fixed points and asymptotic safety of gauge theories

Daniel F Litim

University of Sussex

Lattice Gauge Theory for the LHC and Beyond
KITP, UC Santa Barbara
2 Sept 2015

standard model

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local QFT for fundamental interactions

strong nuclear force
weak force
electromagnetic force

degrees of freedom

spin 0 (the **Higgs** has finally arrived)
spin 1/2 (quite a few)
spin 1

perturbatively renormalisable & **predictive**

standard model

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local QFT for fundamental interactions

strong nuclear force
weak force
electromagnetic force

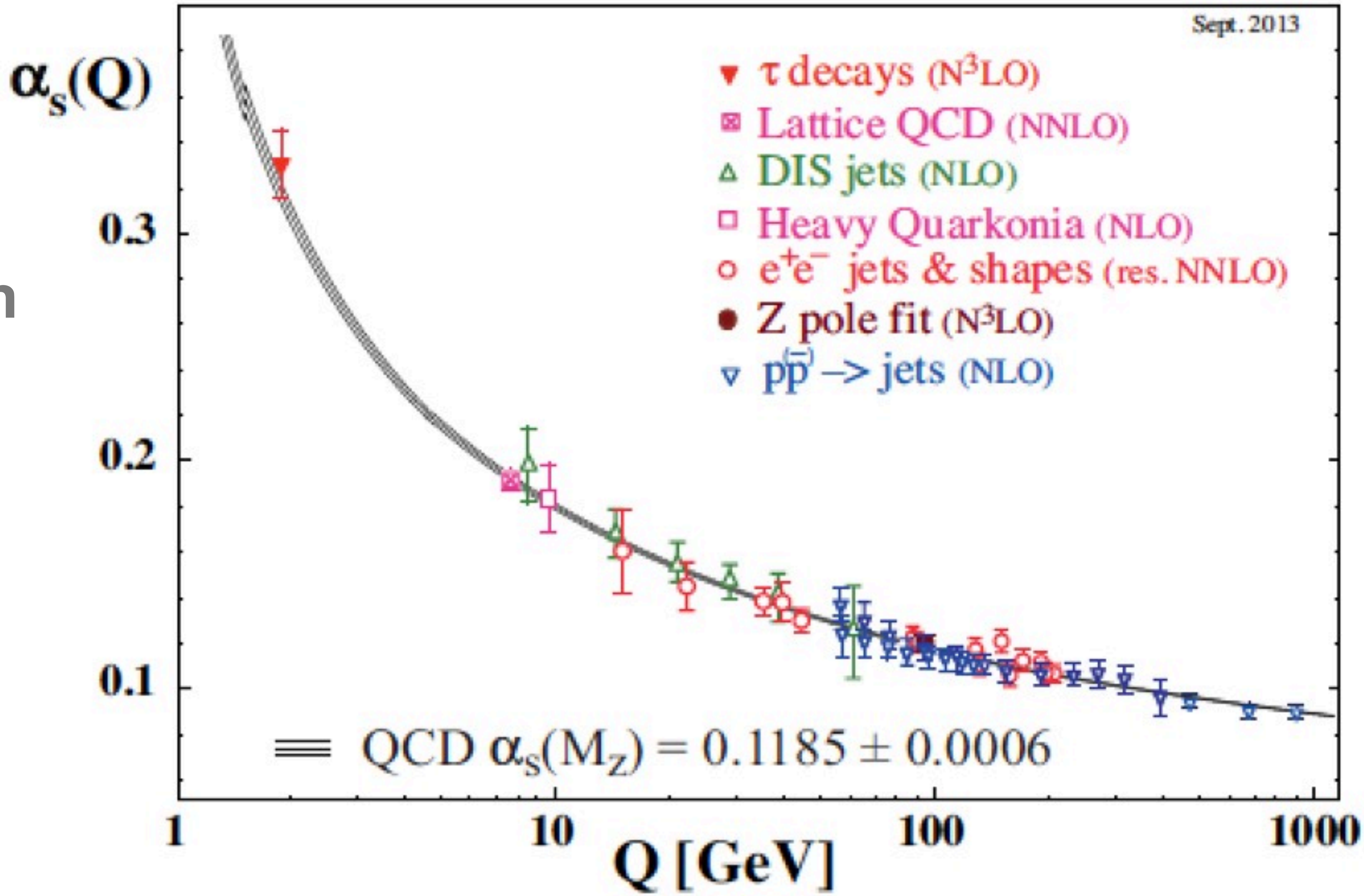
challenges

Higgs, U(1): maximal UV extension?
how does **gravity** fit in?

(interacting) UV fixed points

asymptotic freedom

triumph
of QFT



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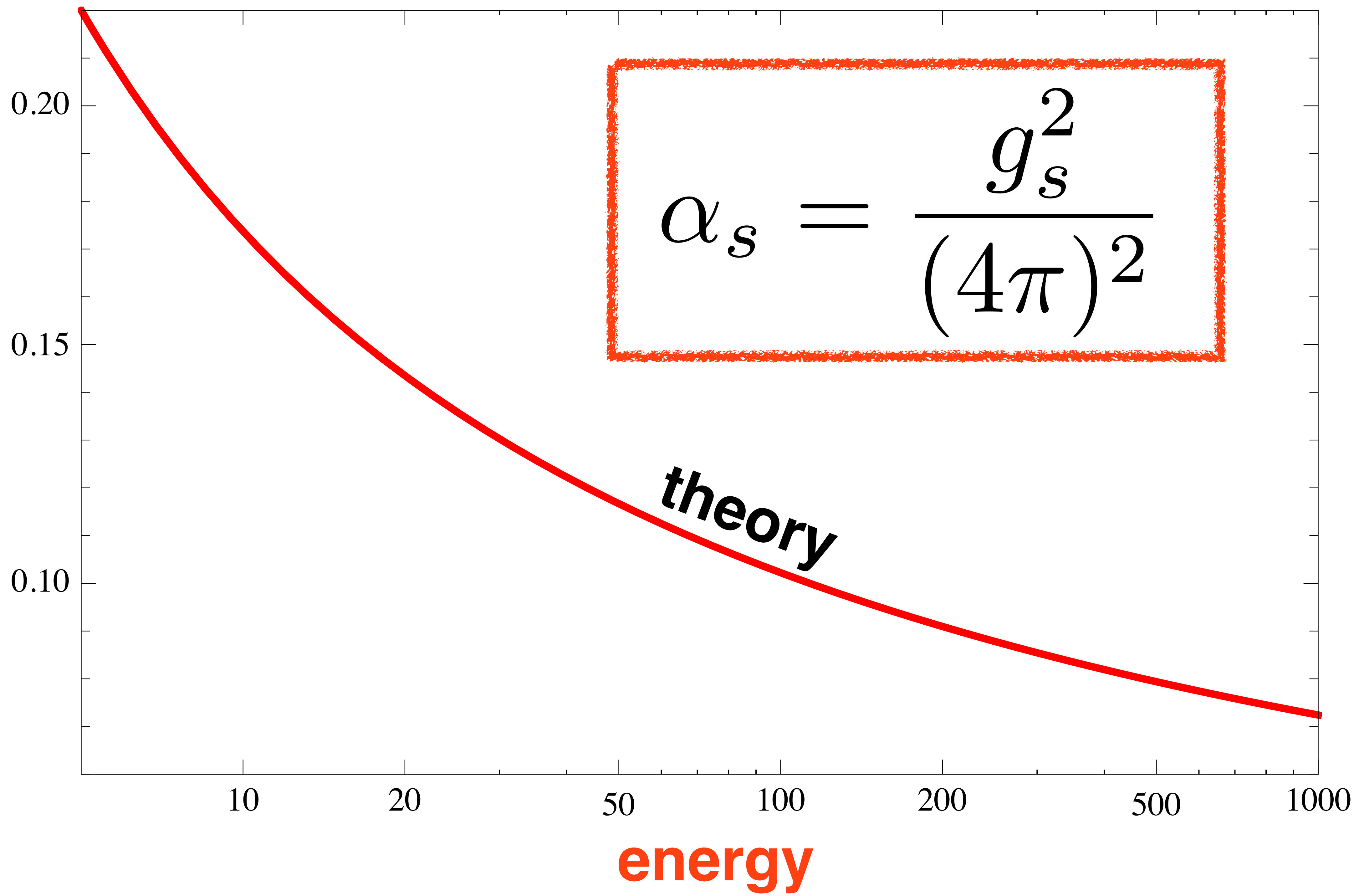
asymptotic freedom

triumph of QFT

Gross, Wilczek '74
Politzer '74



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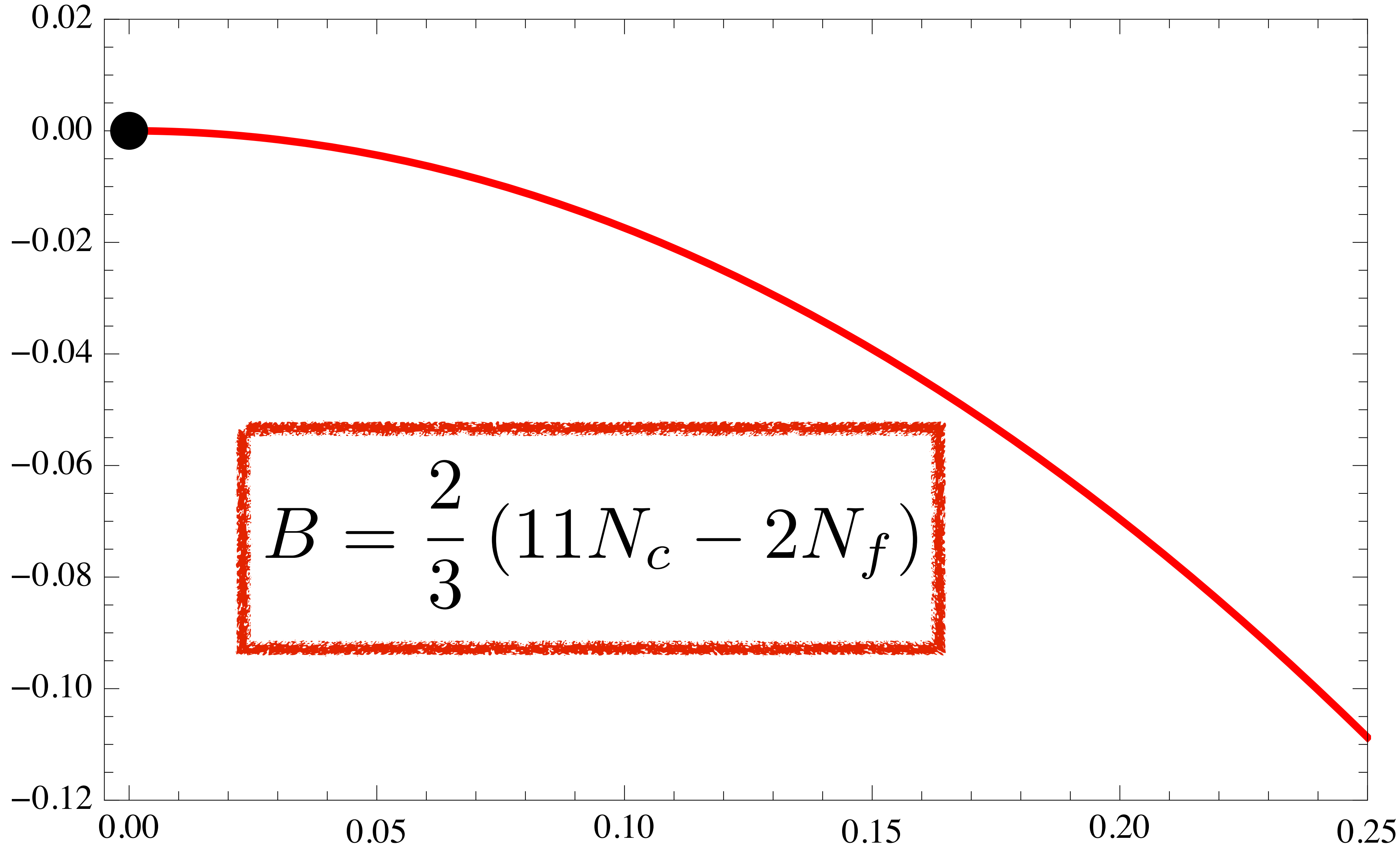
asymptotic freedom

$$\mu \frac{d\alpha_s}{d\mu} = -B\alpha_s^2 < 0$$

QCD beta function (1-loop)



$$B = \frac{2}{3}\left(11N_c - 2N_f\right)$$

gauge α_s coupling

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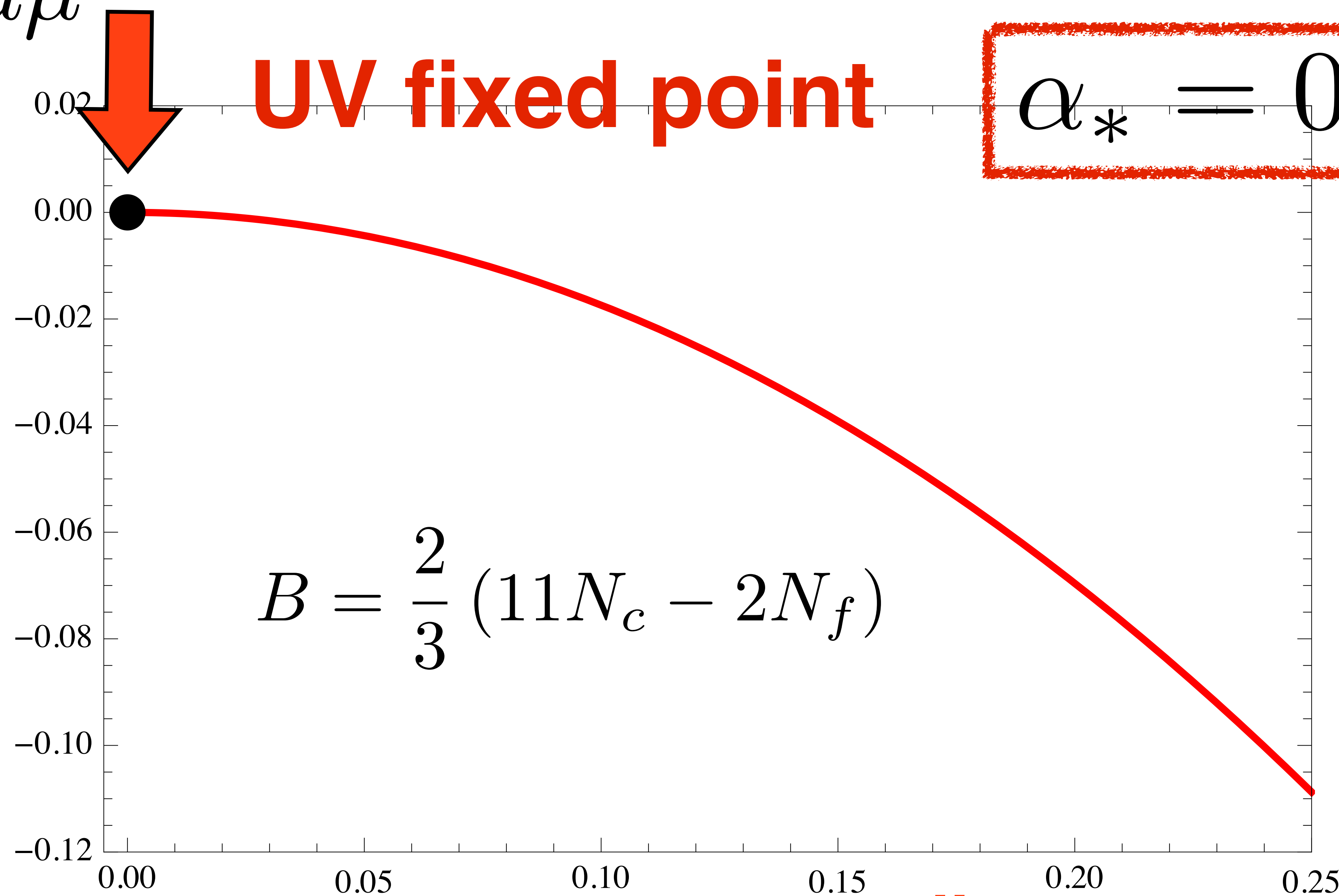
asymptotic freedom

$$\mu \frac{d\alpha_s}{d\mu} = -B\alpha_s^2 < 0$$

QCD beta function

UV fixed point

$$\alpha_* = 0$$



$$B = \frac{2}{3}\left(11N_c - 2N_f\right)$$

gauge α_s coupling

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asymptotic freedom

$$\mu \frac{d\alpha_s}{d\mu} = -B\alpha_s^2 < 0$$

QCD **beta function**

UV fixed point

$$\alpha_* = 0$$

fundamental definition of QFT ⟷ **UV fixed point**

Wilson '71

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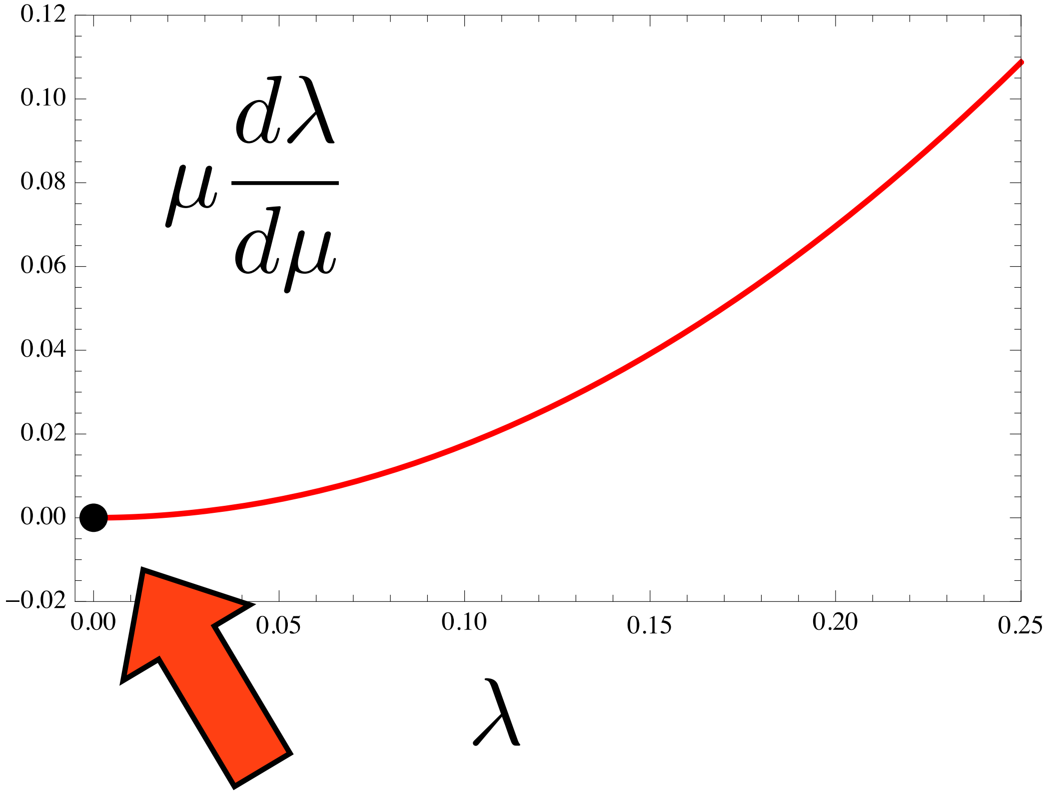
asymptotic freedom

$$\mu \frac{d\alpha_{e.m.}}{d\mu} \propto \alpha_{e.m.}^2 > 0$$

QED beta function

$$\mu \frac{d\lambda}{d\mu} \propto \lambda^2 > 0$$

Higgs self-coupling
Yukawa couplings



IR fixed point

... but no
UV fixed point

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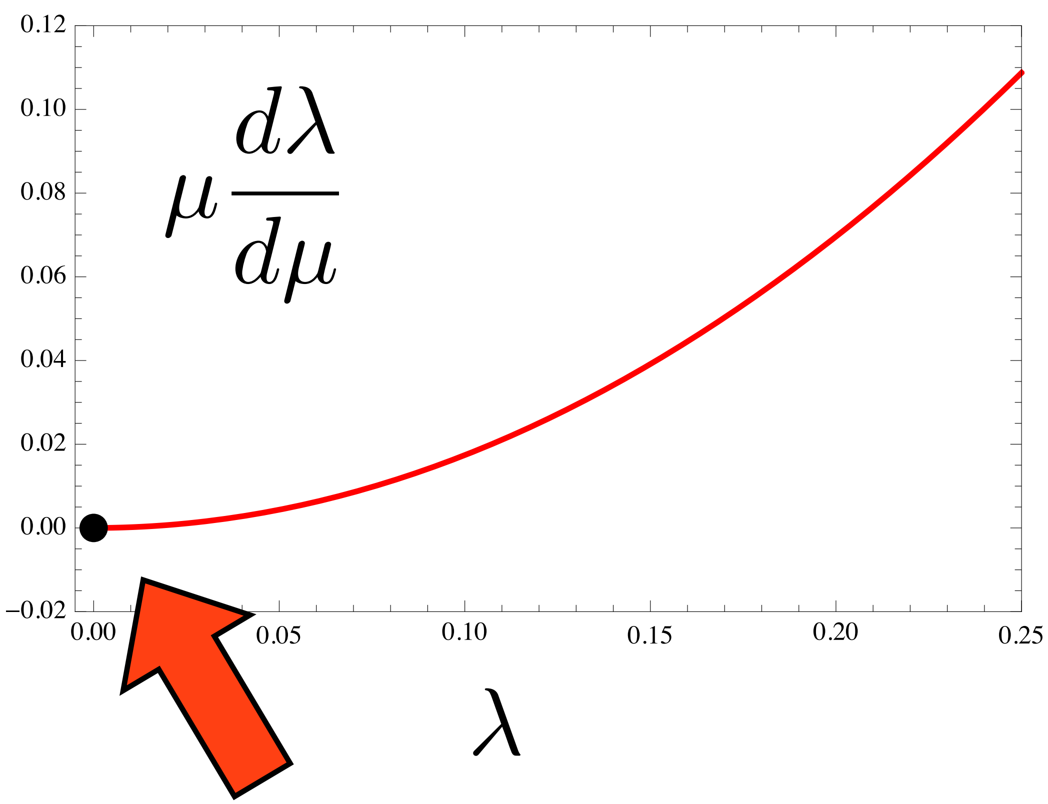
asymptotic freedom

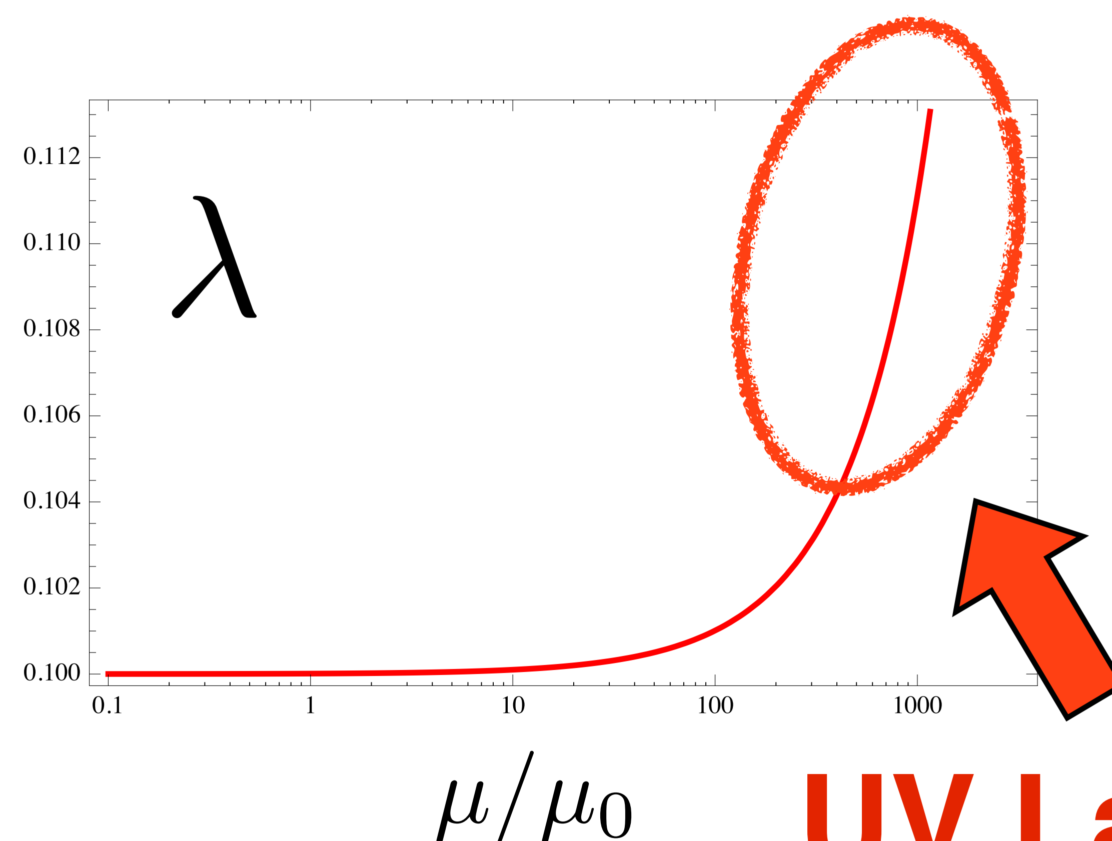
$$\mu \frac{d\alpha_{e.m.}}{d\mu} \propto \alpha_{e.m.}^2 > 0$$

QED beta function

$$\mu \frac{d\lambda}{d\mu} \propto \lambda^2 > 0$$

Higgs self-coupling
Yukawa couplings





IR fixed point

UV Landau pole

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asymptotic freedom

complete asymptotic freedom in 4D:

all couplings achieve non-interacting UV fixed point

fields	cAF?
scalars	no
scalars with fermions	no
non-Abelian gauge fields	yes
non-Abelian fields with fermions	yes*
non-Abelian fields, fermions, scalars	yes*

*) provided certain conditions hold true

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asymptotic safety

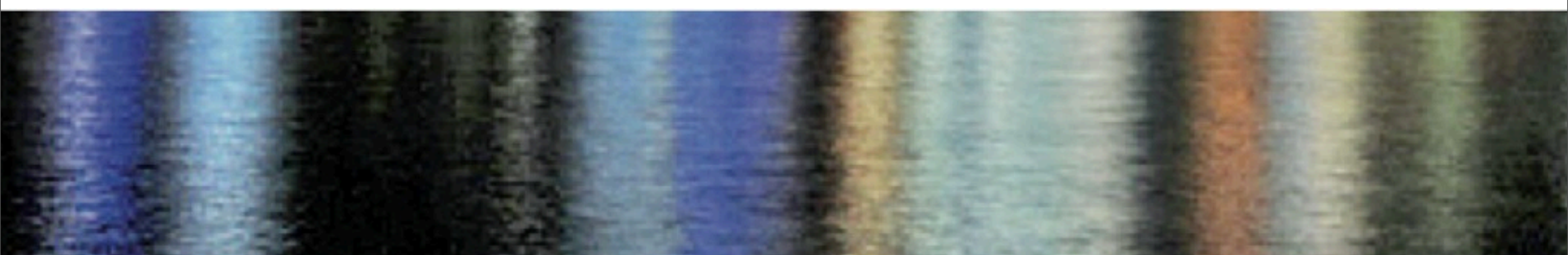
asymptotic safety in 4D:

couplings achieve interacting UV fixed point

fields	AS?
scalars	no
scalars with fermions	no
gauge fields	no
gauge fields with fermions	no
non-Abelian fields, fermions, scalars	yes*

*) provided certain conditions hold true

interacting UV fixed points from perturbation theory



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exact asymptotic safety

theory with coupling α:

$t = \ln \mu/\Lambda$

$$\partial_t \alpha = A\,\alpha - B\,\alpha^2$$

$\alpha_* \ll 1$

perturbative non-renormalisability: $A > 0$

exact asymptotic safety

theory with coupling α **:**

$t = \ln \mu / \Lambda$

$$\partial_t \alpha = A\,\alpha - B\,\alpha^2$$

$\alpha_* \ll 1$

fixed points $\alpha_* = 0$ $\alpha_* = A/B$

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exact asymptotic safety

theory with coupling α**:** $t = \ln \mu/\Lambda$

$$\partial_t \alpha = A\,\alpha - B\,\alpha^2$$

$\alpha_* \ll 1$

fixed points $\alpha_* = 0$ $\alpha_* = A/B$

if $A > 0\,,\ B > 0$**:** **IR** **UV**

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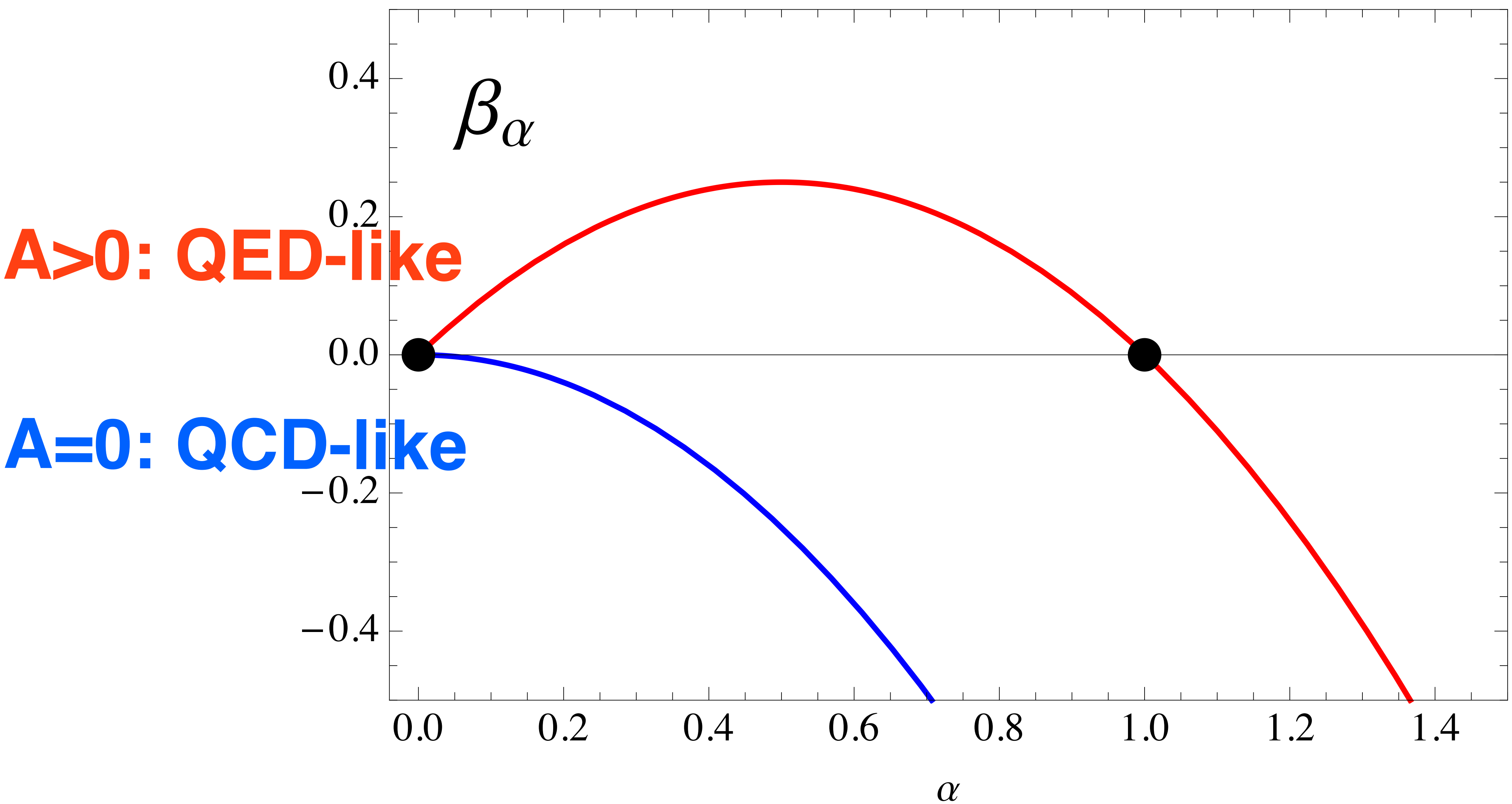
exact asymptotic safety

theory with coupling α**:** $t = \ln \mu/\Lambda$

$$\partial_t \alpha = A\,\alpha - B\,\alpha^2$$

$\alpha_* \ll 1$



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exact asymptotic safety

theory with coupling α**:**

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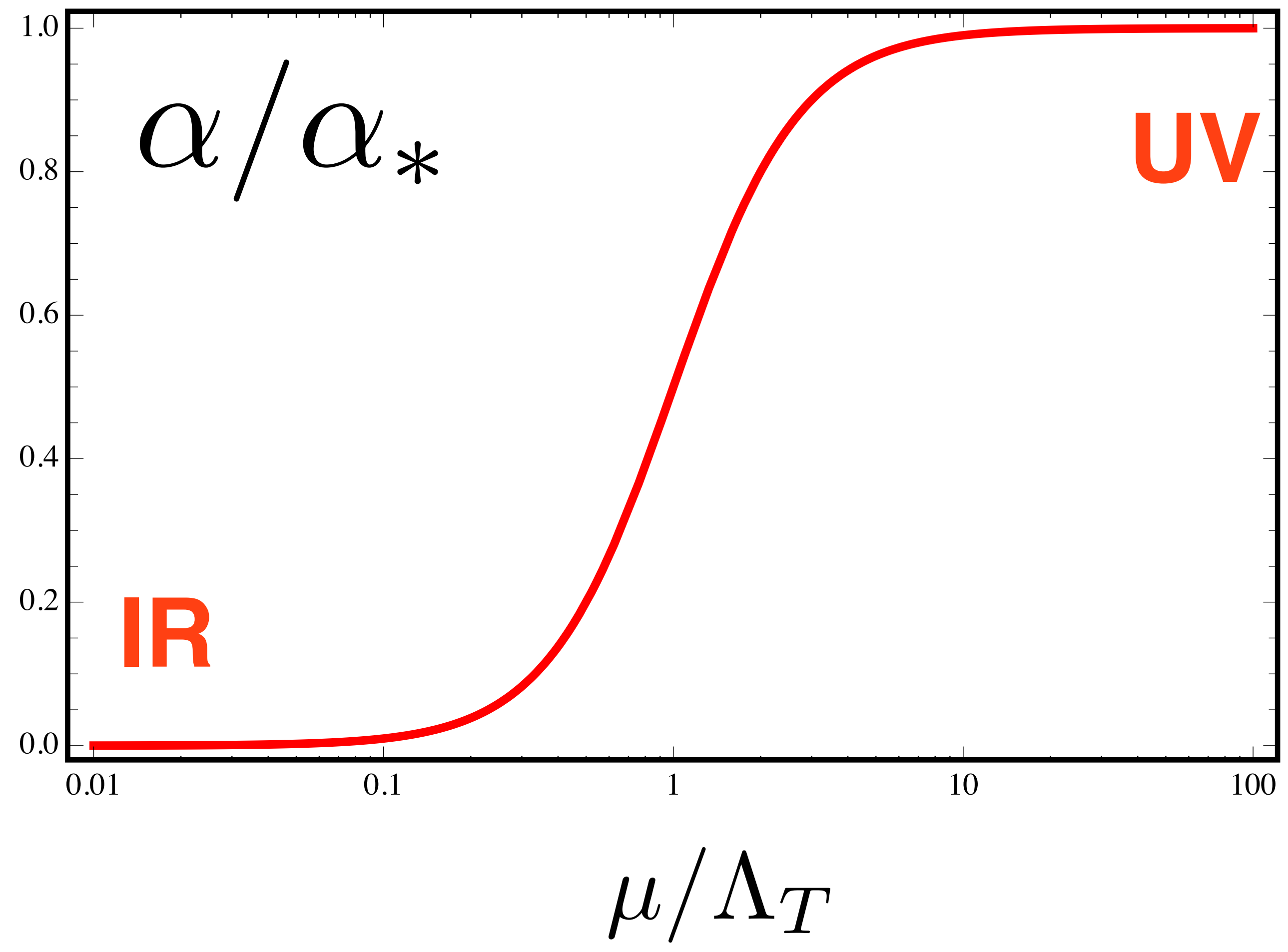

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exact asymptotic safety

how is this predictive?

UV: interactions are softened by fluctuations
UV behaviour characterised by
relevant, marginal, irrelevant invariants

predictivity ⟺ finitely many relevant invariants

exact asymptotic safety

when is this reliable?

need $\alpha_* = A/B \ll 1$

epsilon expansion: $\epsilon = D - D_c$

large-N expansion: many fields

perturbation theory applicable

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exact asymptotic safety

theory with coupling α **:** $t = \ln \mu / \Lambda$

$$\partial_t \alpha = A\,\alpha - B\,\alpha^2 \qquad \alpha_* \ll 1$$

gravitons	$D = 2 + \epsilon : \quad \alpha = G_N(\mu)\mu^{D-2}$	Gastmans et al '78 Weinberg '79 Kawai et al '90
fermions	$D = 2 + \epsilon : \quad \alpha = g_{\rm GN}(\mu)\mu^{2-D}$	Gawedzki, Kupiainen '85 de Calan et al '91
gluons	$D = 4 + \epsilon : \quad \alpha = g^2_{\rm YM}(\mu)\mu^{4-D}$	Peskin '80
scalars	$D = 2 + \epsilon : \quad \alpha = g_{NL}(\mu)\mu^{D-2}$	Brezin, Zinn-Justin '76 Bardeen, Lee, Shrock '76

non-perturbative renormalisability

$$A = \epsilon \ll 1\,, \quad B = \mathcal{O}(1) > 0$$

lesson 1

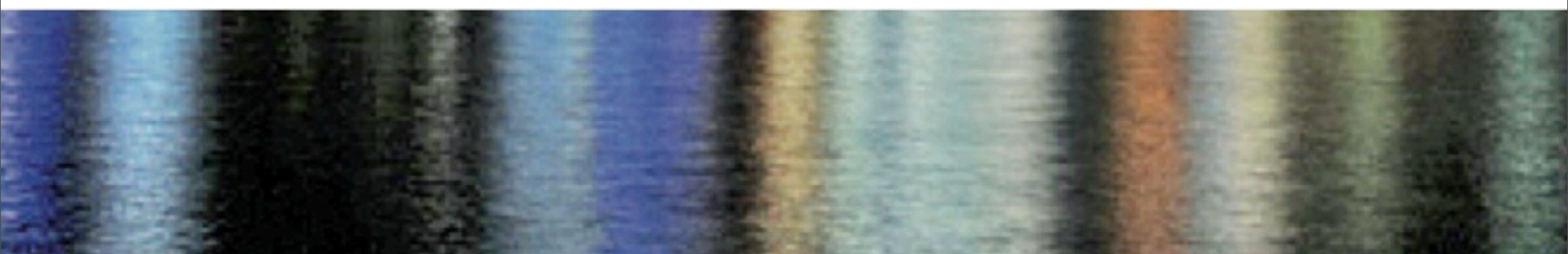
- UV fixed points exist in PT, at least formally, and above critical dimension D_c

- small parameter is required, e.g. $\epsilon = D - D_c$

- extension to $\epsilon = 1, 2$ requires more work

exact asymptotic safety
of 4D gauge-Yukawa theories

Litim, Sannino 1406.2337



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gauge theory + fermions

SU(NC) YM with NF fermions:

$$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2$$

$\alpha_* \ll 1$

gauge theory + fermions

SU(NC) YM with NF fermions:

$$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\, \alpha_g^2$$

$\alpha_* \ll 1$

$B > 0$ **: asymptotic freedom**

UV fixed point

$$\alpha_* = 0$$

$B < 0$ **: no asymptotic freedom**

UV fixed point?

$$\alpha_* \neq 0$$

gauge theory + fermions

SU(NC) YM with NF fermions:

$$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu / \Lambda$

$$\partial_t \alpha_g = -B\, \alpha_g^2 + C \alpha_g^3$$

$\alpha_* \ll 1$

2-loop

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gauge theory + fermions

SU(NC) YM with NF fermions: $$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\alpha_g^3$$

$\alpha_* \ll 1$

$$\alpha_* = 0 \qquad \alpha_g^* = B/C$$

gauge theory + fermions

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SU(NC) YM with NF fermions: $\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$ $t = \ln \mu / \Lambda$

$$\partial_t \alpha_g = -B\, \alpha_g^2 + C \alpha_g^3$$

$\alpha_* \ll 1$

when is this reliable?

$\alpha_* = 0$ $\alpha_g^* = B/C$

large-NF,NC (Veneziano) limit:
ϵ continuous

$$\epsilon = \frac{N_f}{N_c} - \frac{11}{2}$$

Veneziano '79

we consider

$$0 < -B \equiv -B\,(\epsilon) \ll 1$$

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gauge theory + fermions

SU(NC) YM with NF fermions: $$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\alpha_g^3$$ $\alpha_* \ll 1$

however: $\alpha_g^* = B/C$

no perturbative UV fixed point in gauge theories with fermionic matter $(C > 0)$

Caswell '74

gauge theory + fermions

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SU(NC) YM with NF fermions: $$\alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$ $t = \ln \mu/\Lambda$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\alpha_g^3$$

$\alpha_* \ll 1$

~~$$\alpha_g^* = B/C$$~~

➡ **scalar fields & Yukawa couplings required**

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gauge-Yukawa theory

$$\alpha_y = \frac{y^2 N_c}{(4\pi)^2} \qquad \alpha_g = \frac{g^2 N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y$$

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gauge-Yukawa theory

$$\alpha_y = \frac{y^2 N_c}{(4\pi)^2} \qquad \alpha_g = \frac{g^2\, N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y$$

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gauge-Yukawa theory

$$\alpha_y = \frac{y^2 N_c}{(4\pi)^2} \qquad \alpha_g = \frac{g^2 N_c}{(4\pi)^2}$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y$$

sensible interacting UV fixed point

$$D\,F - C\,E > 0$$

exact asymptotic safety:
a gauge-Yukawa template

Litim, Sannino 1406.2337

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gauge-Yukawa theory

Lagrangean

$$L_{YM} = -\frac{1}{2}\mathrm{Tr}\, F^{\mu\nu} F_{\mu\nu}$$

$$L_F = \mathrm{Tr}\left(\overline{Q}\, i\not{D}\, Q\right)$$

$$L_Y = y\, \mathrm{Tr}\left(\overline{Q}\, H\, Q\right)$$

$$L_H = \mathrm{Tr}\,(\partial_\mu H^\dagger\, \partial^\mu H)$$

$$L_U = -u\, \mathrm{Tr}\,(H^\dagger H)^2$$

$$L_V = -v\, (\mathrm{Tr}\, H^\dagger H)^2\,.$$

gauge — Nc colours

Yukawa — Nf flavours

Higgs — Nf times Nf

gauge-Yukawa theory

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Lagrangean

$$L_{YM} = -\frac{1}{2}\mathrm{Tr}\, F^{\mu\nu}F_{\mu\nu}$$

$$L_F = \mathrm{Tr}\left(\overline{Q}\, i\not{D}\, Q\right)$$

$$L_Y = y\,\mathrm{Tr}\left(\overline{Q}\, H\, Q\right)$$

$$L_H = \mathrm{Tr}\left(\partial_\mu H^\dagger\, \partial^\mu H\right)$$

$$L_U = -u\,\mathrm{Tr}\left(H^\dagger H\right)^2$$

$$L_V = -v\left(\mathrm{Tr}\, H^\dagger H\right)^2 .$$

couplings

$$\alpha_g = \frac{g^2\, N_C}{(4\pi)^2} \qquad \alpha_y = \frac{y^2\, N_C}{(4\pi)^2}$$

$$\alpha_h = \frac{u\, N_F}{(4\pi)^2} \qquad \alpha_v = \frac{v\, N_F^2}{(4\pi)^2} .$$

small parameter:

$$0 < \epsilon \ll 1 \qquad \epsilon = \frac{N_f}{N_c} - \frac{11}{2}$$

no asymptotic freedom

gauge-Yukawa theory

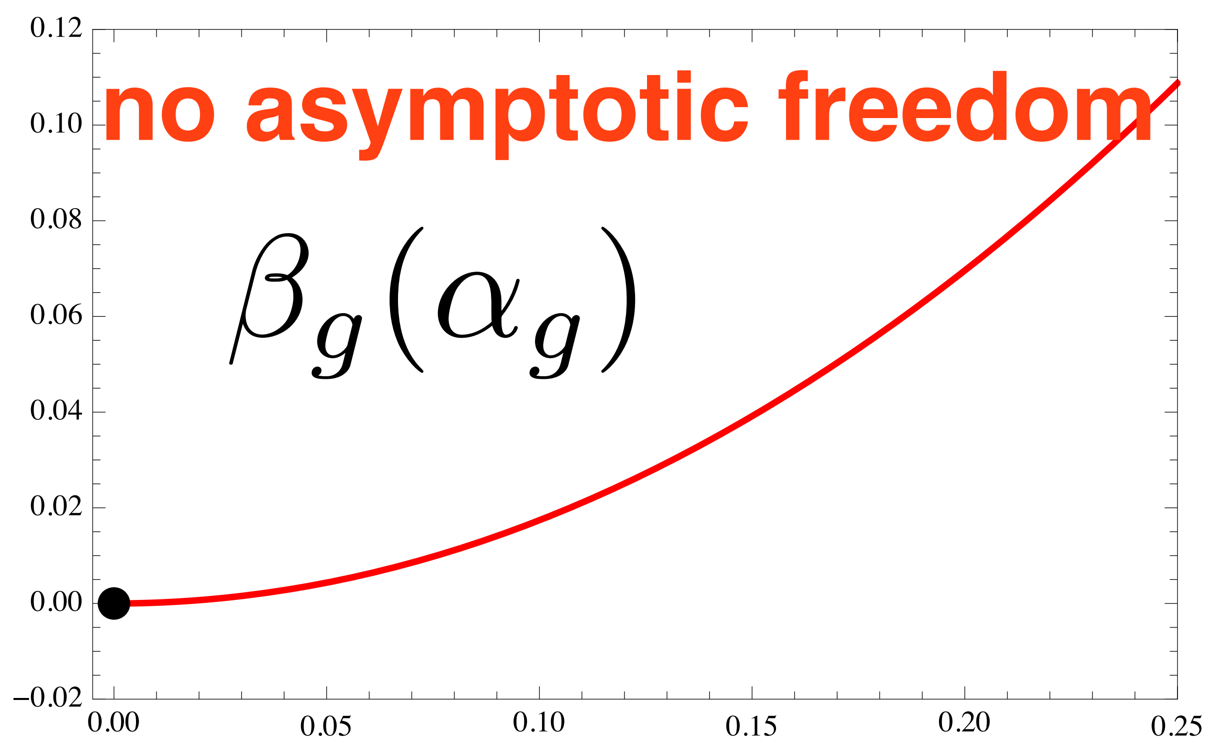
$$\beta_g = \alpha_g^2 \left\{ \frac{4}{3}\epsilon + \left(25 + \frac{26}{3}\epsilon\right)\alpha_g - 2\left(\frac{11}{2} + \epsilon\right)^2 \alpha_y \right\}$$ gauge

$$\beta_y = \alpha_y \left\{ (13 + 2\epsilon)\,\alpha_y - 6\,\alpha_g \right\} .$$ Yukawa

$$\beta_h = -(11 + 2\epsilon)\,\alpha_y^2 + 4\alpha_h(\alpha_y + 2\alpha_h)$$

$$\beta_v = 12\alpha_h^2 + 4\alpha_v\,(\alpha_v + 4\alpha_h + \alpha_y)\ .$$

Higgs



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gauge-Yukawa theory

$$\beta_g = \alpha_g^2 \left\{ \frac{4}{3}\epsilon + \left(25 + \frac{26}{3}\epsilon\right)\alpha_g - 2\left(\frac{11}{2} + \epsilon\right)^2 \alpha_y \right\}$$

gauge

$$\beta_y = \alpha_y \left\{ (13 + 2\epsilon)\,\alpha_y - 6\,\alpha_g \right\} .$$

Yukawa

$$\beta_h = -(11 + 2\epsilon)\,\alpha_y^2 + 4\alpha_h(\alpha_y + 2\alpha_h)$$

Higgs

$$\beta_v = 12\alpha_h^2 + 4\alpha_v\left(\alpha_v + 4\alpha_h + \alpha_y\right) .$$

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gauge-Yukawa theory

$$\beta_g = \alpha_g^2 \left\{ \frac{4}{3}\epsilon + \left(25 + \frac{26}{3}\epsilon\right)\alpha_g - 2\left(\frac{11}{2} + \epsilon\right)^2 \alpha_y \right\}$$

gauge

$$\beta_y = \alpha_y \left\{ (13 + 2\epsilon)\,\alpha_y - 6\,\alpha_g \right\} .$$

Yukawa

$$\beta_h = -(11 + 2\epsilon)\,\alpha_y^2 + 4\alpha_h(\alpha_y + 2\alpha_h)$$

$$\beta_v = 12\alpha_h^2 + 4\alpha_v\,(\alpha_v + 4\alpha_h + \alpha_y) .$$

Higgs

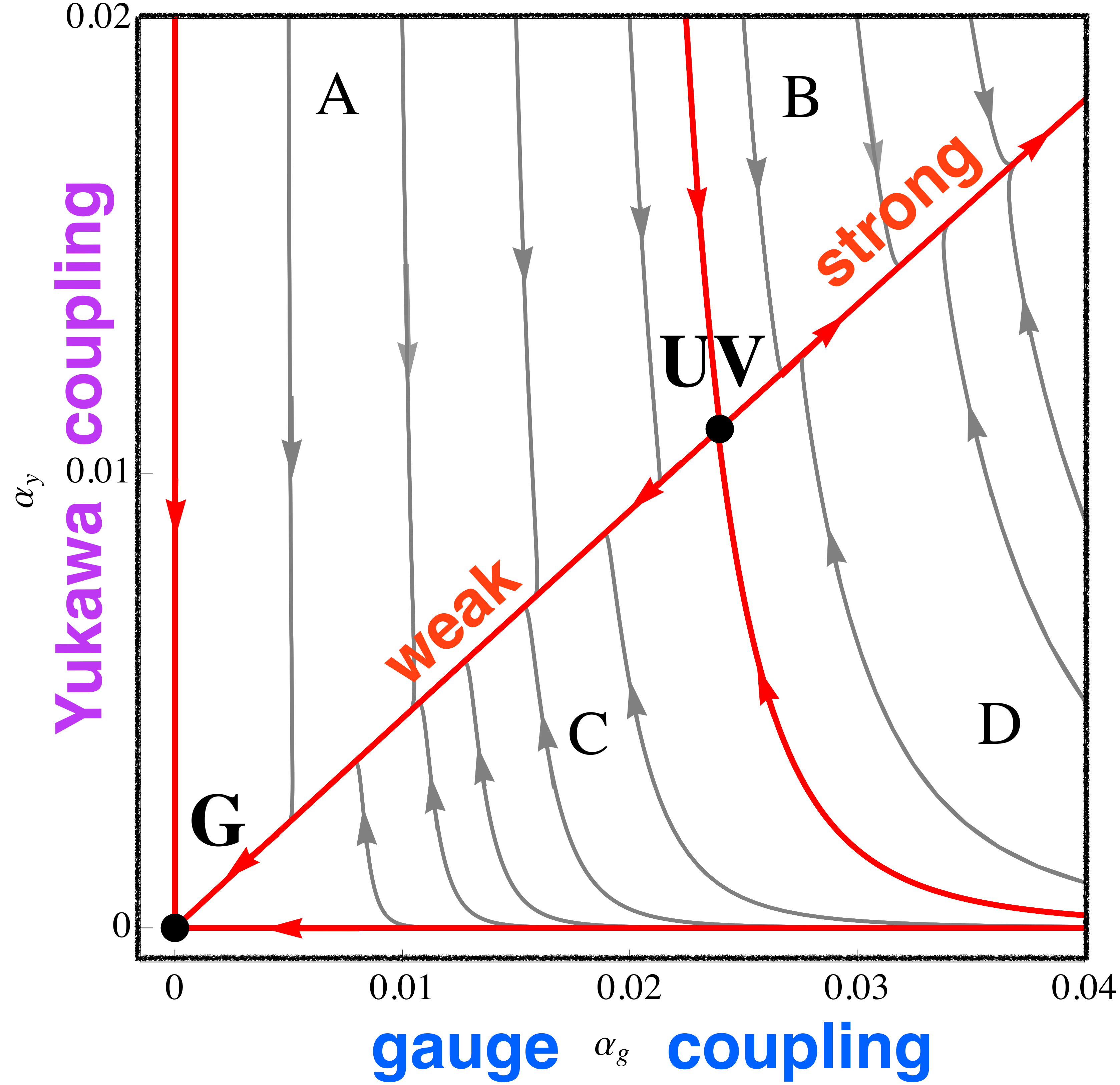
exact

UV fixed point

$$\begin{aligned}
\alpha_g^* &= 0.4561\,\epsilon + 0.7808\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\alpha_y^* &= 0.2105\,\epsilon + 0.5082\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\alpha_h^* &= 0.1998\,\epsilon + 0.5042\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\alpha_v^* &= -0.1373\,\epsilon + \mathcal{O}(\epsilon^2)
\end{aligned}$$

results

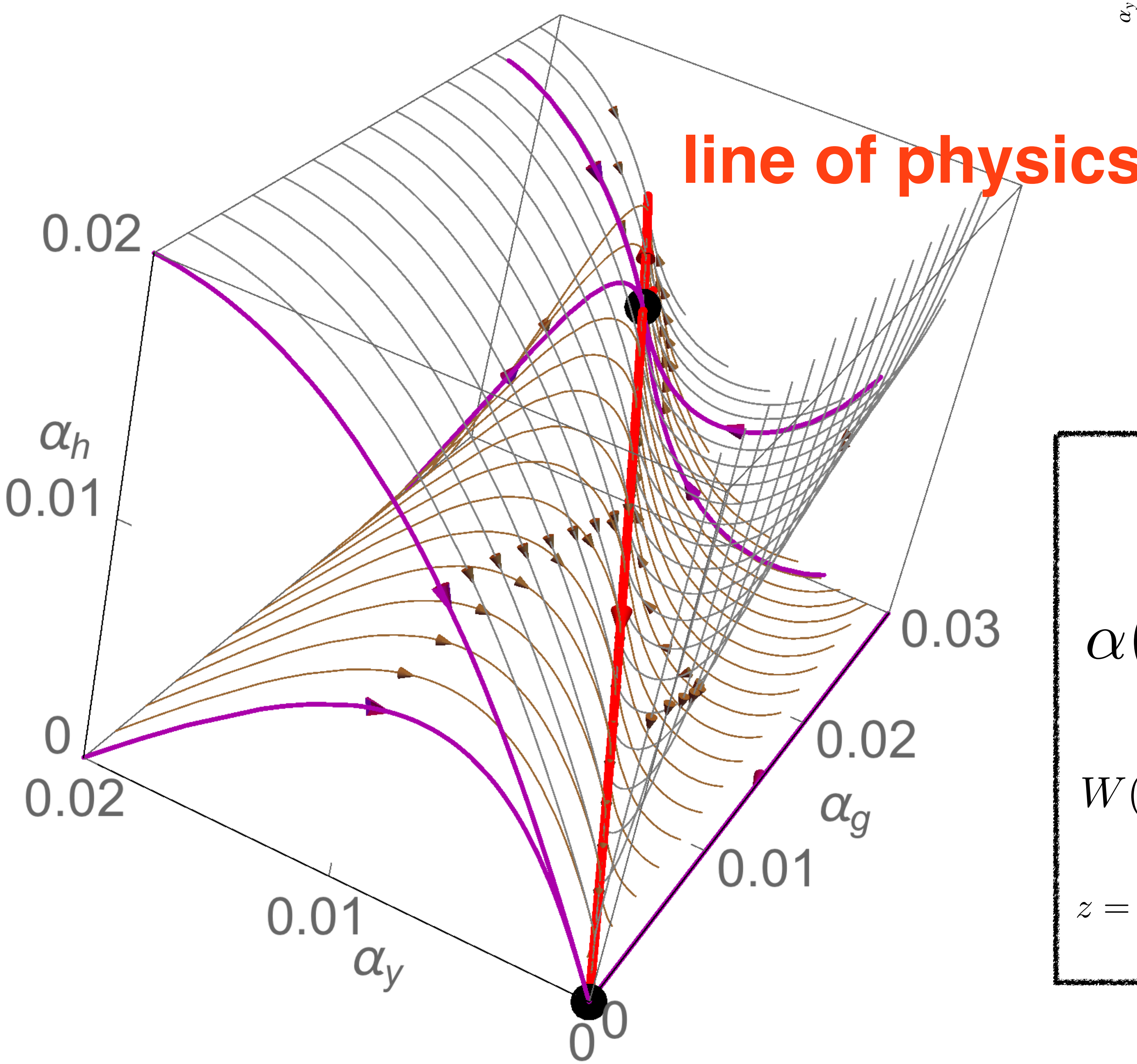
phase diagram

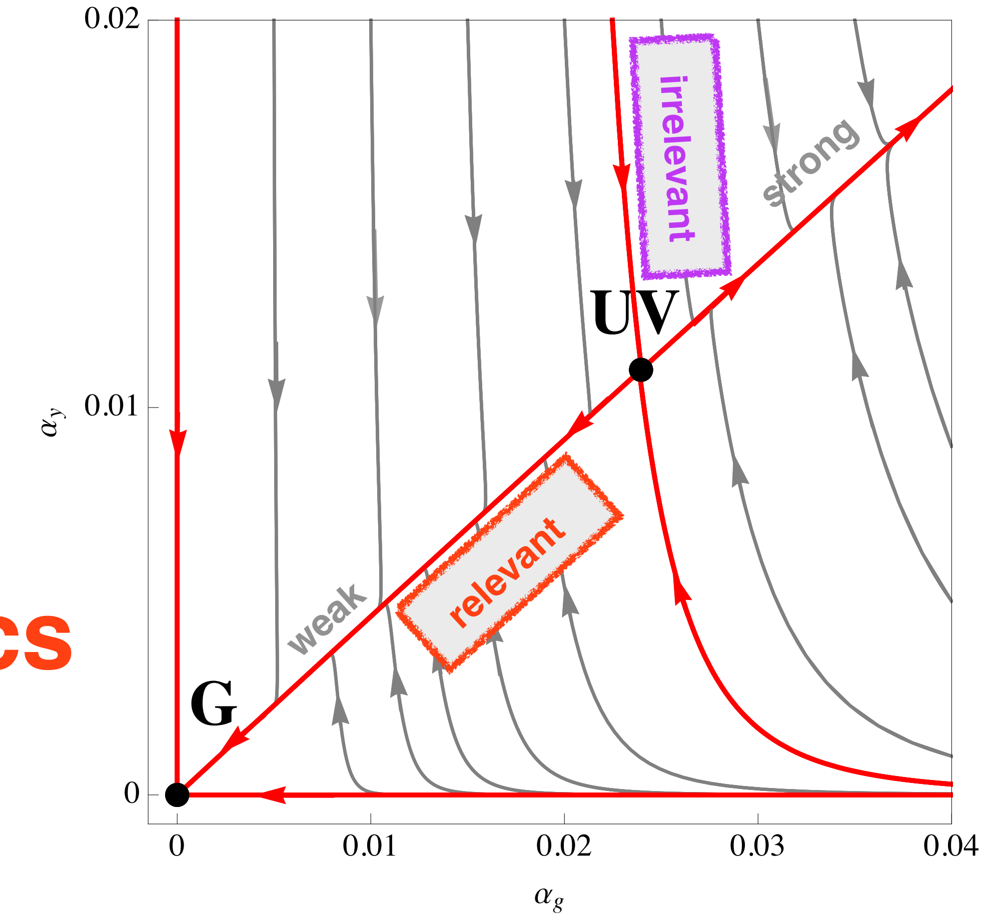


exact UV FP

strict perturbative control

phase diagram





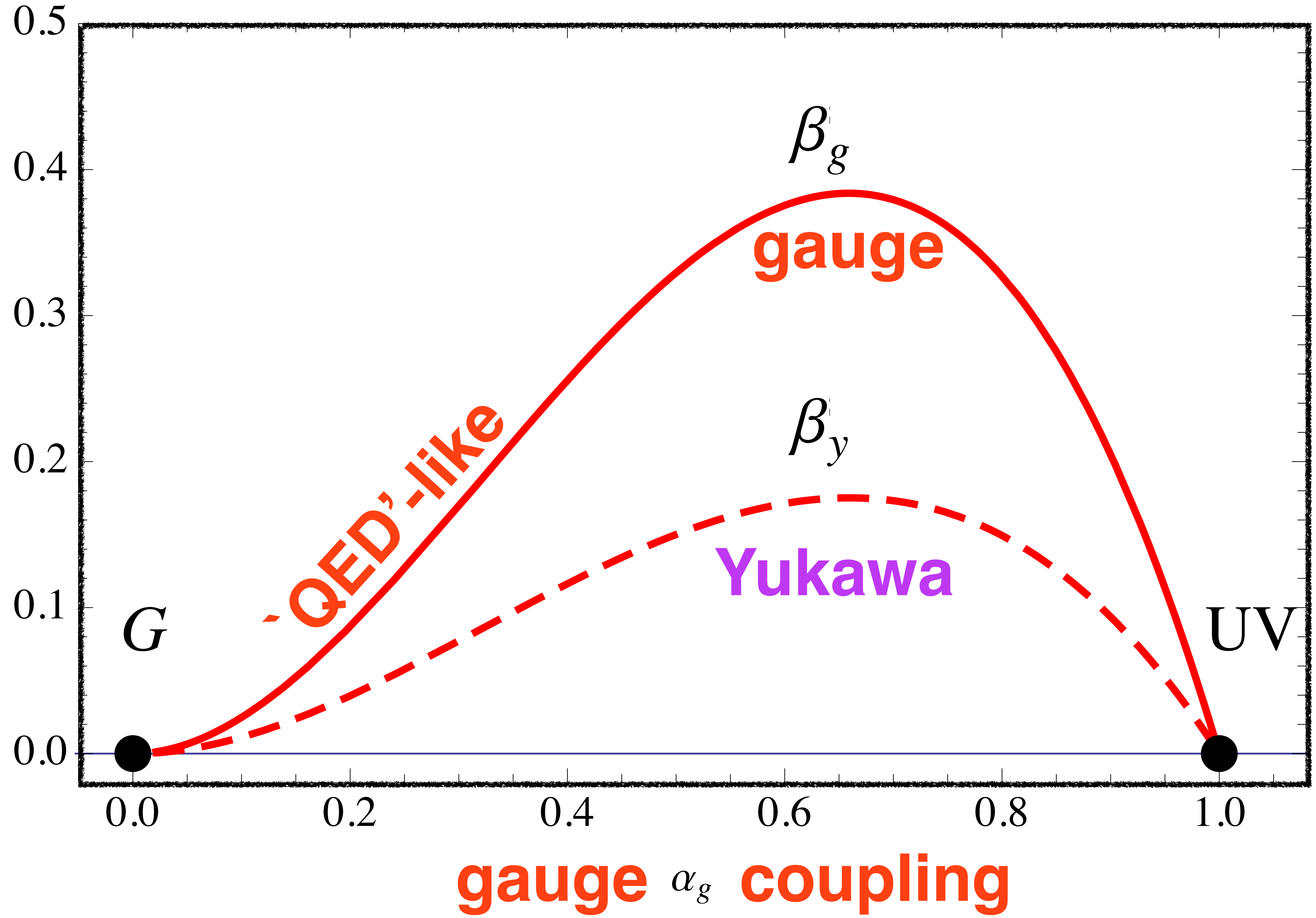
leading order

$$\alpha(\mu) = \frac{\alpha_*}{1 + W(\mu)}$$

$$W(\mu) = W_{\text{Lambert}}[z(\mu)]$$

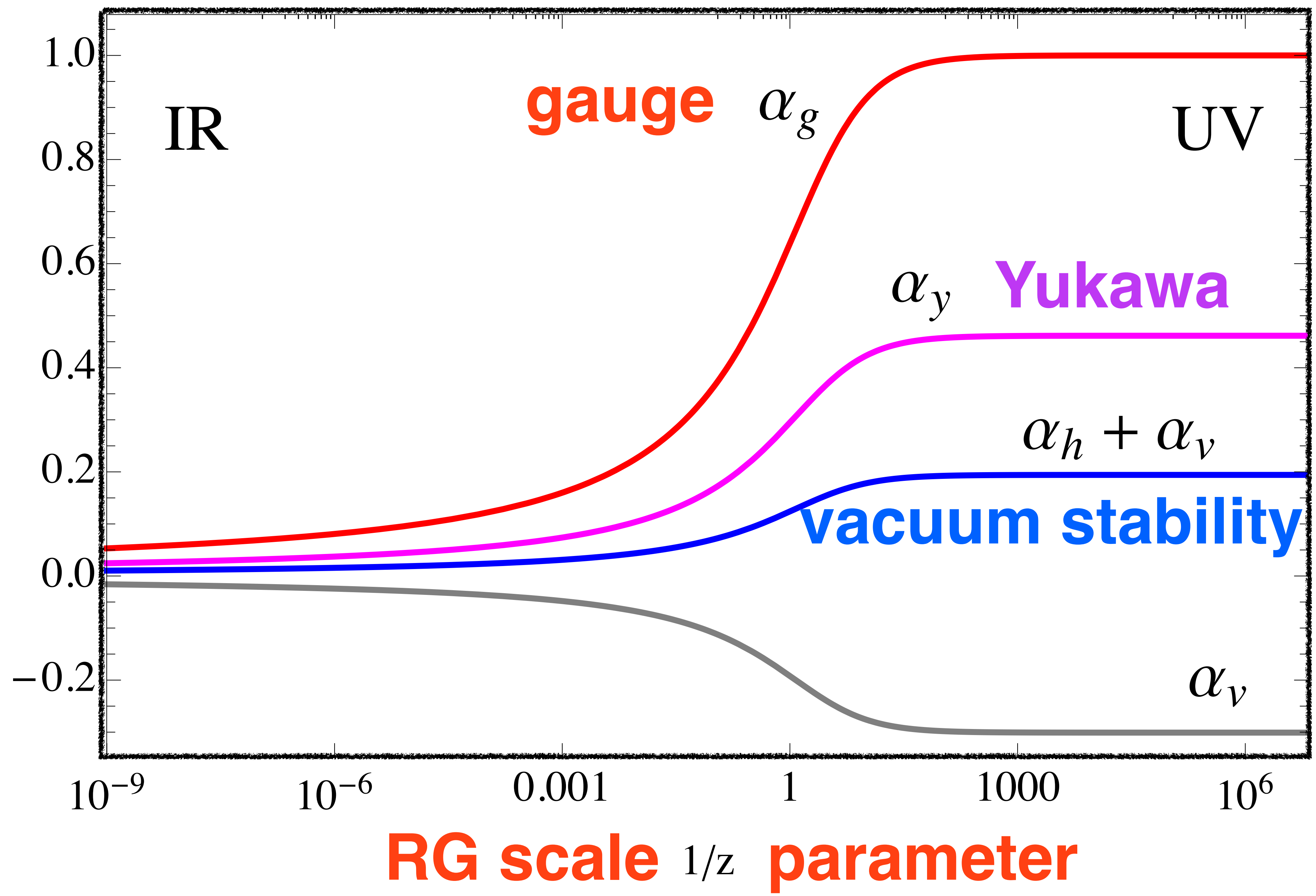
$$z = \left(\frac{\mu_0}{\mu}\right)^{-B\cdot\alpha_*}\left(\frac{\alpha_*}{\alpha_0} - 1\right)\exp\left(\frac{\alpha_*}{\alpha_0} - 1\right).$$

results



interacting UV fixed point
entirely due to `fluctuations'

results

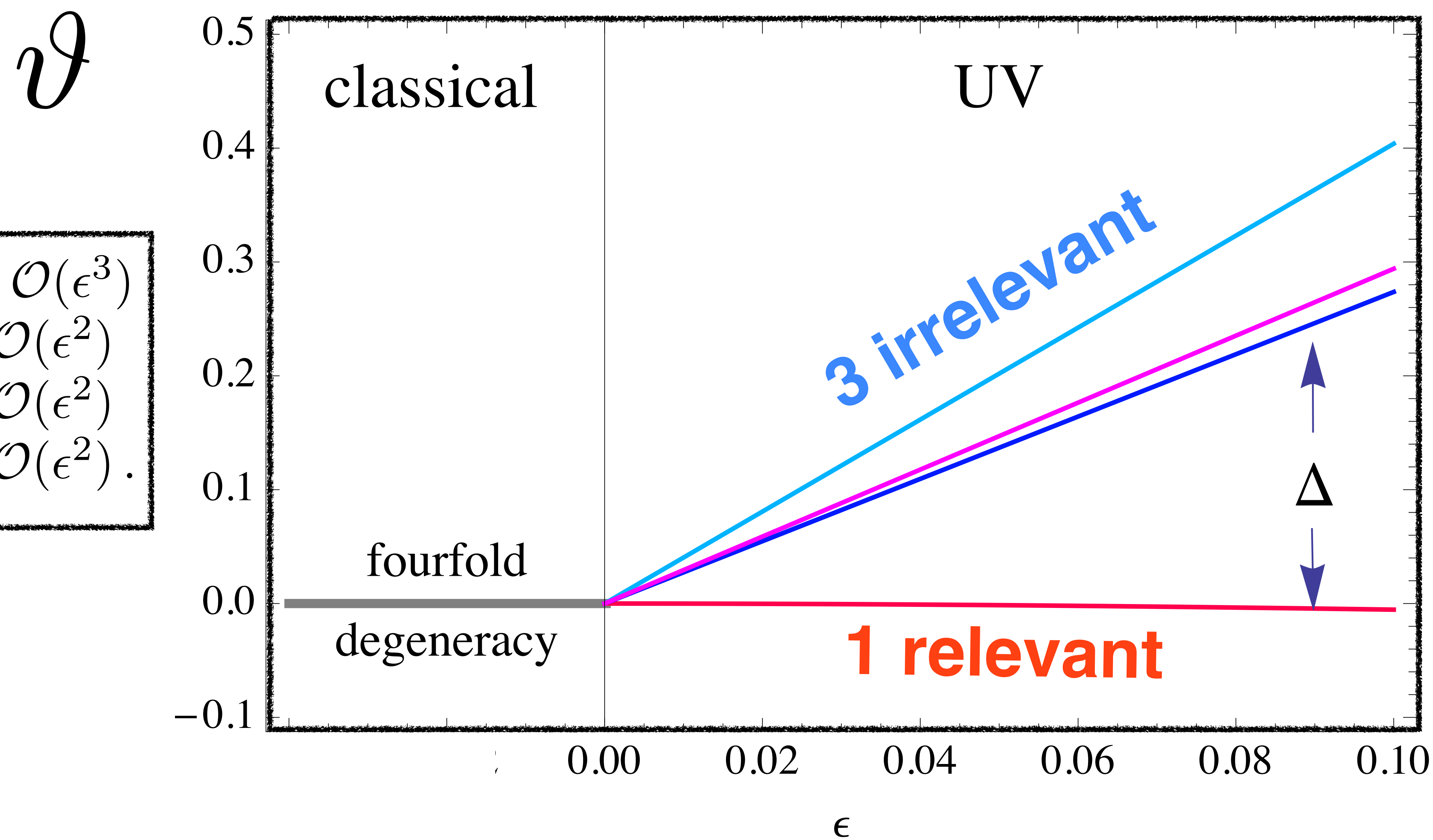

1.0
0.8
0.6
0.4
0.2
0.0
−0.2
IR
gauge α_g
UV
α_y Yukawa
$\alpha_h + \alpha_v$
vacuum stability
α_v
10^{-9}
10^{-6}
0.001
1
1000
10^6
RG scale 1/z parameter

results

UV scaling exponents

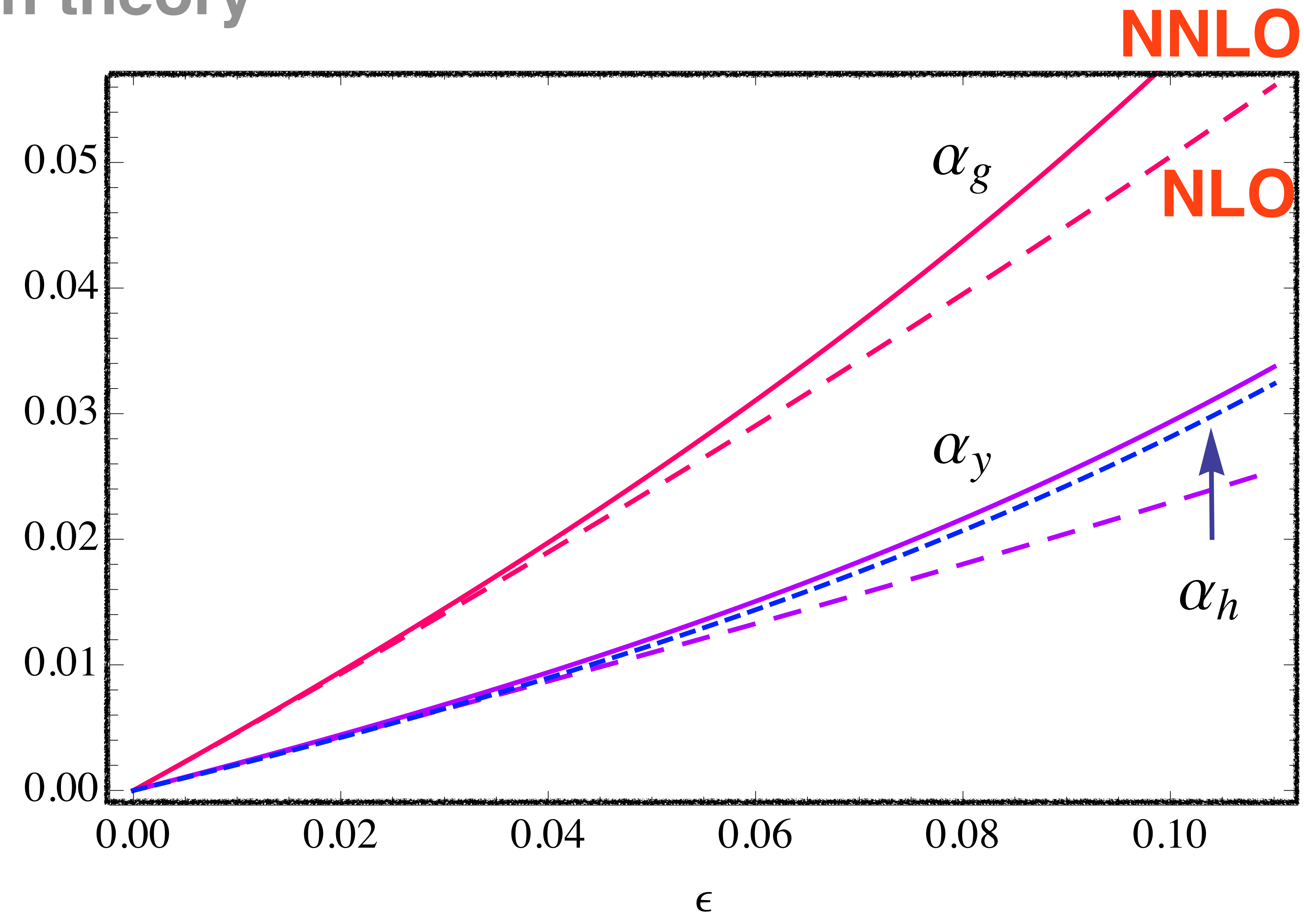
$$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$$

$$\begin{aligned}
\vartheta_1 &= -0.608\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\vartheta_2 &= 2.737\,\epsilon + \mathcal{O}(\epsilon^2) \\
\vartheta_3 &= 4.039\,\epsilon + \mathcal{O}(\epsilon^2) \\
\vartheta_4 &= 2.941\,\epsilon + \mathcal{O}(\epsilon^2)\,.
\end{aligned}$$



results

UV fixed point from perturbation theory



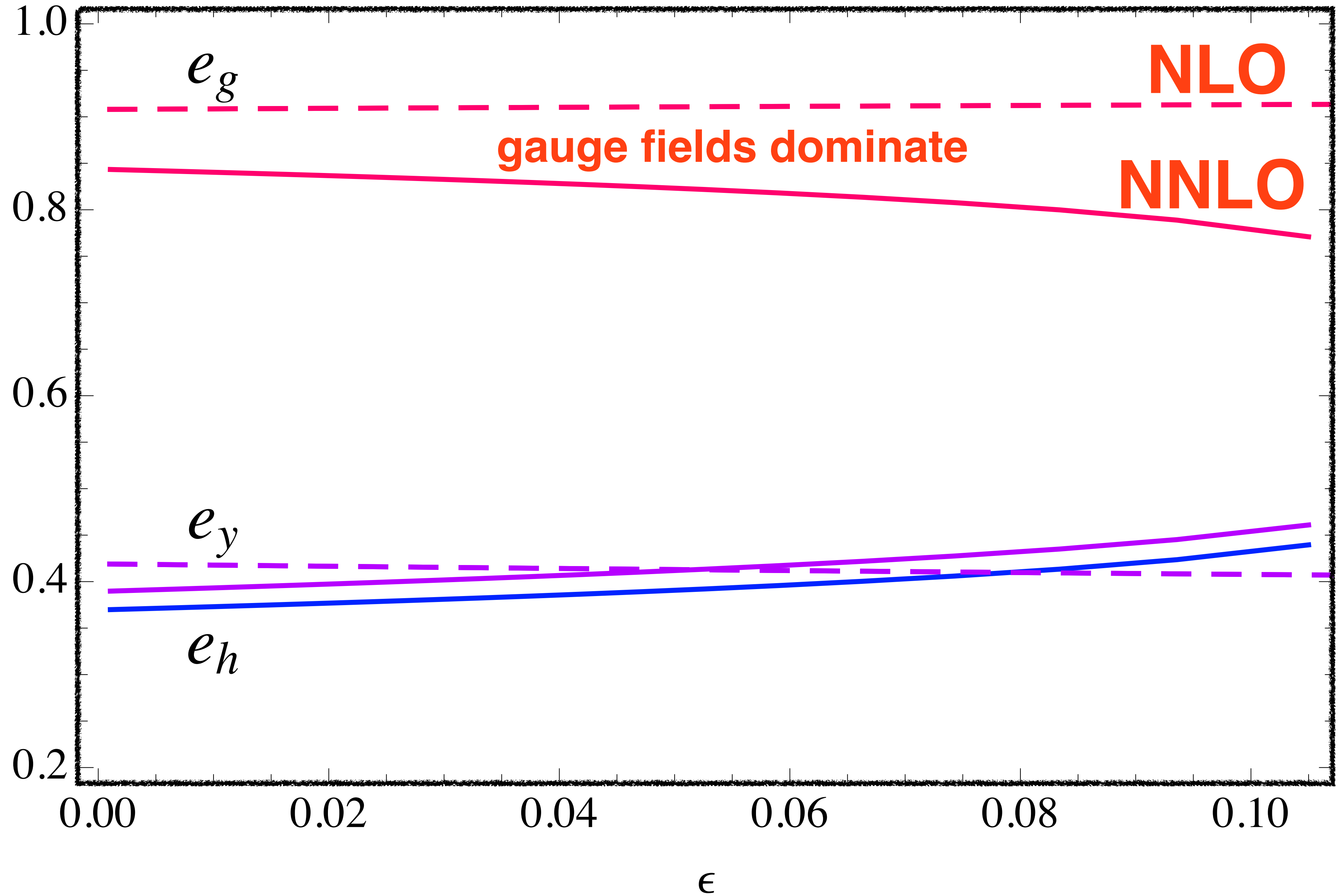
results

UV-relevant eigendirection

gauge

Yukawa

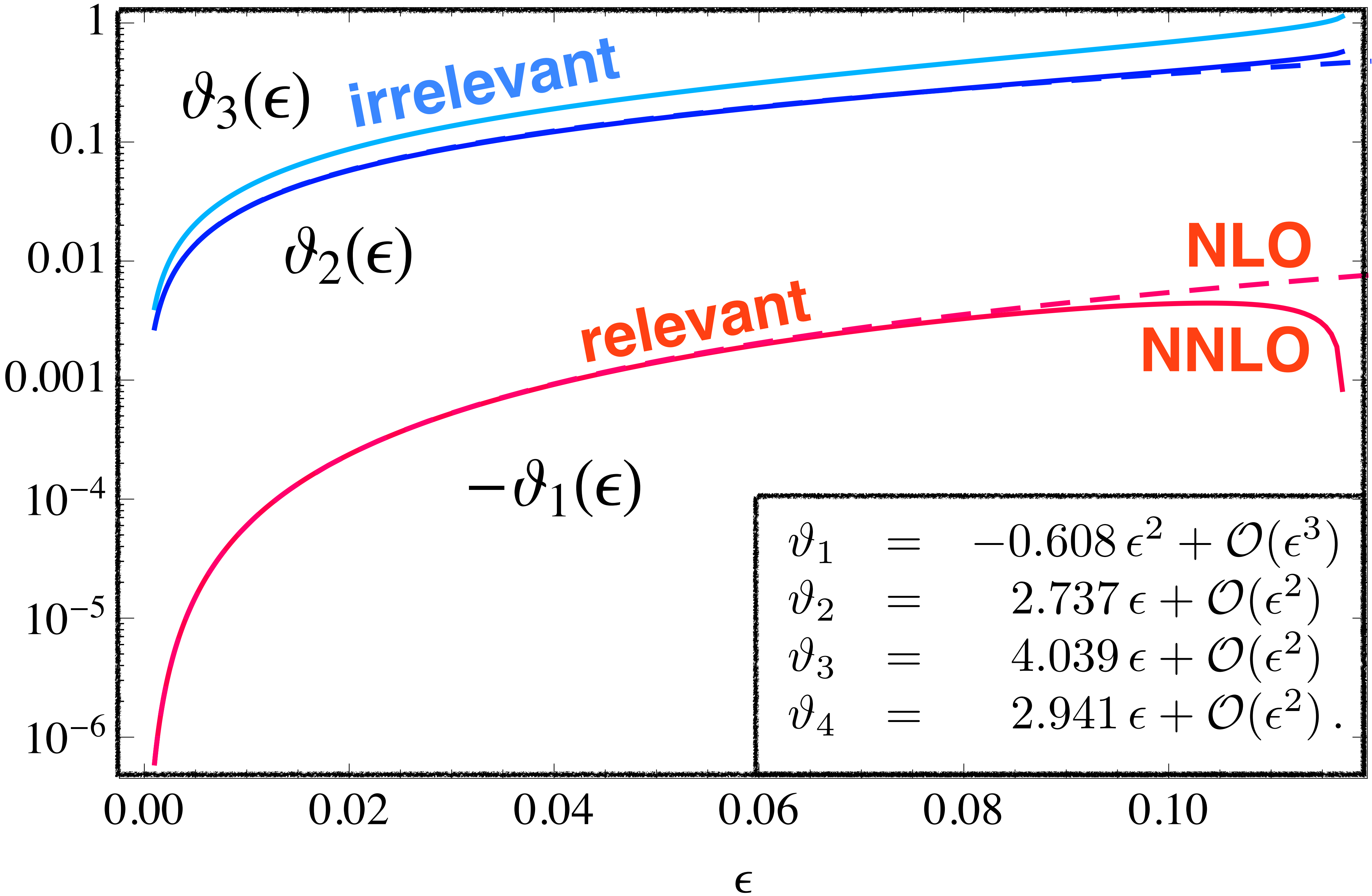
Higgs



results

UV scaling exponents

$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$



vacuum stability

Mojaza, Litim, Sannino
1501.03061

vacuum must be stable classically and quantum-mechanically

$$V \propto \alpha_v \mathrm{Tr}(H^\dagger H)^2 + \alpha_h (\mathrm{Tr} H^\dagger H)^2$$

stability

$$\alpha_h > 0 \quad \text{and} \quad \alpha_h + \alpha_v \geq 0 \qquad H_c \propto \delta_{ij}$$

$$\alpha_h < 0 \quad \text{and} \quad \alpha_h + \alpha_v / N_F \geq 0 \qquad H_c \propto \delta_{i1}$$

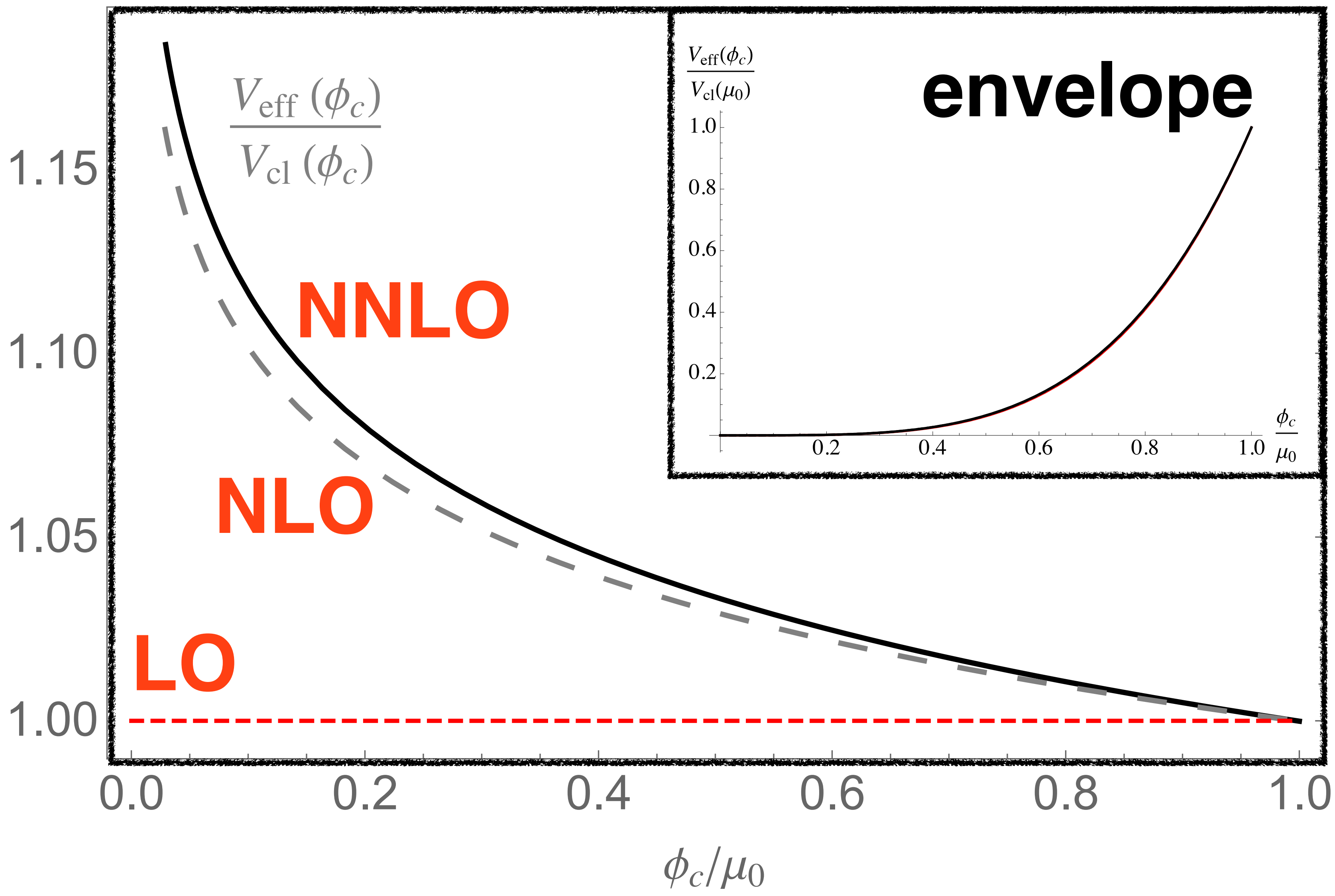
UV FP:

$$0 < \alpha_h^* + \alpha_v^*$$ **ok**

vacuum stability

quantum stability: Coleman-Weinberg type resummation of logs

$$\left(\mu_0 \frac{\partial}{\partial \mu_0} - \gamma(\alpha_j)\, \phi_c \frac{\partial}{\partial \phi_c} + \sum_i \beta_i(\alpha_j) \frac{\partial}{\partial \alpha_i}\right) V_{\rm eff}(\phi_c, \mu_0, \alpha_j) = 0$$



effective potential well-defined for all scales

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asymptotic safety

asymptotic safety in 4D:

couplings achieve **interacting** UV fixed point

fields	AS?
scalars	no
scalars with fermions	no
gauge fields	no
gauge fields with fermions	no
non-Abelian fields, fermions, scalars	yes*

*) provided certain conditions hold true

lesson 2

interacting UV fixed point exist
in **4D gauge-Yukawa theories**

FP **guaranteed** by perturbation theory
and large-N expansion

scalar sector **necessary** within PT
quartic becomes **asymptotically safe**

UV FP entails
enhanced predictivity

outlook:
asymptotic safety of
quantum gravity

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quantum gravity

running coupling $g(k) = G_N(k)k^{D-2}$ $t = \ln k/\Lambda_c$

$$\partial_t g = (D - 2 + \eta_N)\, g$$

$g_* \neq 0$ $g_* = 0$

UV IR fixed points

4D:

large anomalous dimension $\eta_N = \eta_N(g, \text{all other couplings})$

large UV scaling exponents $\vartheta \approx \mathcal{O}(1)$

strong coupling effects $g_* \approx \mathcal{O}(1)$

relevant vs **irrelevant**

invariants not known a priori

quantum gravity

computational methods

4D quantum gravity:

expect large couplings
canonical scaling not applicable
non-perturbative tools mandatory

continuum: non-perturbative renormalisation group

lattice: Monte Carlo simulations

simplicial gravity
dynamical triangulations

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evidence for asymptotic safety

a selection; for overviews, see: DL **0810.3675** and **1102.4624**

gravitation

Einstein-Hilbert (Souma '99, Reuter, Lauscher '01, DL '03)

higher dimensions, dimensional reduction (DL '03, Fischer, DL '05)

f(R), polynomials in R (Lauscher, Reuter, '02, Codello, Percacci, Rahmede '08, Machado, Saueressig '09 Benedetti,Caravelli'12, Dietz, Morris'12, Falls, DL, Nikolakopoulos, Rahmede '13)

local potential approximation (Benedetti,Caravelli'12, Dietz, Morris, '12, Demmel, Saueressig, Zanusso '12, Falls, DL, Nikolakopoulos, Rahmede '13, Benedetti '13, Benedetti, Guarnieri '13)

higher-derivative gravity (Codello, Percacci '05) (Benedetti, Saueressig, Machado '09, Niedermaier '09) (DL, Rahmede, in prep.)

conformally reduced gravity (Reuter,Weyer '09, Machado, Percacci '10, DL, Satz '12)

Holst action + Immirzi parameter (Daum, Reuter '10, Benedetti, Speciale '11)

signature effects (Manrique, Rechenberger, Saueressig '11)

gravitation + matter

matter (Percacci '05, Perini, Percacci '05, Narain, Percacci '09, Narain, Rahmede '09, Codello '11)

Yang-Mills gravity

1-loop: (Robinson,Wilzcek '05, Pietrokowski, '06, Toms '07, Ebett, Plefka, Rodigast '08)

beyond: (Manrique, Reuter, Saueressig '09, Folkerts, DL, Pawlowski, 11, Harst, Reuter '11)

f(R)

$$\Gamma_k \propto f(R)$$

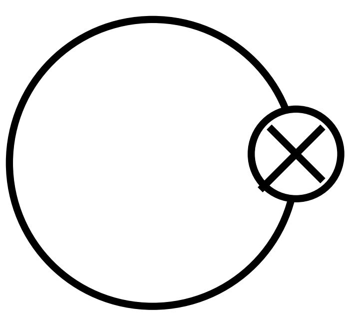
Ricci scalars

$$\Gamma_k = \sum_{n=0}^{N-1} \lambda_n \, k^{d_n} \int d^4x \sqrt{g}\, R^n$$

effective action with invariants up to mass dimension $D = 2(N-1)$

technicalities: **functional renormalisation**

$$k\frac{\mathrm{d}\Gamma_k}{\mathrm{d}k} = \frac{1}{2}\,\mathrm{Tr}\left[\left(\frac{\delta^2\Gamma_k[\phi]}{\delta\phi\,\delta\phi} + R_k\right)^{-1} k\frac{\mathrm{d}R_k}{\mathrm{d}k}\right] = \frac{1}{2}$$



here:

M Reuter hep-th/9605030

DL **hep-th/0103195**

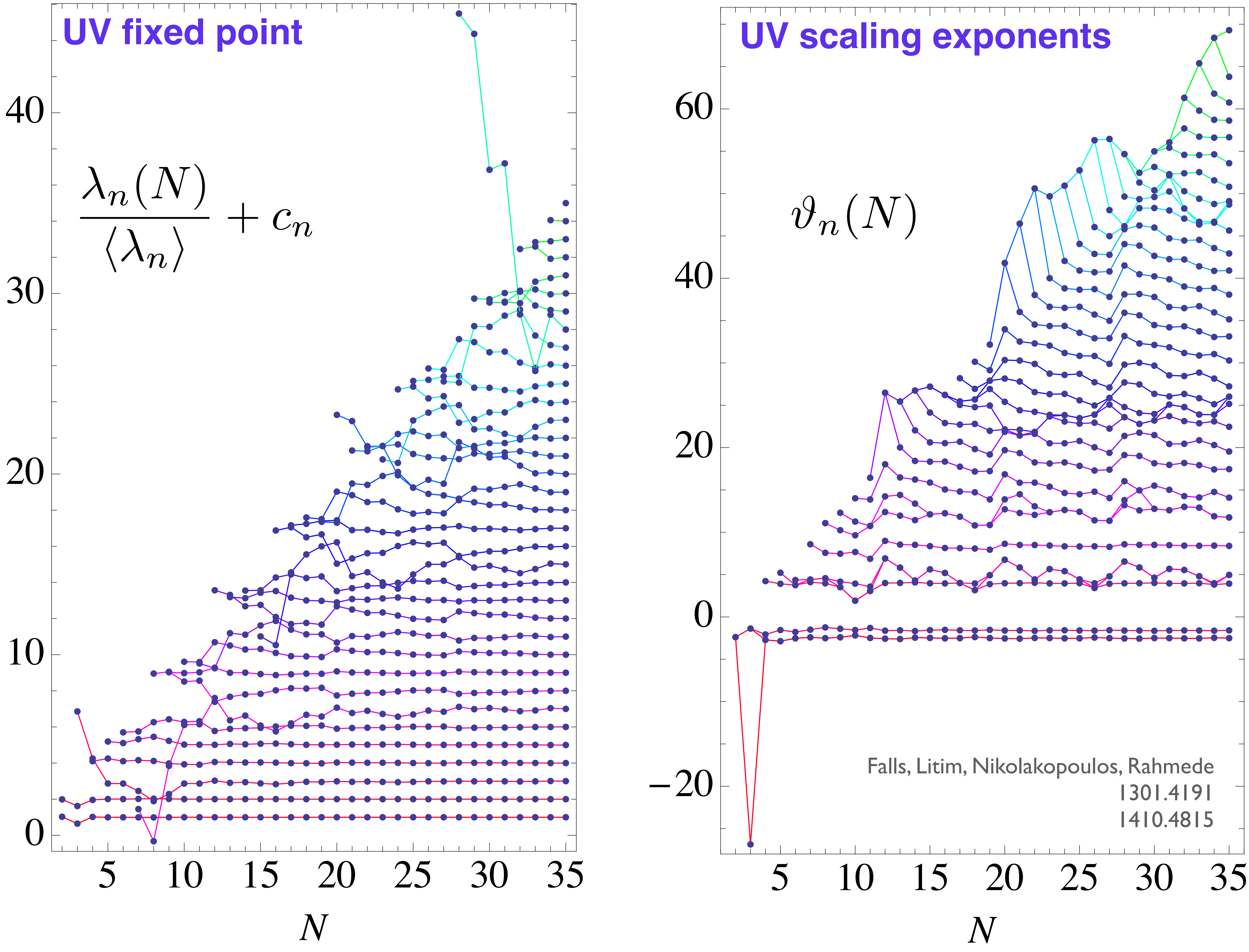
hep-th/0312114

Falls, DL, Nikolakopoulos, Rahmede **1301.4191.pdf**

Falls, DL, Nikolakopoulos, Rahmede 1410.4815

A Codello, R Percacci, C Rahmede 0705.1769, 0805.2909

P Machado, F Saueressig 0712.0445



UV fixed point
$\frac{\lambda_n(N)}{\langle \lambda_n \rangle} + c_n$
0
10
20
30
40
5
10
15
20
25
30
35
N
UV scaling exponents
$\vartheta_n(N)$
−20
0
20
40
60
5
10
15
20
25
30
35
N
Falls, Litim, Nikolakopoulos, Rahmede
1301.4191
1410.4815

scaling exponents

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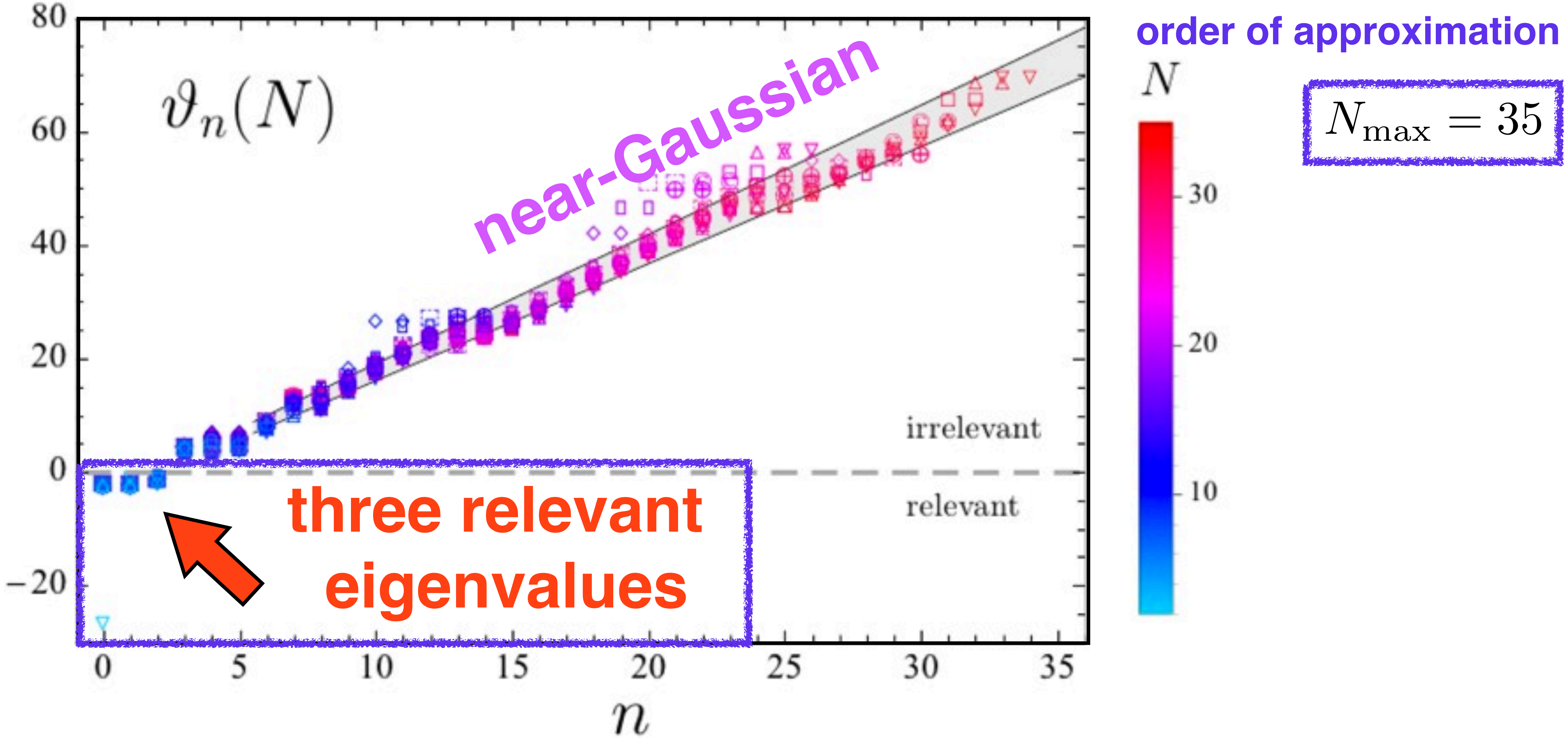
f(R)-type gravity

$$\Gamma_k = \sum_{n=0}^{N-1} \lambda_n \, k^{d_n} \int d^4x \sqrt{g} \, R^n$$



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1301.4191
1410.4815

RG vs lattice

simplicial gravity

lattice fixed point in 4D

Hamber '00, '15

scaling exponent	lattice		RG	
ν	$0.335(9)$	Hamber '00	0.375	Litim '03
	$0.335(4)$	Hamber '15 as quoted in 1503.06233	0.3333	Falls 1503.06233

dynamical triangulations (casual vs euclidean)

lattice fixed point in 4D CDT

Ambjoern, Jordan, Jurkiewicz, Loll '11

spectral dimension $\mathcal{D}_s$		
CDT	Ambjoern, Jurkiewicz, Loll '05	
EDT	Laiho, Coumbe '11	$\mathcal{D}_s = \frac{2D}{2+\delta}$
RG	Reuter, Saueressig, '11	

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conclusions

QFTs beyond asymptotic freedom

4D matter-gauge theories

- **exact proof** of asymptotic safety
- **all types of fields** required
- sensible **UV finite theory**
- no additional (super-)symmetry

4D quantum gravity

- systematic **non-perturbative** search strategies
- **strong hints** for interacting UV fixed point
- intriguing **near Gaussianity**

opportunities for lattice QCD