Title: Conference Talk

Speakers:

Collection: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Date: July 19, 2024 - 9:45 AM

URL: https://pirsa.org/24070053

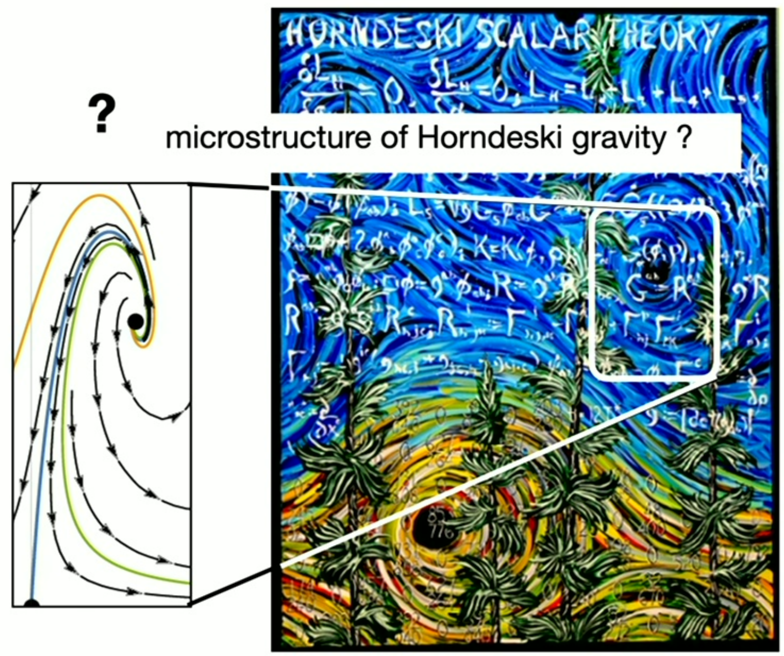
Probing quantum gravity at all scales

50 years of Horndeski gravity

Perimeter Institute & University of Waterloo

July 19, 2024

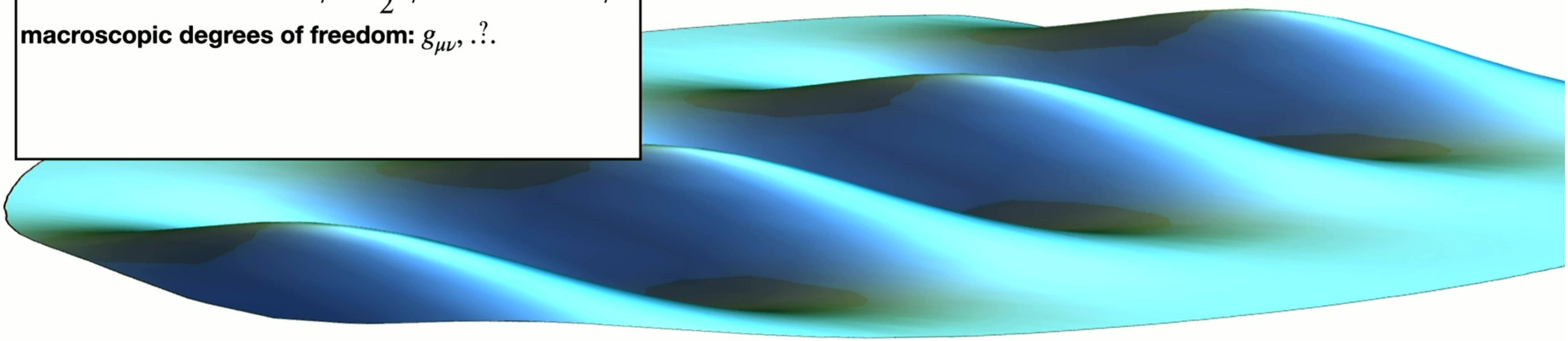
Astrid Eichhorn, University of Southern Denmark



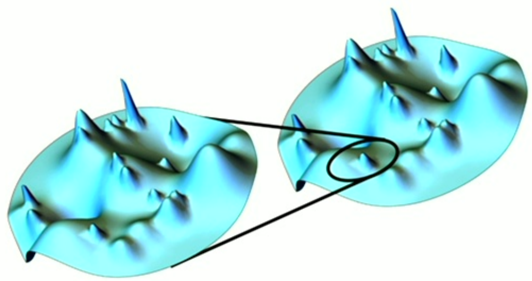
Microscopic and macroscopic dynamics and structure of spacetime

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

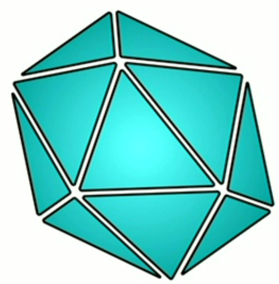
macroscopic degrees of freedom: $g_{\mu\nu}, .?.$



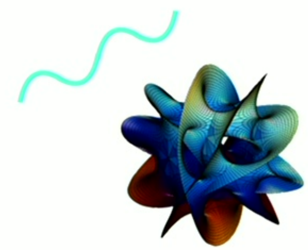
microscopic dynamics: ?
microscopic degrees of freedom: ?



scale-symmetric (safe)

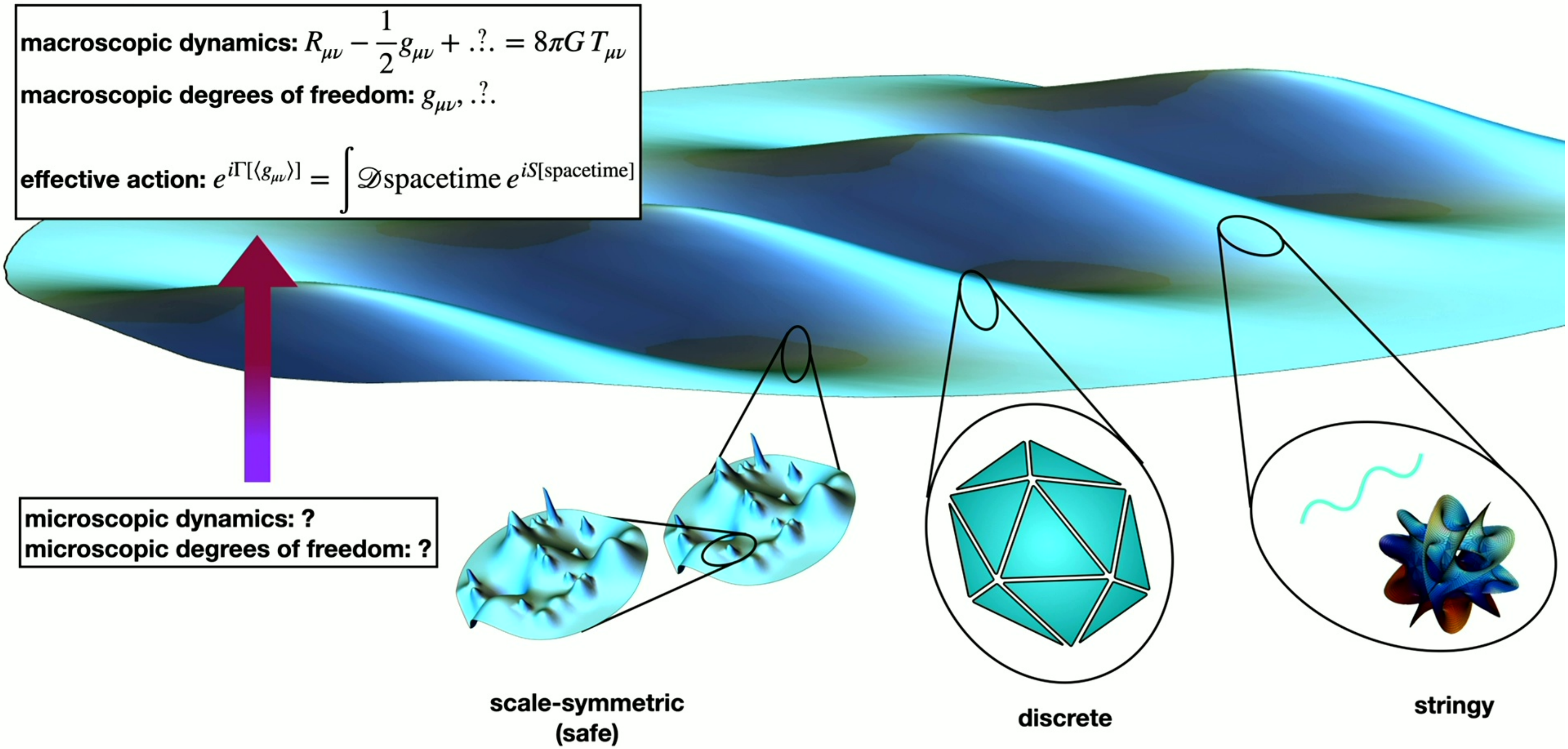


discrete



stringy

Microscopic and macroscopic dynamics and structure of spacetime



Microscopic and macroscopic dynamics and structure of spacetime

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

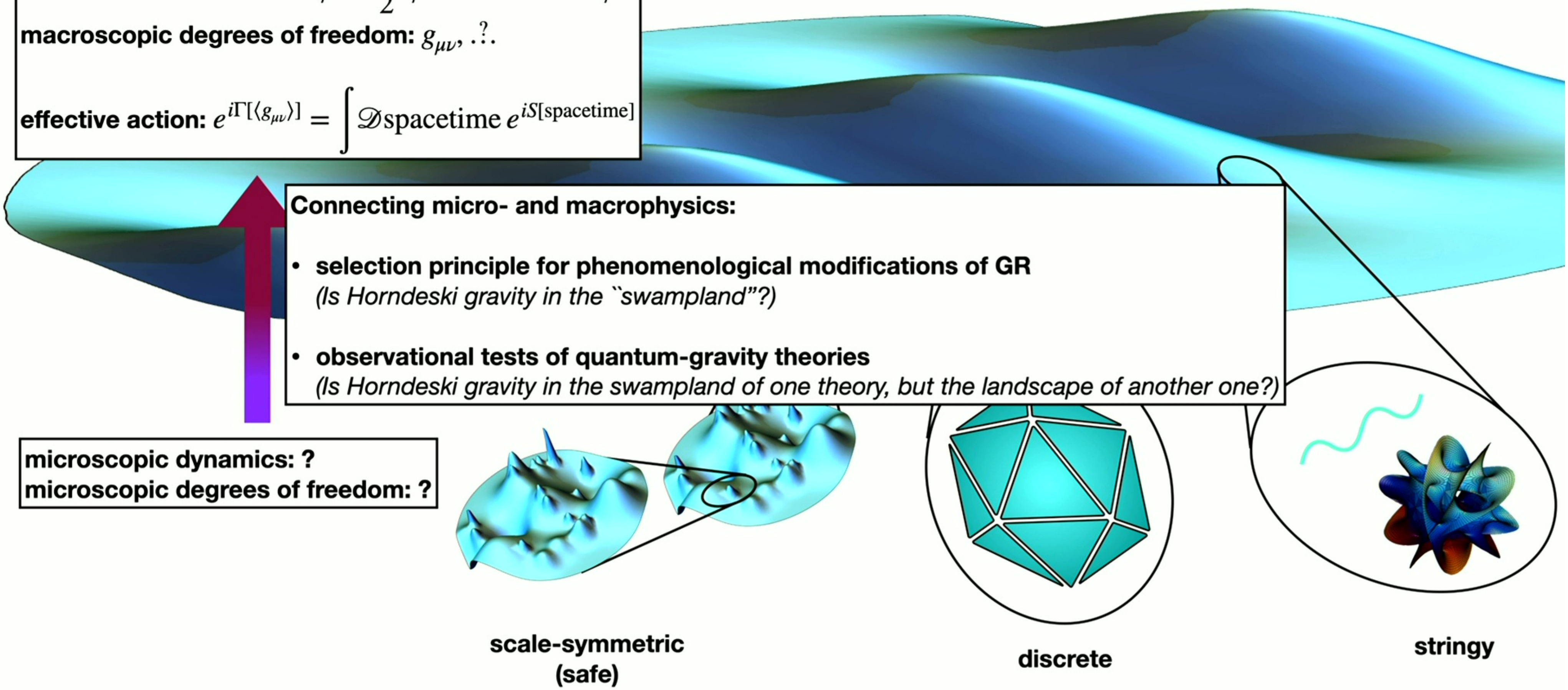
macroscopic degrees of freedom: $g_{\mu\nu}, .\overset{?}{.}.$

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

Connecting micro- and macrophysics:

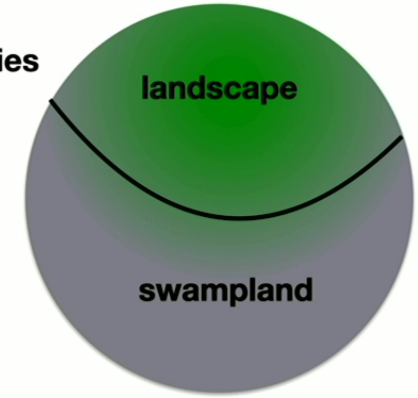
- **selection principle for phenomenological modifications of GR**
  (Is Horndeski gravity in the ``swampland"?)
- **observational tests of quantum-gravity theories**
  (Is Horndeski gravity in the swampland of one theory, but the landscape of another one?)

microscopic dynamics: ?
microscopic degrees of freedom: ?



Relative and absolute swamplands

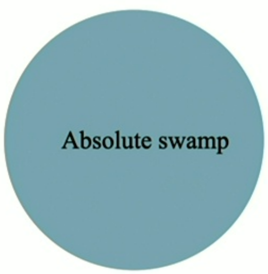
space of all
effective field theories



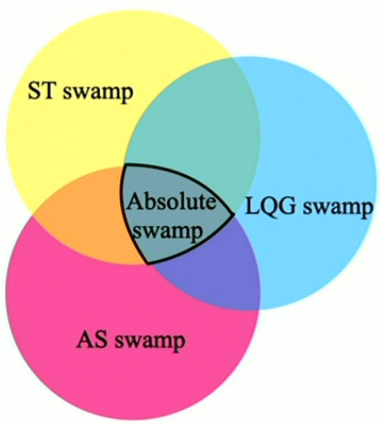
BUT: landscape/swampland of different quantum-gravity theories may differ

[Vafa ’05; Ooguri ’07]

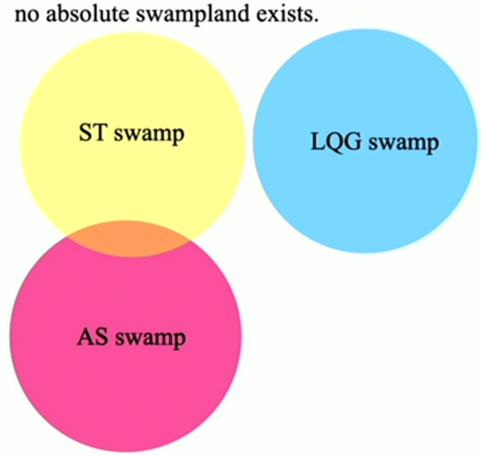
Scenario I:
the absolute swampland is universal.



Scenario II:
the absolute swampland exists.



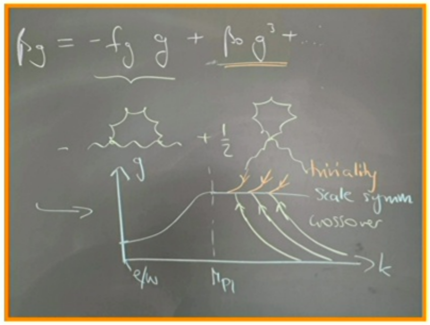
Scenario III:
no absolute swampland exists.



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

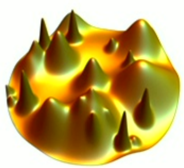
[AE, Hebecker, Pawlowski, Walcher ‘24]

Probing quantum gravity at all scales!

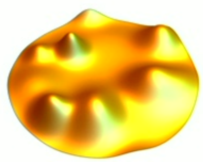


Theory

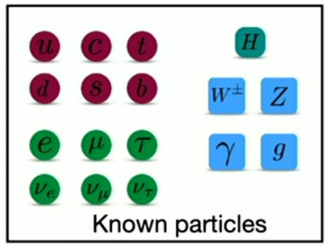
Observational tests



Transplanckian scales

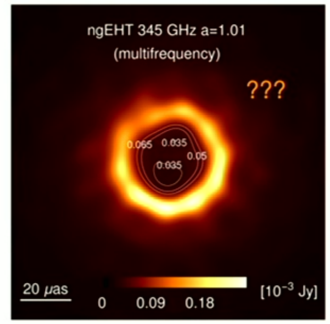


Planck scale

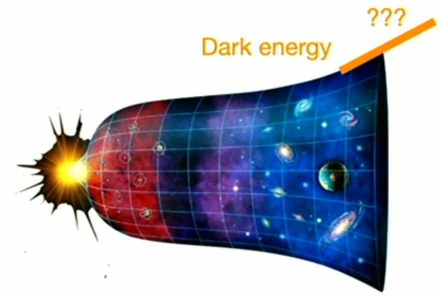


?? ?? Dark matter

Particle physics scales



Black-hole scales



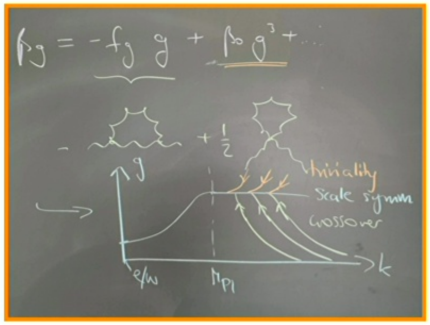
Cosmological scales

distance scale

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

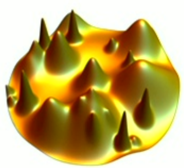
1. Free parameters in the EFT are fixed by the microphysics
   Analogy: viscosity in hydrodynamics
2. Method: Renormalization Group

Probing quantum gravity at all scales!

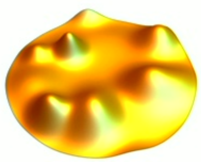


Theory

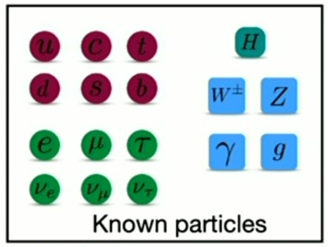
Observational tests



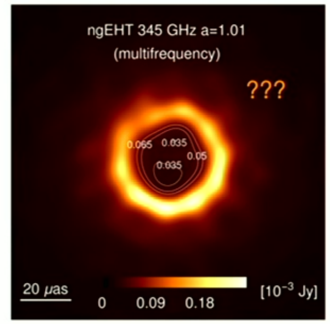
Transplanckian scales

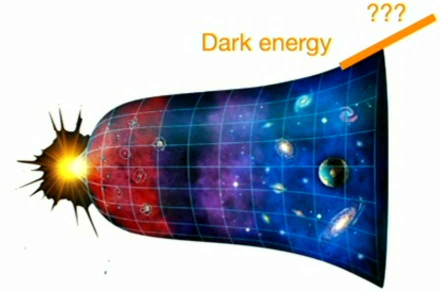


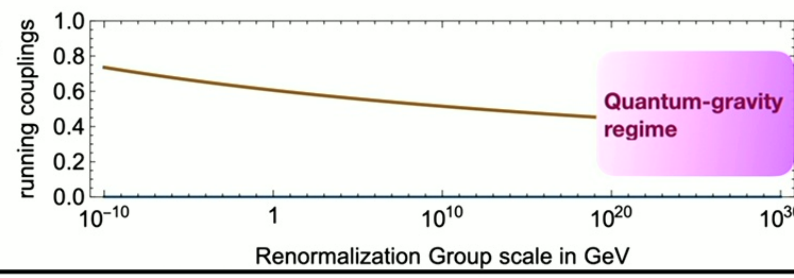
Planck scale



Particle physics scales





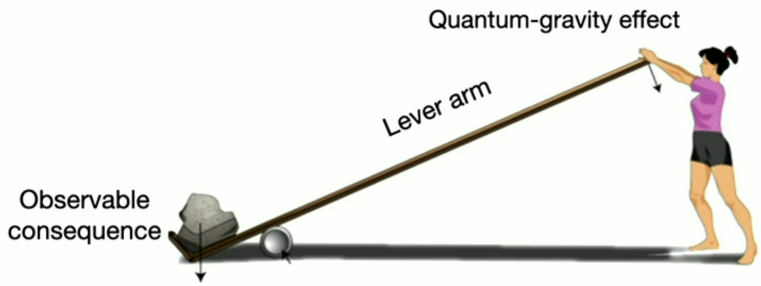


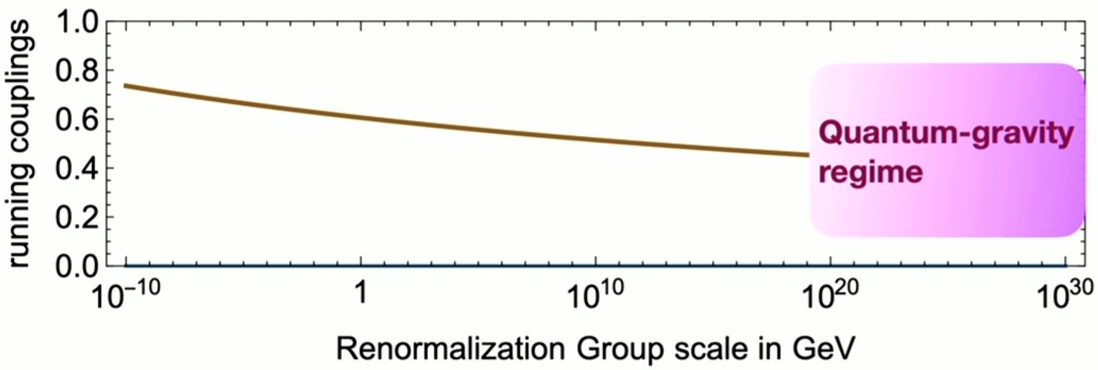
ance scale

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**

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

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

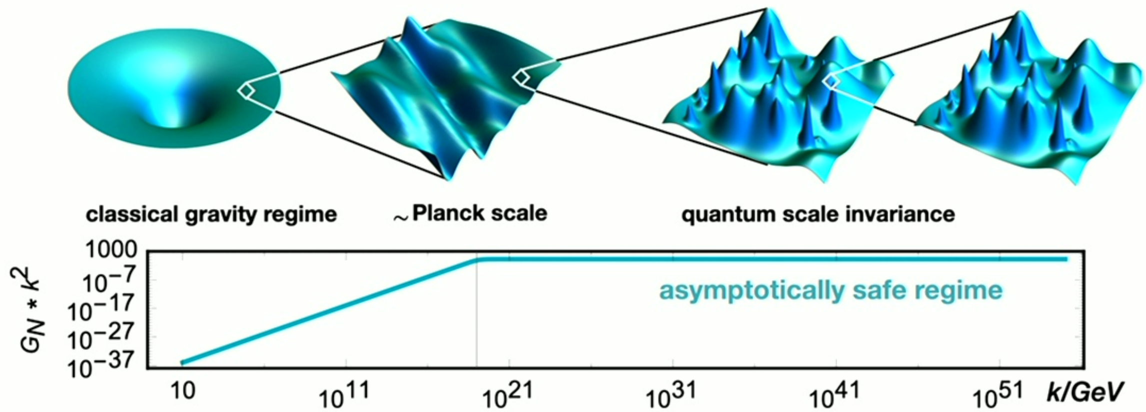
Problem:

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.,

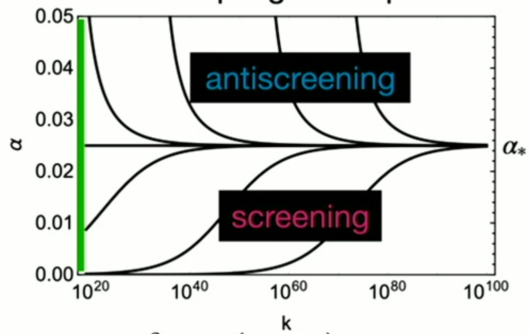
QED: $\beta_e = k\,\partial_k\, e(k) = \frac{1}{12\pi^2} e^3 + \ldots$

$\rightarrow$ $e(k)$ 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

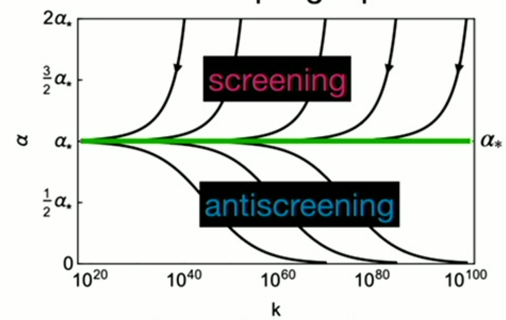


$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

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

$\rightarrow$ 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

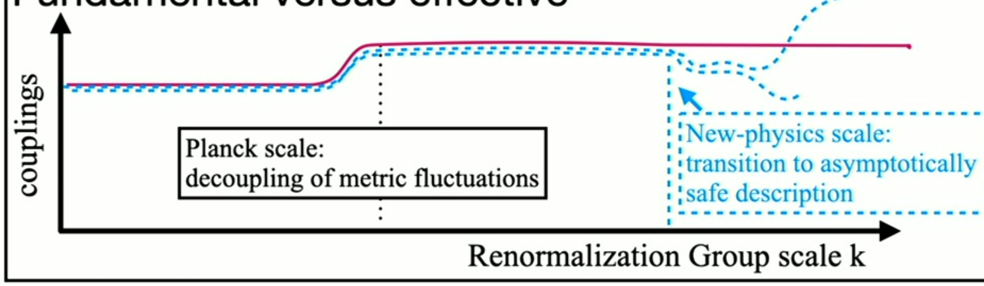
$\rightarrow$ a unique coupling value achievable at the Planck scale

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]

Fundamental versus effective



Origin of predictions at the Planck scale

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

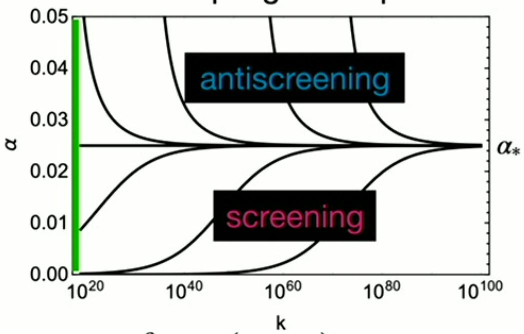
QED: $\beta_e = k\,\partial_k\, e(k) = \frac{1}{12\pi^2} e^3 + \ldots$

→ $e(k)$ decreases as k is lowered

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

→ $g(k)$ increases as k is lowered

relevant coupling = free parameter

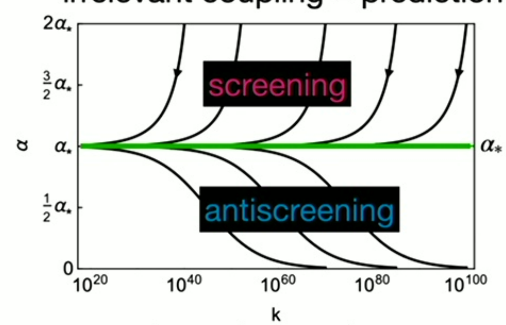


$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

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

→ a range of coupling values achievable at the Planck scale

irrelevant coupling = prediction

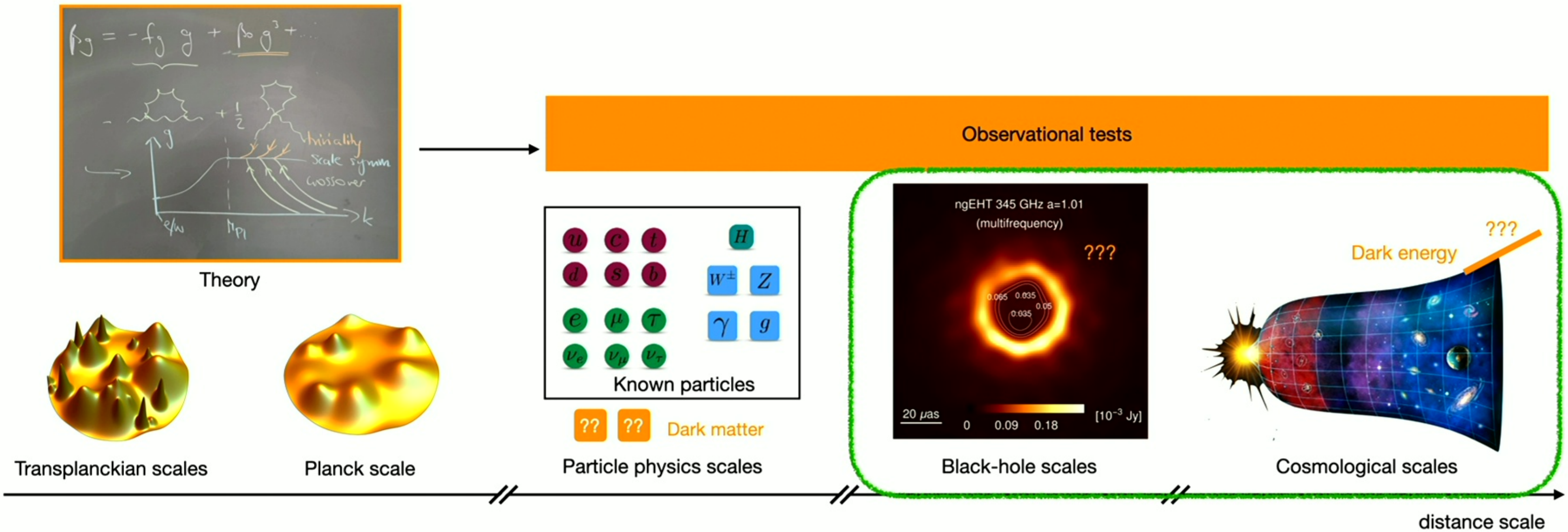


$\beta_\alpha = \alpha\,(-\alpha_* + \alpha)$

quantum fluctuations drive coupling **towards** scale symmetry

→ a unique coupling value achievable at the Planck scale

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

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

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

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

prediction

free parameter

R^{70}

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

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

$\dots \quad \dots$

$\dots$

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

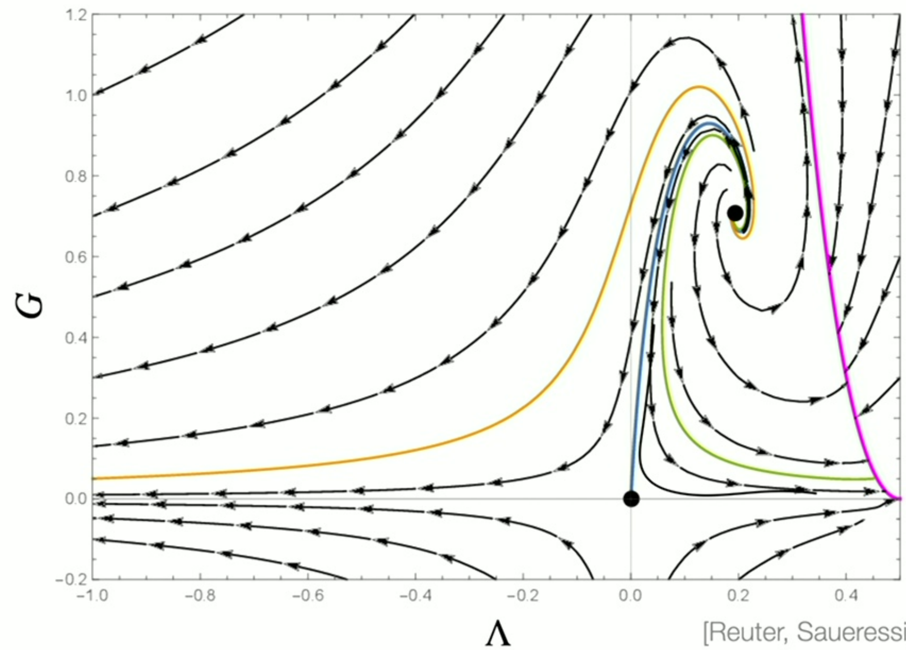
$(R_{\mu\nu}R^{\mu\nu})^2$

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

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

R

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



[Reuter, Saueressig '01]

Scalar-tensor theories in asymptotically safe gravity

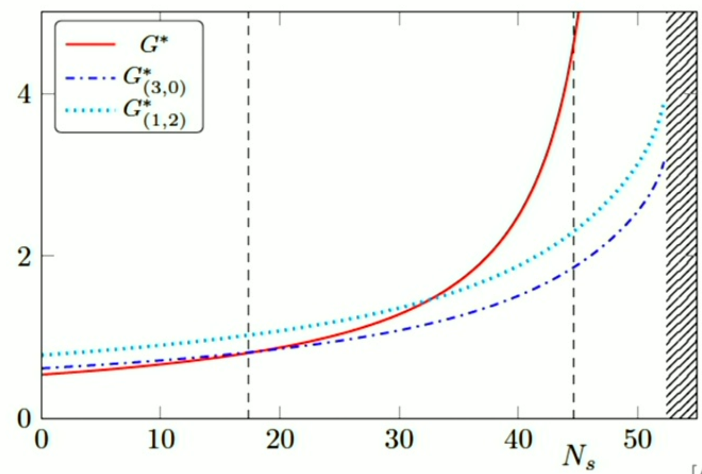
$X = -D_\mu \phi D^\mu \phi / 2$

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

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

can add several scalars and only slightly deform gravitational fixed point

[Dona, AE, Percacci '13]



[AE, Labus, Percacci, Reichert '18]

Scalar-tensor theories in asymptotically safe gravity

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

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

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

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

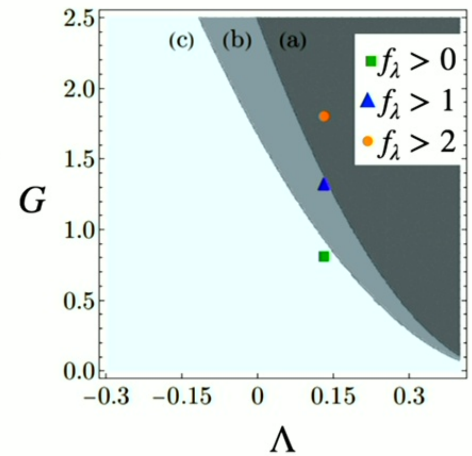
fixed-point values: $m^2 = 0, \lambda = 0, \dots$

predictions?

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

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

⇒ relevant directions: one or zero



[AE, Pauly '18]

Scalar-tensor theories in asymptotically safe gravity

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

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

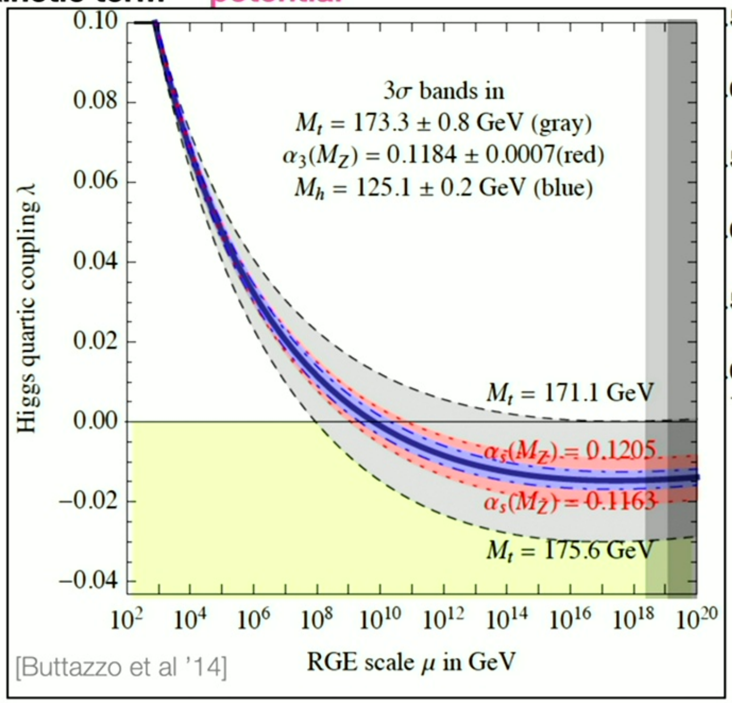
pure gravity | **scalar kinetic term** | **scalar potential** | **non-minimal couplings** | **derivative interactions**

phenomenological consequences:

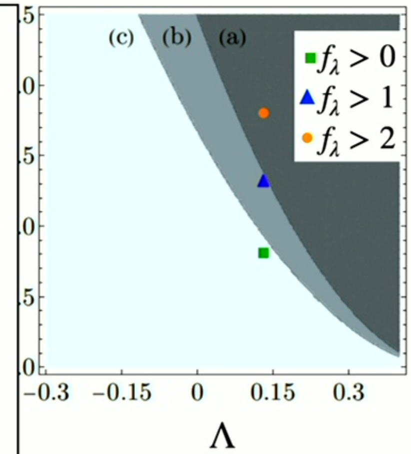
- **Higgs quartic coupling vanishes at the Planck scale**

  → prediction of Higgs mass from asymptotic safety

  [Shaposhnikov, Wetterich '09]



[Buttazzo et al '14]



[AE, Pauly '18]

Scalar-tensor theories in asymptotically safe gravity

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

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

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

phenomenological consequences:

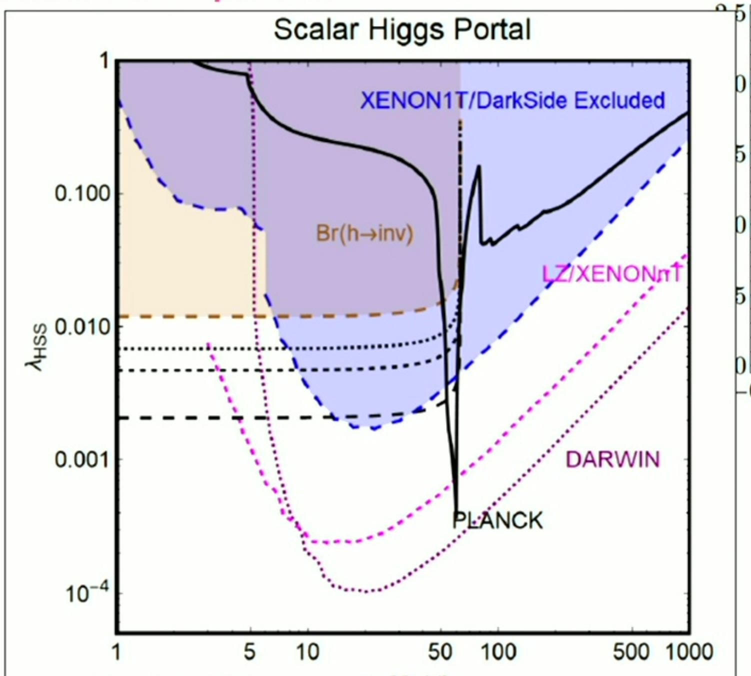
- **Higgs quartic coupling vanishes at the Planck scale**

  → prediction of Higgs mass from asymptotic safety

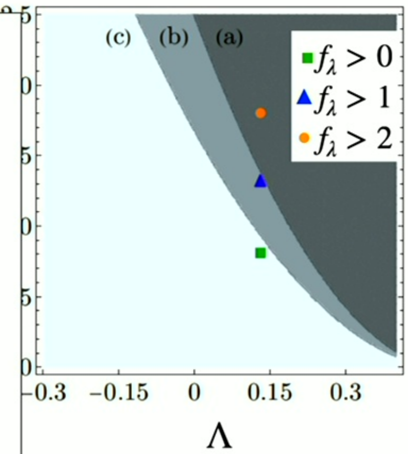
  [Shaposhnikov, Wetterich '09]

- **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

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

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

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]

Scalar-tensor theories in asymptotically safe gravity

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

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

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**

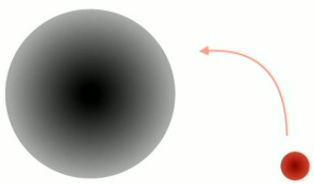
Interlude: Global symmetries in quantum gravity and asymptotic safety

Interlude: global symmetries in quantum gravity and asymptotic safety

No-global symmetries conjecture:

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

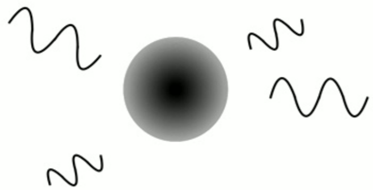
1) Black-hole spacetimes violate conservation of global charges



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]

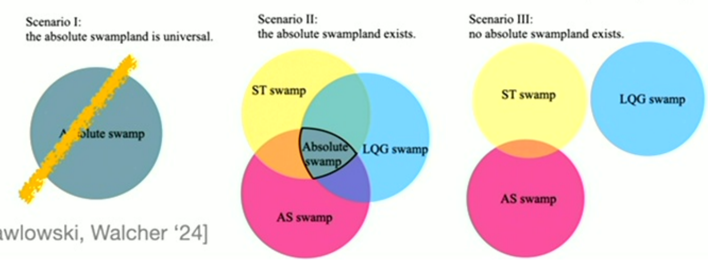
Possibility 3: black holes dynamically suppressed in path integral
$\int \mathcal{D}g_{\mu\nu} e^{iS}$: destructive interference for configurations with $S \to \infty$

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

[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]

Scalar-tensor theories in asymptotically safe gravity

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

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

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

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

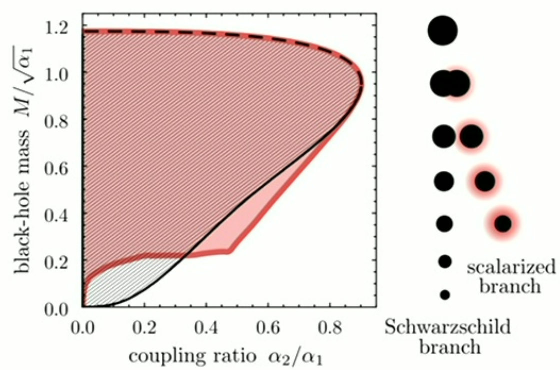
- **black-hole scalarization below critical ADM mass from**
  $\alpha_1 F[\phi]\left(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}\right) = \alpha_1 F[\phi]\mathcal{G}$
  [Damour, Esposito-Faresè '93; Doneza, Yazadijev '17; Silva et al. 17,…]
- **black-hole scalarization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

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

[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



Scalar-tensor theories in asymptotically safe gravity

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

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

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

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]

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

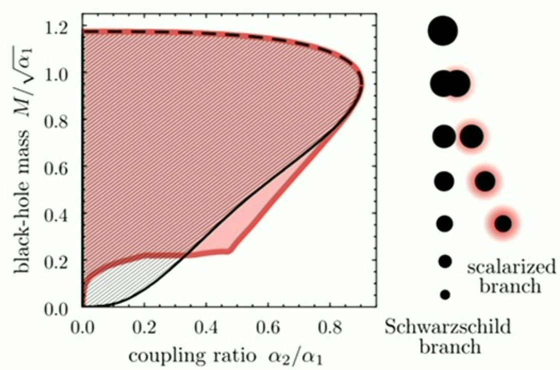
all scalar-Gauss-Bonnet couplings have negative mass-dimension ⇒ expect strong selection among $F[\phi]$'s

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

[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

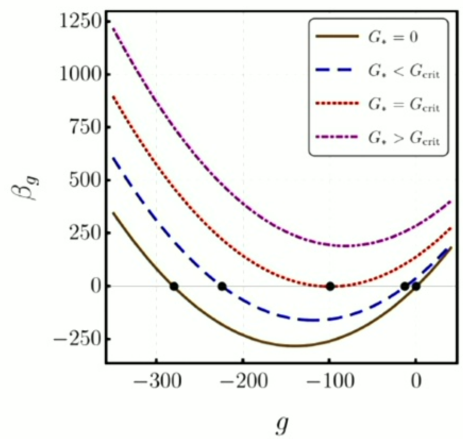


Scalar-tensor theories in asymptotically safe gravity

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

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

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



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]

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

Example: simplest Horndeski theory

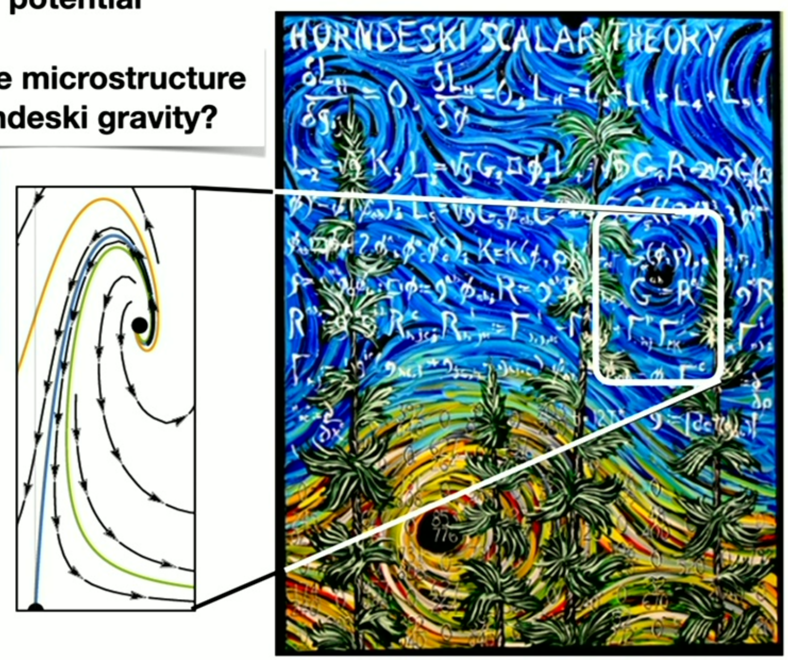
$$\mathcal{L}_2 = -G_2(\phi,\chi), \quad \mathcal{L}_3 = G_3(\phi,\chi)D^2\phi,$$

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

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

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]

Scalar-tensor theories in asymptotically safe gravity

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

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

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

Example: simplest Horndeski theory

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

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

$$\mathscr{L}_5 = G_5(\phi, \chi) G_{\mu\nu} D^\mu D^\nu \phi$$

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

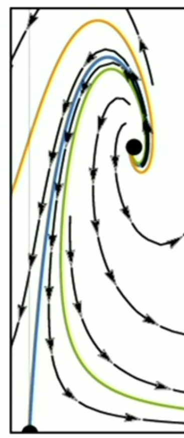
nearly excluded by GW170817 [Creminelli, Vernizzi '17; Ezquiaga, Zumalacárregui '17; Sakstein, Jain '17; Baker et al. '17…]

@ $g \neq 0$, 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]

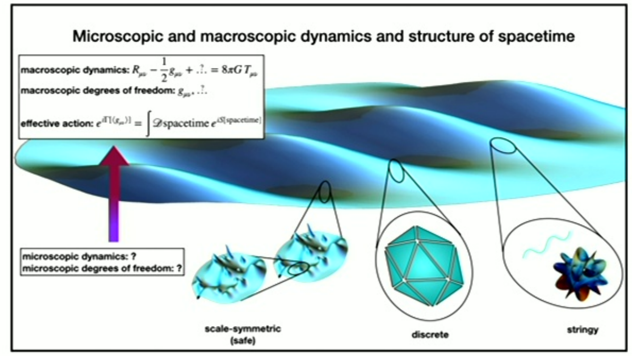
Is this the microstructure of Horndeski gravity?



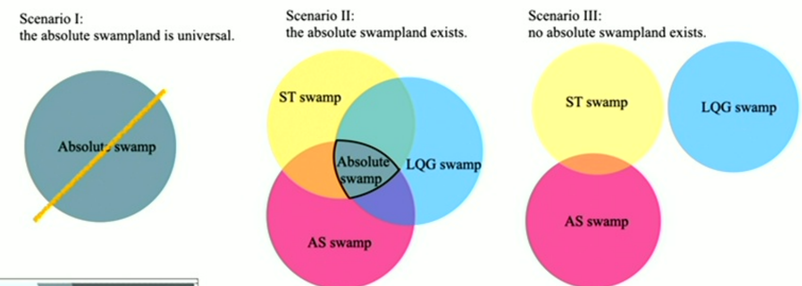
[Horndeski '74]

Summary: key messages

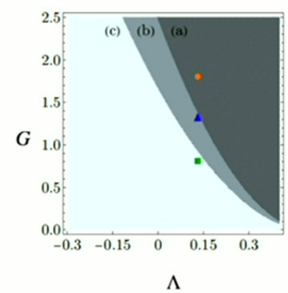
- **quantum gravity and modified gravity:**
  ultraviolet and infrared incarnations of the same physics



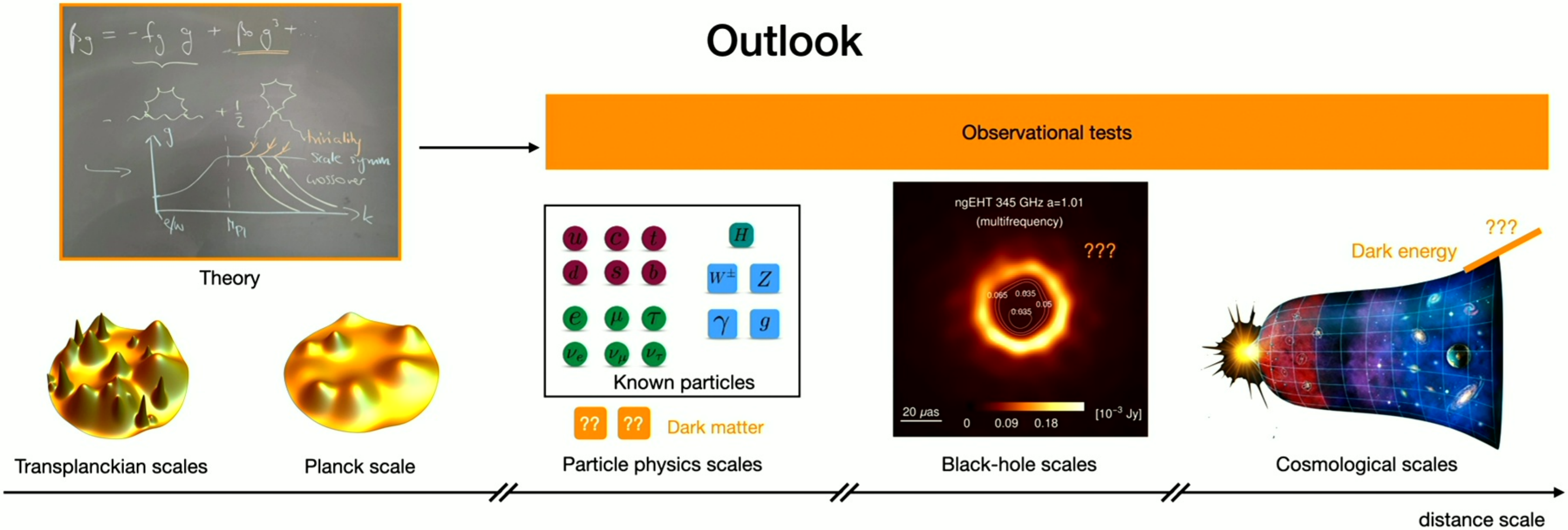
- **absolute swampland probably not universal:**
  observational search for modified gravity can shed light on quantum gravity



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



Outlook



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

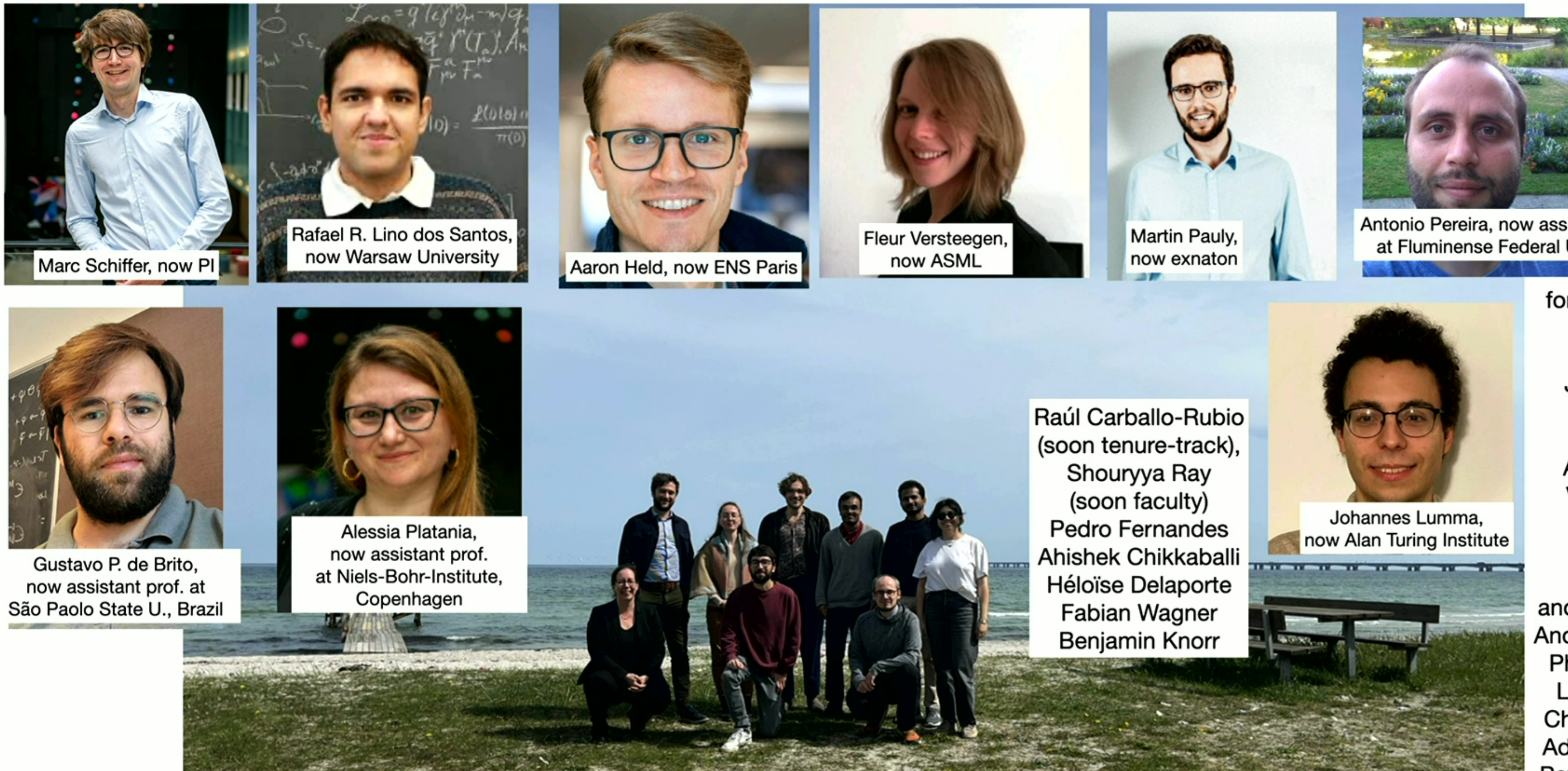
Pheno:

- **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



Nicolai Christiansen

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