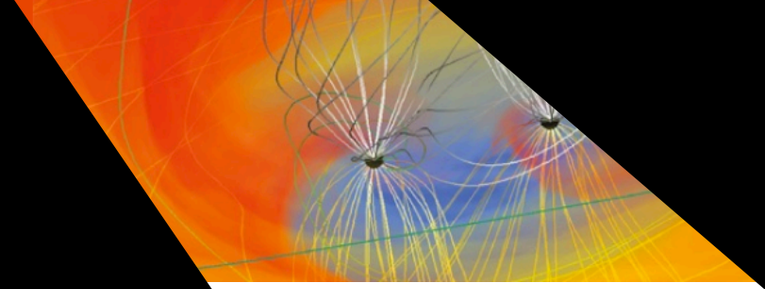

asymptoti
in the spoti

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University of Sussex

S 2019
rnational Symposium

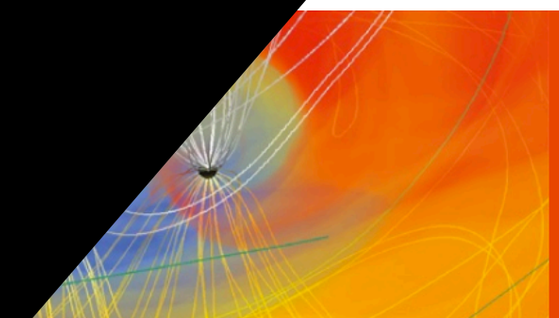
U Manches
1 Jul 2019

sium

ic safety spotlight

Daniel F Litim

University of Sussex



PASCOS 2019
XXV Internation

asymptotic safety in the spotlight

asymptotic safety in the spotlight

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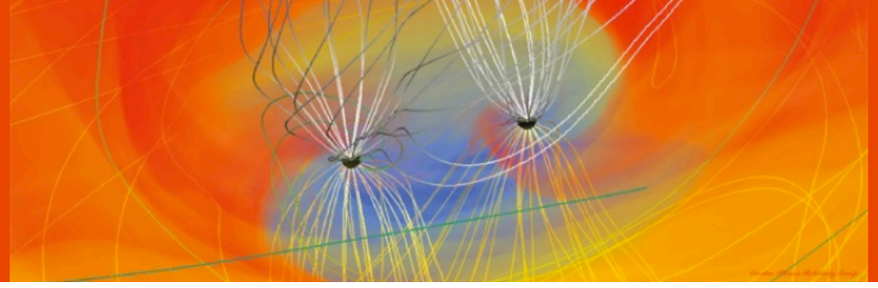

PASCOS 2019
XXV International Symposium

asymptotic safety in the spotlight

Daniel F Litim

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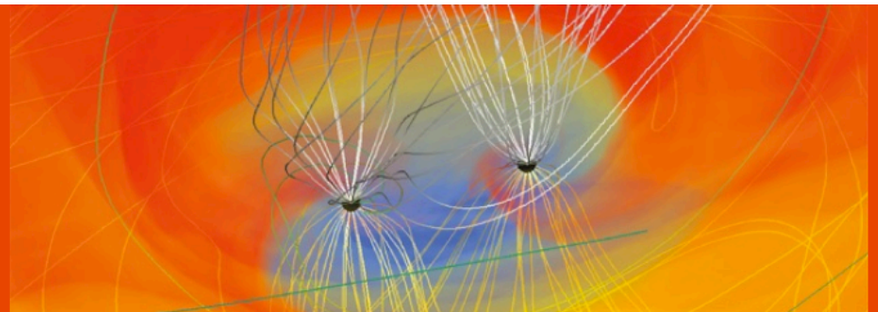

PASCOS 2019
XXV International Symposium

U Manchester
1 Jul 2019

standard model

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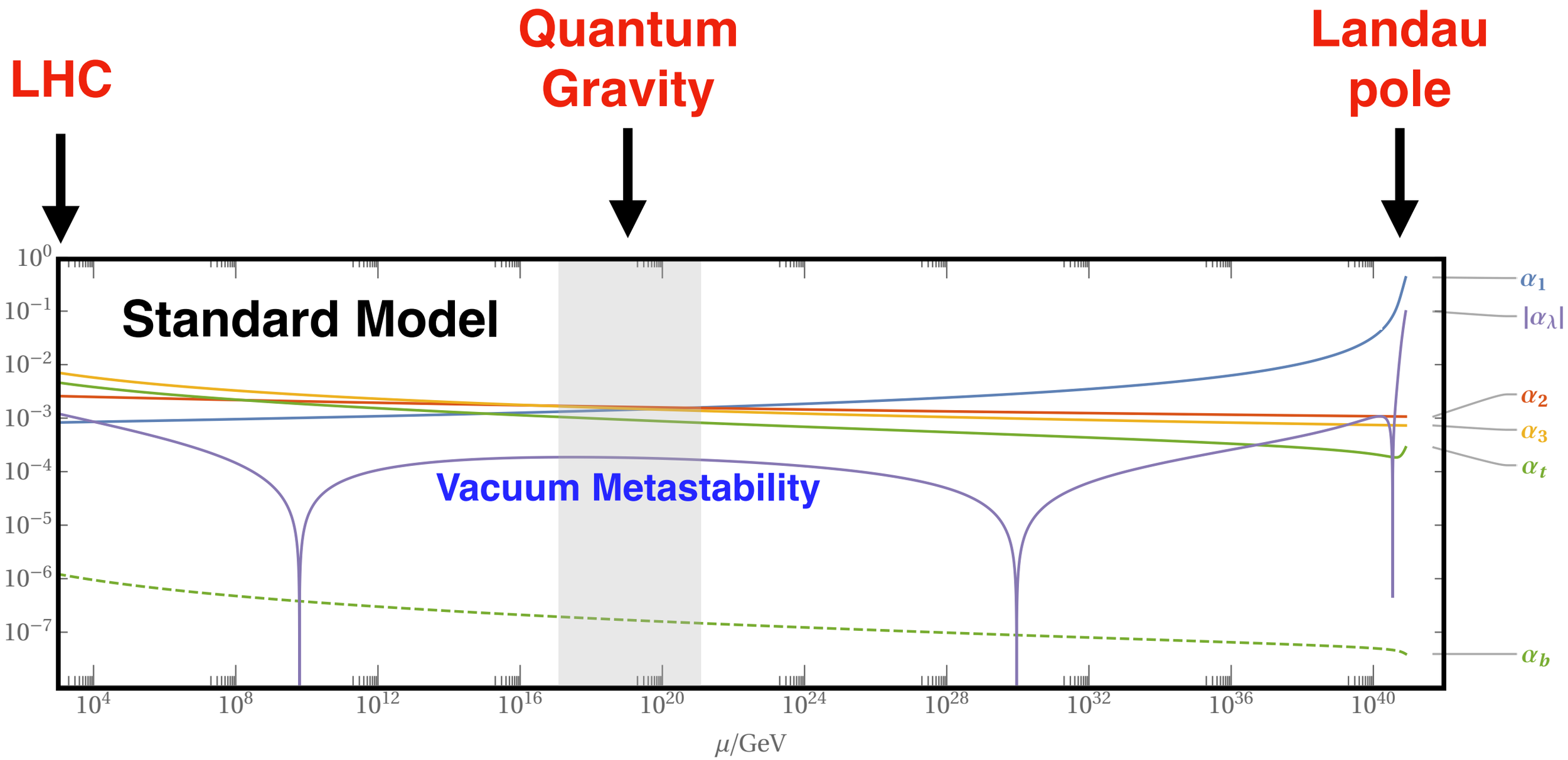
local QFT for fundamental interactions

strong nuclear force
weak force
electromagnetic force

open challenges

what comes **beyond the SM**?
and how does **gravity** fit in?

where are we ?


LHC
Quantum Gravity
Landau pole
Standard Model
Vacuum Metastability
α_1
$|\alpha_\lambda|$
α_2
α_3
α_t
α_b
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^4
10^8
10^{12}
10^{16}
10^{20}
10^{24}
10^{28}
10^{32}
10^{36}
10^{40}
μ/GeV

what is asymptotic safety?

fundamental QFT ⟺ **UV fixed point**

Wilson '71

asymptotic freedom ⟺ **non-interacting UV fixed point**

Gross, Wilzcek '73 , Politzer '73

asymptotic safety ⟺ **interacting UV fixed point**

Weinberg '79

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exact asymptotic safety

	infinite-N non-linear sigma	Brezin, Zinn-Justin ’76 Bardeen, Lee, Shrock ‘76
2+eps	infinite-NF Gross-Neveu	Gawedzki, Kupiainen ‘85
	quantum gravity	Christensen, Duff ’78 Gastmans, Kallosh, Truffin ’78 Weinberg ’79
3d	infinite-N scalars	Pisarski ’82 Bardeen, Moshe, Bander ‘84
	infinite-NF Gross-Neveu	Rosenstein, War, Park’ 89 de Calan, Faria da Veiga, Magnen, de Seneor ’91
4d	gauge + matter	Litim, Sannino ’14 Bond, Litim ’16, ’17, ‘18

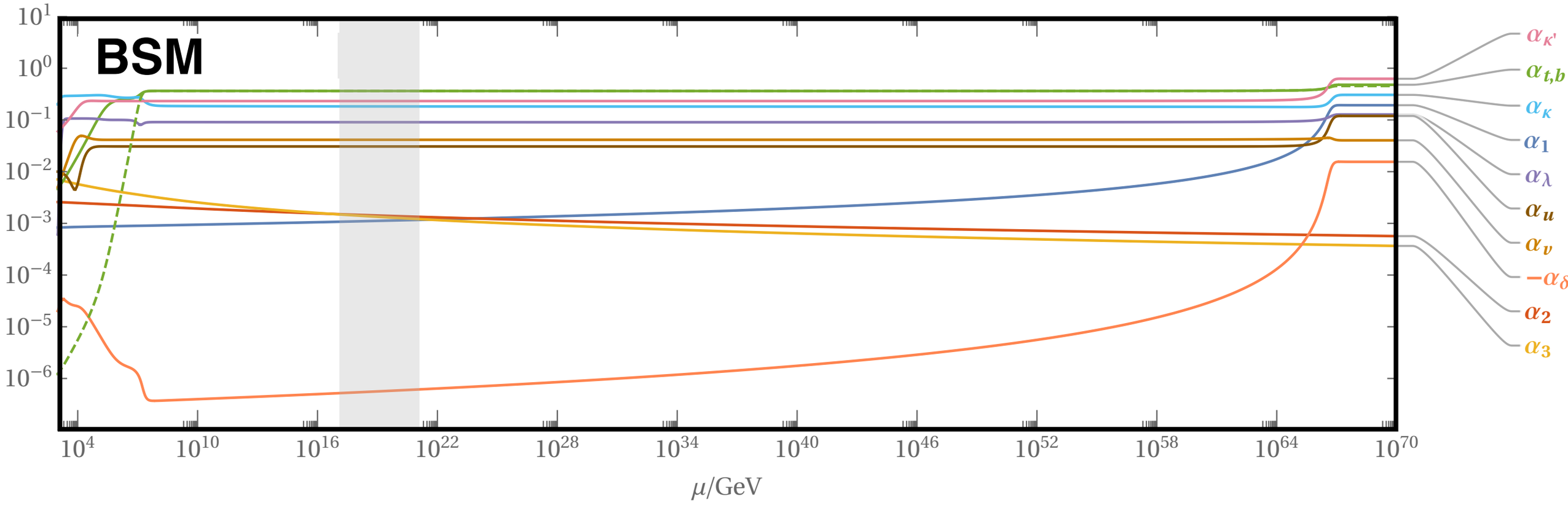
4d	quantum gravity	Reuter ’96 Litim ’03

why asymptotic safety?

LHC

Quantum Gravity

UV fixed points



AS models beyond the SM and their phenomenology:
Talk by Tom Steudtner (today's parallel session 1530)

today:

understand **asymptotic safety**
in general weakly-coupled 4d QFTs

asymptotic safety
and models beyond the SM

signatures of **asymptotic safety**
in **quantum gravity**

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asymptotic safety
in gauge-matter theories

AD Bond, DF Litim, 1608.00519/EPJC
1707.04217/PRD
1709.06953/PRL
1710.07612/PRD
1801.08527/PRL

$$\beta = \frac{d\alpha}{d\ln\mu}$$

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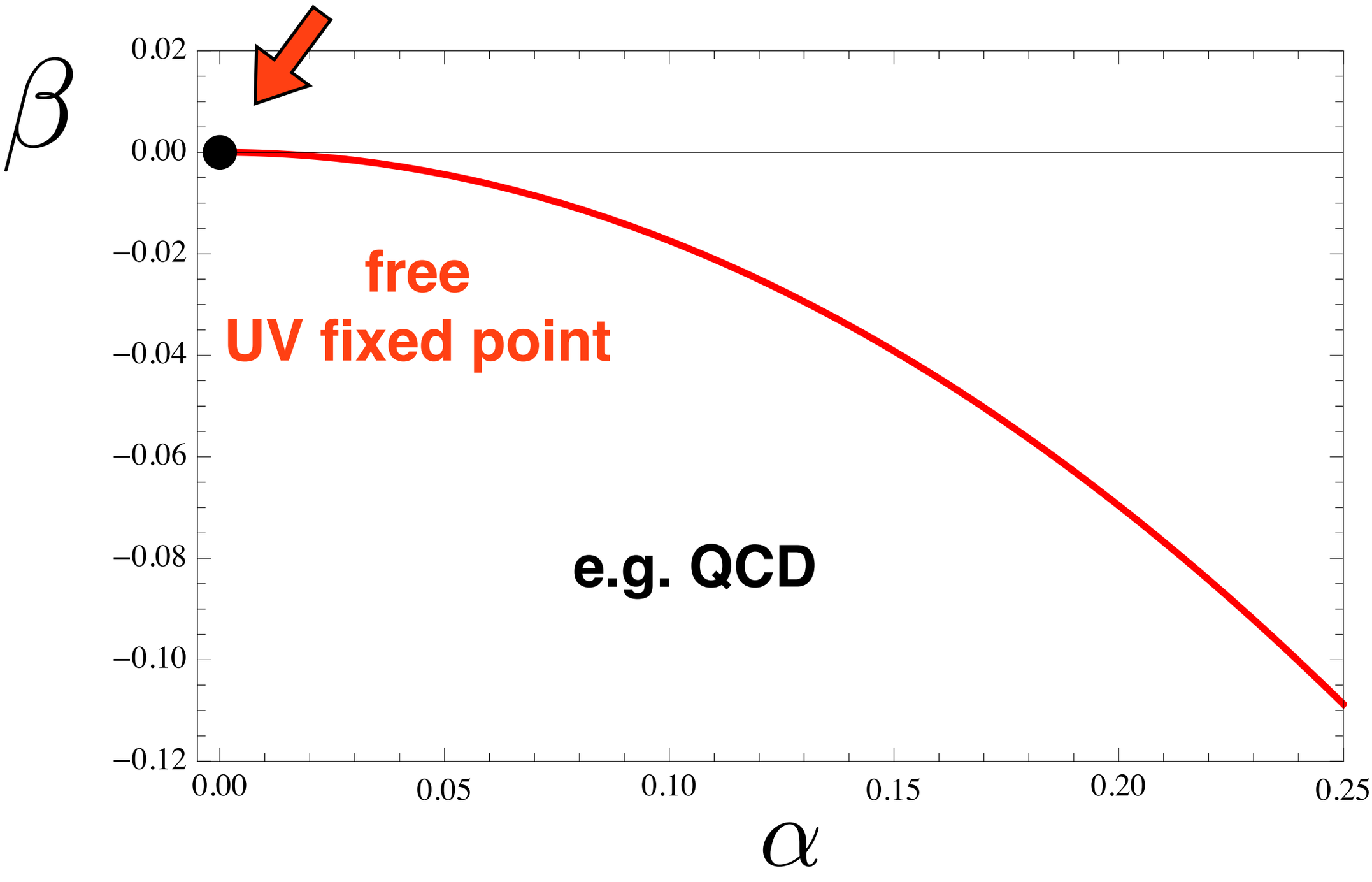
asymptotic freedom



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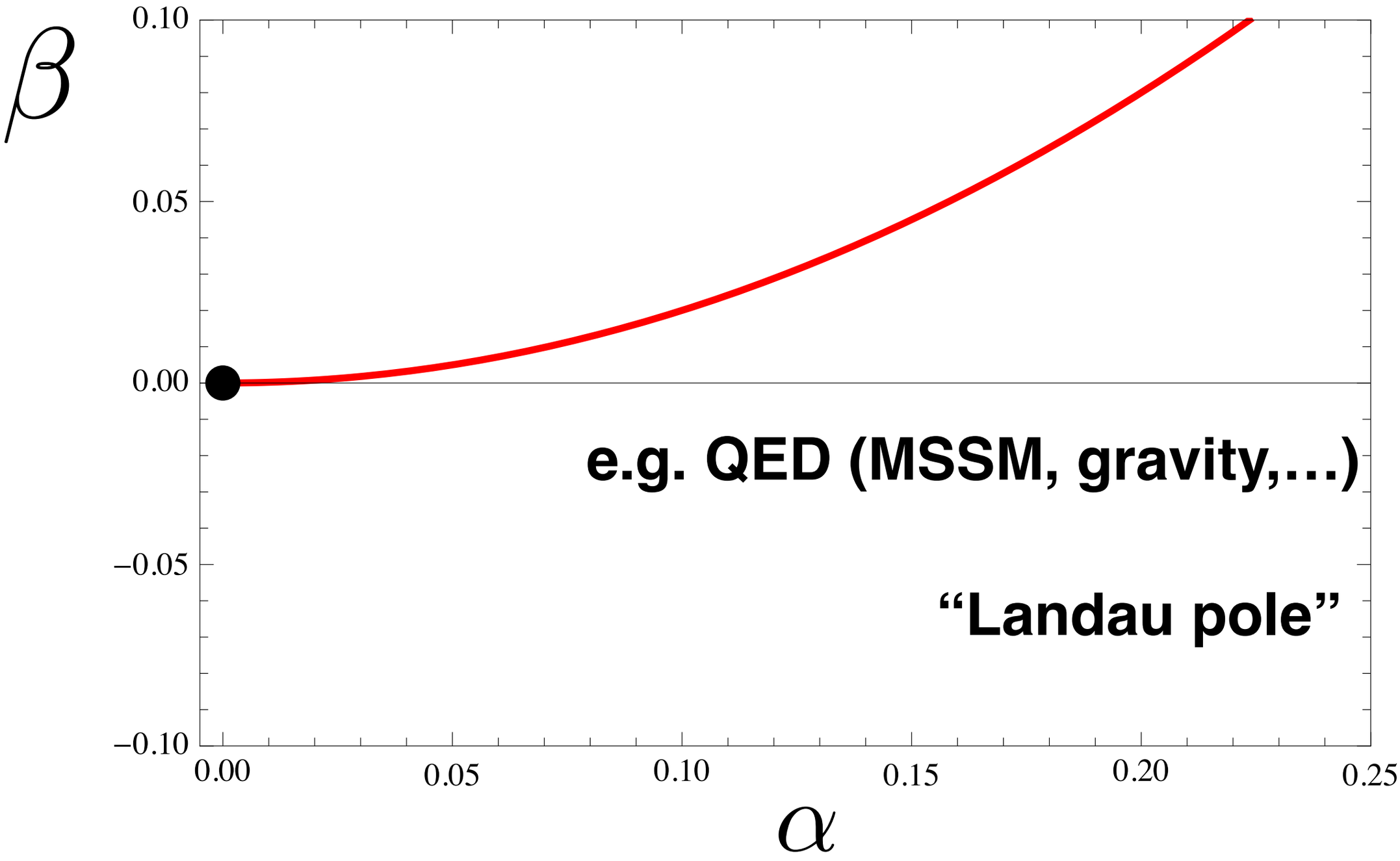
infrared freedom



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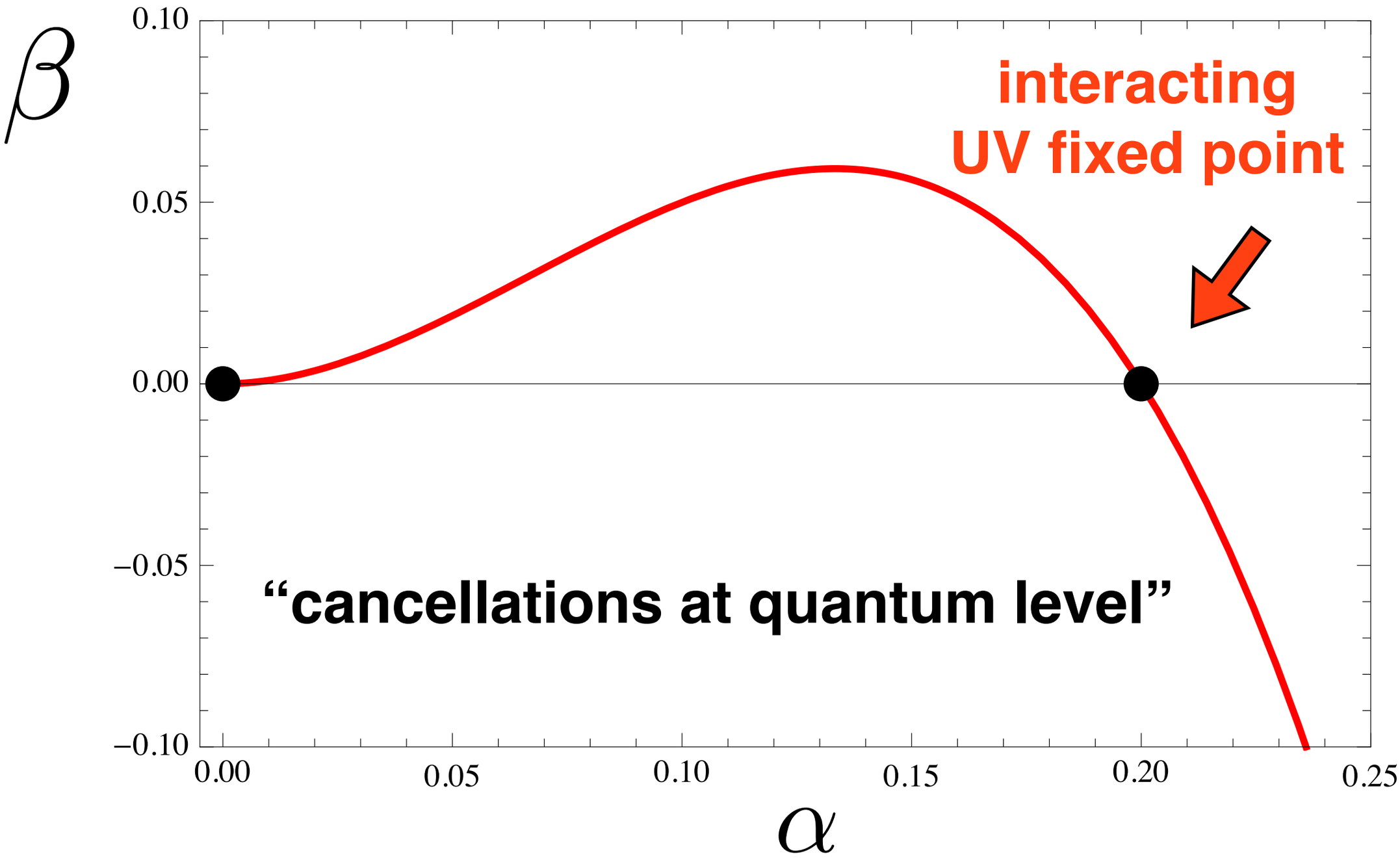
asymptotic safety



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4d QFTs

fields **vectors** A^a_μ , **fermions** ψ_I , **scalars** ϕ^A

path integral

$$Z[J] = \exp -i \int d^4x (L + L_{\rm gf} + L_{\rm gh} + J^i \, \Phi_i)$$

action

$$L = \frac{1}{4g_a^2} \mathrm{Tr}\, F^a_{\mu\nu} F_a^{\mu\nu} + i\psi_I \not{D} \psi_I + \frac{1}{2}(D_\mu \phi^A)^2$$
$$+ \frac{1}{2} Y^A{}_{IJ} \phi^A \, \psi_I \, \xi \, \psi_J + \frac{1}{4!} \lambda_{ABCD} \phi^A \phi^B \phi^C \phi^D$$

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4d QFTs

fields **vectors** A^a_μ , **fermions** ψ_I , **scalars** ϕ^A

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$$+ \frac{1}{2} Y^A{}_{IJ} \phi^A \, \psi_I \, \xi \, \psi_J + \frac{1}{4!} \lambda_{ABCD} \phi^A \phi^B \phi^C \phi^D$$

gauge **Yukawa** **quartics**

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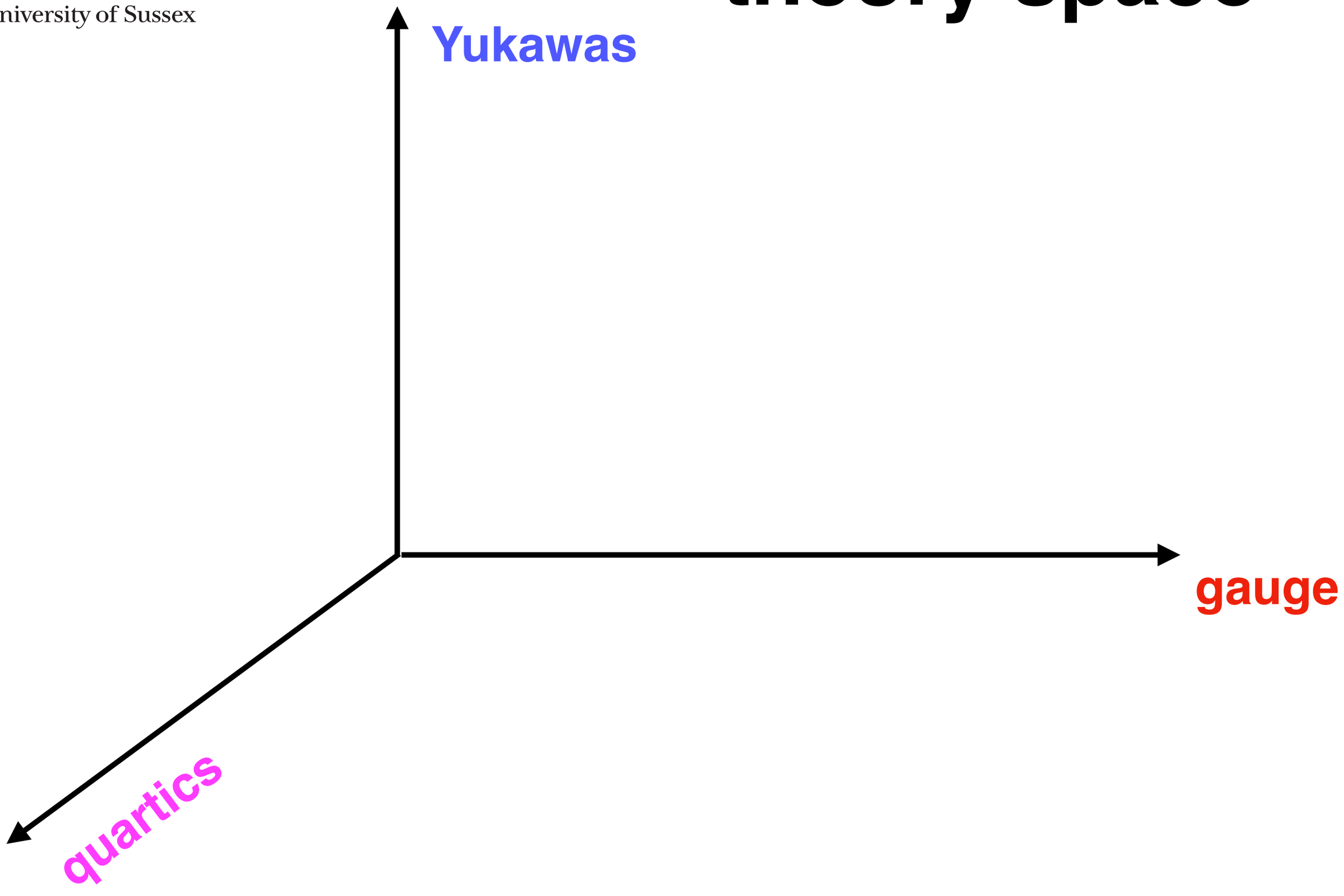
“theory space”



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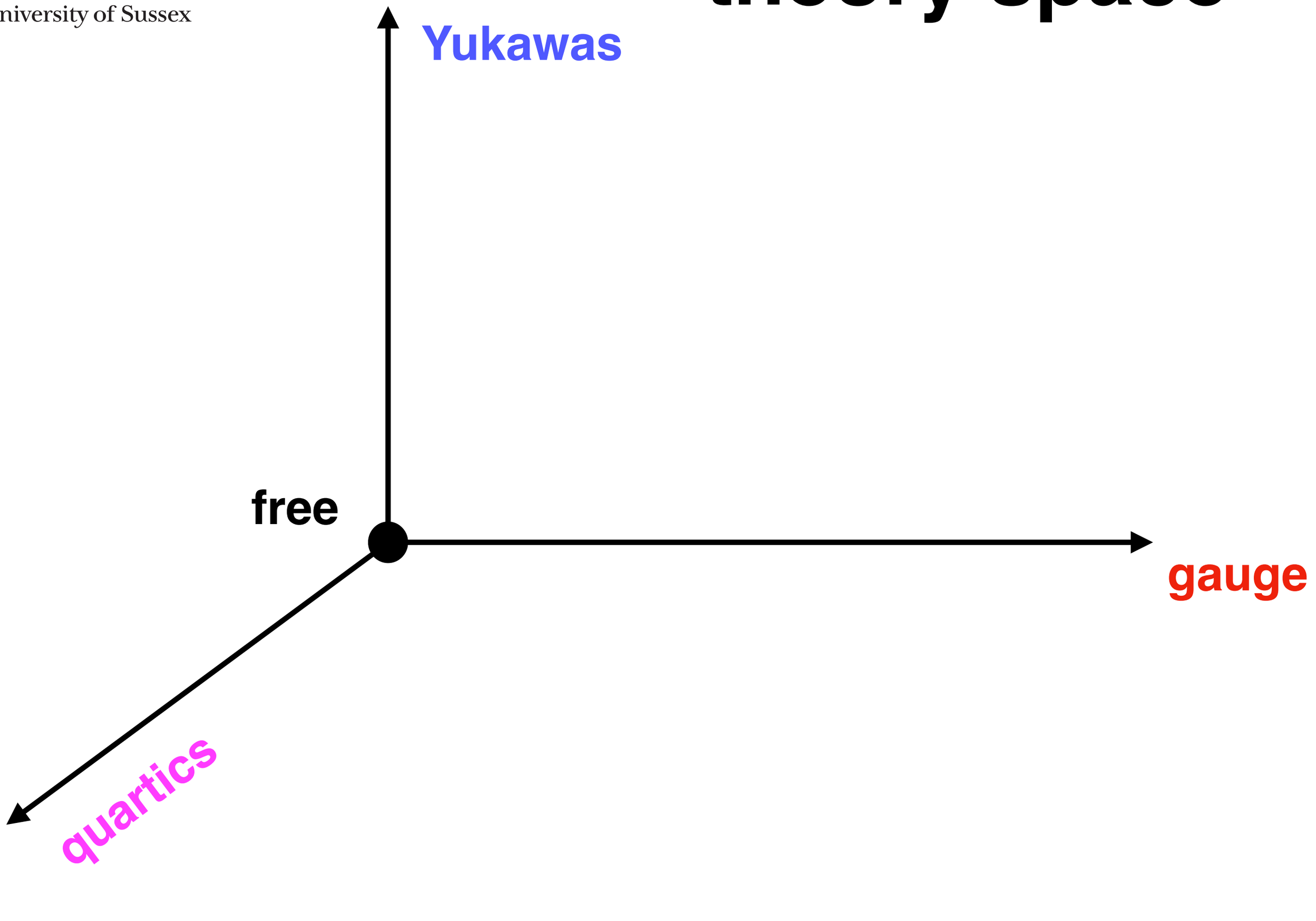
“theory space”



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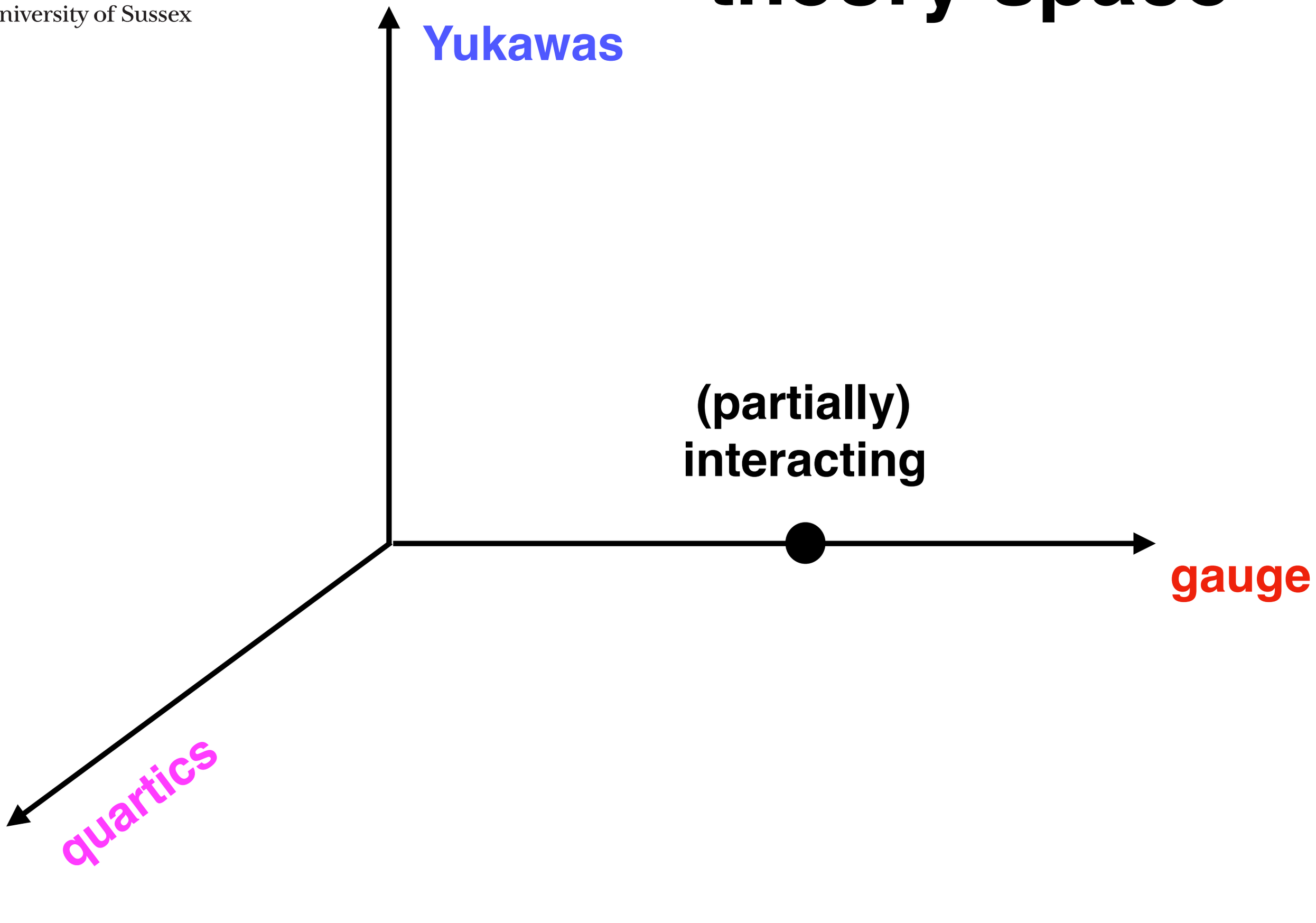
“theory space”



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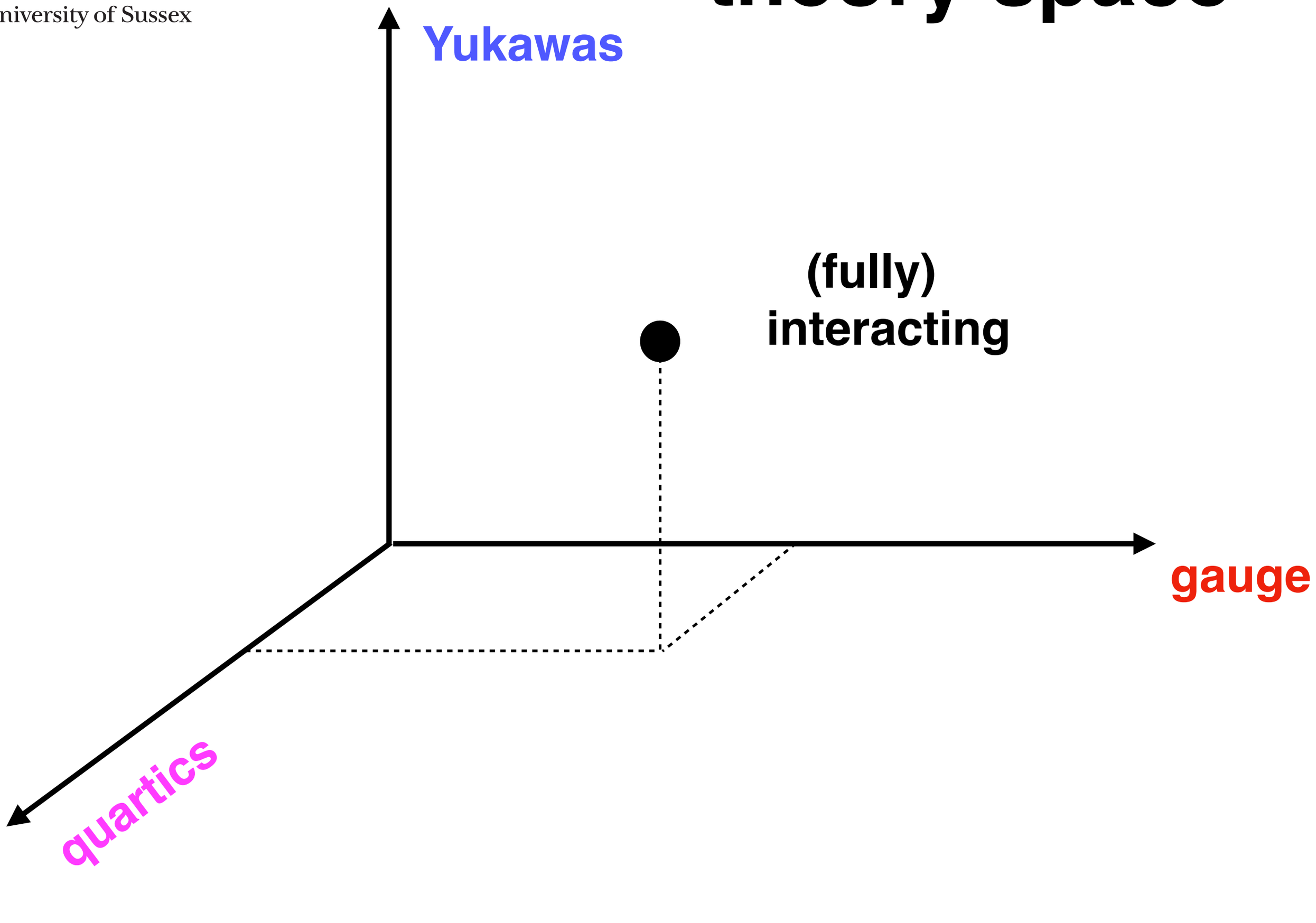
“theory space”



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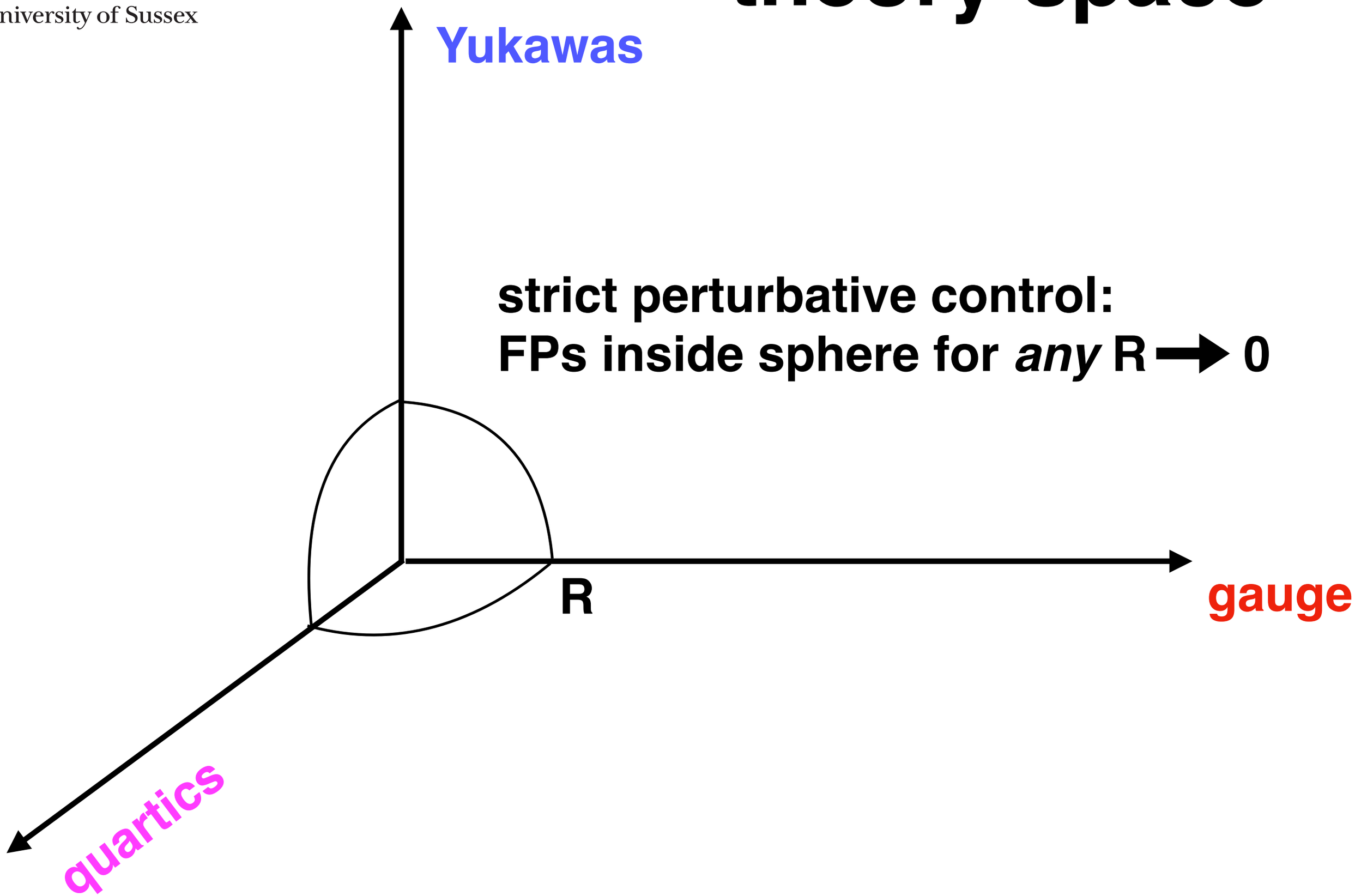
“theory space”



strict perturbative control:
FPs inside sphere for *any* R → 0

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“theory space”

interacting fixed point

gauge	Y	Y	Y	N	N
Yukawas	N	N	Y	N	Y
quartics	N	Y	Y	Y	Y

“Banks Zaks”

“gauge Yukawa”

“scalar”

“scalar Yukawa”

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“theory space”

	YES			NO				
	non-abelian					abelian		
gauge	Y	Y	Y	N	N	Y	Y	Y
Yukawas	N	N	Y	N	Y	N	N	Y
quartics	N	Y	Y	Y	Y	N	Y	Y
weak FPs	IR	IR	IR UV	no	no	no	no	no

Banks
Zaks

gauge
Yukawa

scalar

scalar
Yukawa

Banks
Zaks

gauge
Yukawa

AD Bond, DF Litim, **Price of Asymptotic Safety,** PRL 122 (2019) 211601 [1801.08527]

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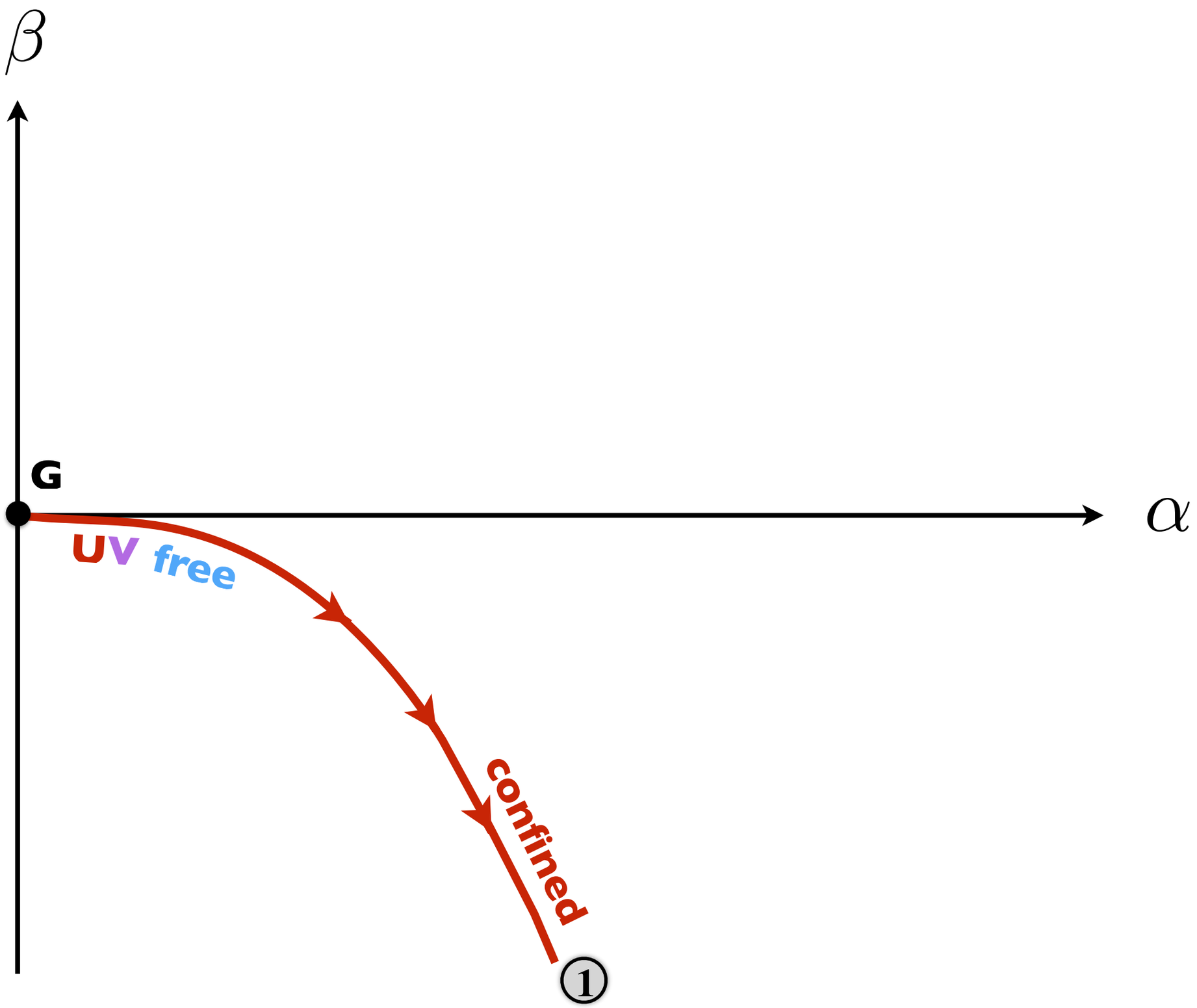
renormalisation group



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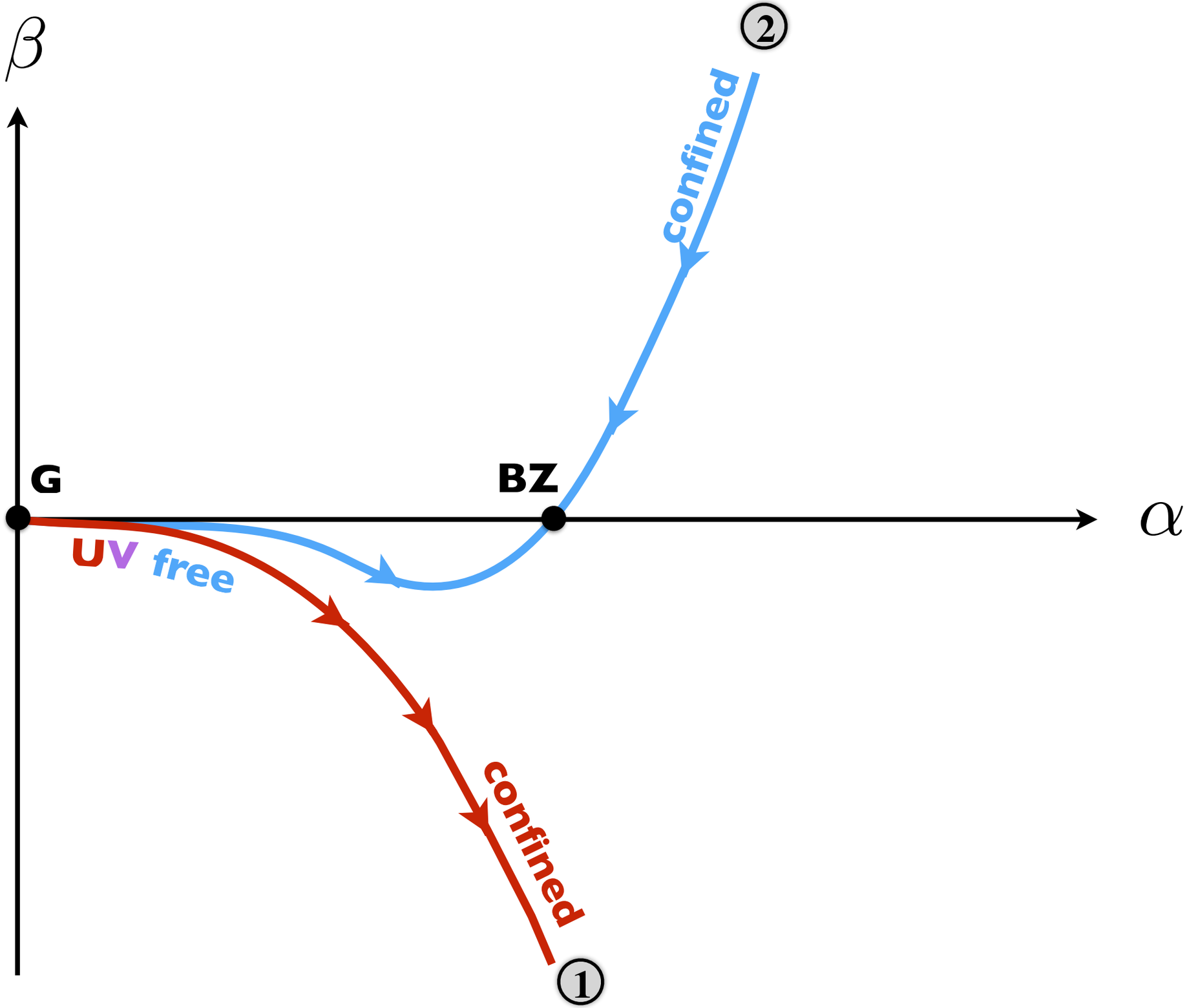
renormalisation group



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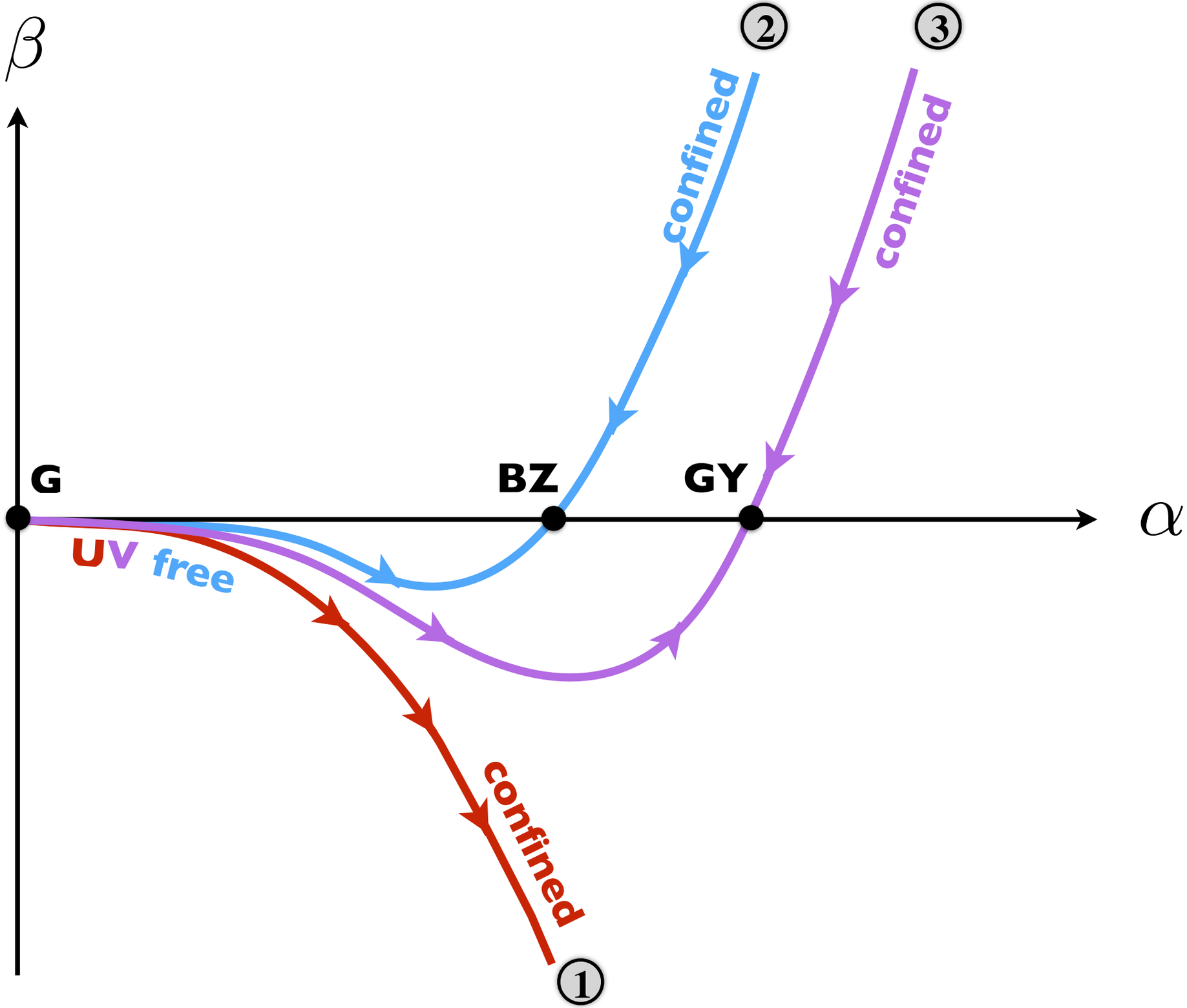
renormalisation group



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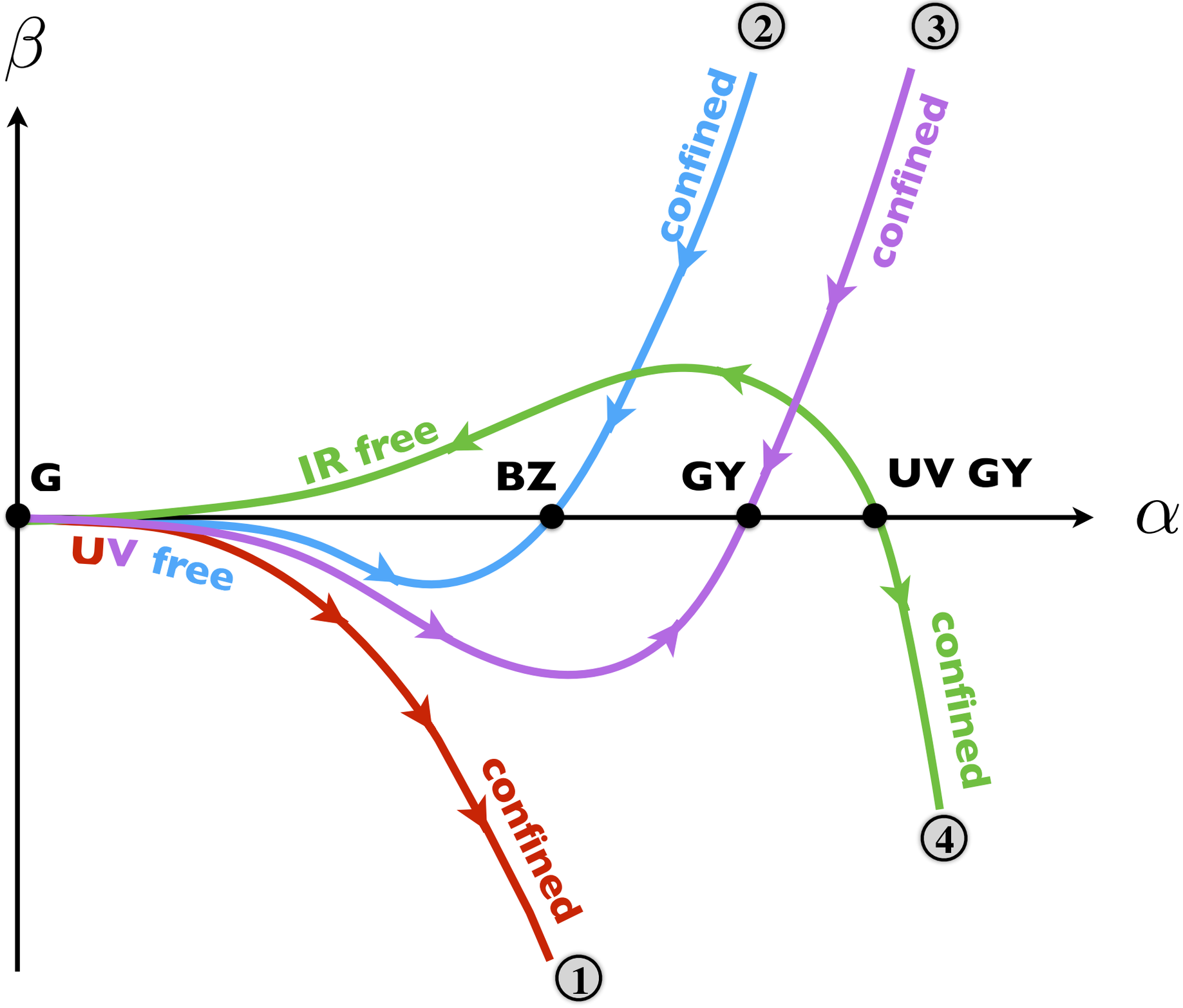
renormalisation group



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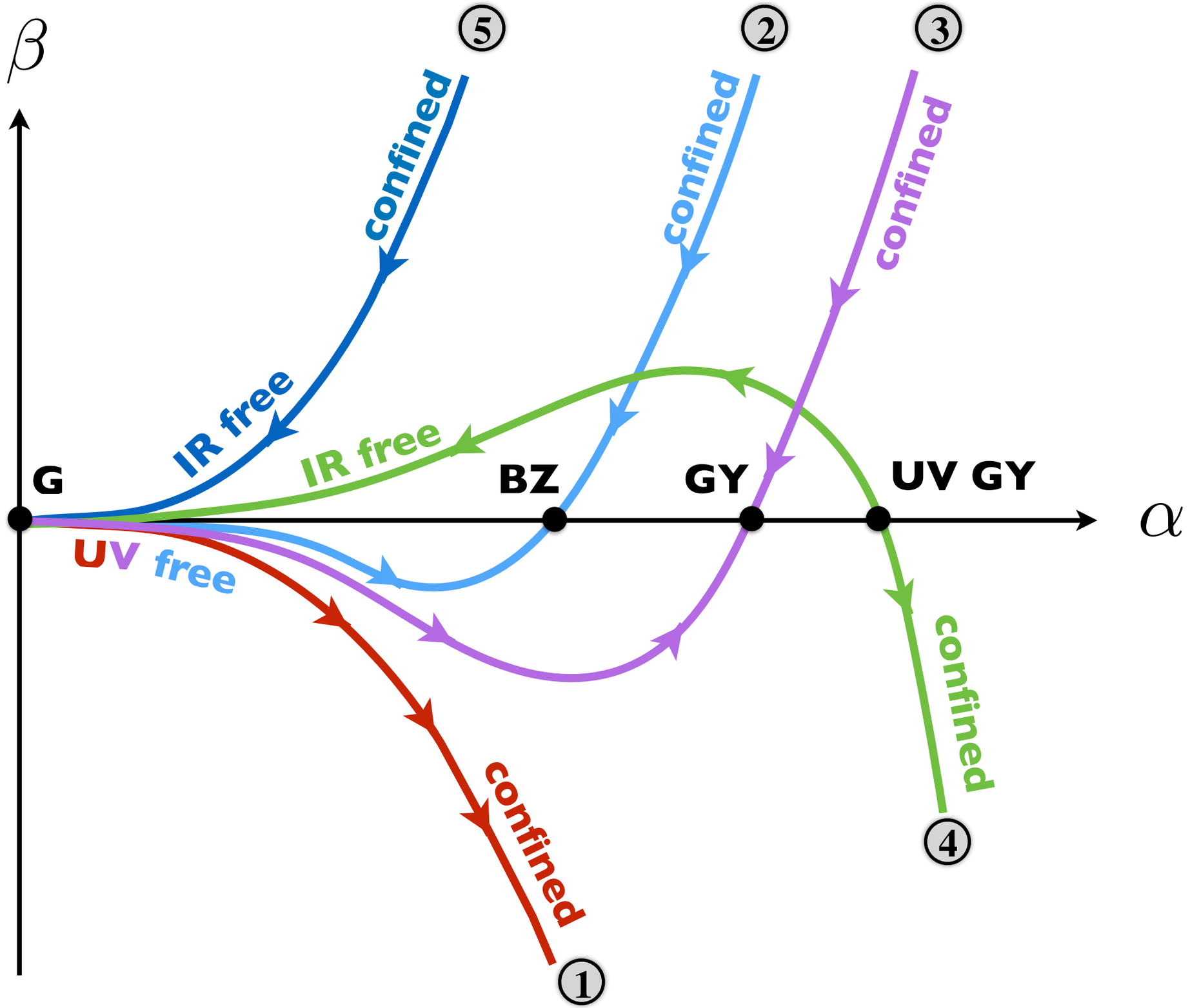
renormalisation group



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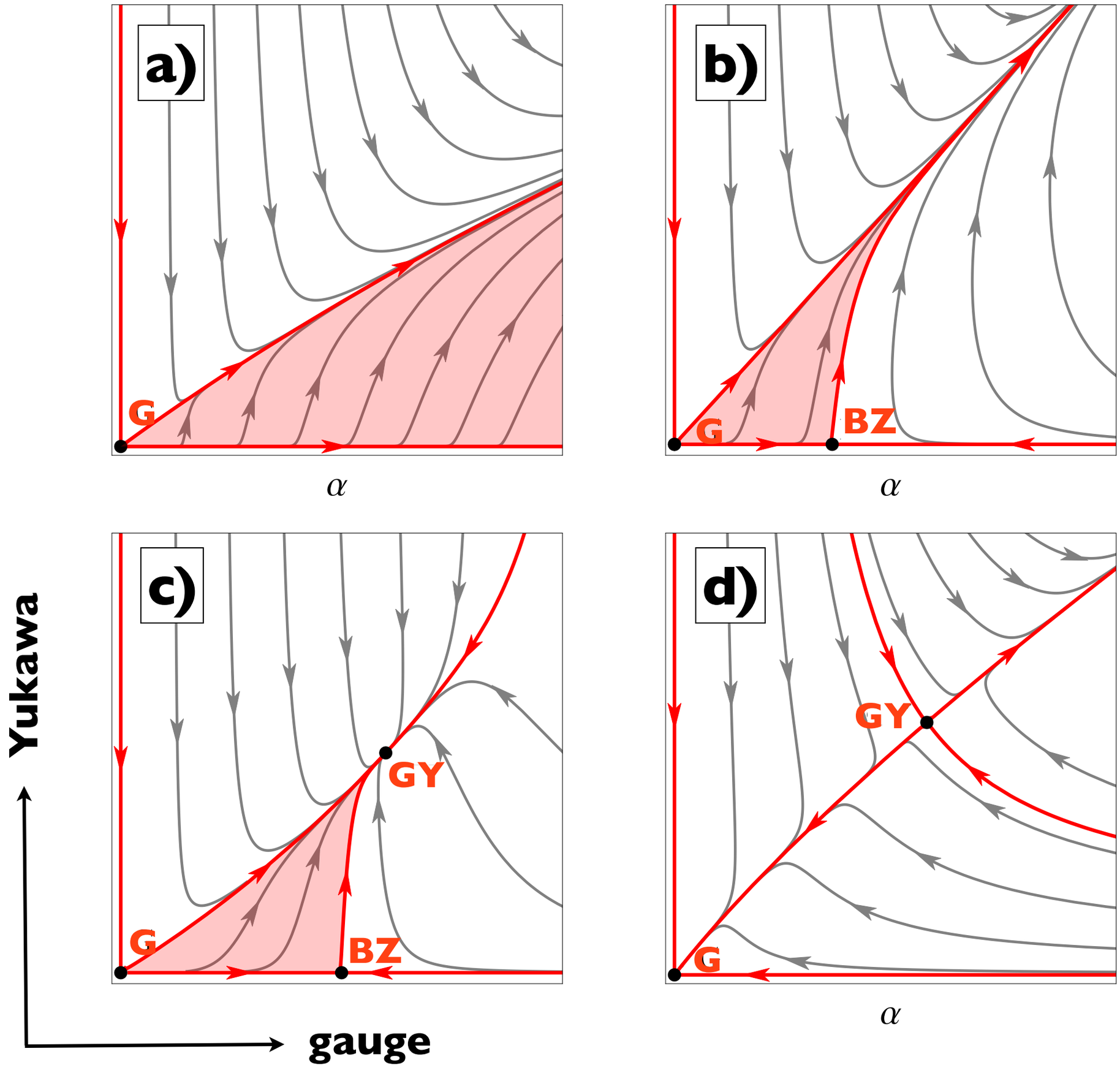
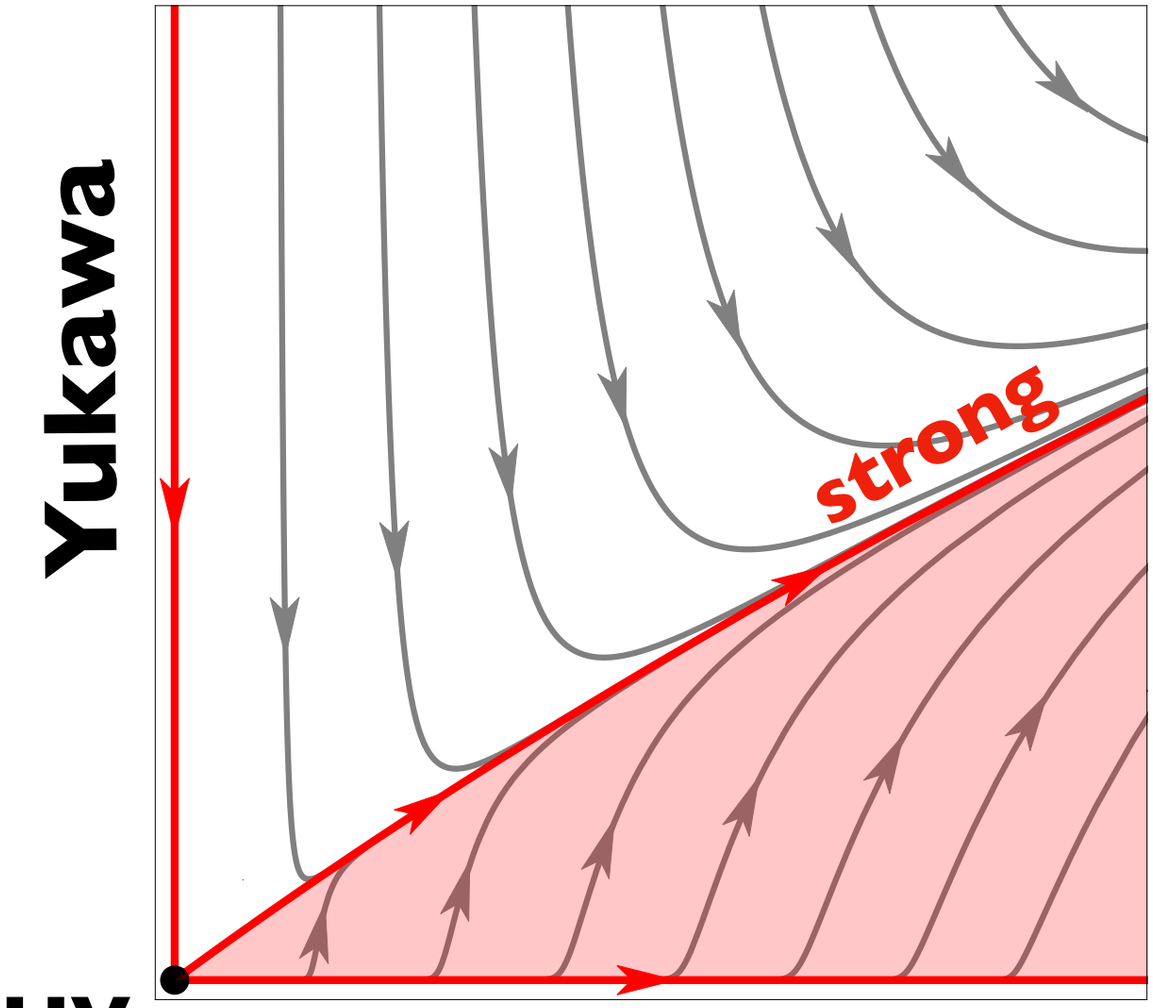


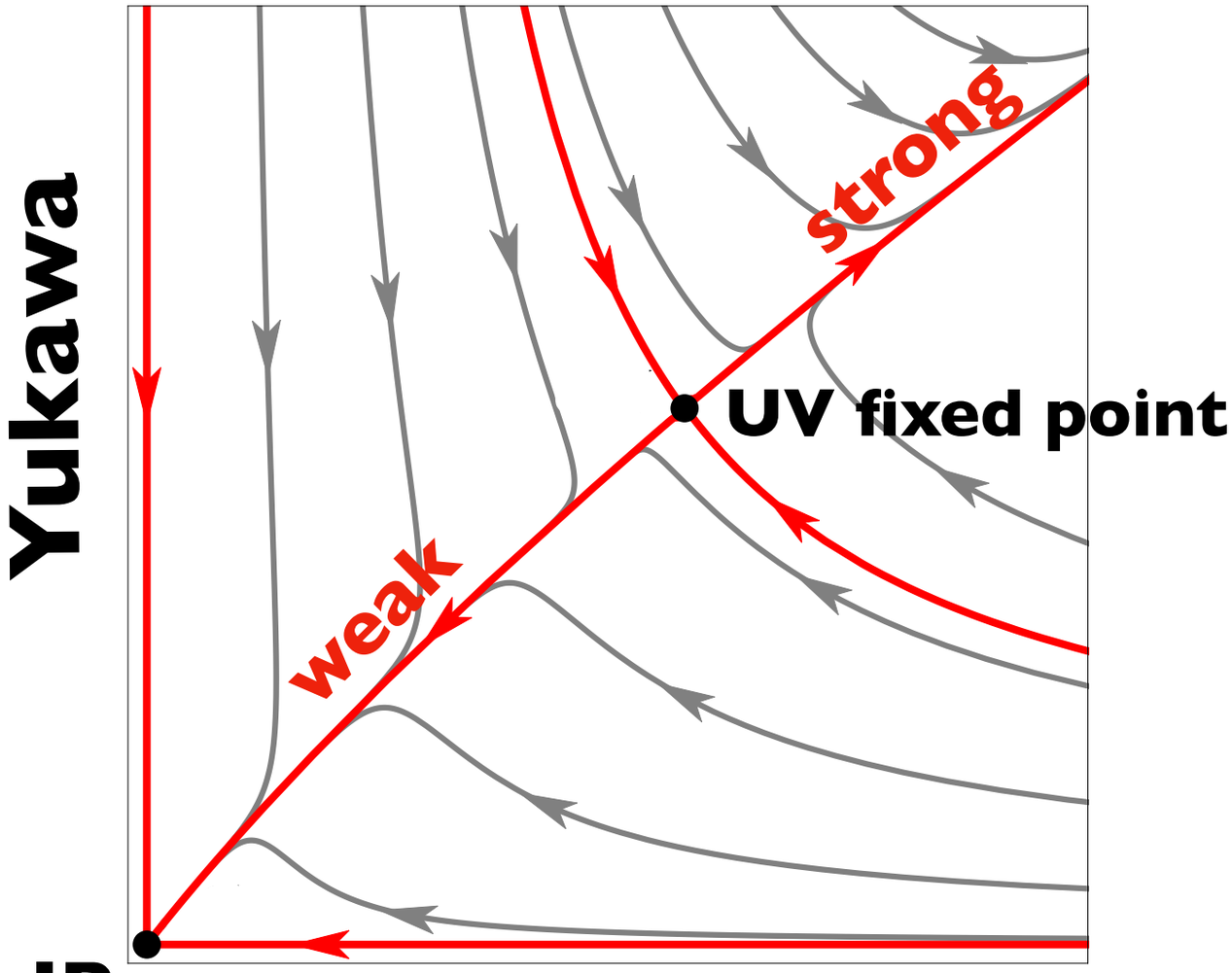
①

asymptotic freedom



④

asymptotic safety



"enhanced predictivity"

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"theory space"

	YES			NO				
	non-abelian			abelian				
gauge	Y	Y	Y	N	N	Y	Y	Y
Yukawas	N	N	Y	N	Y	N	N	Y
quartics	N	Y	Y	Y	Y	N	Y	Y
weak FPs	IR	IR	IR UV	no	no	no	no	no

Banks Zaks

gauge Yukawa

scalar

scalar Yukawa

Banks Zaks

gauge Yukawa

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proofs of fixed points & asymptotic safety

general **theorems** for fixed points

AD Bond, DF Litim, **Theorems for Asymptotic Safety of Gauge Theories,** 1608.00519 (EPJC)
AD Bond, DF Litim, **Price of Asymptotic Safety,** 1801.08527 (PRL)

simple gauge theories with matter

DF Litim, F Sannino, **Asymptotic Safety Guaranteed,** 1406.2337 (JHEP)
AD Bond, DF Litim, G Medina Vazquez, T Steudtner, **Conformal window for asymptotic safety**, 1710.07615 (PRD)

semi-simple SU(N) x SU(M) gauge theories with matter

AD Bond, DF Litim, **More Asymptotic Safety Guaranteed,** 1707.04217 (PRD)

supersymmetric gauge theories with matter

AD Bond, DF Litim, **Asymptotic Safety Guaranteed in Supersymmetry,** 1709.06953 (PRL)

higher order interactions in gauge theories with matter

T Buyukbese, DF Litim, **Asymptotic Safety Beyond Marginal Interactions,** PoS LATTICE2016 (2017) 233

phenomenology and models beyond the Standard Model

A Bond, G Hiller, K Kowalska, DF Litim, **Directions for model building from asymptotic safety,** JHEP1708 (2017) 004
G Hiller, C Hermigos-Feliu, DF Litim, T Steudtner, **Asymptotically safe extensions of the Standard Model and their flavour phenomenology,** Moriond (EW2019) 1905.11020

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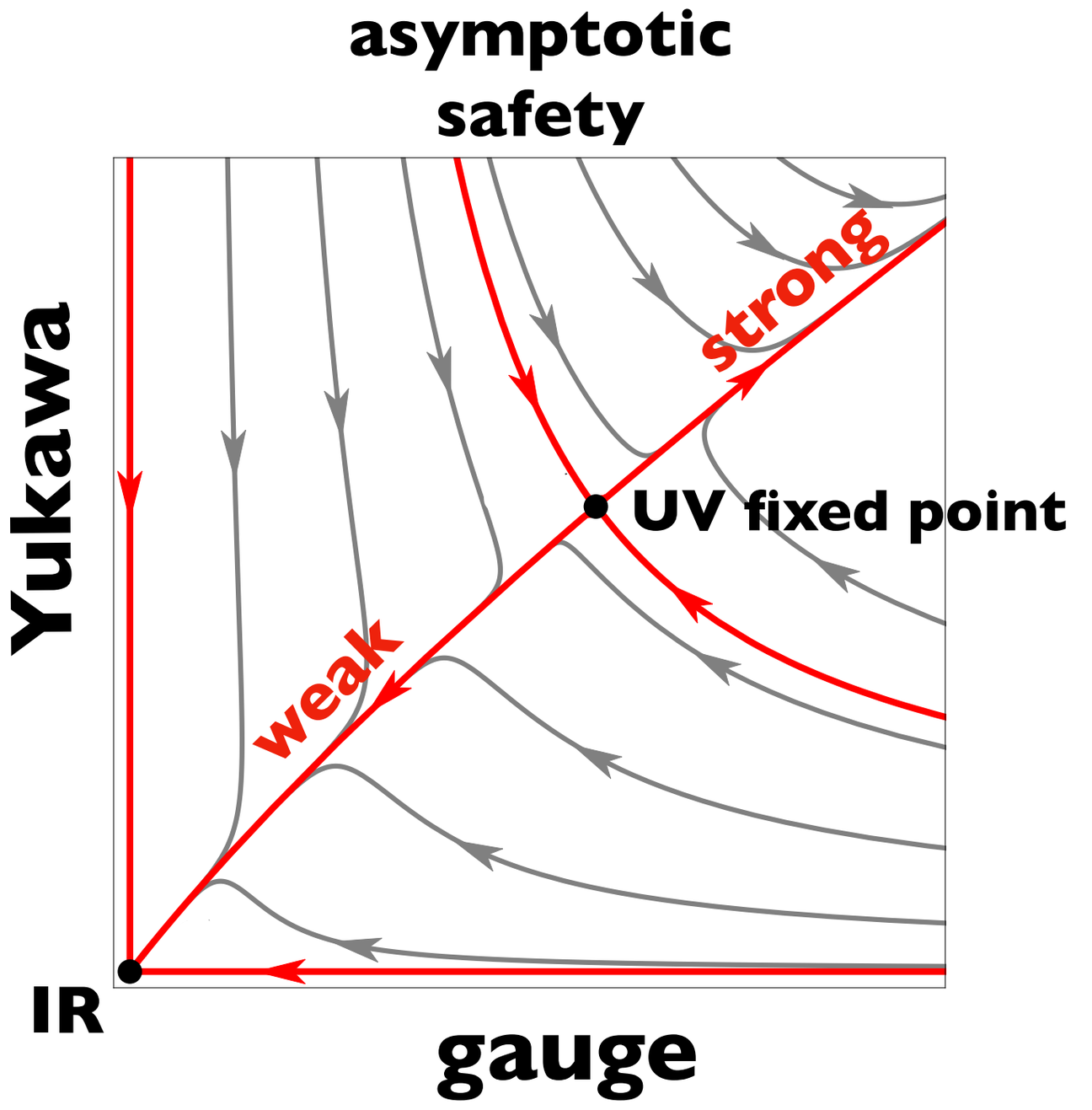
simple

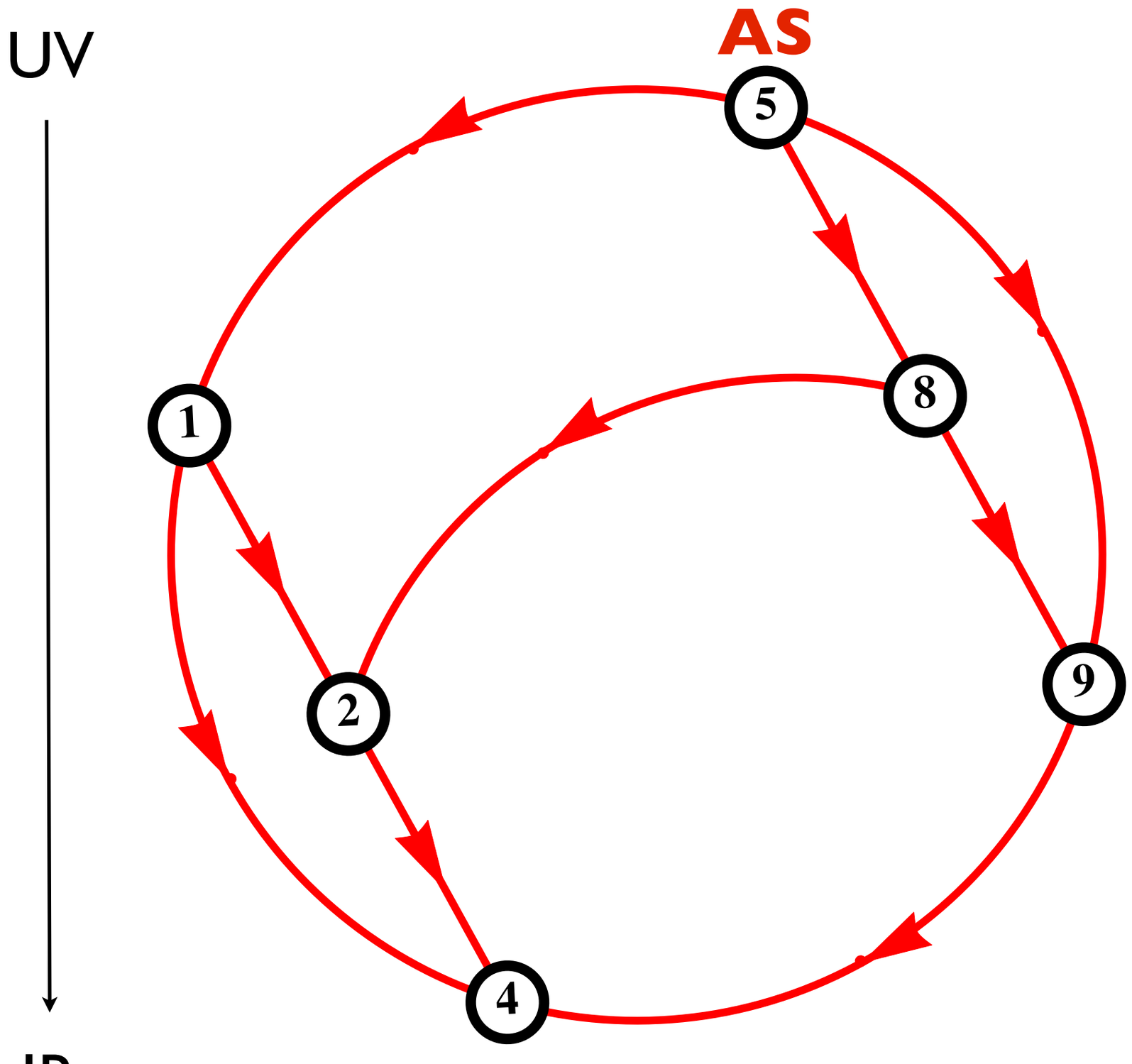


SU(N)
+1 Yukawa
+2 quartics

(NF fermions
+ mesons)

DF Litim, F Sannino, **Asymptotic Safety Guaranteed,** 1406.2337 (JHEP)

semi-simple



SU(N) x SU(M)
+ 2 Yukawas
+ 5 quartics

various fermions
and mesons

AD Bond, DF Litim, **More Asymptotic Safety Guaranteed,** 1707.04217 (PRD)

what about supersymmetry?

AD Bond, DF Litim, **Asymptotic Safety Guaranteed in Supersymmetry,** 1709.06953 (PRL)

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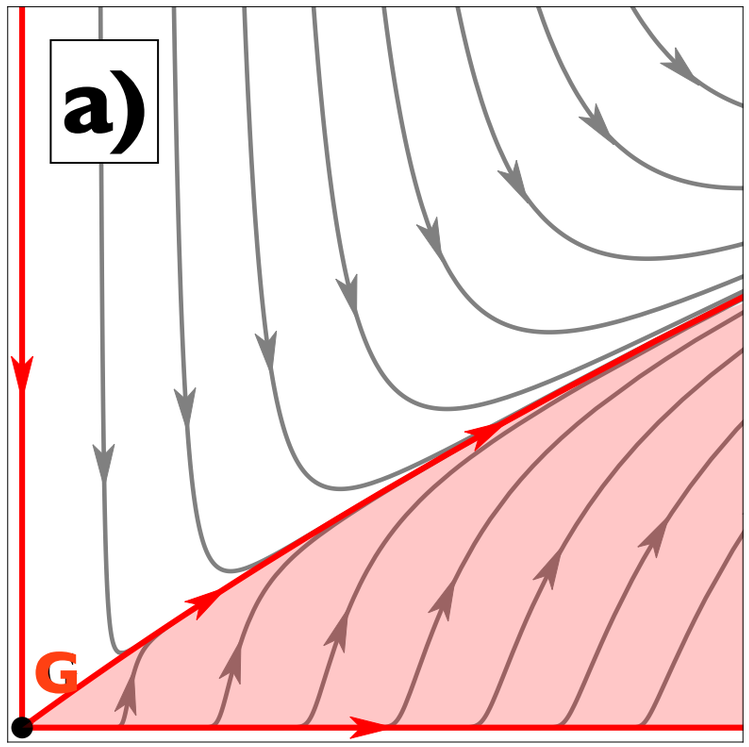
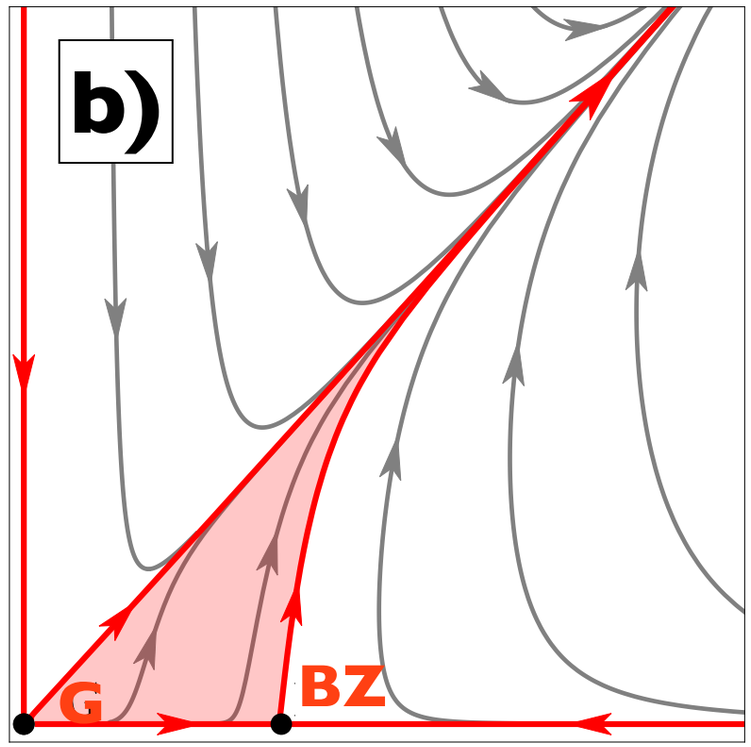
N=0

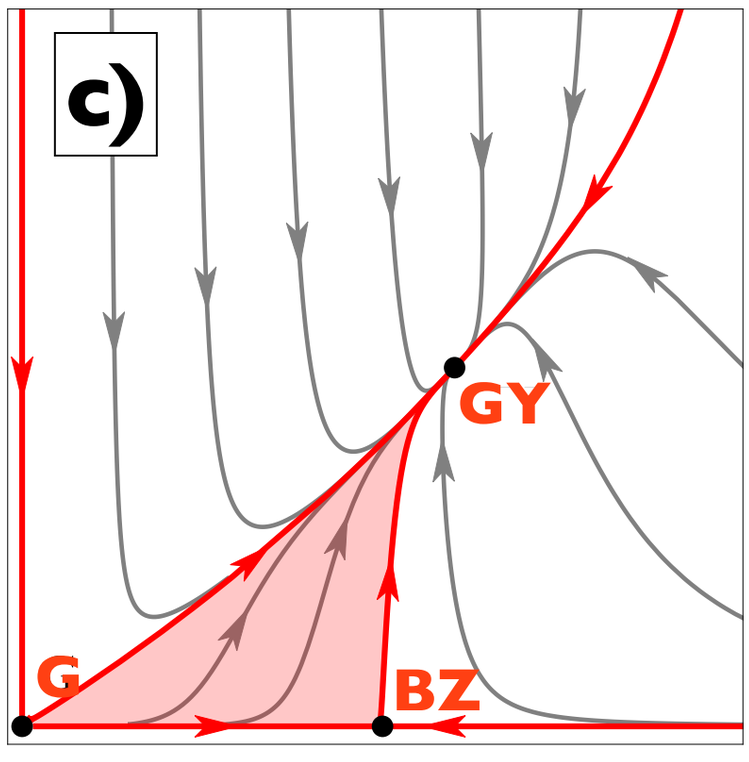
SUSY



α

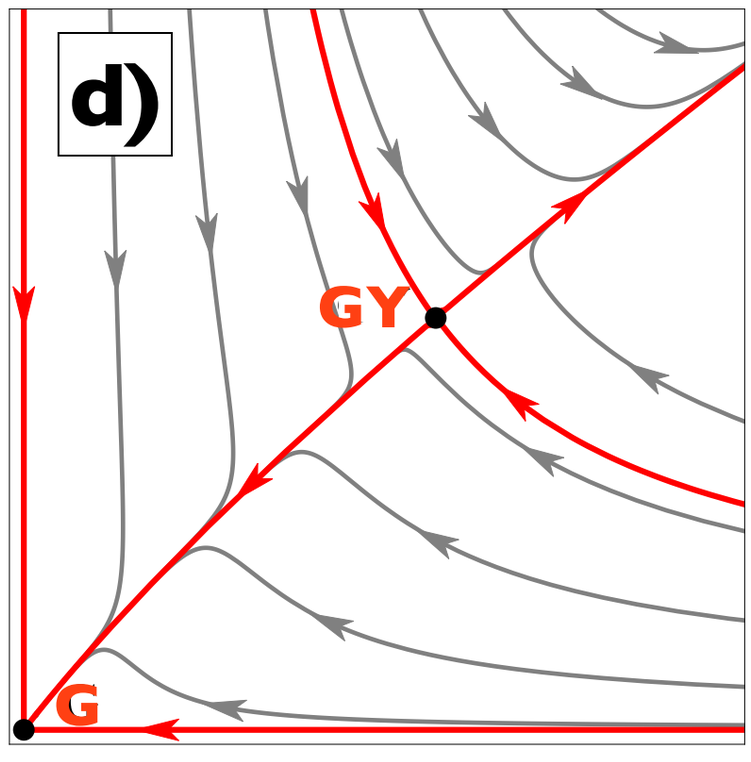


α



Yukawa

gauge



α

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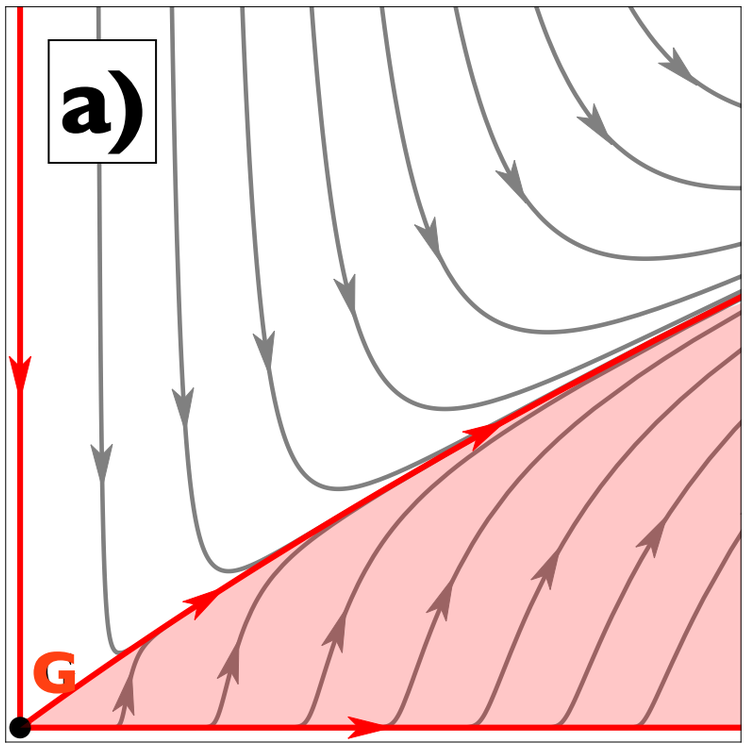
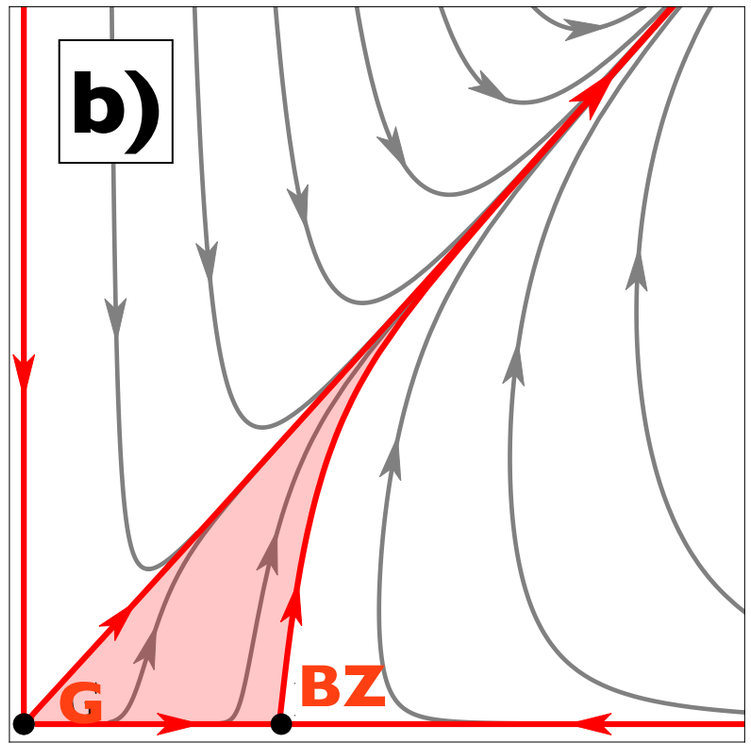
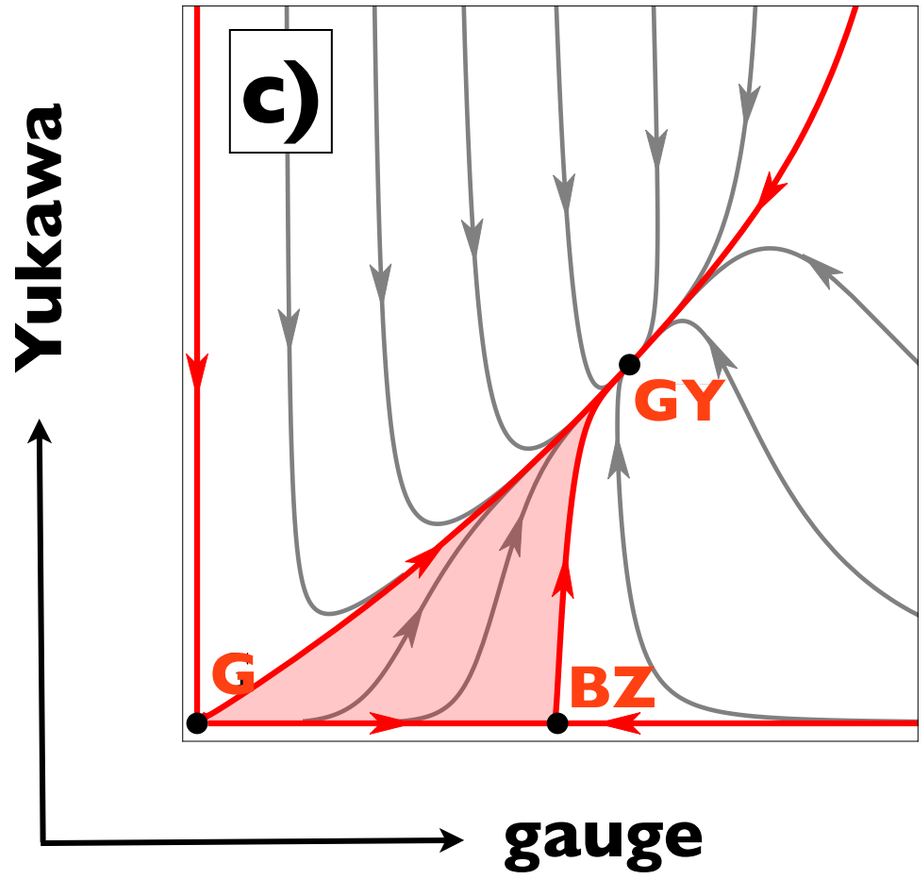
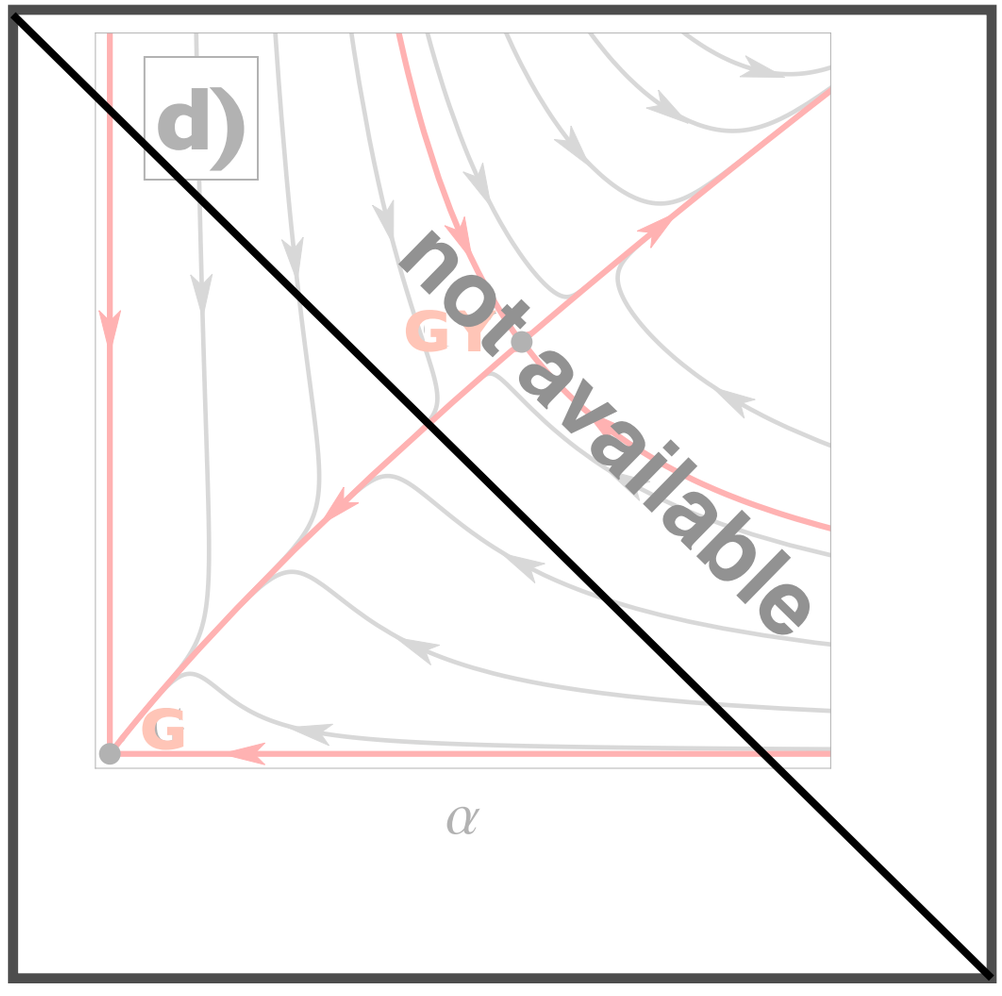
N=1

SUSY









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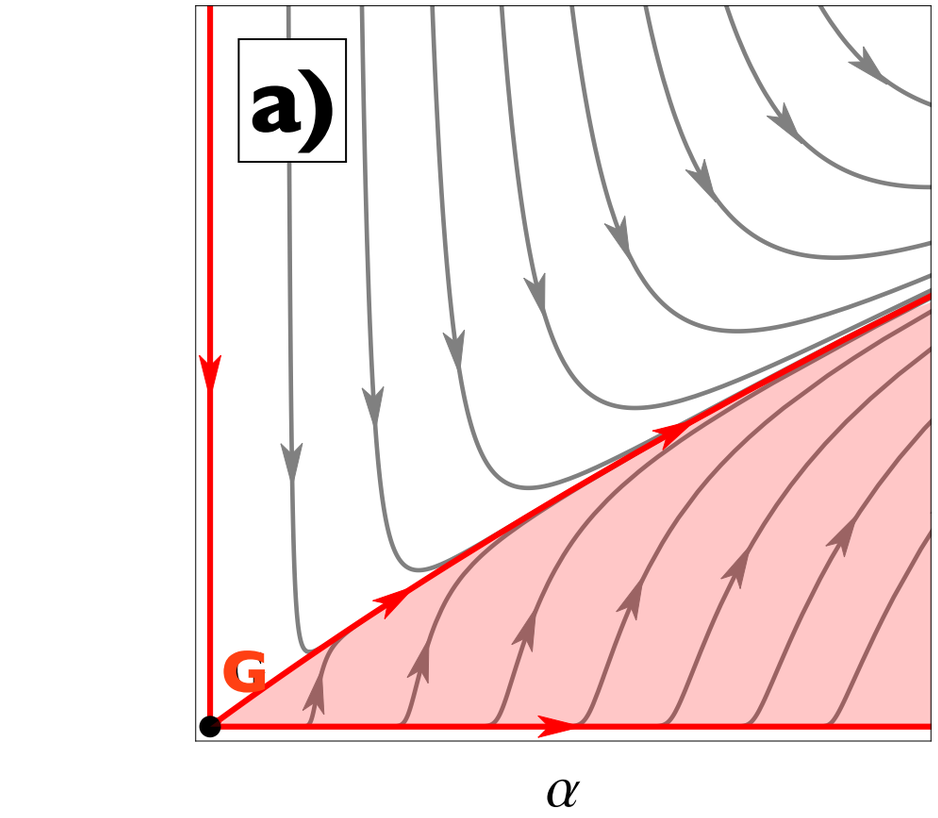
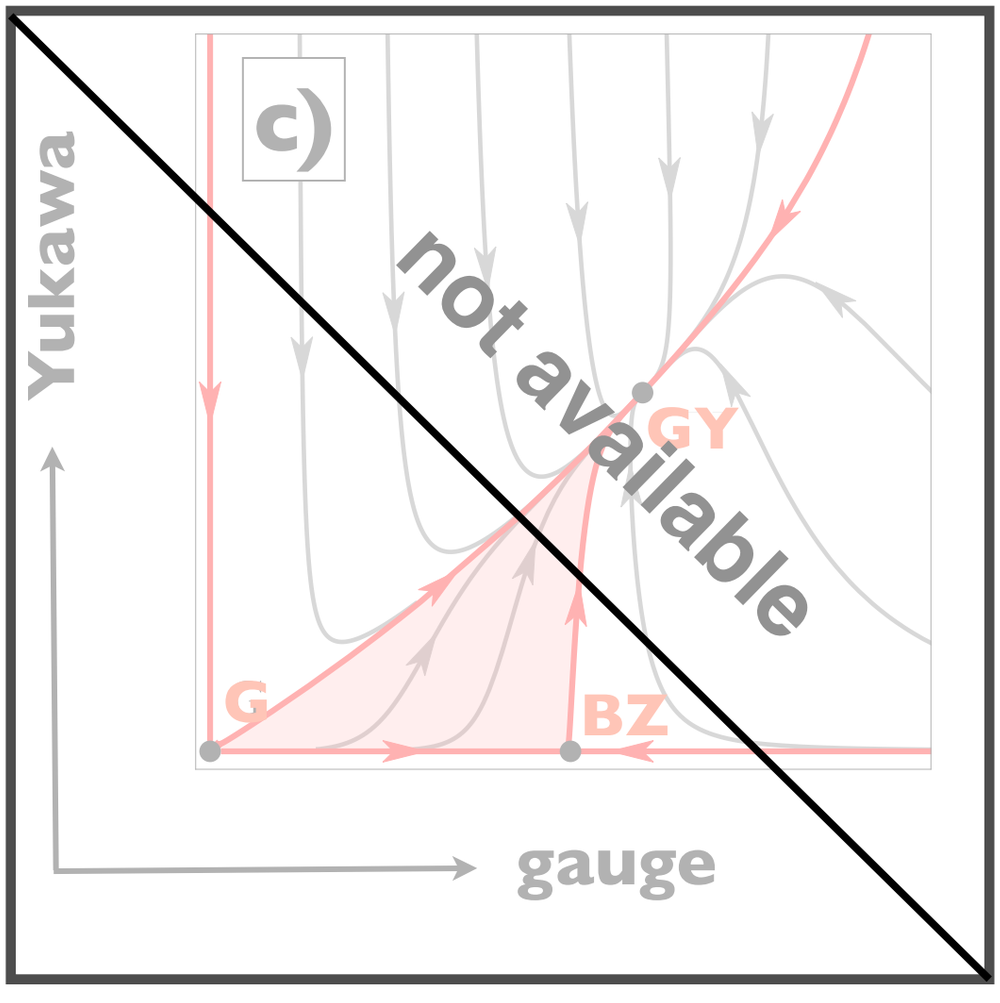
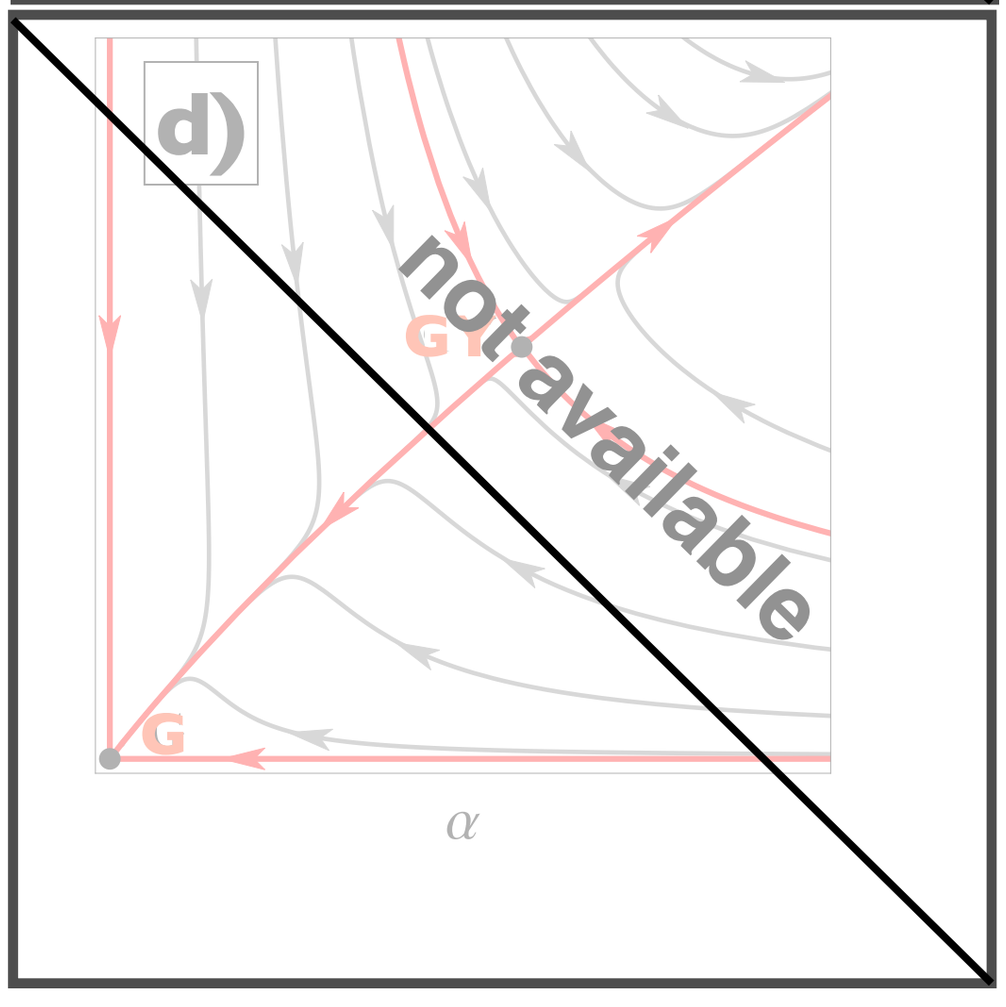
N=2 SUSY







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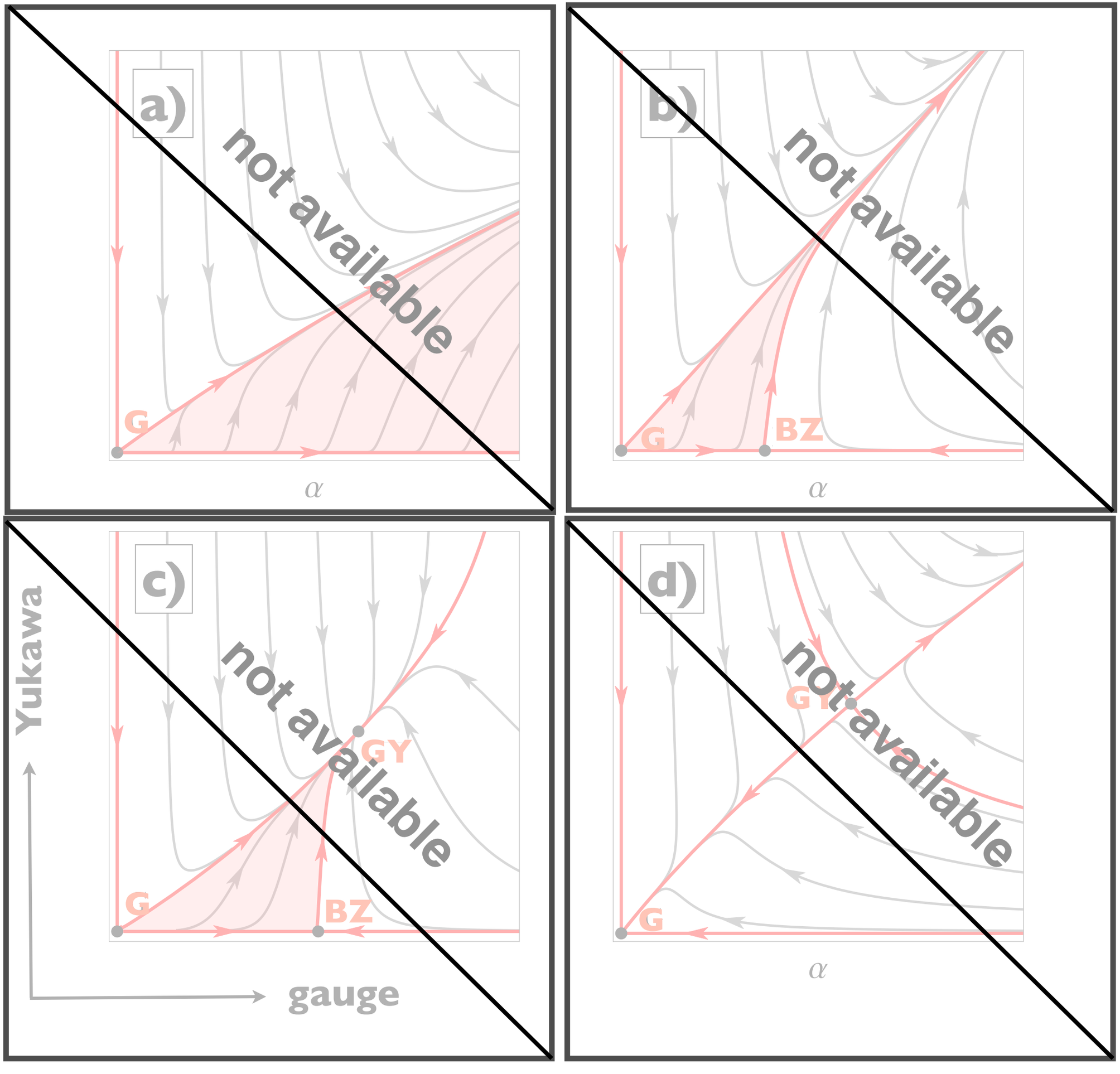
N=4 SUSY



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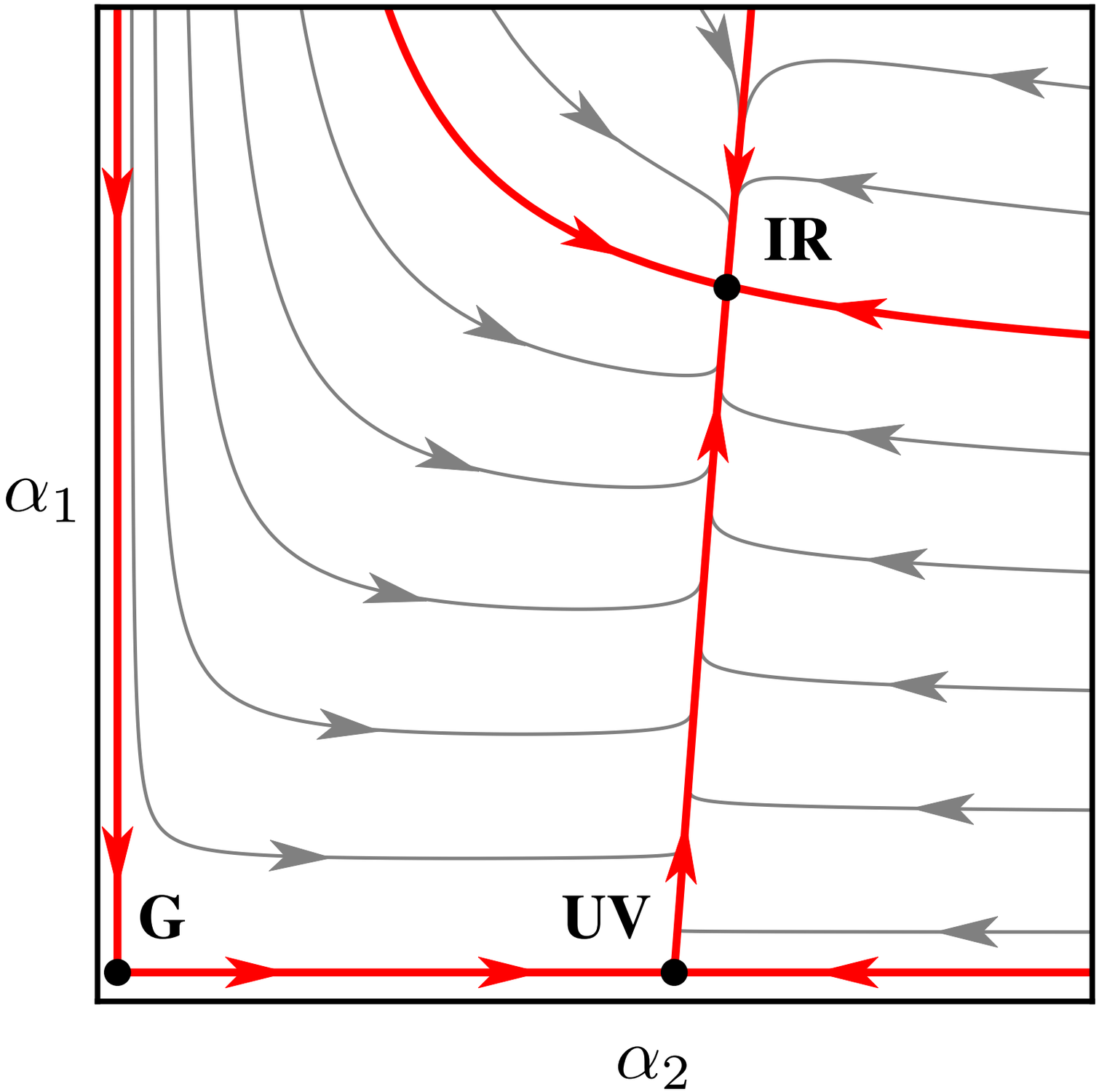
Susy UV fixed point



SU(N)xSU(M)
+ super-
potential

"Susy
enhances
predictivity"

AD Bond, DF Litim, **Asymptotic Safety Guaranteed in Supersymmetry,** 1709.06953 (PRL)

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why no UV BZ?

gauge coupling

$$\alpha = \frac{g^2}{(4\pi)^2}$$

$$\beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

weakly coupled fixed point

$$0 < \alpha^* = B/C \ll 1$$

competition between matter and gauge fields

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why no UV BZ?

$$C = \frac{2}{11}\Big[\,2S_2^F\left(11C_2^F + 7C_2^G\right) + 2S_2^S\left(11C_2^S - C_2^G\right) - 17B\,C_2^G\,\Big]$$

> 0 > 0

must have

$$C_2^S < \frac{1}{11}C_2^G$$

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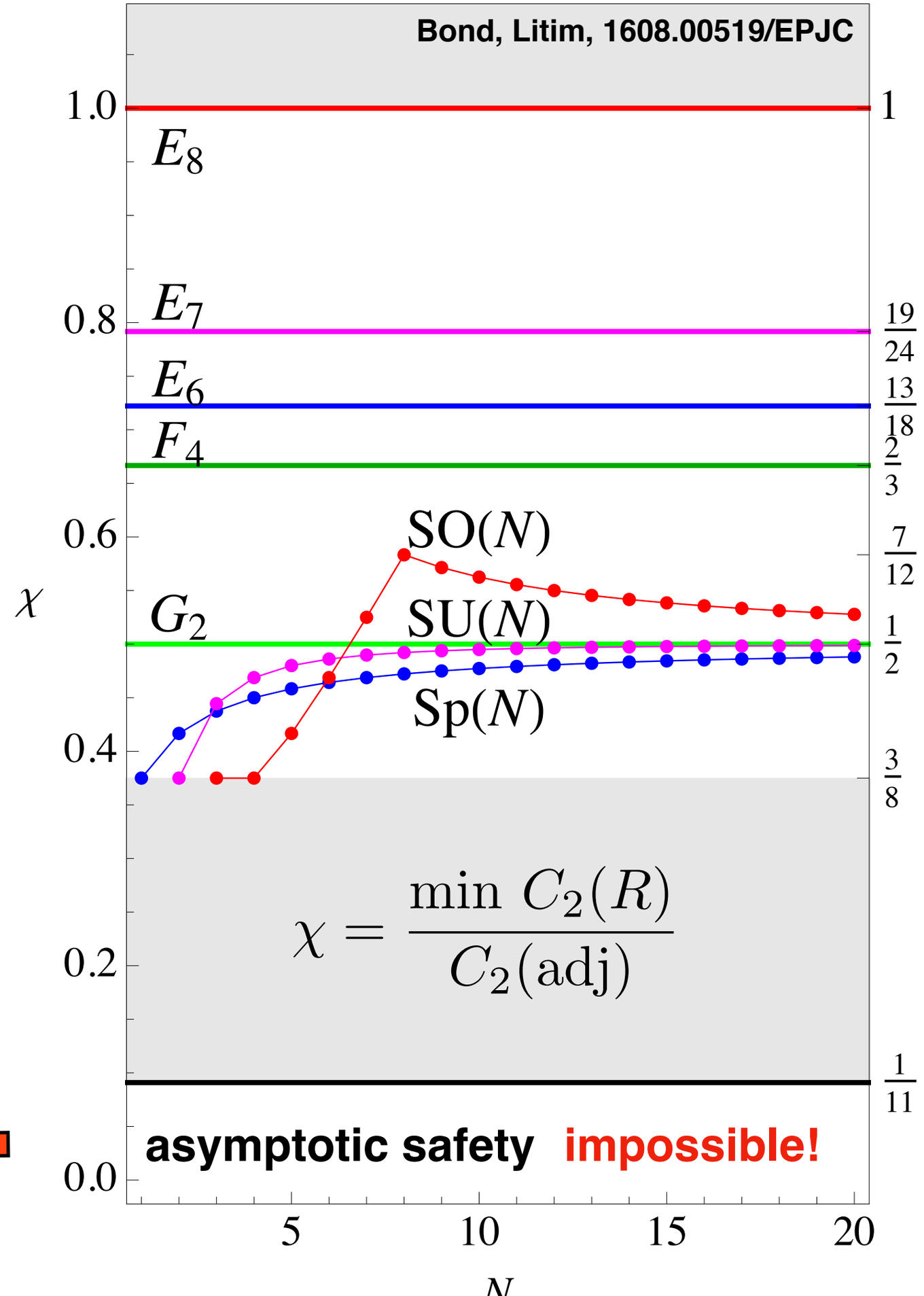
here's why.



weakly coupled BZ are never UV

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summary

Case	Condition	Fixed Point
$i)$	$g_i = \mathbf{Y}^A_{JK} = \lambda_{ABCD} = 0$	Gaussian
$ii)$	some $g_i \neq 0$, all $\mathbf{Y}^A_{JK} = 0$	Banks-Zaks
$iii)$	some $g_i \neq 0$, some $\mathbf{Y}^A_{JK} \neq 0$	gauge-Yukawa

asymptotic safety requires **all types** of matter fields

Yukawa couplings are key

works with **supersymmetry**

AD Bond, DF Litim, **Price of Asymptotic Safety,** PRL 122 (2019) 211601 [1801.08527]

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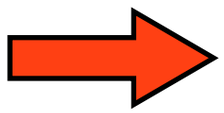
implications

- particle physics: **UV complete 4D theories** (free or safe) require non-abelian gauge fields



asymptotic **freedom** and asymptotic **safety** are **two sides of one and the same medal**

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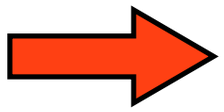
implications

- particle physics: **UV complete 4D theories** (free or safe) require non-abelian gauge fields



new BSM territory to UV-complete the Standard Model

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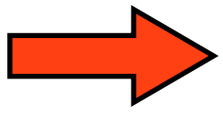
implications

- particle physics: **UV complete 4D theories** (free or safe) require non-abelian gauge fields

- statistical physics: **universality class** of any weakly coupled 4D critical point contains non-abelian gauge fields



systematic classification of weak critical points in 4D

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implications

- particle physics: **UV complete 4D theories** (free or safe) require non-abelian gauge fields

- statistical physics: **universality class** of any weakly coupled 4D critical point contains non-abelian gauge fields

- conformal field theory: **any** weakly-coupled **4D CFT** contains non-abelian gauge fields

"any QFT under perturbative control in the deep UV or IR asymptotes to a conformal field theory"

Polchinski '88
Luty, Polchinski, Rattazzi, '12

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implications

- particle physics: **UV complete 4D theories** (free or safe) require non-abelian gauge fields

- statistical physics: **universality class** of any weakly coupled 4D critical point contains non-abelian gauge fields

- conformal field theory: **any** weakly-coupled **4D CFT** contains non-abelian gauge fields

→ QFT offers infinitely many 4D CFTs
access to CFT data
complementary to conformal bootstrap

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implications

- particle physics: **UV complete 4D theories** (free or safe) require non-abelian gauge fields

- statistical physics: **universality class** of any weakly coupled 4D critical point contains non-abelian gauge fields

- conformal field theory: **any** weakly-coupled **4D CFT** contains non-abelian gauge fields

asymptotic safety BSM

A Bond, G Hiller, K Kowalska, DF Litim, **Directions for model building from asymptotic safety,** JHEP1708 (2017) 004
G Hiller, C Hermigos-Feliu, DF Litim, T Steudtner, **Asymptotically safe extensions of the Standard Model and their flavour phenomenology,** Moriond (EW2019) 1905.11020

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asymptotic safety beyond the SM

minimal framework:

SM gauge symmetry

AD Bond, G Hiller, K Kowalska, DF Litim, 1702.01727 (JHEP)

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

N_F **flavors of BSM fermions** $\psi_i(R_3, R_2, Y)$

BSM singlet scalars S_{ij}

features: **vector-like fermions**

global flavor symmetry $U(N_F) \times U(N_F)$

single BSM Yukawa coupling

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U(1)Y BSM

BSM matter charged under U(1)Y

model	parameter (R_3, R_2, N_F)	UV fixed points α_3^*	α_2^*	α_y^*	AF for $U(1)_Y$	info
A	$(\mathbf{1}, \mathbf{4}, 12)$	0	0.2407	0.3385	$Y > 0.228$	$\mathbf{FP_2}$ ●
B	$(\mathbf{10}, \mathbf{1}, 30)$	0.1287	0	0.1158	$Y > 0.107$	$\mathbf{FP_3}$ ■
		0.1292	0.2769	0.1163	$Y > 0.114$	$\mathbf{FP_4}$ ♦
C	$(\mathbf{10}, \mathbf{4}, 80)$	0.3317	0	0.0995	$Y > 0.024$	$\mathbf{FP_3}$ ■
		0.0503	0.0752	0.0292	$Y > 0.050$	$\mathbf{FP_4}$ ♦
		0	0.8002	0.1500	$Y > 0.018$	$\mathbf{FP_2}$ ●
D	$(\mathbf{3}, \mathbf{4}, 290)$	0	0.0895	0.0066	$Y > 0.042$	$\mathbf{FP_2}$ ●
		0.0416	0.0615	0.0056	$Y > 0.052$	$\mathbf{FP_4}$ ♦
E	$(\mathbf{3}, \mathbf{3}, 72)$	0.1499	0.2181	0.0471	$Y > 0.073$	$\mathbf{FP_4}$ ♦

lower bounds on hypercharge

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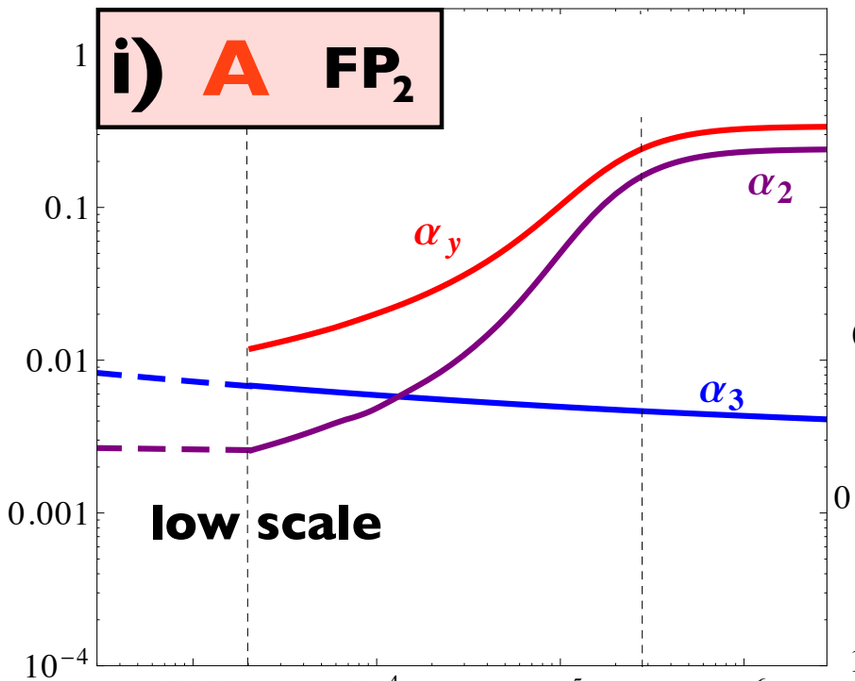
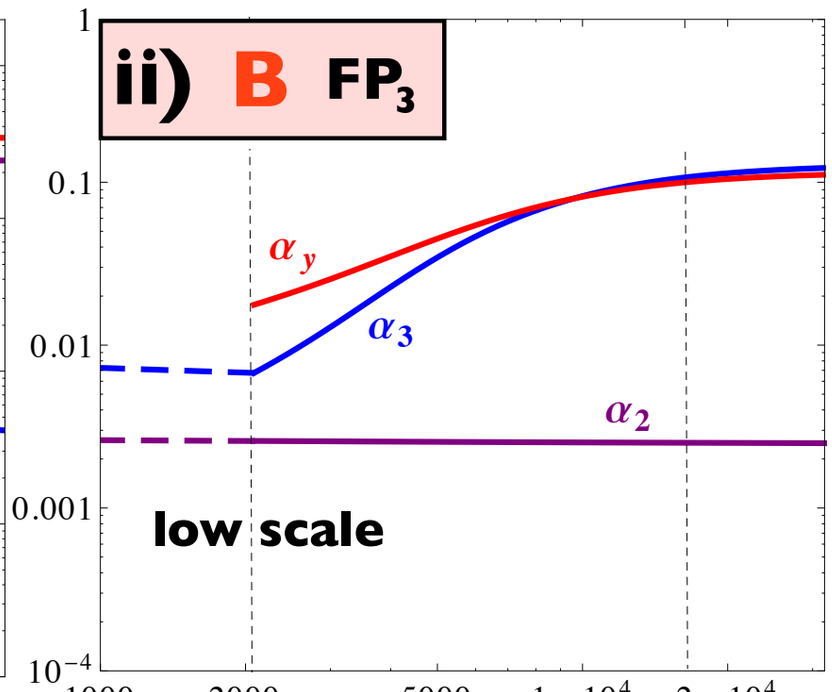
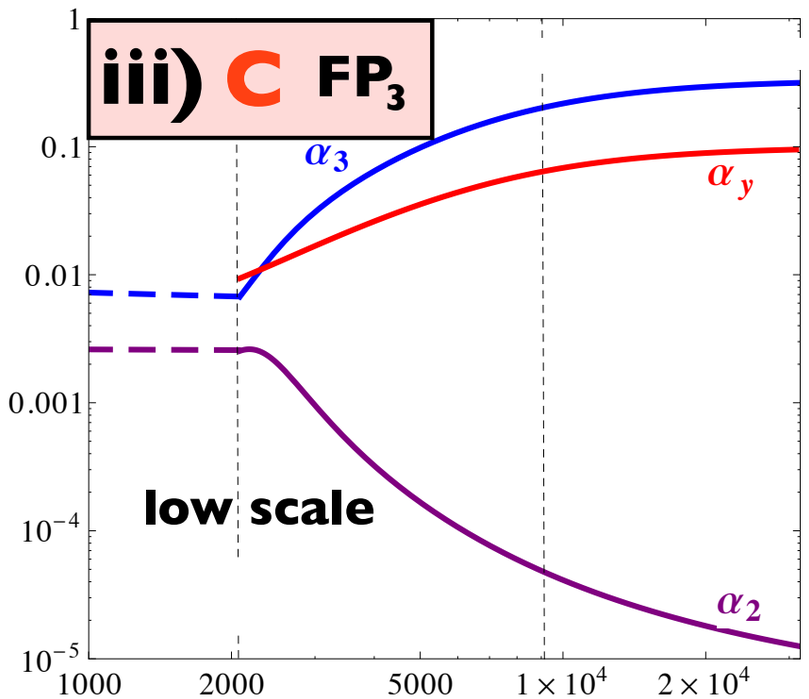
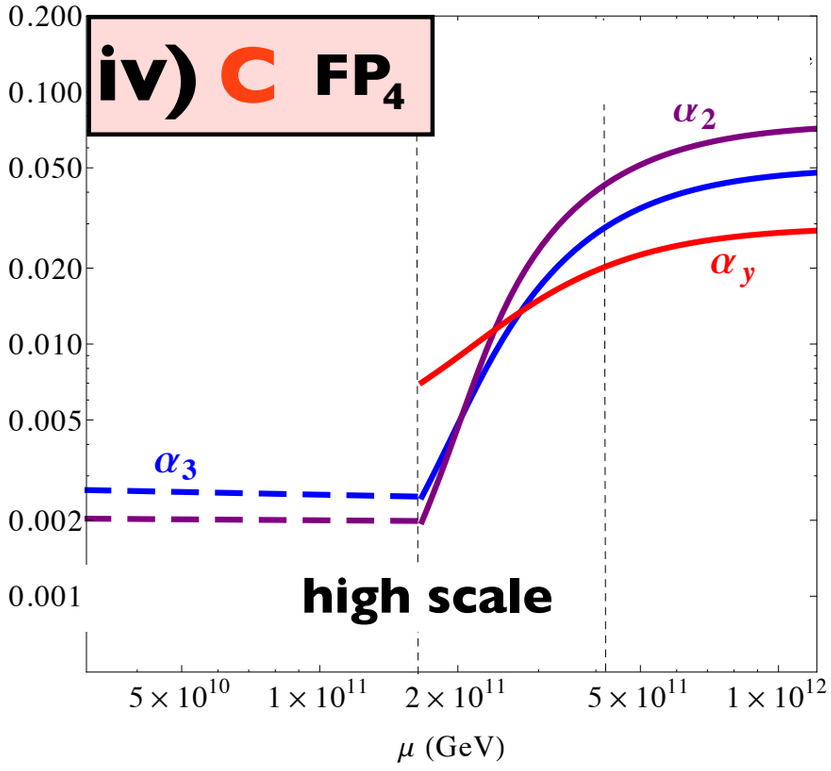
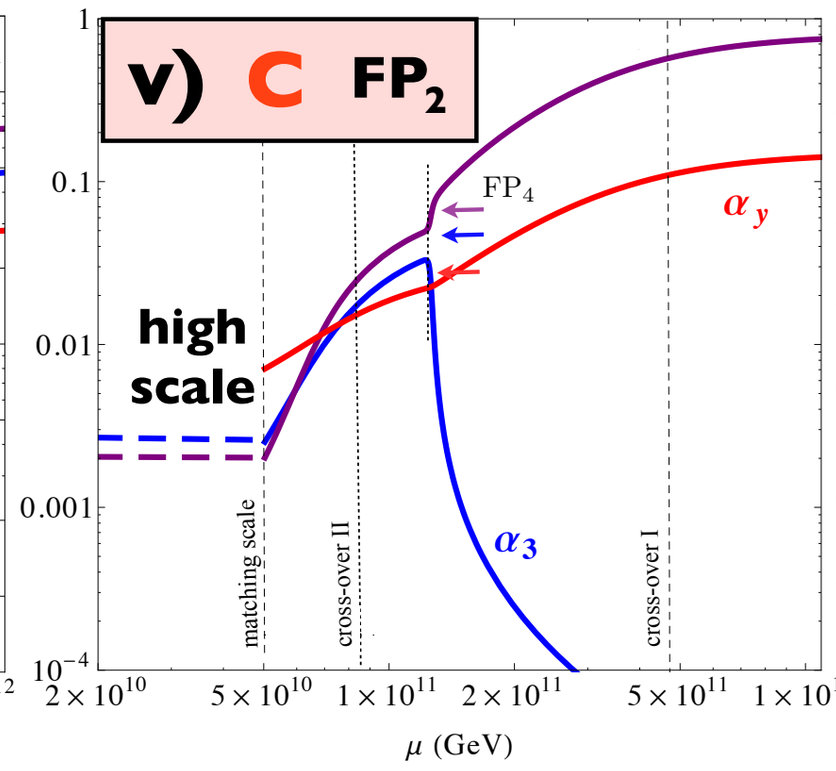
UV fixed points

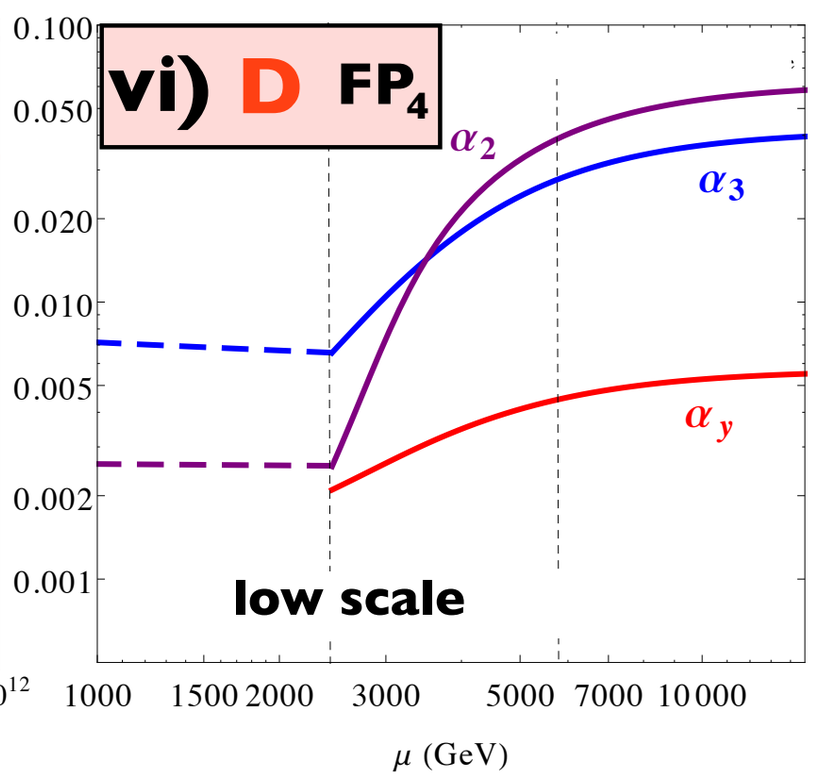












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LHC exclusion bounds

lower limits on the mass of long-lived colored particles that form QCD bound states; exclusion data from ATLAS & CMS (pair production)

$\psi(R_3, R_2)$	$R_2 = 1$		$R_2 = 2$		$R_2 = 3$	
R_3	C_3	$M_\psi^{\min}$ (TeV)	C_3	$M_\psi^{\min}$ (TeV)	C_3	$M_\psi^{\min}$ (TeV)
3	$5\frac{1}{3}$	(1.3)	$10\frac{2}{3}$	(1.4)	16	1.5
6	$66\frac{2}{3}$	1.7	$133\frac{1}{3}$	1.8	200	1.9
8	72	1.7	144	1.8	216	1.9
10	360	2.0	720	2.1	1080	2.2
15	$426\frac{2}{3}$	2.0	$853\frac{1}{3}$	2.1	1280	2.2
15′	$1306\frac{2}{3}$	2.2	$2313\frac{1}{3}$	2.3	3920	2.4

AD Bond, G Hiller, K Kowalska, DF Litim, 1702.01727 (JHEP)

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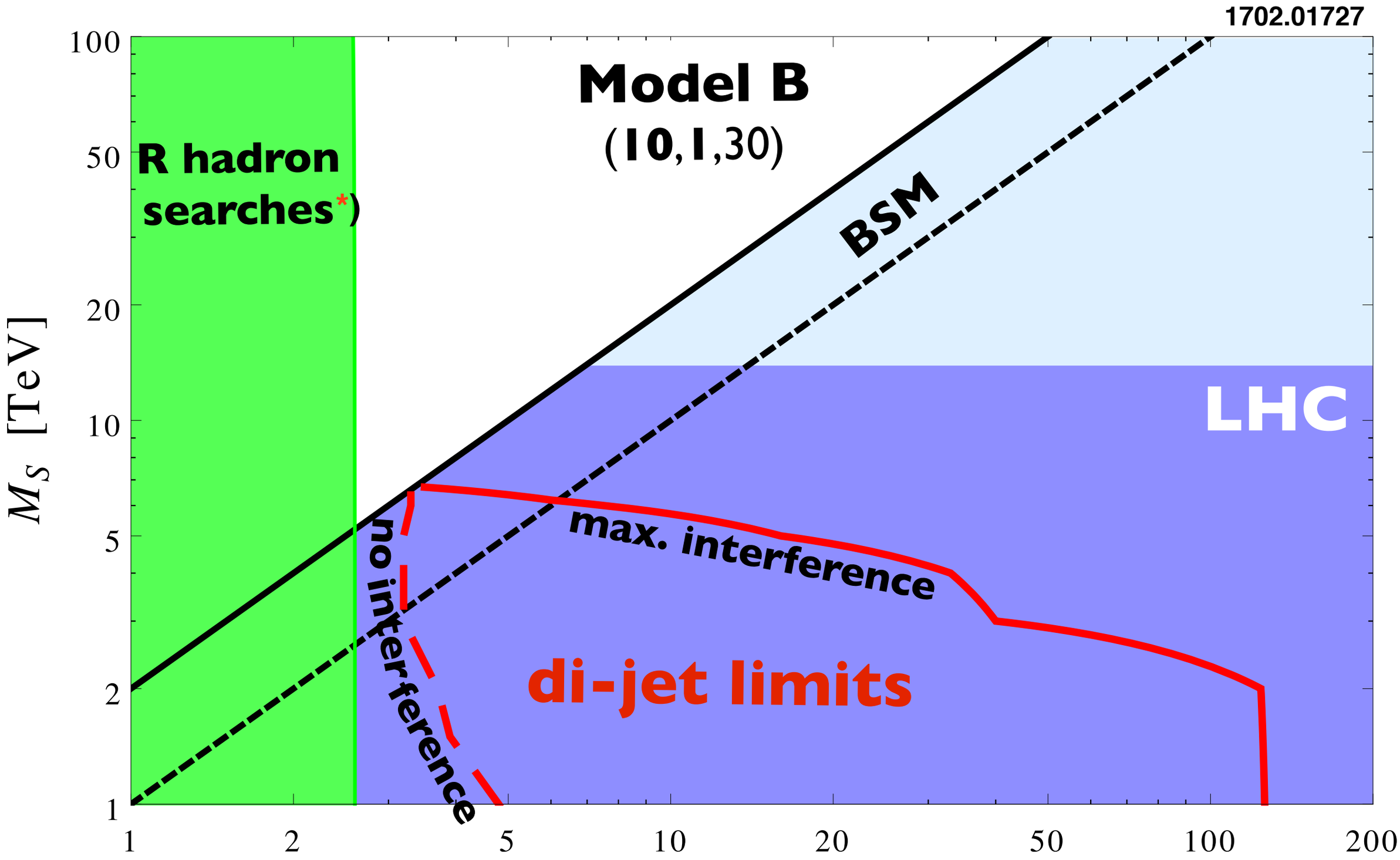
mass exclusion limits



*) fudged from 13 TeV ATLAS + CMS gluino analysis

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fixed points in quantum gravity

gravitation

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physics of classical gravity

Einstein's theory of general relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\Lambda\, g_{\mu\nu} + 8\pi G_N\, T_{\mu\nu}$$

Newton's coupling

$$G_N = 6.7 \times 10^{-11} \frac{\mathrm{m}^3}{\mathrm{kg}\, s^3}$$

cosmological constant

$$\Lambda \approx 10^{-35} s^{-2}$$

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what's new with gravity?

degrees of freedom: spin 2
perturbatively non-renormalisable
Newton's coupling is dimensionful $[G_N] = 2 - D < 0$

asymptotic safety requires large
anomalous dimensions
non-perturbative tools mandatory

Einstein-Hilbert

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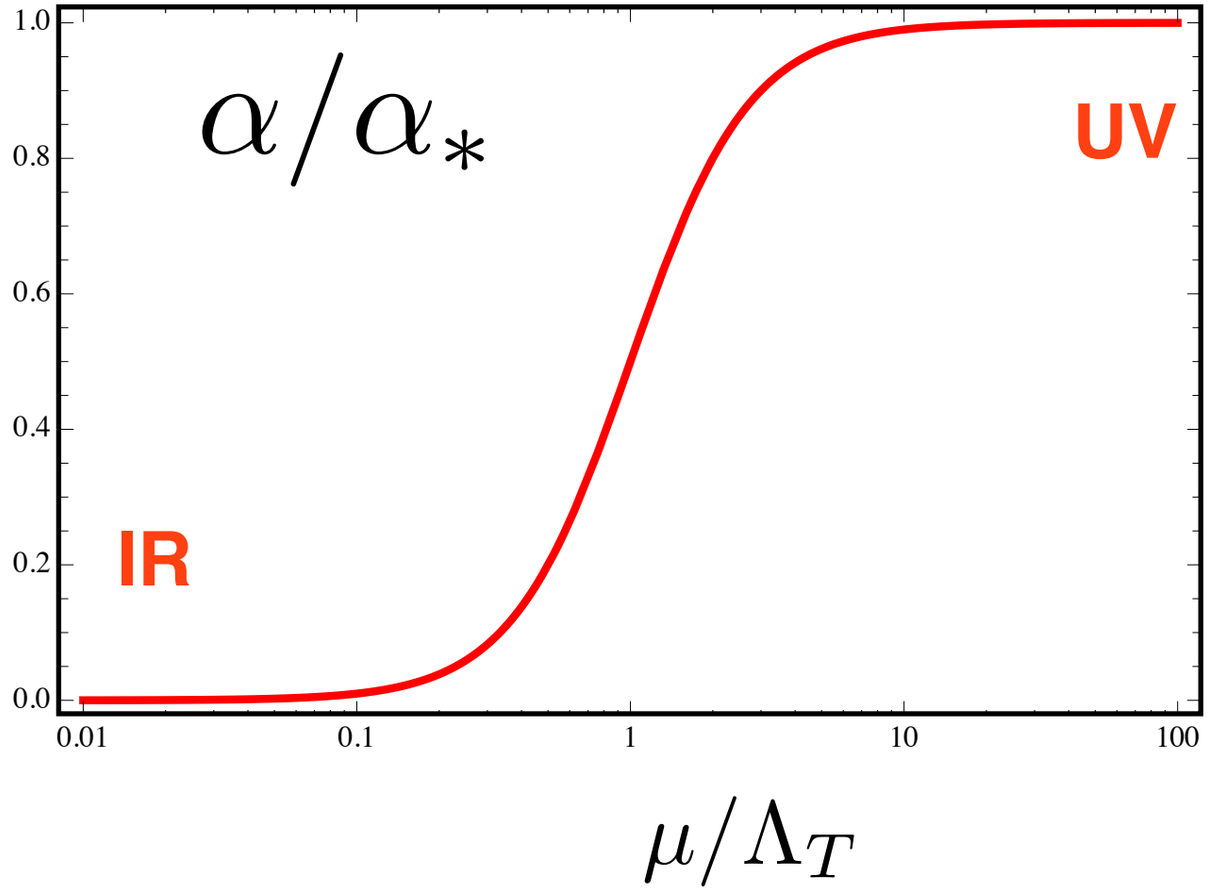
dimension **coupling**

gravitons $D = 2 + \epsilon : \quad \alpha = G_N(\mu)\mu^{D-2}$

Gastmans et al '78
Christensen, Duff '78
Weinberg '79
Kawai et al '90

$G(\mu) \approx G_N$

classical GR



$$G(\mu) \approx \frac{\alpha_*}{\mu^{D-2}}$$

quantum GR

UV fixed point implies weakened gravity

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beyond EH

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

$$\Gamma_k = \int d^4x \sqrt{\det g_{\mu\nu}} \frac{1}{16\pi\, G} \left[-R + 2\Lambda\right] \; + \sum_{n=2}^{N-1} \lambda_n \, R^n$$

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

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beyond EH

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

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

bootstrap search strategy

Falls, DL, Nikolakopoulos, Rahmede '13, '14

1 fix **N**, compute RG flow
2 deduce fixed point and exponents
3 increase **N** to **N+1** and start over at **1**

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beyond EH

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

$$\Gamma_k = \int d^4x \sqrt{\det g_{\mu\nu}} \frac{1}{16\pi\, G} \left[-R + 2\Lambda\right] \; + \sum_{n=2}^{N-1} \lambda_n \, R^n$$

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

up to order

***N* = 2**	Souma, '99, Reuter, Lauscher '01, Litim '03
***N* = 3**	Reuter, Lauscher '01
***N* = 7**	Codello, Percacci, Rahmede '07
***N* = 11**	Bonanno, Contillo,, Percacci '10
***N* = 35**	Falls, Litim, Nikolakopoulos, Rahmede '13, '14, '16
***N* = 71**	Falls, Litim, Schroeder '18

UV fixed point

$$n + \frac{\lambda_n(N)}{\lambda_n(N_{\max})}$$

good convergence

n=2

6

10

14

18

Falls, DL, Schroeder, 1810.08550

N

UV scaling exponents

$\vartheta_n(N)$

good convergence

Falls, Litim, Nikolakopoulos, Rahmede
1301.4191
1410.4815

N

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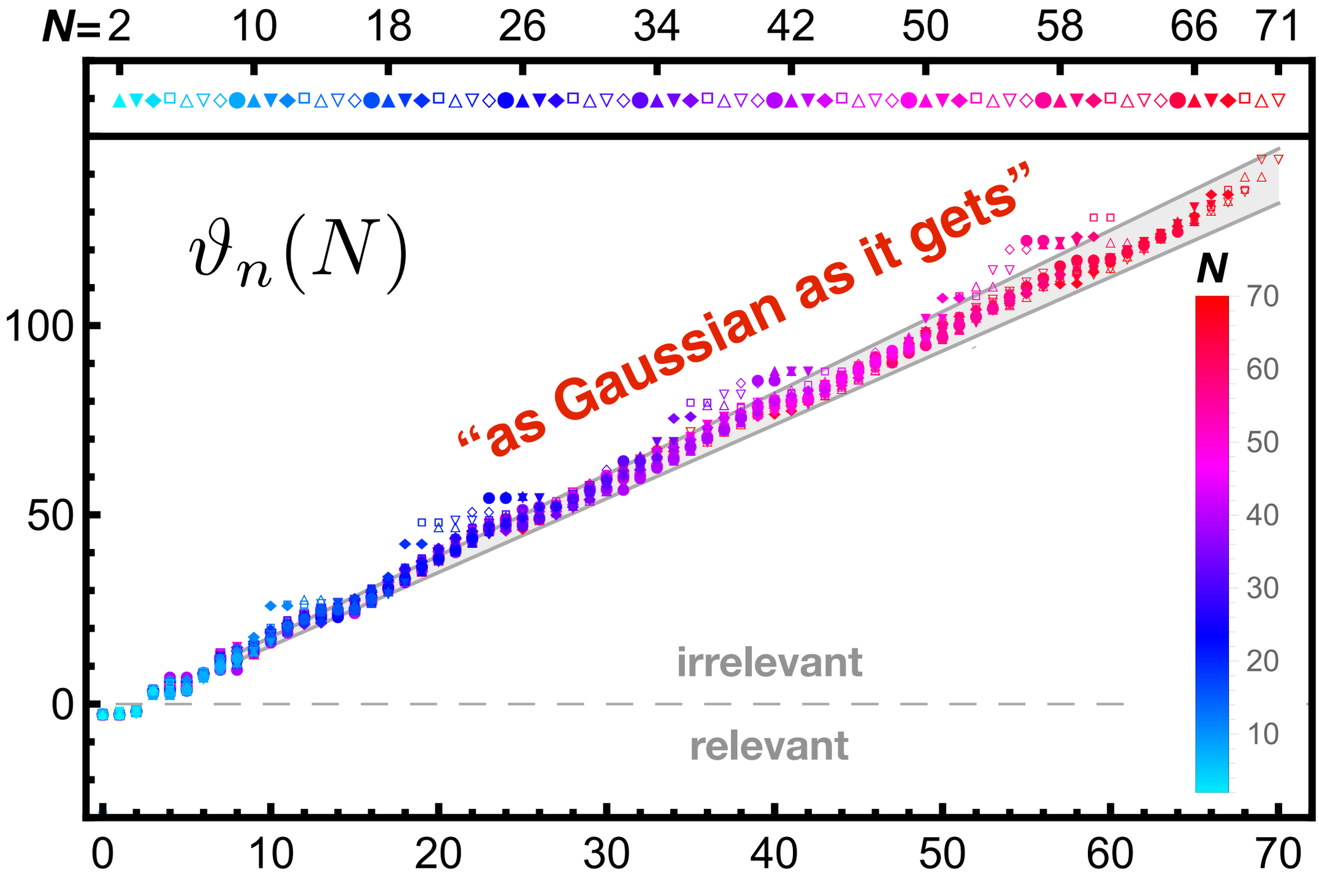
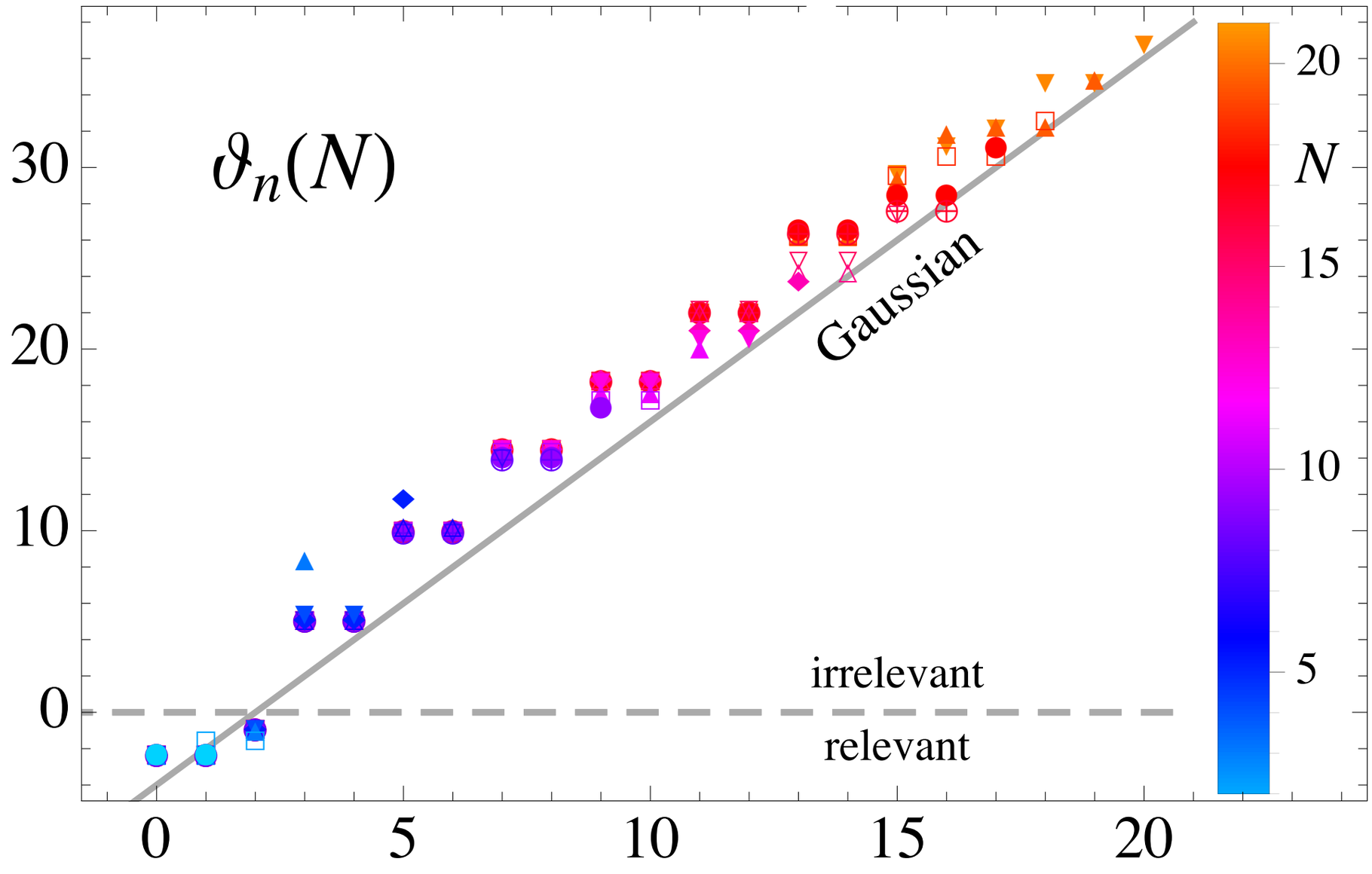


Falls, DL, Nikolakopoulos, Rahmede '13, '14, '16
Falls, DL, Schroeder, '18

Ricci

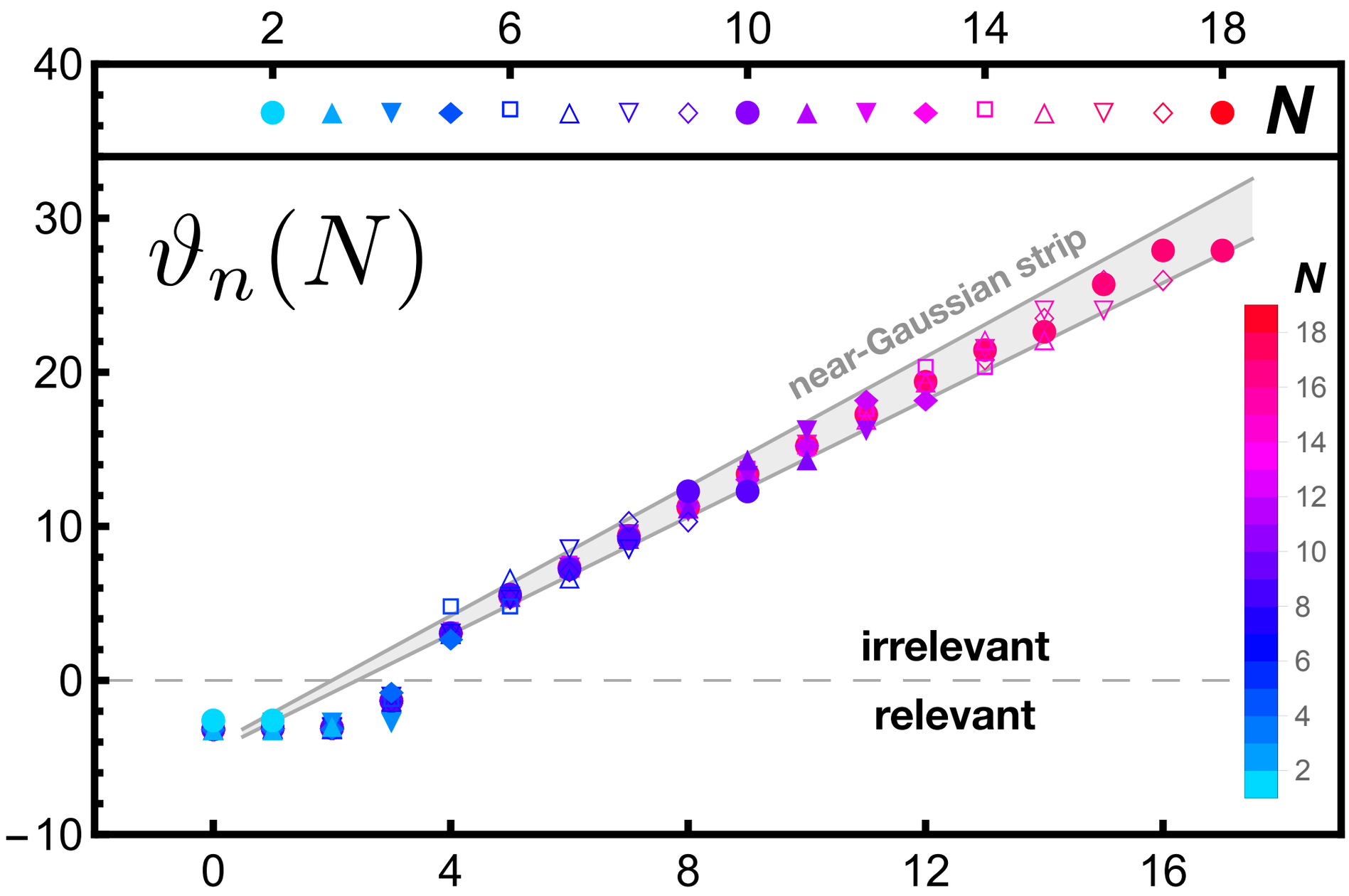
$$\Gamma_k = \int d^d x \sqrt{g} [F_k(\mathrm{Ric}^2) + R \cdot Z_k(\mathrm{Ric}^2)]$$



Falls, King, DL, Nikolakopoulos, Rahmede, '18

Riemann

$$\Gamma_k = \int d^d x \sqrt{g} [F_k(\mathrm{Riem}^2) + R \cdot Z_k(\mathrm{Riem}^2)]$$



Yannick Kluth, DL, Bad Honnef Workshop March 2019 (in prep.)

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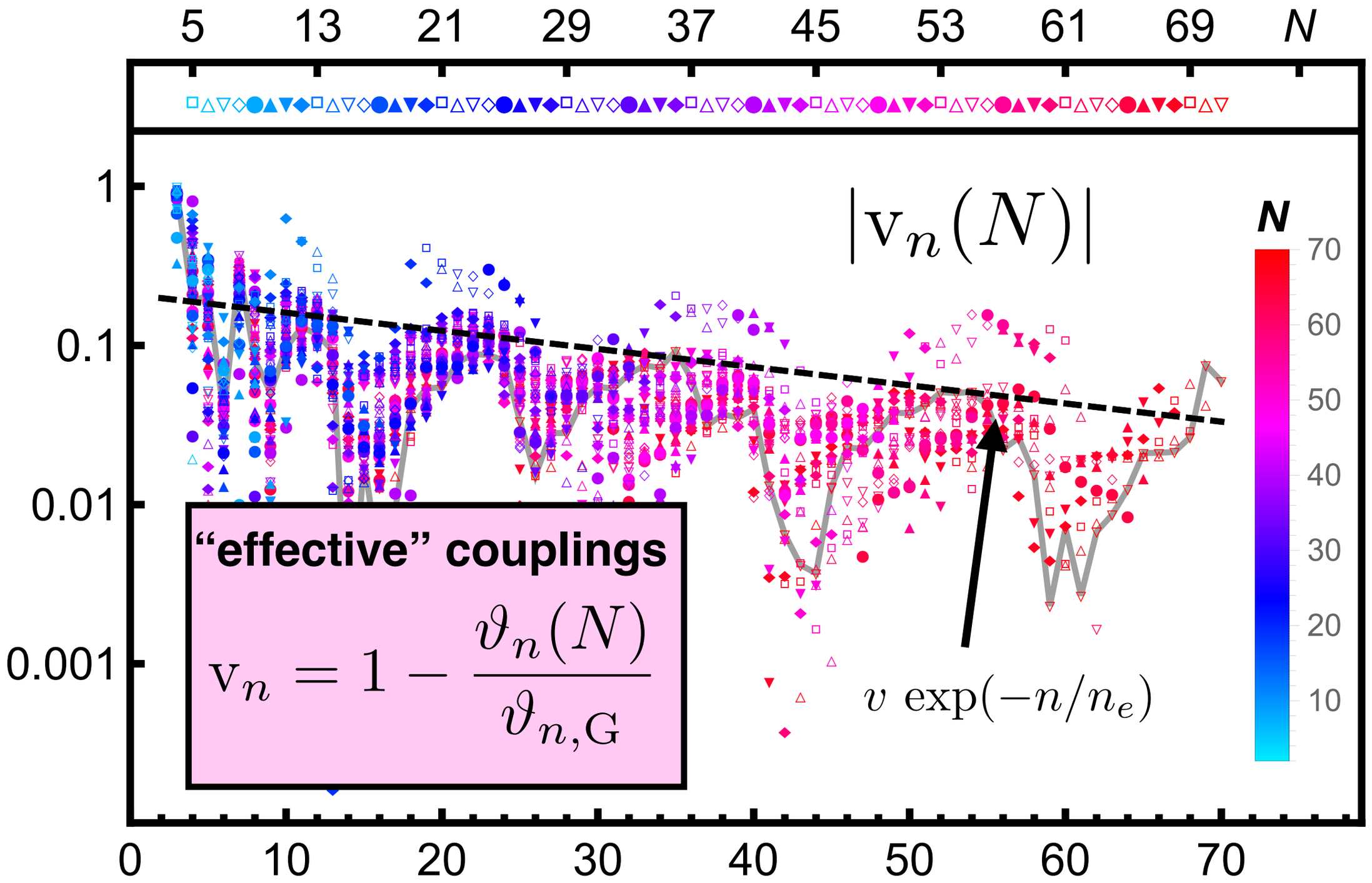
near-Gaussian scaling

signature of weak coupling

weak “effective” coupling



Falls, DL, Nikolakopoulos, Rahmede ’13, ’14, ‘16
Falls, DL, Schroeder, ’18

conclusions

complete
understanding of
asymptotic safety
at weak coupling

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works for
simple, **semi-simple**
and **supersymmetric**
gauge theories,
large variety of
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window of opportunities for model building, BSM physics, dark matter, …

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progress for **asymptotic safety** at strong coupling w or w/o gravity

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