DESY THEORY WORKSHOP

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Quantum field theory meets gravity

Asymptotic safety

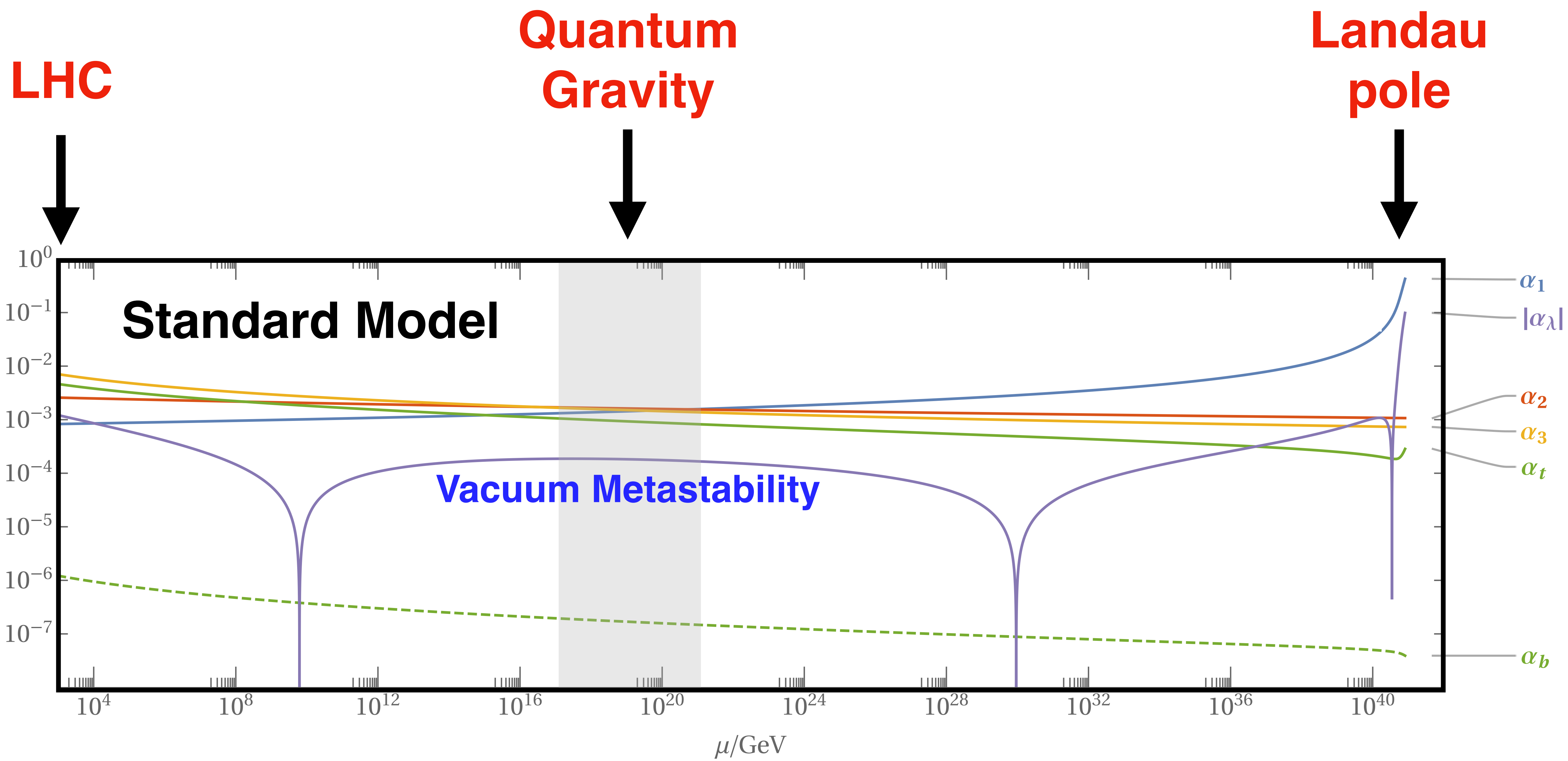
Daniel F Litim

University of Sussex

24 - 27 September 2019

DESY Hamburg, Germany

where are we?


LHC
Quantum Gravity
Landau pole
Standard Model
Vacuum Metastability
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
α_1
$|\alpha_\lambda|$
α_2
α_3
α_t
α_b

what is asymptotic safety?

fundamental QFT ⟷ UV fixed point Wilson '71

asymptotic freedom Gross, Wilzcek '73 Politzer '73 ⟷ free UV fixed point

asymptotic near-freedom Bailin, Love '74

asymptotic safety Weinberg '79 ⟷ interacting UV fixed point

exact asymptotic safety

2+eps	infinite-N non-linear sigma	Brezin, Zinn-Justin '76 Bardeen, Lee, Shrock '76
	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 '02 ⋮

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asymptotic safety in 4d

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4d QFTs

fields vectors A_μ^a , 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

$$L = \frac{1}{4g_a^2} \mathrm{Tr}\, F^a_{\mu\nu} F_a^{\mu\nu} + i\psi_I \not{D} \psi_I + \frac{1}{2}(D_\mu \phi^A)^2$$

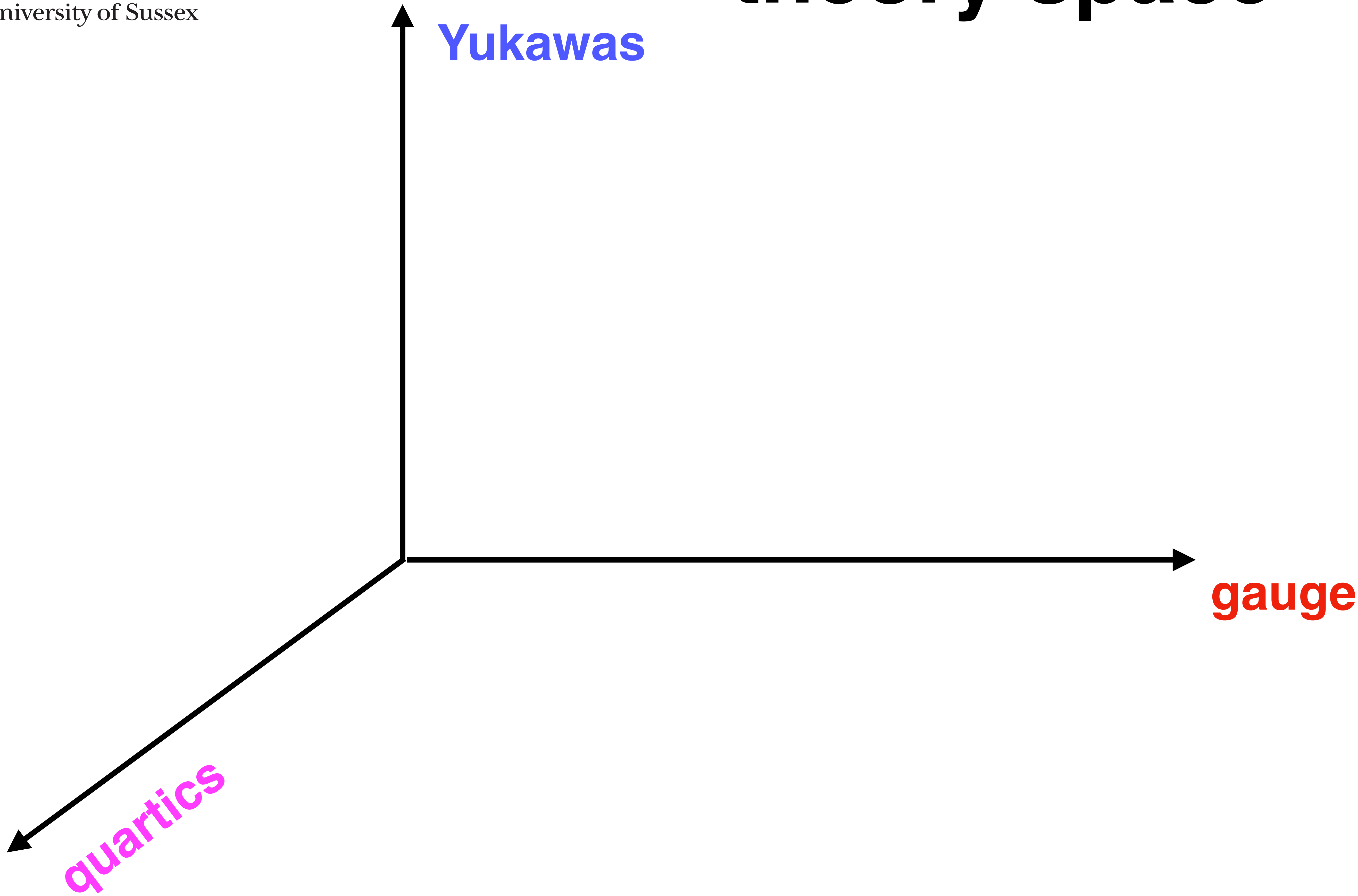
$$+ \frac{1}{2} Y^A{}_{IJ} \phi^A\, \psi_I\, \xi\, \psi_J + \frac{1}{4!} \lambda_{ABCD} \phi^A \phi^B \phi^C \phi^D$$

gauge

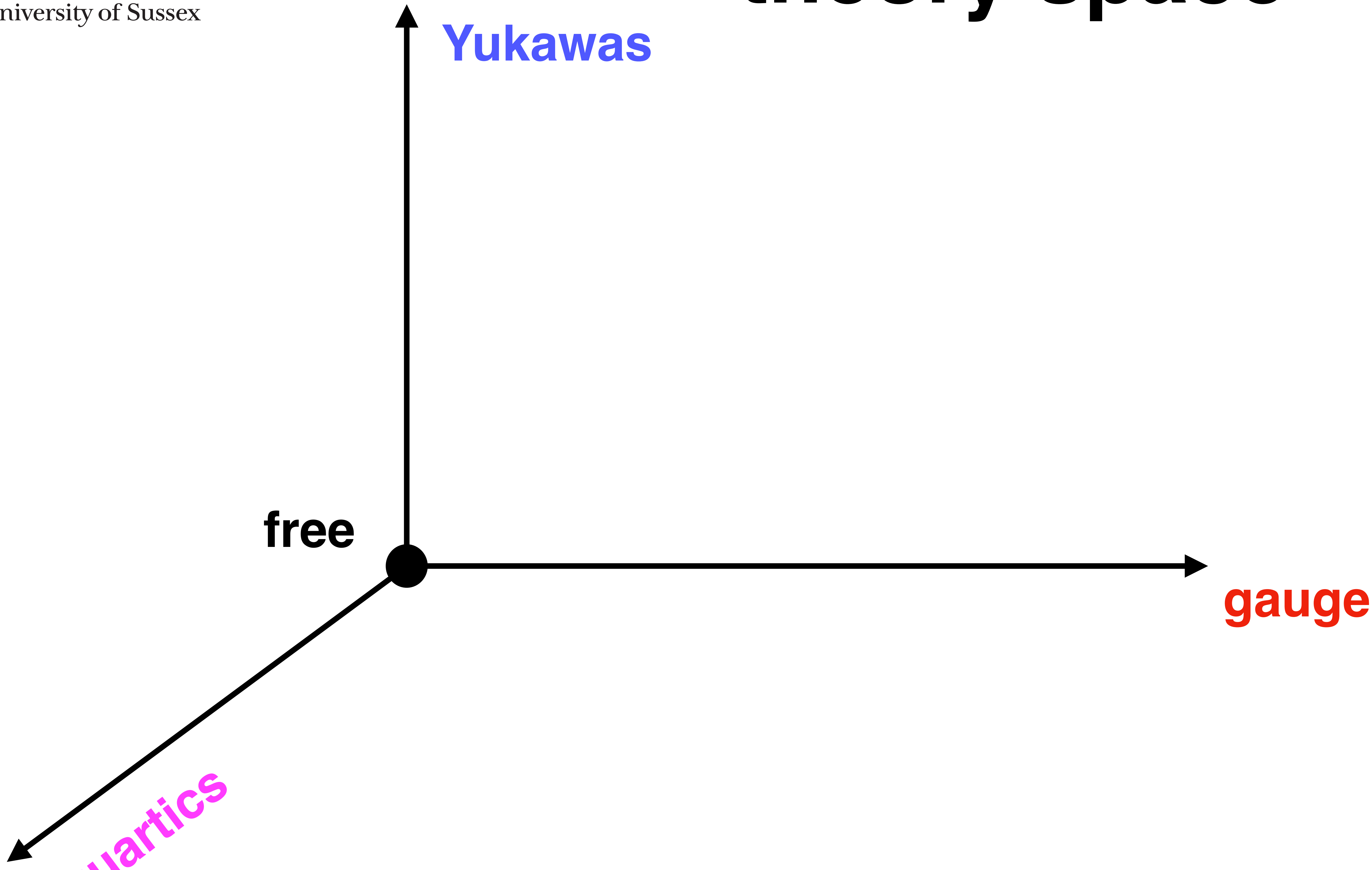
Yukawa

quartics

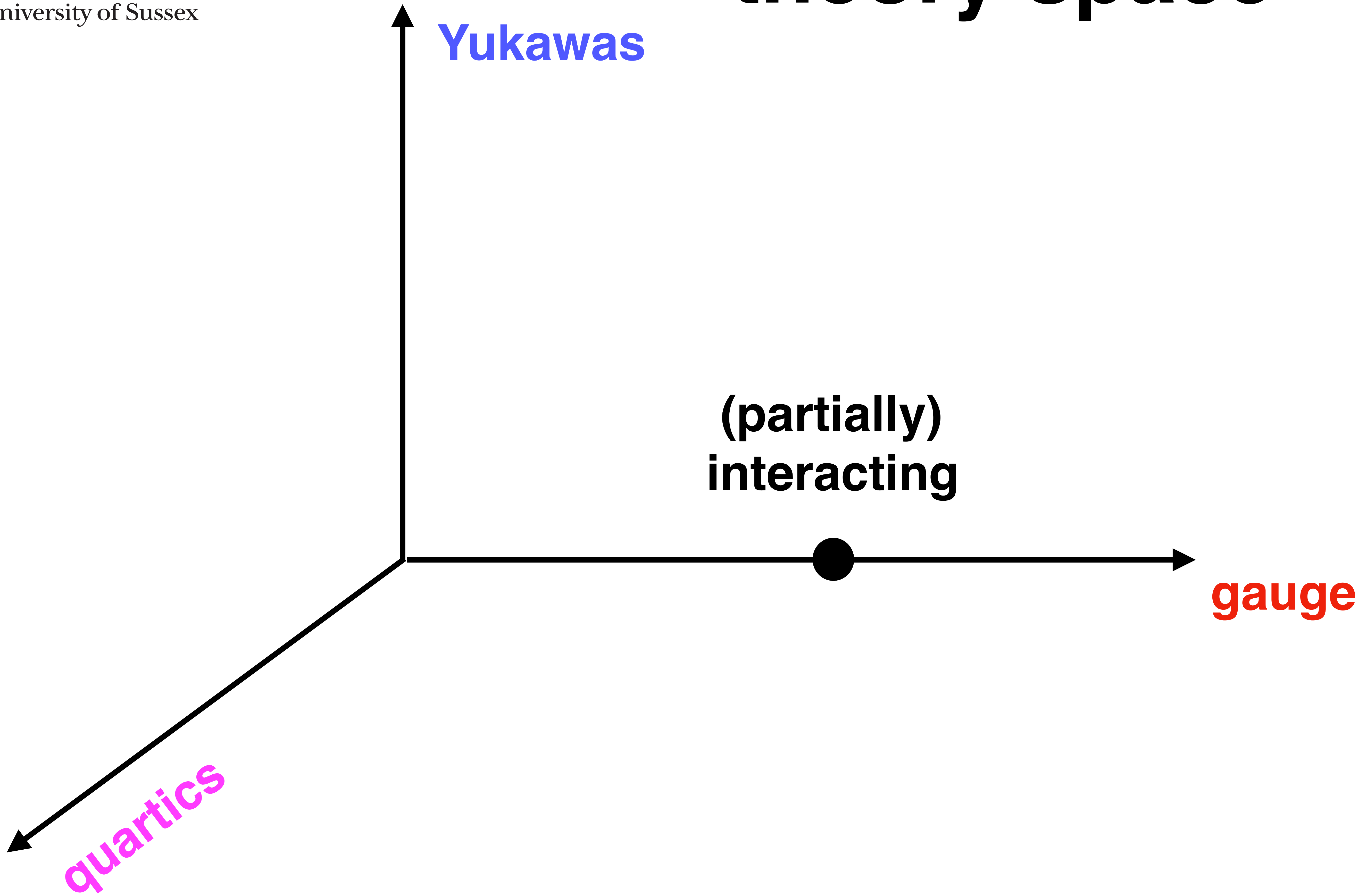
“theory space”



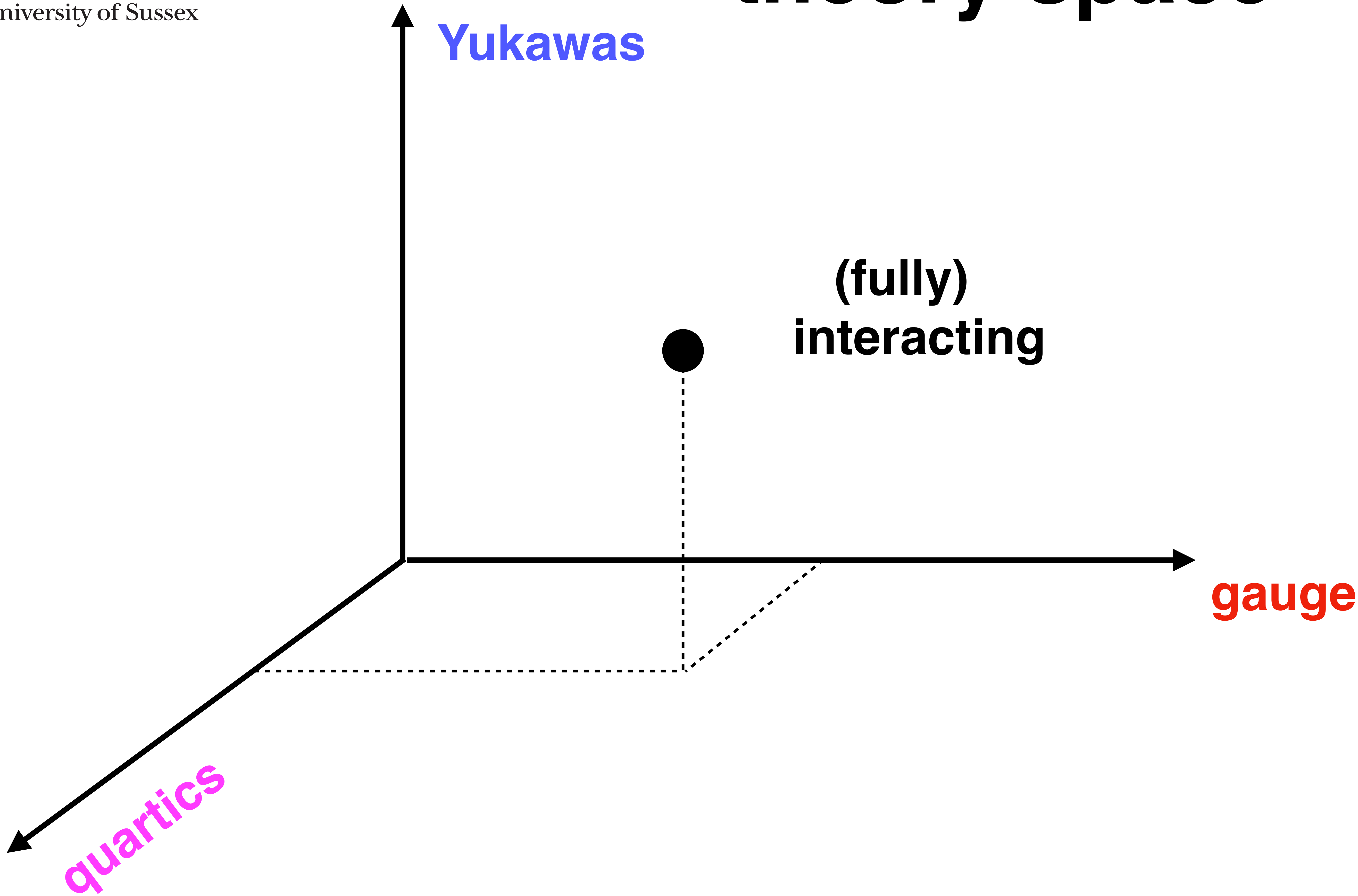
“theory space”



“theory space”



“theory space”



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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

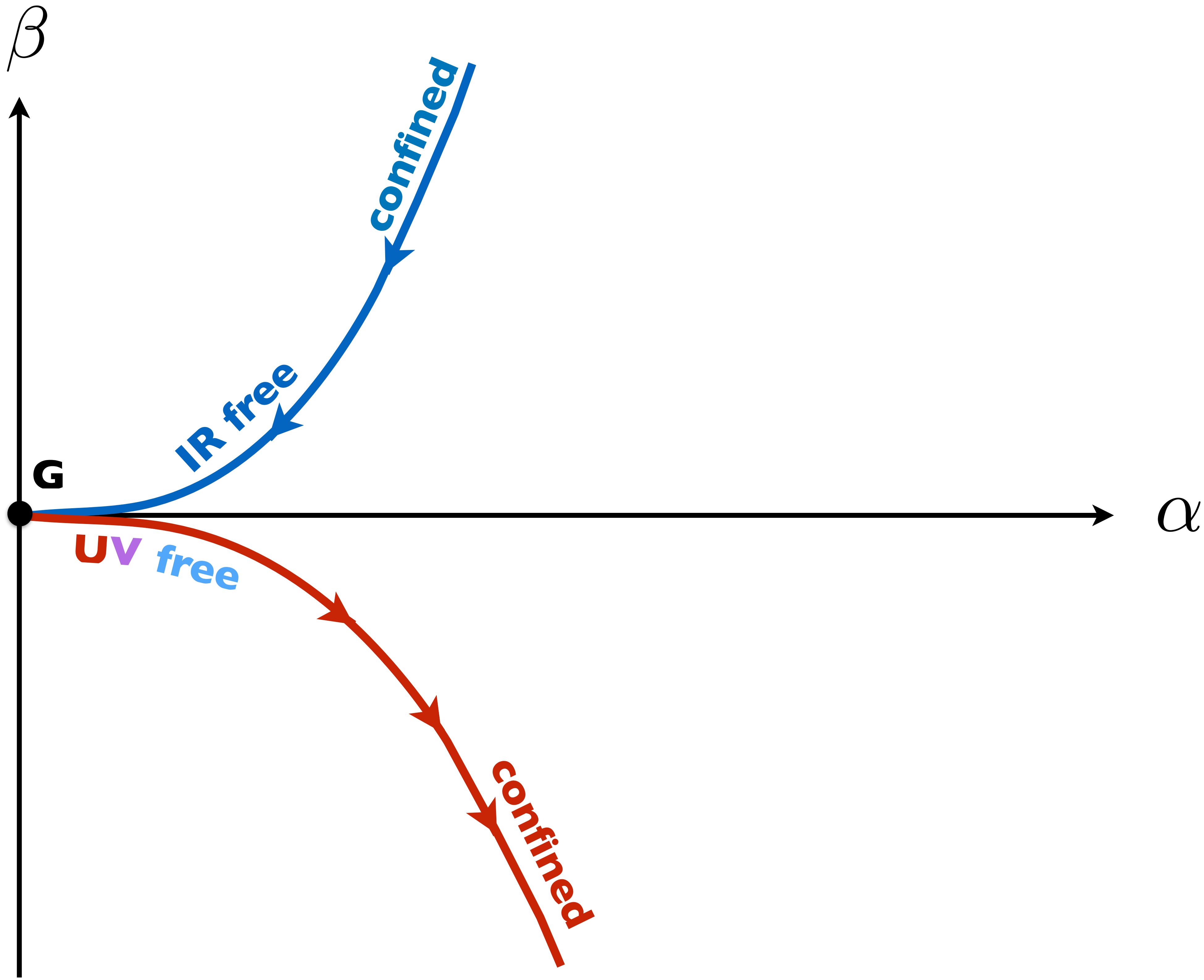
“Banks Zaks”

“gauge Yukawa”

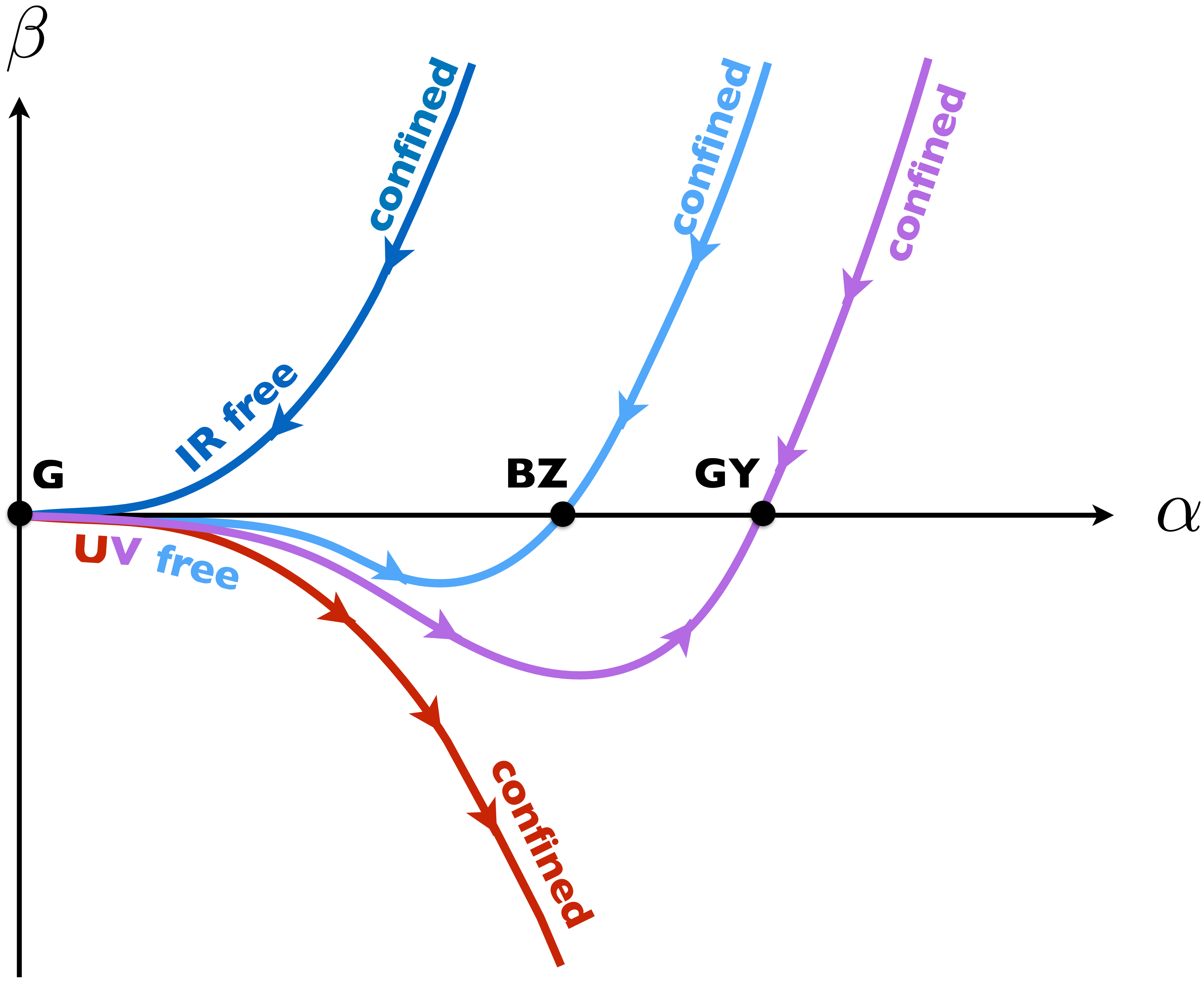
“scalar”

“scalar Yukawa”

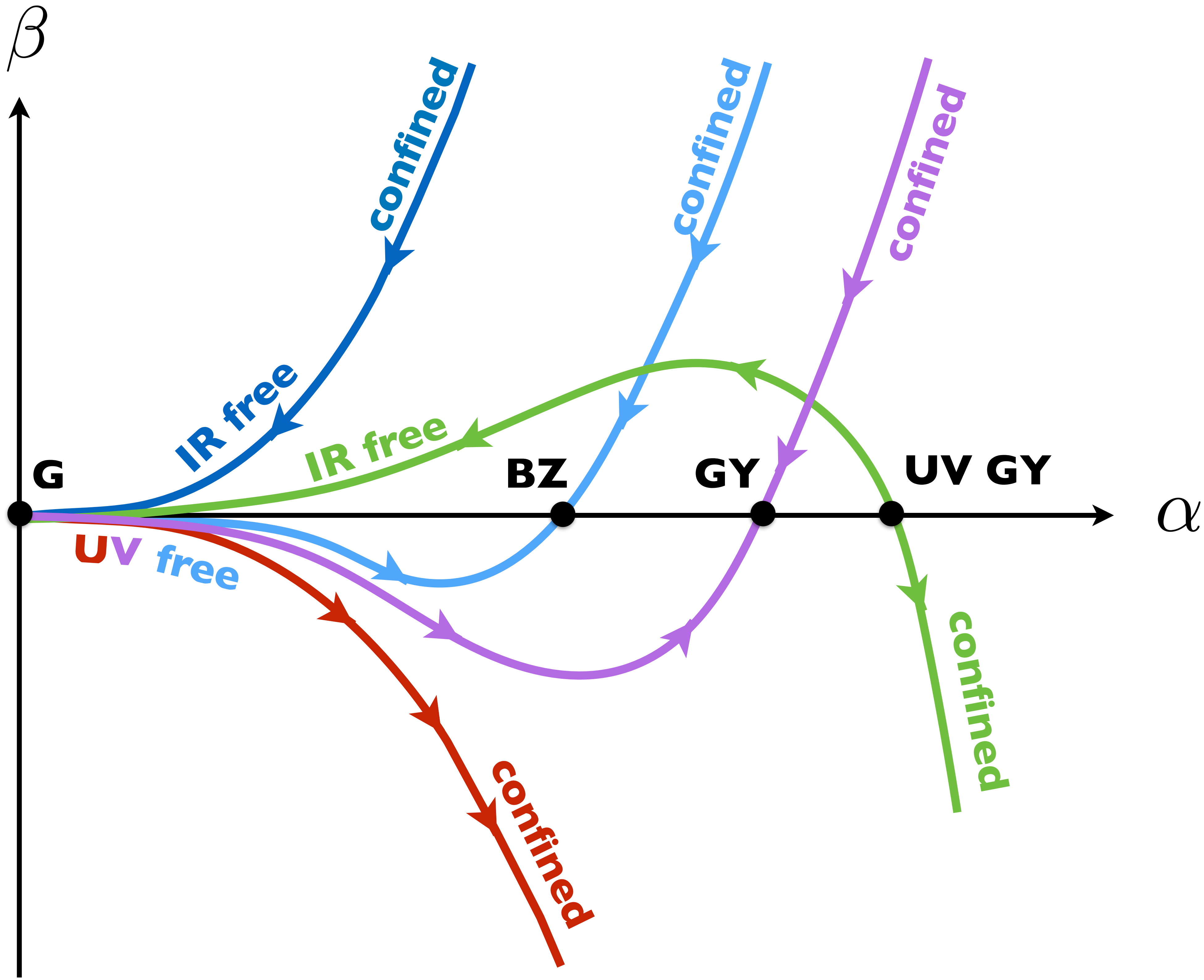
renormalisation group



renormalisation group



renormalisation group



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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 no	IR no	IR UV	no	no	no	no	no

Banks Zaks

gauge Yukawa

scalar

scalar Yukawa

Banks Zaks

gauge Yukawa

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

fixed points

gauge theory

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

weakly coupled fixed point $\quad 0 < \alpha^* = B/C \ll 1$

competition between matter and gauge fields

fixed points

gauge theory

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

weakly coupled fixed point

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

competition between matter and gauge fields

$$B = \frac{2}{3}\left(11 C_2^G - 2 S_2^F - \frac{1}{2} S_2^S\right)$$

$$C = 2\left[\left(\frac{10}{3} C_2^G + 2 C_2^F\right) S_2^F + \left(\frac{1}{3} C_2^G + 2 C_2^S\right) S_2^S - \frac{34}{3}(C_2^G)^2\right]$$

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fixed points

gauge theory

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

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

weakly coupled fixed point $0 < \alpha^* = B/C \ll 1$

competition between matter and gauge fields

$B, C > 0 :$

asymptotic freedom

Banks-Zaks IR FP

Caswell '74

fixed points

gauge theory

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

weakly coupled fixed point $0 < \alpha^* = B/C \ll 1$

competition between matter and gauge fields

$B, C > 0:$ asymptotic freedom
Banks-Zaks IR FP

Caswell '74

$B, C < 0:$ asymptotic safety
UV Banks-Zaks impossible!

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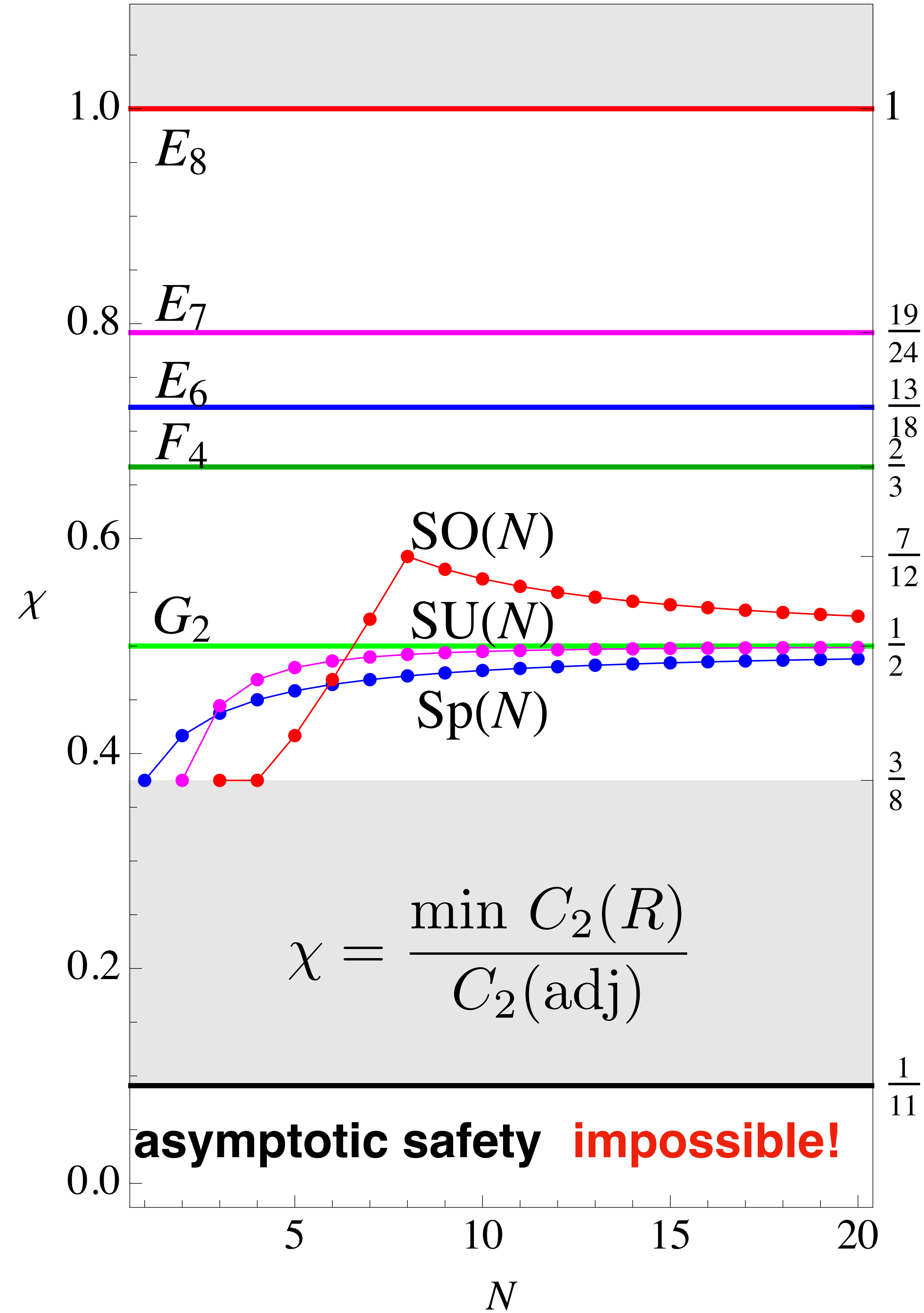
why no UV BZ?

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

> 0   > 0

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

here's why.



weakly coupled BZ are never UV

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asymptotic safety

result

case	gauge group	matter	Yukawa	asymptotic safety
a)	simple	fermions in irreps	No	No
b)	simple or abelian	fermions, any rep	No	No
		scalars, any rep	No	No
		fermions and scalars, any rep	No	No
c)	semi-simple, with or without abelian factors	fermions, any rep	No	No
		scalars, any rep	No	No
		fermions and scalars, any rep	No	No

strict no go theorems

AD Bond, DF Litim 1608.00519/EPJC

can more couplings help?

more gauge couplings	**No** (same sign)
scalar self-couplings	**No** (start at 3- or 4-loop)
Yukawa couplings	**Yes!** (start at 2-loop)

why Yukawas?

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

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

one loop gauge Yukawa

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why Yukawas?

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

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

one loop gauge Yukawa

Yukawas slow down the running of gauge couplings

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basics of asymptotic safety

gauge Yukawa theory

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y \qquad t = \ln \mu/\Lambda$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y \qquad \alpha_* \ll 1$$

interacting UV fixed point provided that

$$\boxed{\begin{aligned} C' = C - \frac{D\,F}{E} &< 0 \\ B &< 0 \end{aligned}}$$

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theorems for asymptotic safety

case	gauge group	matter	Yukawa	asymptotic safety
a)	simple	fermions in irreps	No	No
b)	simple or abelian	fermions, any rep scalars, any rep fermions and scalars, any rep	No No No	No No No
c)	semi-simple, with or without abelian factors	fermions, any rep scalars, any rep fermions and scalars, any rep	No No No	No No No
d)	simple or abelian	fermions and scalars, any rep	Yes	Yes *)
e)	semi-simple, with or without abelian factors	fermions and scalars, any rep	Yes	Yes *)

*) provided certain auxiliary conditions hold true

AD Bond, DF Litim 1608.00519/EPJC

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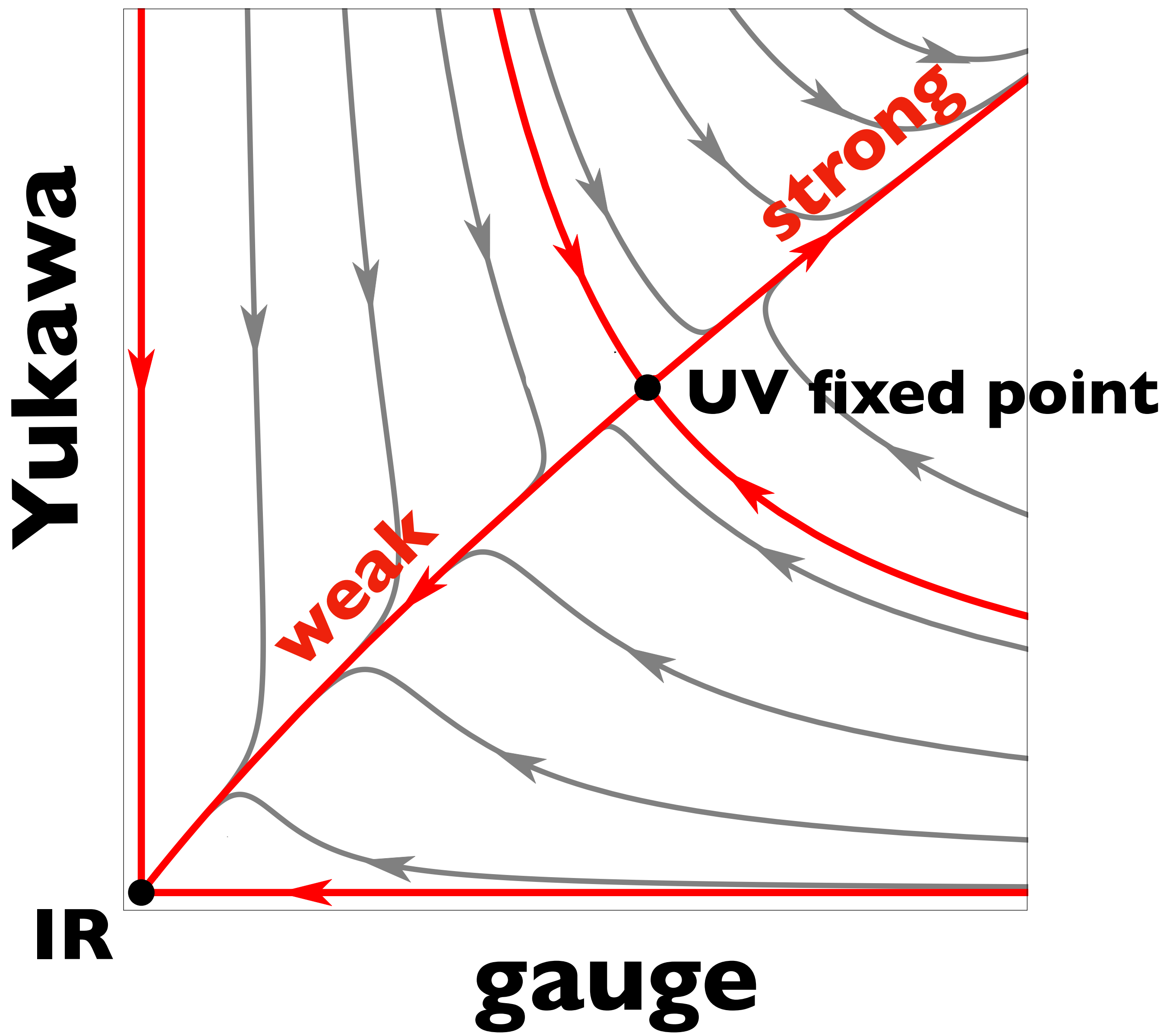
template UV fixed point



SU(N) local
NF fermions
mesons

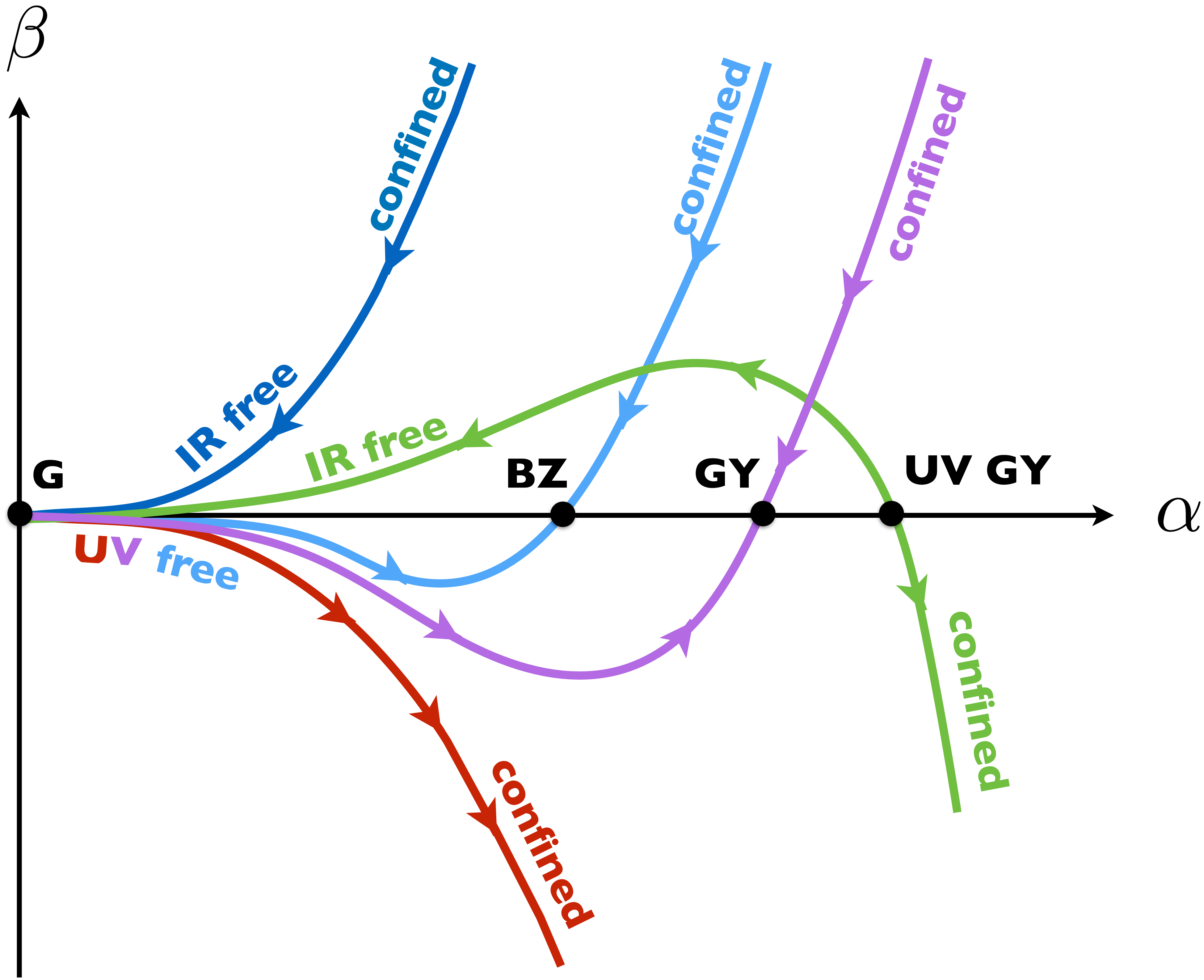
1 gauge
1 Yukawa
2 quartics

SU(Nf)xSU(Nf)
global

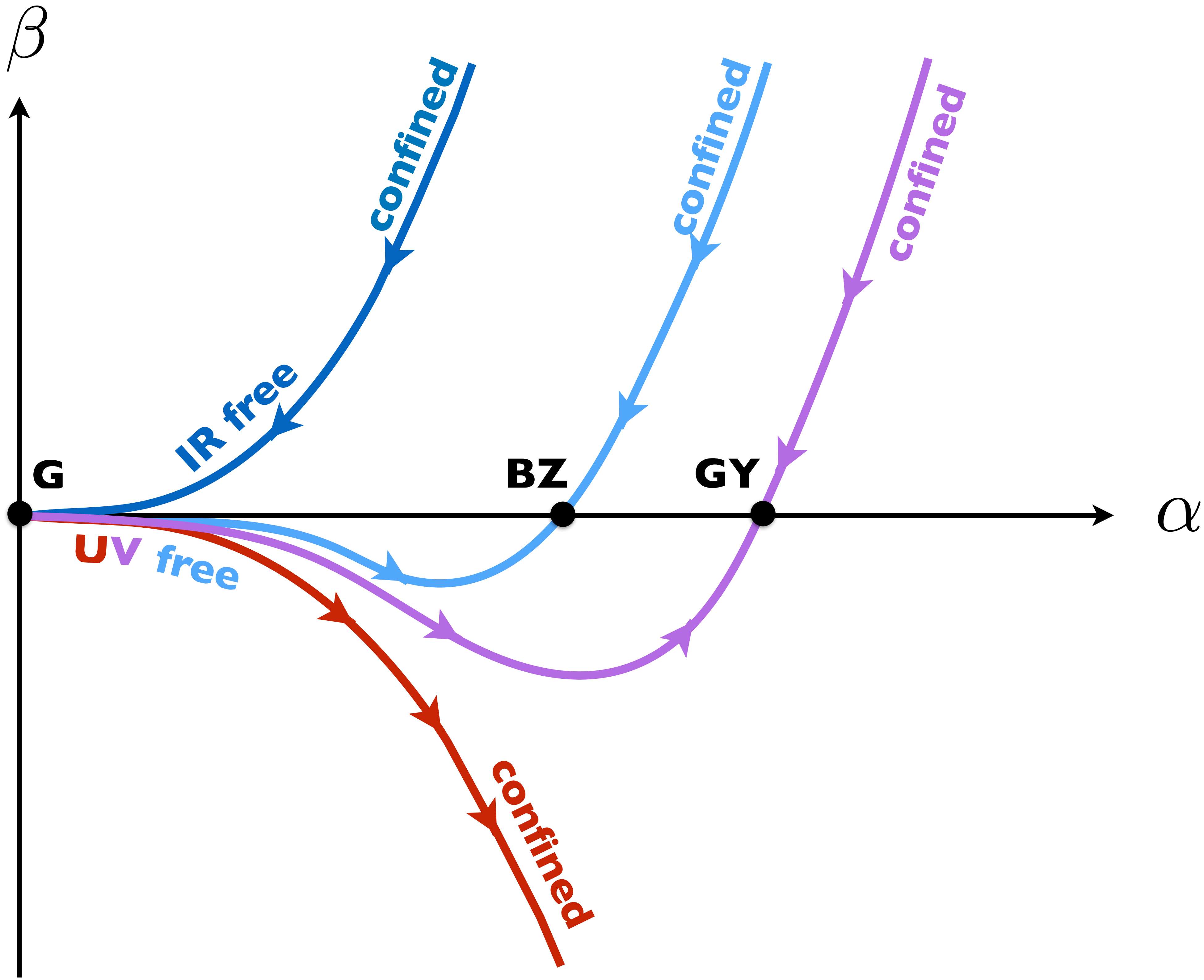
(Veneziano limit)

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

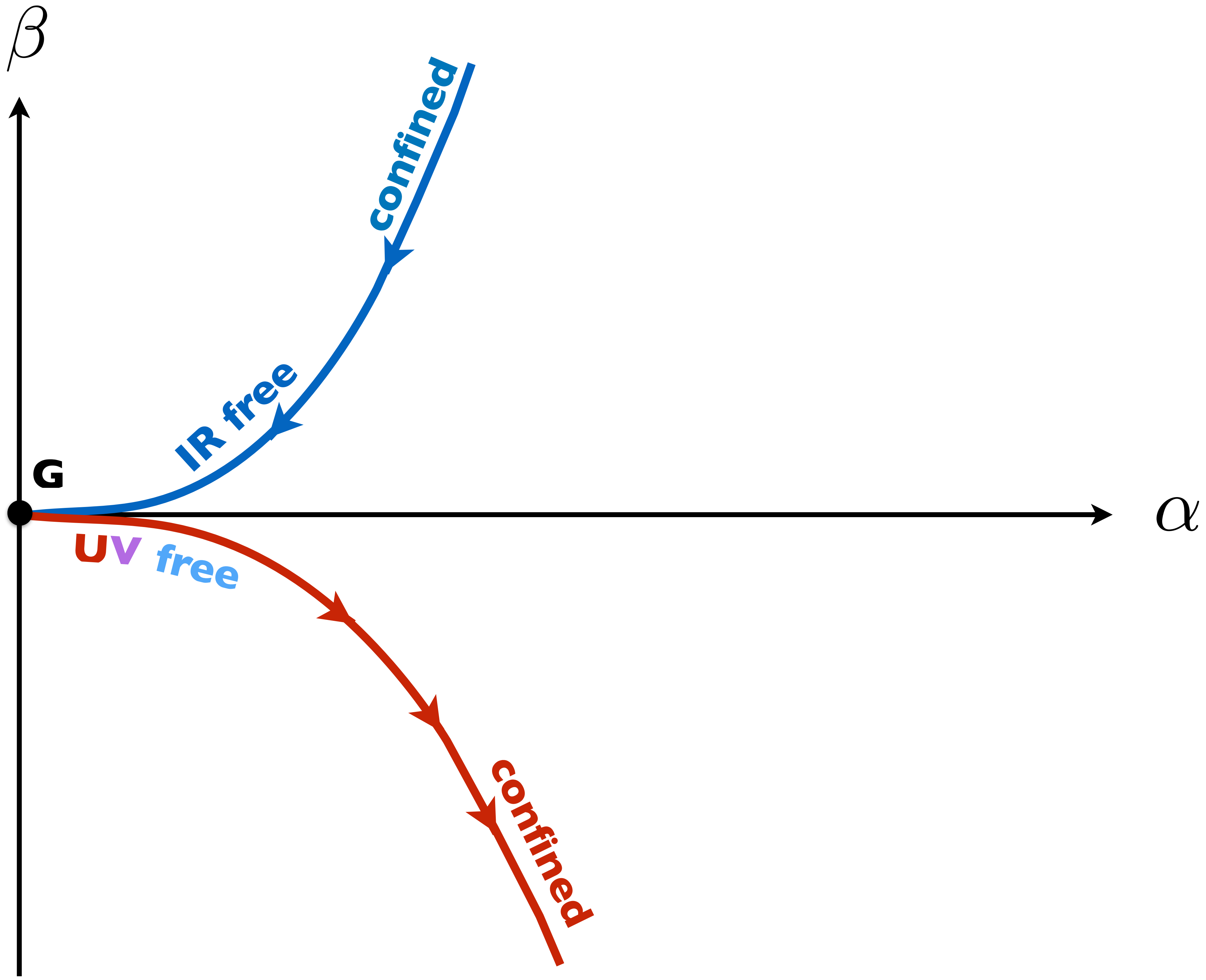
N=0 supersymmetry



N=1 supersymmetry



N=2 supersymmetry



N=3 supersymmetry

N=4 supersymmetry

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N=1 asymptotic safety

superfield anomalous dimension

$$2\,\frac{d_R}{d_G}\,|\gamma_R|^2 = B\,\alpha_* + \mathcal{O}(B\,\alpha_*^2, \alpha_*^3)$$

S Martin, J Wells, hep-ph/0011382

primary mechanism does not work

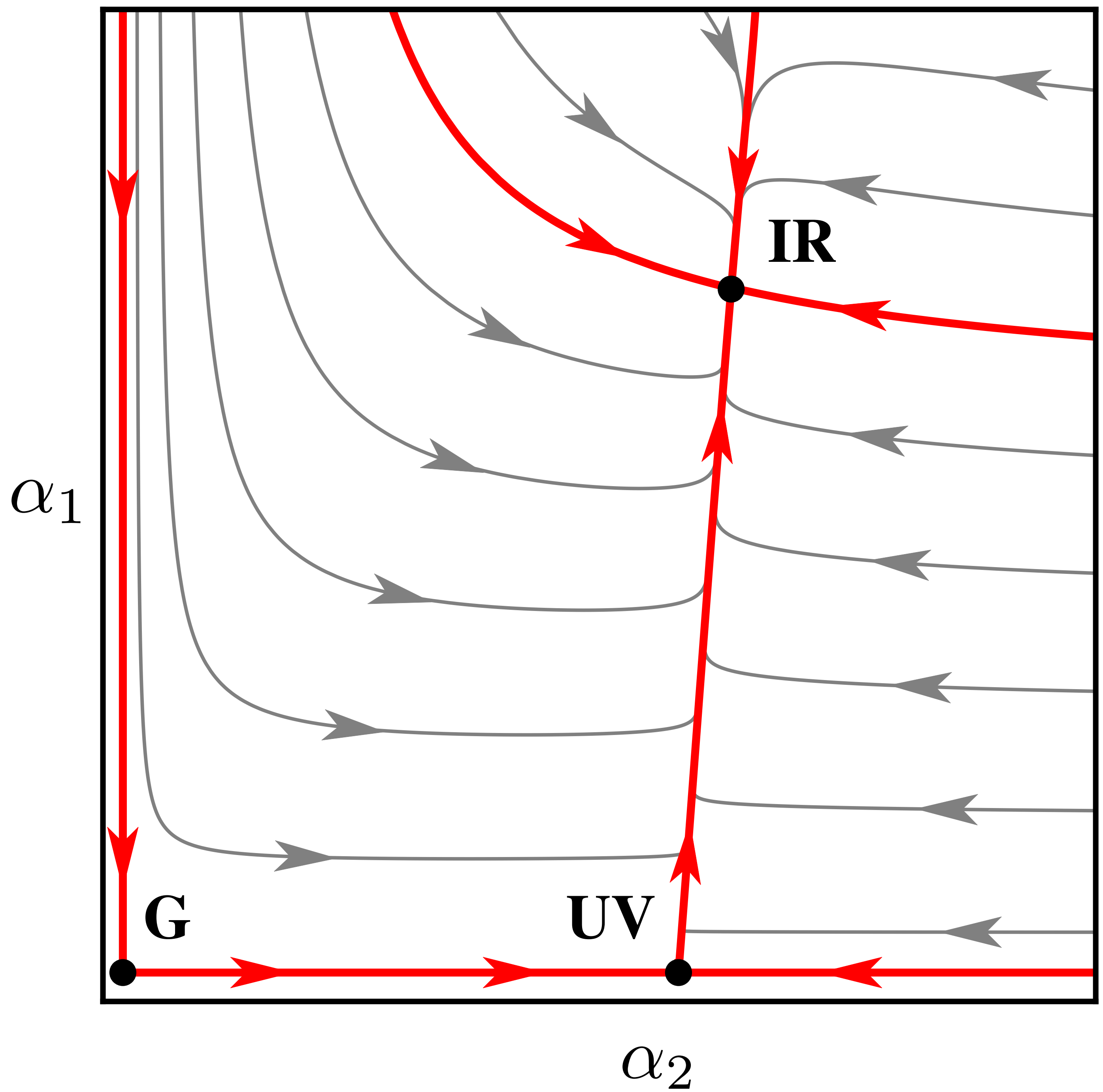
(asymptotic freedom with B > 0 is necessary)

however: secondary mechanism

semi-simple susy gauge theory

AD Bond, DF Litim, 1709.06953/PRL

Susy UV fixed point

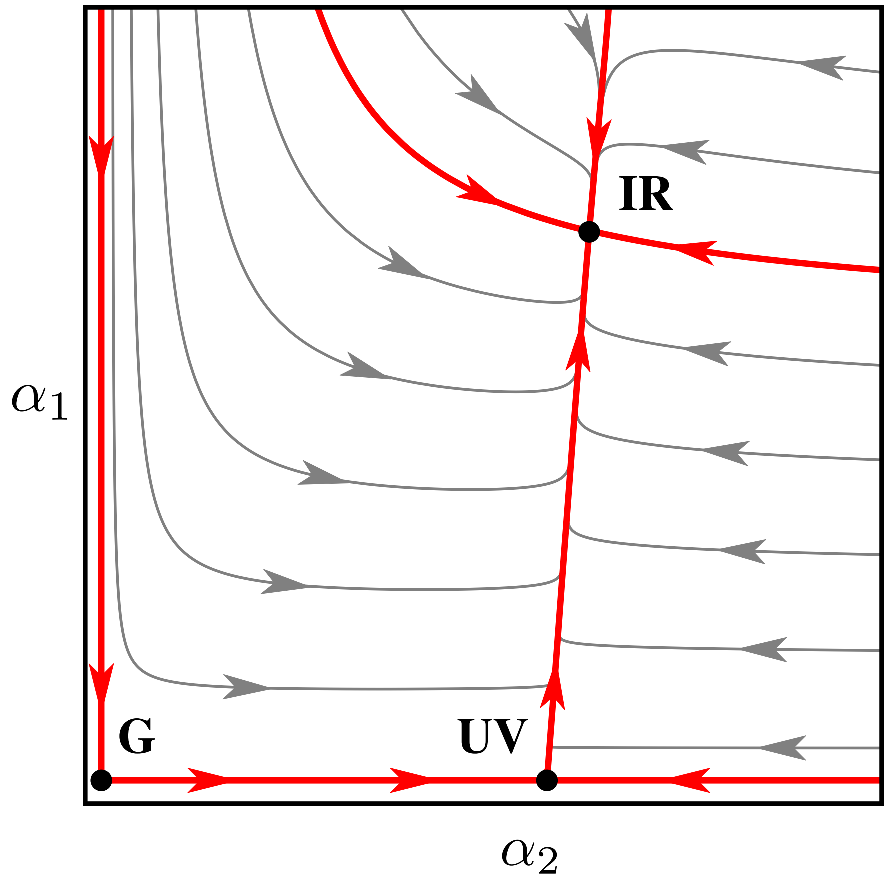


SU(N)xSU(M)
\+ super-
potential

"Susy enhances predictivity"

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

Susy UV fixed point



asymptotically safe supersymmetric SM extensions

Kevin Moch

(on Wednesday)

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- summary of weakly interacting fixed points

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 or w/o **N=1 supersymmetry**

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

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:

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

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

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

$$L_{\text{BSM, Yukawa}} = -y\,\text{Tr}(\overline{\psi}_L\, S\, \psi_R + \overline{\psi}_R\, S^\dagger\, \psi_L)$$

signatures

for low scale matching

some BSM masses within TeV energy range

if $R_3 \neq 1$ for LHC direct production

($R_3 = 1$ can be tested at future e^+e^- colliders)

flavor symmetry: stable BSM fermions

broken flavor symmetry: lightest BSM fermion stable

constraints from

running couplings

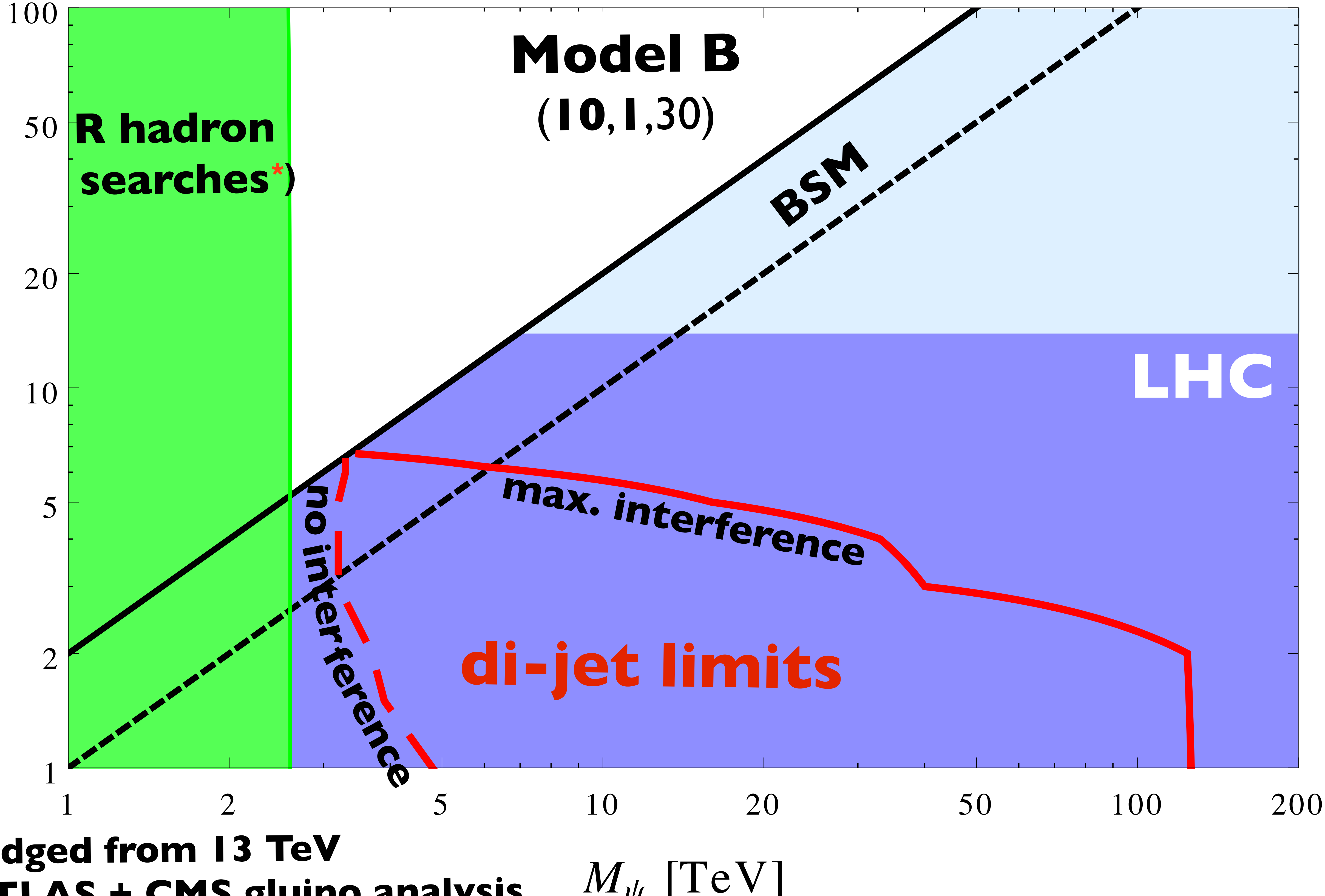
the weak sector

long-lived QCD bound states (R hadrons)

di-boson searches

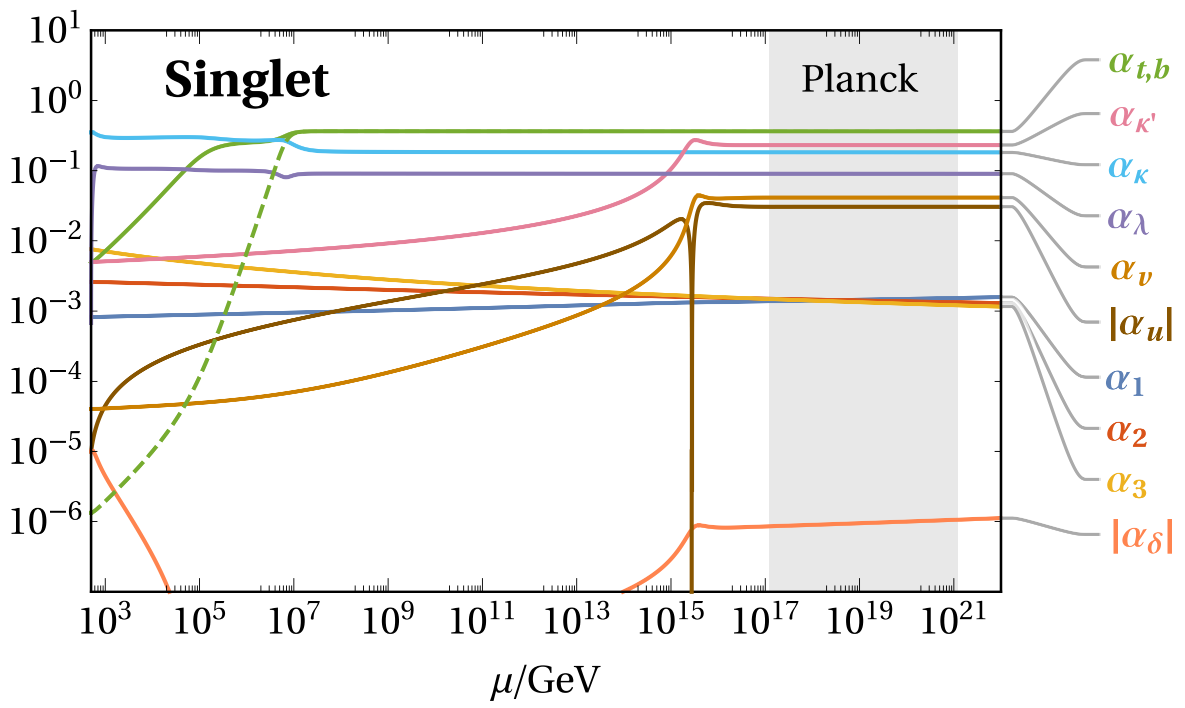
mass exclusion limits

1702.01727



*) fudged from 13 TeV ATLAS + CMS gluino analysis

more model building



asymptotically safe SM extensions

Tom Steudtner

(on Wednesday)

4d quantum gravity

gravitation

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

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

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what's new with gravity?

degrees of freedom: **spin 2**

Newton's coupling is **dimensionful** $[G_N] = 2 - D < 0$

perturbatively non-renormalisable

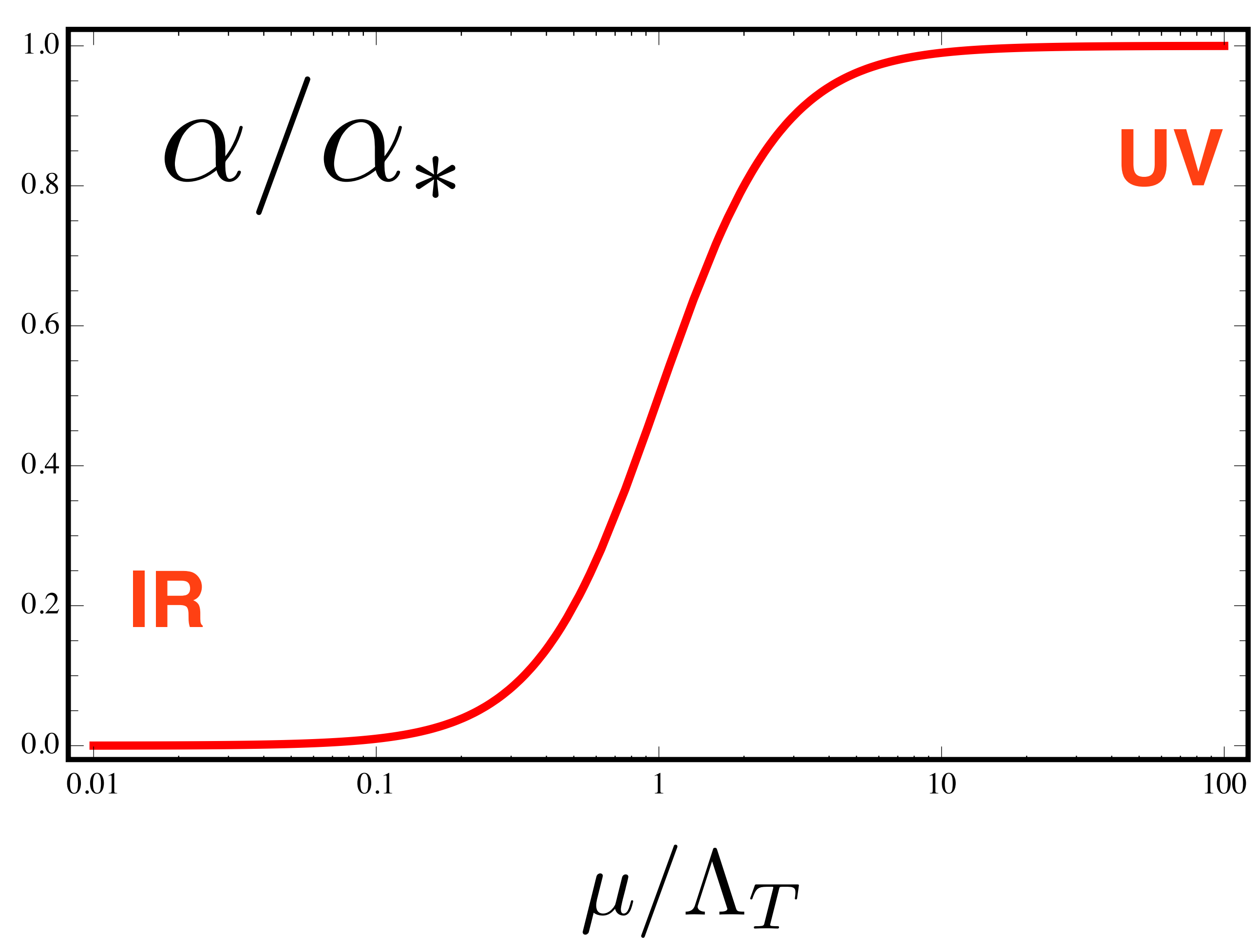
interacting fixed point requires **large** anomalous dimensions

why it might work...

dimensionless coupling $\alpha = G_N(\mu)\,\mu^{D-2}$

$G(\mu) \approx G_N$

classical GR



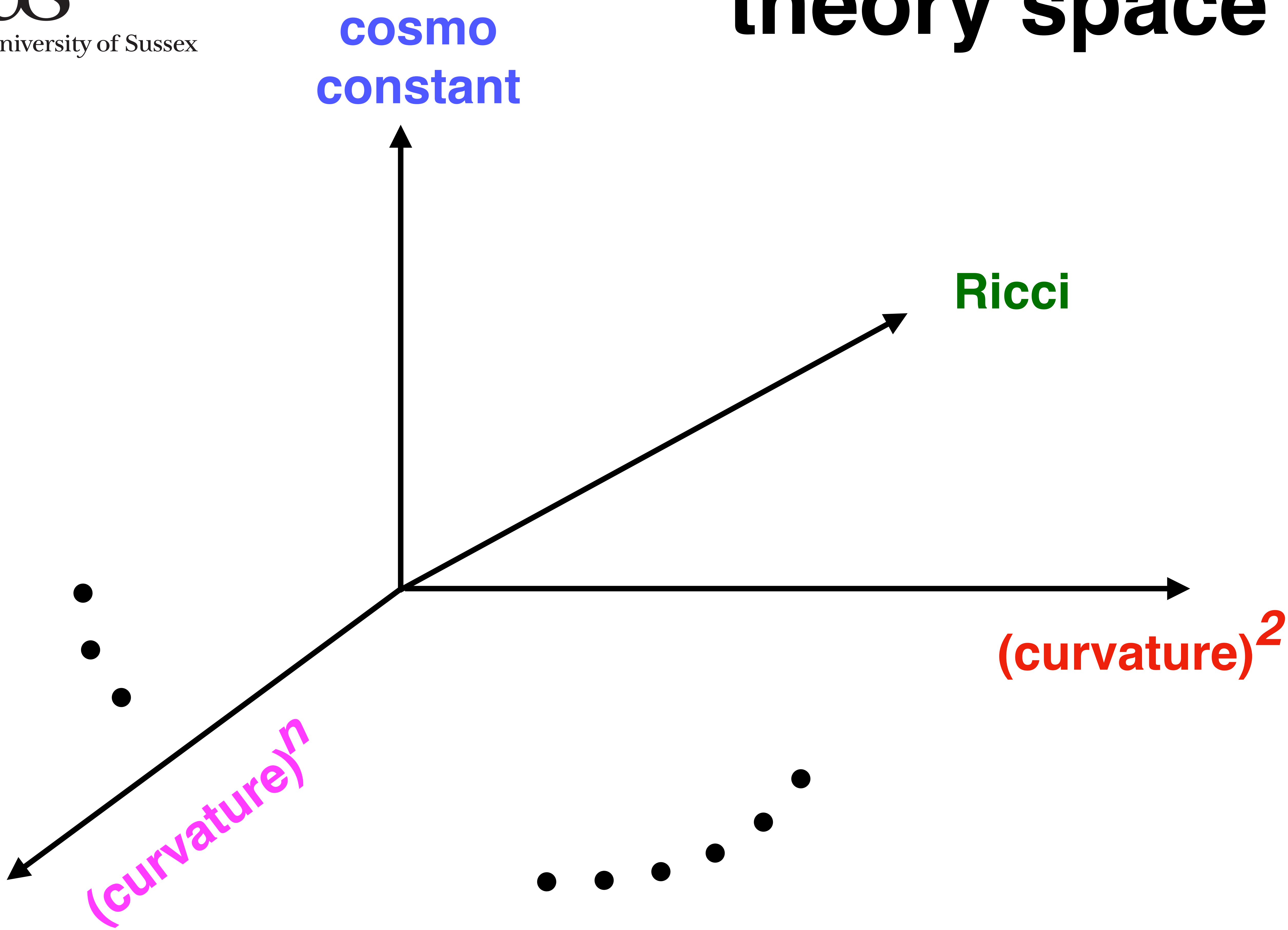
$G(\mu) \approx \dfrac{\alpha_*}{\mu^{D-2}}$

quantum GR

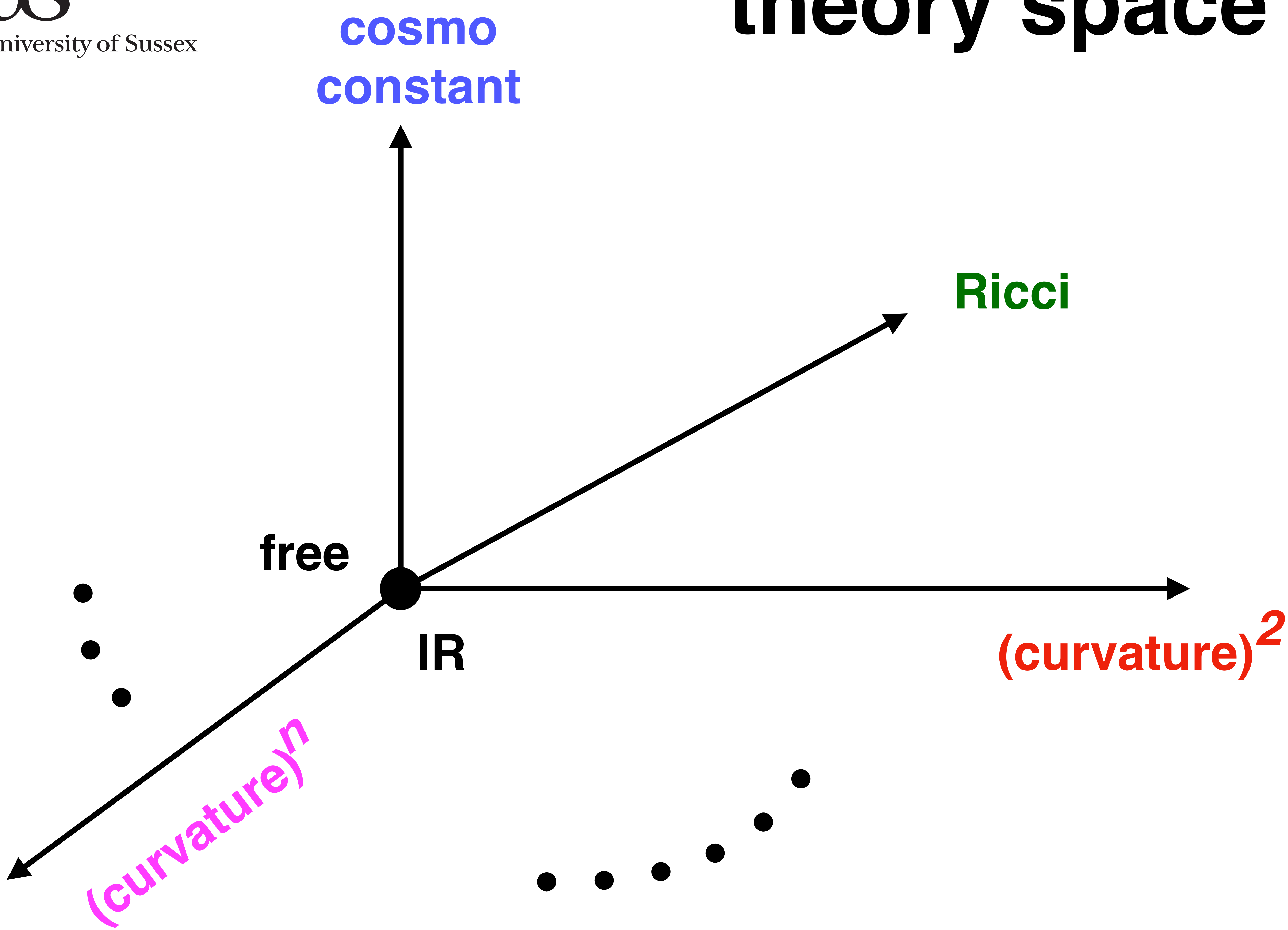
UV fixed point implies "weak gravity"

Litim, '03, '06

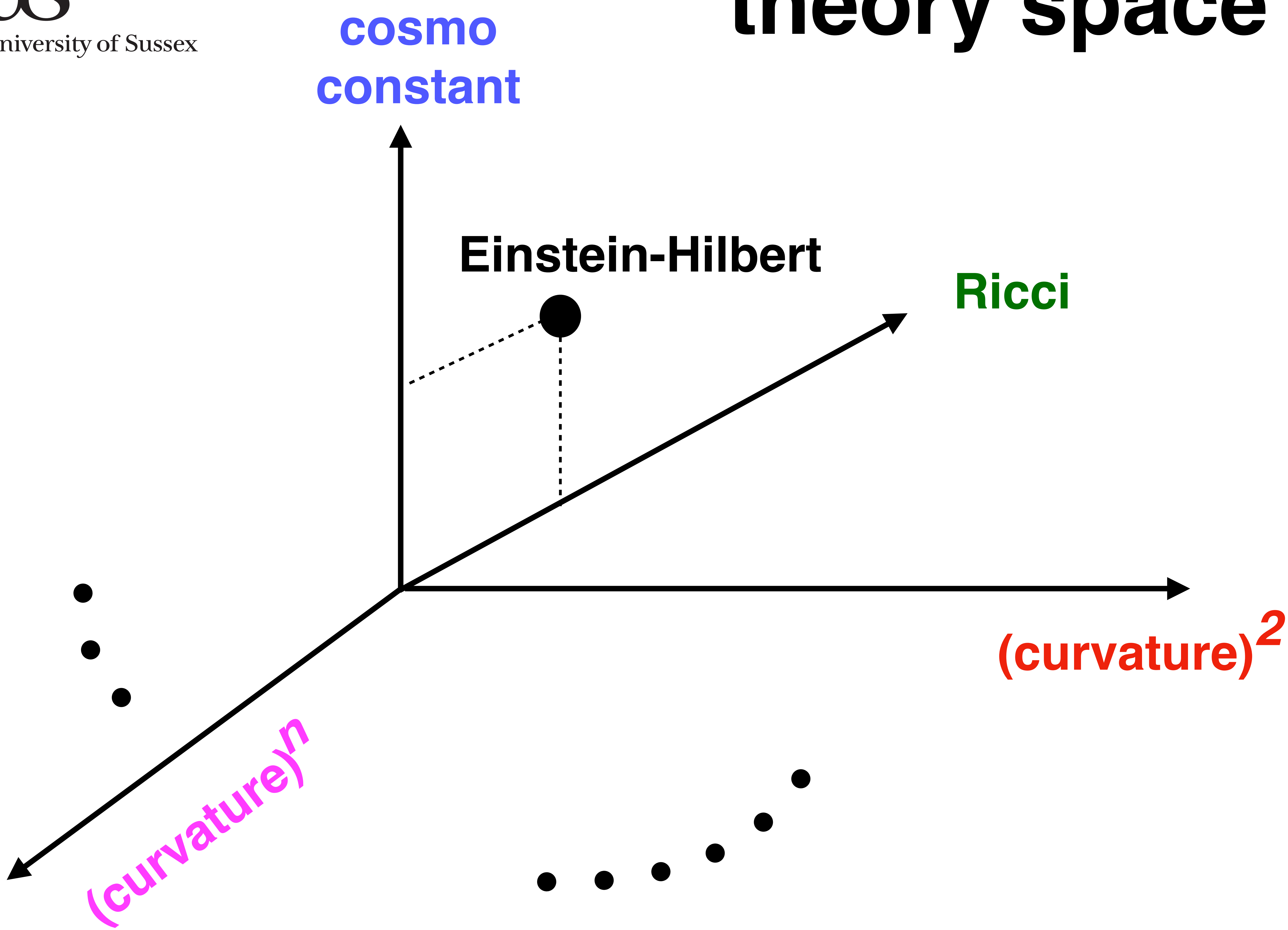
“theory space”



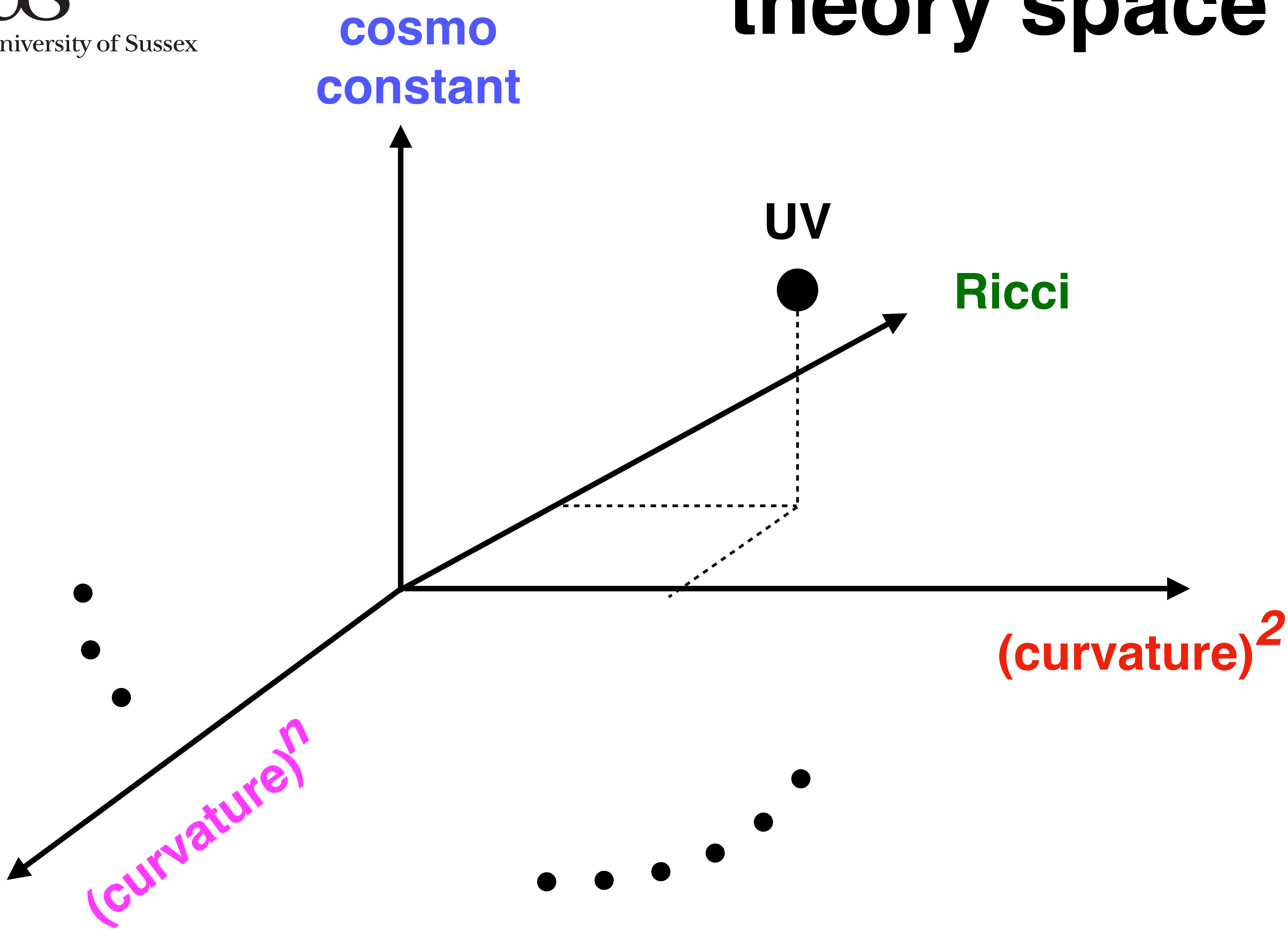
“theory space”



"theory space"



“theory space”



bootstrap

non-perturbative tools, e.g.

Wilson's Renormalisation Group, Lattice

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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bootstrap

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

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

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

up to order $N = 2$ Souma, '99, Reuter, Lauscher '01, Litim '02

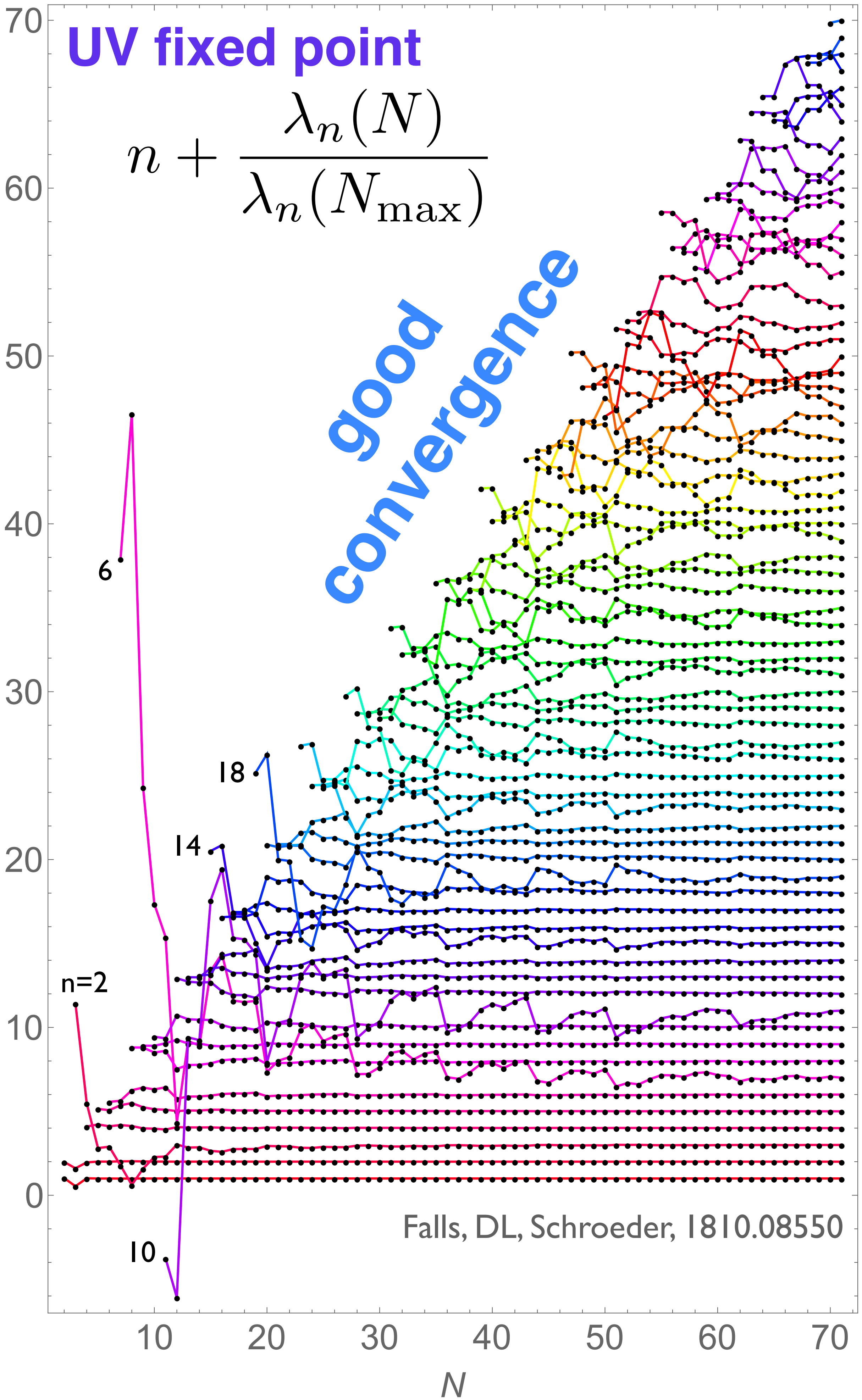
$N = 3$ Reuter, Lauscher '01

$N = 7$ Codello, Percacci, Rahmede '07

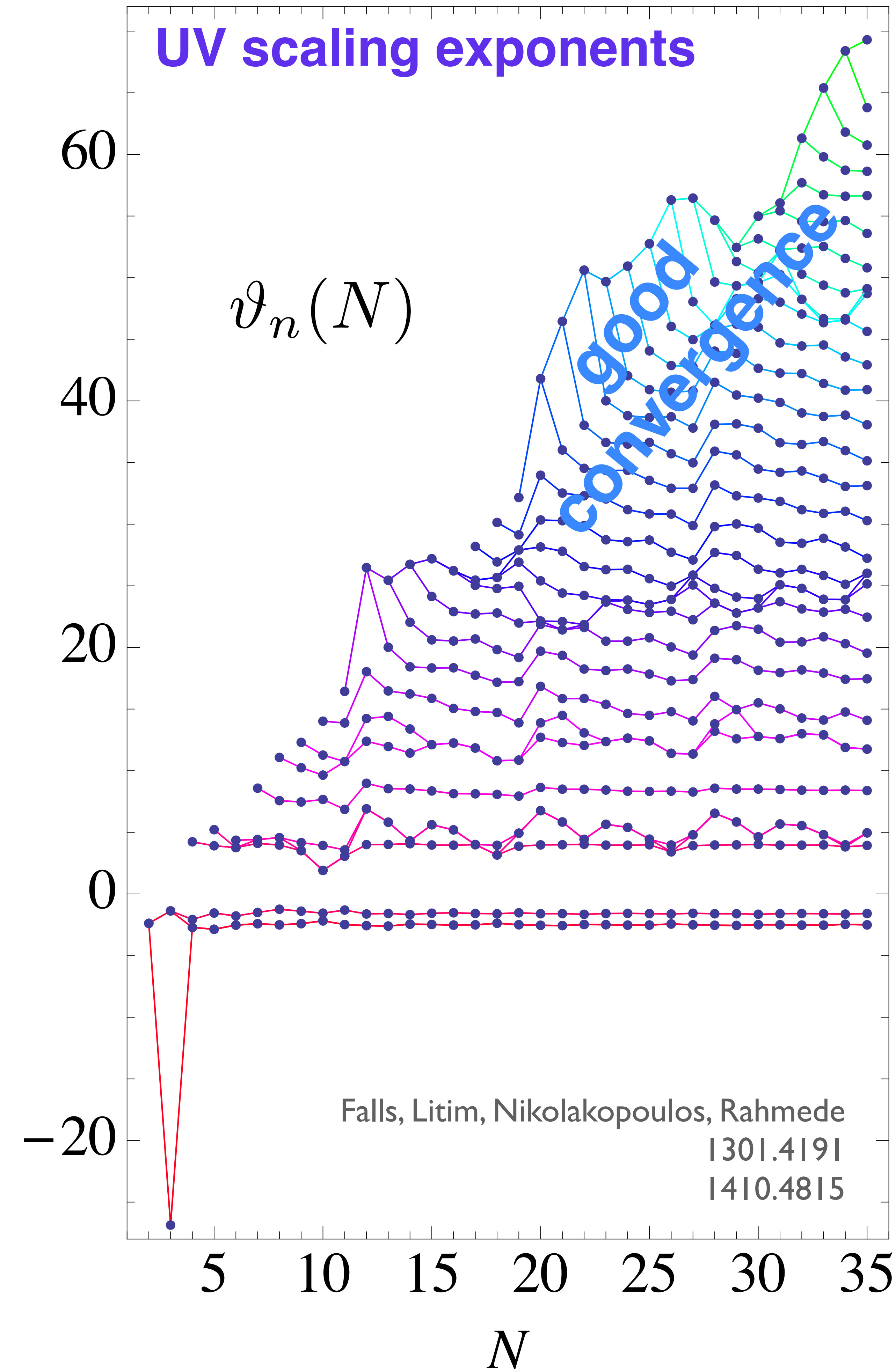
$N = 11$ Bonanno, Contillo,, Percacci '10

$N = 35$ 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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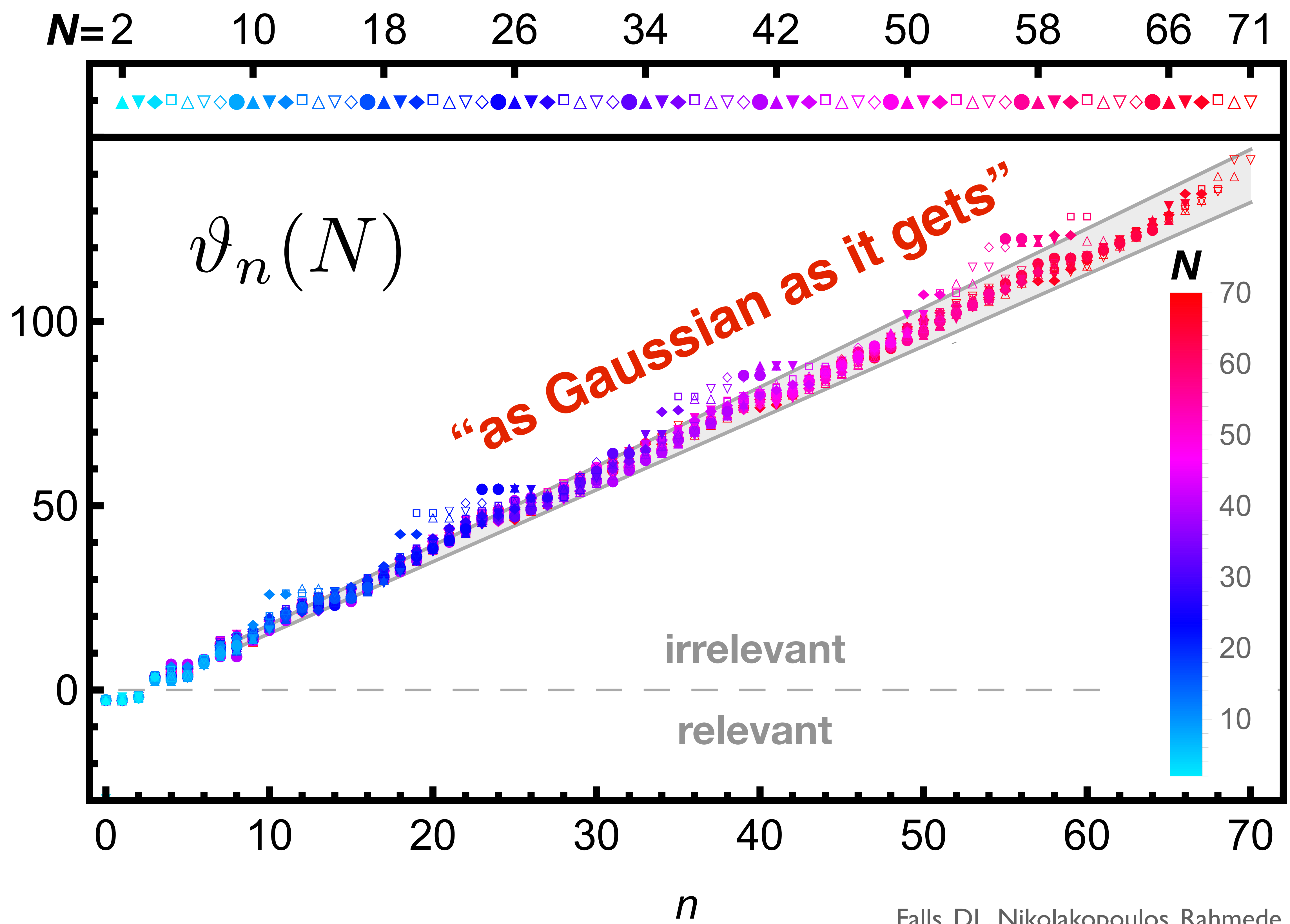
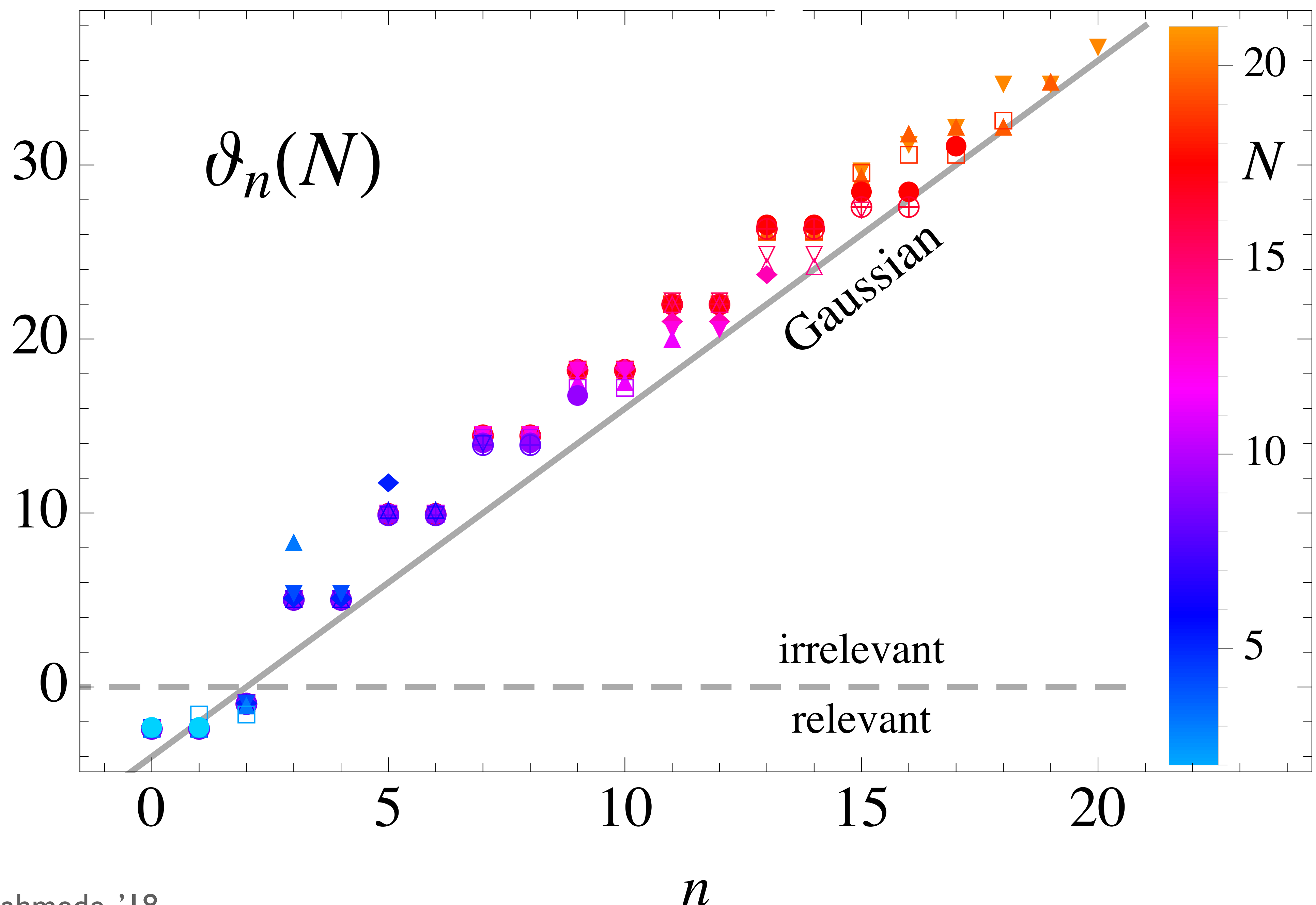
R



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

Ricci

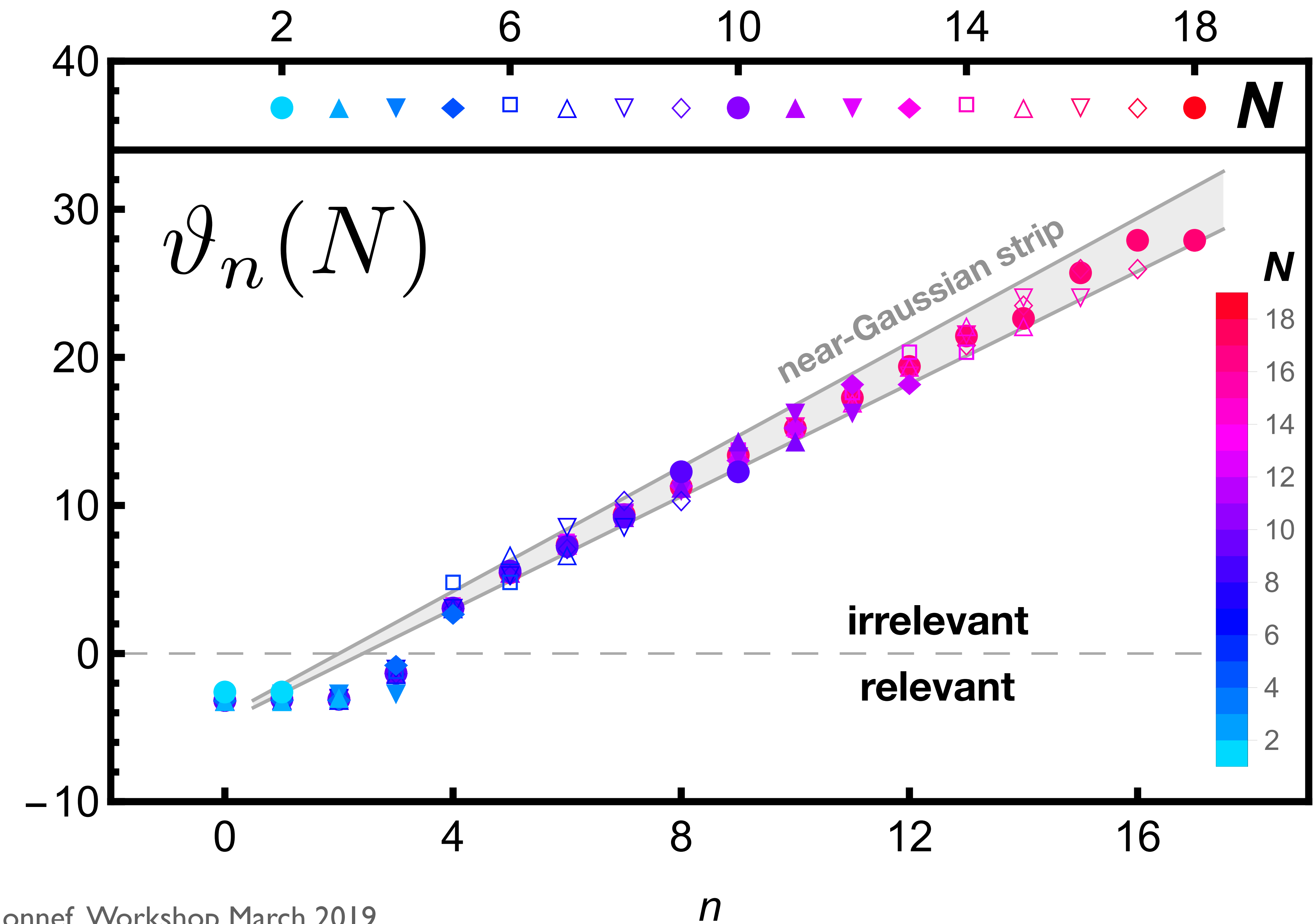
$$\Gamma_k = \int d^dx\sqrt{g}[F_k(\mathrm{Ric}^2) + R\cdot Z_k(\mathrm{Ric}^2)]$$



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

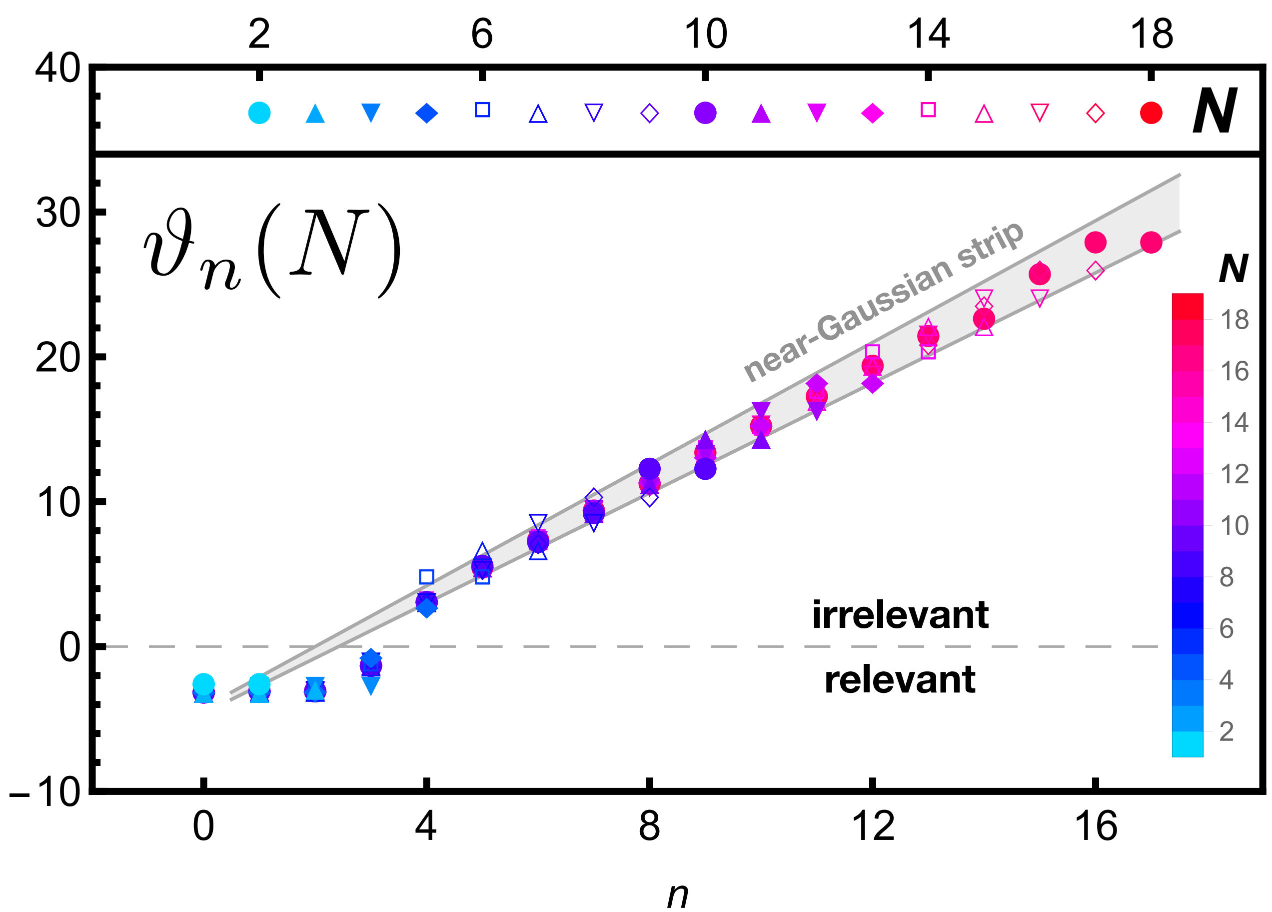
Riemann

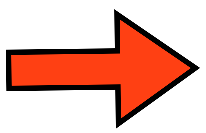
$$\Gamma_k = \int d^d x \sqrt{g}[F_k(\mathrm{Riem}^2) + R \cdot Z_k(\mathrm{Riem}^2)]$$



Yannick Kluth, DL, Bad Honnef Workshop March 2019

Quantum Gravity with SM





Asymptotic safety of gravity with SM matter

Gustavo Medina Vazquez

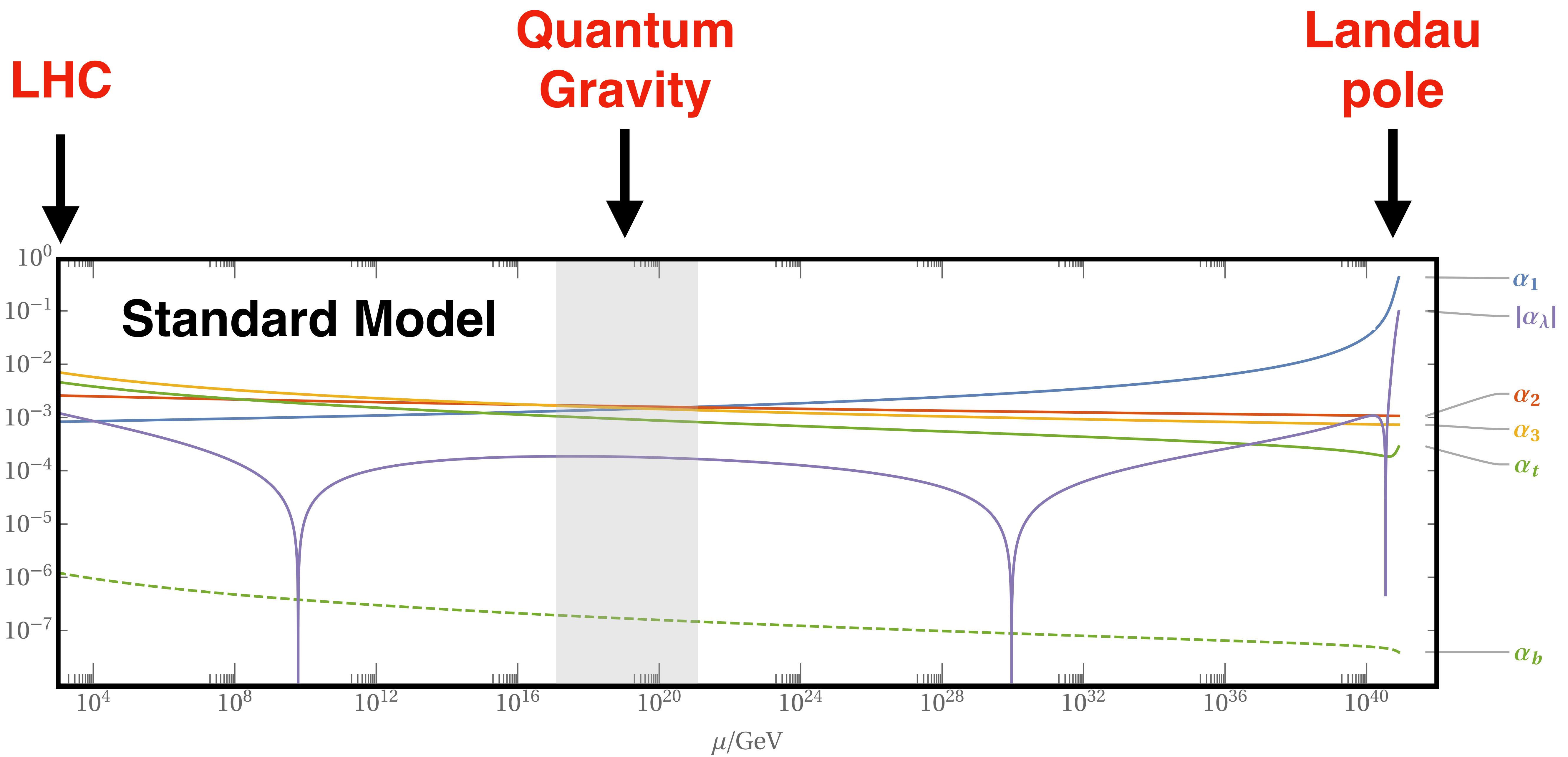
(on Wednesday)

conclusions

rigorous results for **asymptotic safety**
at weak coupling in general 4d QFTs w/o gravity
new directions for model building

strong hints for **asymptotic safety**
in 4d quantum gravity from bootstrap
and higher order curvature interactions

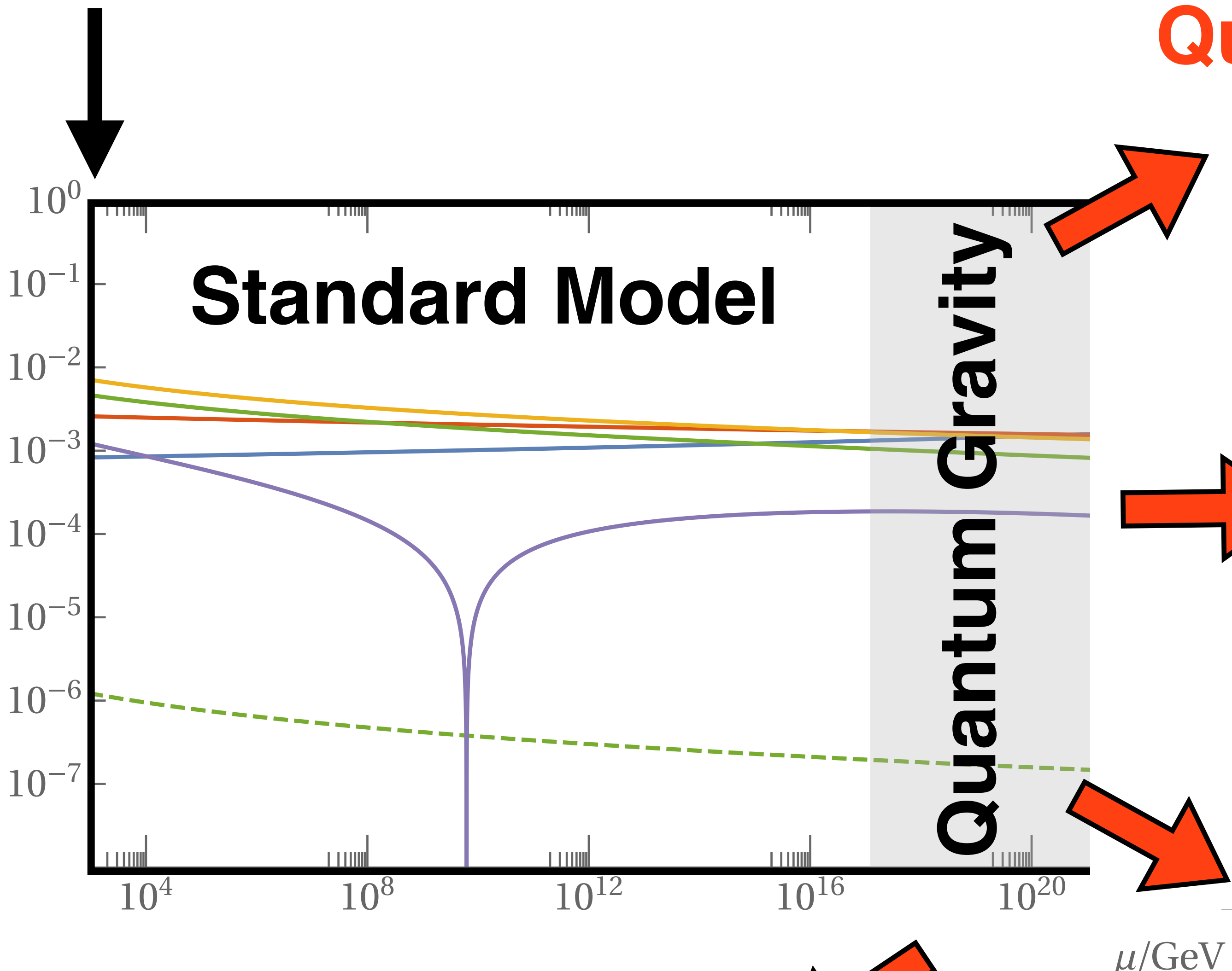
outlook...



LHC
Quantum Gravity
Landau pole
Standard Model
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
α_1
$|\alpha_\lambda|$
α_2
α_3
α_t
α_b

outlook…

LHC



Quantum Gravity with SM matter

Gustavo Medina Vazquez

asymptotically safe
SM extensions

Tom Steudtner

asymptotically safe
supersymmetric SM extensions

Kevin Moch

further aspects
of asymptotic safety

Frank Saueressig (Thursday)

(all on Wednesday…)