Weyl Symmetry
&
the Structure of 4D RG Flows

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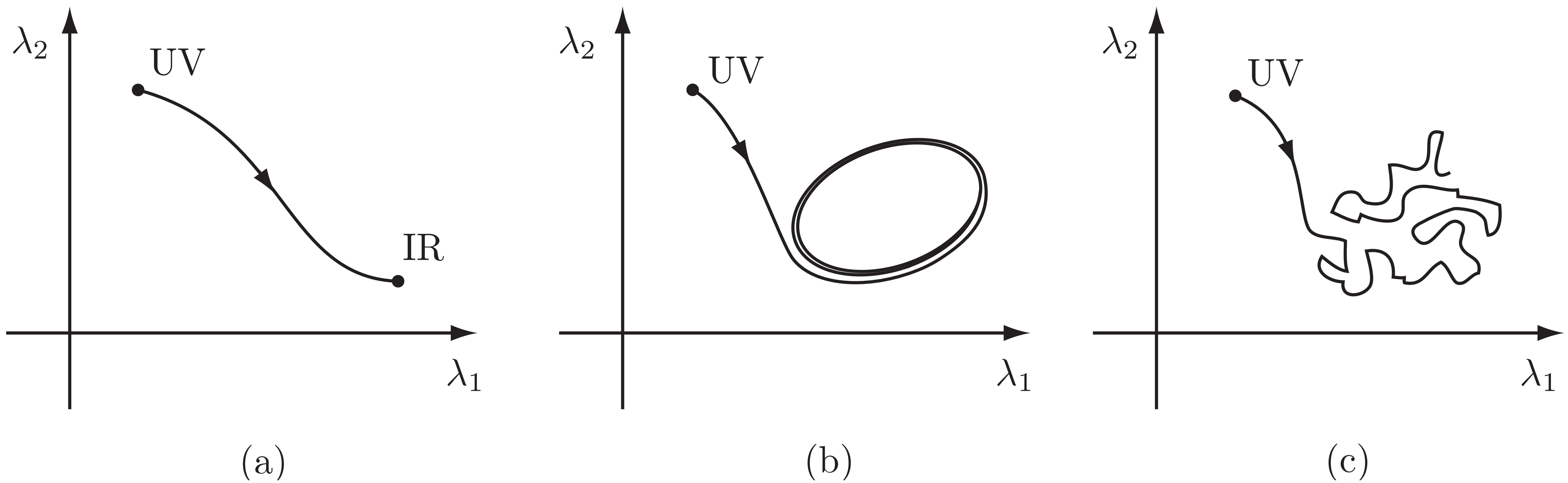
M. Luty, J. Polchinski, RR — arXiv:1204.5221

F. Baume, B. Keren-Zur, RR, L. Vitale — in preparation

conceivable RG flows



but all known examples asymptote to a CFT fixed point

Is there a way to understand that?

Two approaches to constrain RG-flow structure

- Wess-Zumino consistency conditions for Weyl anomaly off-criticality

Jack, Osborn 1990 Osborn 1991

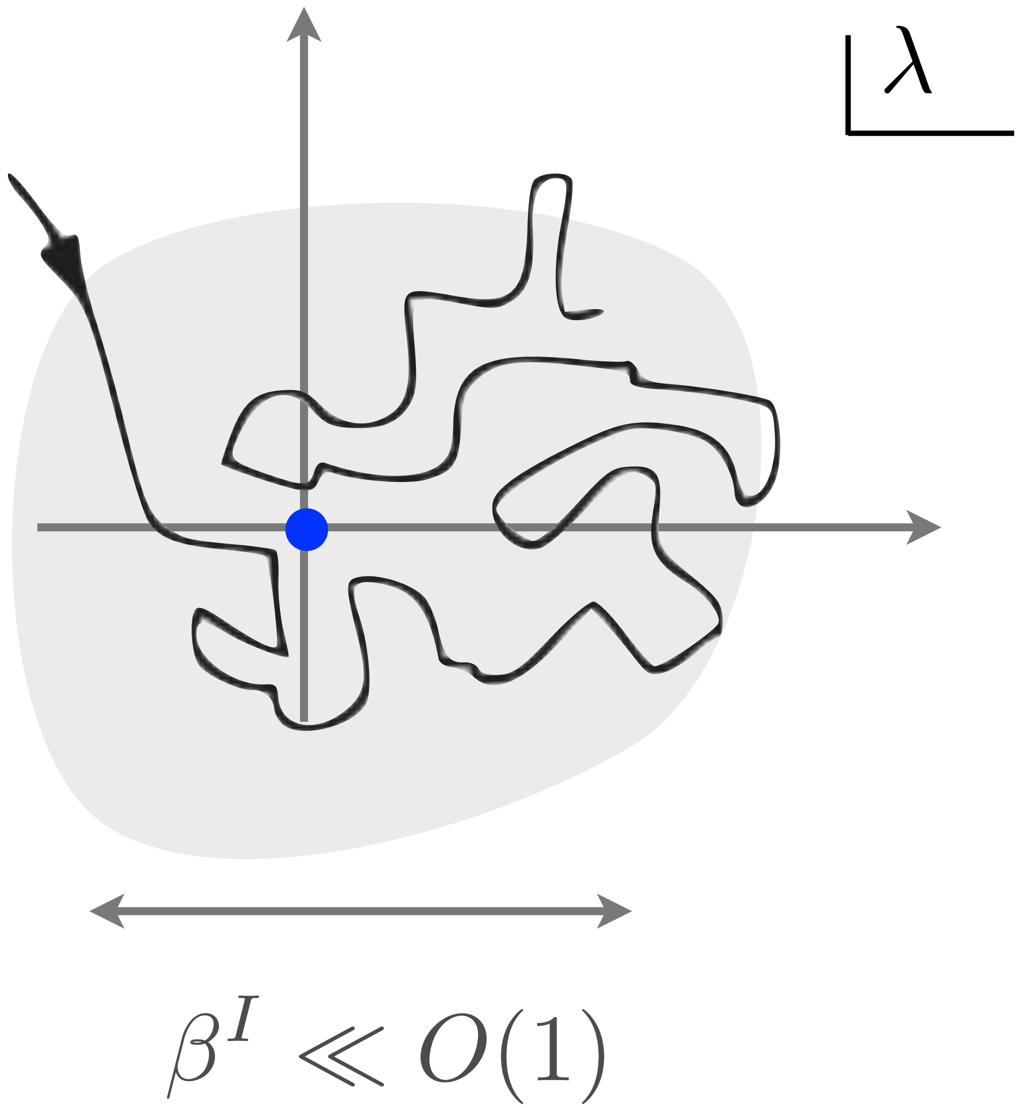
- Dispersion relations for $\langle T \ldots T \rangle$
Optical theorem for scattering amplitudes of background dilaton

Komargodski and Schwimmer 2011

Results

- $a_{UV} > a_{IR}$
- CFT is the only possible asymptotics in weakly coupled 4D QFT
- the occurrence of SFTs is severely constrained (ruled out...) even beyond perturbation theory

Goal: study RG flow in a domain around a fixed point



$$\mathcal{L} = \mathcal{L}_{CFT} + \sum_I \lambda^I \mathcal{O}_I$$

- CFT, not necessarily free
- $\lambda^I \ll O(1)$ not necessary

  provided $\beta^I \ll O(1)$

  in whole domain

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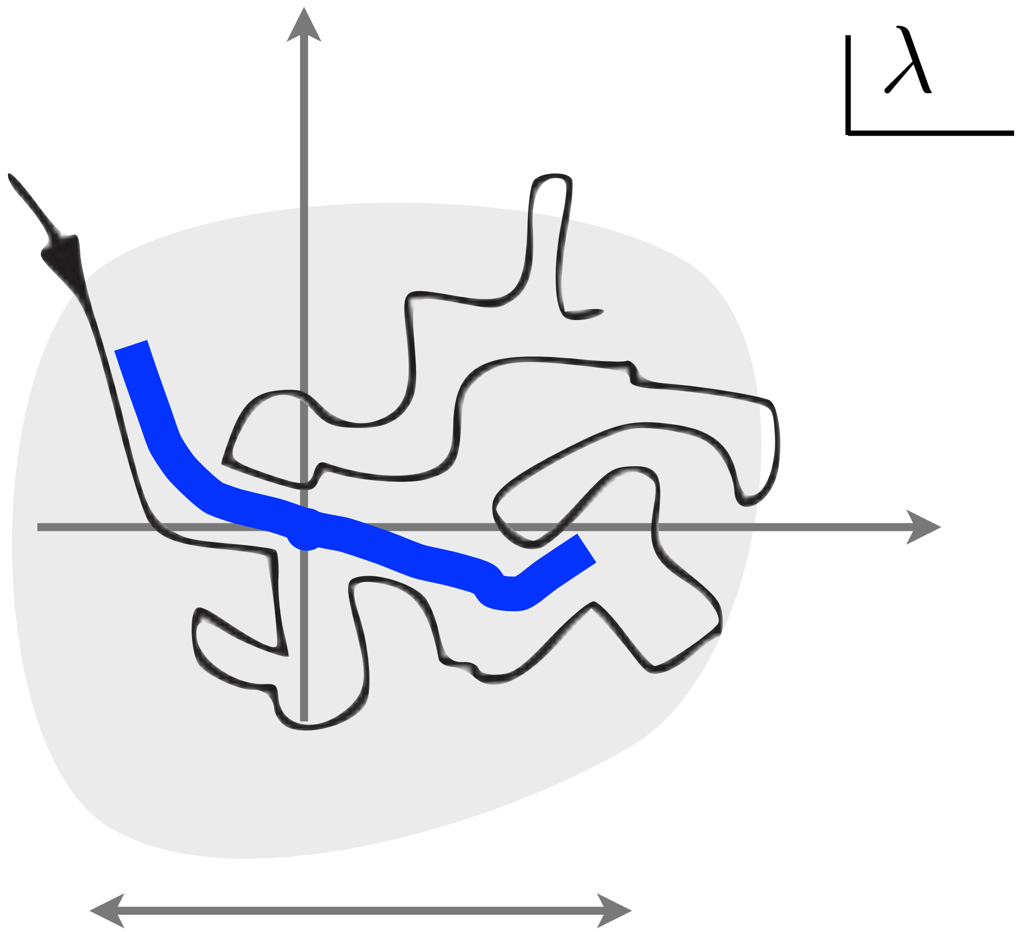

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RG flow $\longleftrightarrow$ correlators of $T \equiv T^\mu_\mu$

current for flavor symm broken by $\lambda^I \neq 0$

complete 'basis' for T^μ_μ $\Rightarrow$ $\mathcal{O}_I, \quad \partial^\mu J^A_\mu, \quad \Box\mathcal{O}_a$

- Ex: free CFT with scalars and fermions relevant object ≡ effective action for sources

$$T_{\mu\nu} \leftrightarrow g_{\mu\nu}(x)$$

$$\mathcal{O}_I \leftrightarrow \lambda_I(x)$$

$$J_\mu^A \leftrightarrow A_\mu^A(x)$$

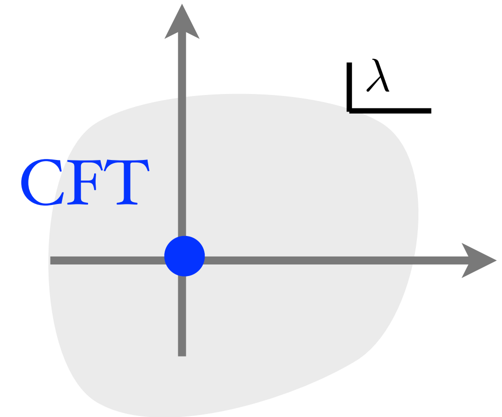
$$\mathcal{O}_a \leftrightarrow m_a(x)$$

$$W \equiv W[g_{\mu\nu}, \lambda^I, A_\mu^A, m_a, \ldots]$$

$$T_{\mu\nu} = \frac{2}{\sqrt{g}} g^{\mu\nu} \frac{\delta}{\delta g^{\mu\nu}} W \qquad \mathcal{O}_I(x) = \frac{1}{\sqrt{g}} \frac{\delta}{\delta \lambda_I(x)} W$$

etc ...

At fixed point



$$W[g_{\mu\nu}, \lambda = 0, A_\mu = 0, m_a = 0]$$

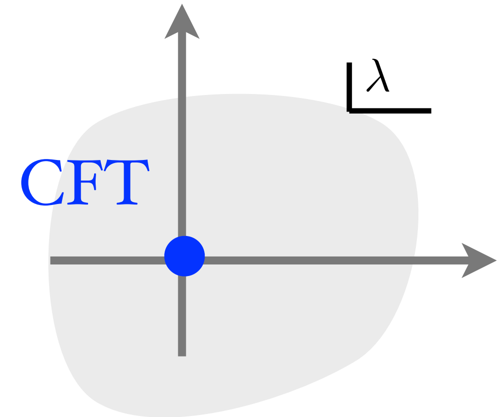
Weyl invariant up to anomaly

Capper, Duff '73

$$\frac{2g^{\mu\nu}}{\sqrt{g}} \frac{\delta}{\delta g^{\mu\nu}} W = aE_4 - bR^2 - cW^2 - d\Box R$$

$$= aE_4 - cW^2 - \delta(F_{\text{local}})$$

At fixed point



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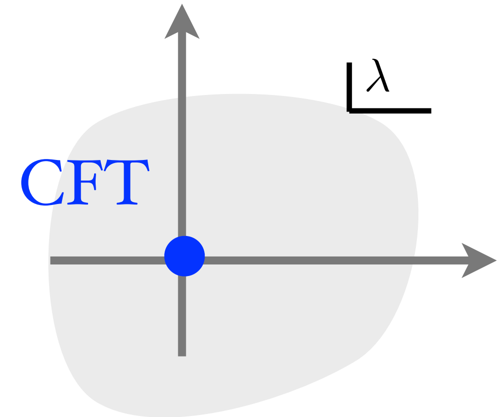

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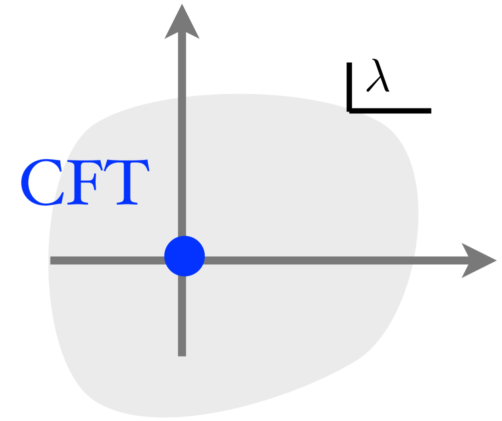

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$$\frac{2g^{\mu\nu}}{\sqrt{g}} \frac{\delta}{\delta g^{\mu\nu}} W = aE_4 - \cancel{bR^2} - cW^2 - d\Box R \quad \boxed{+ e\Lambda^2 R + f\Lambda^4}$$

$$= aE_4 - cW^2 - \delta(F_{\text{local}})$$

Weyl anomaly equation can be extended off criticality by assigning transformation properties to sources

→ local Callan-Symanzik equation

Osborn 1991

$$\int d^4x \Big\{ \sigma(x) \left[2g^{\mu\nu} \frac{\delta}{\delta g^{\mu\nu}(x)} - \beta^I \frac{\delta}{\delta \lambda^I(x)} - \rho_I^A \nabla_\mu \lambda^I \frac{\delta}{\delta A_\mu^A(x)} + \tilde{m}^a \frac{\delta}{\delta m^a(x)} \right] +$$

$$+ \nabla_\mu \sigma(x) \left[\theta_I^a \nabla^\mu \lambda^I \frac{\delta}{\delta m^a(x)} - S^A \frac{\delta}{\delta A_\mu^A(x)} \right] - \Box \sigma(x) t^a \frac{\delta}{\delta m^a(x)} \Big\} W \quad =$$

$$= \quad \int d^4x \, \sigma(x) \, \mathcal{A}(x)$$

- $$2\tilde{m}^a \; = \; 2m^b(\delta_b^a + \gamma_b^a) + \frac{1}{3}\eta^a R + d_I^a \Box \lambda^I + \frac{1}{2}\epsilon_{IJ}^a \nabla_\mu \lambda^I \nabla^\mu \lambda^J$$

- $\mathcal{A}(x) \; =$ all possible dim 4 covariant terms

Easy to derive local CS eq. in ordinary (near free) QFT using dim reg

$$S_0 \;=\; S_1[\text{fields, sources}] + S_{CT}[\text{sources}]$$

- S_1 obviously Weyl invariant

$$\lambda_0^I \to e^{\epsilon\sigma(x)}\lambda_0^I \quad \Rightarrow \quad \delta_\sigma(\lambda^I) \;=\; \sigma\beta^I$$

- S_{CT} not Weyl invariant (unless new sources added)

$$\delta_\sigma S_{CT} \;=\; \sigma\mathcal{A}$$

Redundancies in source parametrization

$$\delta_\sigma \equiv \sigma(x)\left[2g^{\mu\nu}\frac{\delta}{\delta g^{\mu\nu}(x)} - \beta^I\frac{\delta}{\delta\lambda^I(x)} - \rho_I^A\nabla_\mu\lambda^I\frac{\delta}{\delta A_\mu^A(x)} + \tilde{m}^a\frac{\delta}{\delta m^a(x)}\right] +$$

$$+\nabla_\mu\sigma(x)\left[\theta_I^a\nabla^\mu\lambda^I\frac{\delta}{\delta m^a(x)} - S^A\frac{\delta}{\delta A_\mu^A(x)}\right] - \Box\sigma(x)t^a\frac{\delta}{\delta m^a(x)}$$

$$m^a \to m^a + \frac{1}{6}f^a R(g) + f_I^a\Box\lambda^I$$

$$T_{\mu\nu} \to T_{\mu\nu} + f^a(\partial_\mu\partial_\nu - \eta_{\mu\nu}\Box)\mathcal{O}_a$$

$$\mathcal{O}_I \to \mathcal{O}_I + \theta_{Ia}\Box\mathcal{O}_a$$

$$t^a \to t^a + f^a$$

$$\theta_I^a \to \theta_I^a + f_I^a$$

scheme choice

$$t^a = 0$$

$$\theta_I^a = 0$$

Redundancies in source parametrization

$$\delta_\sigma \equiv \sigma(x)\left[2g^{\mu\nu}\frac{\delta}{\delta g^{\mu\nu}(x)} - \beta^I\frac{\delta}{\delta\lambda^I(x)} - \rho_I^A\nabla_\mu\lambda^I\frac{\delta}{\delta A_\mu^A(x)} + \tilde{m}^a\frac{\delta}{\delta m^a(x)}\right] +$$

$$+\nabla_\mu\sigma(x)\left[\cancel{\theta_I^a\nabla^\mu\lambda^I\frac{\delta}{\delta m^a(x)}} - S^A\frac{\delta}{\delta A_\mu^A(x)}\right] - \Box\sigma(x)\cancel{t^a\frac{\delta}{\delta m^a(x)}}$$

$$m^a \to m^a + \frac{1}{6}f^aR(g) + f_I^a\Box\lambda^I \quad \Longrightarrow \quad \begin{array}{l} T_{\mu\nu} \to T_{\mu\nu} + f^a(\partial_\mu\partial_\nu - \eta_{\mu\nu}\Box)\mathcal{O}_a \\ \mathcal{O}_I \to \mathcal{O}_I + \theta_{Ia}\Box\mathcal{O}_a \end{array}$$

$$t^a \to t^a + f^a \qquad\qquad t^a = 0$$

scheme choice

$$\theta_I^a \to \theta_I^a + f_I^a \qquad\qquad \theta_I^a = 0$$

“Flavor freedom” in defining Weyl transformation

$$\delta'_\sigma \; = \; \delta_\sigma \; + \; \delta^{\text{flavor}}_{\sigma\alpha^A}$$

local flavor rotation
with Lie parameter $\sigma\alpha^A$

$\alpha^A(\lambda) \; = \;$ Flavor adjoint constructed with couplings

$$\begin{aligned} \beta^I &\rightarrow \beta^I - (\alpha^A T_A \lambda)^I \\ \tilde{m}^a &\rightarrow \tilde{m}^a - (\alpha^A T_A \tilde{m})^a \\ \rho_I^A &\rightarrow \rho_I^A + \partial_I \alpha^A \\ S^A &\rightarrow S^A - \alpha^A \end{aligned}$$

$$\alpha^A = S^A \quad \Longrightarrow$$

$$\begin{aligned} B^I &= \beta^I - (S^A T_A \lambda)^I \\ \tilde{M}^a &= \tilde{m}^a - (S^A T_A \tilde{m})^a \\ P_I^A &= \rho_I^A + \partial_I S^A \end{aligned}$$

The Weyl transformation operator can be finally simplified as

$$\int \sigma(x) \left[2g^{\mu\nu} \frac{\delta}{\delta g^{\mu\nu}(x)} - B^I \frac{\delta}{\delta \lambda^I(x)} - P_I^A \nabla_\mu \lambda^I \frac{\delta}{\delta A_\mu^A(x)} + \tilde{M}^a \frac{\delta}{\delta m^a(x)}\right] W = \int \sigma \mathcal{A}$$

up to contact terms:

$$T_\mu^\mu = \sum_I B^I \mathcal{O}_I$$

$$\left(g_{\mu\nu} = \eta_{\mu\nu}, \quad \nabla_\mu \lambda^I = A_\mu^A = m_a = 0\right)$$

CFT $\quad B^I = 0$

SFT $\quad B^I = N^A (T_A \lambda)^I \equiv$ pure flavor rotation

$$[\delta_{\sigma_1}, \delta_{\sigma_2}] = 0$$

Two types of consistency conditions

I. On coefficients of δ_σ

- $\dfrac{\delta}{\delta A^A_\mu}$

$$\boxed{B^I P^A_I = 0}$$

$$T(x)T(y) = \cdots + \cancel{\delta^4(x-y) B^I P^A_I \partial^\mu J_{A\mu}}$$

- $\dfrac{\delta}{\delta m^a}$

similar story

II. genuine WZ condition: $\int \left[\sigma_1(y)\delta_{\sigma_2(x)}\mathcal{A}(y) - \sigma_2(x)\delta_{\sigma_1(y)}\mathcal{A}(x)\right] = 0$

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$$
\begin{aligned}
\frac{1}{\sqrt{-g}}\sigma\mathcal{A} = {} & \sigma\left(\beta_a W^2 + \beta_b E_4 + \frac{1}{9}\beta_c R^2\right) - \nabla^2\sigma\left(\frac{1}{3}dR\right) \\
& + \sigma\Big(\frac{1}{3}\chi^e_I \nabla_\mu\lambda^I\nabla^\mu R + \frac{1}{6}\chi^f_{IJ}\nabla_\mu\lambda^I\nabla^\mu\lambda^J R + \frac{1}{2}\chi^g_{IJ}G^{\mu\nu}\nabla_\mu\lambda^I\nabla_\nu\lambda^J \\
& \quad + \frac{1}{2}\chi^a_{IJ}\nabla^2\lambda^I\nabla^2\lambda^J + \frac{1}{2}\chi^b_{IJK}\nabla_\mu\lambda^I\nabla^\mu\lambda^J\nabla^2\lambda^K + \frac{1}{4}\chi^c_{IJKL}\nabla_\mu\lambda^I\nabla^\mu\lambda^J\nabla_\nu\lambda^K\nabla^\nu\lambda^L \\
& + \nabla^\mu\sigma\Big(G_{\mu\nu}w_I\nabla^\nu\lambda^I + \frac{1}{3}RY_I\nabla_\mu\lambda^I + S_{IJ}\nabla_\mu\lambda^I\nabla^2\lambda^J + \frac{1}{2}T_{IJK}\nabla_\nu\lambda^I\nabla^\nu\lambda^J\nabla_\mu\lambda^K\Big) \\
& - \nabla^2\sigma\left(U_I\nabla^2\lambda^I + \frac{1}{2}V_{IJ}\nabla_\nu\lambda^I\nabla^\nu\lambda^J\right) \\
& + \sigma\Big(\frac{1}{2}p_{ab}\hat{m}^a\hat{m}^b + \hat{m}^a\left(\frac{1}{3}q_a R + r_{aI}\nabla^2\lambda^I + \frac{1}{2}s_{aIJ}\nabla_\mu\lambda^I\nabla^\mu\lambda^J\right)\Big) \\
& + \nabla_\mu\sigma\left(\hat{m}^a j_{aI}\nabla^\mu\lambda^I\right) - \nabla^2\sigma\left(\hat{m}^a k_a\right) \\
& + \sigma\left(\frac{1}{4}\kappa_{AB}F^A_{\mu\nu}F^{B\mu\nu} + \frac{1}{2}\zeta_{AIJ}F^A_{\mu\nu}\nabla^\mu\lambda^I\nabla^\nu\lambda^J\right) + \nabla^\mu\sigma\left(\eta_{AI}F^A_{\mu\nu}\nabla^\nu\lambda^I\right) \qquad (2.49)
\end{aligned}
$$

10 differential constraints involving 25 tensorial coefficients

all but a few constraints can be "solved"

$$\mathcal{A} = \underbrace{\mathcal{A}_{R^2} + \mathcal{A}_{W^2}}_{\text{manifestly consistent}} + \overbrace{\mathcal{A}_{E_4} + \mathcal{A}_{F^2}}^{\text{non-trivial}} + \underbrace{\delta_{Weyl} F_{local}}_{\substack{\text{trivial} \\ \text{(scheme dep)}}}$$

$$\frac{1}{\sqrt{g}}\sigma\mathcal{A}_{R^2} = \sigma\left(\frac{1}{2}b_{ab}\Pi^a\Pi^b + \frac{1}{2}b_{aIJ}\Pi^a\Pi^{IJ} + \frac{1}{4}b_{IJKL}\Pi^{IJ}\Pi^{KL}\right)$$

$$\Pi^{IJ} = \nabla_\mu\lambda^I\nabla^\mu\lambda^J - B^{(I}\Lambda^{J)}$$

$$\Lambda^J \propto \left(\Box\lambda^J + \frac{1}{6}B^J R(g)\right)$$

$$\Pi^a = m^a - \frac{1}{6}t^a R(g) - \theta^a_I\Lambda^I$$

$$\delta_\sigma\Pi^{IJ} = \sigma\,(\dots) + \nabla_\mu\sigma\,(\dots) + \nabla^2\sigma\,(\dots)$$

absence of derivative terms: consistency is manifest

$$\frac{1}{\sqrt{g}}\sigma\mathcal{A}_{R^2} = \sigma\left(\frac{1}{2}b_{ab}\Pi^a\Pi^b + \frac{1}{2}b_{aIJ}\Pi^a\Pi^{IJ} + \frac{1}{4}b_{IJKL}\Pi^{IJ}\Pi^{KL}\right)$$

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$$\delta_\sigma\Pi^{IJ} = \sigma\,(\ldots) + \cancel{\nabla_\mu\sigma\,(\ldots)} + \cancel{\nabla^2\sigma\,(\ldots)}$$

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Non-trivial anomalies

$$\frac{1}{\sqrt{g}}\mathcal{A}_{E_4} = \sigma\, a E_4 + \sigma\,\frac{1}{2}\chi_{IJ} G_{\mu\nu}\nabla^\mu\lambda^I\nabla^\nu\lambda^J + \nabla^\mu\sigma\, w_I G_{\mu\nu}\nabla^\nu\lambda^I + \ldots \cdots$$

$$\frac{1}{\sqrt{g}}\mathcal{A}_{F^2} = \sigma\,\frac{1}{4}\kappa_{AB}F^A_{\mu\nu}F^{B\mu\nu} + \sigma\,\frac{1}{2}\zeta_{AIJ}F^A_{\mu\nu}\nabla^\mu\lambda^I\nabla^\nu\lambda^J + \nabla^\mu\sigma\,\eta_{AI}F^A_{\mu\nu}\nabla^\nu\lambda^I +$$

$$\boxed{\begin{aligned}\mathcal{L}[w_I] &= -8\partial_I a + \chi_{IJ}B^J \\ \mathcal{L}[\eta_{AI}] &= \kappa_{AB}P^B_I + \zeta_{AIJ}B^J - \chi^g_{IJ}(T_A\lambda)^J \\ 0 &= \eta_{AI}B^I + w_I(T_A\lambda)^I\end{aligned}}$$

Gradient flow equation

$$\tilde{a} \;\equiv\; a + \frac{1}{8} w_I B^I$$

$$\boxed{8\partial_I \tilde{a} \;=\; \left(\chi_{IJ} + \partial_I w_J - \partial_J w_I + P_I^A \eta_{AJ}\right) B^J}$$

- non-trivial constraint on perturbative expansion of B^I
- at fixed points $\tilde{a}(\lambda)$ is stationary
- along line of fixed points $\tilde{a} = a = \text{const}$

$$\boxed{8\mu \frac{d\tilde{a}}{d\mu} \;\equiv\; 8B^I \partial_I \tilde{a} \;=\; \chi_{IJ} B^I B^J}$$

$$\langle \mathcal{O}_I(x)\mathcal{O}_J(0)\rangle = \frac{\chi_{IJ}}{x^8} + O(\partial B, B)$$

by unitarity $\chi_{IJ} > 0$

$$\boxed{8\mu\frac{d\tilde{a}}{d\mu} = \chi_{IJ}B^I B^J \geq 0}$$

$$\tilde{a}(\lambda(\mu_1)) - \tilde{a}(\lambda(\mu_2)) = \frac{1}{8}\int_{\mu_1}^{\mu_2} \chi_{IJ}B^I B^J \, d\ln\mu$$

since $\tilde{a}$ is finite the only possible asymptotics must satisfy $B^I = 0$

CFT, free or interacting, is the only possible asymptotics

The story with dilatons and dispersion relations

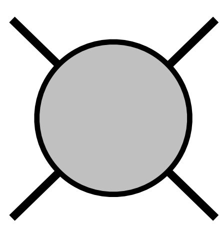
$$\langle T \ldots T \rangle \quad \xleftrightarrow{\text{K.S.}} \quad \text{scattering amplitudes of background dilaton}$$

$$g_{\mu\nu} \equiv \Omega(x)^2 \eta_{\mu\nu}$$

analize counterterms at $\Box\Omega = 0$ $\Rightarrow$ $W[\Omega^2 \eta_{\mu\nu}]$ is finite up to CC term

Luty, Polchinski, RR 2012

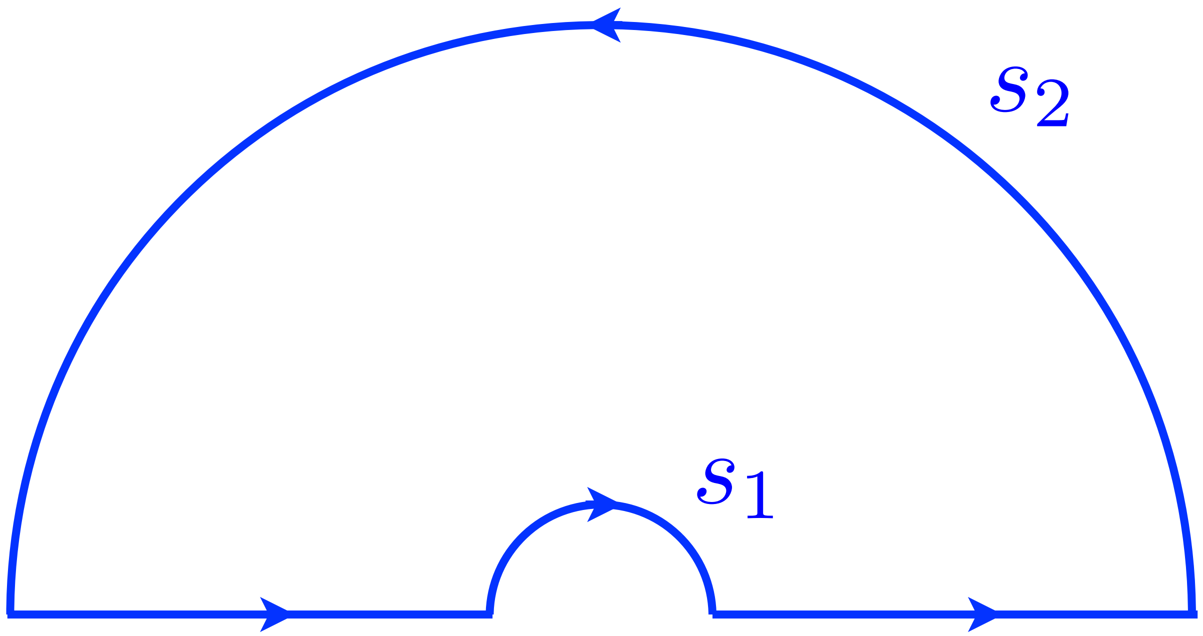
forward amplitude



$$A(s) = -\alpha(\lambda(\sqrt{s}))\, s^2 + \Lambda$$

CFT limit

$$A(s) = -8a\, s^2$$



$$\bar{\alpha}(s) \equiv \frac{1}{\pi}\int_0^{\pi} d\theta\, \alpha(se^{i\theta})$$

$$\bar{\alpha}(s_2) - \bar{\alpha}(s_1) = \frac{2}{\pi}\int_{s_1}^{s_2} \frac{ds}{s}\, \mathrm{Im}\, \alpha(s)$$

≥ 0 **by unitarity**

$$\boxed{\bar{\alpha}(s) \quad \textbf{finite} \quad \Rightarrow \quad \lim_{s\to\pm\infty} \mathrm{Im}\,\alpha(s) = 0}$$

Local Callan-Symanzik elucidates both sides of dispersion relation

$$\bar{\alpha}(s) \;=\; 8\,\tilde{a}(s) \,+\, O(B^2)$$

this ensure a scheme choice exists where $\bar{\alpha}(s) \;=\; 8\,\tilde{a}(s)$

$$\mathrm{Im}\,\alpha(s) \;=\; \frac{1}{s^2}\sum_{\Psi}\left|\langle\Psi|B^I(\delta_I^J + \partial_I B^J)\mathcal{O}_J(p_1+p_2) + B^I B^J \mathcal{O}_I(p_1)\mathcal{O}_J(p_2)|0\rangle\right|^2$$

$$= \; B^I B^J\, G_{IJ}$$

$$G_{IJ} \;=\; \frac{1}{s^2}\sum_{\Psi}\langle 0|\mathcal{O}_I + \partial_I B^L\mathcal{O}_L + B^L\mathcal{O}_I\mathcal{O}_L|\Psi\rangle\langle\Psi|\mathcal{O}_J + \partial_J B^K\mathcal{O}_K + B^K\mathcal{O}_J\mathcal{O}_K|0\rangle \;\geq\; 0$$

$$\boxed{s\,\frac{d\bar{\alpha}(s)}{ds} \;=\; \frac{2}{\pi}\,G_{IJ}B^I B^J}$$

There thus exists a scheme where

$$\bar{\alpha} = \tilde{a} \qquad \chi_{IJ} = \frac{4}{\pi} G_{IJ} + \Delta_{IJ}$$

$$G_{IJ} \geq 0$$

$$\Delta_{IJ} B^I B^J = 0$$

G_{IJ} is the 4D analogue of Zamolodchikov metric in 2D

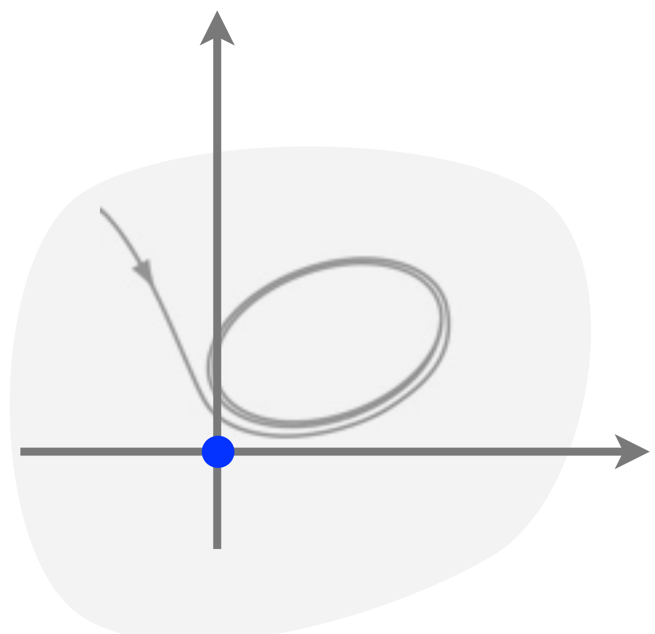
but 2D case simpler
(just 2-point funtions)

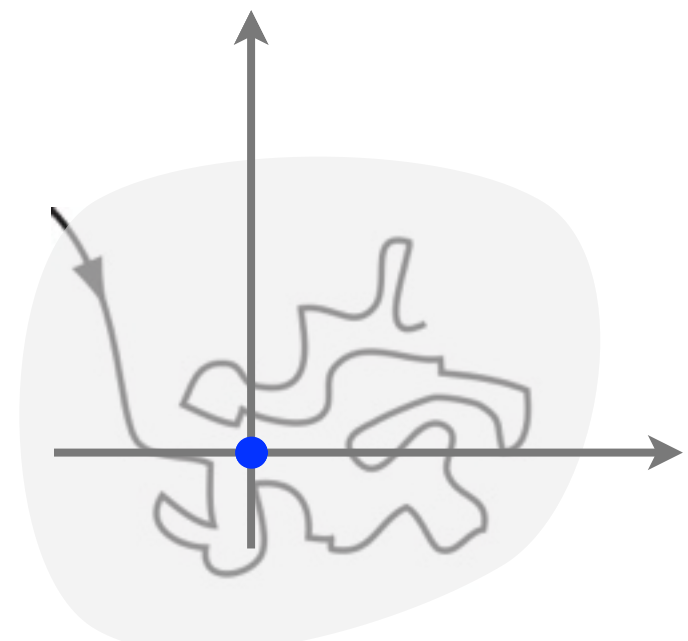
$$G_{IJ} = \frac{1}{p^2} \sum_{\Psi} \langle 0|\mathcal{O}_I(p)|\Psi\rangle \langle\Psi|\mathcal{O}_J(p)|0\rangle$$

without dilaton as guideline harder to figure things out in 4D

Near CFT fixed point, irreversibility of RG flow concretely expressed by

$$\boxed{8\mu\frac{d\tilde{a}}{d\mu} \equiv 8B^I\partial_I\tilde{a} = \chi_{IJ}B^IB^J} \qquad \chi_{IJ} > 0$$





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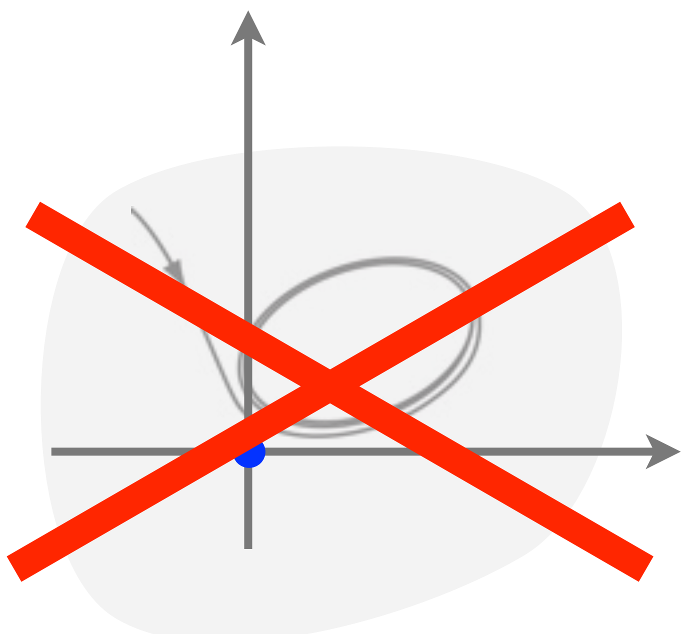

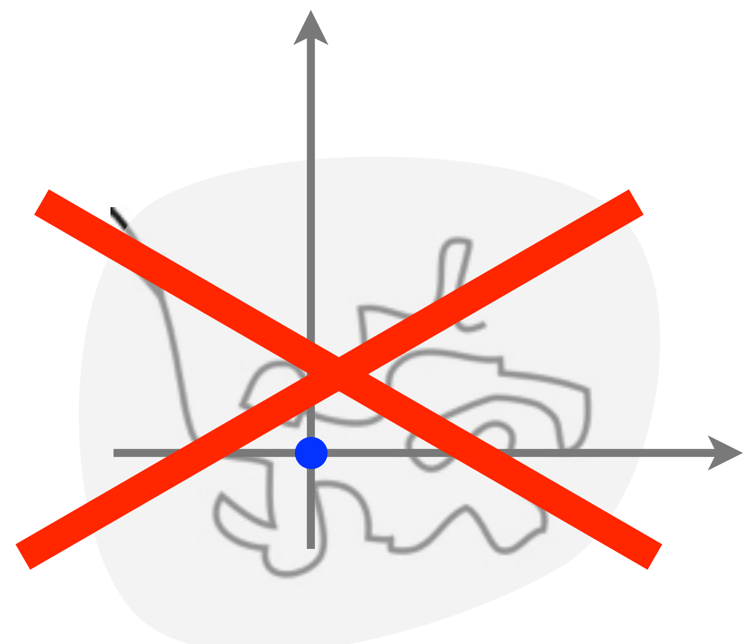

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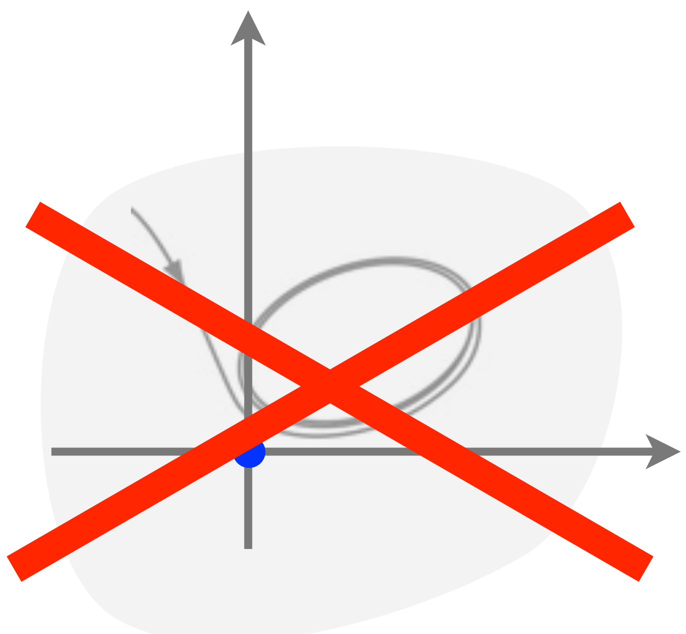

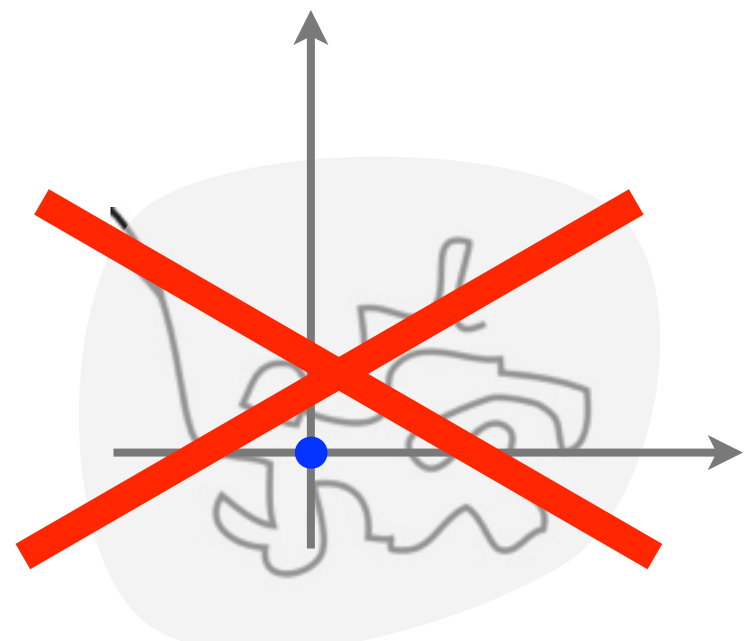

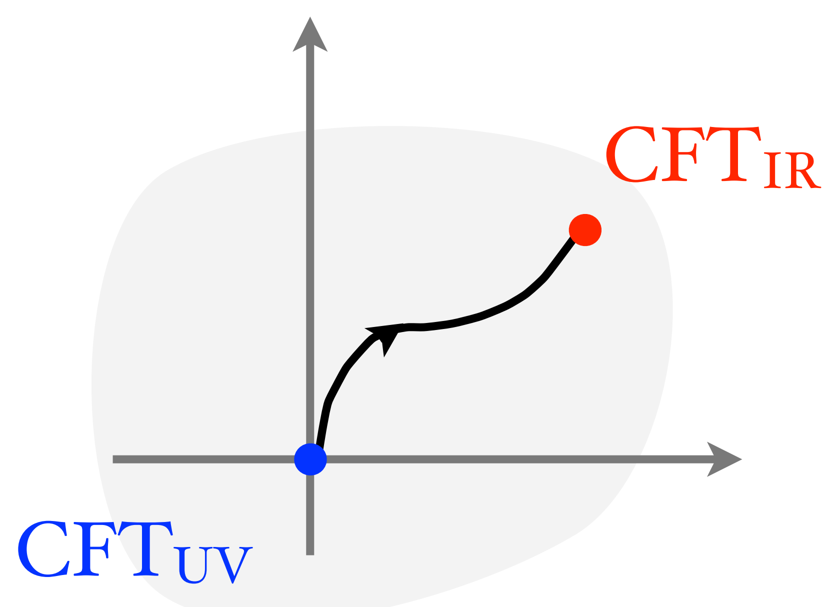

Only option

Luty, Polchinski, RR 2012
Fortin, Grinstein, Stergiou 2012

More on the local Callan-Symanzik equation:

- Any lessons hidden in the remaining consistency condition?
- What about the special case of supersymmetry?
- What about flows around CFT that break parity?