Title: Status, perspective and three challenges in the asymptotic-safety paradigm for quantum gravity - VIRTUAL

Speakers: Astrid Eichhorn

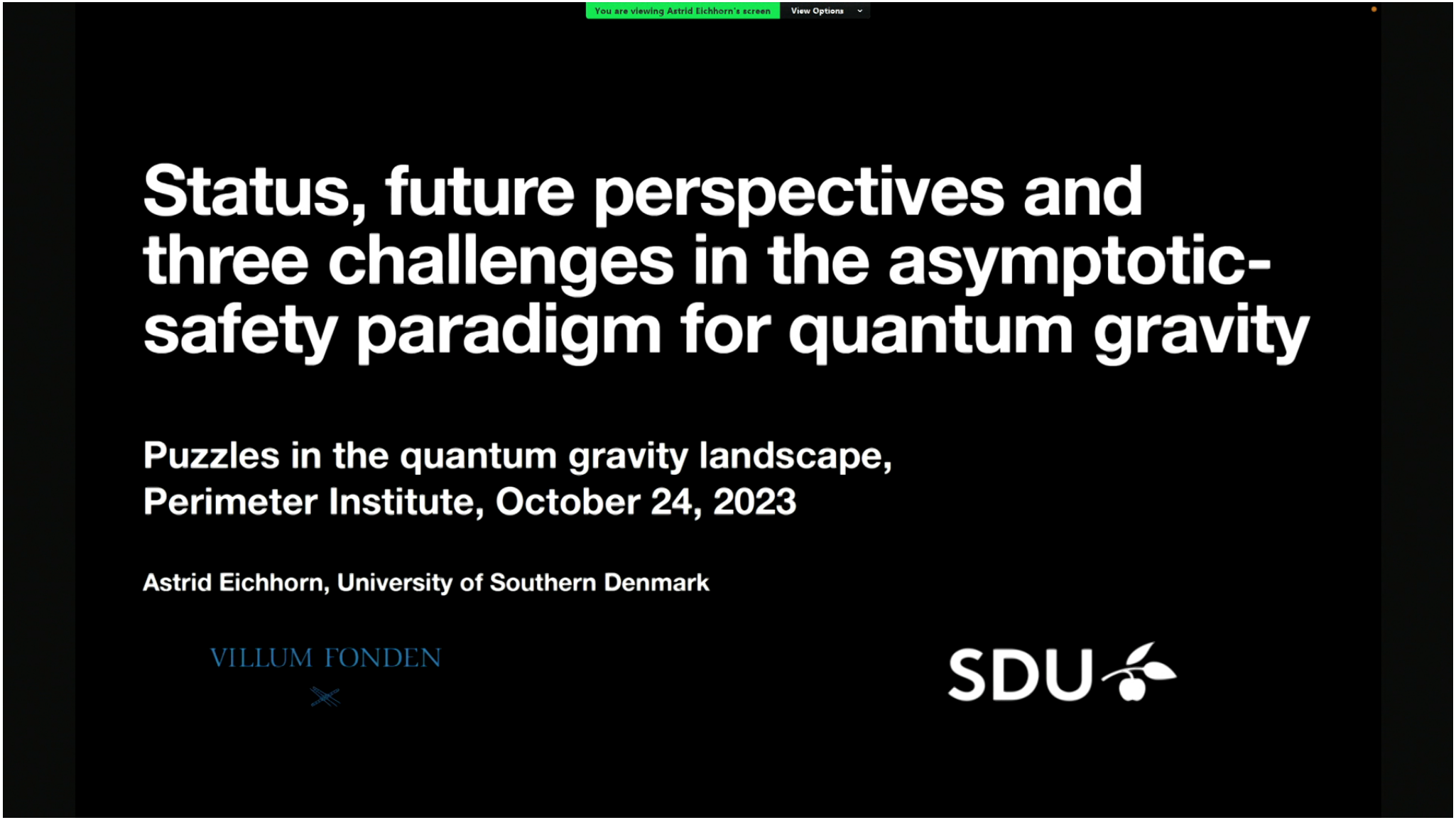
Collection: Puzzles in the Quantum Gravity Landscape: viewpoints from different approaches

Date: October 24, 2023 - 9:00 AM

URL: https://pirsa.org/23100005

Abstract: In my talk, I'll review the key idea underlying asymptotically safe quantum gravity, before giving an overview of the current status and open questions. I'll then spotlight three challenges. The first challenge is how to test quantum gravity and I'll advocate that by linking quantum gravity to particle physics and cosmology, we can probe quantum gravity at all scales. The second challenge is how to connect to other ideas about quantum spacetime and I'll discuss effective asymptotic safety as a way to link to, e.g., string theory. The third challenge is the status of global symmetries and I'll discuss what we know about the preservation of global symmetries in asymptotic safety and what this implies for a broader perspective on the question.

The presenter will be joining via Zoom for this talk.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Status, future perspectives and three challenges in the asymptotic-safety paradigm for quantum gravity
Puzzles in the quantum gravity landscape,
Perimeter Institute, October 24, 2023
Astrid Eichhorn, University of Southern Denmark
VILLUM FONDEN
SDU

Asymptotically safe gravity: Key concepts

Key assumptions:

- Metric* carries the fundamental degrees of freedom
- Path integral has a finite number of free parameters

$$\int \mathscr{D} g_{\mu\nu}\, e^{iS}$$

$$S = S_{\text{Einstein-Hilbert}} = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}\,(R - 2\Lambda)$$

Problem:

perturbative non-renormalizability

→ breakdown of predictivity

Solution:

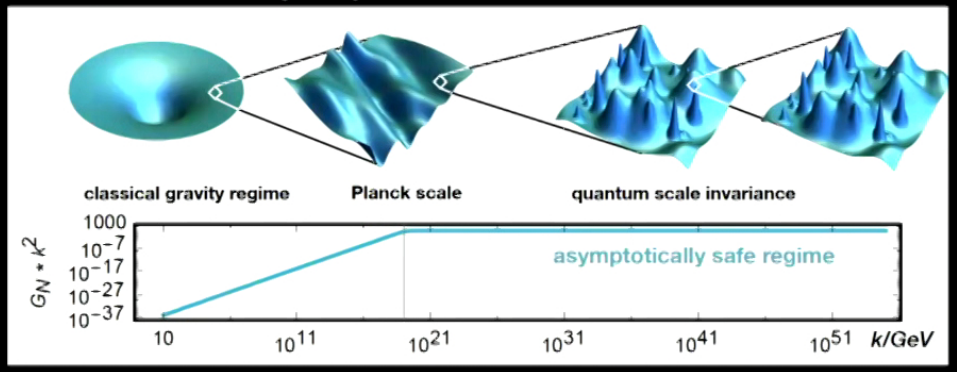
Quantum scale symmetry

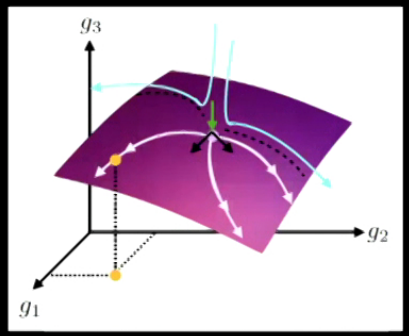
→ relations between the couplings restore predictivity

* vielbein [Harst, Reuter '12], metric+connection [Harst, Reuter '14]

⇒ quantum scale symmetry: Reuter fixed point

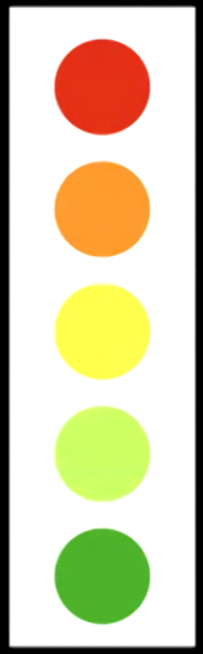
[Weinberg '76; Reuter '96; Dou, Percacci '97; Souma '99; Lauscher, Reuter '01; Reuter, Saueressig '01…]





Asymptotically safe gravity: Status and open challenges*

Traffic light



Unsolved problem

Solution has been proposed

Several studies supporting solution/result exist

Numerous studies supporting solution/result exist

(Largely) solved problem/ Answered question

* "Critical reflections on asymptotically safe gravity", Bonanno, AE, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca '20

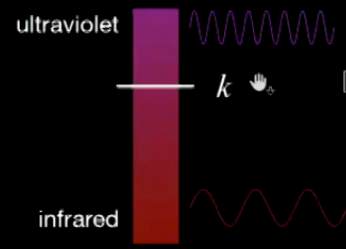
Asymptotically safe gravity: Status and open challenges*

Evidence for asymptotically safe fixed point:

- method: functional Renormalization Group

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

$$e^{-\Gamma_k} = \int \mathcal{D} g_{\mu\nu} e^{-S[g_{\mu\nu}] + \Delta S_k}$$



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

[Wetterich '93; Reuter '96; review: Dupuis, Canet, AE et al. '20]

$$\rightarrow \beta_g = k \partial_k g(k)$$

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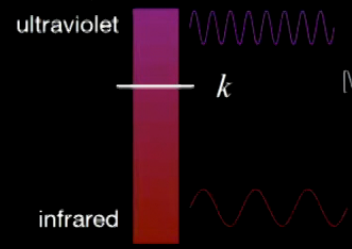

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[Wetterich '93; Reuter '96; review: Dupuis, Canet, AE et al. '20]

$$\rightarrow \beta_g = k \partial_k g(k)$$

- robust in $\gg$ 100 studies that vary:
  - included interactions ($\sqrt{g}R, \sqrt{g}f(R), \sqrt{g}f(R_{\mu\nu}R^{\mu\nu}), \sqrt{g}R_{\mu\nu\kappa\lambda}R^{\kappa\lambda\rho\sigma}R_{\rho\sigma}{}^{\mu\nu}, \ldots$
  - treatment of auxiliary background metric
  - RG scheme
  - gauge parameters

recent reviews: Saueressig '23; Pawlowski, Reichert '23

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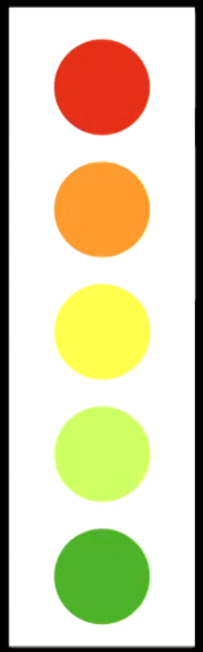

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Evidence for asymptotically safe fixed point

recent reviews: Saueressig '23; Pawlowski, Reichert '23

Traffic light

Evidence for asymp
with Standa
recent reviews: A

Evidence for asymptotically safe fixed point with Standard Model matter:

- robust in many studies that vary:
  - included interactions

    ($\sqrt{g}R, \sqrt{g}f(R), \sqrt{g}R_{\mu\nu}R^{\mu\nu}$ for gravity, various non-minimal interactions, many higher-order matter interactions)
  - treatment of auxiliary background metric
  - RG scheme to some extent
  - gauge parameters to some extent

recent reviews: AE, Schiffer '22, AE '22

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Evidence for asymptotically safe fixed point

recent reviews: Saueressig '23; Pawlowski, Reichert '23

Evidence for asymptotically safe fixed point with Standard Model matter

recent reviews: AE, Schiffer '22, AE '22

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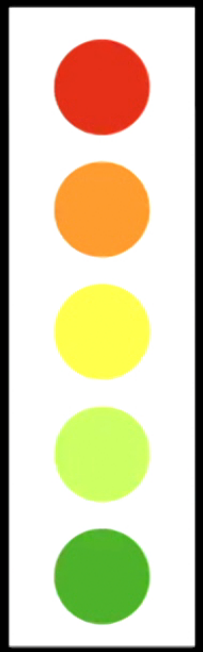

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Evidence for asymptotically safe fixed point with Standard Model matter

recent reviews: AE

Properties and predict

Traffic light

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Properties and predictivity of the fixed point:

- near-perturbative scaling spectrum [Falls, Litim et al. '13, '14, '17]
- three free parameters (Newton coupling, cosmological constant, superposition of curvature squared couplings) [Falls, Ohta, Percacci '20]

* "Critical reflections on asymptotically safe gravity", Bonanno, AE, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca '20

Asymptotically safe gravity: Status and open challenges*

Resolution of curvature singularities:

- Regular black holes constructed by Renormalization- Group improvement

  recent reviews: AE, Held '22; Platania '23

- potential between point sources non-singular

  [Bosma, Knorr, Saueressig '19]

- singularities dynamically suppressed in path integral

  $\int \mathscr{D} g_{\mu\nu} e^{iS}$: destructive interference for configurations with $S \to \infty$

  $S = \ldots + \int d^4x \sqrt{-g} R_{\mu\nu\kappa\lambda} R^{\mu\nu\kappa\lambda} \to \infty$ for singular black holes

  [Borissova, AE '20; Borisssova '23]

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Asymptotically safe gravity: Status and open challenges*

Evidence for asymptotically safe fixed point
recent reviews: Saueressig '23; Pawlowski, Reichert '23

Evidence for asymptotically safe fixed point with Standard Model matter
recent reviews: AE, Schiffer '22, AE '22

Properties and predictivity of the fixed point

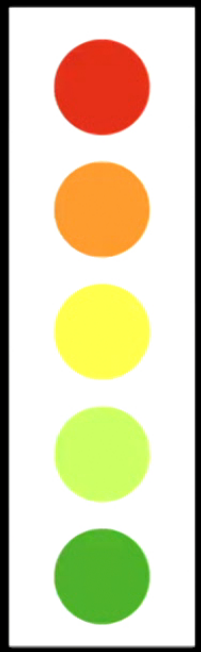
Classical gravity in the IR

Viable phenomenology in particle physics

Resolution of curvature singularities

Connection to other QG approaches

Traffic light



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Asymptotically safe gravity: Status and open challenges*

Propagating degrees of freedom & stability:

- fixed-point action features higher-order curvature invariants
- generically, higher-order time derivatives lead to Ostrogradsky instability (→ non-unitarity) ,

  BUT: important caveats:
  - degeneracies in the Hamiltonian (e.g., DHOST theories [Gleyzes, Langlois, Piazza, Vernizzi '14])
  - entire function vs its expansion (e.g, ``non-local gravity")
  - decoupling mechanisms for unstable modes, e.g., [Deffayet, Held, Mukohyama, Vikman '23]
  - choice of vacuum/ground state
  - …
- fake instabilities in expansion of effective action of unitary theory to finite order [Platania, Wetterich '20]
- examples of propagators which satisfy unitarity and causality and allow analytic continuation [Platania '22]

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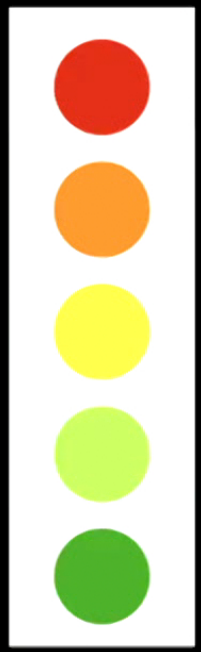

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Evidence for asymptotically s… with Standard Model…

recent reviews: AE, Schiffer '2…

Properties and predictivity of …

Classical gravity in …

Viable phenomenology in pa…

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Traffic light

Lorentzian signature:

- most studies with functional RG techniques in Euclidean signature
- Einstein-Hilbert truncation in Lorentzian signature

  [Saueressig et al. '11; Fehre, Litim, Pawlowski, Reichert '21]
- other methods:
  - CDTs → see talk by R. Loll
  - causal sets as Lorentzian regularization [AE '19]

…sed

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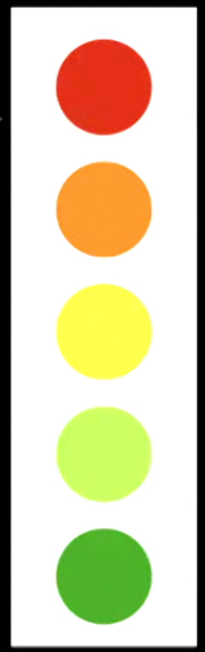

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Properties and predictivity of the fixed point

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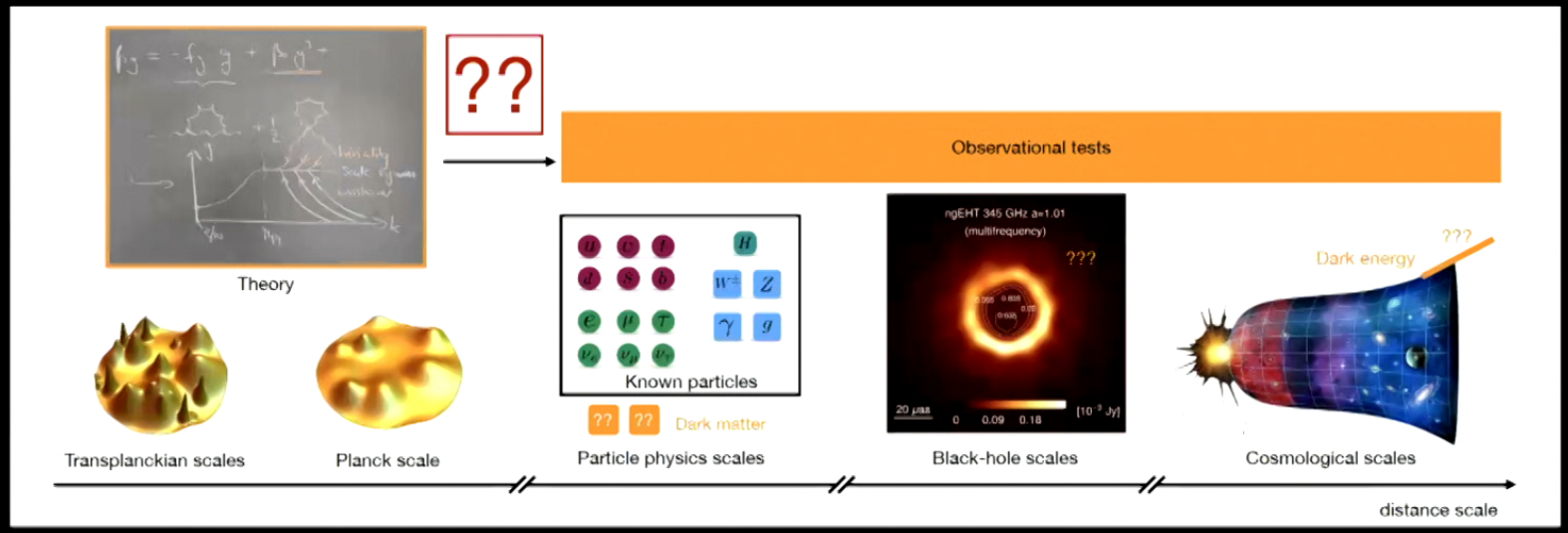
Three challenges:

1) Phenomenology: How to test asymptotically safe quantum gravity?
2) Status of global symmetries
3) Connection to other quantum gravity approaches

* "Critical reflections on asymptotically safe gravity", Bonanno, AE, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca '20

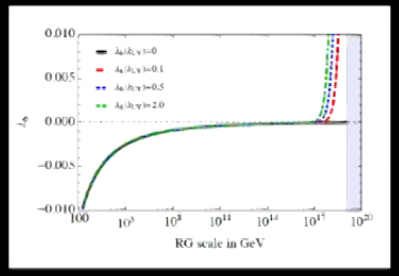
Challenge 1: How to test (asymptotically safe) quantum gravity?



Excluding models (swampland-ish ideas): when a given model in particle physics/cosmology is incompatible with a UV completion

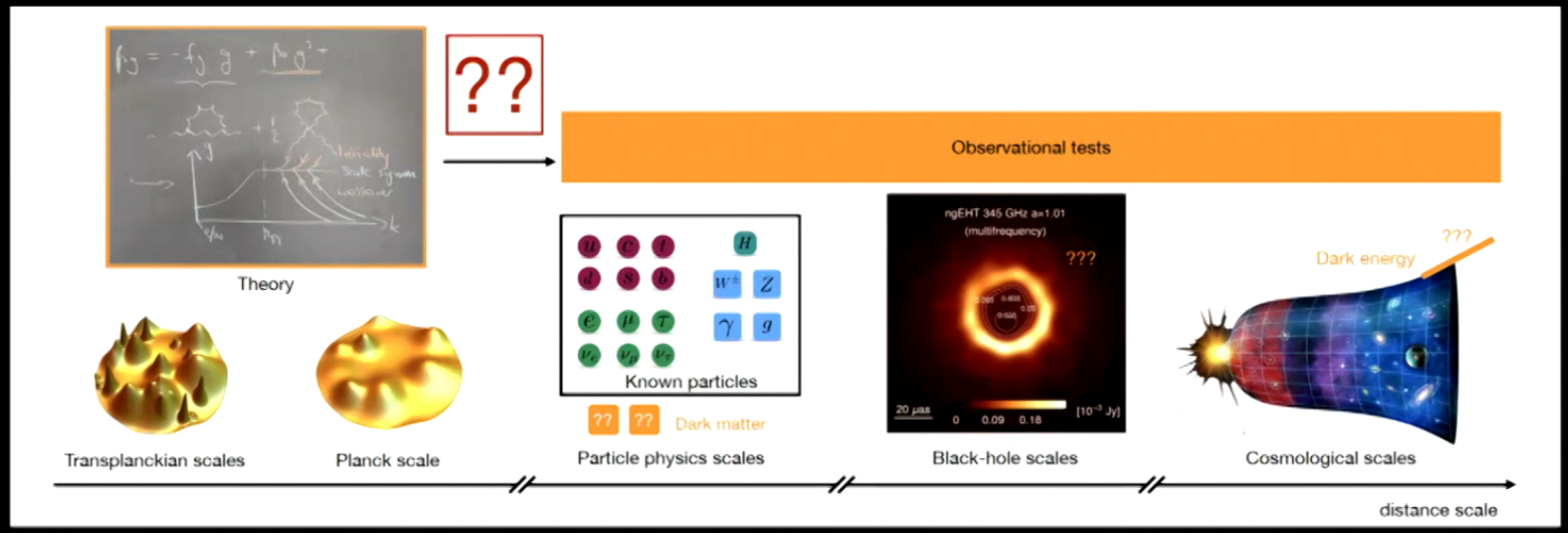
Constraining models: when the parameters in a model (the coupling constants) are constrained by the UV completion

Why should the low-energy theory
be sensitive to the high-energy theory?
Don't we lose microscopic information,
when we zoom out to construct the effective theory?



universality of IR theory:
microscopic information
is ``washed out" by RG flow

Challenge 1: How to test (asymptotically safe) quantum gravity?



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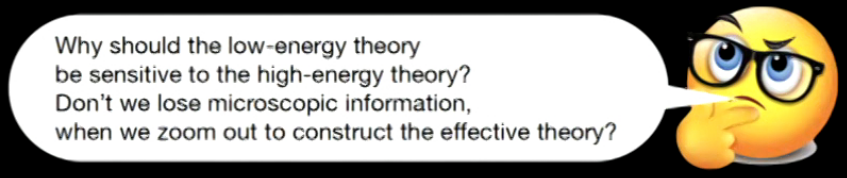
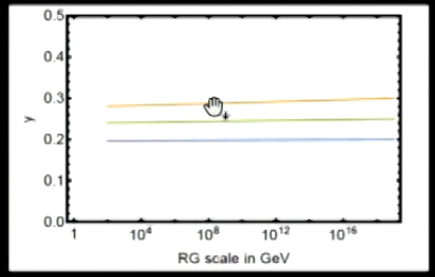
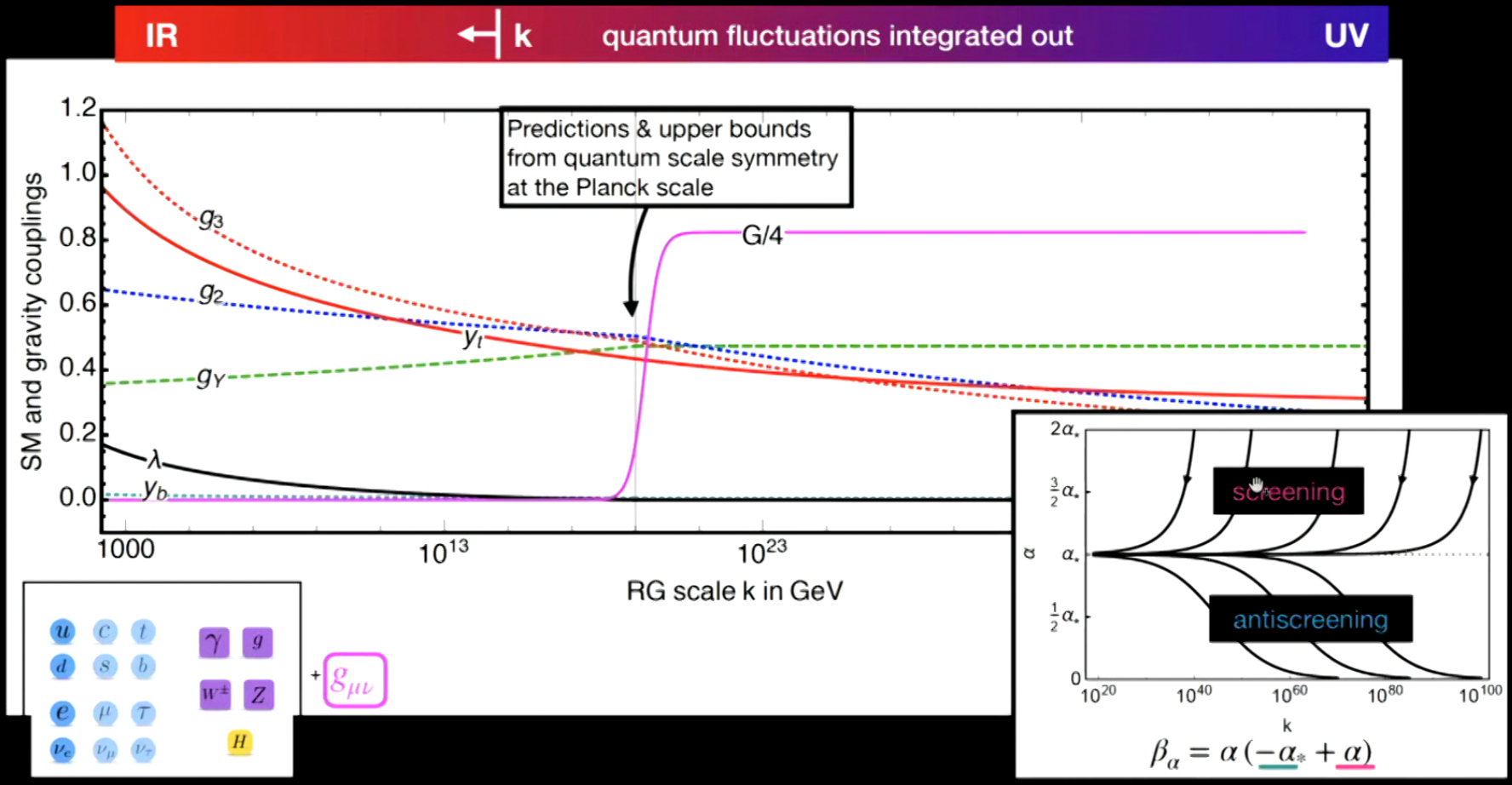


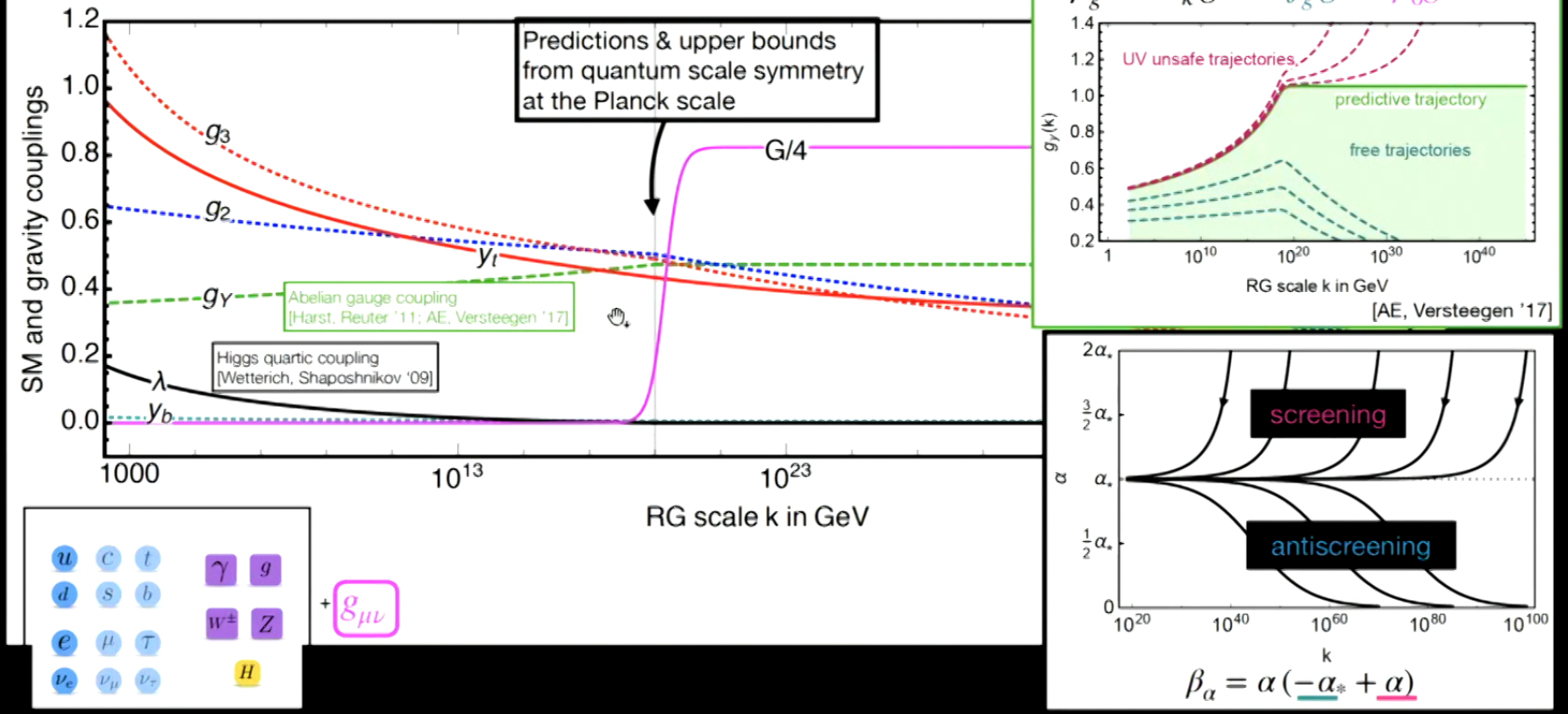


Asymptotically safe Standard Model with gravity



Asymptotically safe Standard Model with gravity

IR ← k quantum fluctuations integrated out UV



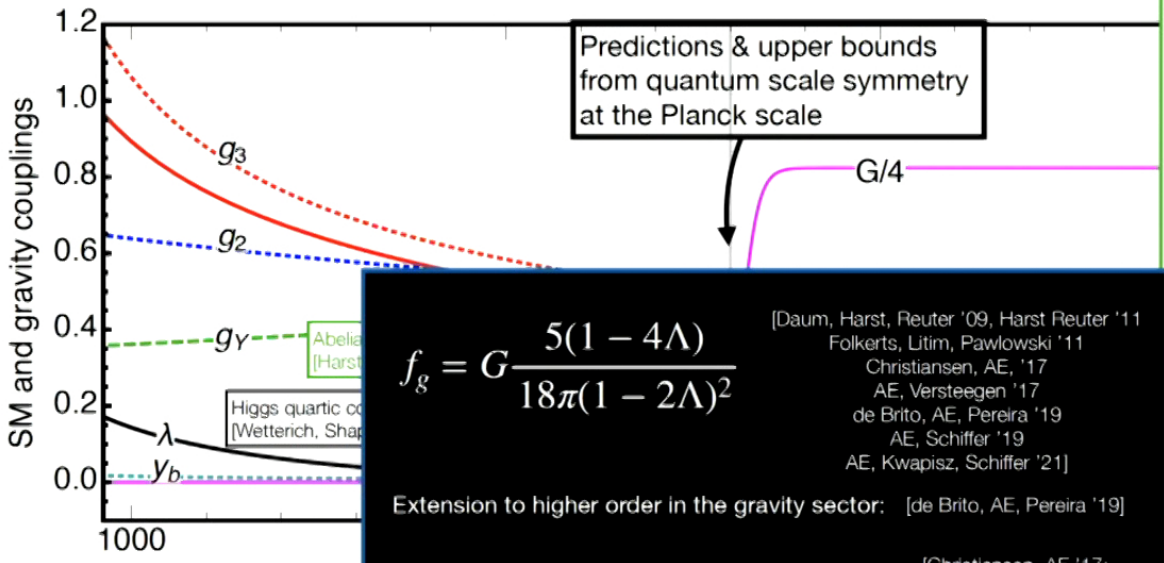
$$\beta_g = k\partial_k g = -f_g g + \beta_0 g^3 + \dots$$

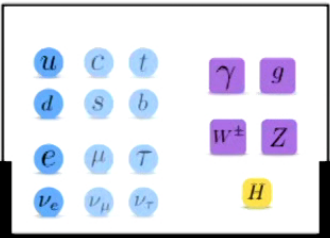
[AE, Versteegen '17]

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

Asymptotically safe Standard Model with gravity

IR ← k quantum fluctuations integrated out → UV





$$f_g = G\frac{5(1-4\Lambda)}{18\pi(1-2\Lambda)^2}$$

[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]

Extension to higher order in the gravity sector: [de Brito, AE, Pereira '19]

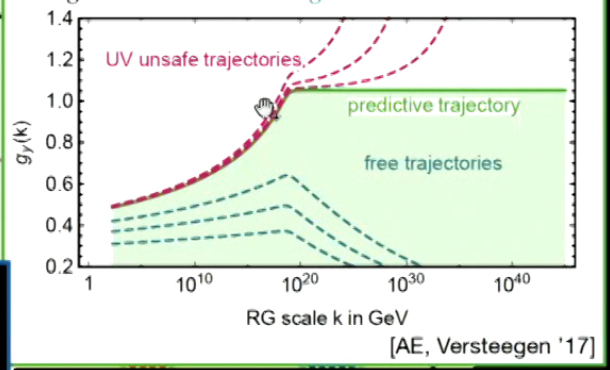
Extension to higher order in the gauge sector: [Christiansen, AE '17; AE, Schiffer '19; AE, Kwapisz, Schiffer '21]

Universality and connection to perturbative results: [de Brito, AE '22]

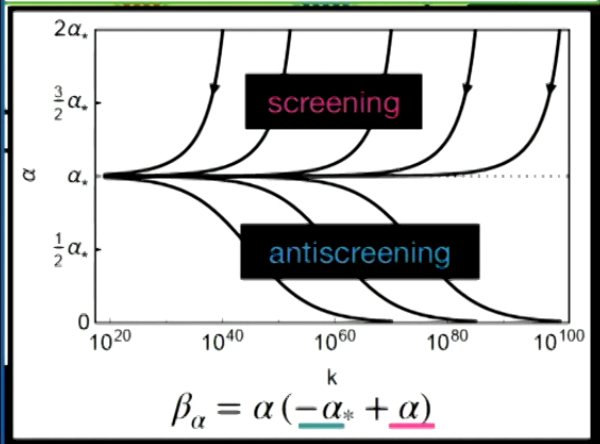
Key properties: $f_g = \text{const} > 0$ above M_{Pl}

$f_g \to 0$ below M_{Pl}

$$\beta_g = k\partial_k g = -f_g\, g + \beta_0 g^3 + \dots$$



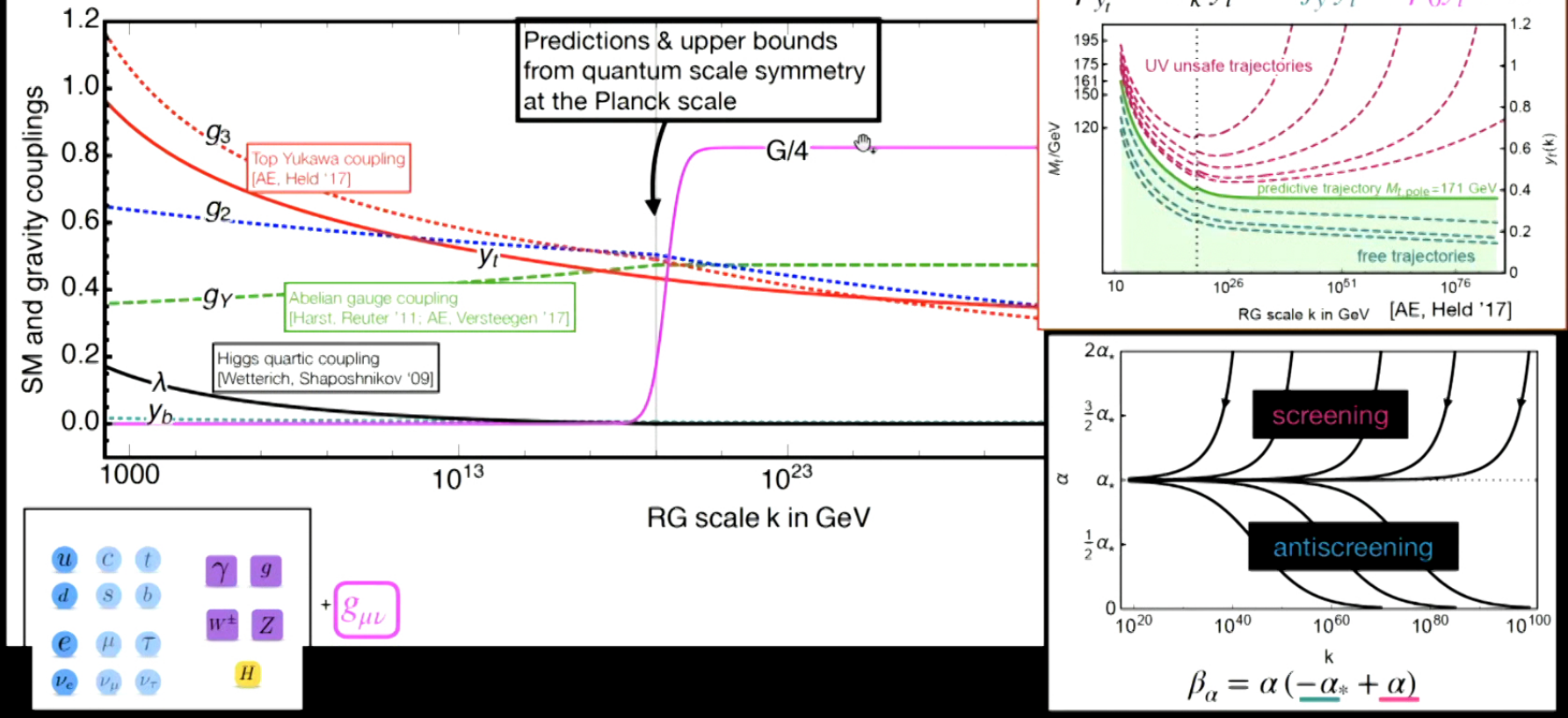
[AE, Versteegen '17]



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

Asymptotically safe Standard Model with gravity

IR ← k quantum fluctuations integrated out UV



$$\beta_{y_t} = k\partial_k y_t = -f_y y_t + \beta_0 y_t^3 + \dots$$

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

Asymptotically safe Standard Model with gravity

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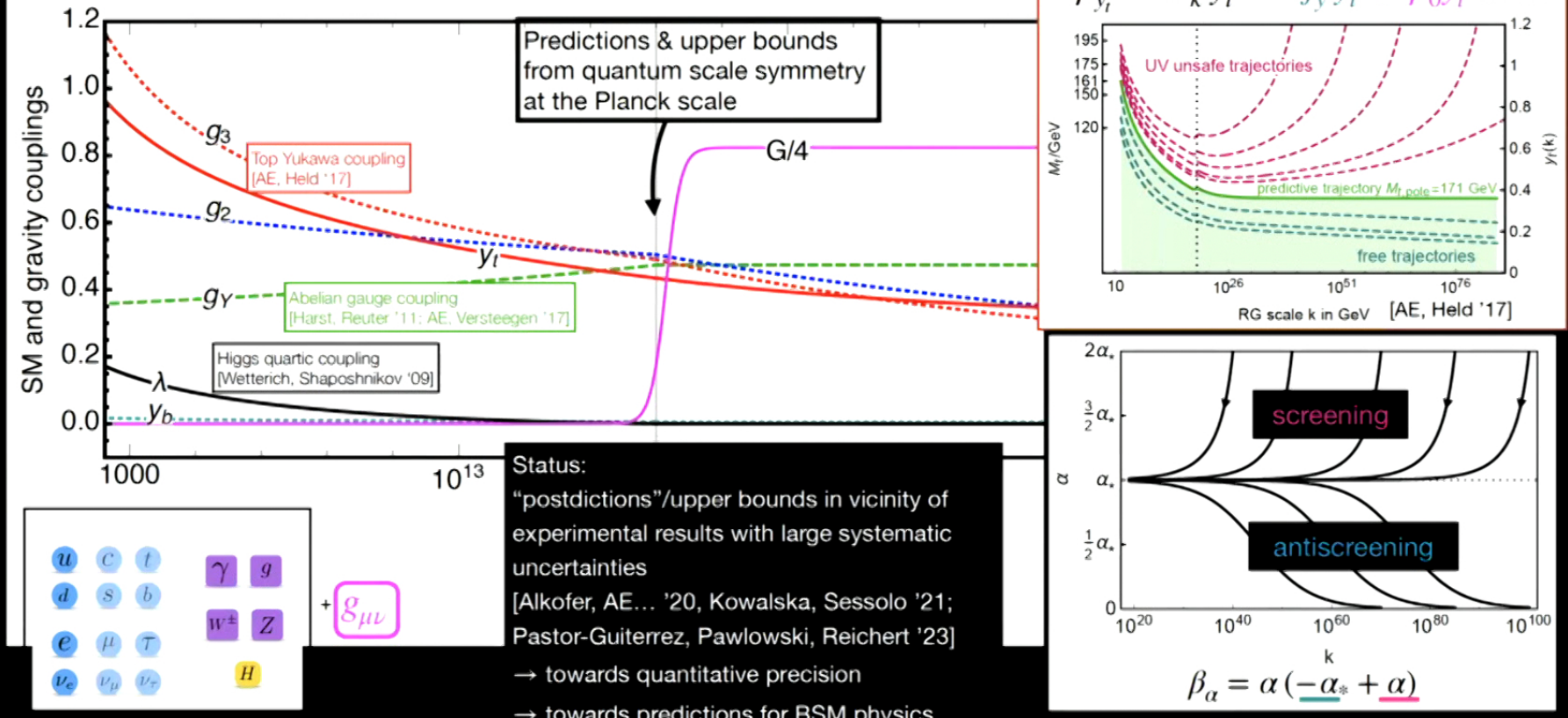
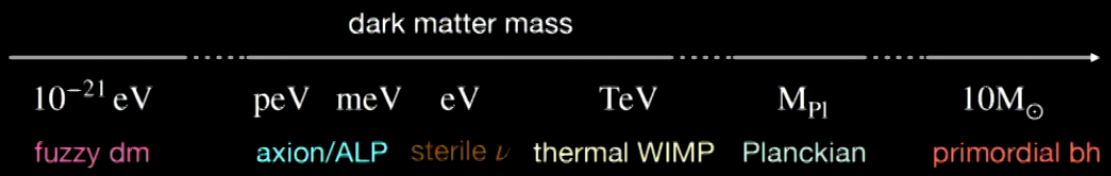


Status:
"postdictions"/upper bounds in vicinity of experimental results with large systematic uncertainties
[Alkofer, AE… '20, Kowalska, Sessolo '21; Pastor-Guiterrez, Pawlowski, Reichert '23]

→ towards quantitative precision

→ towards predictions for BSM physics

Predictions for BSM physics: spotlight on dark matter

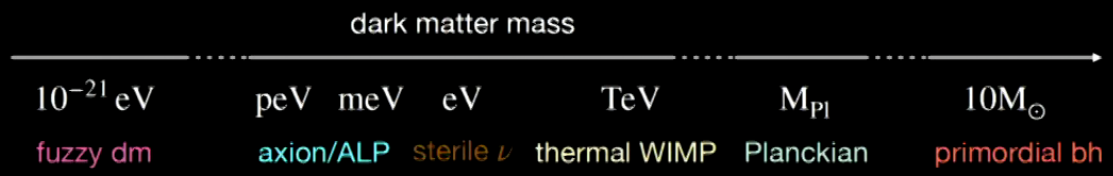


- ALP-photon coupling vanishes
  [de Brito, AE, Lino dos Santos '21]

- neutrinos Yukawa couplings driven to zero dynamically (prerequiste for ν dark matter)
  [Held '19; Kowalska, Sessolo '22; AE, Held '22; Chikkabali, Kowalska, Sessolo '23]

- Higgs portal to single dark scalar excluded
  [AE, Hamada, Lumma, Yamada '17]
- Higgs portal to dark scalar with dark gauge charge excluded
  [de Brito, AE, Frandsen, Rosenlyst, Thing, Vieira, to appear]
- Higgs portal to extended dark sectors constrained
  [Reichert, Smirnov '19; Hamada, Tsumura, Yamada '20; AE, Pauly '20; Kowalska, Sessolo '20]

Predictions for BSM physics: spotlight on dark matter



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- Higgs portal to dark scalar with dark gauge charge excluded
  [de Brito, AE, Frandsen, Rosenlyst, Thing, Vieira, to appear]
- Higgs portal to extended dark sectors constrained
  [Reichert, Smirnov '19; Hamada, Tsumura, Yamada '20; AE, Pauly '20; Kowalska, Sessolo '20]

Many phenomenological models of dark matter use global symmetries to stabilize dark-matter candidates

→ are those automatically excluded when quantum gravity is considered?

Challenge 2: What is the status of global symmetries?

No-global symmetries conjecture:

1) Black-hole spacetimes violate conservation of global charges

2) Gravity-matter path integral contains black-hole configurations

⇒ effective theory for matter has no conserved global charges

$$\int \mathscr{D}g_{\mu\nu}\mathscr{D}\bar{\psi}\mathscr{D}\psi \ \ldots \ e^{iS} = \int \mathscr{D}\bar{\psi}\mathscr{D}\psi \ \ldots \ e^{iS_{\rm eff}}$$

But: explicit calculations in asymptotic safety:

No interactions are generated by gravity which violate global symmetries of matter fields

[AE '12; AE, Held '17;
de Brito, AE, Lino dos Santos '20,
Laporte, Pereira, Saueressig, Wang '21,...

(full list in review AE, Schiffer '22]

Possibility 1: black-hole configurations not adequately accounted for in functional RG (due to Euclidean signature?)

Possibility 2: remnants

asymptotic-safety inspired black holes have vanishing temperature at Planckian mass [Bonanno, Reuter '06]

Possibility 3: black holes dynamically suppressed in path integral

$\int \mathscr{D}g_{\mu\nu}e^{iS}$: destructive interference for configurations with $S \to \infty$

$S = \ldots + \int d^4x\sqrt{-g}R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda} \to \infty$ for singular black holes

[Borissova, AE '20; Borisssova '23]

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[Bonsova, AE '20, Bonsova '23]

No-global symmetries conjecture is part of the string-inspired swampland program.

→ What is the relation of the asymptotically (un)safe swampland to the stringy swampland?

Challenge 3: What is the relation to other ideas about quantum spacetime?

Asymptotically (un)safe swampland and stringy swampland:

(Refined) de Sitter conjecture:

[Obied, Ooguri, Spodyneiko, Vafa '18]

$$\nabla V \geq \frac{c}{M_{\text{Planck}}} V \quad \text{for scalar potential } V$$

$\Rightarrow$ no deSitter vacua

Asymptotically safe view:

- Cosmological constant (of correct size) compatible

  [Reuter, Saueressig '01]

- Dynamical dark energy?
  Not everything goes! Example: simplest Horndeski model excluded

  [AE, Lino dos Santos, Wagner '23]

Weak gravity conjecture:

$$e \geq m \sqrt{8\pi G_N}$$

Asymptotically safe view: [de Alwis, AE, Held, Pawlowski, Schiffer, Versteegen '20; Basile, Platania '21]

- requires $e_* > 0$ and constrains fixed-point properties

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[Arkani-Hamed, Motl, Nicolis, Vafa 06]

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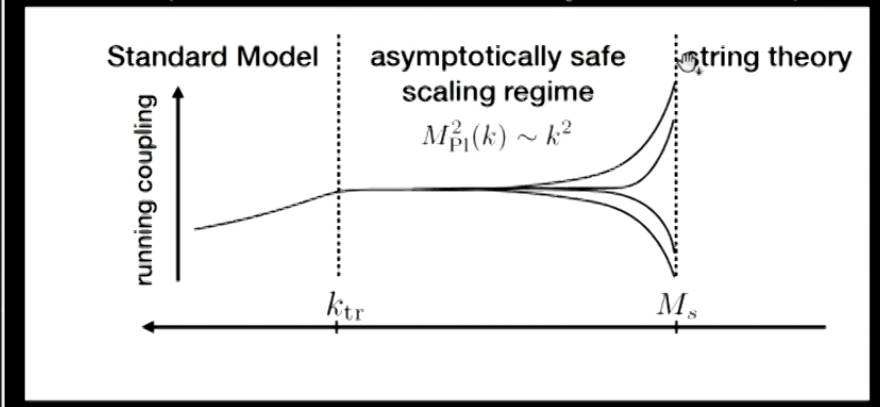
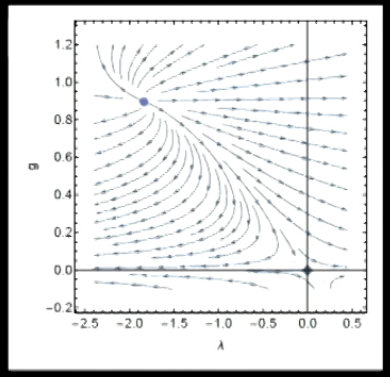
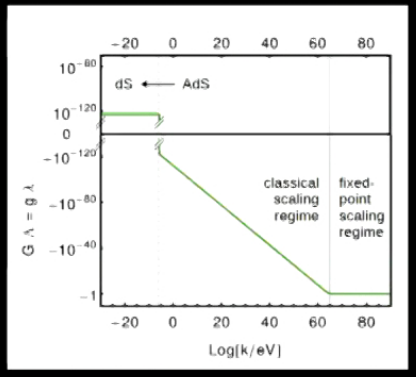
From string theory through asymptotic safety to the Standard Model?

[de Alwis, AE, Held, Pawlowski, Schiffer, Versteegen '19; Basile, Platania '21]

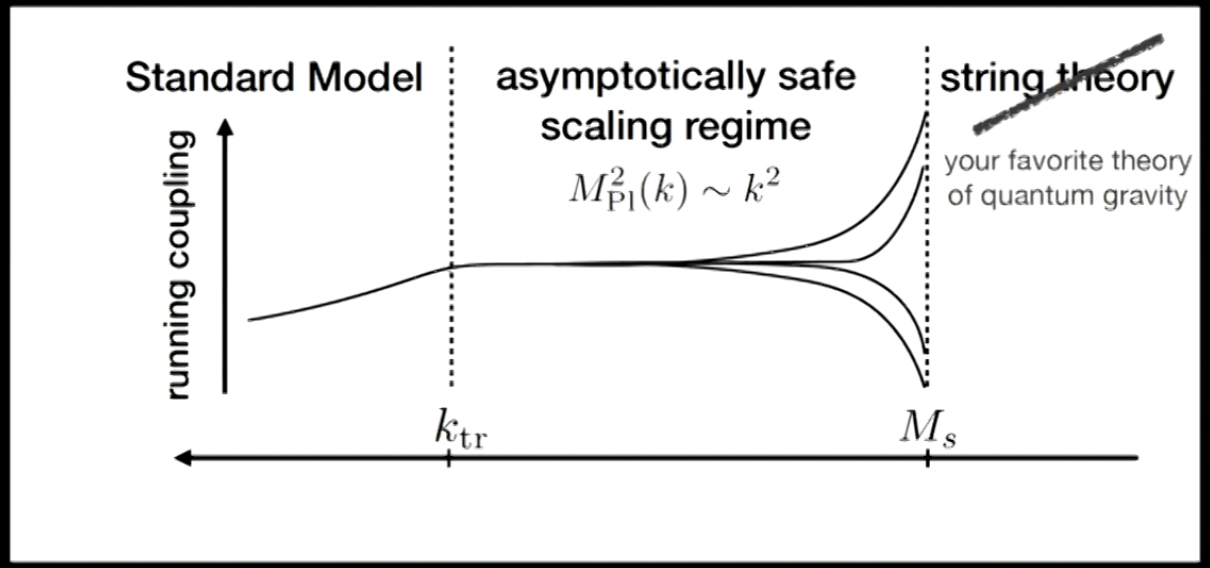






Challenge 3: What is the relation to other ideas about quantum spacetime?

Generalization: effective vs. fundamental asymptotic safety



Asymptotically safe gravity: Status and open challenges*

Evidence for asymptotically safe fixed point

recent reviews: Saueressig '23; Pawlowski, Reichert '23

Evidence for asymptotically safe fixed point with Standard Model matter

recent reviews: AE, Schiffer '22, AE '22

Properties and predictivity of the fixed point

Classical gravity in the IR

Viable phenomenology in particle physics

Resolution of curvature singularities

Connection to other QG approaches

Propagating degrees of freedom & stability

Lorentzian signature

Three challenges:

1) Phenomenology: How to test asymptotically safe quantum gravity?
2) Status of global symmetries
3) Connection to other quantum gravity approaches

Phenomenological status with matter:

- upper bounds on subset of SM couplings have large systematic uncertainties
- first constraints on/exclusions of BSM particle physics (e.g., dark matter)
- ongoing work: delineate the asymptotically safe landscape

Global symmetries:

- intact in functional RG calculations
- related to absence of black-hole spacetimes in the path integral?

Relation to other approaches:

- first studies of relation to string-inspired swampland conjectures
- proposal of effective asymptotic safety

* "Critical reflections on asymptotically safe gravity", Bonanno, AE, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca '20