UV fixed points - from gauge theories to quantum gravitation

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standard model

University of Sussex

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

University of Sussex

local QFT for fundamental interactions

strong nuclear force
weak force
electromagnetic force

challenges

Higgs, QED: maximum UV extension?
complete asymptotic freedom?
how does quantum gravity fits in?
...

interacting UV fixed points

UV fixed points

perturbation theory

theory with coupling α**:**

$$t = \ln \mu/\Lambda$$

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

$$\alpha_* \ll 1$$

perturbation theory

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

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

$\alpha_* \ll 1$

free fixed point $\boxed{\alpha_* = 0}$

perturbation theory

theory with coupling α:

$t = \ln \mu / \Lambda$

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$\alpha_* \ll 1$

free fixed point

$$\boxed{\alpha_* = 0}$$

QED, Higgs $\quad B < 0 \quad$ **IR fixed point**

perturbative UV Landau pole
predictive up to maximal UV extension

asymptotic freedom

theory with coupling α:

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

free fixed point $\boxed{\alpha_* = 0}$

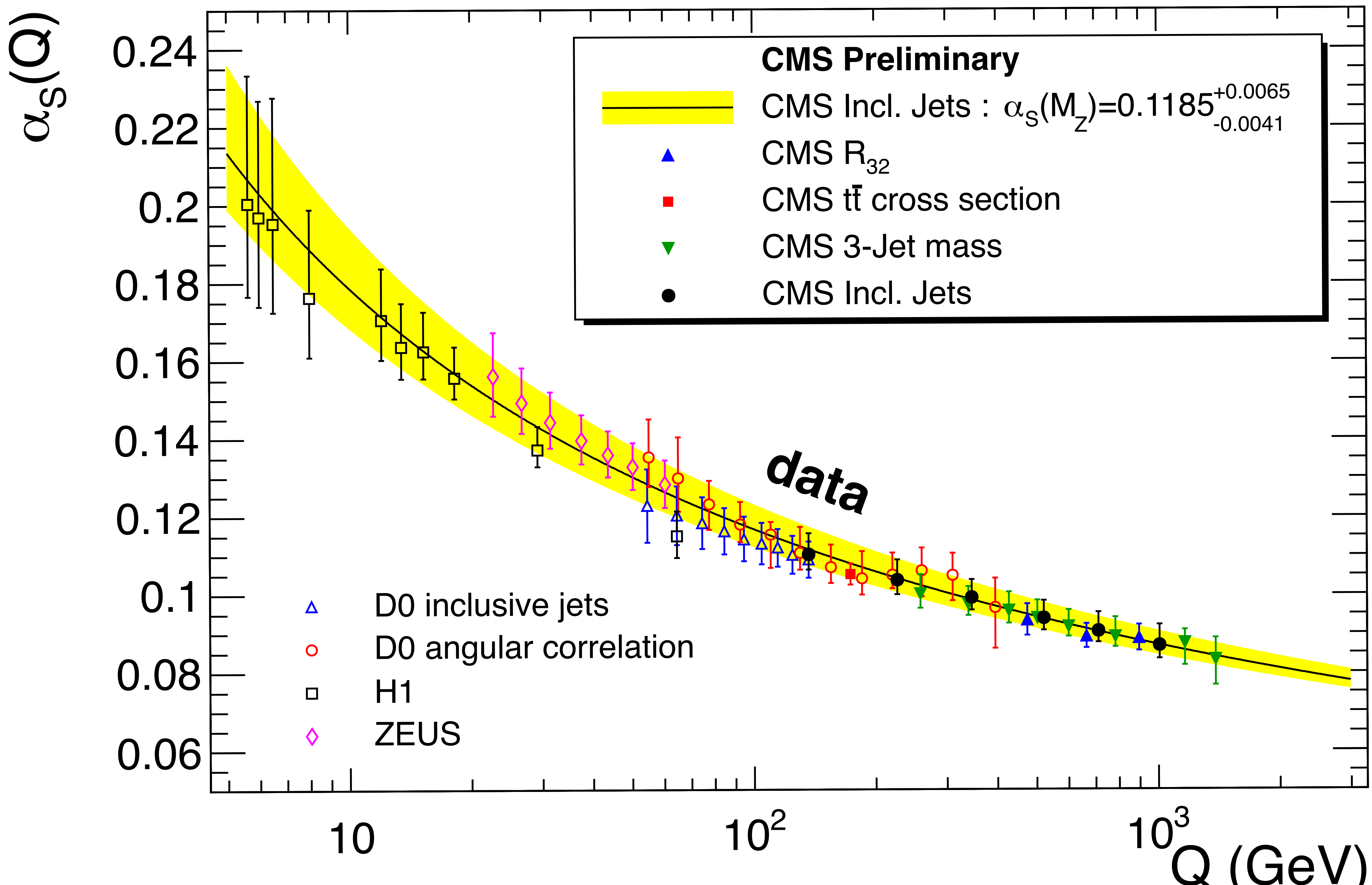
QCD $B > 0$ UV fixed point

perturbative renormalisability & asymptotic freedom
predictive up to highest energies

fundamental definition of QFT $\Longleftrightarrow$ UV fixed point

Wilson '71

asymptotic freedom



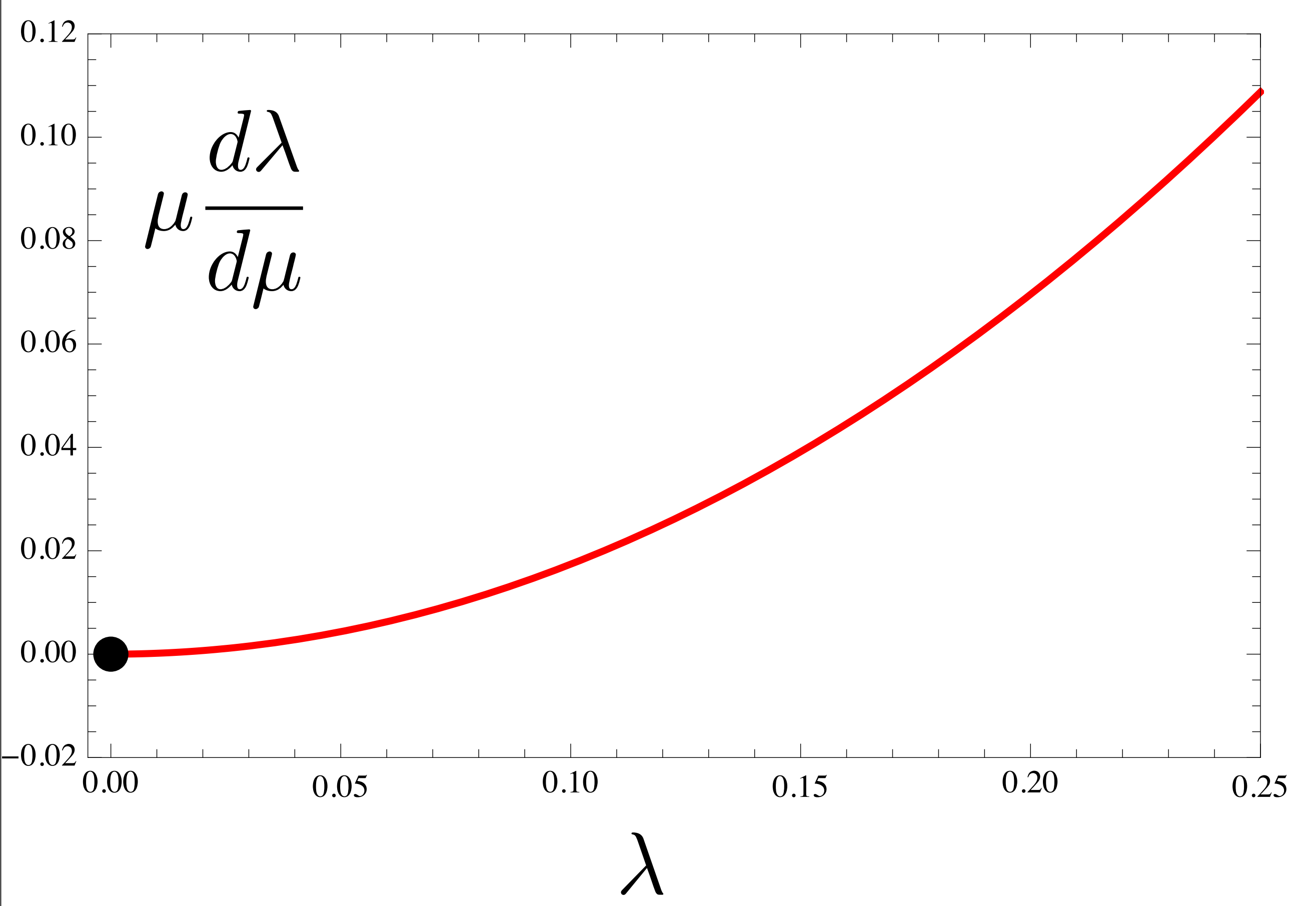
asymptotic freedom

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

QED beta function

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

Higgs self-coupling
Yukawa couplings



perturbative UV Landau pole:
maximal UV extension

cure:
complete asymptotic freedom

interacting fixed point

theory with coupling α :

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

perturbative non-renormalisability: $A > 0$

interacting fixed point

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

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

$\alpha_* \ll 1$

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

interacting fixed point

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

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

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

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

interacting fixed point

theory with coupling α**:**

$t = \ln \mu / \Lambda$

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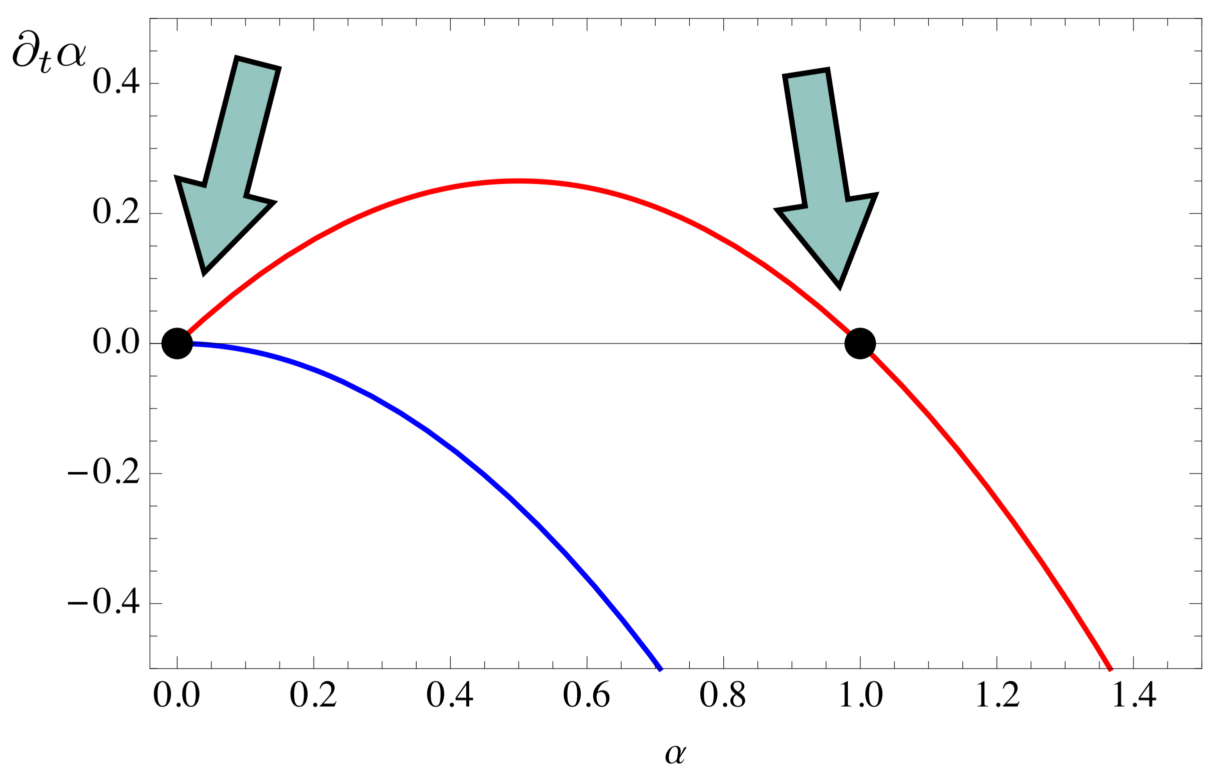

interacting fixed point

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

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

$\alpha_* \ll 1$

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

epsilon expansion: $\epsilon = D - D_c$

large-N expansion: many fields

perturbation theory

theory with coupling α:

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

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 Morris '04
scalars	$D = 2 + \epsilon: \quad \alpha = g_{NL}(\mu)\mu^{D-2}$	Brezin, Zinn-Justin '76 Bardeen, Lee, Shrock '76

non-perturbative renormalisability

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

UV fixed points in 4D quantum gauge theories

DL, F Sannino, JHEP1214(2014)178 arXiv:1406.2337
DL, M Mojaza, F Sannino, arXiv:1501.03061

gauge theory with fermions

SU(NC) YM with NF fermions:

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

$$t = \ln \mu/\Lambda$$

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

$$\alpha_* \ll 1$$

gauge theory with fermions

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

gauge theory with fermions

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$\alpha_* \ll 1$

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

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

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

Veneziano ’79

we consider $\boxed{0 < -B \equiv -B\,(\epsilon) \ll 1}$

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

interacting fixed points:

$B > 0 \;\; \& \;\; C > 0:$ **Caswell - Banks-Zaks IR fixed point**

Caswell '74
Banks, Zaks '82

$B < 0 \;\; \& \;\; C < 0:$ **UV fixed point no asymptotic freedom**

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

we are in the regime $\boxed{0 < \epsilon \ll 1}$

here: $B = -\frac{4\epsilon}{3} < 0 \;\;\&\;\; C > 0$

hence:
no physical fixed point

Caswell '74

gauge theory with fermions

SU(NC) YM with NF fermions:

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

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

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

$\boxed{\Rightarrow \text{ scalar fields \& Yukawa couplings required}}$

gauge-Yukawa theory

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

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

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

gauge-Yukawa theory

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

$t = \ln \mu/\Lambda$

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

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gauge-Yukawa theory

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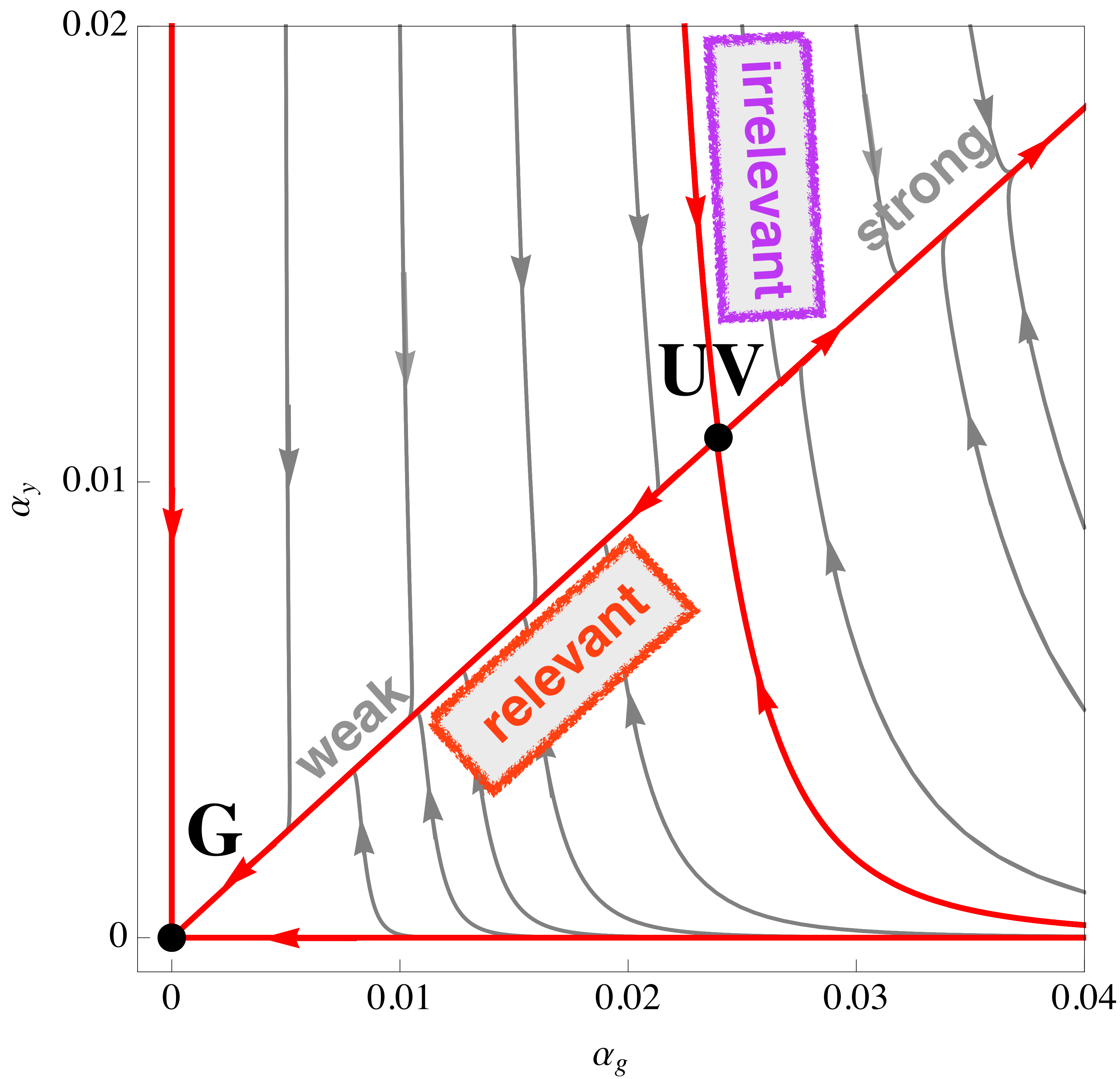
$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y$$

$\Rightarrow$ **sensible interacting UV fixed point**

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

phase diagram

UV finite theories (weak & strong)



exact UV FP
strict perturbative control

template gauge-Yukawa theory

Lagrangean

$$L_{\rm YM} = -\frac{1}{2}\mathrm{Tr}\, F^{\mu\nu}F_{\mu\nu}$$
$$L_F = \mathrm{Tr}\left(\overline{Q}\, i\not{D}\, Q\right)$$
$$L_Y = y\,\mathrm{Tr}\left(\overline{Q}\, H\, Q\right)$$
$$L_H = \mathrm{Tr}\left(\partial_\mu H^\dagger\, \partial^\mu H\right)$$
$$L_U = -u\,\mathrm{Tr}\left(H^\dagger H\right)^2$$
$$L_V = -v\left(\mathrm{Tr}\, H^\dagger H\right)^2 .$$

couplings

$$\alpha_g = \frac{g^2\, N_C}{(4\pi)^2}\,, \quad \alpha_y = \frac{y^2\, N_C}{(4\pi)^2}$$
$$\alpha_h = \frac{u\, N_F}{(4\pi)^2}\,, \quad \alpha_v = \frac{v\, N_F^2}{(4\pi)^2}\,.$$

no asymptotic freedom

small parameter

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

global symmetry

$$SU(N_F)\times SU(N_F)\times U(1)$$

template gauge-Yukawa theory

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

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

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

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

up to 3-, 2-, 1-loop order in the gauge, Yukawa and scalar couplings

coupling	order in perturbation theory		
α_g	1	2	3
α_y	0	1	2
α_h	0	0	1
α_v	0	0	1
approximation level	LO	NLO	NNLO

template gauge-Yukawa theory

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

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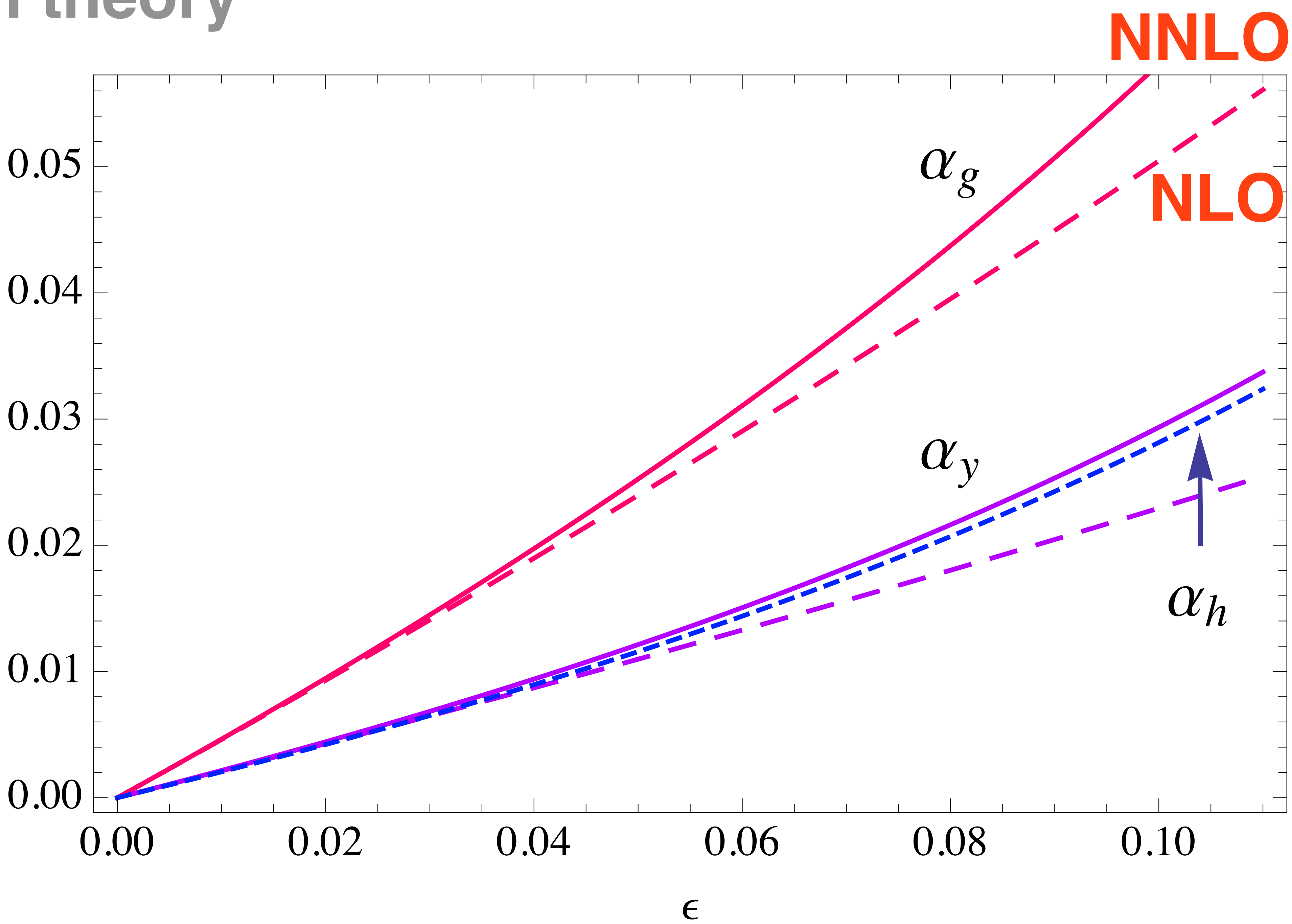
$$\beta_v = 12\alpha_h^2 + 4\alpha_v\,(\alpha_v + 4\alpha_h + \alpha_y)\ .$$

universal
UV fixed point

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

results

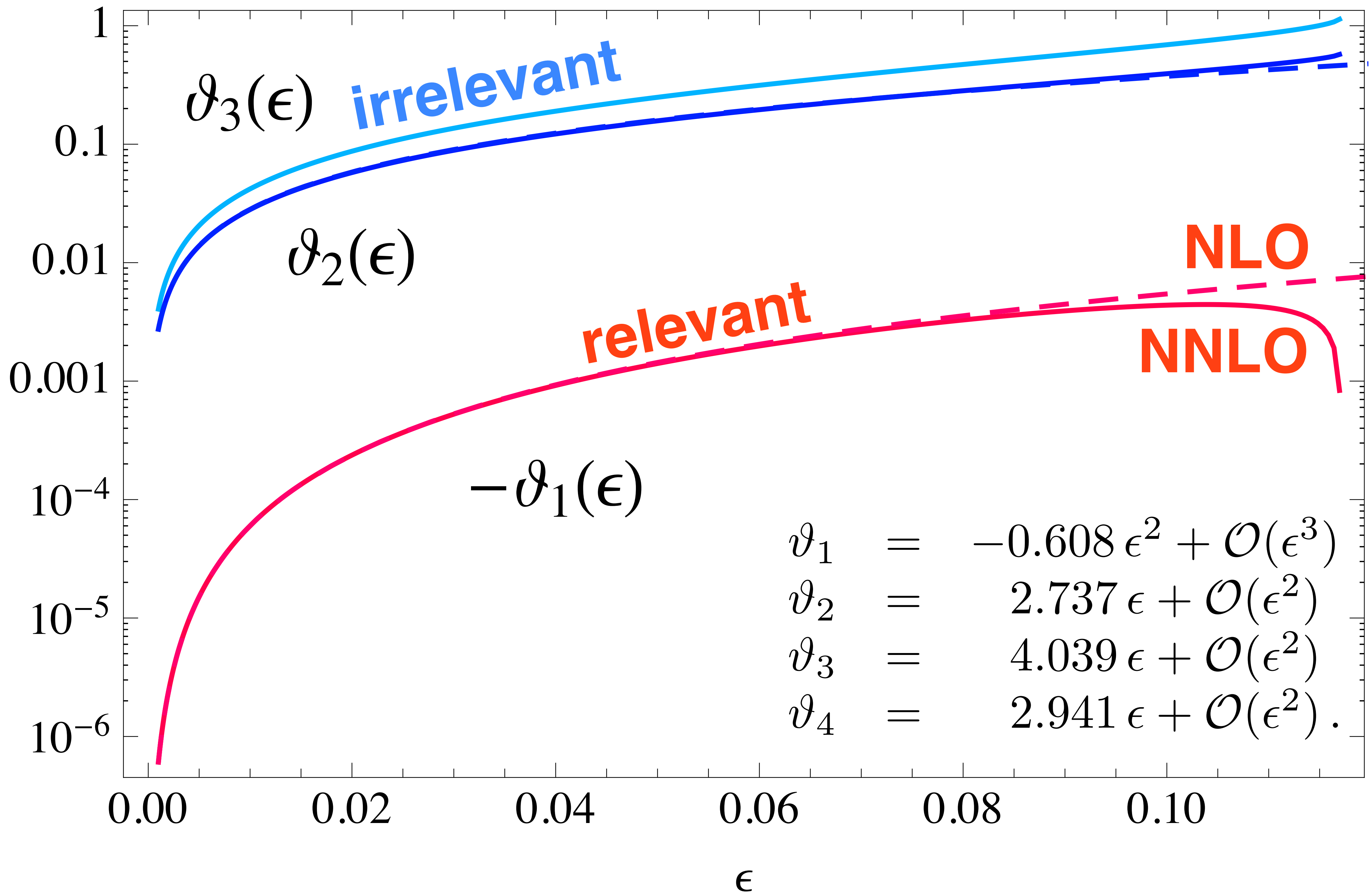
UV fixed point from perturbation theory



results

UV scaling exponents

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

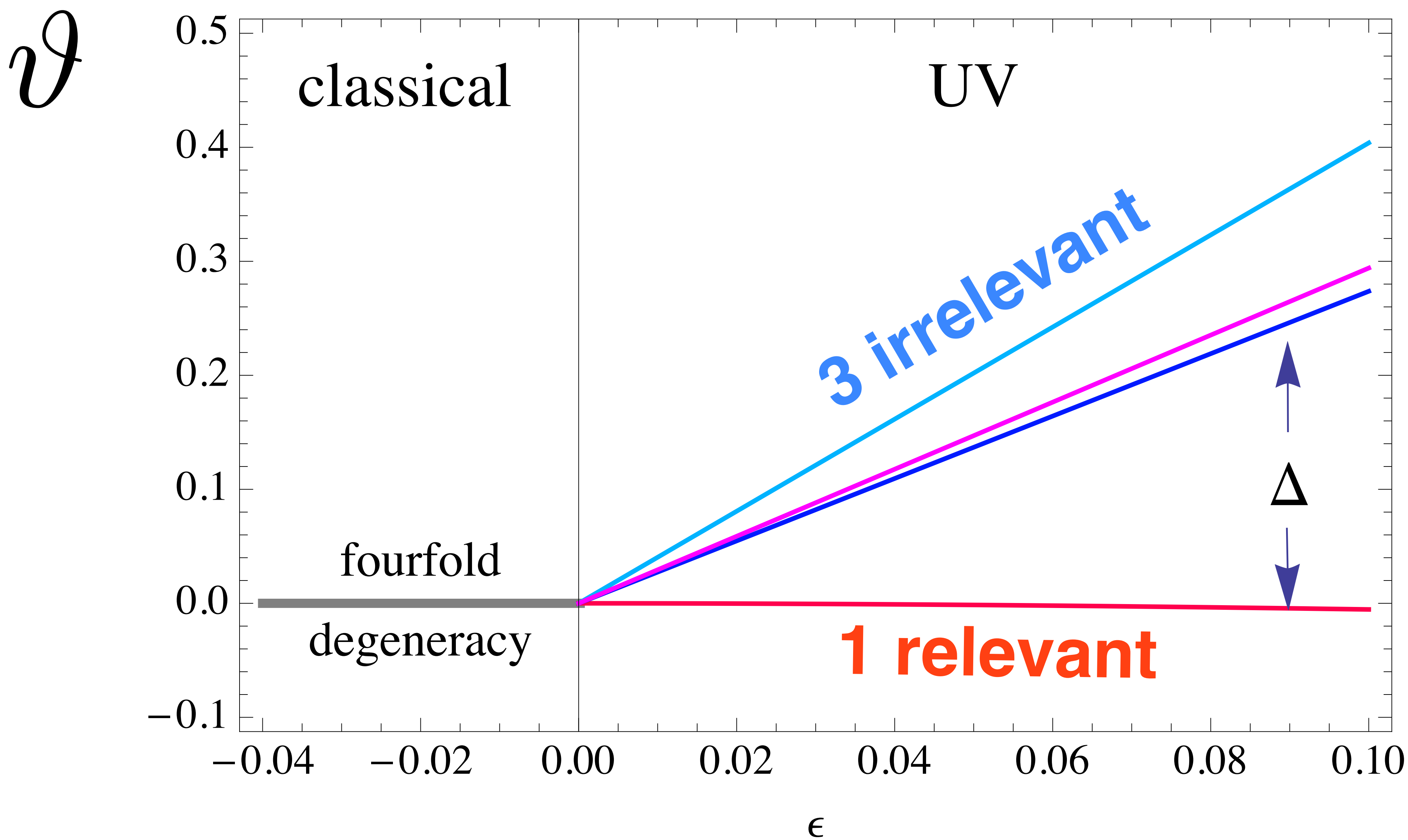


$$\begin{aligned}
\vartheta_1 &= -0.608\,\epsilon^2 + \mathcal{O}(\epsilon^3) \\
\vartheta_2 &= 2.737\,\epsilon + \mathcal{O}(\epsilon^2) \\
\vartheta_3 &= 4.039\,\epsilon + \mathcal{O}(\epsilon^2) \\
\vartheta_4 &= 2.941\,\epsilon + \mathcal{O}(\epsilon^2)\,.
\end{aligned}$$

results

UV scaling exponents

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

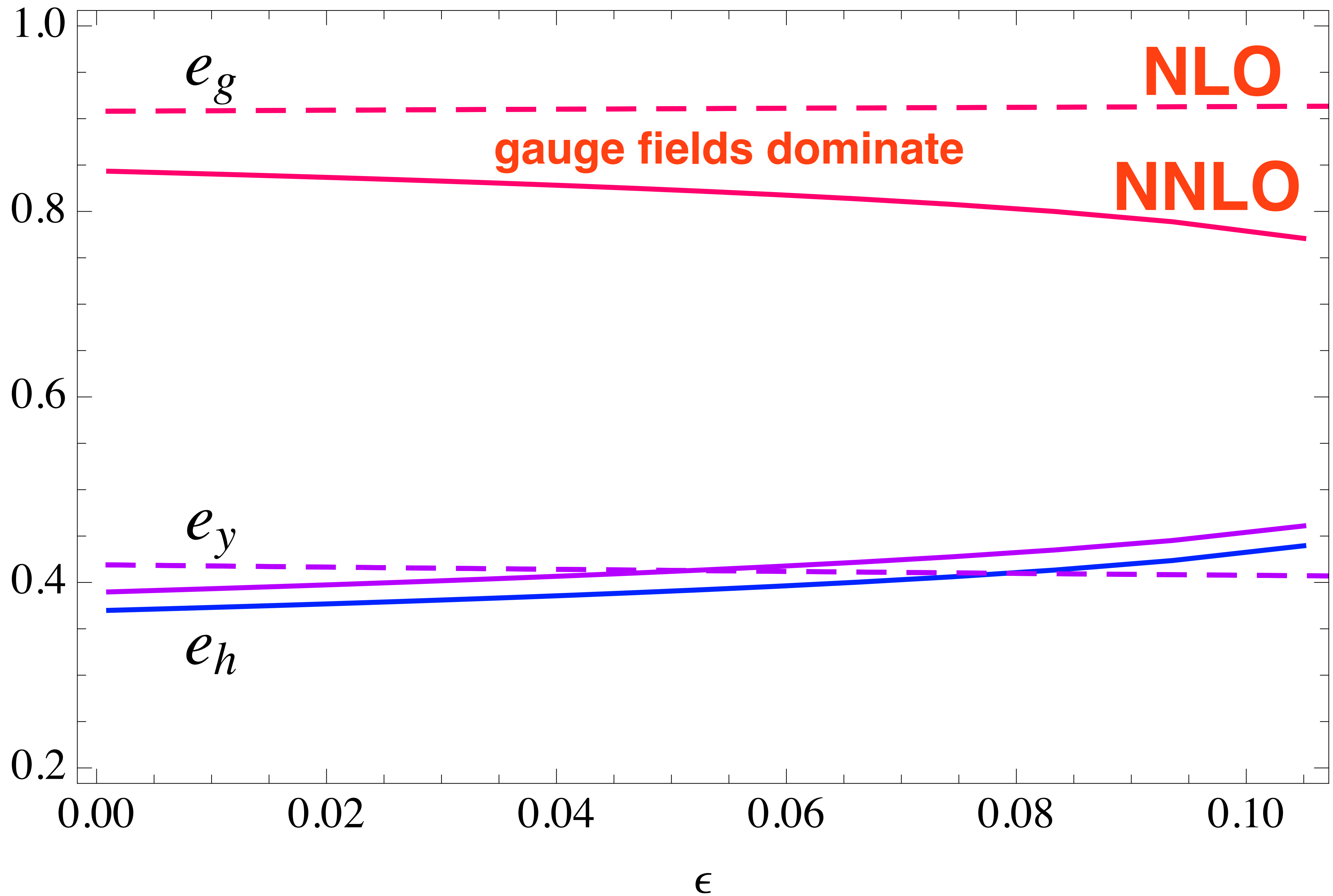


results

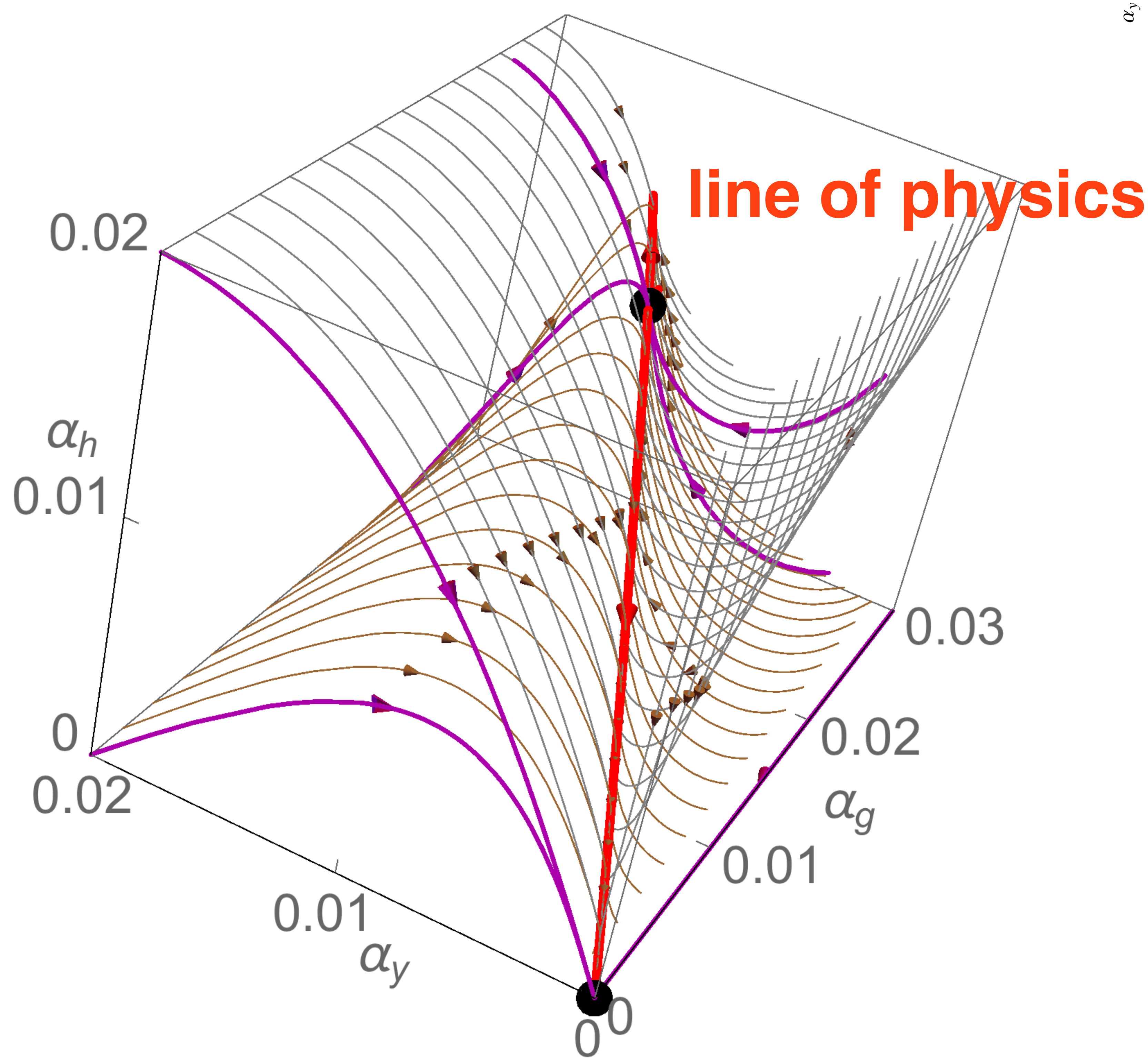
UV-relevant
eigendirection

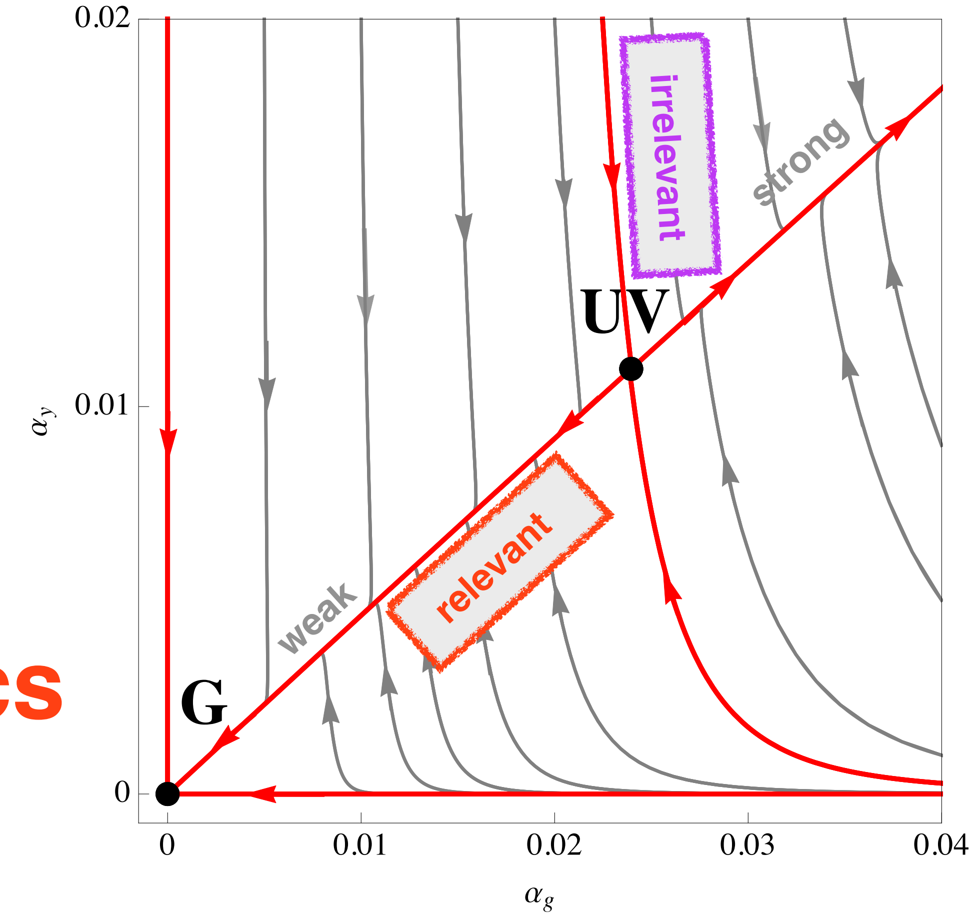
gauge

Yukawa
Higgs



phase diagram



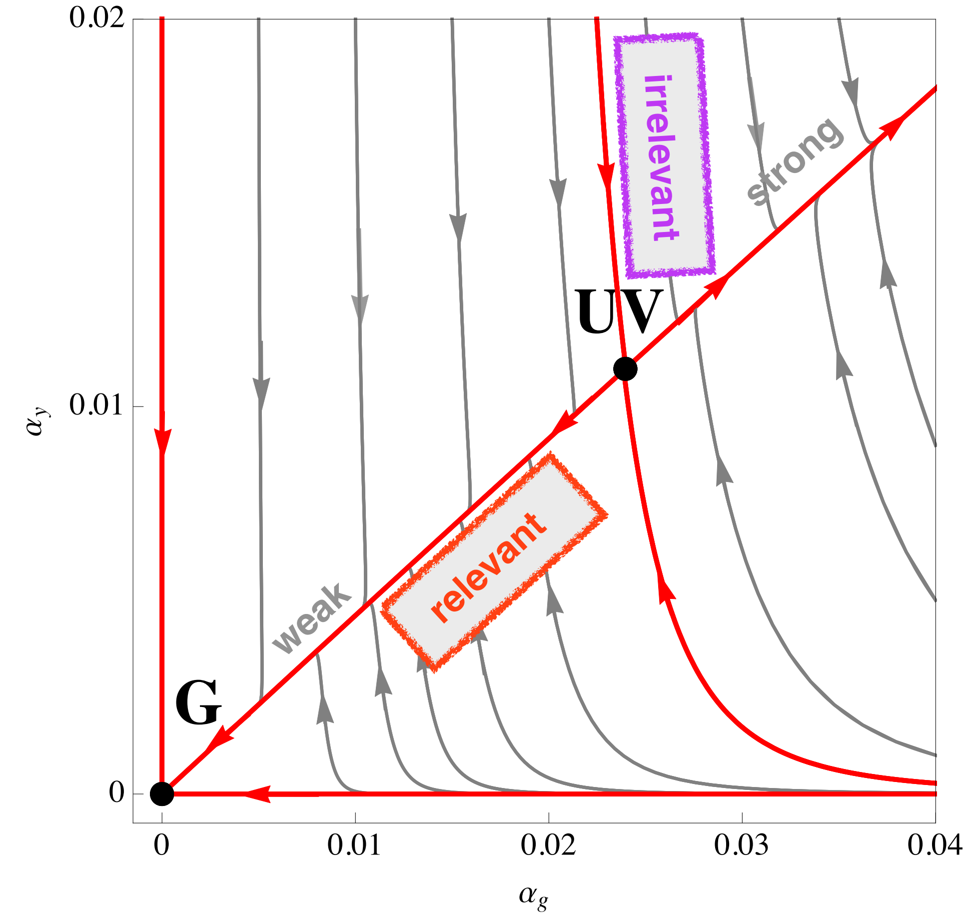


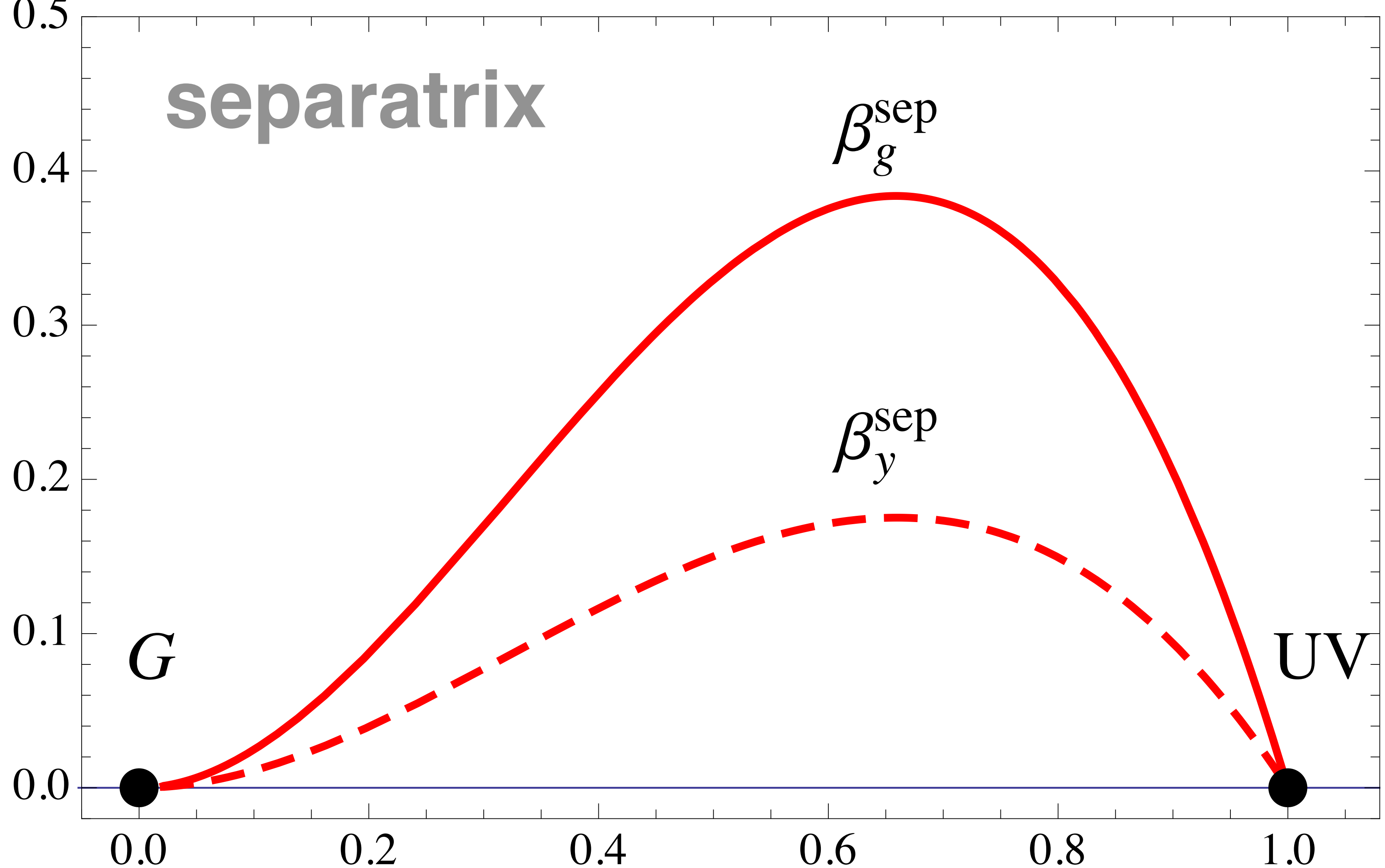
lines of physics

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

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

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





vacuum stability

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

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

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

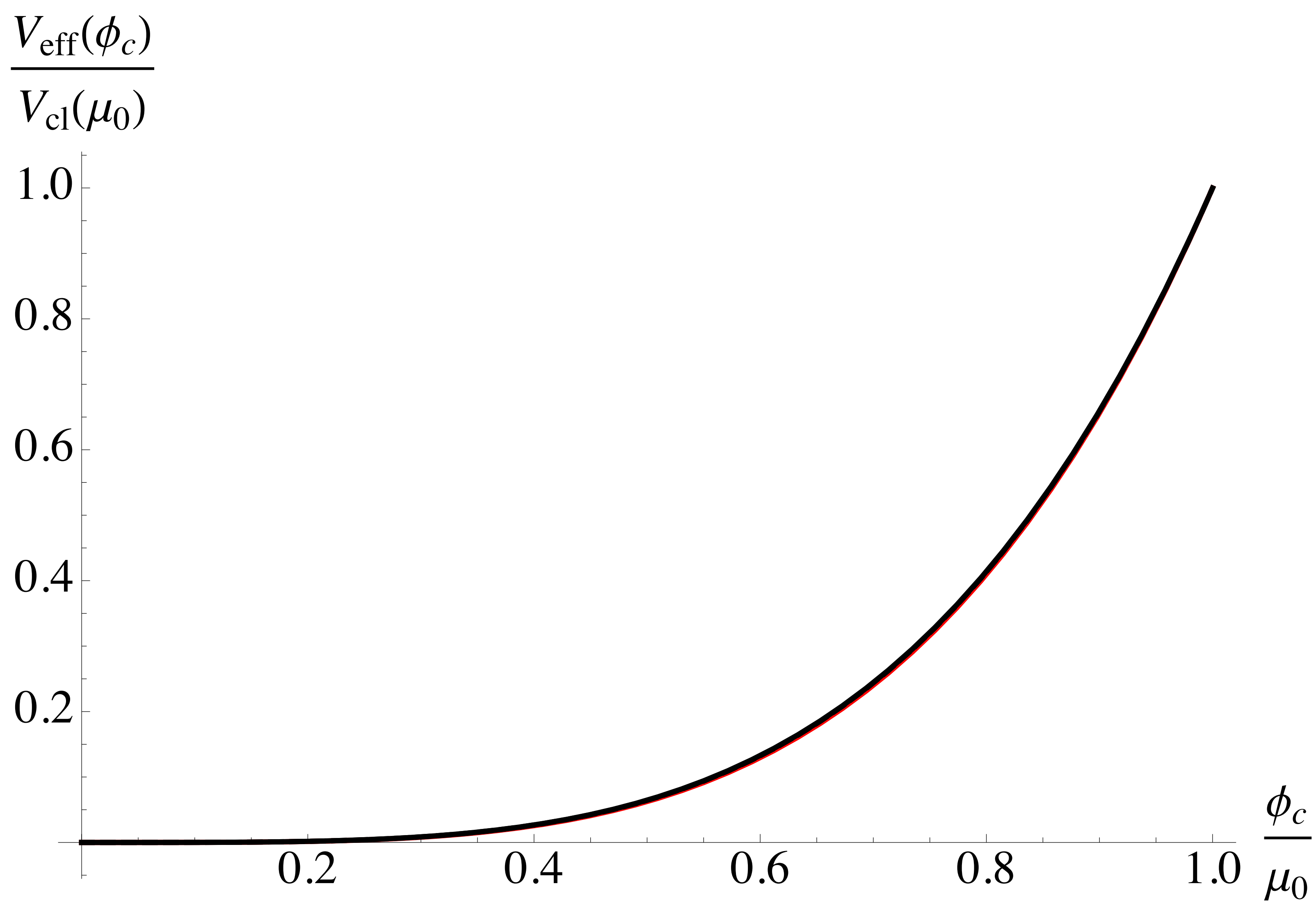
UV FP: $0 < \alpha_h^* + \alpha_v^*$ **ok**

quantum effects: integrate exact RG

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

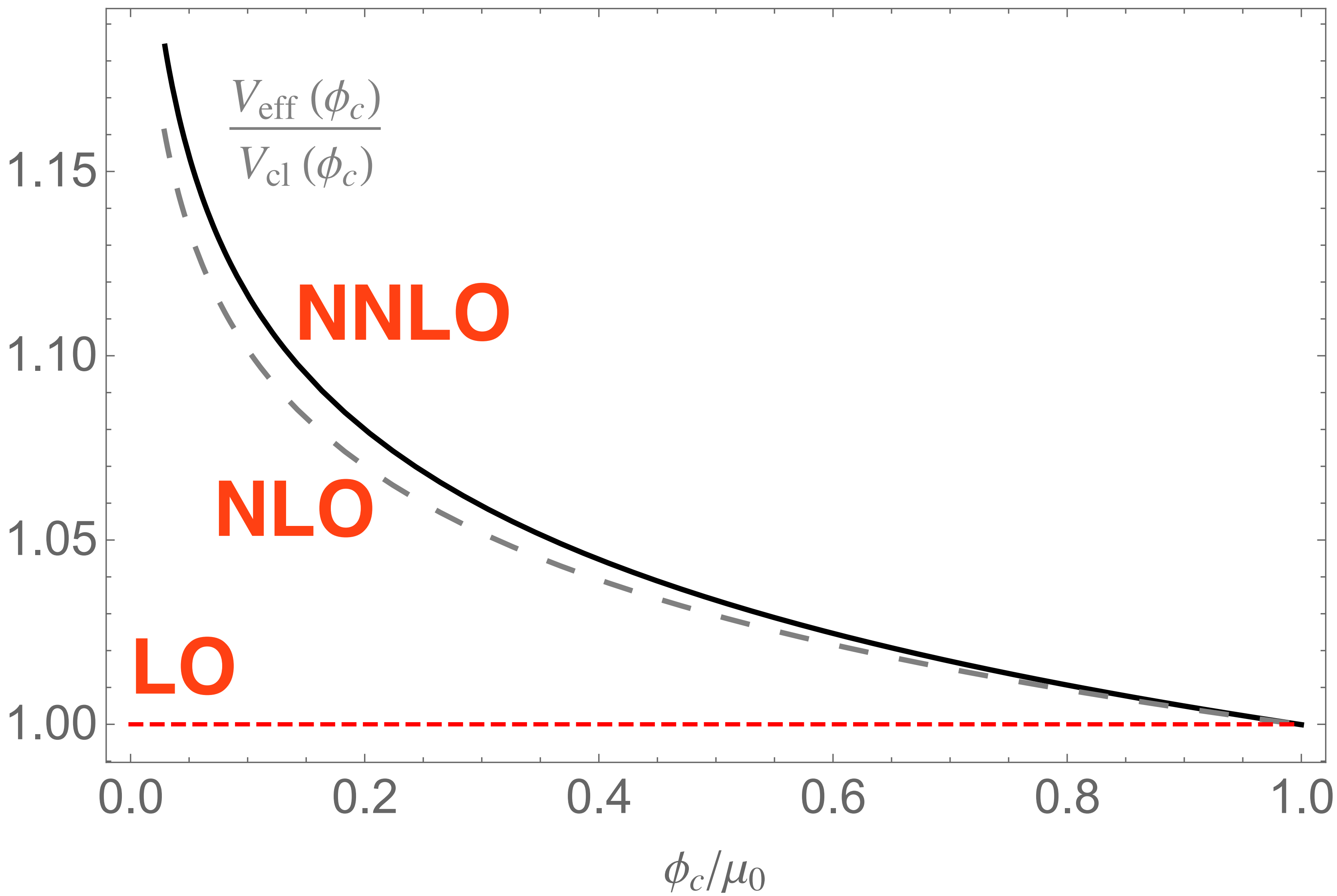
vacuum stability

Coleman-Weinberg potential



vacuum stability

quantum stability: resummation of logarithms



scalar effective potential defined for all scales

quantum vacuum is stable

summary

QFTs beyond asymptotic freedom

4D matter-gauge theories

exact perturbative proof of existence
all types of fields required
sensible interacting & UV finite theory
no supersymmetry

UV fixed points in 4D quantum gravity

quantum gravity

running coupling $$g(k) = G_N(k) k^{D-2}$$

$$\partial_t g = (D - 2 + \eta_N)\, g \qquad t = \ln k/\Lambda_c$$

quantum gravity

running coupling $$g(k) = G_N(k) k^{D-2}$$

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

$$t = \ln k/\Lambda_c$$

$$g_* \neq 0$$

UV

non-trivial anomalous dimension

$$g_* = 0$$

IR

fixed points

quantum gravity

running coupling $$g(k) = G_N(k)k^{D-2}$$

$$\partial_t g = (D - 2 + \eta_N)\, g \qquad t = \ln k/\Lambda_c$$

$g_* \neq 0$ — **UV**

$g_* = 0$ — **IR**

fixed points

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

asymptotic freedom vs asymptotic safety

asymptotic freedom	asymptotic safety
$g_* = 0$	$g_* \neq 0$
anomalous dimensions	anomalous dimensions
$\eta_A = 0$	$\eta_N \neq 0$
canonical power counting	**non-canonical** power counting
$\{\vartheta_{\mathrm{G},n}\}$ are known	$\{\vartheta_n\}$ are **not** known
F^{256} irrelevant !	R^{256} relevant marginal irrelevant **?**

bootstrap search strategy

hypothesis relevancy of invariants follows canonical dimension

strategy

Step 1 retain invariants up to mass dimension D

Step 2 compute $\{\vartheta_n\}$ (eg. RG, lattice, holography)

Step 3 enhance D, and iterate

convergence (no convergence) of the iteration:

hypothesis supported (refuted)

f(R)

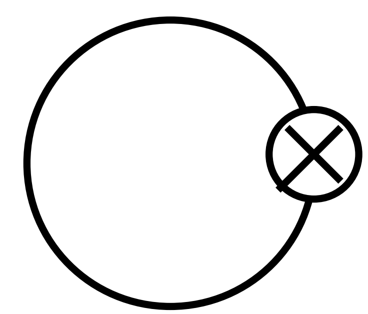
$$\Gamma_k \propto f(R)$$

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

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

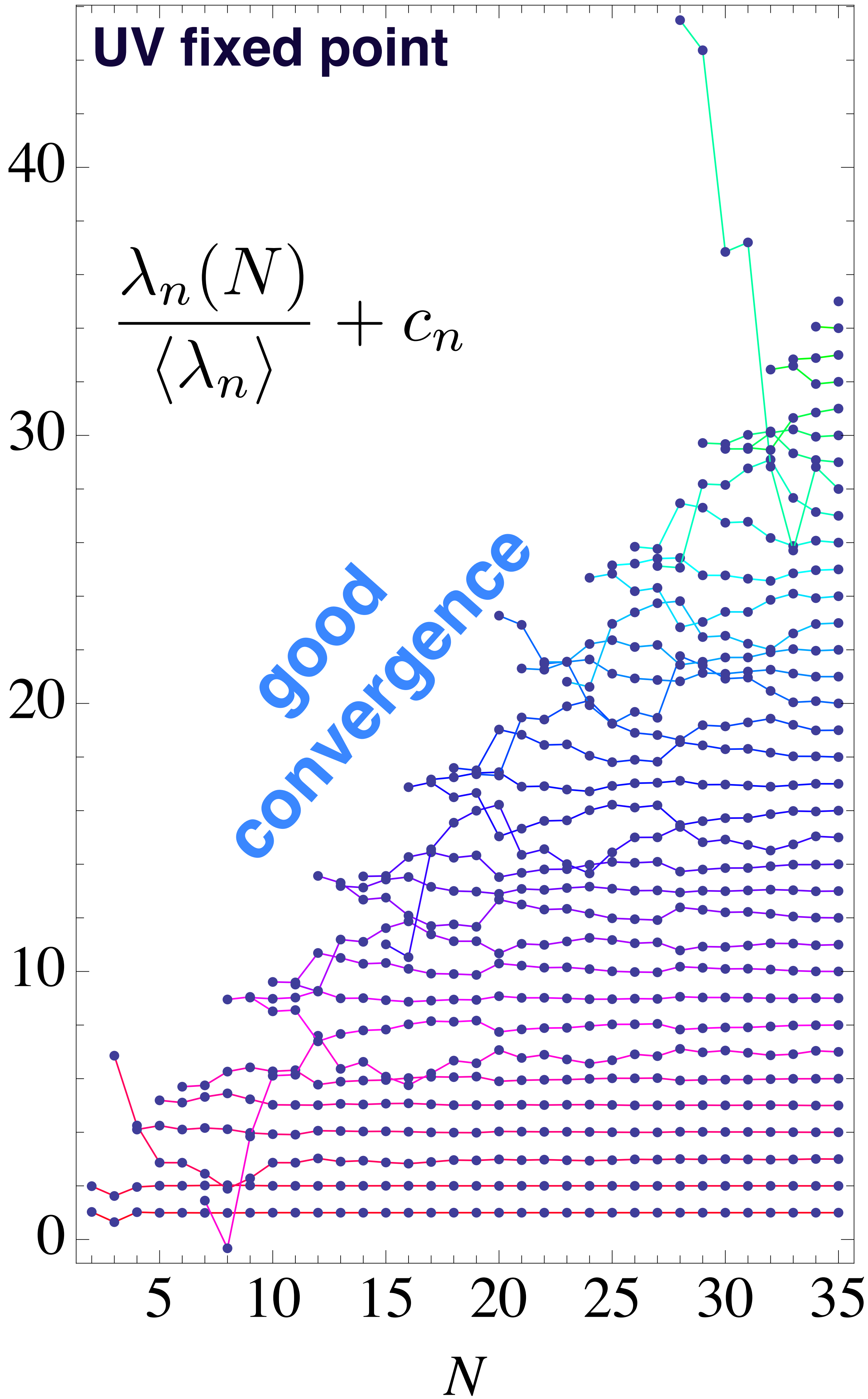
hep-th/0312114

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

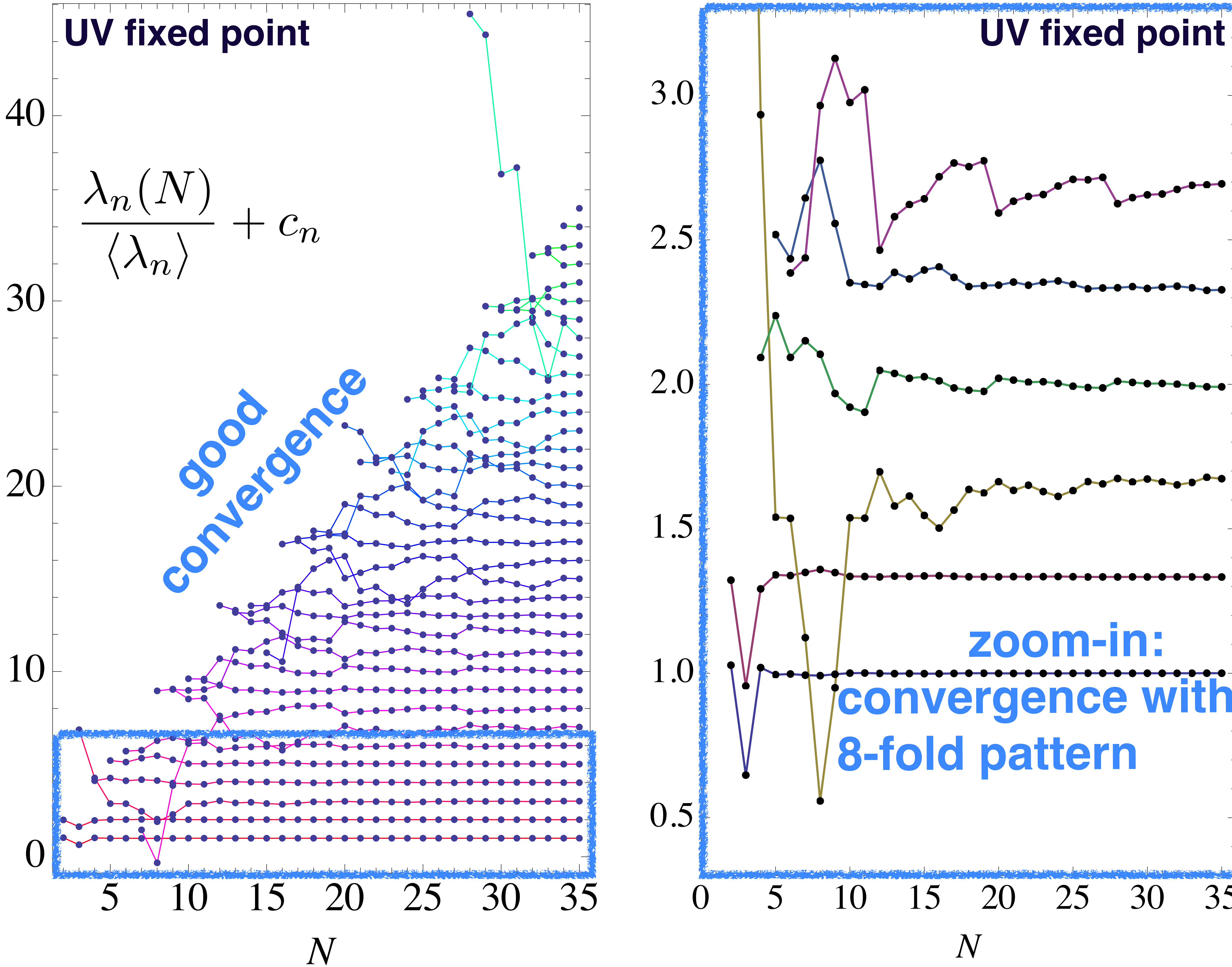
Falls, DL, Nikolakopoulos, Rahmede 1410.4815

A Codello, R Percacci, C Rahmede 0705.1769, 0805.2909

P Machado, F Saueressig 0712.0445

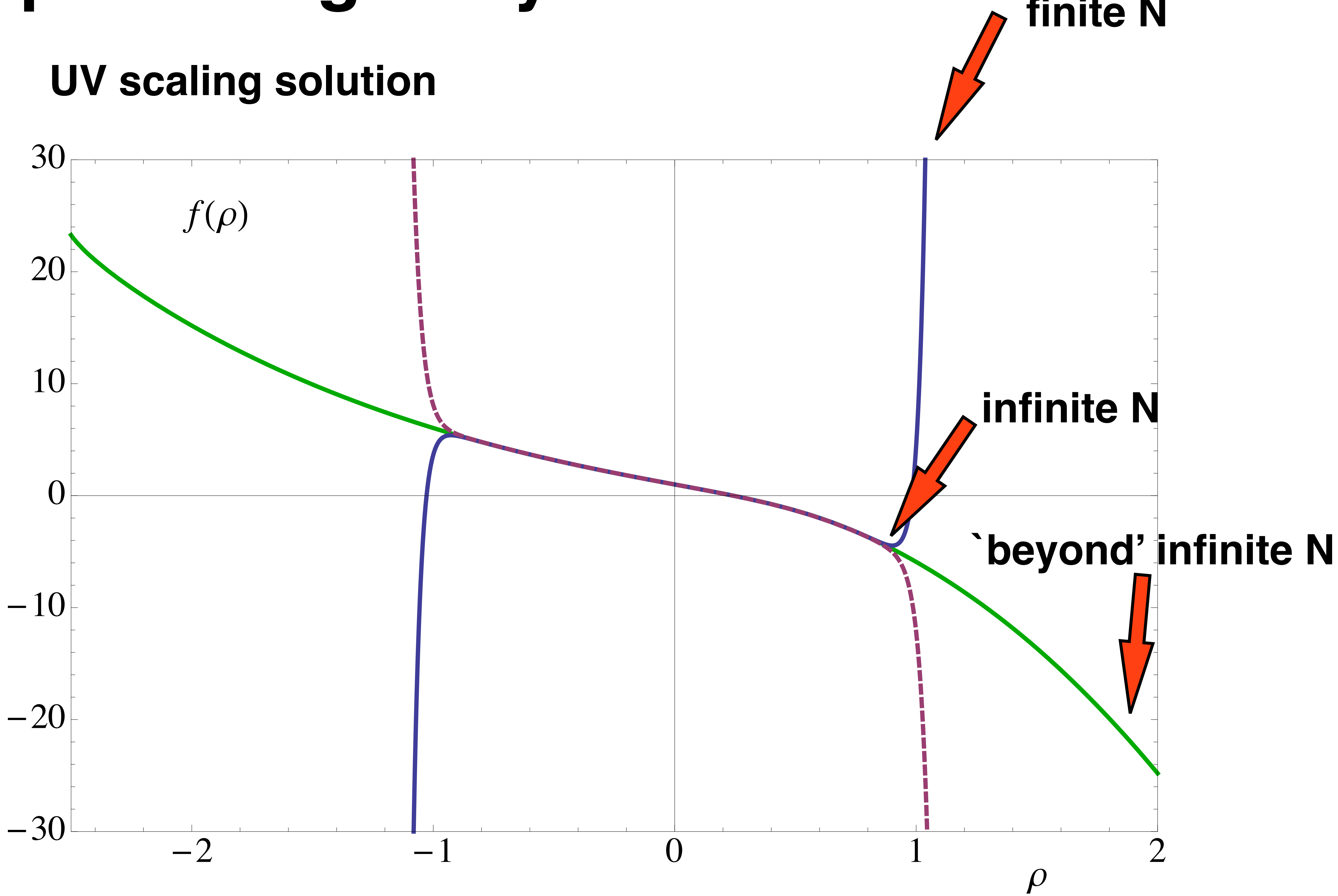


UV fixed point
$\frac{\lambda_n(N)}{\langle\lambda_n\rangle} + c_n$
good convergence
0
10
20
30
40
5
10
15
20
25
30
35
N

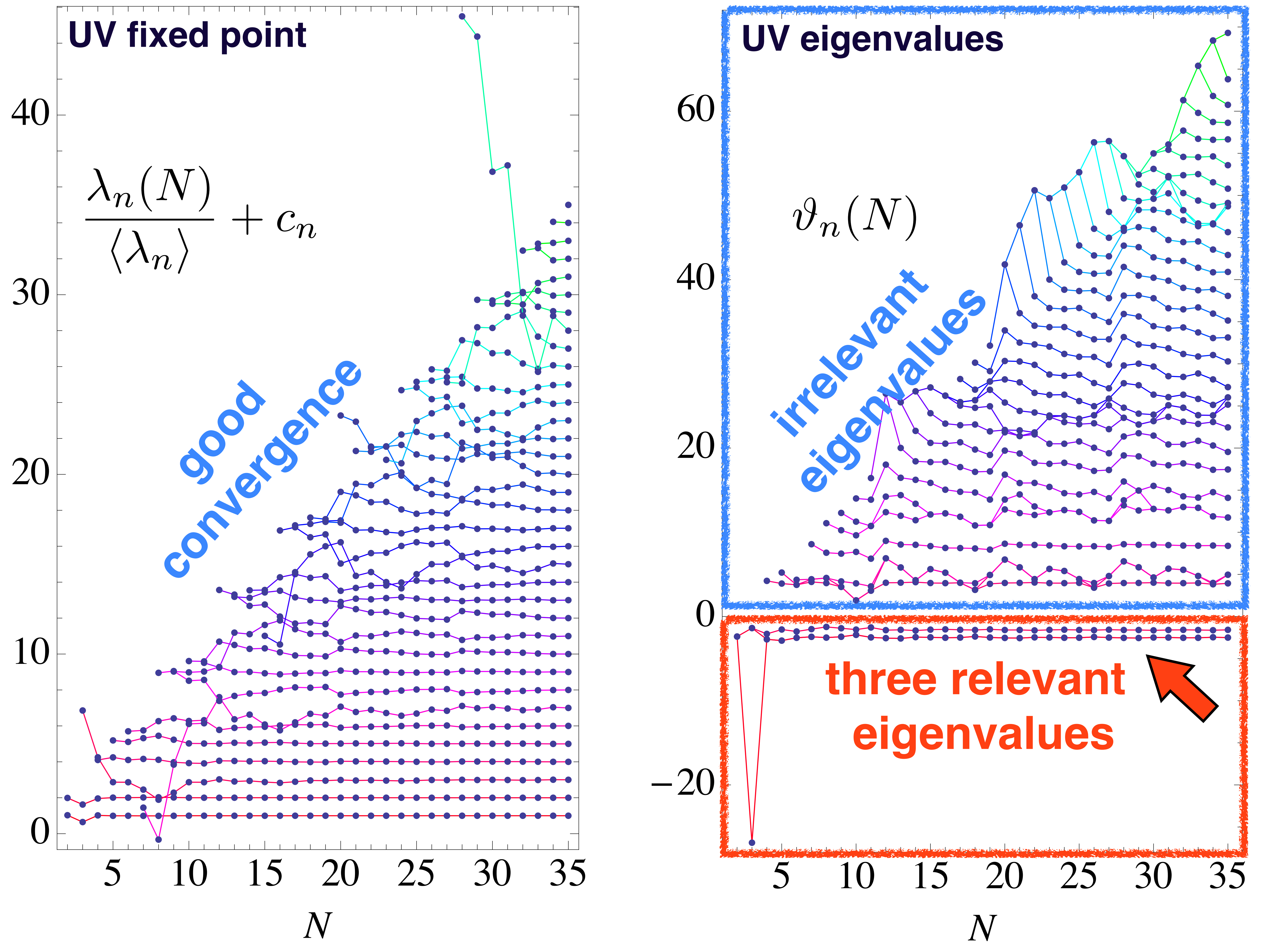

UV fixed point
$$\frac{\lambda_n(N)}{\langle\lambda_n\rangle} + c_n$$
good convergence
N
UV fixed point
zoom-in:
convergence with
8-fold pattern
N

f(R) quantum gravity

UV scaling solution

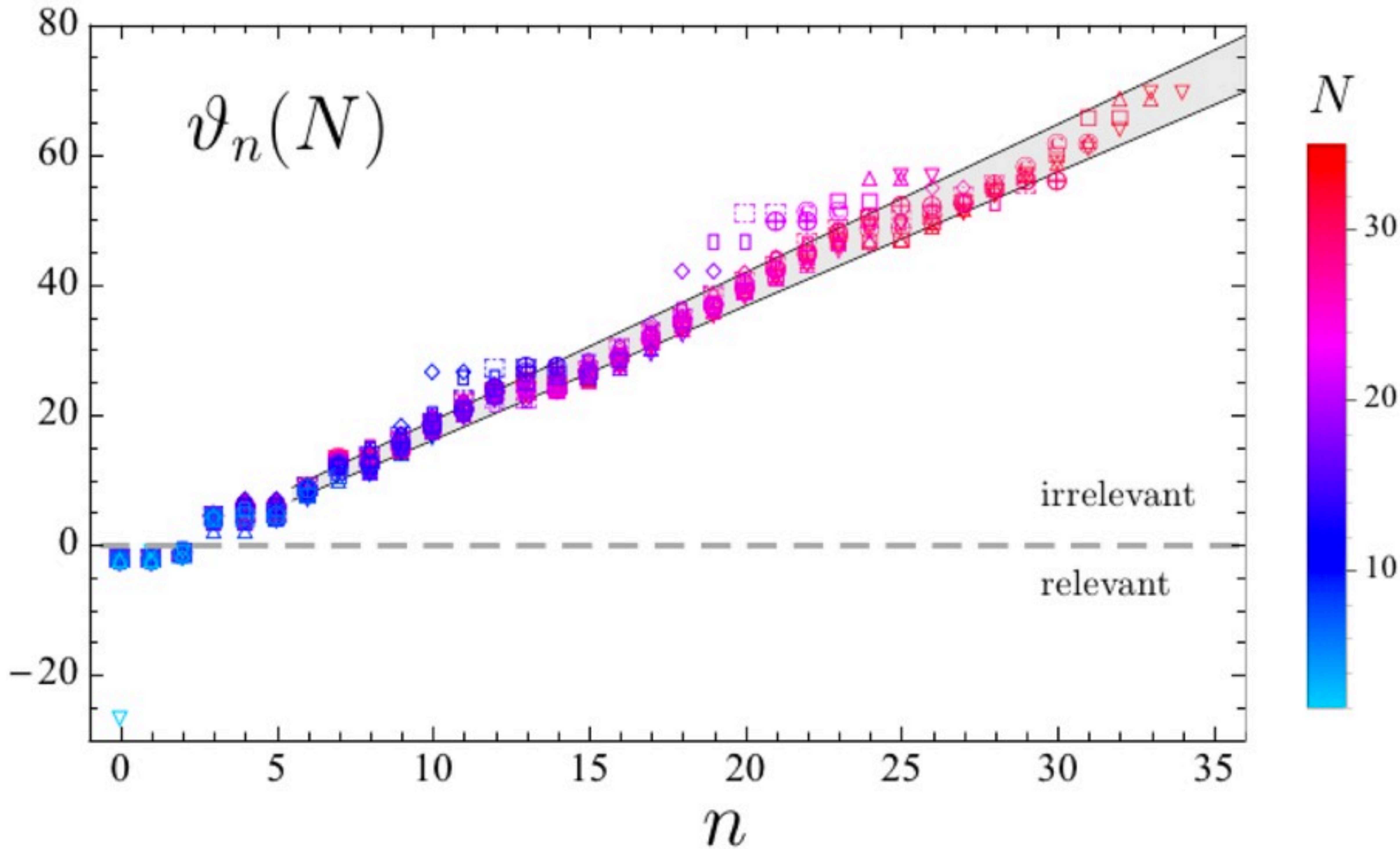


radius of convergence $\rho_c \approx 0.82 \pm 5\%$



UV fixed point
$\frac{\lambda_n(N)}{\langle \lambda_n \rangle} + c_n$
good convergence
UV eigenvalues
$\vartheta_n(N)$
irrelevant eigenvalues
three relevant eigenvalues
N

near-Gaussian



f(Ricci)

$$\Gamma_k \propto \int d^dx\sqrt{g}\,[f_k(R_{\mu\nu}R^{\mu\nu}) + R\cdot z_k(R_{\mu\nu}R^{\mu\nu})]$$

$$\begin{aligned}\partial_t\Gamma[\bar{g},\bar{g}] =& \frac{1}{2}\mathrm{Tr}_{(2T)}\left[\frac{\partial_t\mathcal{R}_k^{h^T h^T}}{\Gamma^{(2)}_{h^T h^T}}\right] + \frac{1}{2}\mathrm{Tr}'_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\xi\xi}}{\Gamma^{(2)}_{\xi\xi}}\right] + \frac{1}{2}\mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\sigma\sigma}}{\Gamma^{(2)}_{\sigma\sigma}}\right] + \frac{1}{2}\mathrm{Tr}_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{hh}}{\Gamma^{(2)}_{hh}}\right]\\ &+ \mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\sigma h}}{\Gamma^{(2)}_{\sigma h}}\right] - \mathrm{Tr}_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\bar{C}^T C^T}}{\Gamma^{(2)}_{\bar{C}^T C^T}}\right] - \mathrm{Tr}_{(0)'}\left[\frac{\partial_t\mathcal{R}_k^{\bar{\eta}\eta}}{\Gamma^{(2)}_{\bar{\eta}\eta}}\right] - \mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\bar{\lambda}\lambda}}{\Gamma^{(2)}_{\bar{\lambda}\lambda}}\right]\\ &+ \frac{1}{2}\mathrm{Tr}''_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\omega\omega}}{\Gamma^{(2)}_{\omega\omega}}\right] - \mathrm{Tr}'_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\bar{c}^T c^T}}{\Gamma^{(2)}_{\bar{c}^T c^T}}\right] + \frac{1}{2}\mathrm{Tr}'_{(1T)}\left[\frac{\partial_t\mathcal{R}_k^{\zeta^T\zeta^T}}{\Gamma^{(2)}_{\zeta^T\zeta^T}}\right] + \mathrm{Tr}'_{(0)}\left[\frac{\partial_t\mathcal{R}_k^{\bar{s}s}}{\Gamma^{(2)}_{\bar{s}s}}\right]\end{aligned}$$

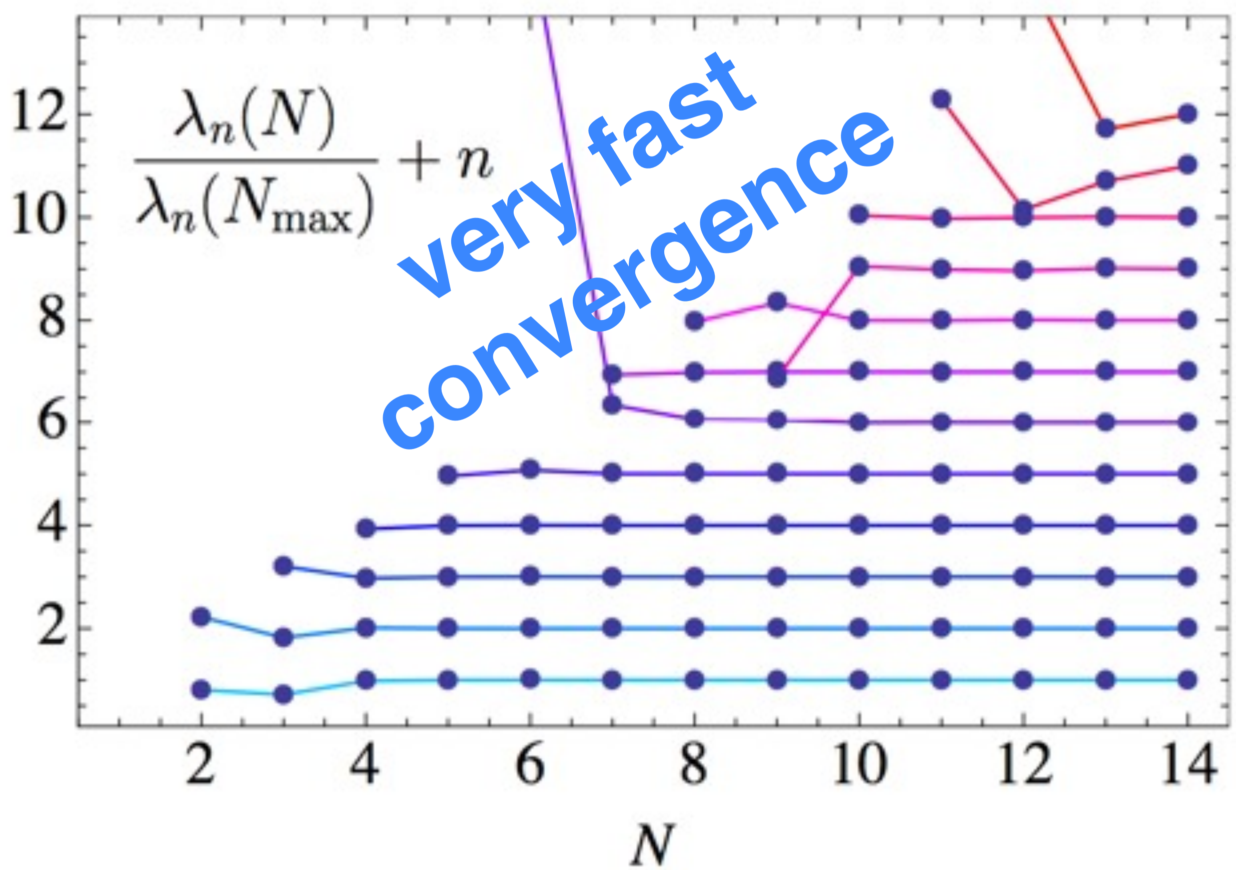
K Falls, DL, K Nikolakopoulos & C Rahmede, (to appear)

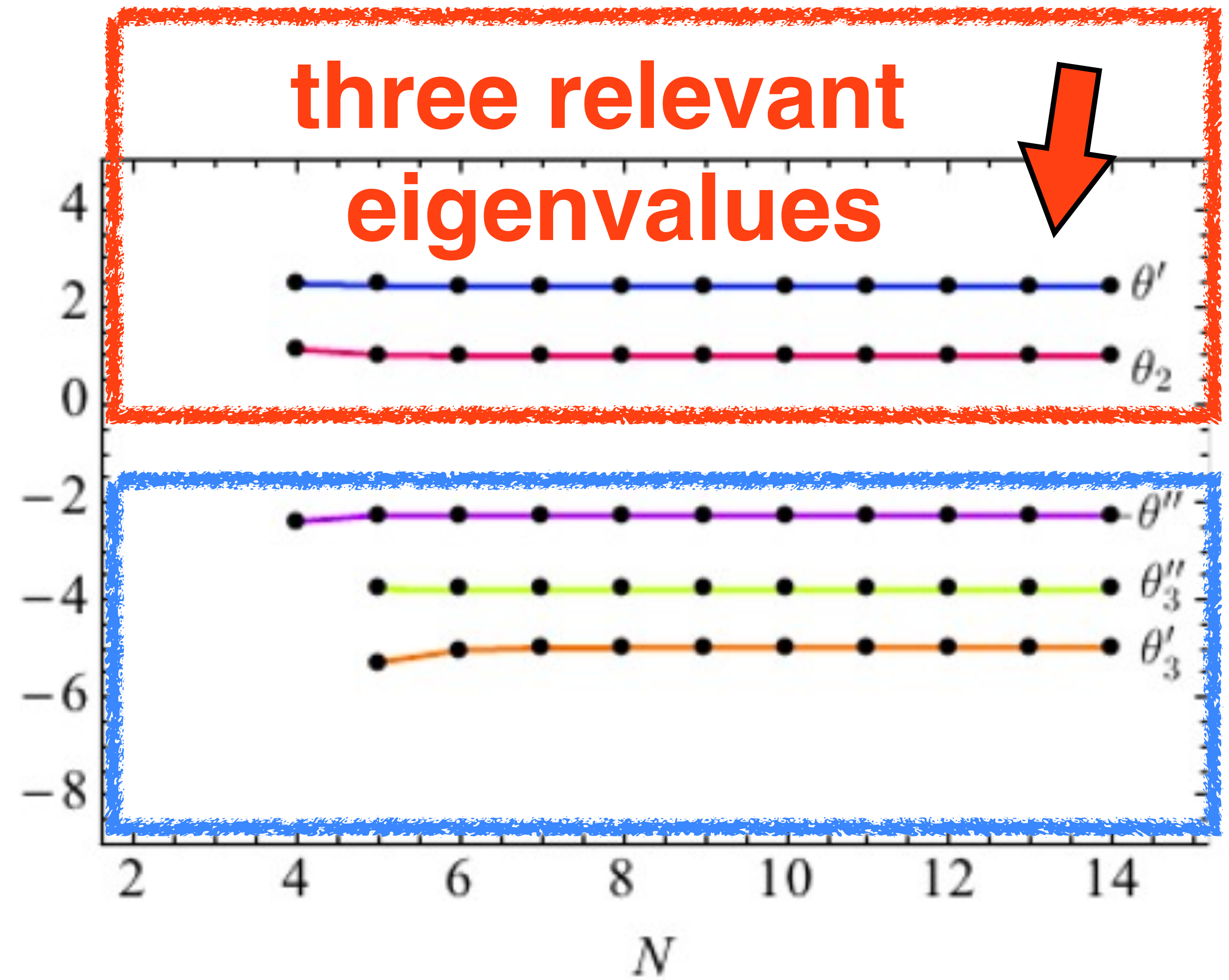
f(Ricci)

K Falls, DL, K Nikolakopoulos & C Rahmede, (to appear)

$$\Gamma_k \propto \int d^dx\sqrt{g}\,[f_k(R_{\mu\nu}R^{\mu\nu}) + R\cdot z_k(R_{\mu\nu}R^{\mu\nu})]$$

fixed point





conclusions

QFTs beyond asymptotic freedom

4D matter-gauge theories

exact **proof of existence**
requires **elementary** scalars, fermions, vectors
no additional (super)symmetry

4D quantum gravity

systematic **non-perturbative** search strategies
strong hints towards interacting UV fixed point
field-dependent **anomalous dimension**

conclusions

what's next?

4D matter-gauge theories

composite operators
UV FP beyond perturbation theory?
realistic models beyond SM?

4D quantum gravity

test further curvature invariants
include matter fields
combined FP for gravity-matter theories?