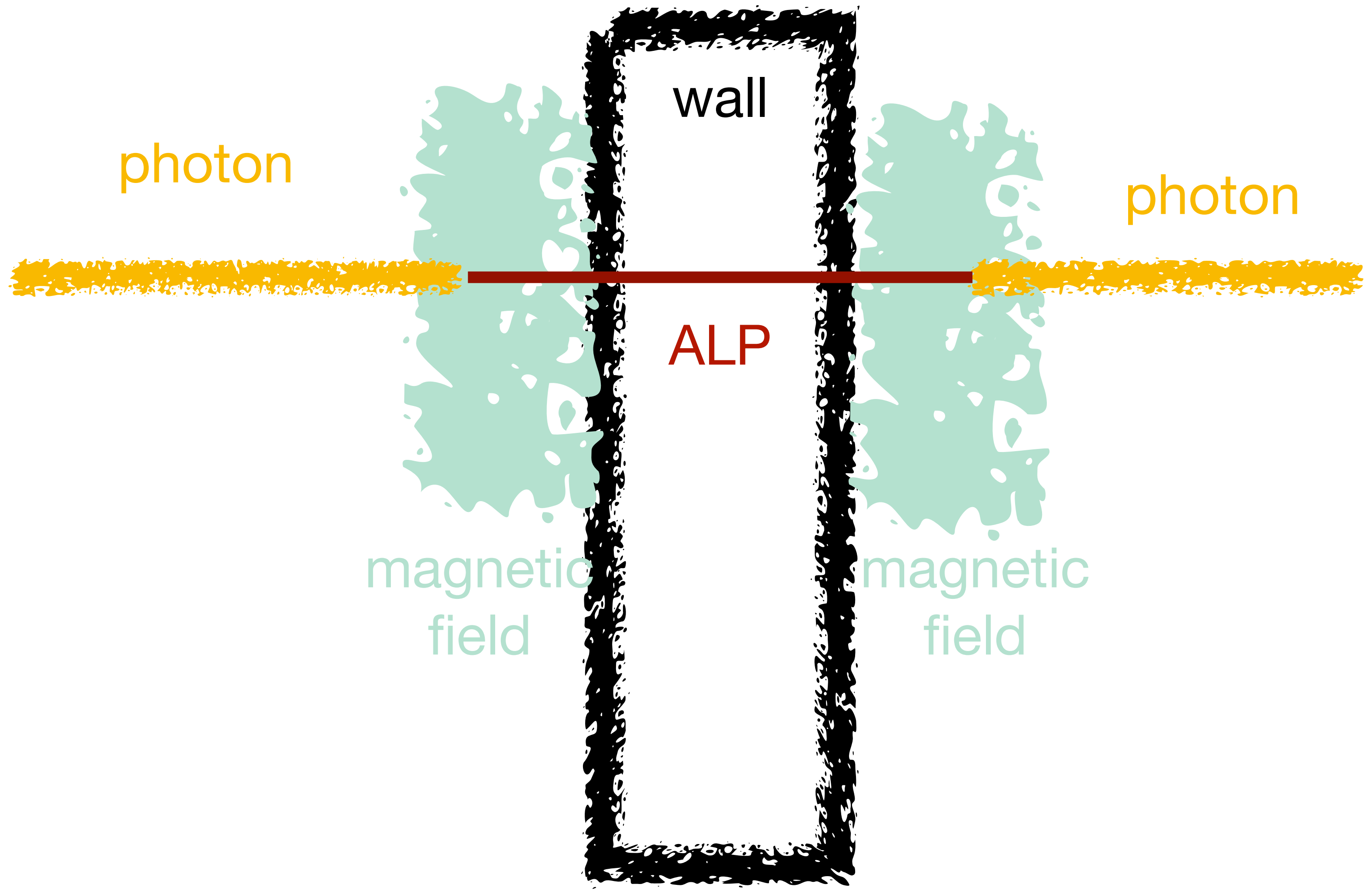


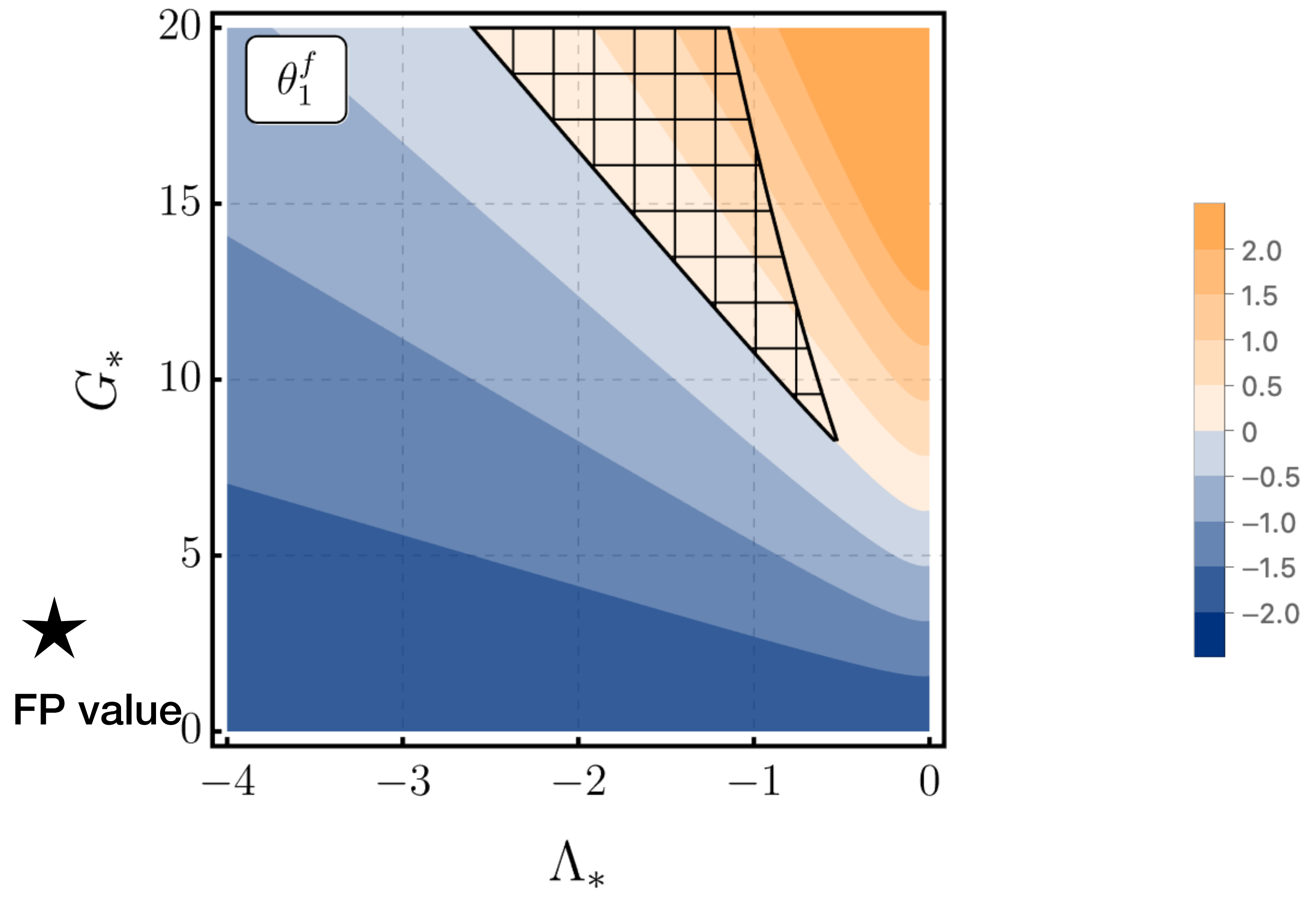
without gravity: $$\beta_{g_a^2} = 2g_a^2 + \frac{7}{48\pi^2} g_a^4 + \dots$$

→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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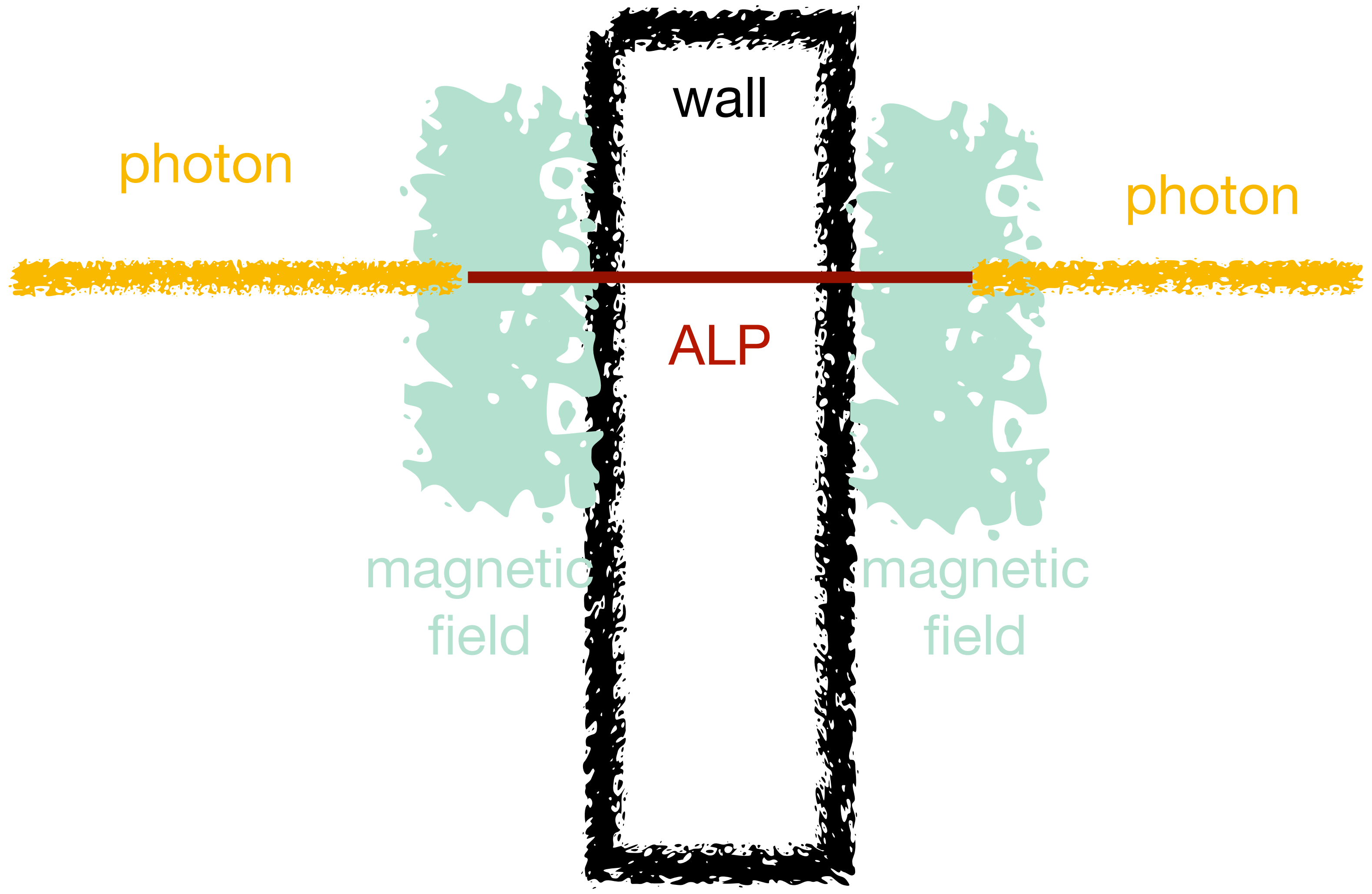

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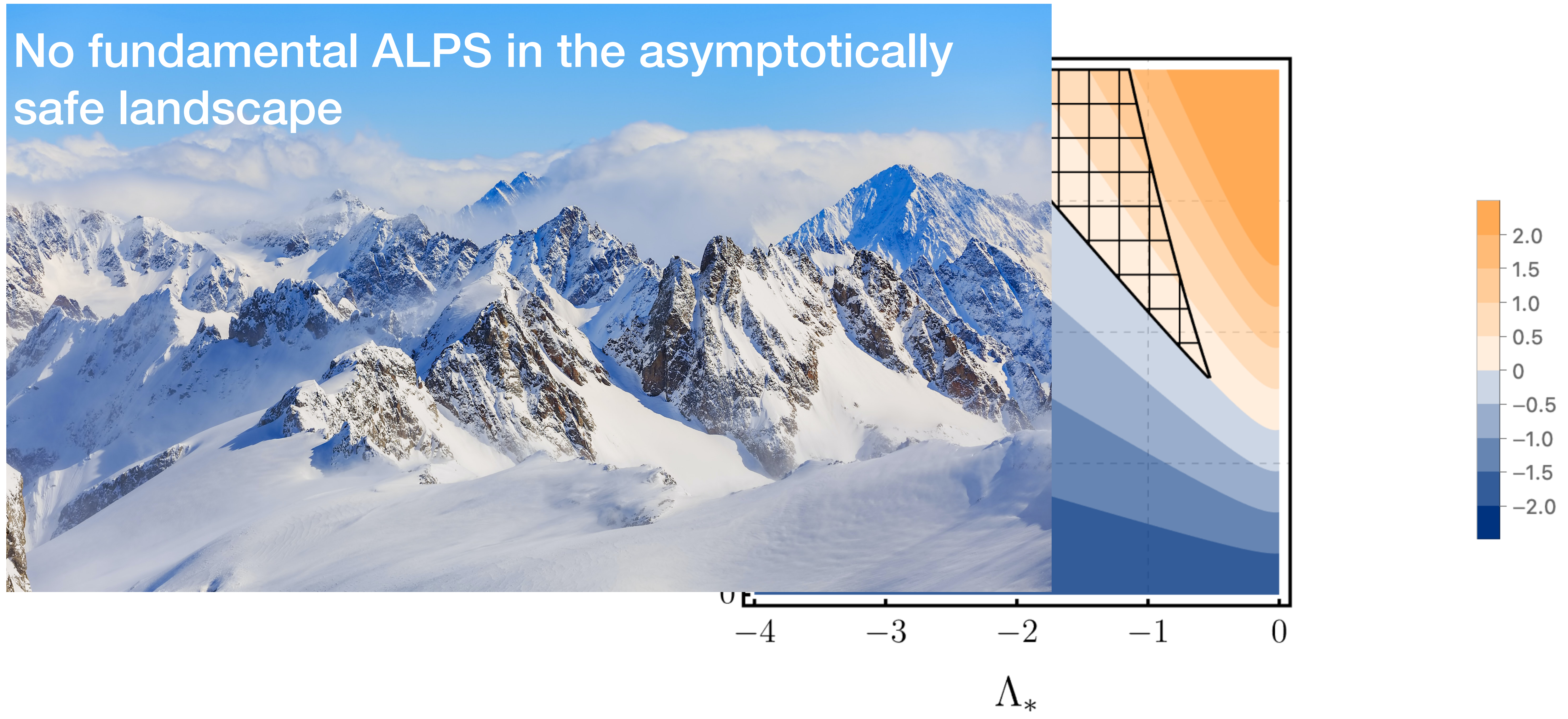
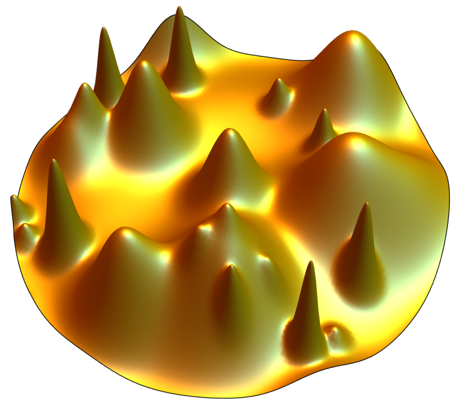


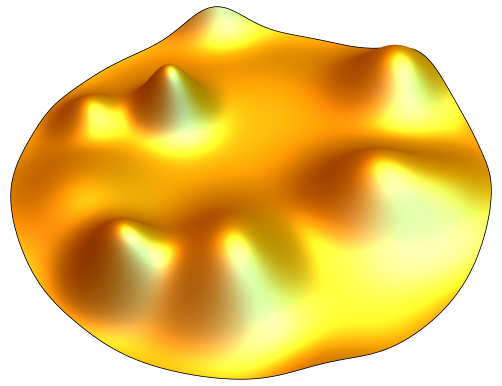
Summary and outlook

Theory

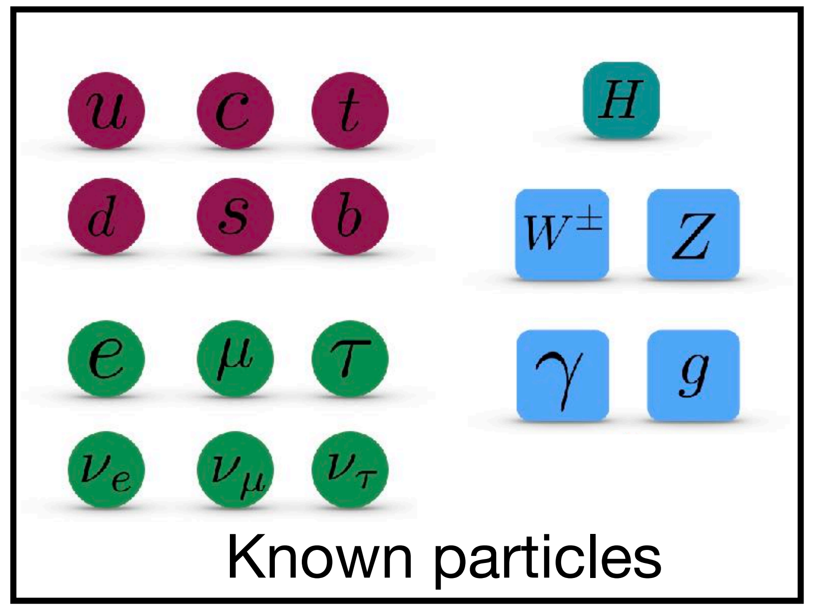
Observational tests



Transplanckian scales

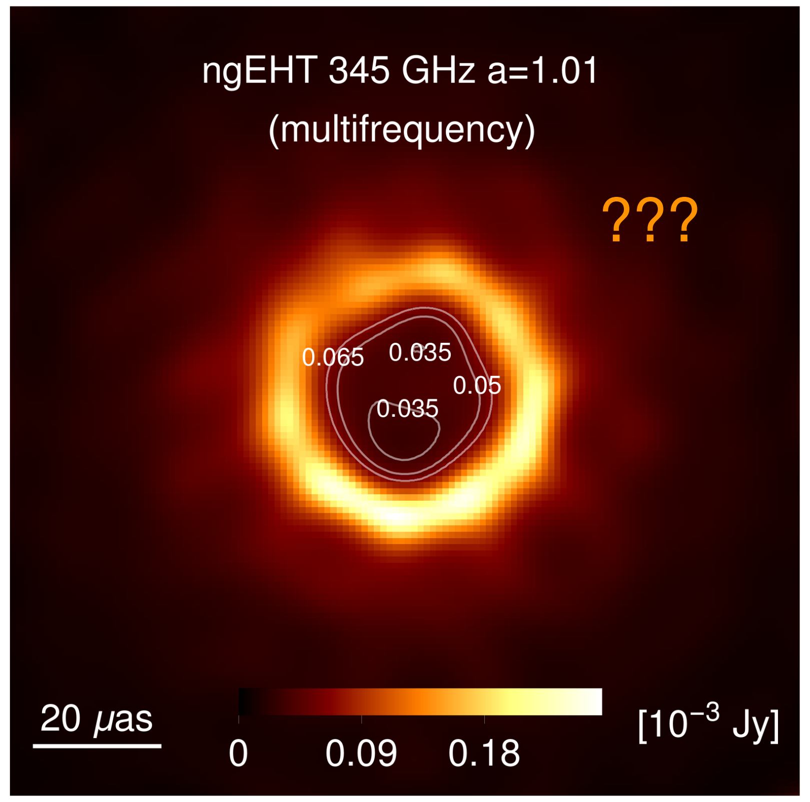


Planck scale



?? ?? Dark matter

Particle physics scales



Black-hole scales

Cosmological scales

distance scale

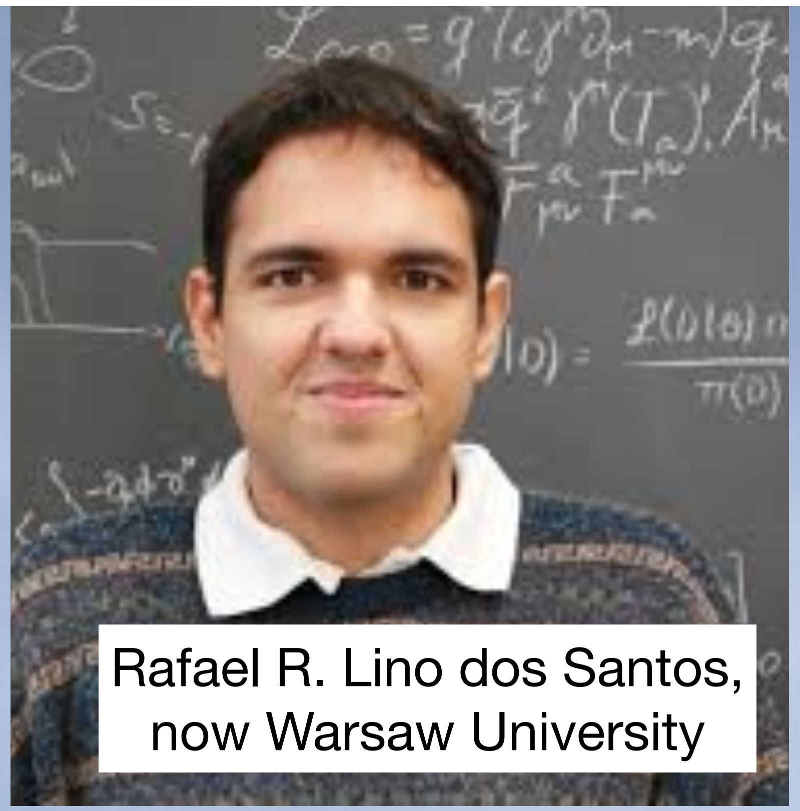
- Ensure quantitative control over truncations
- Work in Lorentzian signature
- understand relation to other approaches

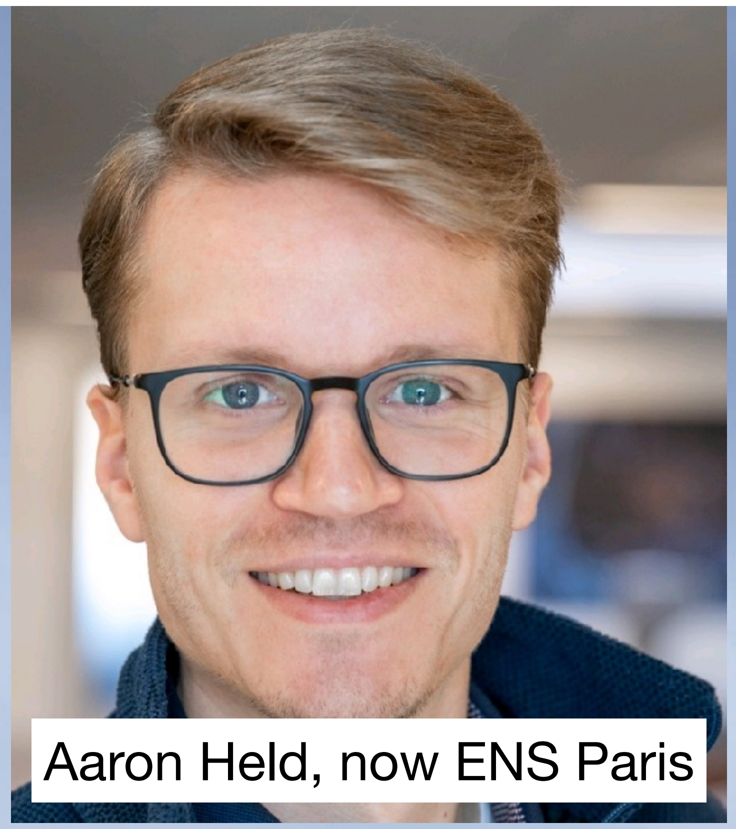
- dark matter
- neutrino masses
- matter-antimatter asymmetry

- dark energy

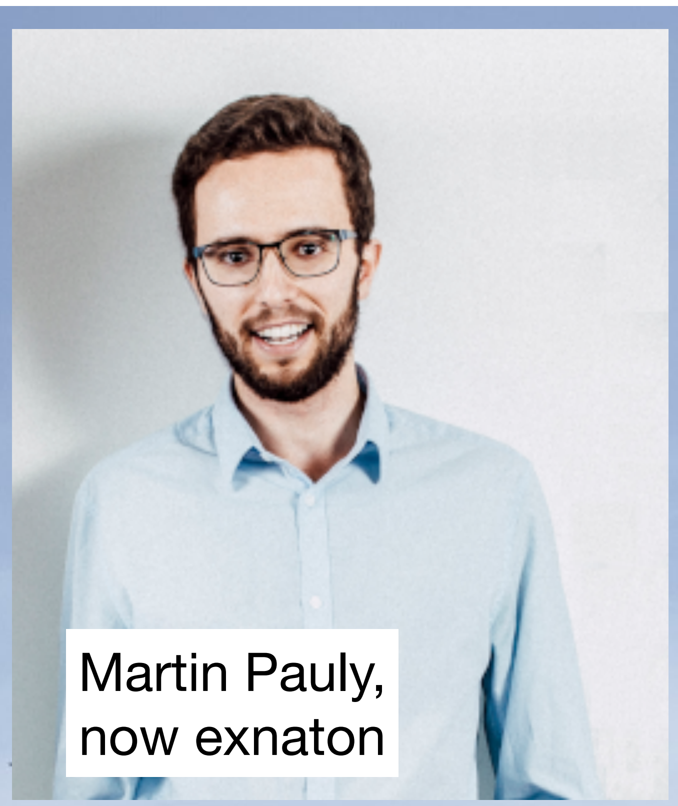
Thanks to current and former group members


Marc Schiffer, now PI


Rafael R. Lino dos Santos, now Warsaw University

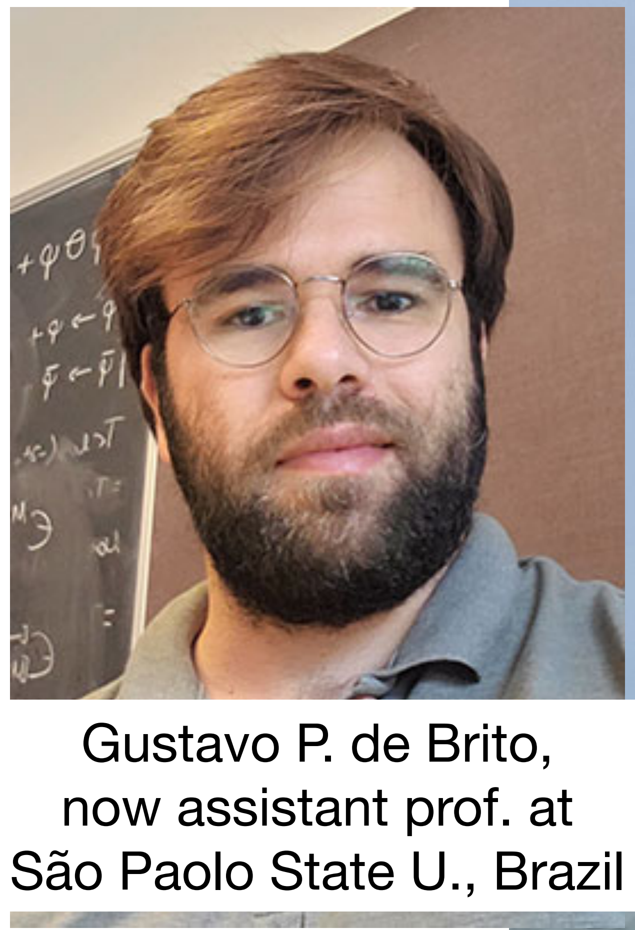

Aaron Held, now ENS Paris


Fleur Versteegen, now ASML


Martin Pauly, now exnaton


Antonio Pereira, now assistant prof. at Fluminense Federal U., Brazil

Nicolai Christiansen


Gustavo P. de Brito, now assistant prof. at São Paolo State U., Brazil


Alessia Platania, now assistant prof. at Niels-Bohr-Institute, Copenhagen


Johannes Lumma, now Alan Turing Institute

Raúl Carballo-Rubio,
Shouryya Ray
Pedro Fernandes
Ahishek Chikkaballi
Héloïse Delaporte
Fabian Wagner
Benjamin Knorr

former visiting PhD students

Joao Miqueleto
Jan Kwapisz
Arthur Vieira
Arslan Sikandar
Vedran Skrinjar
Carlos Nieto

and master students
Andreas O. Pedersen
Philipp Johannsen
Ludivine Fausten
Christopher Pfeiffer
Ademola Adeifeoba
Peter Vander Griend