Higgs inflation:

idea: non-minimal coupling $\xi R H^\dagger H$

could explain inflation without extra field

how: conformal transformation of the metric removes

ξ and produces an appropriate potential

for inflation

status: evidence that ξ is predicted in AS

but not compatible with CMB data

needs improved approximations

Eichhorn, Pauly
2005.03661

Structural aspects

Q: can we assume that all higher-order matter couplings have a free fixed point?

e.g. $\lambda_1 (\partial_\mu \phi)(\partial^\mu \phi)(\partial_\nu \phi)(\partial^\nu \phi)$ or

$\lambda_2 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma}$

$\rightarrow$ are $\lambda_1 = 0$, $\lambda_2 = 0$ fixed points?

no: some couplings **cannot** have a Gaussian FP in AS! — Eichhorn 1204.0965

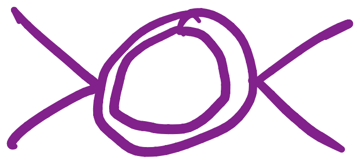
how: there must be terms in $\beta_{\lambda_{1,2}}$ that do not vanish if $\lambda_{1,2} = 0$

example: consider "free" scalar field + gravity

$$\to \quad \Gamma_k \sim \int d^4x \sqrt{g}\left[-\frac{R}{16\pi G_{N,k}} + \frac{1}{2}(D_\mu\phi)(D^\mu\phi)\right]$$

Can we generate a contribution to β_{λ_1} from this?

<u>yes</u>: from the kinetic term of the scalar, we get vertices with two gravitons

→ can build  $\propto G_N^2$

contributes to β_{λ_1}

upshot: any term that has the same symmetries as the kinetic term (e.g. shift symmetry $\phi \to \phi + c$, c const.)

cannot have a Gaussian FP

$\rightarrow$ it is necessarily induced by QG fluctuations

other couplings <u>can</u> have a Gaussian FP, but it might not be the physically relevant one

Beyond SM

why: • dark matter

• neutrino oscillations

DM: two scalar examples

de Brito, Eichhorn, Lino dos Santos 2112.08972

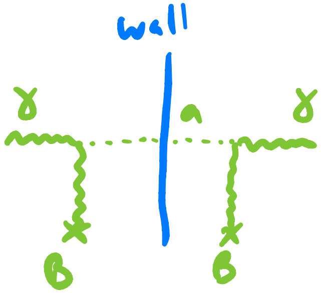
1) ALP (axion-like particle) – pseudoscalar

→ solves strong CP problem: coupling of $F\tilde{F}$ is exceptionally small (or zero) in QCD even though it is not protected by symmetry

might be observed by light-shining-through-wall

→ axion couples to $F\tilde{F}$, $\tilde{g}\, a F\tilde{F}$ dim 5!

experiments



magnetic field on both sides

→ vev of a is driven to zero dynamically

→ string theory is expected to have an axion

→ Q: can AS generate nonzero $\tilde{g}$?

2) ultralight scalar DM

Assant, Eichhorn, Knorr 2510.23808

→ couples to F^2, $g \Phi F^2$ (dim 5)

→ might be measured by Thorium-based nuclear clocks

↳ DM induces time-dependent corrections to SM parameters if light enough

→ occupation of at least 1 per de Broglie volume

→ ULDM = classical field

→ oscillation determined by mass

clocks pick up signal by comparing rates
of frequency standards that depend on
DM parameters differently]

for both: indications that g ($\tilde{g}$ <u>not</u> generated
by QG fluctuations (irrelevant at
fixed point $g/\tilde{g} = 0$)

↳ potentially not viable DM candidates

but more advanced computations needed

AS-inspired black holes

- evidence that AS + SM could work!

→ discuss what AS can say about genuine QG questions, e.g. black holes

recall: black holes in GR have singularities where curvature diverges

e.g. $R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} = \frac{48 G^2 M^2}{r^6}$

for a Schwarzschild BH

→ hard question – can we cheat a bit?

review of RGI for AS-inspired BHs: Platania 2302.04272

⇝ RG improvement (RGI)

idea: get leading-order quantum corrections in physical quantities by replacing classical couplings with running couplings and identifying the RG scale with a physical scale

will absolutely never be a problem

example: QED at high energies (short distances, $r \ll 1/m_e$)

- classical potential: $V^{cl}(r) = -\frac{e^2}{4\pi r}$

- one-loop β function: $\beta_e = \frac{e^3}{12\pi^2}$

$$\hookrightarrow \quad e^2(\mu) \simeq e^2(\mu_0)\left[1 + \frac{e^2(\mu_0)}{6\pi^2} \ln\frac{\mu}{\mu_0} + \dots\right]$$

- identify $\mu \leftrightarrow \frac{1}{r}$ (and $\mu_0 \leftrightarrow \frac{1}{r_0}$)

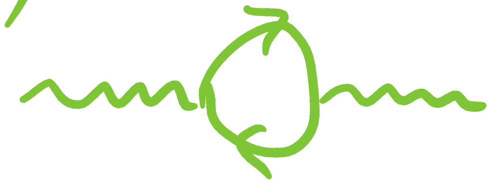
and plug into V^{cl}:

$$V^{RGI}(r) \approx -\frac{e^2(r_0)}{4\pi r}\left[1 - \frac{e^2(r_0)}{6\pi^2} \ln\frac{r}{r_0} + \dots\right]$$

correct functional form of the Uehling potential

= one-loop QED potential

measurable contribution to Lamb shift (~ 2%) →



⌜ Uehling potential: usually derived in perturbation theory

→ quantum corrections to photon propagator

→ Fourier transform

→ potential

(similar to Newton potential) ⌟

Second example: Coleman-Weinberg effective potential

RGI in AS

Bonanno, Reuter gr-qc/9811026
hep-th/0002196

→ apply RGI to BHs, using RG flow of the EH truncation

Schwarzschild BH: → $\Lambda = 0$, asymptotically flat

$$ds^2 = -f(r)\,dt^2 + \frac{1}{f(r)}\,dr^2 + r^2 d\Omega^2$$

$$f^{cl}(r) = 1 - \frac{2G_N M}{r}$$

M: BH mass (not a running parameter)

↑ ~ classical potential

RGI: in $f^{cl}(r)$, we replace

somewhere here there is a hidden wick rotation!

$$G_N \longrightarrow G_N(k) \longrightarrow G_N(k(r))$$

"upgrade" ↑   ↑ scale identification

1) to a good approximation,

"the" Newton's constant $G_N = G_N(k=0)$

$$G_N(k) \approx \frac{G_N}{1 + \frac{G_N k^2}{g_*}}$$

solution to β function, i.e. a trajectory

FP value of dimensionless Newton's constant

2) scale identification – different choices possible

original choice: proper distance from origin to generic point along radial geodesic

up to an $\mathcal{O}(1)$ factor ξ

$$\to \quad k \approx \xi / D(r),$$

$$D(r) = \int_0^r d\tilde{r} \, \left| f^{cl}(\tilde{r}) \right|^{-1/2} \sim \begin{cases} \frac{2}{3} \frac{r^{3/2}}{\sqrt{2 G_N M}} \left(1 + \mathcal{O}(r)\right) & (r \to 0) \\ r + \mathcal{O}(r^0) & (r \to \infty) \end{cases}$$

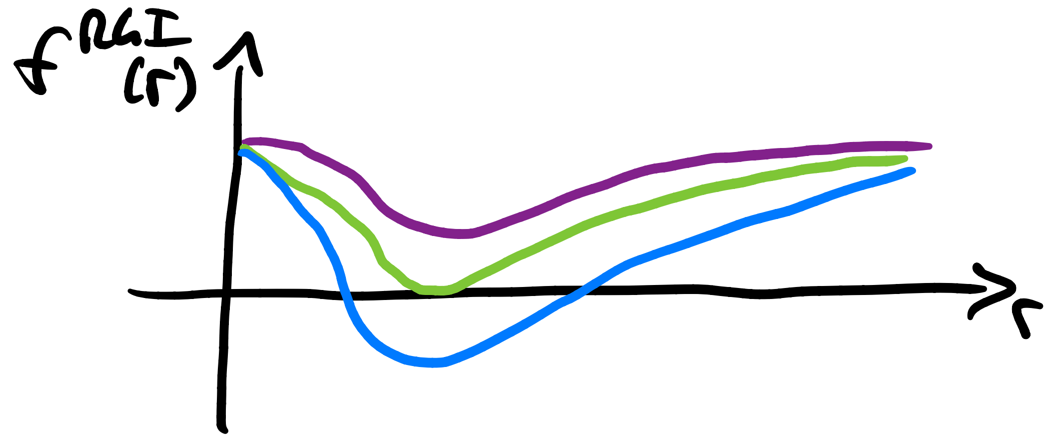
analytic approximation: $D(r) \approx \sqrt{\dfrac{r^3}{r + \frac{9}{2} G_N M}}$

plug in:

$$f^{RGI}(r) \simeq 1 - \frac{2 G_N M r^2}{r^3 + \xi^2 \frac{G_N}{g_*}\left(r + \frac{9}{2} G_N M\right)}$$

- $r \to \infty$: sub-leading correction to f^{cl}
  could be matched with one-loop result to fix ξ
- $r \to 0$: regular
- intermediate r: can have 0, 1, 2 horizons

"Bonanno-Reuter BHs"



→ behave like commonly studied models of regular BHs

→ have a de Sitter core with $\Lambda_{eff} = \frac{4 g_*}{3 \xi^2 G_N}$

⇝ finite positive R in center

→ can study evaporation

Bonanno, Reuter hep-th/0602159

BH temperature $T = \frac{1}{4\pi} f^{RGI\,\prime}(r_+)$ = a mass

↑ outer horizon

evaporation stops at finite mass

⇒ remnant

note: (regular) BHs with two horizons might suffer from an instability called mass inflation

upshot: instability of inner horizon

→ infinite energy buildup since energy flows to smaller r from outside, but to larger r from inside, meeting at the inner horizon at r_-

→ need to account for backreaction

→ intense discussion in the literature

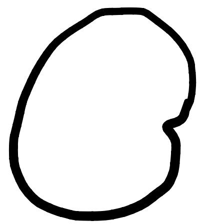
Kerr BH

Held, Gold, Eichhorn 1904.07133

↗ some really nice plots!

- more complicated
- can compute BH shadows
  - → event horizon shrinks ⇒ smaller shadow
  - → characteristic dent

Planck-suppressed effects!



highly exaggerated

- to describe realistic scenarios, need to model gravitational collapse ⇒ need astrophysics

↑ generally considered hard

more topics on RGI: Platania 2302.04272