Baryon number and other global symmetries in field theories of quantum gravity

Quantum Spacetime and the Renormalisation Group
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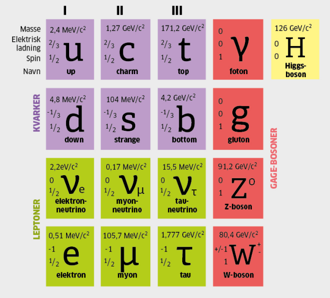
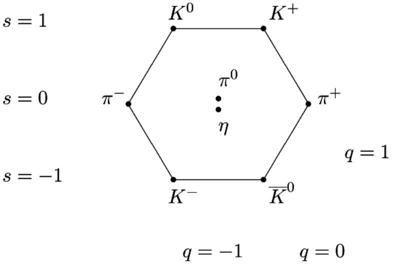
Symmetries . . .

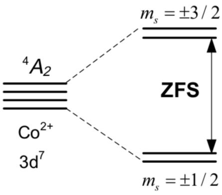
. . . are an impotant part of fundamental theories (physics)

- Allows one to organise ‘zoo’ of particles (excitations) into multiplets

elementary particles ***composite particles*** ***quasiparticles***







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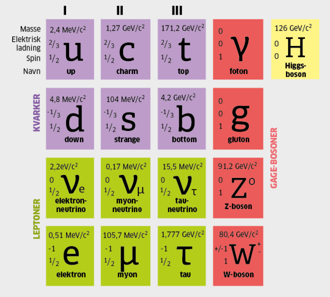

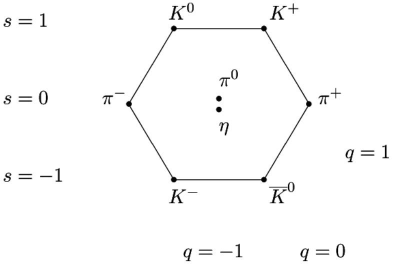

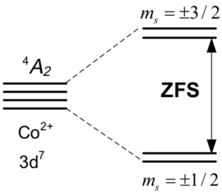

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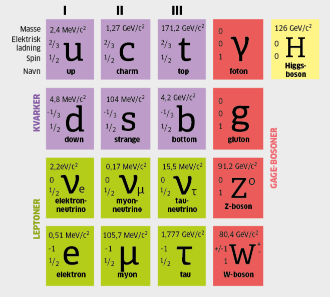

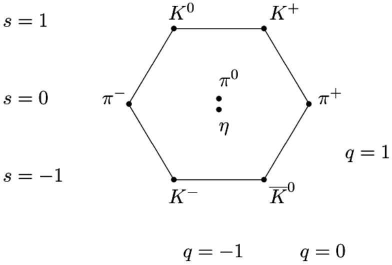

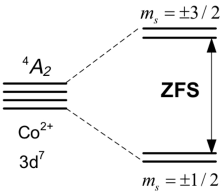

- Determines selection rules, forbids certain processes $\Rightarrow$ stability
- ***(Folk) theorem:*** *In quantum gravity, any continuous symmetry must be gauge*
  Banks/Dixon ’88; Giddings/Strominger ’88; Kallosh *et al.* ’95; Arkani-Hamed *et al.* ’07; Banks/Seiberg ’11; Harlow/Ooguri 19, 21; . . .

Symmetries in quantum gravity

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Problem?

- ...most fundamental symmetries are gauged in nature
  e.g., charge conservation $\leftrightarrow \mathrm{U}(1)$
  SM: $\mathrm{U}(1) \times \mathrm{SU}(2) \times \mathrm{SU}(3)$ is gauged

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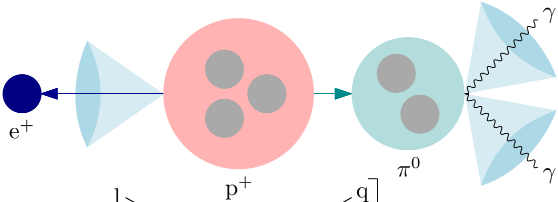
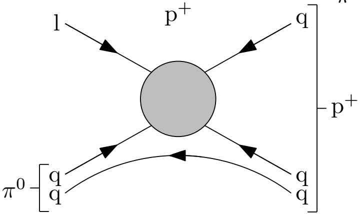
- Example: proton decay $p^+ \to \pi^0 e^+ \gamma\gamma$
  $\Rightarrow$ forbidden by baryon number conservation, symmetry $\mathrm{U}(1)_\mathrm{B}$ only global
  $\Rightarrow$ potential candidate

Proton decay in numbers

. . . is known to be a *very* rare process, if possible at all





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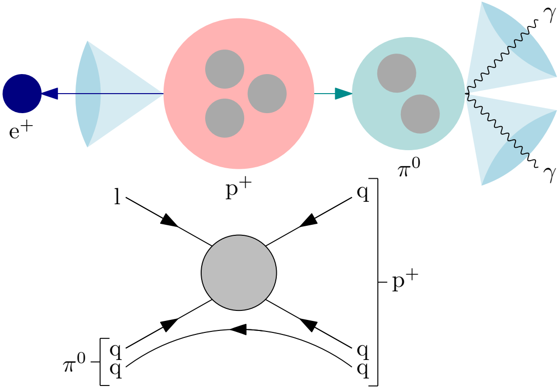
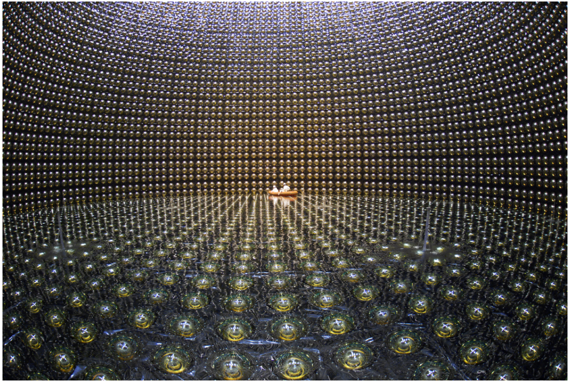
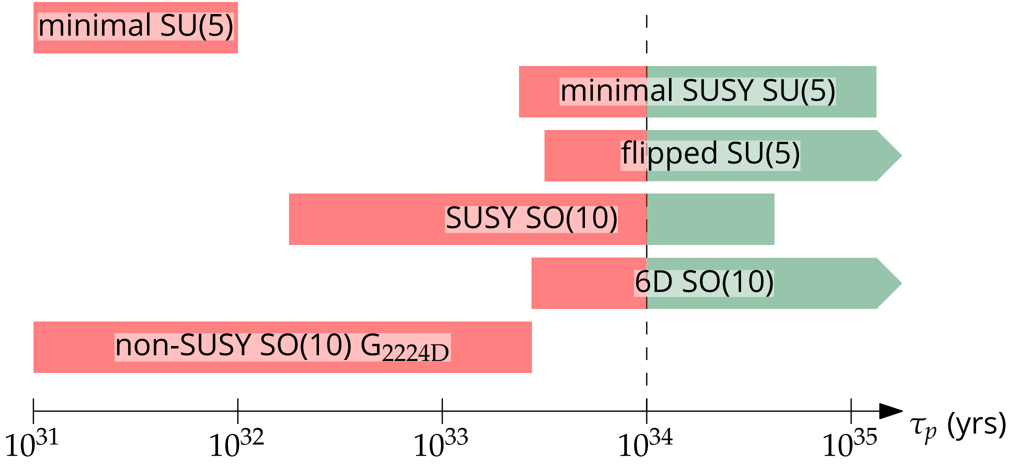




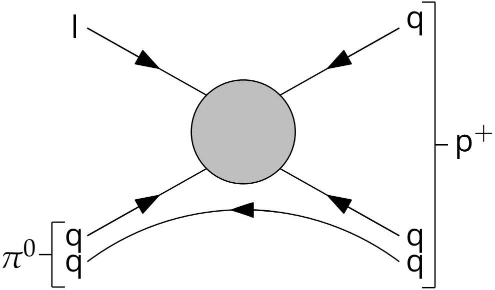
- Experimental non-observation leads to lower bounds for proton lifetime τ_p
- Current estimate: $\tau_p \gtrsim 10^{34}$ yrs Super-Kamiokande '17

Proton stability . . .

. . . has already been a (serious) constraint on other deep-UV physics, e.g., GUTs



From proton lifetime to new-physics scale



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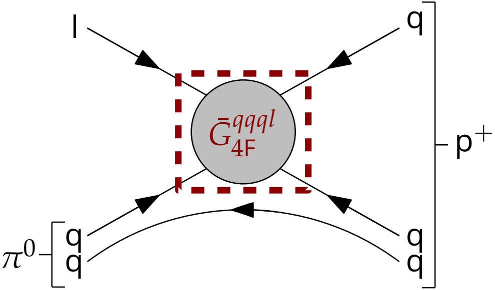

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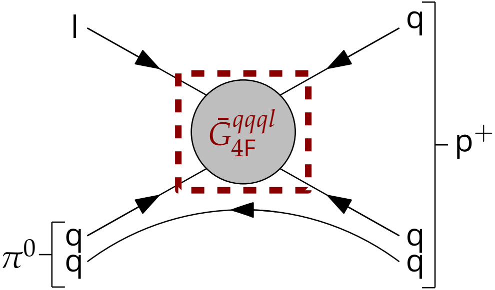

cf., e.g., Manohar ’18

$$\tau_p \approx 16\pi M_p^{-1} \left(G_{4F}^{qqql}(k = M_p) \right)^{-2}$$

dim’less

$$G_{4F}(k) = \bar{G}_{4F}(k) k^2$$

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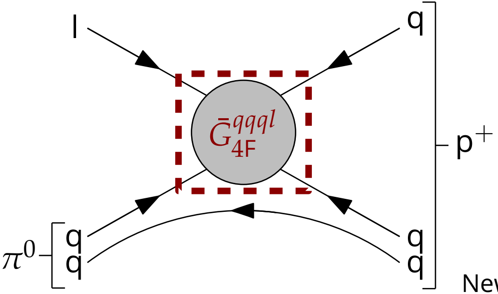

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$$G_{\text{4F}}(k) \approx G_{\text{4F}}(M_X)(k/M_X)^2$$

New (B-violating) physics scale
e.g. (but not only): GUT

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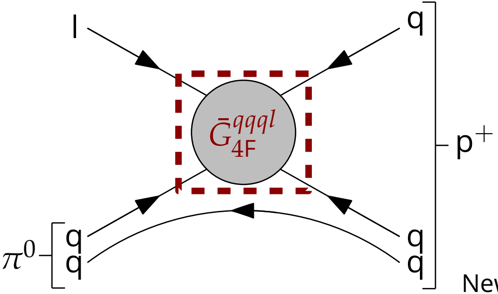

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$$\tau_p \sim G_{4F}^{qqql}(M_X) \frac{M_X^4}{M_p^5}$$

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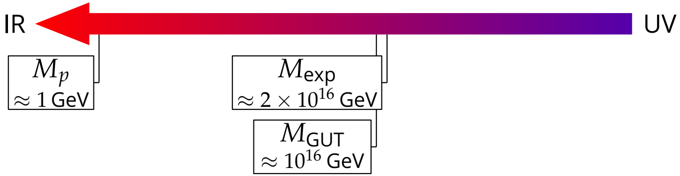
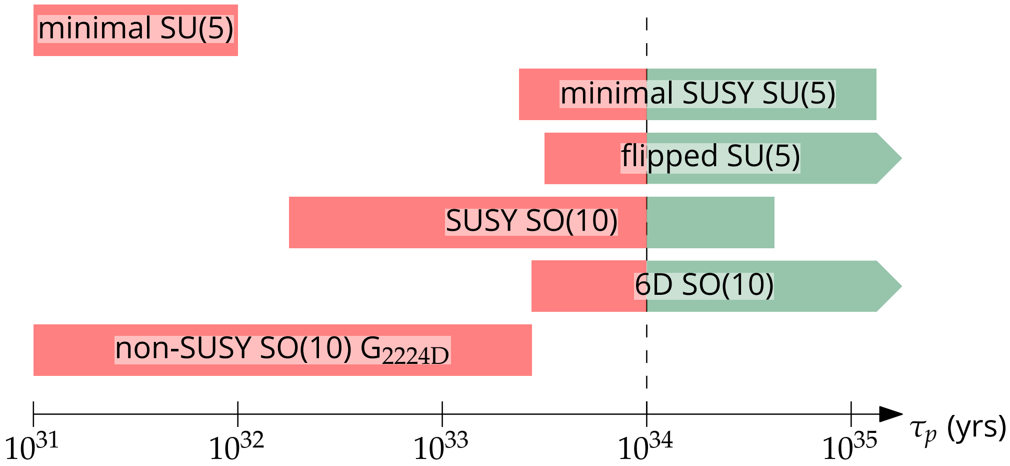


Remarks:

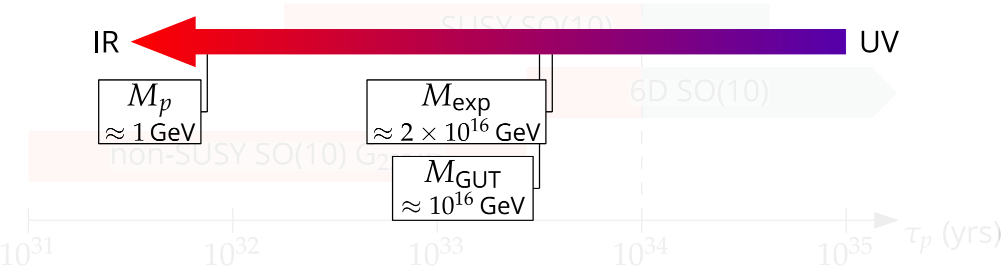
- IR measurement ($M_p \approx 1$ GeV) constrains deep UV ($M_{\text{exp}} \approx 2 \times 10^{16}$ GeV).
- $M_{\text{GUT}} \approx M_{\text{exp}}$ Caveat: $G_{\text{4F}}^{qqql}(M_X) \approx 1$ ('naturalness')
- E.g., room for viable GUTs with $M_X \equiv M_{\text{GUT}} \sim M_{\text{exp}}$ if $G_{\text{4F}}^{qqql}(M_X) \ll 1$

Proton stability and new physics at high energies...



Q: What about quantum gravity?

$$X \to \mathrm{QG}$$



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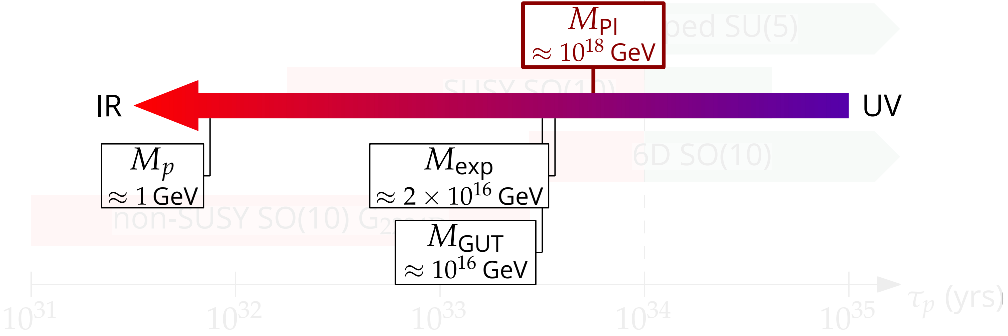

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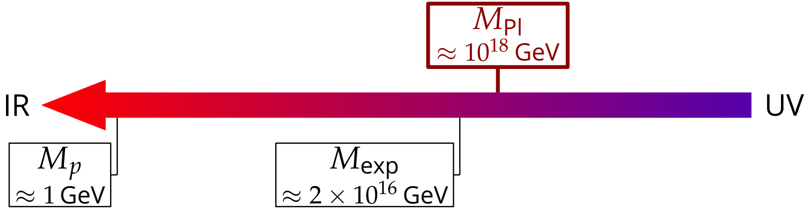

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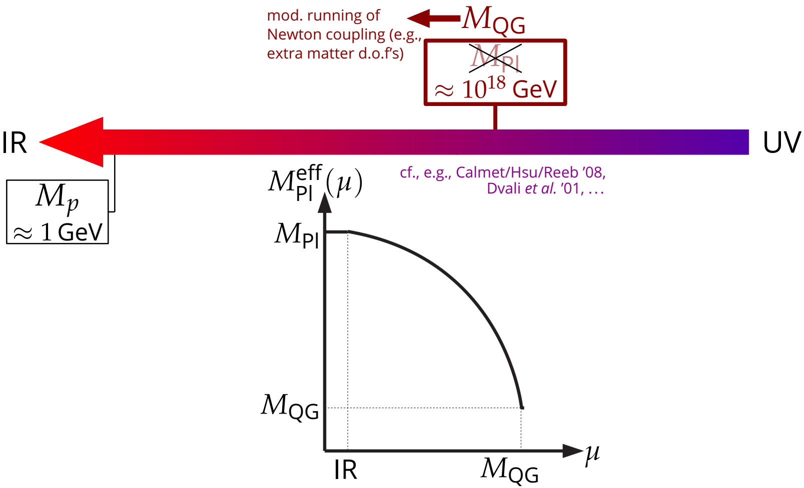

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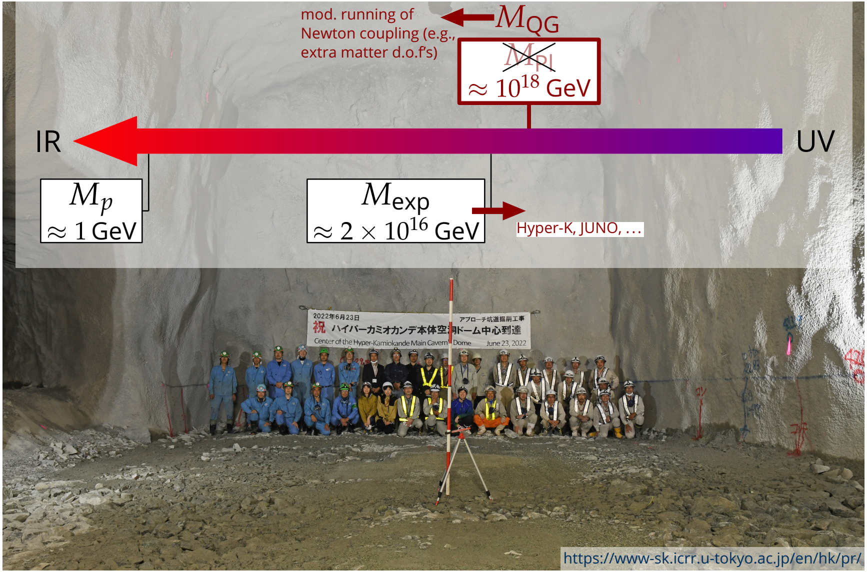

https://www-sk.icrr.u-tokyo.ac.jp/en/hk/pr/

Folklore: proton decay in gravity

No global (i.e., ungauged) symmetries in quantum gravity

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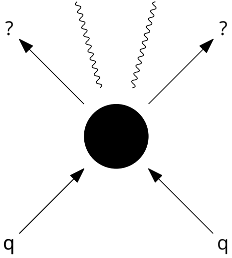
- Heuristic picture: virtual black holes adapted from: Barrow '87; Alsaleh *et al.* '17



estimated proton lifetime: Zel'dovich '76; Adams *et al.* '01; ...

$$\tau_p \sim M_p^{-1} \left(\frac{M_{\text{QG}}}{M_p} \right)^4 \sim 10^{45} \text{ yrs} \times \left(\frac{M_{\text{QG}}}{M_{\text{Pl}}} \right)^4$$

$(*)$ Effectively assuming $G_{\text{4F}}^{qqql}(M_{\text{QG}}) \sim 1$

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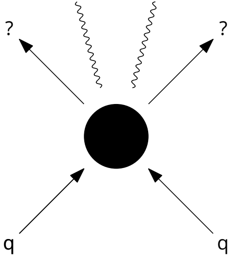

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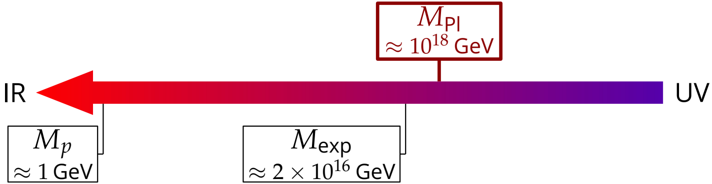
- Here: Explicitly test validity of $(*)$ within Asymptotically Safe Quantum Gravity (ASQG)

Model

Key assumption:



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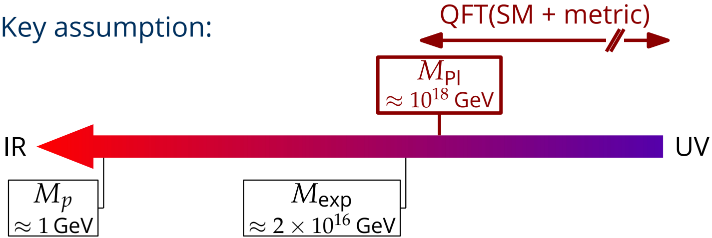

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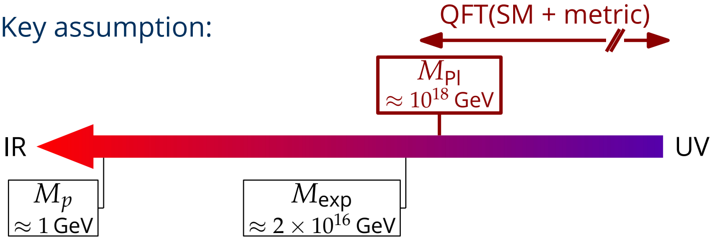

$\ast$ Toy model for QFT(SM + metric):

$$S = S_{\text{EH}} + S_{\text{kin,F}} + S_{4\text{F}}$$

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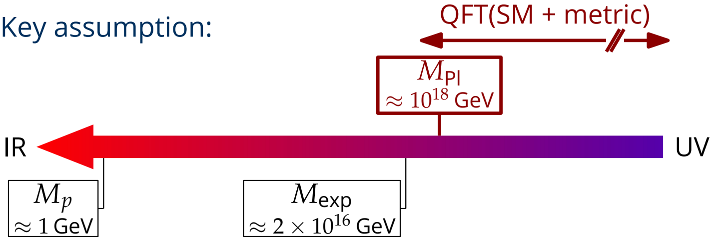

∗ Toy model for QFT(SM + metric):

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∗ ψ: contains all SM fermions
Ψ = Nambu–Gor'kov spinor

…Dirac fermions, right-handed neutrinos included; $SU(2)_L$ gauge coupling asymptotically free in ASQG

∗ split $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$

…in general: eigenvalues of $-\Delta_{\bar{g}}$ defines notion of scale

…often in practice (i.e., here): $\bar{g}_{\mu\nu} \to \delta_{\mu\nu} \implies$ momentum is 'good quantum number' after all …

(Pure) gravity sector

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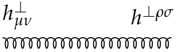
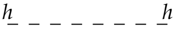
- Fluctuations $h_{\mu\nu}$ decompose into spin-2, 1, and 0 parts
- Landau–DeWitt gauge: only transverse traceless $h^{\perp}_{\mu\nu}$ and conformal $h = h^{\mu}_{\mu}$ modes propagate



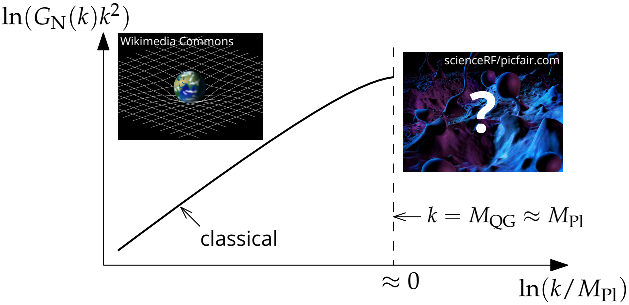
$$= \frac{32\pi G_{\text{N}}}{p^2 - 2\Lambda_{\text{cc}}}(\delta^{\rho}_{\mu}\delta^{\sigma}_{\nu} + \ldots)$$

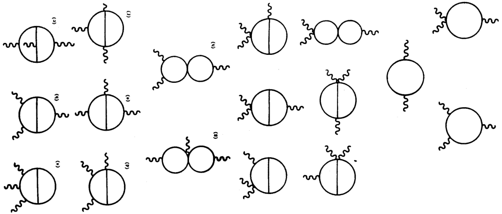


$$= \frac{32\pi G_{\text{N}}}{-\frac{3}{8}p^2 + \frac{1}{2}\Lambda_{\text{cc}}}$$

Remark: (Pure) gravity sector – renormalisation

- Obs.! $[G_\mathrm{N}] = 1/(\mathrm{mass})^2$ – ‘perturbatively non-renormalizable’





$$\Gamma^{(2)}_\infty = \frac{209}{2880(4\pi)^4}\frac{1}{\epsilon}\int d^4x\sqrt{-g}\,R^{\alpha\beta}{}_{\gamma\delta}\,R^{\gamma\delta}{}_{\rho\sigma}\,R^{\rho\sigma}{}_{\alpha\beta}$$

Goroff/Sagnotti ’86

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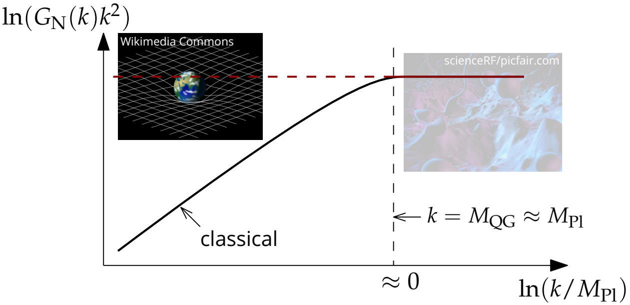
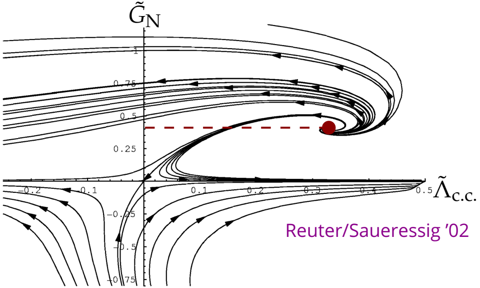
- Predictivity restored by imposing UV quantum scale symmetry
  (= Asymptotic Safety; latest reviews: Eichhorn '19; Reichert '19; Bonanno *et al.* '20; Eichhorn/Schiffer '24; ...)





Reuter/Saueressig '02

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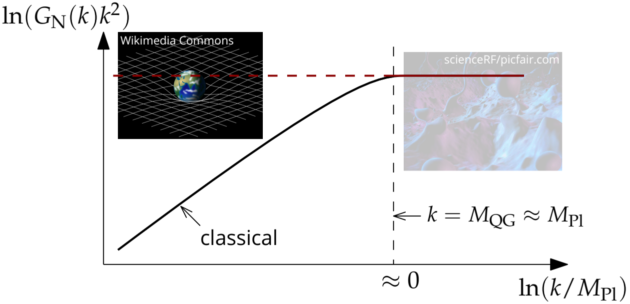
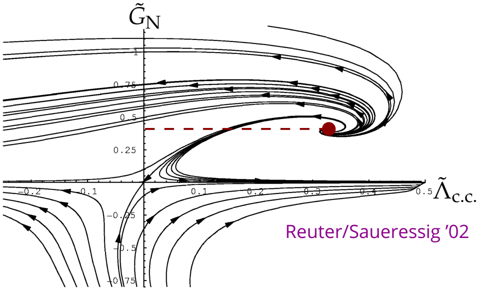




Reuter/Saueressig '02

- Use as 'backdrop' for fermions (i.e.: neglect backreaction of fermions on metric)

Fermions

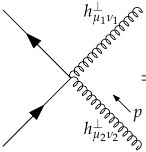
- Propagator has standard form

$$= \frac{\not p}{p^2}$$

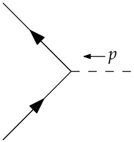
- Vertices coupling metric fluctuations with fermions from $\not\nabla$ and $\sqrt{g}$

…keep only to $\mathcal{O}((h_{\mu\nu})^2)$

$\mathcal{O}\big((\bar{G}_{4\mathrm{F}}^{ABCD})^0\big)$



$$= -\tfrac{1}{128} p_\sigma \gamma^{[\rho_1}\gamma^{\rho_2}\gamma^{\sigma]} \times \left(\delta_{\mu_1\rho_1}\delta_{\mu_2\rho_2}\delta_{\nu_1\nu_2} \pm \cdots\right)$$



$$= \tfrac{3}{16}\not p$$

$$S = S_{\mathrm{EH}} + S_{\mathrm{kin,F}} + S_{4\mathrm{F}}$$

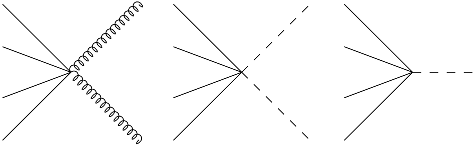
$$S_{\mathrm{EH}} = \frac{1}{16\pi G_{\mathrm{N}}} \int_x \sqrt{g}\left(-R + 2\Lambda_{\mathrm{cc}}\right)$$

$$S_{\mathrm{kin,F}} = \int_x \sqrt{g}\,\bar\psi \mathrm{i}\not\nabla \psi \qquad \Psi = \begin{pmatrix}\psi \\ \psi^c\end{pmatrix}$$

$$S_{4\mathrm{F}} = \bar{G}_{4\mathrm{F}}^{ABCD} \int_x \sqrt{g}\, \Psi_A \Psi_B \Psi_C \Psi_D$$

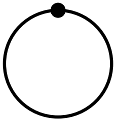
- $G_{4\mathrm{F}}^{ABCD}$: Most general 4-Fermi interaction; proton decay $\sim G_{4\mathrm{F}}^{qqql}$ cf.: Grzadkowski *et al.* '10

$\mathcal{O}\big(\bar{G}_{4\mathrm{F}}^{ABCD}\big)$



Computational framework

$$\frac{\partial \Gamma_k[\Phi]}{\partial \ln k} = \frac{1}{2}\,\mathrm{STr}\left[\left(\frac{\delta^2 \Gamma_k[\Phi]}{\delta\Phi\delta\Phi^\top} + R_k[\Phi]\right)^{-1} \frac{\partial R_k[\Phi]}{\partial \ln k}\right] =$$



cf., e.g.: Berges *et al.* Phys. Rep. '02; Metzner *et al.* Rev. Mod. Phys. '12; Dupuis *et al.* Phys. Rept. '21; and refs. therein

$\Phi = (h^{\perp}_{\mu\nu}, h, \psi, \bar{\psi}^c)^\top$; k — RG scale; R — regulator

Functional renormalization group (FRG), general version

- Γ — 1PI effective action aka Legendre effective action, quantum effective action, …
  Γ_k — average 1PI effective action aka 'blocked' –"–
  — fluctuations above scale k 'integrated out'
- 1-loop exact in principle
  assuming self-consistent solution
  loop expansion – start with $\Gamma = S$ plus fixed-point iteration
- Ansatz for Γ_k defines approximation scheme
- Often: expand in canonical dimension (i.e., powers of $\psi, h_{\mu\nu}, \partial_\mu$), keep least irrelvant terms
  justification: 'near perturbative' nature, cf. Codello/Percacci '06; Niedermaier '09, '10; Eichhorn *et al.* '18a,b; …

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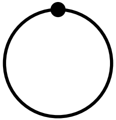

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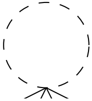
Functional renormalization group (FRG), 'quick and dirty' version

- Ansatz: $\Gamma_k = S\big|_{h_{\mu\nu}\to\sqrt{Z_\mathrm{N}}h_{\mu\nu}, G_\mathrm{N}\to G_\mathrm{N}(k), \Lambda_\mathrm{cc}\to\Lambda_\mathrm{cc}(k), \psi\to\sqrt{Z_\psi}\psi, G_\mathrm{F}\to G_\mathrm{F}(k)}$
- Draw one-loop diagrams with vertices and propagators from before
- Replace couplings and propagators with 'dressed' versions
- Replace momentum integrals with 'threshold functions'
  diagram with n_F internal fermion lines, $n_\perp$ spin-2 lines, n_conf conformal mode lines $\Rightarrow I_{n_\mathrm{F}, n_\perp, n_\mathrm{conf}}$

e.g.:



$$\sim \int_p' \frac{32\pi G_\mathrm{N}}{-\frac{3}{8}p^2 + \frac{1}{2}\Lambda_\mathrm{cc}} \mapsto I_{001} \sim \frac{(-6+\eta_\mathrm{N})g_\mathrm{N}}{(3-4\lambda_\mathrm{cc})^2}$$

$$\eta_\mathrm{N} = -k\partial_k \ln Z_\mathrm{N},\ g_\mathrm{N} = G_\mathrm{N}k^2;\ \lambda_\mathrm{cc} = \Lambda_\mathrm{cc}/k^2$$

Diagrammatics

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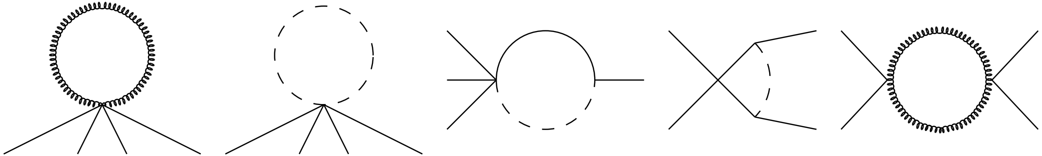

- Result: N.B.: η_{4F} in fact independent of precise index structure $ABCD \leftrightarrow$ 'gravity blind to internal indices'

$$k\partial_k G^{qqql}_{\text{4F}}(k) = (2+\eta_{\text{4F}})\, G^{qqql}_{\text{4F}}(k) + \mathcal{O}((G^{qqql}_{\text{4F}})^2)$$

- Explicitly: Litim regulator, Landau–DeWitt gauge, cf. Eichhorn/Gies '11

$$\eta_{\text{4F}} = 2g_{\text{N}}\left[-\frac{9(2\lambda-3)}{4\pi(3-4\lambda_{\text{cc}})^2} + \frac{6(4\lambda_{\text{cc}}-9)}{5\pi(3-4\lambda_{\text{cc}})^2} + \frac{5}{4\pi(1-\lambda_{\text{cc}})^2} + \frac{3}{2\pi(4\lambda_{\text{cc}}-3)^2}\right]$$
$$= \frac{29 g_{\text{N}}}{15\pi} + \frac{32 g_{\text{N}}\lambda_{\text{cc}}}{9\pi} + \mathcal{O}(\lambda_{\text{cc}}^2)$$

Discussion I: General

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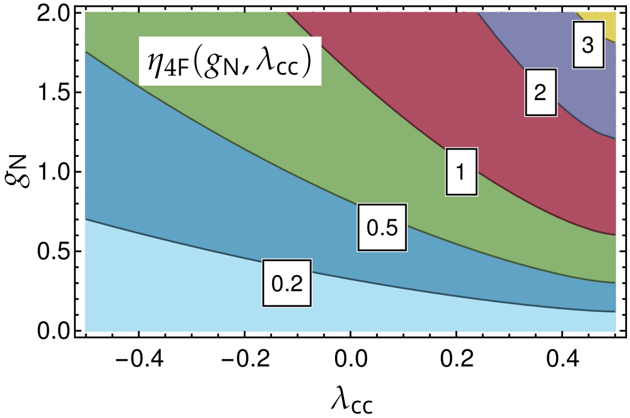
$$k\partial_k G_{4\mathrm{F}}^{qqql}(k) = (2+\eta_{4\mathrm{F}})\, G_{4\mathrm{F}}^{qqql}(k) + \mathcal{O}((G_{4\mathrm{F}}^{qqql})^2)$$



- Generally: $\eta_{4\mathrm{F}} > 0$
  …assuming $\lambda_{\mathrm{cc}} > -9$ (pheno. relevant)
  'metric fluctuations suppress proton decay'
- hence *a fortiori*: $2 + \eta_{4\mathrm{F}} > 0$

  $\Rightarrow$ naïvely 'unnatural' $G_{4\mathrm{F}}^{qqql}(M_{\mathrm{QG}}) \ll 1$ is actually 'natural' if QFT(SM + metric) holds at $M_{\mathrm{QG}} < k < k_{\mathrm{UV}}$ for k_{UV} large enough

  N.B.: *Much* milder assumption than (eff.) AS!
  Caveats/assumptions:
  $*$ Einstein–Hilbert truncation should remain good approximation
  $*$ B-violation from UV completion is (at most) 'natural': $G_{4\mathrm{F}}^{qqql}(k_{\mathrm{UV}}) \sim 1$

Discussion II: AS and effective AS

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- Assumption: Running of $g_{\mathrm{N}}, \lambda_{\mathrm{cc}}$ negligible for $M_{\mathrm{QG}} < k < k_{\mathrm{UV}}$ ($=$ quasi-FP regime)

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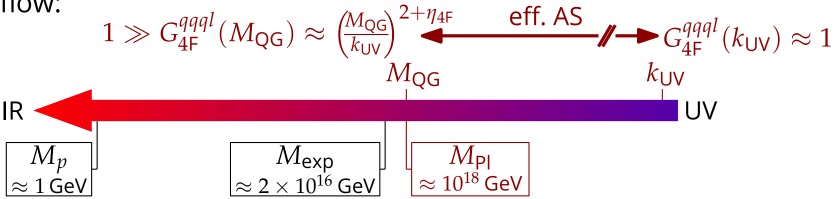

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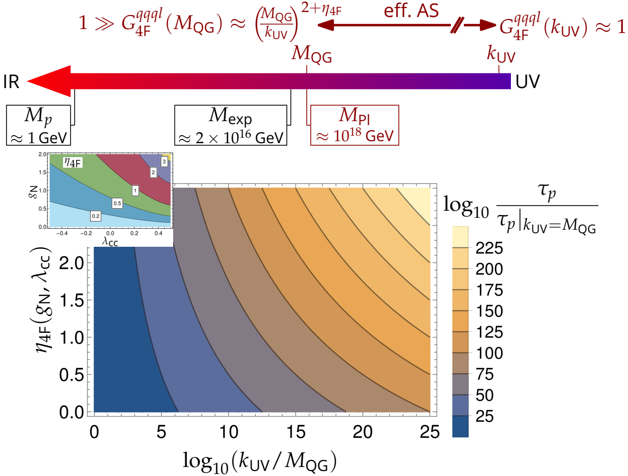

Discussion III: GUTs

Eichhorn/S.R. *Phys. Lett. B* '24

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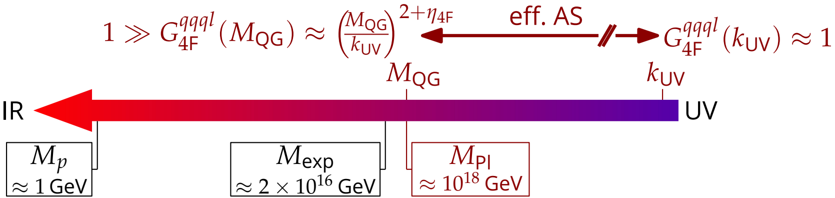
- Typical numbers for C's and f's[2] $\implies \left| G_{4F,*}^{qqql} \right|^2 \lesssim 10^{-7}$

[2] Eichhorn/Held/Wetterich '18

Discussion IV: B-symmetry in ASQG

Eichhorn/S.R. *Phys. Lett. B* '24



- Corollary (strict AS limit): $k_{UV} \to \infty \implies G_{4F}^{qqql}(M_{QG}) \to 0$
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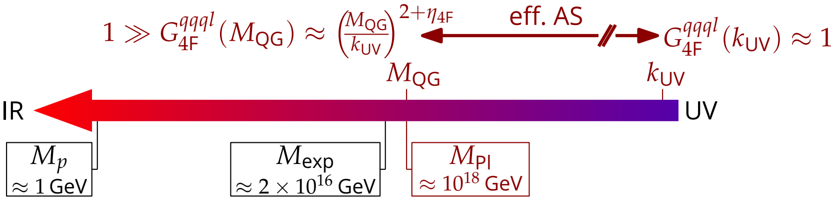

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$\Downarrow$

ASQG = B-conserving UV completion of GR

Discussion IV: B-symmetry in ASQG

Eichhorn/S.R. *Phys. Lett. B* '24

- $G^{qqql}_{4F,*} = 0 \Rightarrow$ ASQG = B-conserving UV completion of GR

$\rightarrow$ Truncation-independent 'proof': Use Quantum Action Principle for regularized effective action Γ_k

$$e^{-\Gamma_k[\Phi]} = \int \mathcal{D}\tilde{\Phi}\, e^{-S[\tilde{\Phi}]+(\tilde{\Phi}_X-\Phi_X)\Gamma_{k,}{}^{X}[\Phi]-\frac{1}{2}\mathcal{R}_k^{XY}(\tilde{\Phi}_X-\Phi_X)(\tilde{\Phi}_Y-\Phi_Y)}$$

$$\delta_\epsilon \Gamma_k[\Phi] = \left\langle \delta_\epsilon \left(S[\tilde{\Phi}] - (\tilde{\Phi}_X - \Phi_X)\Gamma_{k,}{}^{X}[\Phi] + \frac{1}{2}\mathcal{R}_k^{XY}(\tilde{\Phi}_X - \Phi_X)(\tilde{\Phi}_Y - \Phi_Y) \right) \right\rangle_{k;\Phi}$$

with

$$\langle \mathcal{F}[\tilde{\Phi}] \rangle_{k;\Phi} := e^{\Gamma_k[\Phi]} \int \mathcal{D}\tilde{\Phi} e^{-S[\Phi]+(\tilde{\Phi}_X-\Phi_X)\Gamma_{k,}{}^{X}[\Phi]-\frac{1}{2}\mathcal{R}_k^{XY}(\tilde{\Phi}_X-\Phi_X)(\tilde{\Phi}_Y-\Phi_Y)} \mathcal{F}[\tilde{\Phi}]$$

Ward–Takahashi identity for B-symmetry

N.B.: Assuming reg. preserves B-symmetry, manifest for Dirac fermions (more tricky for Weyl!)

$$\delta_\epsilon S = 0 \implies \delta_\epsilon \Gamma_k = 0$$

B-symmetry in ASQG vs QG folklore

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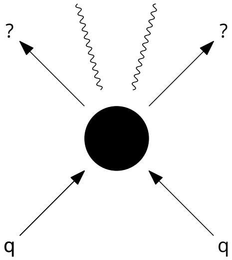

- Assumptions that generically lead to B-violation may not be valid in ASQG, many open questions

  e.g., what do ASQG black holes 'look like'? How about their dynamics?
  $\rightarrow$ difficult from first principles – see however Pawlowski/Tränkle '24; usually based on 'RG improvement' of classical solutions Bonanno/Reuter '99, '00, '06; Reuter/Weyer '04; Cai/Easson '10; Liu *et al.* '12; Falls *et al.* '12; Falls/Litim '14; Koch/Saueressig '13, '14; Saueressig *et al.* '15; González/Koch '16; Torres '17; Adéìféoba *et al.* '18; Held *et al.* '19; Bosma *et al.* '19; Platania '20; Bonanno *et al.* '21; Ishibashi *et al.* '21; Borissova/Platania '23; …

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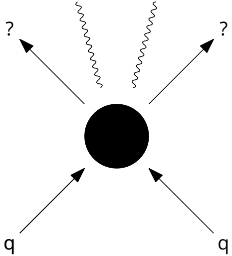

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- More generally: Horizons 'eat' global charge
  $\longrightarrow$ *Now: Can these 'problematic' contribs to gravitational path integral be suppressed by non-minimal curvature terms?*

Dynamical suppression of horizons: construction

Borissova/Eichhorn/S.R. *Class. Quant. Grav.* '25

Assume gravitational path integral given by $\int \mathcal{D}g\, e^{iS_{\text{eff}}(g)}$.

Can (quasi-)local contribution to Lagrangian $\int_x \mathcal{L}_{\text{hor}}(g(x))\mu_g(x) \subset S_{\text{eff}}(g)$ ($\mu_g(x) = \sqrt{-\det(g(x))}\, d^4x$) be found so that $S_{\text{eff}}(g) \to \infty$ if g has horizon?

Similar to: Higher-order curvature terms in $S_{\text{eff}} \Rightarrow S_{\text{eff}}$ divergent for (many) types of g with curvature singularities cf. Borissova/Eichhorn '21, Borissova '24

Claim:

$$\mathcal{L}_{\text{hor}} = \frac{(C^2)^8}{[4C^2(\nabla C)^2 - (\nabla C^2)^2]^2}$$

C — Weyl tensor w.r.t. g

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1. Is positive everywhere, $\mathcal{L}_{\text{hor}}(g(x)) > 0$ for all x
2. $S_{\text{eff}}(g) = \infty$ if g is rotationally symmetric and has (apparent) horizon(!)

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Borissova/Eichhorn/S.R. *Class. Quant. Grav.* '25

Assume gravitational path integral given by $\int \mathcal{D}g\, e^{iS_{\text{eff}}(g)}$.

Can (quasi-)local contribution to Lagrangian $\int_x \mathcal{L}_{\text{hor}}(g(x))\mu_g(x) \subset S_{\text{eff}}(g)$ ($\mu_g(x) = \sqrt{-\det(g(x))}\, d^4x$) be found so that $S_{\text{eff}}(g) \to \infty$ if g has horizon?

Similar to: Higher-order curvature terms in $S_{\text{eff}} \Rightarrow S_{\text{eff}}$ divergent for (many) types of g with curvature singularities
cf. Borissova/Eichhorn '21, Borissova '24

Claim:

$$\mathcal{L}_{\text{hor}} = \frac{(C^2)^8}{[4C^2(\nabla C)^2 - (\nabla C^2)^2]^2}$$

C — Weyl tensor w.r.t. g

1. Is positive everywhere, $\mathcal{L}_{\text{hor}}(g(x)) > 0$ for all x
2. $S_{\text{eff}}(g) = \infty$ if g is rotationally symmetric and has (apparent) horizon(!)
3. Can be defined(!) and is not divergent(!) for many 'nice enough' spacetimes

Dynamical suppression of horizons: construction

Borissova/Eichhorn/S.R. *Class. Quant. Grav.* '25

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   Use that $4C^2(\nabla C)^2 - (\nabla C^2)^2$ changes sign with $m(v,r) - R(r)$, cf. Coley/McNutt '18, McNutt *et al.* '21

$$ds^2 = -e^{2\beta(v,r)}\left(1 - \frac{2m(v,r)}{R(r)}\right)dv^2 + 2e^{\beta(v,r)}dv\,dr + R(r)^2dr^2 + r^2d\Omega^2$$

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3. Compute explicitly for $ds^2 = -(1+cr^2)dt^2 + a(t)^2(dr^2 + r^2d\Omega^2)$
   Finite for all c, vanishes for Weyl-flat $c \to 0$ (flat Minkowski $g = \eta$ *a fortiori*)

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- Usual disclaimers (unitarity, stability, ...) apply

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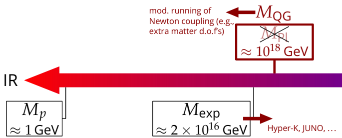

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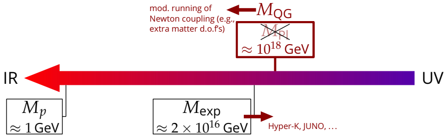

- Horizons (i.e. those that 'eat' global charge) may potentially be suppressed in path integrals using actions that are only mildly non-local
  Unified construction for general horizons? Wormholes/topology change?
  Black-hole entropy?
  Derivation from more fundamental (e.g., discrete) approach or integrating out DOFs?

Acknowledgement

Based on:

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