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Speakers: Jan Pawlowski
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Abstract: Abstract TBA

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Zoom link
Particle physics & quantum black holes from asymptotically safe correlation functions

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Virtual seminar Perimeter Institute, January 25th 2024
Outline

- Asymptotic safety

- Asymptotically safe correlation functions

- Some remarks on unitarity

- Applications I: asymptotically safe Standard Model

- Applications II: asymptotically black holes

- Summary
Asymptotic safety

Einstein-Hilbert action

\[ S[g] = \frac{1}{16\pi G_N} \int d^4 x \sqrt{g} \left( -R(g) + 2\Lambda \right) \]

Newton constant \( G_N \)  

Ricci scalar \( R(g) \)

Momentum dimension of couplings

\[ \dim G_N = -2 \quad \dim \Lambda = 2 \]

perturbatively non-renormalisable

- graviton propagator: \( \propto \frac{1}{p^2} \)
- 3-grav. vertex: \( \propto \sqrt{G_N p^2} \)
- 4-grav. vertex: \( \propto G_N p^2 \)
  \[ \vdots \]
Asymptotic safety

Einstein-Hilbert action

\[ S[g] = \frac{1}{16\pi G_N} \int d^4 x \sqrt{g} \left( -R(g) + 2\Lambda \right) \]

- **Metric** \( g \)
- **Cosmological constant** \( \Lambda \)
- **Newton constant** \( G_N \)
- **Ricci scalar** \( R(g) \)

Momentum dimension of couplings

\[ \dim G_N = -2 \]
\[ \dim \Lambda = 2 \]

Perturbatively non-renormalisable

Correlation functions

- **Diffeomorphism invariant**
  \[ \langle R(g(x_1)) \cdots R(g(x_n)) \rangle \]
  - **Ricci scalar correlations**

- **Not diffeomorphism invariant**
  \[ \langle g(x_1) \cdots g(x_n) \rangle \]
  - **Metric correlations**
Asymptotic safety

Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

Consider an observable \( \mathcal{O}(g) \) with fundamental coupling \( g \)

- **Standard perturbation theory**

  \[
  \mathcal{O}(g) = \mathcal{O}_0 + \mathcal{O}_1 g + \frac{1}{2} \mathcal{O}_2 g^2 + \cdots
  \]

- **Generalised perturbation theory**

  \[
  \mathcal{O}(g) = \mathcal{O}^* + \mathcal{O}_1^*(g - g^*) + \frac{1}{2} \mathcal{O}_2^*(g - g^*)^2 + \cdots
  \]

  e.g. aiming at better convergence fundamental coupling
  non-perturbative example: analytic perturbation theory in QCD

- **Renormalisation group fixed points**

  **beta functions**

  \[
  \partial_t g = \beta_g(g, \mu)
  \]

  \[
  \partial_t \mu = \beta_\mu(g, \mu)
  \]

  Logarithmic momentum (RG) scale: \( t = \log \frac{k}{k_0} \)
Asymptotic safety

Consider an observable $\mathcal{O}(g)$ with fundamental coupling $g$

- **Ultraviolet running**
  
  **QCD**
  \[
  \beta_g(g) = -\frac{1}{16\pi^2} \frac{22N_c}{3} g^3
  \]
  
  Asymptotic freedom

  **quantum gravity**
  \[
  \beta_{gN} = \left[2 + \eta_{N}(g_N, \lambda)\right] g_N
  \]
  
  dimensional running quantum fluctuations

  Asymptotic safety
  \[
  g_N = G_N k^2 \quad \lambda = \frac{\Lambda}{k^2}
  \]

- **Renormalisation group fixed points**

  **beta functions**
  \[
  \partial_t g = \beta_g(g, \mu)
  \]
  \[
  \partial_t \mu = \beta_\mu(g, \mu)
  \]

  **Fixed points**
  \[
  \beta_g(g^*, \mu^*) = 0
  \]
  \[
  \beta_\mu(g^*, \mu^*) = 0
  \]

  Logarithmic momentum scale
Asymptotic safety

Consider an observable $O(g)$ with fundamental coupling $g$

- Ultraviolet running

  QCD

  $$\beta_g(g) = -\frac{1}{16\pi^2} \frac{22 N_c}{3} g^3$$

  Asymptotic freedom

  Gaussian fixed point

- Renormalisation group fixed points

  beta functions

  $$\partial_t g = \beta_g(g, \mu)$$

  $$\partial_t \mu = \beta_\mu(g, \mu)$$

  Fixed points

  $$\beta_g(g^*, \mu^*) = 0$$

  $$\beta_\mu(g^*, \mu^*) = 0$$

  quantum gravity

  $$\beta_{g_N} = \left[2 + \eta_N \left(\frac{\tau}{g_N}, \lambda\right)\right] g_N$$

  dimensional running

  quantum fluctuations

  Asymptotic safety

  $$\eta_N = -2$$

  non-Gaussian fixed point

  Logarithmic momentum scale

  $$(g_N^*, \lambda^*) \neq 0$$
From vertex dressings/distribution functions to physics
aka
form factors

Effective action

\[ \Gamma[g, h, c_\mu, \bar{c}_\mu] = \int_x \left[ \frac{2\Lambda - R}{16\pi G_N} + R f_R(\Delta) R + C f_C(\Delta) C + \cdots \right] \bigg|_{\text{BRST-inv}} + S_{gf} + S_{gh} \]

Background effective action

\[ \Gamma[g_{\mu\nu}] = \frac{1}{16\pi} \int_x \sqrt{g} \left\{ R(\Delta, R) + R f_{R^2}(\Delta) R + R_{\mu\nu} f_{R^2}(\Delta) R^{\mu\nu} + \cdots \right\} \]

Enforced by IR-UV consistence

\[ R f_{R^2}(\Delta, R) R = R(\Delta, R) + R f_{R^2}(\Delta) R \]
Background independence in gravity

\[ k \partial_k \Gamma_k[\bar{g}, \phi] = \frac{1}{2} \]

Linear split
\[ g = \bar{g} + h \]

Effective action

\[ \Gamma_k[\bar{g}, \bar{h}] = \Gamma_k[\bar{g}] + \Gamma_k^{(0,1)}[\bar{g}] \ast \bar{h} + \frac{1}{2} \Gamma_k^{(0,2)}[\bar{g}] \ast \bar{h}^2 + \frac{1}{6} \Gamma_k^{(0,3)}[\bar{g}] \ast \bar{h}^3 + \cdots \]

\[ \bar{h} = \langle h \rangle \]

\[ \left\{ \Gamma_k[\bar{g}], \Gamma_k^{(0,1)}[\bar{g}], \Gamma_k^{(0,2)}[\bar{g}], \Gamma_k^{(0,3)}[\bar{g}] \right\}, \ldots \]
From vertex dressings/distribution functions to physics
aka
form factors

Effective action

$$\Gamma[g,h,c_\mu,\bar{c}_\mu] = \int \left[ \frac{2\Lambda - R}{16\pi G_N} + BRST-inv \left[ f_R(\Delta) R + f_C(\Delta) C + \cdots \right] \right] + S_{gf} + S_{gh}$$
gauge dependent

Background effective action

$$\Gamma[g_{\mu\nu}] = \frac{1}{16\pi} \int \sqrt{g} \left\{ \mathcal{R}(\Delta,R) + R f_R(\Delta) R + R_{\mu\nu} f_R(\Delta) R^{\mu\nu} + \cdots \right\}$$
gauge independent

JMP, Tränkle, 2309.17043

Enforced by IR-UV consistence

$$R f_R(\Delta,R) R = \mathcal{R}(\Delta,R) + R f_R(\Delta) R$$

How much do they differ?
A lesson from graviton spectral functions

Spectral representation

\[ G_k(p) = \int_{-\infty}^{\infty} \frac{d\lambda}{2\pi} \frac{\lambda \rho_k(\lambda, \vec{p})}{\lambda^2 + P_0^2} \]

Reconstruction (inverse problem): \[ \rho_k[G_k] \]

Direct Lorentzian computation with symmetry preserving

\[ x_p = \frac{p^2}{k^2} \]
A lesson from graviton spectral functions

Spectral representation

\[ G_k(p) = \int_{-\infty}^{\infty} \frac{d\lambda}{2\pi} \frac{\lambda \rho_k(\lambda, \bar{p})}{\lambda^2 + p_0^2} \]

Reconstruction (inverse problem): \( \rho_k[G_k] \)

Direct Lorentzian computation with symmetry preserving

Lorentz invariance & Causality
Callan-Symanzik regulator

\[ R_{CS} = Z_{\phi}k^2 \]

Finiteness lost

fQCD, Reichert, SciPost Phys.Core 6 (2023) 061
Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501
A lesson from graviton spectral functions

Fehre, Litim, JMP, Reichert, PRL 130 (2023) 081501

Bonanno, Denz, JMP, Reichert, SciPost Phys. 12 (2022) 1, 001

Spectral properties ‘resemble’ that of an asymptotic

\[ \rho_h(\lambda) \in \mathbb{R}^+ \quad \int_{\mathbb{R}} \frac{d\lambda}{2\pi} \lambda \rho_h(\lambda) = \infty \]

Spectral properties of an unphysical mode

\[ \rho_\beta(\lambda) \in \mathbb{R} \quad \int_{\mathbb{R}} \frac{d\lambda}{2\pi} \lambda \rho_\beta(\lambda) = 0 \]

How much do they differ?
Background spectral function and scattering amplitudes

**(RG-invariant vertex)**
\[
\frac{\Gamma_{hh}^{(3)}(p_1, p_2, p_3)}{Z_h^3(p_1)Z_h^3(p_2)Z_h^3(p_3)}
\]
aka

**(RG-invariant coupling)**

/ form factor

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**Graviton-graviton scattering**

---

**(RG-invariant vertex)**
\[
\frac{\Gamma_{hhh}^{(3)}(p_1, p_2, p_3)}{Z_h^3(p_1)Z_h^3(p_2)Z_h^3(p_3)}
\]
aka

**(RG-invariant coupling)**

/ form factor

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**Bonanno, Denz, JMP, Reichert, SciPost Phys. 12 (2022) 1, 001**

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**Fluctuation approach: 2012** ...

**Form factor approach: 2018** ...

**Knorr, Ripken, Saueressig, ...**

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**Suggestive educated guess**
\[
\tilde{\Gamma}_{\tilde{g}^n}^{(n)}(p_1, ..., p_n) \approx \frac{\Gamma_{h^n}^{(n)}(p_1, ..., p_n)}{Z_h^{3/2}(p_1) \cdots Z_h^{3/2}(p_n)}
\]

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**JMP, Reichert, Front.in Phys. 8 (2021) 527**

**2309.10785**
The physics of thresholds
Bonanno et al., Critical reflections on asymptotically safe gravity, Front.in Phys. 8 (2020) 269
QCD & SM thresholds in the RG since (many) decades
QCD with the fRG since a decade

Example: asymptotically safe Standard Model
Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105

\[ m_t, m_H, m_Z, m_W \]

\[ m_b, m_c, m_e, m_d, m_u, m_W \]

\[ k \text{ [GeV]} \]

\[ m_{t, H, Z, W} \]

\[ k\text{-mirrors of physical thresholds} \]

\[ k \text{-mirrors of physical thresholds: feature, not bug!} \]
The physics of thresholds

Bonanno et al., Critical reflections on asymptotically safe gravity, Front.in Phys. 8 (2020) 269
QCD & SM thresholds in the RG since (many) decades

QCD with the fRG since a decade

Example: asymptotically safe Standard Model

Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105

Full physics: momentum-dependent correlation functions & S-matrix elements at k=0
Towards apparent convergence in quantum gravity

vertex expansion

\[ \partial_t \Gamma_k = \frac{1}{2} \]
\[ \partial_t \Gamma_k^{(h)} = -\frac{1}{2} \]
\[ \partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \]
\[ \partial_t \Gamma_k^{(c2)} = \]
\[ \partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \]
\[ \partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \]

Aiming at apparent convergence

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785
Towards apparent convergence in quantum gravity
vertex expansion

\[ \Gamma^{(m,n \geq 2)} \]

bi-metric approach: Manrique, Reuter, Saueressig, Annals Phys. 326 (2011) 463

\[
\begin{align*}
\partial_t \Gamma_k^{(m,n \geq 2)} &= \frac{1}{2} + 2 - 2 \\
\partial_t \Gamma_k^{(h)} &= -\frac{1}{2} + + 3 - 3 + 6 \\
\partial_t \Gamma_k^{(2h)} &= -\frac{1}{2} + 3 - 3 + 4 - 6 \\
\partial_t \Gamma_k^{(3h)} &= -\frac{1}{2} + 12 - 12 - 24 \\
\partial_t \Gamma_k^{(4h)} &= -\frac{1}{2} + 12 - 24 \\
\end{align*}
\]

level 1: \[ \Gamma^{(m,n)} \approx \Gamma^{(m+n-1,1)} \]

Aiming at apparent convergence

JMP, Reichert, Front. in Phys. 8 (2021) 527
2309.10785
Towards apparent convergence in quantum gravity

vertex expansion

\[ \Gamma^{(m,n \geq 2)} \]

\[ \partial_t \Gamma_k = \frac{1}{2} \]
\[ \partial_t \Gamma_k^{(h)} = -\frac{1}{2} \]
\[ \partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \]
\[ \partial_t \Gamma_k^{(\infty)} = \]
\[ \partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \]
\[ \partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \]

level 4: \( \Gamma^{(m,n)} \approx \Gamma^{(m+n-4,4)} \)

\[ Z_h(p), \quad Z_c(p), \quad \mu = -2\lambda_2 \]
\[ g_3(p), \quad \lambda_3 \]
\[ g_4(p), \quad \lambda_4 \]

Aiming at apparent convergence

Denz, JMP, Reichert, EPJ C78 (2018) 4, 336

JMP, Reichert, Front.in Phys. 8 (2021) 527

2309.10785
Momentum-dependent vertices

Flow of three-graviton vertex

\[
\frac{\langle \text{Flow}^3(p^2) \rangle}{-\frac{3}{2} \eta_0(p^2) - 1}
\]

no \( R^2_{\mu\nu} \) - tensor structure generated!

Flow of four-graviton vertex

\[
\frac{\langle \text{Flow}^4(p^2) \rangle}{-2 \eta_0(p^2) - 2}
\]

\( R^2 \) - tensor structure generated

\( R \) - tensor structure sustained

IR fine-tuning of diffeomorphism invariance

Denz. JMP, Reichert. EPJ C78 (2018)

Full momentum dependence
of
two-, three- and four-point function
at \( k=0 \)

classical general relativity
asymptotically safe fixed point scaling
Spectral properties

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785
Towards apparent convergence in quantum gravity

Why does/could it work?

Typically diagrams with higher order vertices are strongly suppressed

(a) couplings stay finite

(b) combinatorical suppression of diagrams with higher vertices

(c) phase space (angular) suppression of diagrams with higher vertices

turns out to be very efficient!
Towards apparent convergence in quantum gravity

Why does/could it work?
Typically diagrams with higher order vertices are strongly suppressed

(a) couplings stay finite
(b) combinatorical suppression of diagrams with higher vertices
(c) phase space (angular) suppression of diagrams with higher vertices

turns out to be very efficient!

Why does/could it fail?
Resonant interaction channels and their interactions circumvent (b) and make (a) irrelevant

(a) couplings diverge
(b) hadrons, diquarks, glueballs, ... in QCD
(c) graviballs in gravity

Emergent composites, BSE
Gies, Wetterich, PRD 65 (2002) 0650016
JMP, AP 322 (2007) 2831
Flörchinger, Wetterich, PLB 680 (2009) 371

JMP, Reichert, Front.in Phys. 8 (2021) 527
2309.10785
Towards apparent convergence in quantum gravity

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(c) graviballs in gravity

Emergent composites, BSE

Gies, Wetterich, PRD 65 (2002) 0650016
JMP, AP 322 (2007) 2831
Flörchorger, Wetterich, PLB 680 (2009) 371

QG as perturbative as possible & apparently converging

... slight oversimplification for the sake of this talk ...
Applications I: asymptotically safe Standard Model

Dona, Eichhorn, Percacci, PRD 89 (2014) 084035
Meibohm, JMP, Reichert, EPJC 76 (2016) 285
Christiansen, Litim, JMP, Reichert PRD 97 (2018) 4, 046007

Shaposhnikov, Wetterich, PLB 683 (2010) 196
Eichhorn, Versteegen, JHEP 1801 (2018) 030
Eichhorn, Held, PRL 121 (2018) 151302

Latest 'status report': Eichhorn, Schiffer, 2212.07456
Asymptotically safe Standard Model

![Graph showing various functions](image)

**top pole mass (getting real)**

\[ M_{T,\text{pole}}^{\text{exp}} = 172.5 \pm 0.7 \text{ GeV} \]

Experimental value (PDG)
Asymptotically safe Standard Model

Flat Higgs FP potential

Top pole mass (getting real)

$\Gamma_{t,\text{pole}}^{(\text{theo})} = 1.72^{+0.09}_{-0.41} \text{ GeV}$

Experimental value (PDG)

$\Gamma_{t,\text{pole}}^{(\text{exp})} = 1.42^{+0.19}_{-0.15} \text{ GeV}$

Experimental value (PDG)

$M_{\text{t,pole}}^{(\text{exp})} = 172.5 \pm 0.7 \text{ GeV}$

Euclidean curvature mass

Two relevant directions
Asymptotically safe Standard Model

Phase structure

Where are we?

\[ M_t \text{ [GeV]} \]

\[ M_H \text{ [GeV]} \]

Pastor-Gutiérrez, JMP, Reichert, SciPost Phys. 15 (2023) 105
Applications II: asymptotically black holes

Black Holes in Asymptotically Safe Gravity: Platania, 2309.17043
and beyond: Held, Eichhorn, 2212.09495
Asymptotically black holes

Unfolding the background effective action

\[ \Gamma[g_{\mu\nu}] = \frac{1}{16\pi} \int_x \sqrt{g} \left\{ \mathcal{R}(\Delta, R) + R f_R^2 (\Delta) R + R_{\mu\nu} f_R^2 (\Delta) R^{\mu\nu} + \cdots \right\} \]

\begin{align*}
gauge\ dependent & \quad RG\-invariant \\
\bar{\Gamma}^{(2)}_{\bar{h}} (p) & \quad \bar{\Gamma}^{(3)}_{\bar{\theta}^3} (p) \\
\bar{\Gamma}^{(3)}_{\bar{h}^3} (p) & \quad \bar{\Gamma}^{(4)}_{\bar{\theta}^4} (p) \\
\bar{\Gamma}^{(4)}_{\bar{h}^4} (p) &
\end{align*}
Asymptotically black holes

Unfolding the background effective action

\[ \Gamma[g_{\mu\nu}] = \frac{1}{16\pi} \int_x \sqrt{g} \left\{ \mathcal{R}(\Delta, R) + R f_{R^2}(\Delta) R + R_{\mu\nu} f_{R^2}(\Delta) R^{\mu\nu} + \ldots \right\} \]

- **gauge dependent**
  - \( \tilde{\Gamma}^{(2)}_{hh}(p) \)
  - \( \tilde{\Gamma}^{(3)}_{h^3}(p) \)
  - \( \tilde{\Gamma}^{(4)}_{h^4}(p) \)

- **RG-invariant**
  - \( \tilde{\Gamma}^{(3)}_{\tilde{g}^3}(p) \)
  - \( \tilde{\Gamma}^{(4)}_{\tilde{g}^4}(p) \)

- **gauge independent**
  - \( \mathcal{R}(\Delta, R) \)
  - Unfolding
  - Educated guess
  - \( R f_{R^2}(\Delta) R \)
  - Maps
  - \( R_{\mu\nu} f_{R^2}(\Delta) R^{\mu\nu} \)
Asymptotically black holes

Unfolding the background effective action

\[ \Gamma[g_{\mu\nu}] = \frac{1}{16\pi} \int_x \sqrt{g} \left\{ \mathcal{R}(\Delta, R) + Rf_{R^2}(\Delta)R + R_{\mu\nu} f_{R^2}(\Delta)R^{\mu\nu} + \cdots \right\} \]

- \text{gauge dependent:} \quad \tilde{\Gamma}_{hh}^{(2)}(p), \quad \tilde{\Gamma}_{h^3}^{(3)}(p), \quad \tilde{\Gamma}_{h^4}^{(4)}(p)
- \text{RG-invariant:} \quad \tilde{\Gamma}_{\bar{g}^2}^{(3)}(p), \quad \tilde{\Gamma}_{\bar{g}^4}^{(4)}(p)
- \text{gauge independent:} \quad \mathcal{R}(\Delta, R) \quad \text{Unfolding} \quad \text{Educated guess} \quad Rf_{R^2}(\Delta)R \quad \text{Maps} \quad R_{\mu\nu} f_{R^2}(\Delta)R^{\mu\nu}

Results for form factors

\[ \mathcal{R}(\Delta, R) = R \frac{\gamma^g(\Delta) - \gamma_3 \Delta}{\Delta + R} R \]

JMP, Tränkle, 2309.17043
Asymptotically black holes

Infrared asymptotic effective action

\[ \Gamma_{IR}[g_{\mu\nu}] = \frac{1}{16\pi} \int_x \sqrt{-g} \left( G_N^{-1} R + g_{R_{\mu\nu}}^2 R_{\mu\nu} + g_{R^2 R^\theta}^2 + c_1 R_{\mu\nu \theta \phi} R^{\mu\nu} + c_2 R R \right) \]

Spherical symmetric solution

\[ ds^2 = -f(r)dt^2 + \frac{1}{g(r)} dr^2 + r^2 d\Omega^2 \]

Weak field solutions

\[ f(r) = 1 - \frac{2M}{r} + S_0 \frac{e^{-m_0 r}}{r} + S_2 \frac{e^{-m_2 r}}{r} \]

\[ g(r) = 1 - \frac{2M}{r} - S_0 \frac{e^{-m_0 r}}{r} (1 + m_0 r) + \frac{1}{2} S_2 \frac{e^{-m_2 r}}{r} (1 + m_2 r) \]
Asymptotically black holes

Weak field solutions

\[
f(r) = 1 - \frac{2M}{r} + S_0 \frac{e^{-m_0 r}}{r} + S_2 \frac{e^{-m_2 r}}{r}
\]

\[
g(r) = 1 - \frac{2M}{r} - S_0 \frac{e^{-m_0 r}}{r} (1 + m_0 r) + \frac{1}{2} S_2 \frac{e^{-m_2 r}}{r} (1 + m_2 r)
\]

Numerical Solutions for $S_2 = 1 = M$

- $S_0 = -1$
- $S_0 = 1$
- $S_0 = 4$
Asymptotically black holes

Weak field solutions

\[ f(r) = 1 - \frac{2M}{r} + S_0 \frac{e^{-m_0 r}}{r} + S_2 \frac{e^{-m_2 r}}{r} \]

\[ g(r) = 1 - \frac{2M}{r} - S_0 \frac{e^{-m_0 r}}{r} (1 + m_0 r) + \frac{1}{2} S_2 \frac{e^{-m_2 r}}{r} (1 + m_2 r) \]

Numerical Solutions for \( S_0 = 1 = M \)

\( S_0 = -1 \)

\( S_0 = 1 \)

\( S_0 = 4 \)

Phase structure

\[ T = \frac{1}{4\pi} \sqrt{|f'(r_h)g'(r_h)|} \]

'Hawking temperature'

see also Borissova, Held, Afshordi, CQuant.Grav. 40 (2023) 7, 075011
Summary

\[ \partial_t \Gamma_k[\Phi] = \frac{1}{2} \]

Asymptotically safe SM

Quantum black holes

Phase structure

Where are we?

Phase structure
Asymptotically black holes

Weak field solutions

\[ f(r) = 1 - \frac{2M}{r} + S_0 \frac{e^{-m_0 r}}{r} + S_2 \frac{e^{-m_2 r}}{r} \]

\[ g(r) = 1 - \frac{2M}{r} - S_0 \frac{e^{-m_0 r}}{r} (1 + m_0 r) + \frac{1}{2} S_2 \frac{e^{-m_2 r}}{r} (1 + m_2 r) \]

Numerical Solutions for \( S_2 = 1 = M \)

\( S_0 = -1 \)  \( S_0 = 1 \)  \( S_0 = 4 \)

Phase structure

\[ T = \frac{1}{4\pi} \sqrt{|f'(r_h)g'(r_h)|} \]

‘Hawking temperature’

see also Borissova, Held, Afshordi,
CQuant.Grav. 40 (2023) 7, 075011

JMP, Tränkle, 2309.17043
Asymptotically black holes

Infrared asymptotic effective action

\[
\Gamma_{IR}[g_{\mu\nu}] = \frac{1}{16\pi} \int \sqrt{-g} \left( G^{-1}_N R + g_{R_{\mu\nu}} R_{\mu\nu} + g_{R^2} R^2 + c_1 R_{\mu\nu} \Box R^{\mu\nu} + c_2 R \Box R \right)
\]

Spherical symmetric solution

\[
ds^2 = -f(r)dt^2 + \frac{1}{g(r)} dr^2 + r^2 d\Omega^2
\]

Weak field solutions

\[
f(r) = 1 - \frac{2M}{r} + S_0 \frac{e^{-m_0 r}}{r} + S_2 \frac{e^{-m_2 r}}{r}
\]

\[
g(r) = 1 - \frac{2M}{r} - S_0 \frac{e^{-m_0 r}}{r} (1 + m_0 r) + \frac{1}{2} S_2 \frac{e^{-m_2 r}}{r} (1 + m_2 r)
\]
Asymptotically black holes

Unfolding the background effective action

\[ \Gamma_{g_{\mu\nu}} = \frac{1}{16\pi} \int_{\mathcal{M}} \sqrt{g} \left\{ \mathcal{R}(\Delta, R) + R f_{\mathcal{R}^2}(\Delta) R + R_{\mu\nu} f_{R_{\mu\nu}^2}(\Delta) R_{\mu\nu} + \ldots \right\} \]

**gauge dependent**

\[ \tilde{\Gamma}_{h_h}^{(2)}(p) \]

\[ \tilde{\Gamma}_{h_3}^{(3)}(p) \]

\[ \tilde{\Gamma}_{h_4}^{(4)}(p) \]

**RG-invariant**

\[ \tilde{\Gamma}_{\tilde{g}^2}^{(3)}(p) \]

\[ \tilde{\Gamma}_{\tilde{g}^4}^{(4)}(p) \]

**gauge independent**

\[ \mathcal{R}(\Delta, R) \]

Unfolding

Educated guess

\[ R f_{\mathcal{R}^2}(\Delta) R \]

Maps

\[ R_{\mu\nu} f_{R_{\mu\nu}^2}(\Delta) R_{\mu\nu} \]

Results for form factors

\[ \mathcal{R}(\Delta, R) = R \frac{\gamma_{\tilde{g}}^{(3)}(\Delta) - \gamma_{\mathcal{R}} \Delta}{\Delta + R} R \]
Asymptotically black holes

Weak field solutions

\[ f(r) = 1 - \frac{2M}{r} + S_0 \frac{e^{-m_0 r}}{r} + S_2 \frac{e^{-m_2 r}}{r} \]

\[ g(r) = 1 - \frac{2M}{r} - S_0 \frac{e^{-m_0 r}}{r} (1 + m_0 r) + \frac{1}{2} S_2 \frac{e^{-m_2 r}}{r} (1 + m_2 r) \]

Numerical Solutions for \( S_2 = 1 = M \)

\[ S_0 = -1 \]
\[ S_0 = 1 \]
\[ S_0 = 4 \]

Phase structure

\[ T = \frac{1}{4\pi} \sqrt{|f'(r_h)g'(r_h)|} \]

'Hawking temperature'
see also Borissova, Held, Afshordi,
CQuant.Grav. 40 (2023) 7, 075011

JMP, Tränkle, 2309.17043