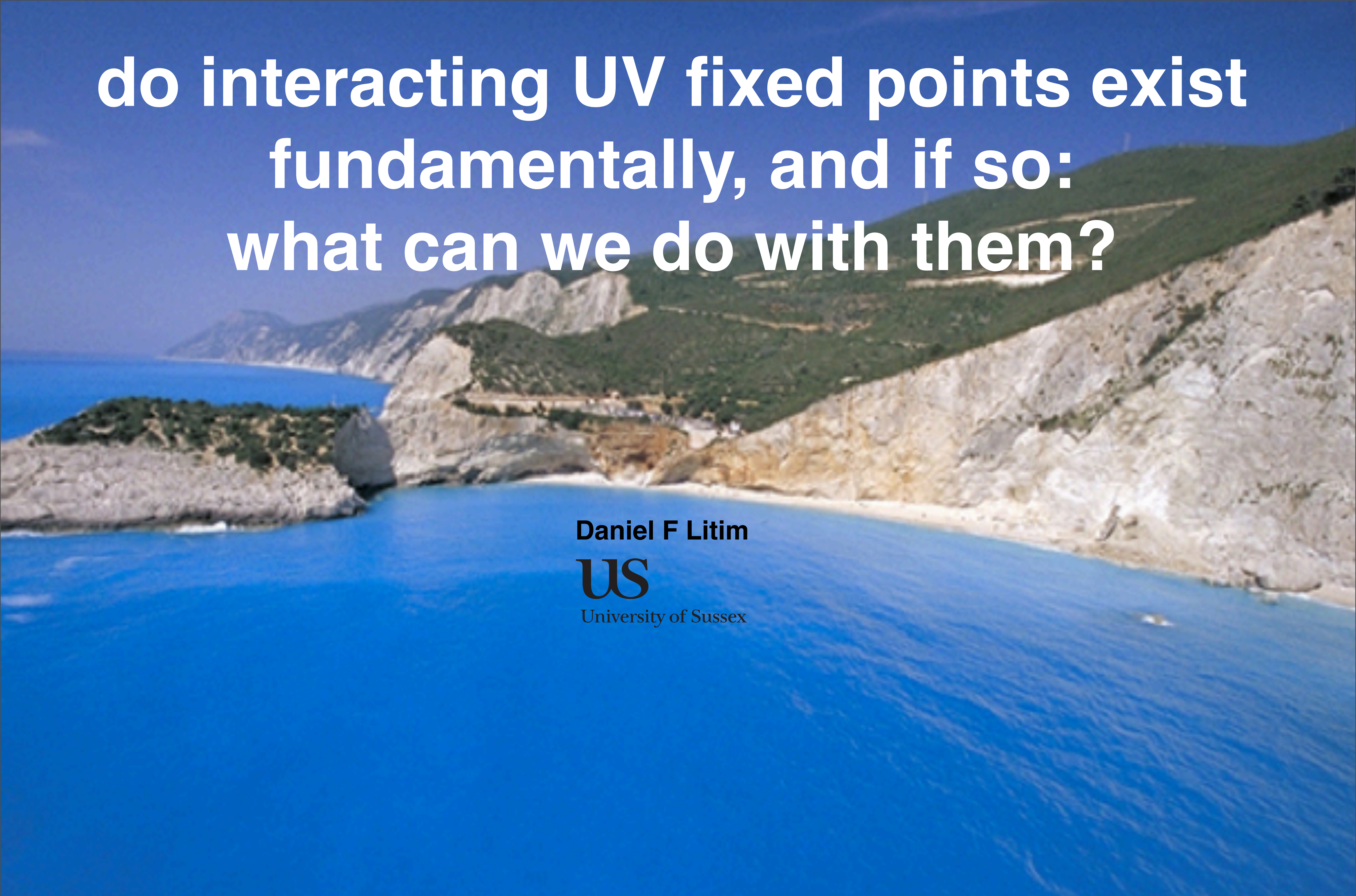


do interacting UV fixed points exist fundamentally, and if so: what can we do with them?

Daniel F Litim

University of Sussex

ERG2014

7th International Conference on the Exact Renormalization Group

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?
how does quantum gravity fit in?
...

interacting UV fixed points

UV fixed points

perturbation theory

theory with coupling α :

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

free fixed point

$$\alpha_* = 0$$

perturbation theory

theory with coupling α:

$t = \ln \mu / \Lambda$

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

$\alpha_* \ll 1$

free fixed point $\alpha_* = 0$

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

predictive up to maximal UV extension

asymptotic freedom

theory with coupling α:

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

free fixed point $\alpha_* = 0$

QCD $B > 0$ UV fixed point

perturbative renormalisability & asymptotic freedom
predictive up to highest energies

fundamental definition of QFT ⟺ UV fixed point

Wilson '71

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:

$t = \ln \mu/\Lambda$

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

$\alpha_* \ll 1$

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

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

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:

$t = \ln \mu/\Lambda$

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

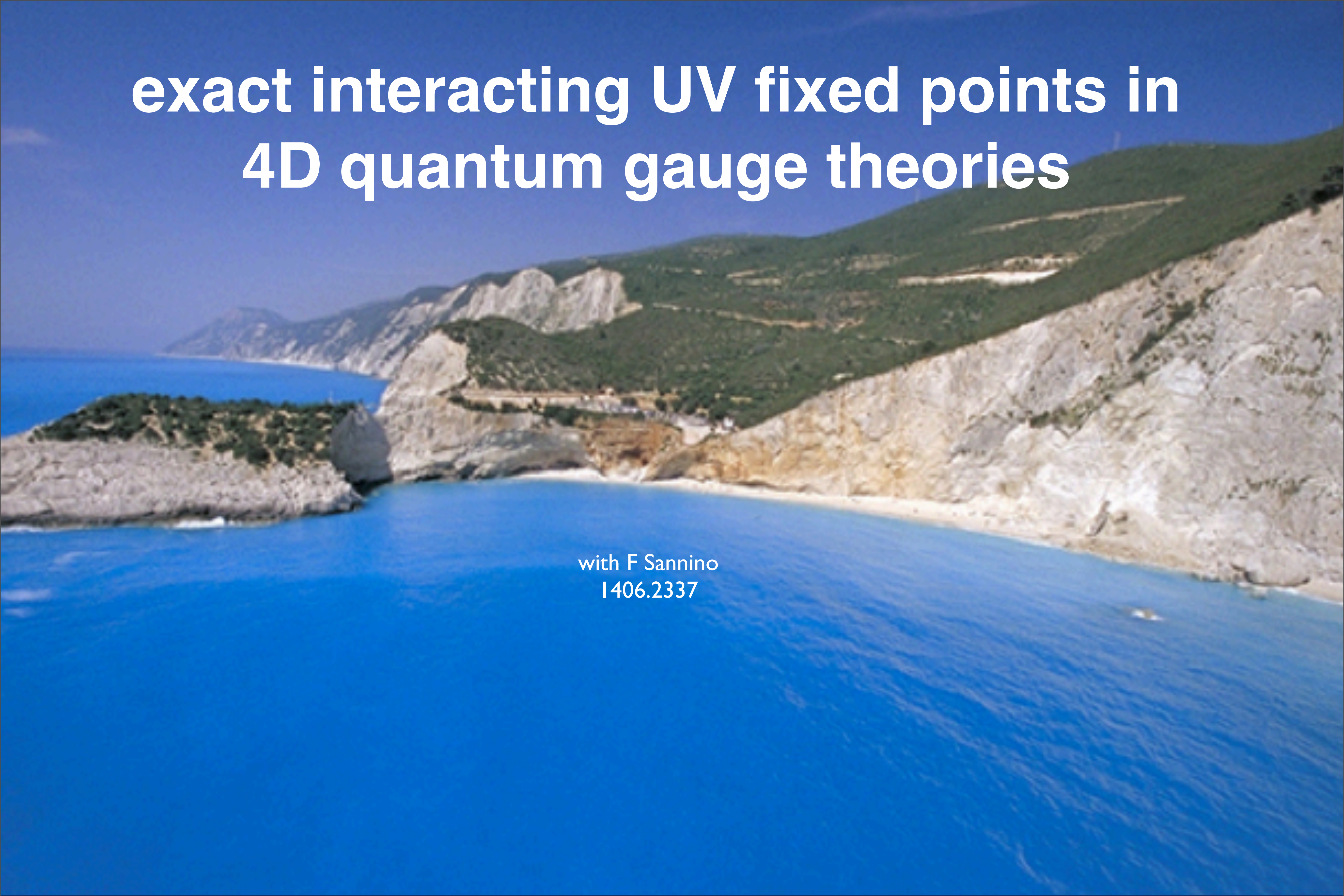
$\alpha_* \ll 1$

gravitons	$D = 2+\epsilon:$	$\alpha = G_N(\mu)\mu^{D-2}$	Gastmans et al '78 Weinberg '79 Kawai et al '90
fermions	$D = 2+\epsilon:$	$\alpha = g_{\rm GN}(\mu)\mu^{2-D}$	Gawedzki, Kupiainen '85 de Calan et al '91
gluons	$D = 4+\epsilon:$	$\alpha = g^2_{\rm YM}(\mu)\mu^{4-D}$	Peskin '80 Morris '04

non-perturbative renormalisability

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

exact interacting UV fixed points in 4D quantum gauge theories



with F Sannino
1406.2337

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

large-NF,NC (Veneziano) limit:

ϵ continuous

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

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

interacting fixed points:

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

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

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

here: $B = -\dfrac{4\epsilon}{3} < 0 \;\; \& \;\; C > 0$ **no physical fixed point**

gauge theory with fermions

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

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

$\alpha_* \ll 1$

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

→ **scalar fields & Yukawa couplings required**

gauge-Yukawa theory

Lagrangean

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

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

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

gauge-Yukawa theory

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

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

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

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

gauge-Yukawa theory

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

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

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

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

results

NLO NNLO NNNLO

UV fixed point

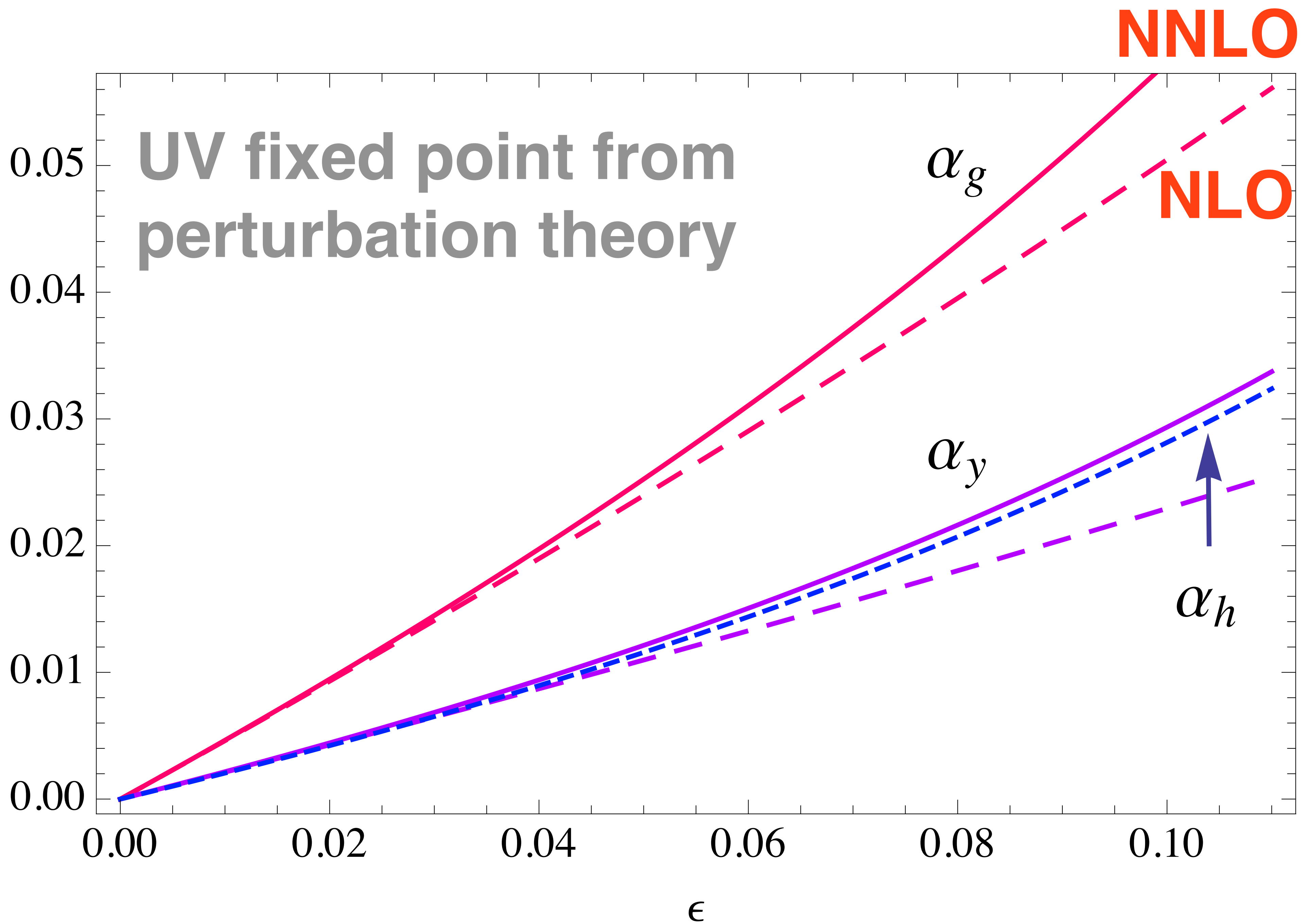
$$\alpha_g^* = 0.4561\,\epsilon + 0.7808\,\epsilon^2 + \mathcal{O}(\epsilon^3)$$
$$\alpha_y^* = 0.2105\,\epsilon + 0.5082\,\epsilon^2 + \mathcal{O}(\epsilon^3)$$
$$\alpha_h^* = 0.1998\,\epsilon + 0.5042\,\epsilon^2 + \mathcal{O}(\epsilon^3)\,.$$

vacuum stability

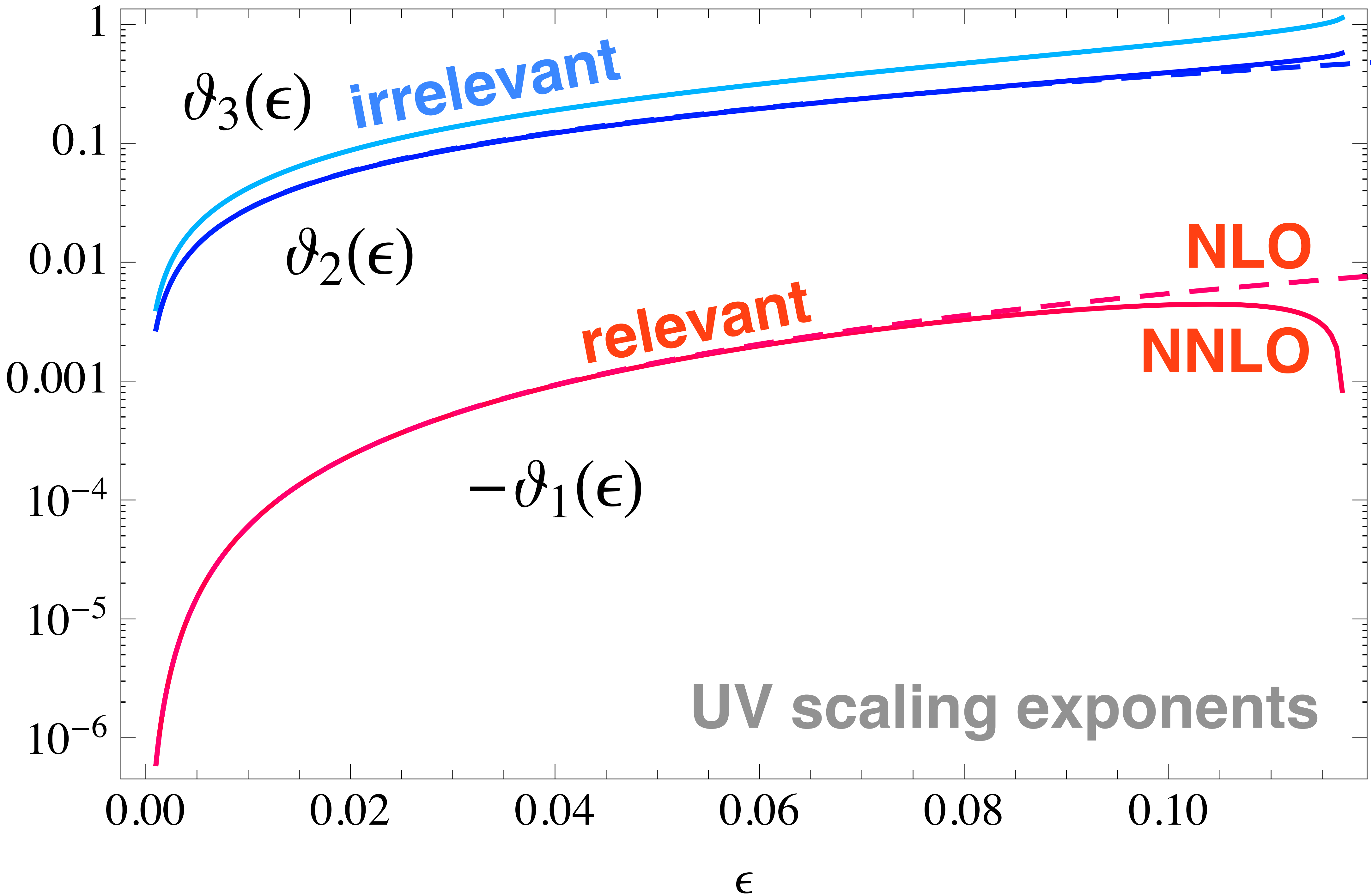
$$\alpha_h^* + \alpha_{v2}^* < 0 < \alpha_h^* + \alpha_{v1}^*$$

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

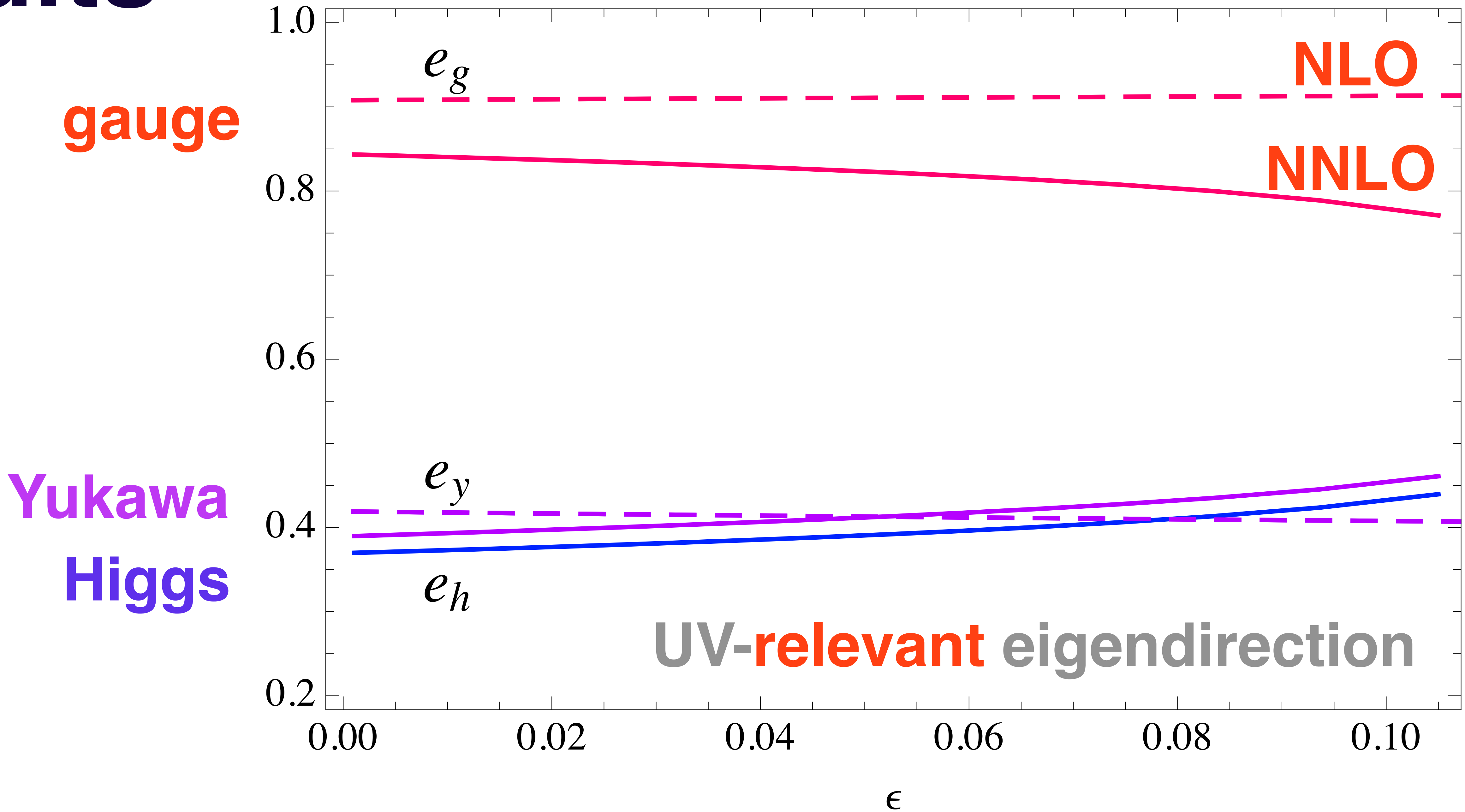
results


NNLO
NLO
UV fixed point from
perturbation theory
α_g
α_y
α_h
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.02
0.04
0.06
0.08
0.10
ϵ

results

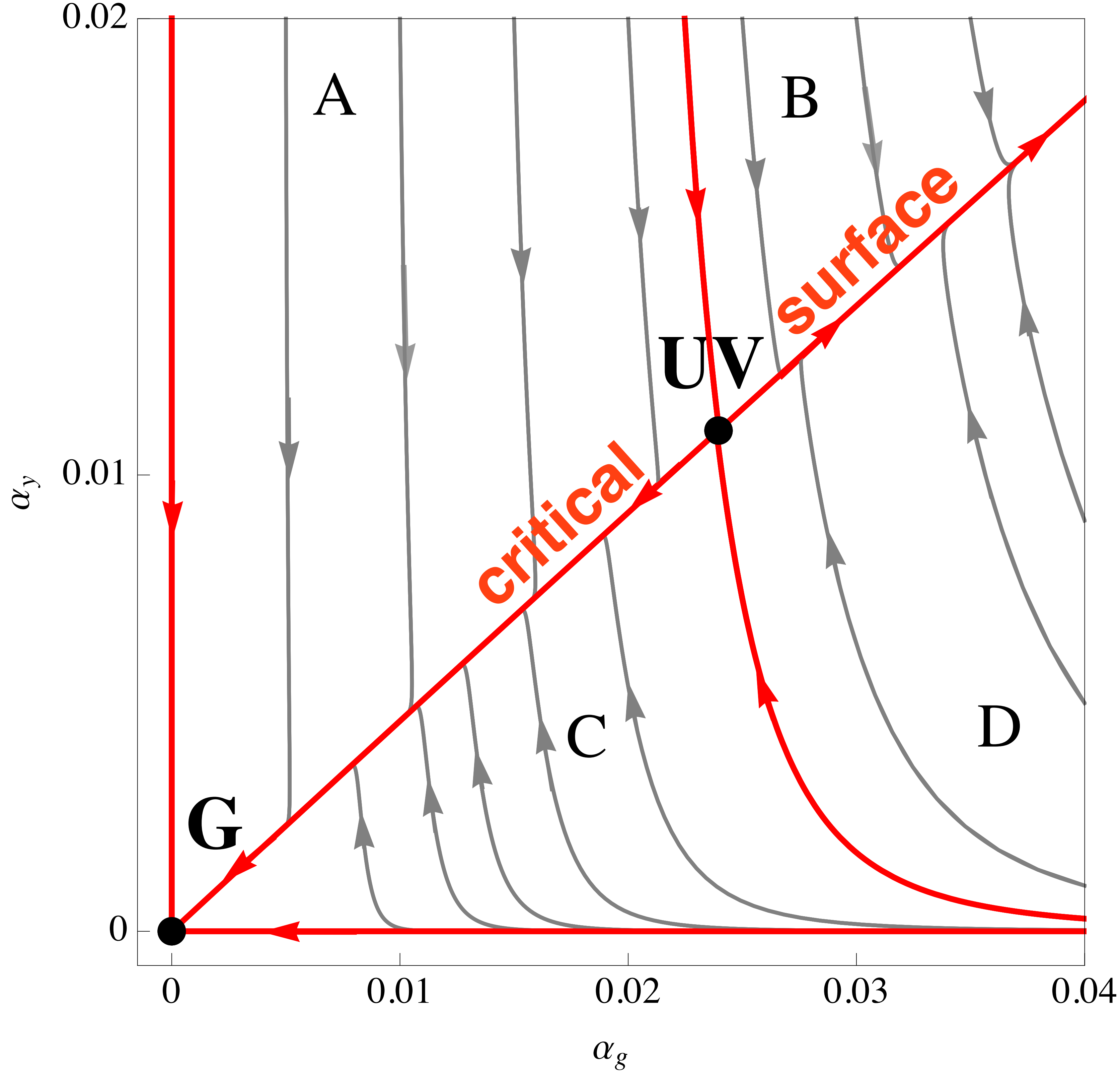

1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
$\vartheta_3(\epsilon)$
irrelevant
$\vartheta_2(\epsilon)$
NLO
relevant
NNLO
$-\vartheta_1(\epsilon)$
UV scaling exponents
0.00
0.02
0.04
0.06
0.08
0.10
ϵ

results

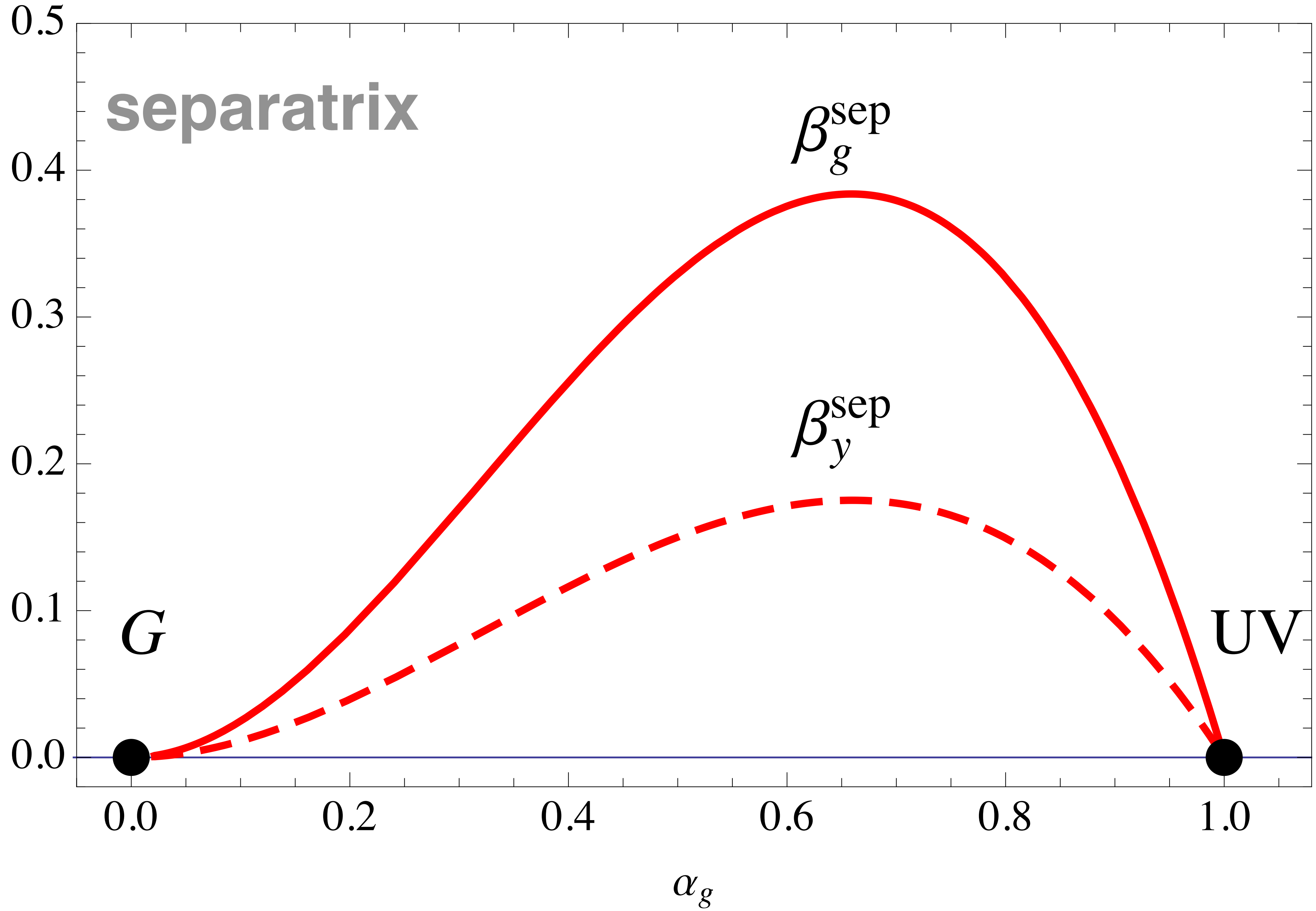

gauge
Yukawa
Higgs
e_g
e_y
e_h
NLO
NNLO
UV-relevant eigendirection
1.0
0.8
0.6
0.4
0.2
0.00
0.02
0.04
0.06
0.08
0.10
ϵ

results

phase diagram



results



separatrix
β_g^{sep}
β_y^{sep}
G
UV
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0
α_g

results

asymptotic safety at small epsilon

unitarity

non-triviality and elementary scalars

asymptotic safety at large epsilon

what can we do with it?

interacting UV fixed points in 4D

cooperation decisive

generic, largely independent of gauge group, representation & gauge charges

exploit ideas from AdS/CFT & holography

Seiberg duality - without supersymmetry?

what can we do with it?

interacting UV fixed points in 4D

UV-complete extensions of the Standard Model

applicable for finite N e.g. (NC,NF) = (5,28)

new handle on
(i) hierarchy problem
(ii) (non-)triviality of scalar sector in 4D
scalars elementary

what can we do with it?

interacting UV fixed points in 4D

UV-complete extensions of the Standard Model

helps with canonical quantisation of gravity

conformal matter + conformal mode ('t Hooft)

asymptotically safe gravity with matter

UV fixed points in 4D quantum gravity

with K Falls, DL, K Nikolakopoulos & C Rahmede
1301.4191 and forthcoming

evidence for UV fixed point

overviews: 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, Eichhorn et al ’13)

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)

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 ?

K Falls, DL, K Nikolakopoulos & C Rahmede, 1301.4191

bootstrap

hypothesis ordering 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)

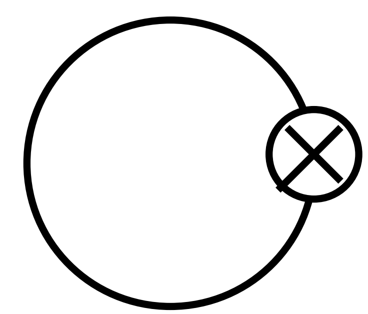
$$\Gamma_k \propto f(R)$$

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

invariants up to $D = 2(N-1)$

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**

A Codello, R Percacci, C Rahmede 0705.1769, 0805.2909

P Machado, F Saueressig 0712.0445

f(R)

recursive solution

$$\lambda_n(\lambda_0, \lambda_1) = \frac{P_n(\lambda_0, \lambda_1)}{Q_n(\lambda_0, \lambda_1)}$$

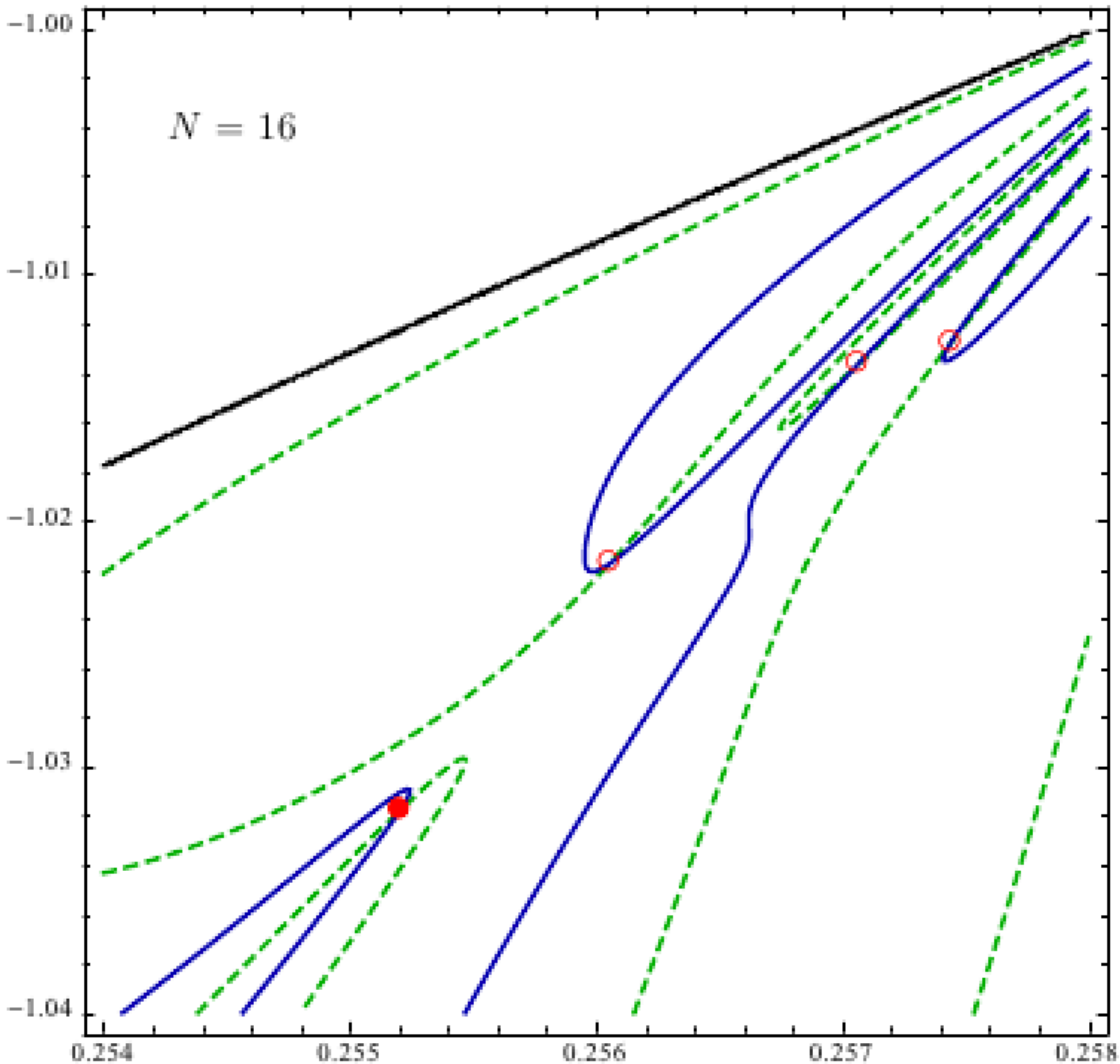
boundary condition

$$\lambda_N = 0 \quad \& \quad \lambda_{N+1} = 0$$

polynomials grow large, eg.

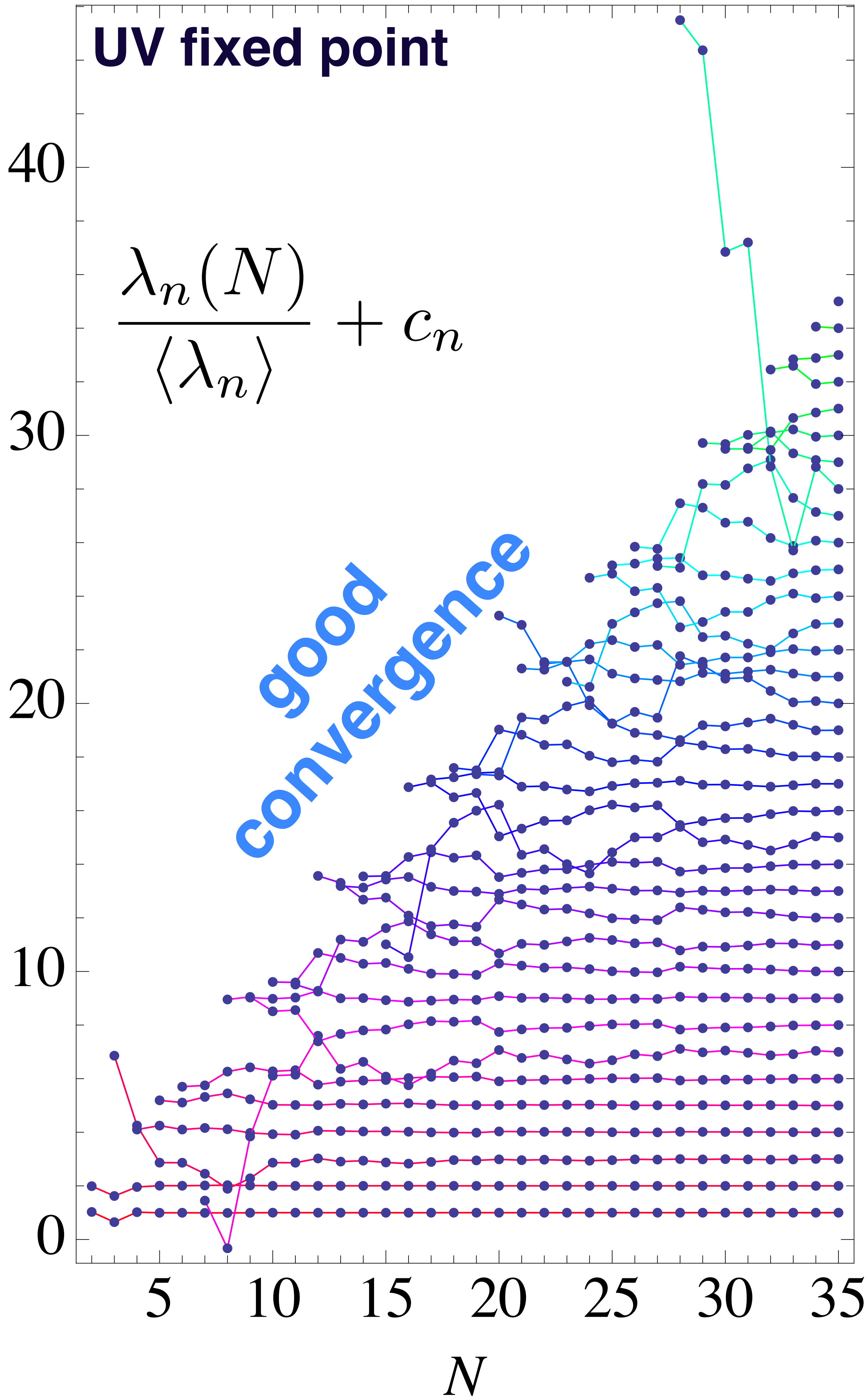
$P_{35} \approx 45.000$ terms

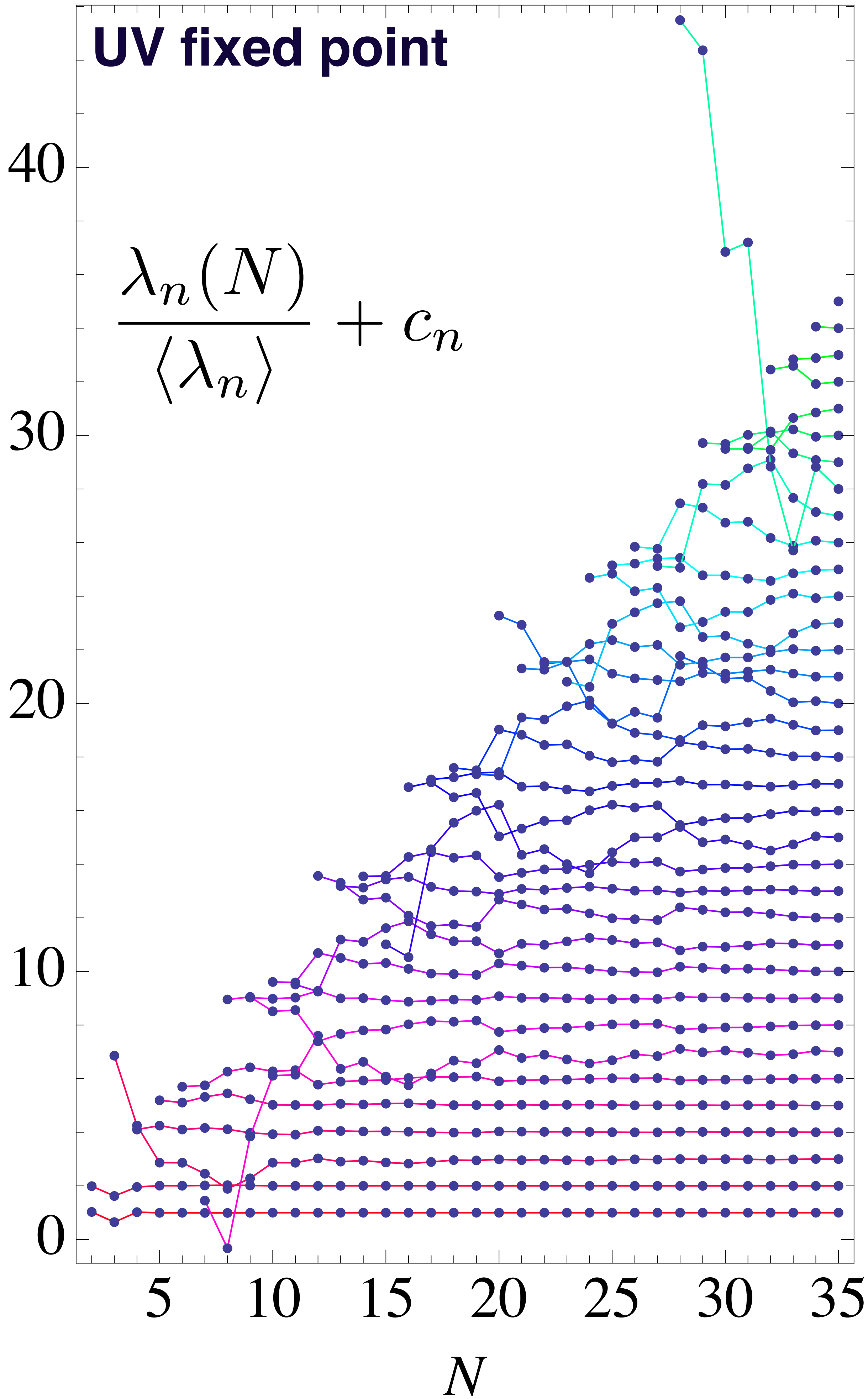
f(R)

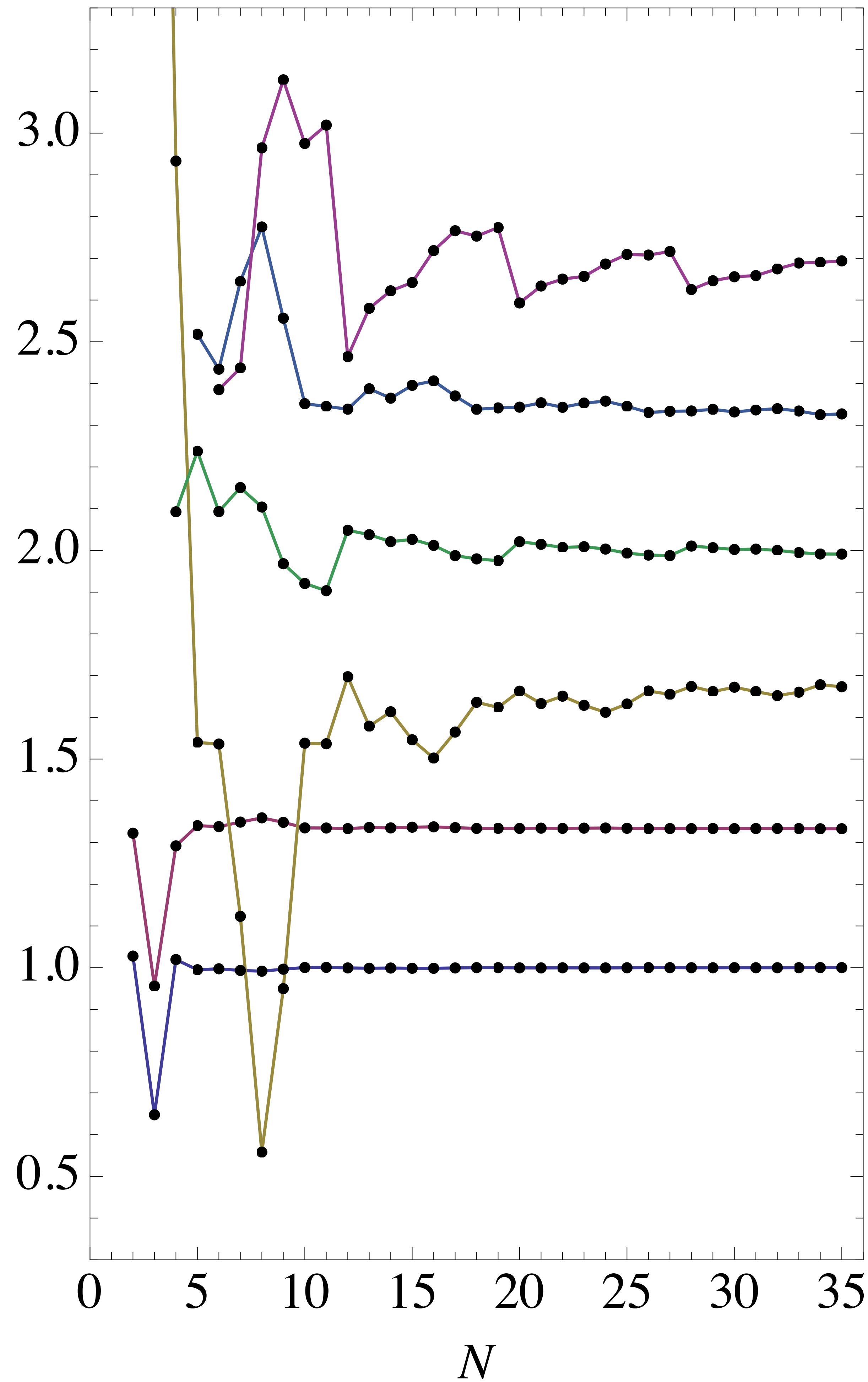


boundary condition

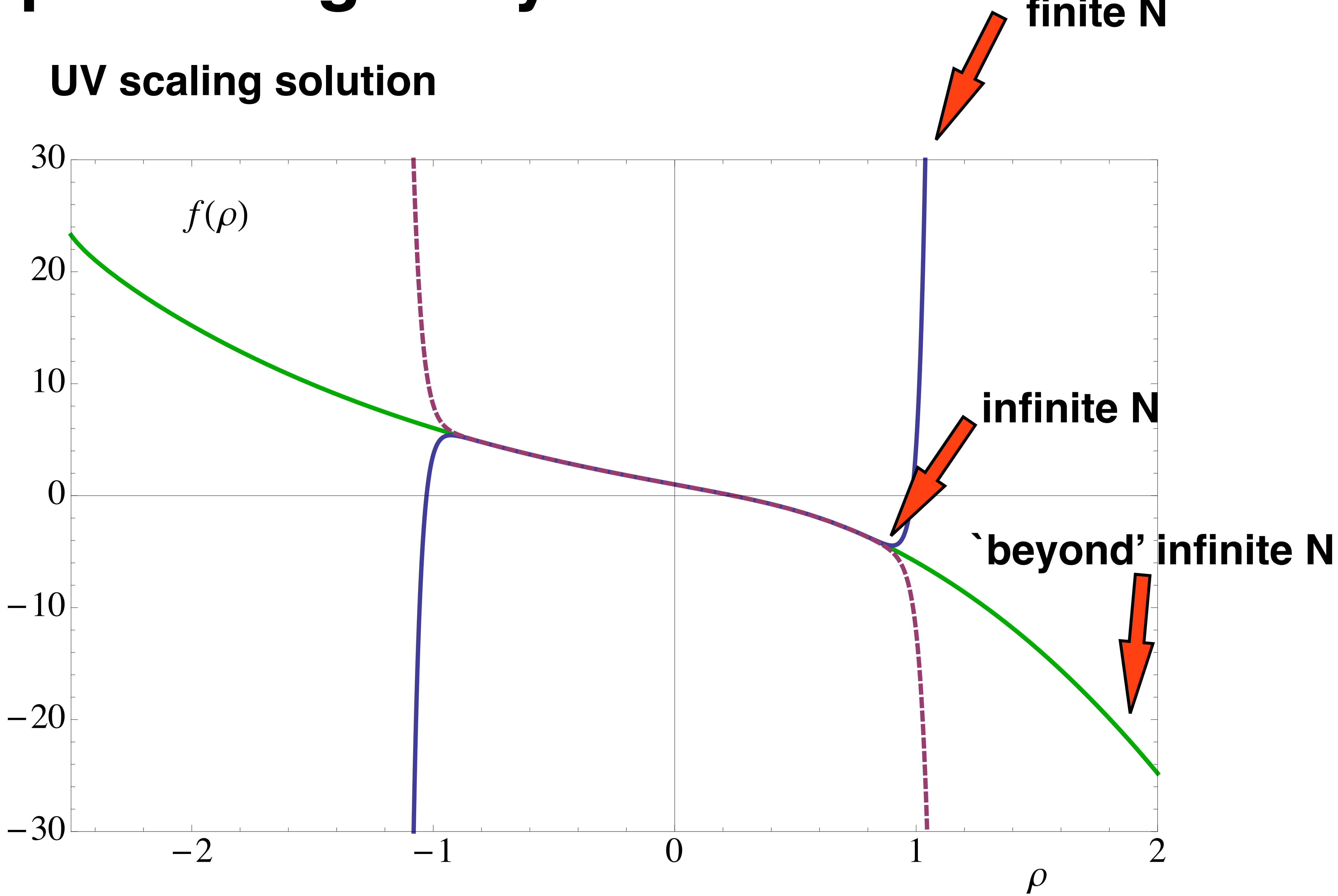
$$\lambda_N = 0$$
$$\lambda_{N+1} = 0$$


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

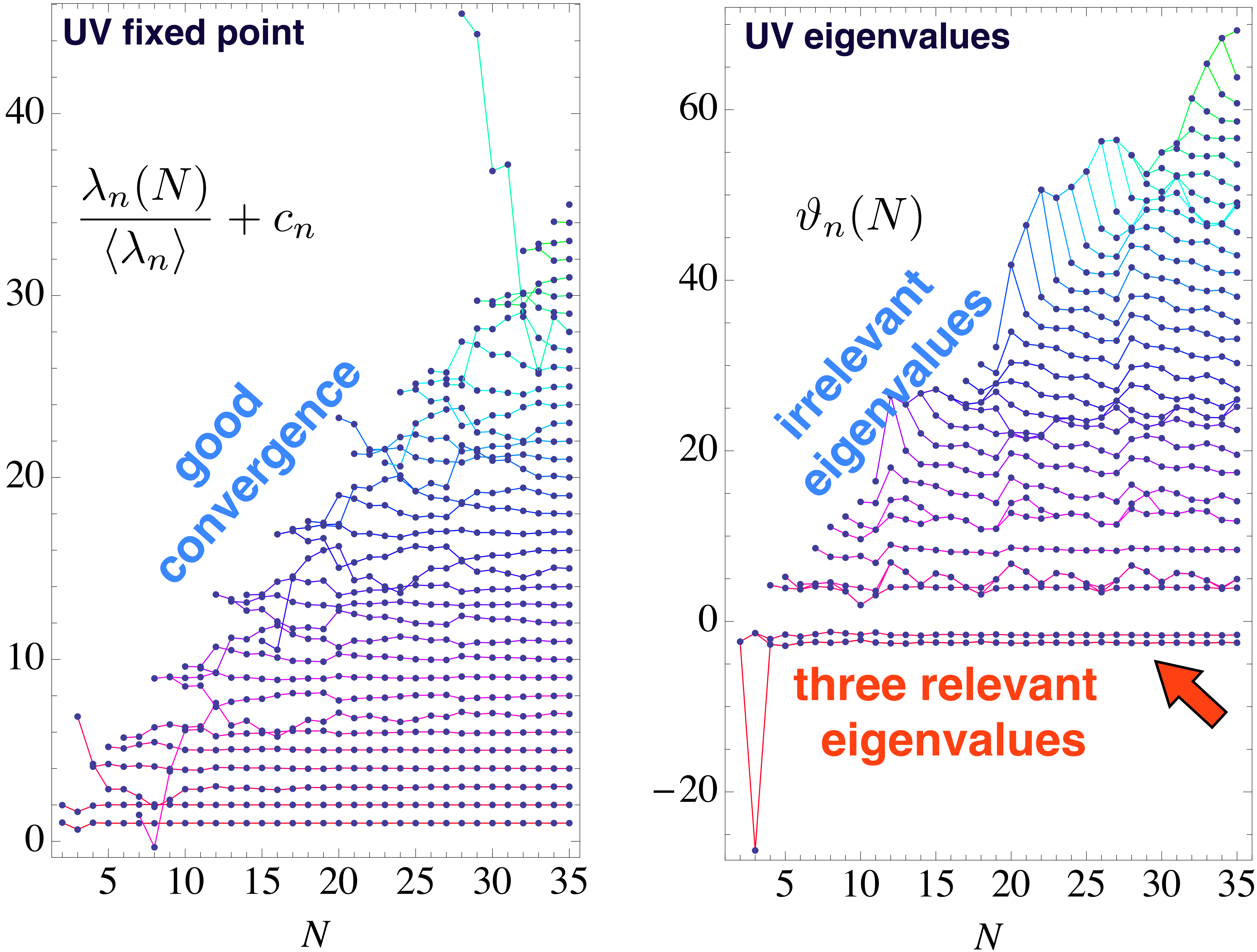

UV fixed point
$$\frac{\lambda_n(N)}{\langle\lambda_n\rangle} + c_n$$
40
30
20
10
0
5
10
15
20
25
30
35
N


3.0
2.5
2.0
1.5
1.0
0.5
0
5
10
15
20
25
30
35
N

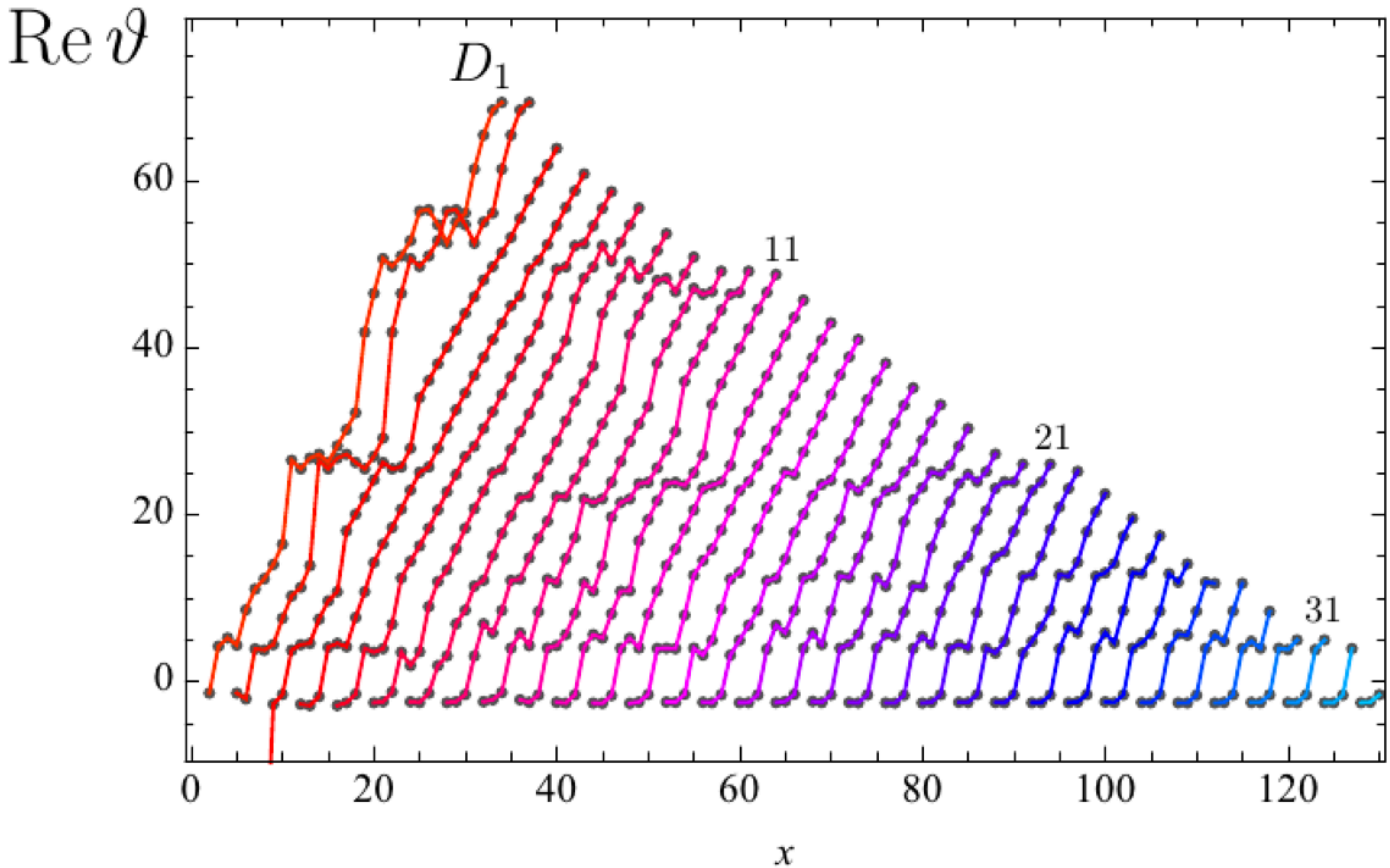
f(R) quantum gravity



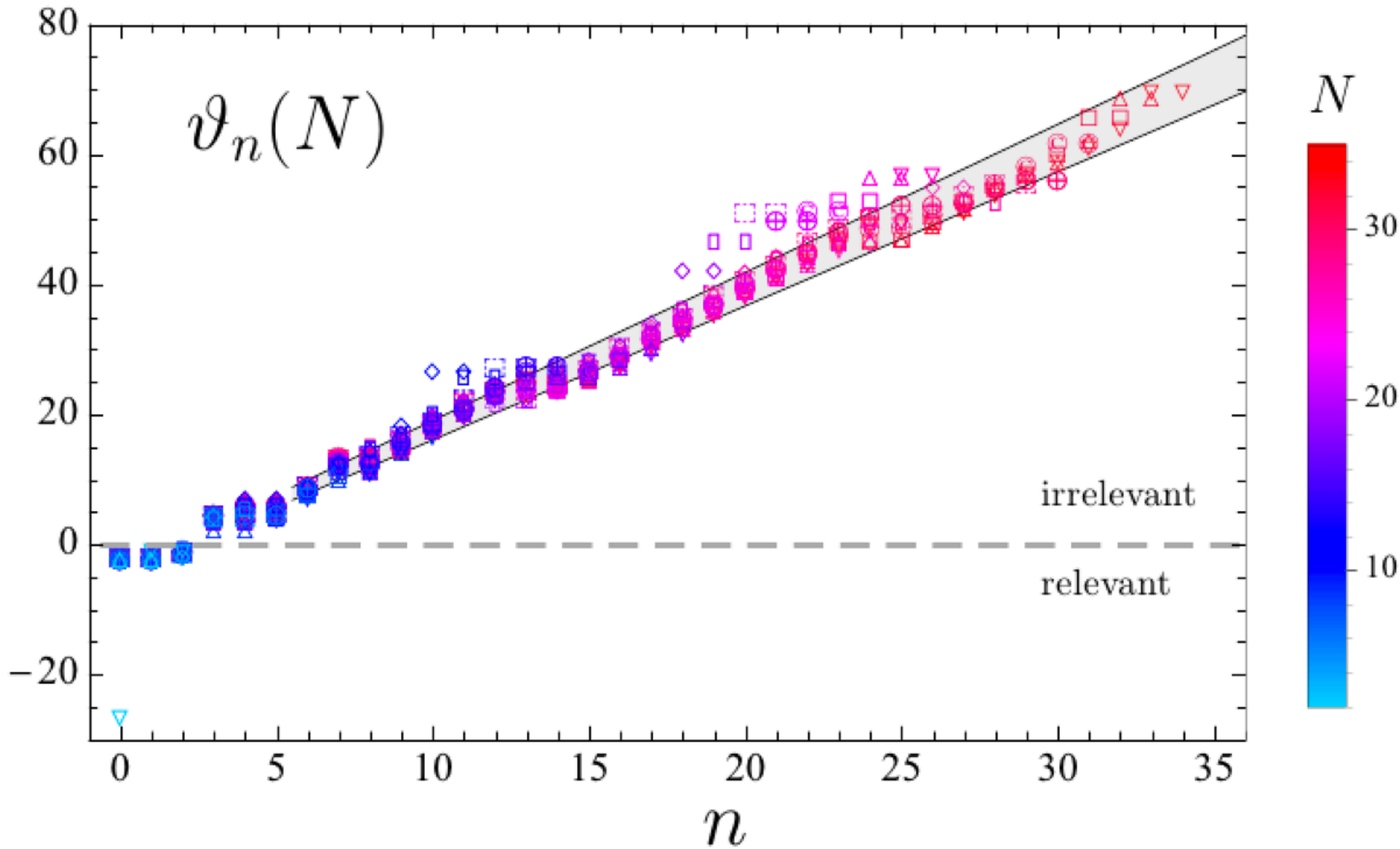
radius of convergence $\rho_c \approx 0.82 \pm 5\%$


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

bootstrap test



near-Gaussian



f(Ricci)

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

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

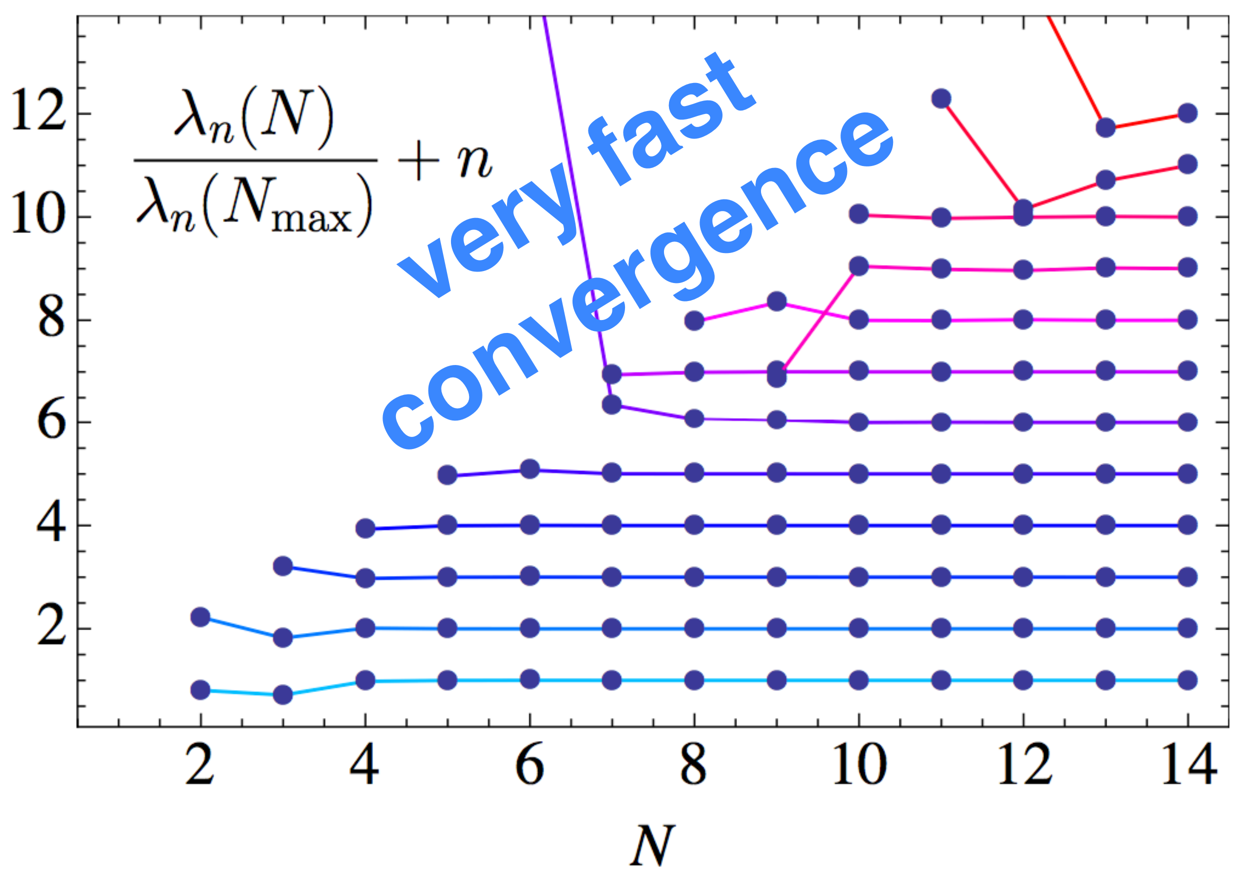
K Falls, DL, K Nikolakopoulos & C Rahmede, (to appear)

f(Ricci)

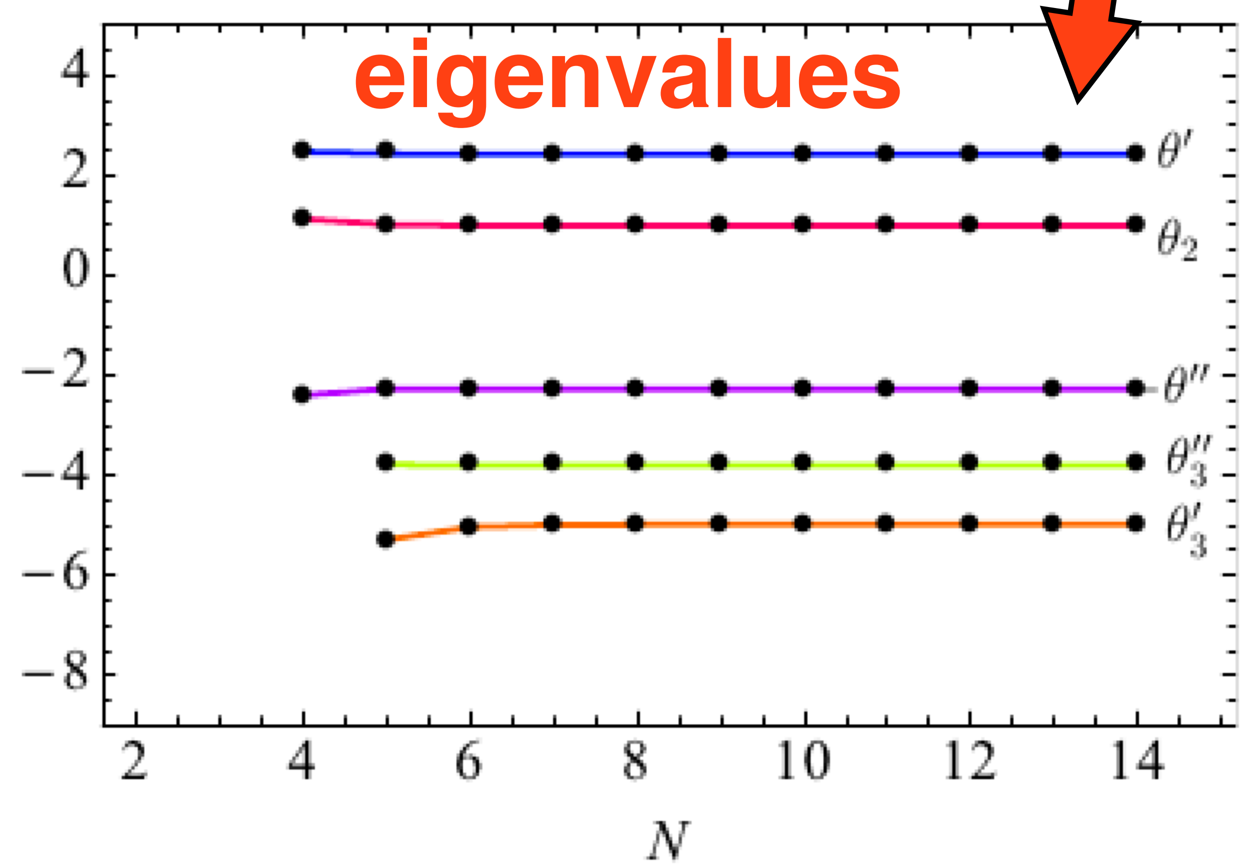
K Falls, DL, K Nikolakopoulos & C Rahmede, (to appear)

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

fixed point

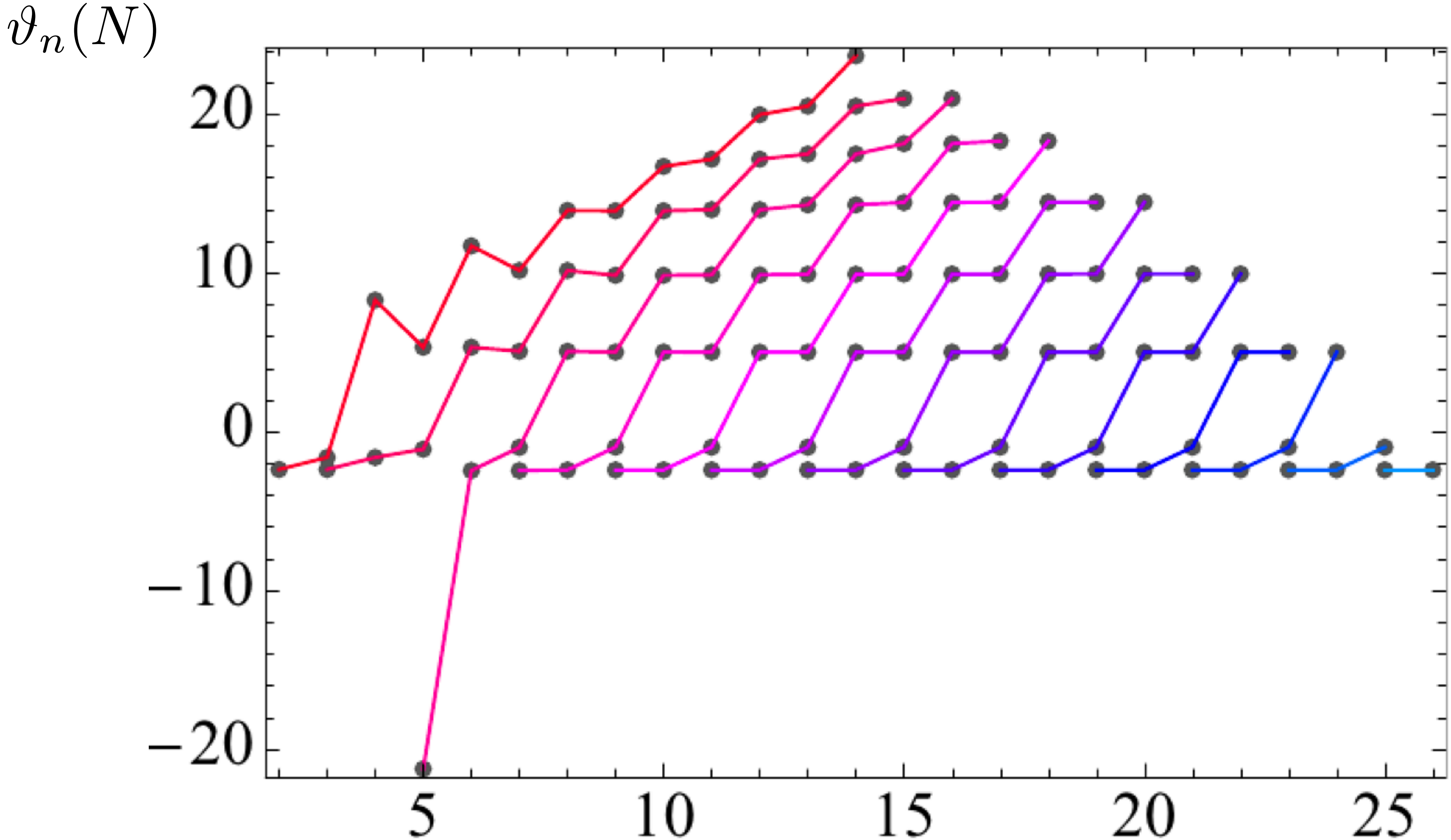


three relevant eigenvalues



bootstrap test

K Falls, DL, K Nikolakopoulos, C Rahmede (to appear, 2014)



UV fixed points and black hole thermodynamics

with K Falls, K Nikolakopoulos & A Raghuraman

1002.0260 (IJMPA)

1212.1821 (PRD)

1308.5630 (JHEP)

black hole thermodynamics

entropy = horizon area

temperature = surface gravity

Bekenstein '73
Bardeen, Carter, Hawking '73
Gibbons, Hawking '77
...
Jacobson '95
...

black hole thermodynamics

input:
saddle point of effective action

Gibbons, Hawking '77

$$S \approx \int d^4x \sqrt{-\det g_{\mu\nu}} \left[\frac{1}{8\pi G_0} R + \frac{1}{4\alpha_0} F^{\mu\nu} F_{\mu\nu} \right] + S_m$$

central building block

IR limit

$$G_0 \approx 6.674 \times 10^{-11} \ \mathrm{N}\,(\mathrm{m}/\mathrm{kg})^2$$

$$\alpha_0 \approx 1/137$$

renormalisation group

new input:
scale-dependent effective action

Falls & DL, 1212.8121 (PRD)

$$\Gamma_k \approx \int d^4x \sqrt{-\det g_{\mu\nu}} \left[\frac{1}{8\pi G_k} R + \frac{1}{4\alpha_k} F^{\mu\nu} F_{\mu\nu} \right] + S_m$$

running couplings

family of Kerr-Newman BH solutions

$$A = A(M, J, q; k) \qquad S = \frac{A}{4G_k}$$

choice of RG scale

determined by physical parameters of the BH: $k = k_{\rm opt}(M, J, q)$

renormalisation group

Bekenstein's thought experiment
infinitesimal amount of matter crossing the horizon, with heat flow

$$\frac{\delta Q}{T} = \frac{\delta A}{4G_k}$$

BH settles in a new state

$$M \to M + \delta M \quad J \to J + \delta J$$
$$q \to q + \delta q \quad k_{\rm opt} \to k_{\rm opt} + \delta k_{\rm opt}$$

total change of horizon area

$$\left(1 - \frac{2\pi}{\kappa} T\right) \delta A = \left.\frac{\partial A(M, J, q; k)}{\partial \ln k}\right|_{k=k_{\rm opt}} \frac{\delta k_{\rm opt}}{k_{\rm opt}}$$

Falls & DL, 1212.8121 (PRD)

renormalisation group

results

RG scale
$$k^2_{\rm opt}(M,J,q) \equiv k^2_{\rm opt}(A) = \frac{4\pi\xi^2}{A}$$

state function
$$M^2 \equiv \frac{4\pi}{A}\left[\left(\frac{A+4\pi G(A)e^2(A)q^2}{8\pi G(A)}\right)^2 + J^2\right]$$

temperature
$$T = 4G(A)\,\frac{\partial M}{\partial A}$$

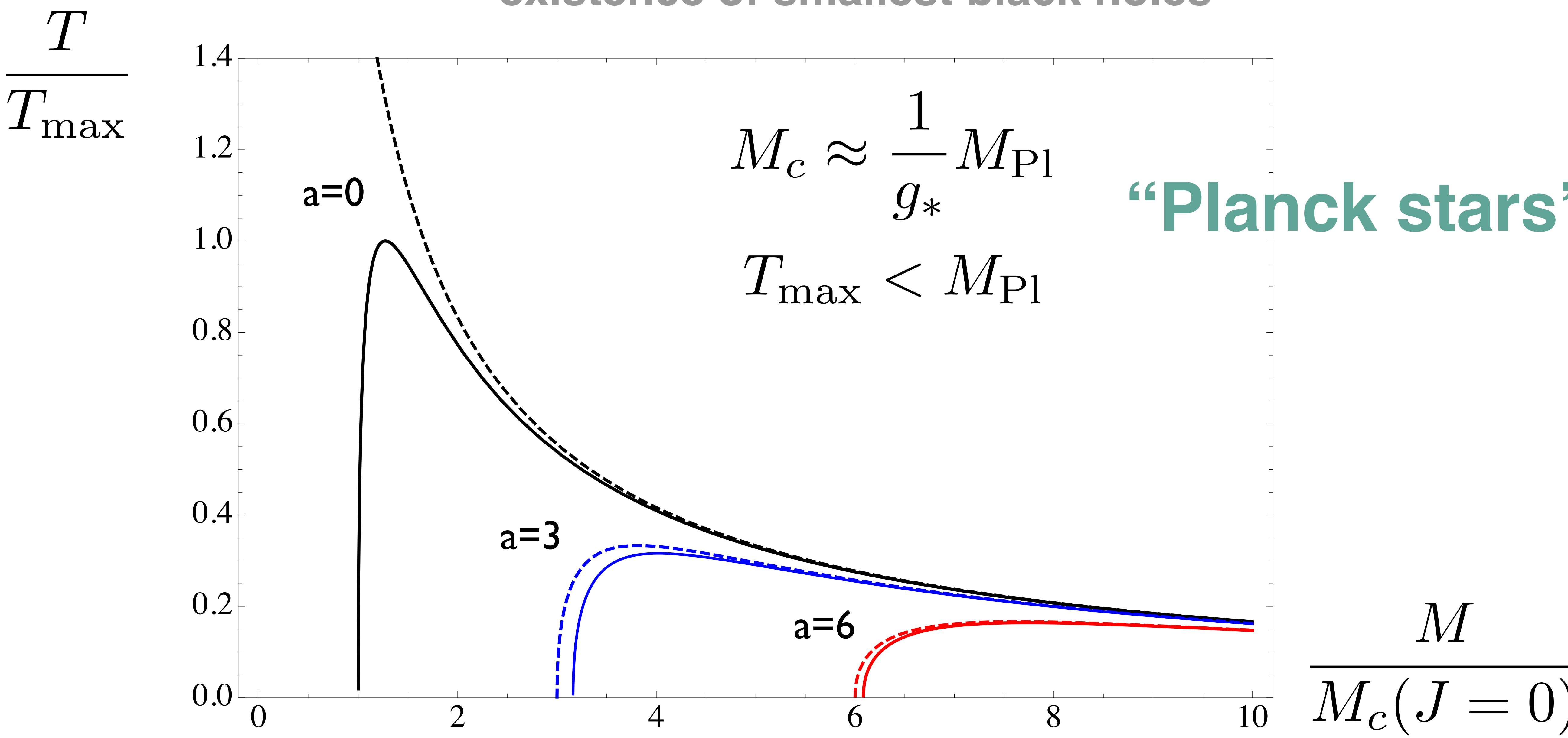
entropy
$$S = \frac{A}{4G_k}$$
with
$$k = k_{\rm opt}$$

Falls & DL, 1212.8121 (PRD)

asymptotic safety

prediction I: temperature & mass

finite maximum temperature
existence of smallest black holes



“Planck stars”

Falls & DL, 1212.8121 (PRD)

conformal scaling

Aharony, Banks '98, Shomer '07

conformal scaling in QFT

$$S \sim (RT)^{d-1}, \qquad E \sim R^{d-1} T^d$$

$$S \sim E^{\nu} \quad \Rightarrow \quad \nu_{\text{CFT}} = \frac{d-1}{d}$$

Schwarzschild BH scaling

$$S \sim R^{d-2}/G_N \qquad E \sim R^{d-3}/G_N$$

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except for $d = \frac{3}{2}$

conformal scaling

Falls, Litim '12

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conformal scaling

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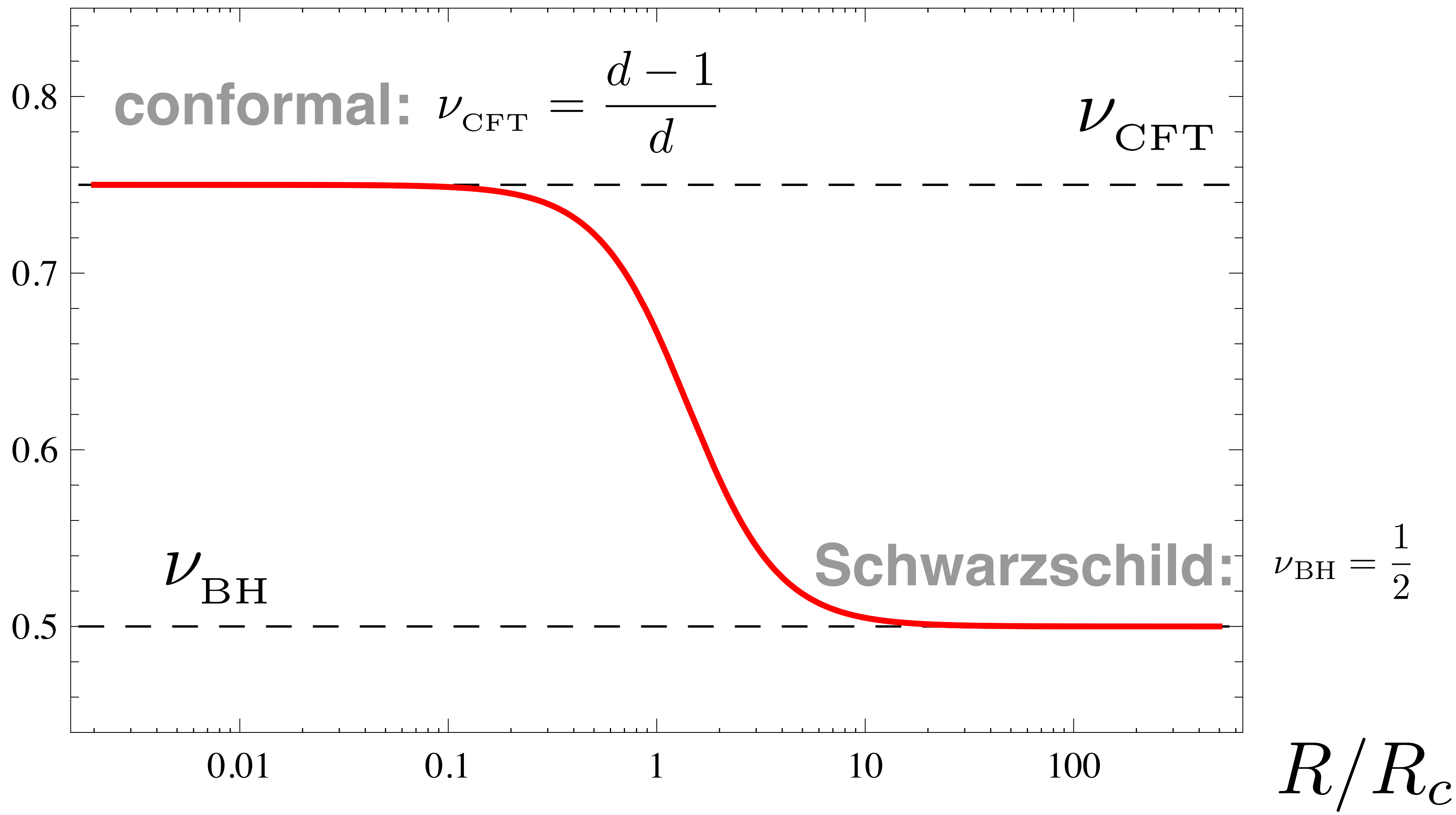
$$\nu_{\rm BH} \neq \nu_{\rm CFT}$$

except for $d = 2$

asymptotic safety

prediction II: conformal scaling from AS black holes



Falls & DL, 1212.8121 (PRD)

asymptotic safety

prediction III: entropy

thermodynamical entropy

$$S = \frac{A}{4G(A)} = \frac{A}{4G_N} + \frac{\pi}{g_*}$$

Clausius' entropy

$$S = \int \frac{dA}{4G(A)} = \frac{A}{4G_N} + \frac{\pi}{g_*}\left(1 + \ln\frac{A}{A_c}\right)$$

statistical entropy

$$F = M - S\,T$$

valid for all RG scales

[using "off-shell" conical singularity method] (Soludkhin '96)

Falls & DL, 1212.8121 (PRD)

conclusions

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      - **black hole thermodynamics:** conformal scaling, entropy