Title: Probing quantum gravity at all scales

Speakers: Astrid Eichhorn

Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Subject: Cosmology, Strong Gravity, Mathematical physics

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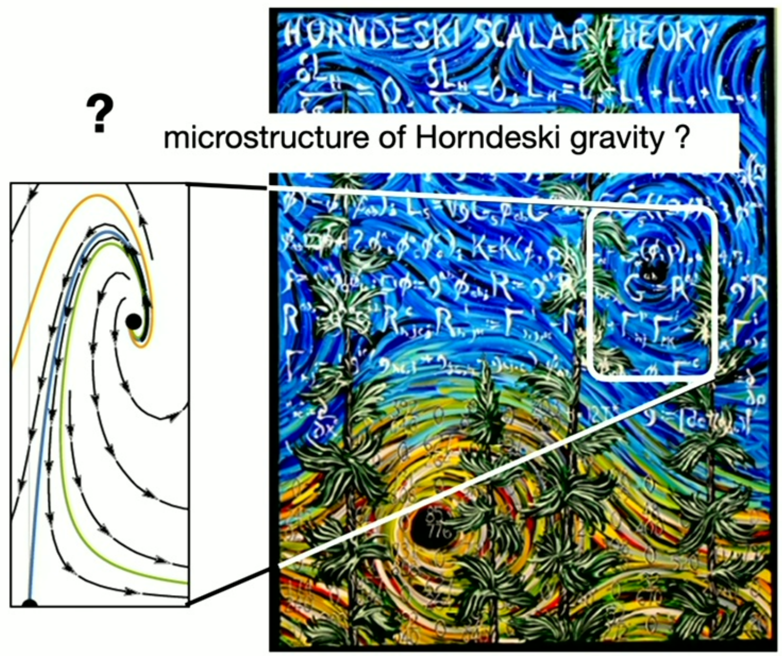
Probing quantum gravity at all scales

50 years of Horndeski gravity

Perimeter Institute & University of Waterloo

July 19, 2024

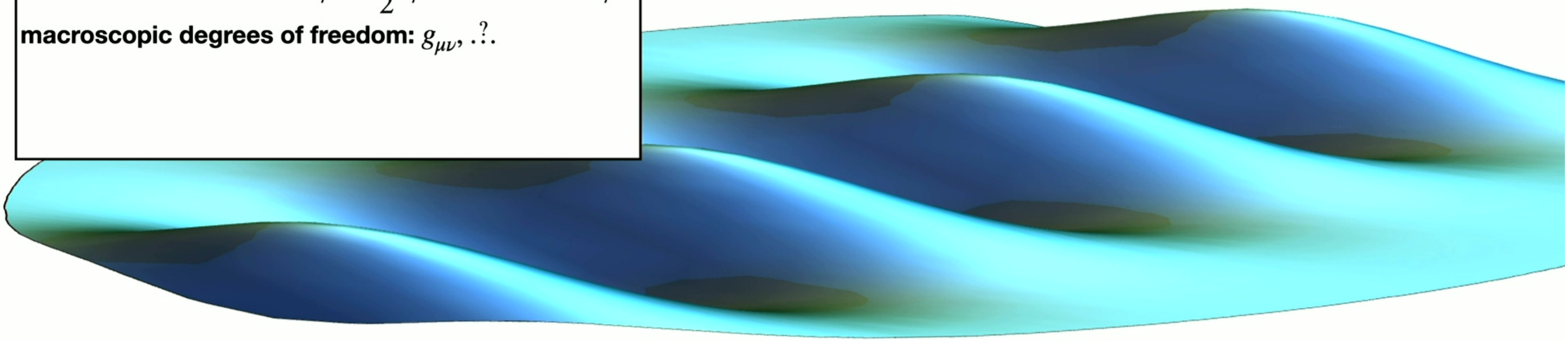
Astrid Eichhorn, University of Southern Denmark



Microscopic and macroscopic dynamics and structure of spacetime

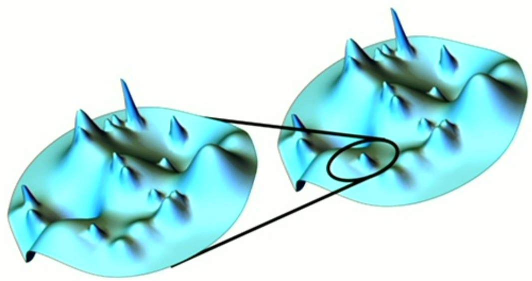
macroscopic dynamics: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} + .?. = 8\pi G\, T_{\mu\nu}$

macroscopic degrees of freedom: $g_{\mu\nu}, .?.$

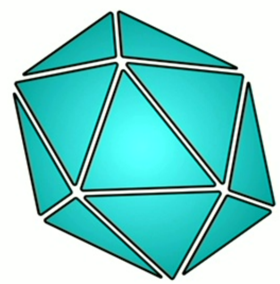


microscopic dynamics: ?

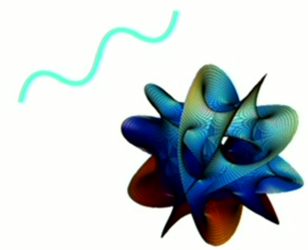
microscopic degrees of freedom: ?



scale-symmetric (safe)



discrete



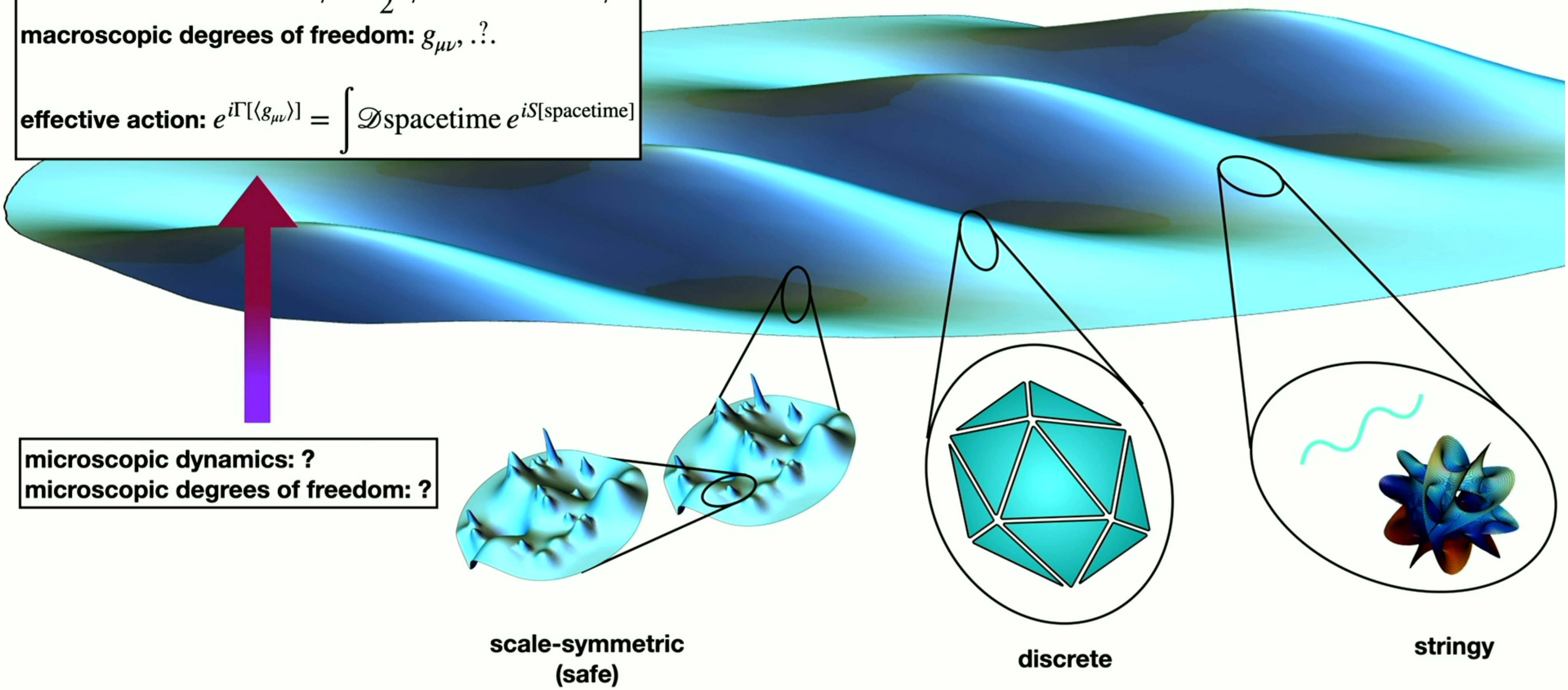
stringy

Microscopic and macroscopic dynamics and structure of spacetime

macroscopic dynamics: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} + .\overset{?}{.}. = 8\pi G\, T_{\mu\nu}$

macroscopic degrees of freedom: $g_{\mu\nu}, .\overset{?}{.}.$

effective action: $e^{i\Gamma[\langle g_{\mu\nu}\rangle]} = \int \mathscr{D}\text{spacetime}\, e^{iS[\text{spacetime}]}$



microscopic dynamics: ?
microscopic degrees of freedom: ?

Microscopic and macroscopic dynamics and structure of spacetime

macroscopic dynamics: $R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} + .\overset{?}{.}. = 8\pi G\, T_{\mu\nu}$

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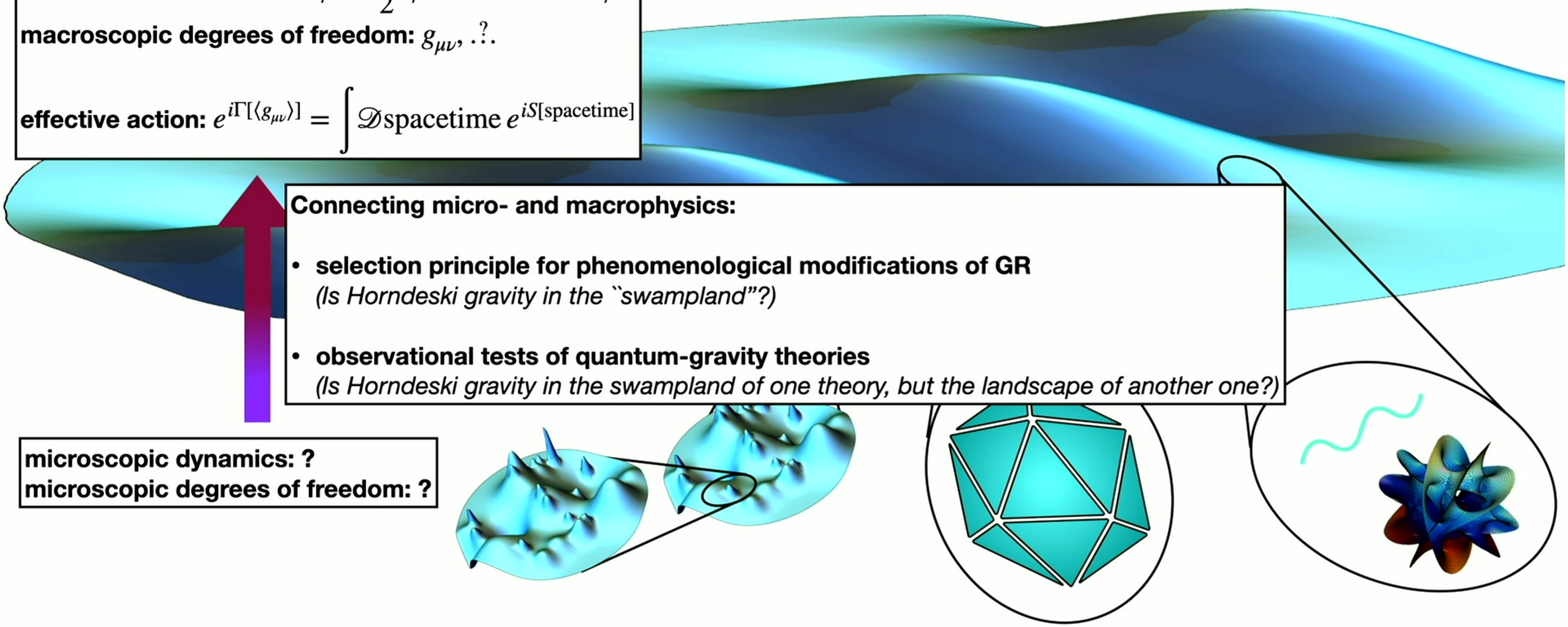
effective action: $e^{i\Gamma[\langle g_{\mu\nu}\rangle]} = \int \mathscr{D}\text{spacetime}\, e^{iS[\text{spacetime}]}$

Connecting micro- and macrophysics:

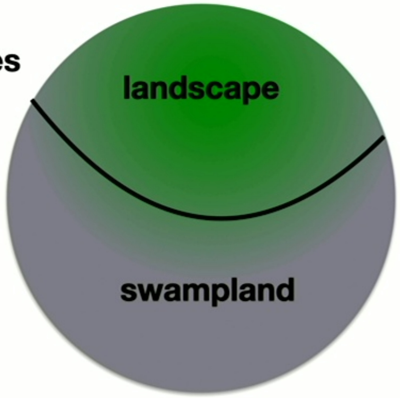
- **selection principle for phenomenological modifications of GR**
  (Is Horndeski gravity in the ``swampland"?)
- **observational tests of quantum-gravity theories**
  (Is Horndeski gravity in the swampland of one theory, but the landscape of another one?)

microscopic dynamics: ?
microscopic degrees of freedom: ?



Relative and absolute swamplands

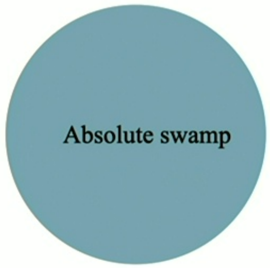
space of all
effective field theories



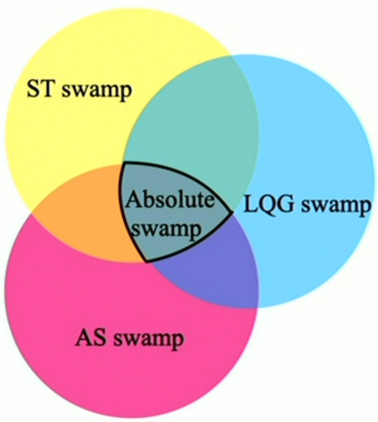
BUT: landscape/swampland of different quantum-gravity theories may differ

[Vafa '05; Ooguri '07]

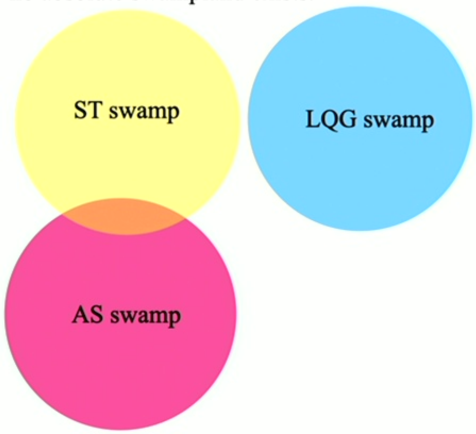
Scenario I:
the absolute swampland is universal.



Scenario II:
the absolute swampland exists.



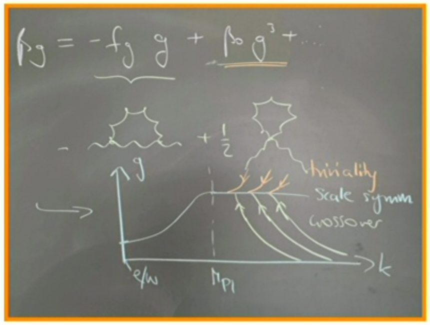
Scenario III:
no absolute swampland exists.



- **modified gravity model in the absolute swamp: not viable**
- **modified gravity model in a relative swamp: testing ground for quantum gravity at cosmological scales**

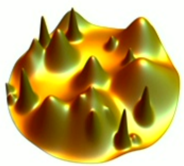
[AE, Hebecker, Pawlowski, Walcher '24]

Probing quantum gravity at all scales!

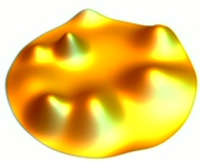


Theory

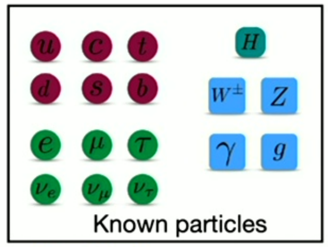
Observational tests



Transplanckian scales

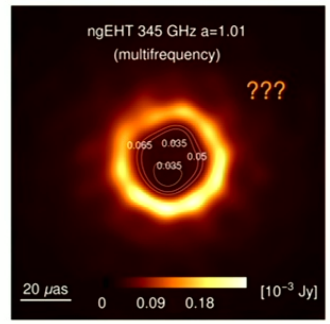


Planck scale



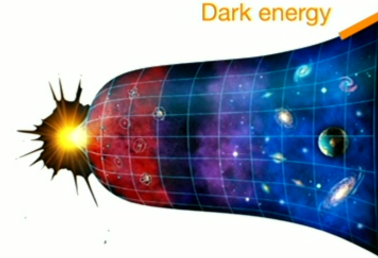
?? ?? Dark matter

Particle physics scales



Black-hole scales

???
Dark energy



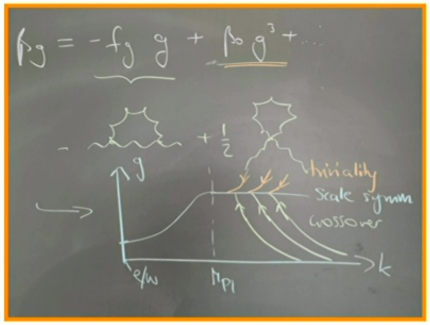
Cosmological scales

distance scale

1. **Why does quantum gravity matter at $\ell \gg \ell_{\text{Planck}}$?**
2. **How to bridge the gap in scales?**

1. **Free parameters in the EFT are fixed by the microphysics**
   Analogy: viscosity in hydrodynamics
2. **Method: Renormalization Group**

Probing quantum gravity at all scales!



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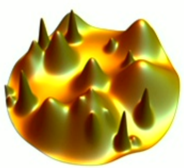
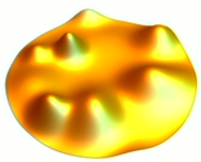
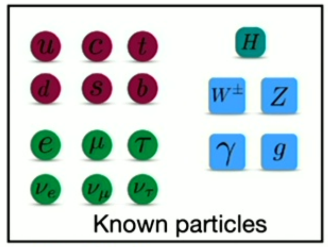


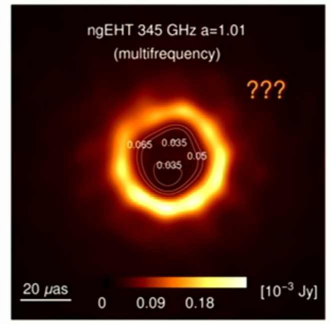


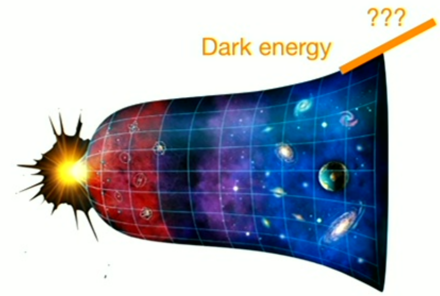
Transplanckian scales

Planck scale

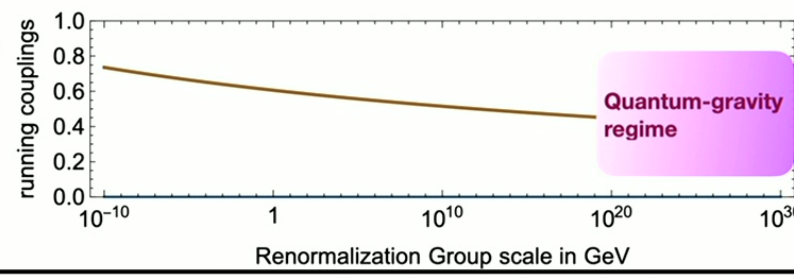


Particle physics scales





ance scale



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2. **How to bridge the gap in scales?**

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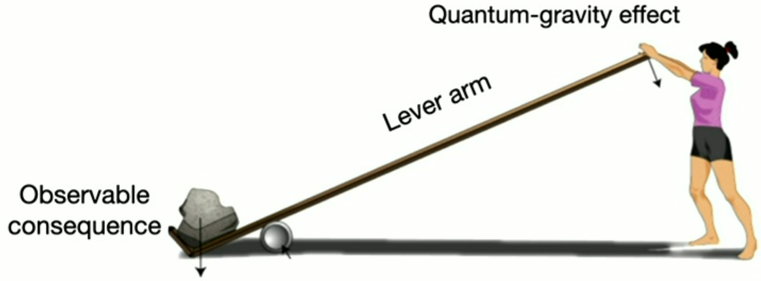
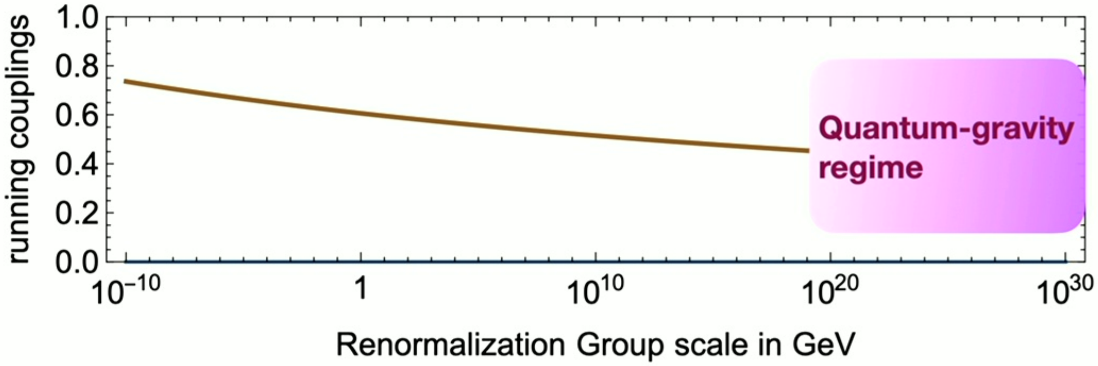
2. **Method: Renormalization Group**

Renormalization Group flow as a lever arm





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

- String theory (see also stringy swampland conjectures)
  [Vafa, Valenzuela, Montero, Ooguri, Palti, Heidenreich, McNamara, Rudelius, Shiu…]
- 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!

Lightning review of asymptotic safety & its predictive power

Key assumptions:

- Metric (plus matter and potential extra fields) carry the fundamental degrees of freedom
- Path integral has a finite number of free parameters

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

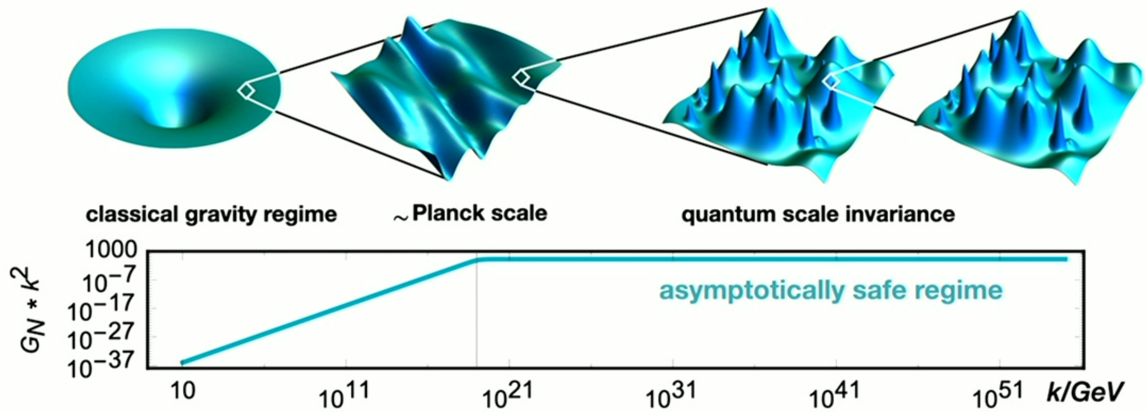
Problem:

perturbative non-renormalizability → breakdown of predictivity

Solution:

Quantum scale symmetry

→ relations between the couplings restore predictivity



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]

Origin of predictions at the Planck scale

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

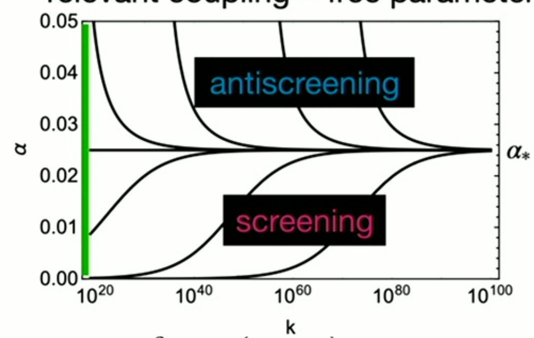
QED: $\beta_e = k\,\partial_k\, e(k) = \frac{1}{12\pi^2} e^3 + \ldots$

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

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

$\rightarrow g(k)$ increases as k is lowered

relevant coupling = free parameter

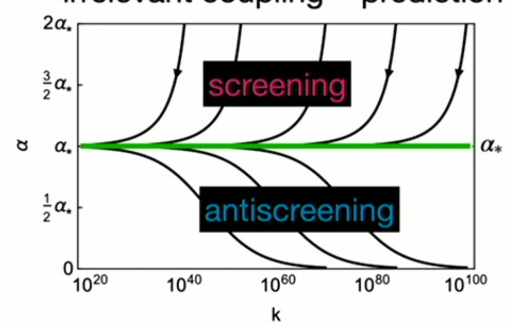


$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

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

Lightning review of asymptotic safety & its predictive power

Asymptotic safety in gravity-matter systems

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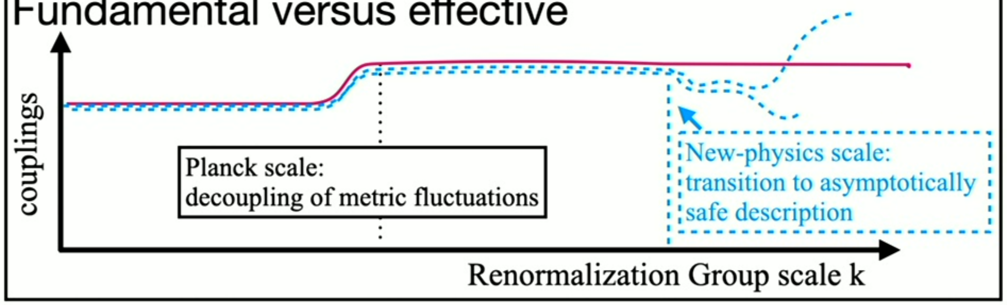
Fundamental versus effective



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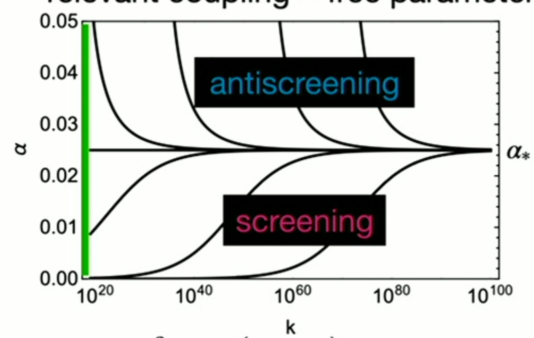
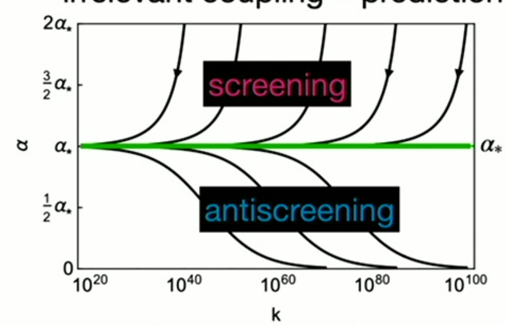


$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

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

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

irrelevant coupling = prediction



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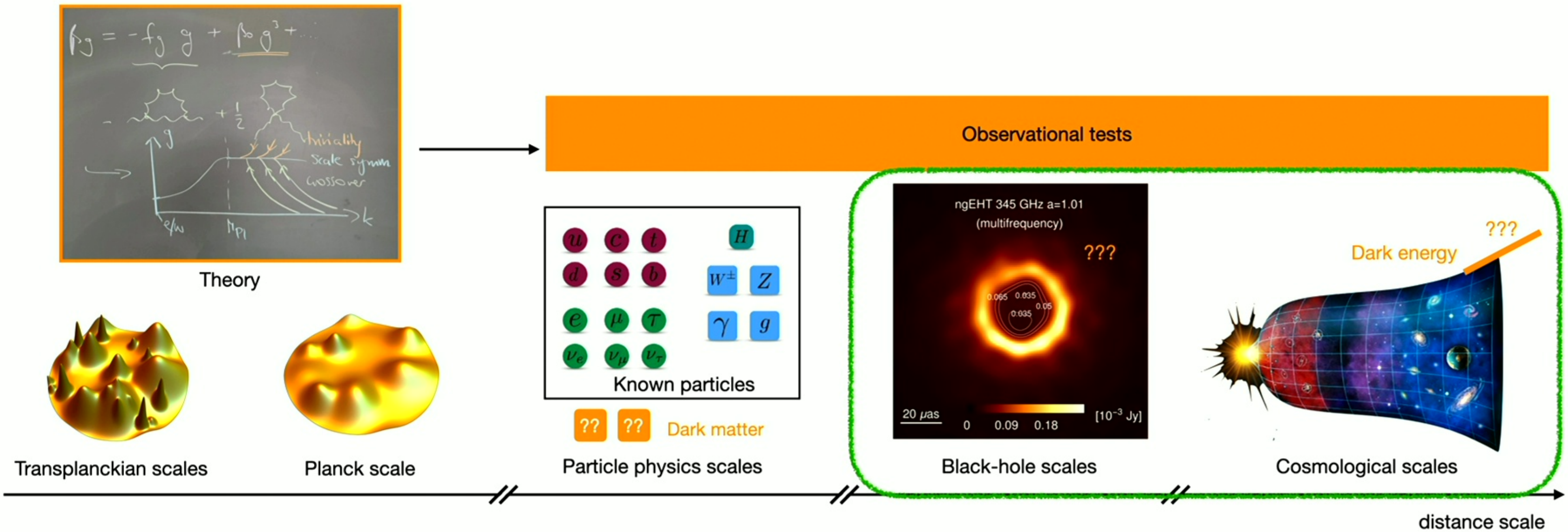
quantum fluctuations drive coupling **towards** scale symmetry

$\rightarrow$ a unique coupling value achievable at the Planck scale

Scalar-tensor theories in asymptotically safe gravity



scalar-tensor theories in asymptotic safety

Scalar-tensor theories in asymptotically safe gravity

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

$$\Gamma_k = \int d^4x \sqrt{\det g_{\mu\nu}} \Big[-\frac{1}{16\pi G(k)\, k^{-2}} \left(R - 2\Lambda(k)k^2\right) + f(k)[R, R_{\mu\nu}, R_{\mu\nu\kappa\lambda}, D_\mu] \quad + Z_\phi(k)(D^2)X \quad + V(k)[\phi] \quad + f_\phi(k)[R]\phi^2 + \frac{\sigma(k)}{k^2} R_{\mu\nu}\partial^\mu\phi\partial^\nu\phi + \ldots \quad + \frac{g(k)}{k^4}X^2 + \frac{h(k)}{k^3}XD^2\phi + ..$$

pure gravity	scalar kinetic term	scalar potential	non-minimal couplings	derivative interactions

- **Question 1: Do these couplings become asymptotically safe in the UV?**
- **Question 2: Are these couplings free parameters or are their values predicted at the Planck scale (and thus calculable at cosmological scales)?**

Scalar-tensor theories in asymptotically safe gravity

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

$$\Gamma_k = \int d^4x \sqrt{\det g_{\mu\nu}} \left[-\frac{1}{16\pi G(k)\, k^{-2}} \left(R - 2\Lambda(k)k^2\right) + f(k)[R, R_{\mu\nu}, R_{\mu\nu\kappa\lambda}, D_\mu] \quad + Z_\phi(k)(D^2)X \quad + V(k)[\phi] \quad + f_\phi(k)[R]\phi^2 + \frac{\sigma(k)}{k^2} R_{\mu\nu}\partial^\mu\phi\partial^\nu\phi + \dots \quad + \frac{g(k)}{k^4}X^2 + \frac{h(k)}{k^3} X D^2 \phi + ..\right.$$

pure gravity | **scalar kinetic term** | **scalar potential** | **non-minimal couplings** | **derivative interactions**

prediction

free parameter

R^{70}

$(R_{\mu\nu}R^{\mu\nu})^{10}$

$R(R_{\mu\nu}R^{\mu\nu})^9$

$\dots$ $\quad \dots$

$\dots$

$R(R_{\mu\nu}R^{\mu\nu})^2$

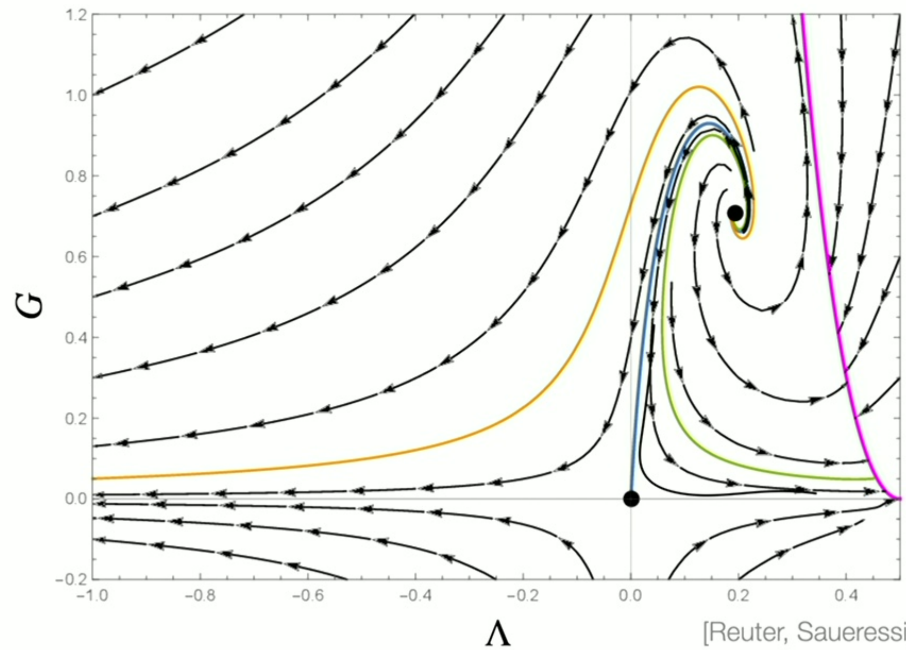
$(R_{\mu\nu}R^{\mu\nu})^2$

$R^3 \quad C_{\mu\nu\kappa\lambda}C^{\mu\nu\alpha\beta}C_{\alpha\beta}{}^{\kappa\lambda} \quad RR_{\mu\nu}R^{\mu\nu}$

$R^2 \quad C_{\mu\nu\kappa\lambda}C^{\mu\nu\kappa\lambda}$

R

[Codello, de Brito, AE, Falls, Gies, Knorr, Litim, Pawlowski, Percacci, Rahmede, Reichert, Reuter, Saueressig, Schiffer…]



[Reuter, Saueressig '01]

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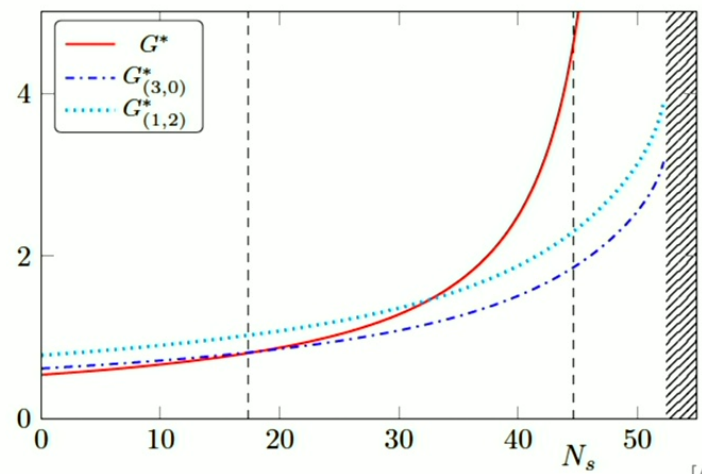
pure gravity | **scalar kinetic term** | **scalar potential** | **non-minimal couplings** | **derivative interactions**

can add several scalars and only slightly deform gravitational fixed point

[Dona, AE, Percacci '13]



[AE, Labus, Percacci, Reichert '18]

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pure gravity | **scalar kinetic term** | **scalar potential** | **non-minimal couplings** | **derivative interactions**

$$V[\phi] = \frac{m(k)^2}{2k^2}\phi^2+\frac{\lambda(k)}{8}\phi^4+\ldots$$

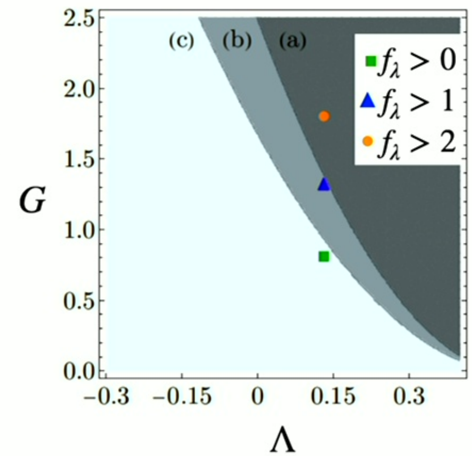
fixed-point values: $m^2=0, \lambda=0, \ \ldots$

predictions?

$$k\partial_k m^2 = \left(-2+f_\lambda\right)m^2+\ldots$$
$$k\partial_k\lambda = f_\lambda\lambda+\ldots$$

$f_\lambda > 0:$
gravity fluctuations screen scalar potential

⇒ relevant directions: one or zero



[AE, Pauly '18]

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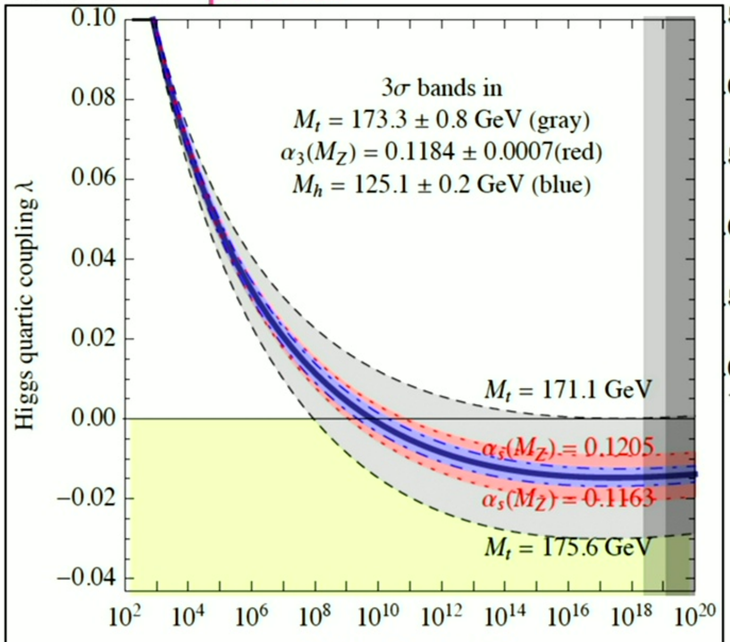
pure gravity | **scalar kinetic term** | **scalar potential** | **non-minimal couplings** | **derivative interactions**

phenomenological consequences:

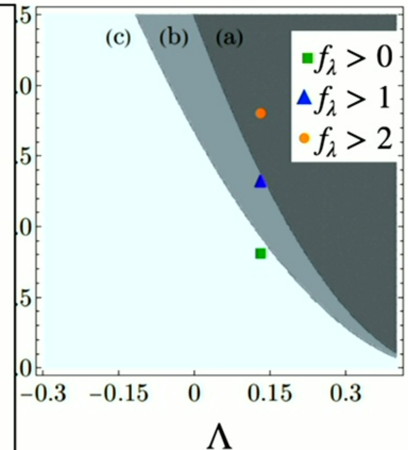
- **Higgs quartic coupling vanishes at the Planck scale**

  → prediction of Higgs mass from asymptotic safety

  [Shaposhnikov, Wetterich '09]



[Buttazzo et al '14]



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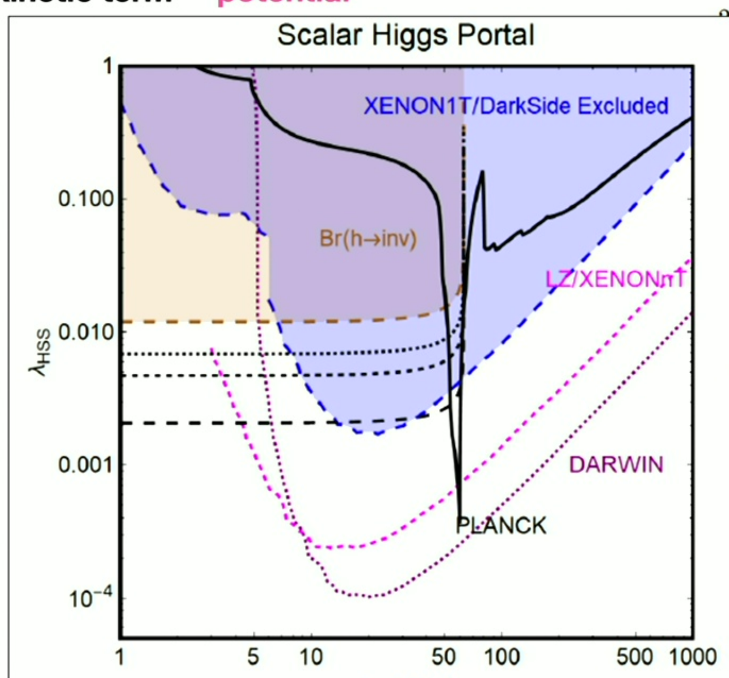
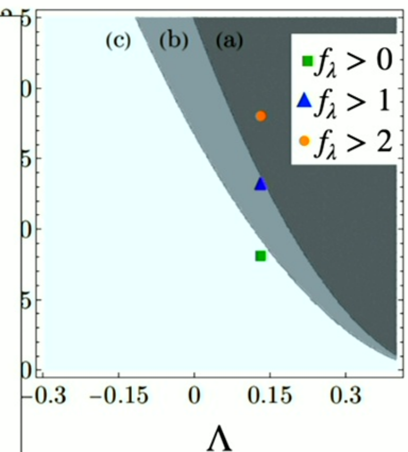
  [Shaposhnikov, Wetterich '09]

- **Higgs portal coupling to dark scalar $\lambda_{HSS}H^\dagger H\,S^2$ vanishes at all scales**

  [AE, Hamada, Lumma, Yamada '17]



[Arcadi et al '19]



[AE, Pauly '18]

Scalar-tensor theories in asymptotically safe gravity

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

$$\Gamma_k = \int d^4x \sqrt{\det g_{\mu\nu}} \Big[-\frac{1}{16\pi G(k)\, k^{-2}} \left(R - 2\Lambda(k)k^2\right) + f(k)[R, R_{\mu\nu}, R_{\mu\nu\kappa\lambda}, D_\mu] \quad + Z_\phi(k)(D^2)X \quad + V(k)[\phi] \quad + f_\phi(k)[R]\phi^2 + \frac{\sigma(k)}{k^2} R_{\mu\nu}\partial^\mu\phi\partial^\nu\phi + \dots \quad + \frac{g(k)}{k^4}X^2 + \frac{h(k)}{k^3} X D^2\phi + \dots$$

pure gravity | **scalar** | **scalar** | **non-minimal couplings** | **derivative interactions**

phenomenological consequences:

- **Higgs quartic coupling vanishes at the Planck scale**

  → prediction of Higgs mass from asymptotic safety

  [Shaposhnikov, Wetterich '09]

- **Higgs portal coupling to dark scalar $\lambda_{HSS} H^\dagger H S^2$ vanishes at all scales**

  [AE, Hamada, Lumma, Yamada '17]

- **flat potentials for dark energy/inflation can be accommodated, $|V'|/V \approx 0$**

  [AE, Pauly '18]

difference to stringy swampland conjecture:

$|V'|/V > c, \quad c \sim \mathcal{O}(1)$ [Obied, Ooguri, Spodyneiko, Vafa '18]

equation-of-state-parameter of dark energy: $w > 0.15c^2 - 1$

[Heisenberg, Bartelmann, Brandenberger, Refregier '18]

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pure gravity — **scalar kinetic term** — **scalar potential** — **non-minimal couplings** — **derivative interactions**

$f_\phi[R] = 0, \quad \sigma \neq 0$

[Percacci, Narain '09] [AE, Lippoldt, Skrinjar '17]

accident or deeper reason?

σ **respects global shift-symmetry** $\phi \to \phi + a$**,**
$f_\phi[R]$ **does not**

Interlude: Global symmetries in quantum gravity and asymptotic safety

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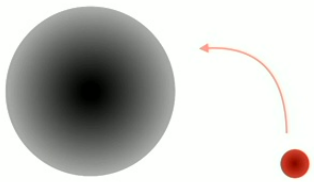
No-global symmetries conjecture:

[Banks, Dixon '88; Giddings, Strominger '88; Abbott, Wise '89; Kallosh, Linde, Linde, Susskind '95….]

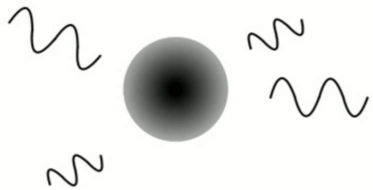
1) Black-hole spacetimes violate conservation of global charges



black hole

particle w. global charge

with Hawking entropy



black hole undergoes complete Hawking evaporation (no remnants)

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

⇒ effective theory for matter has no conserved global charges

string theory: any global symmetry automatically becomes local [Banks, Dixon '88]

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

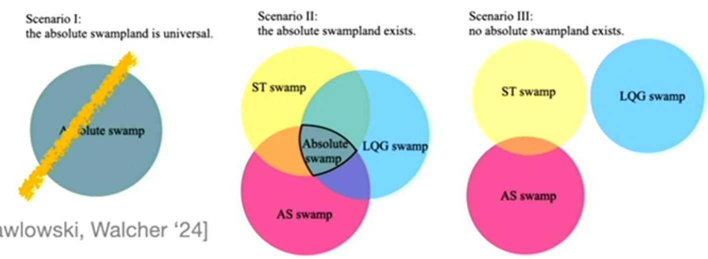
$\int \mathcal{D}g_{\mu\nu} e^{iS}$: destructive interference for configurations with $S \to \infty$

$$S = \ldots + \int d^4x \sqrt{g}\, C^2 \to \infty \text{ for singular black holes}$$

[Borissova, AE '20; Borisssova '23]

$$S = \ldots + \int d^4x \sqrt{-g} \frac{(C^2)^8}{4C^2(\nabla_\mu C)^2 - (\nabla_\mu C^2)^2} \to \infty \text{ at the horizon}$$

Borissova, AE, Ray '24



[AE, Hebecker, Pawlowski, Walcher '24]

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pure gravity | **scalar kinetic term** | **scalar potential** | **non-minimal couplings** | **derivative interactions**

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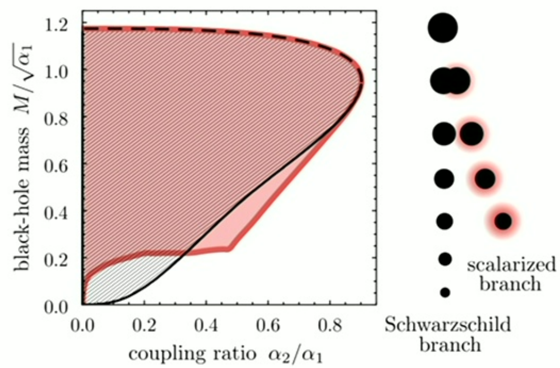
σ respects global shift-symmetry $\phi \to \phi + a$, $f_\phi[R]$ does not

symmetry-based outlook on scalar-Gauss-Bonnet-gravity:

- **black-hole scalarization below critical ADM mass from**
  $\alpha_1 F[\phi]\left(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}\right) = \alpha_1 F[\phi]\mathcal{G}$
  [Damour, Esposito-Faresè '93; Doneza, Yazadijev '17; Silva et al. 17,…]
- **black-hole scalarization in finite ADM mass range from**
  $\alpha_1 F[\phi]\left(\mathcal{G} - \frac{\alpha_2}{\alpha_1}\mathcal{G}^2\right)$ [AE, Fernandes, Held, Silva '23]



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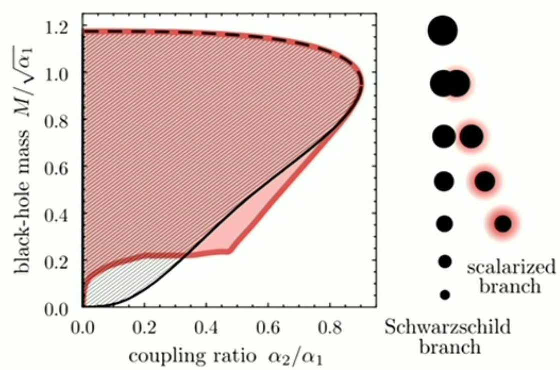
  [AE, Fernandes, Held, Silva '23]

all scalar-Gauss-Bonnet couplings break shift symmetry or $\mathbb{Z}_2$-symmetry ⇒ expect zero fixed-point values

all scalar-Gauss-Bonnet couplings have negative mass-dimension ⇒ expect strong selection among $F[\phi]$'s



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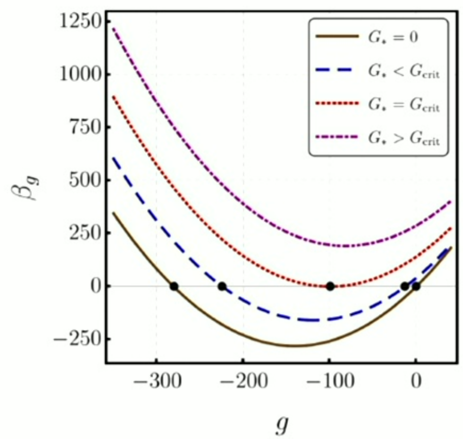

there is no fixed point at $g_* = 0$ in the presence of gravity fluctuations

[AE '12; de Brito, AE, Lino dos Santos '21]

beyond $G_{\rm crit}$, gravity fluctuations change the scaling exponent and derivative interactions are relevant

[de Brito, Knorr, Schiffer '23]

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pure gravity — **scalar kinetic term** — **scalar potential** — **non-minimal couplings** — **derivative interactions**

Example: simplest Horndeski theory

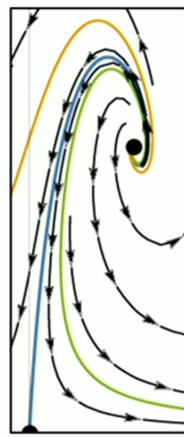
$$\mathscr{L}_2 = -G_2(\phi,\chi), \quad \mathscr{L}_3 = G_3(\phi,\chi)D^2\phi,$$

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

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

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

Is this the microstructure of Horndeski gravity?



[Horndeski '74]

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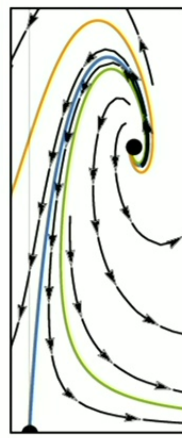
@ $g \neq 0$, need $h \neq 0$ to provide dark energy

asymptotic-safety condition:

$h(k) \to 0$ at all k [AE, Rafael R. Lino dos Santos, Fabian Wagner '23]

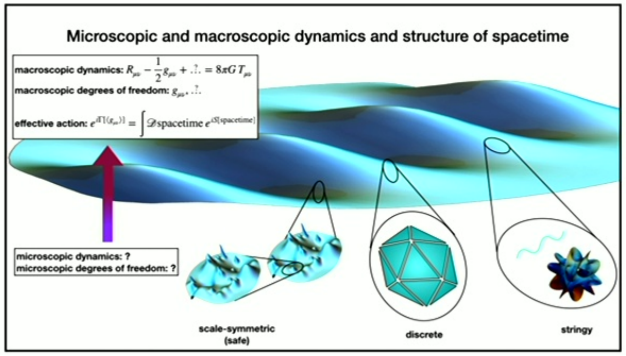
Is this the microstructure of Horndeski gravity?



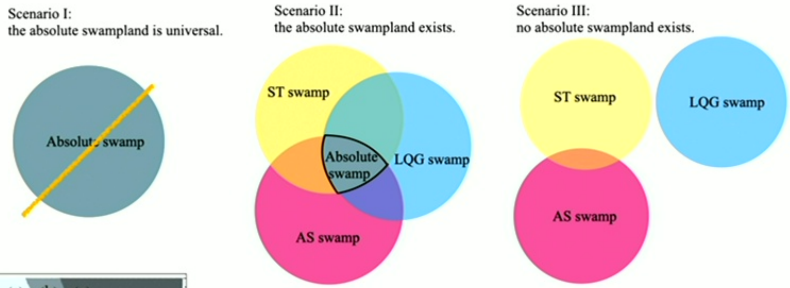
[Horndeski '74]

Summary: key messages

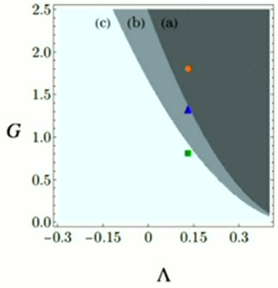
- **quantum gravity and modified gravity:**
  ultraviolet and infrared incarnations of the same physics



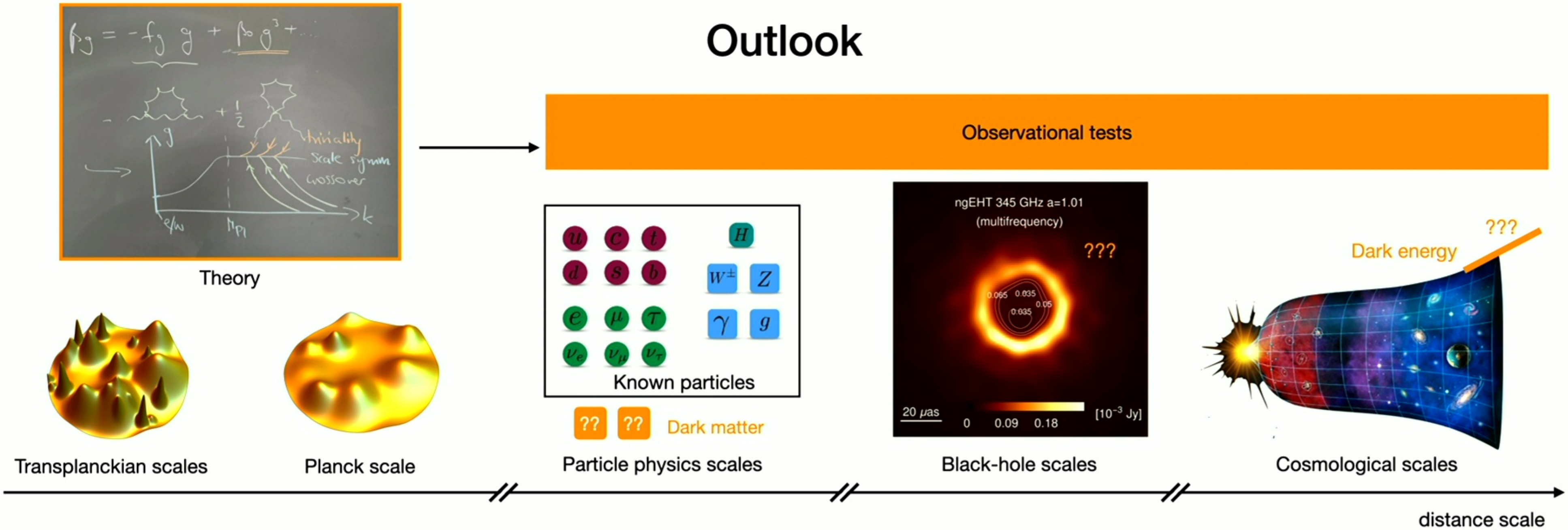
- **absolute swampland probably not universal:**
  observational search for modified gravity can shed light on quantum gravity



- **asymptotically safe gravity has predictive power for scalar-tensor theories**



Outlook



Horndeski, DHOST and beyond: which phenomenological models are asymptotically safe?

Pheno:

- **Which equation-of-state-parameters for dark energy are compatible with asymptotic safety?**
- **Is scalarization of black holes viable in asymptotic safety?**

Theory:

- **Is unitarity preserved?**
- **Which modes propagate?**

Thanks to current and former group members

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Arthur Vieira
Arslan Sikandar
Vedran Skrinjar
Carlos Nieto

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Philipp Johannsen
Ludivine Fausten
Christopher Pfeiffer
Ademola Adeifeoba
Peter Vander Griend