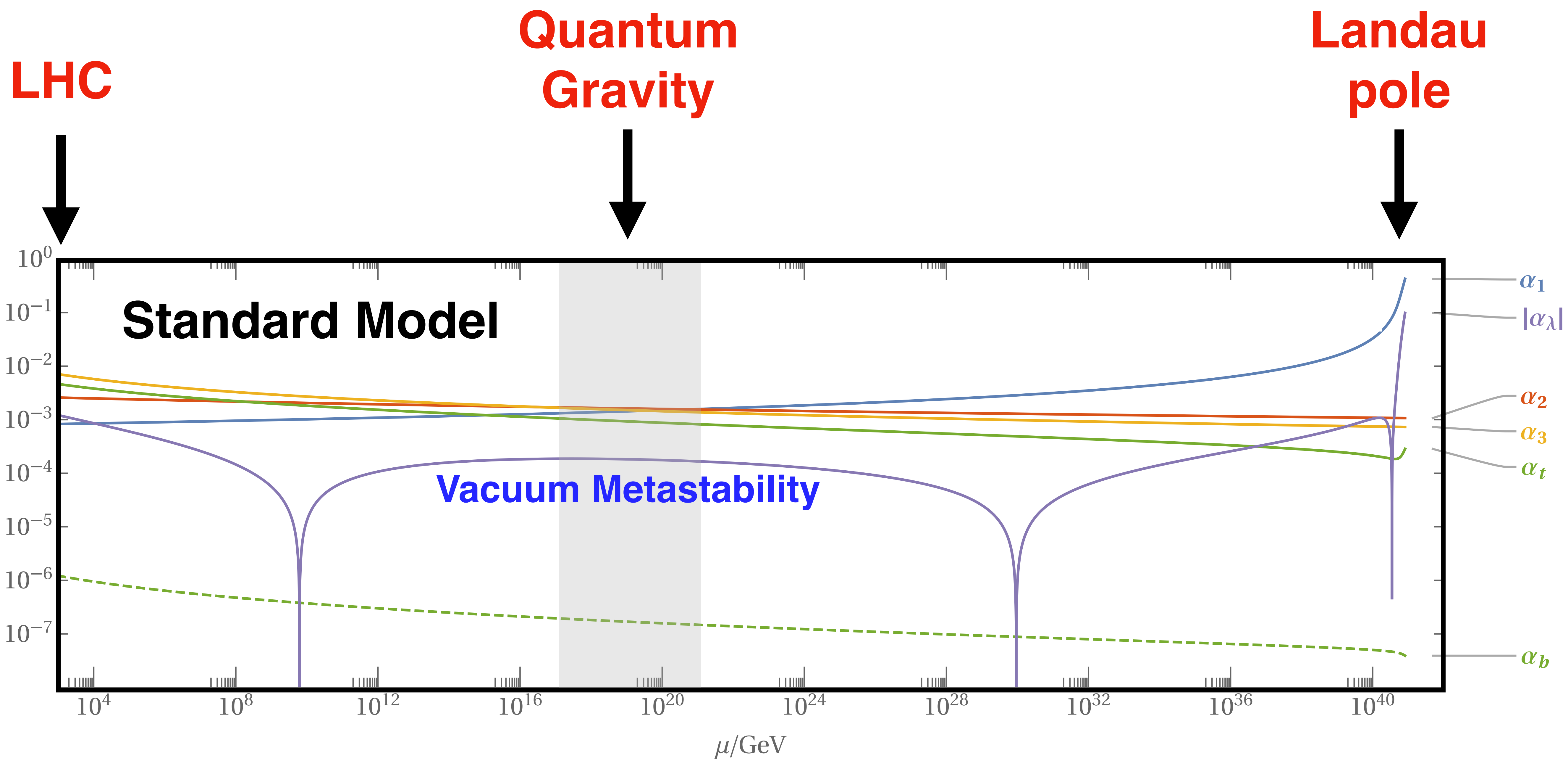
asymptotic safety and physics beyond the SM

Daniel F Litim

University of Sussex

zoom seminar U Helsinki
2 Sep 2020

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 ⟷ free UV fixed point

Gross, Wilzcek ’73 , Politzer ‘73

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asymptotic near-freedom Bailin, Love ‘74

asymptotic safety Weinberg ‘79

⟷ interacting UV fixed point

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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 Bond, Litim, Steudtner, '19

4d	quantum gravity	Reuter '96 Litim '03

today:

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

investigate **asymptotic safety**
in concrete models beyond BSM

(and if time permits:)

status of **asymptotic safety**
in **quantum gravity**

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asymptotic safety

in 4d gauge-matter theories

running couplings

quantum fluctuations modify interactions
couplings depend on energy

$$\mu \frac{d\alpha}{d\mu} = \beta(\alpha)$$

fluctuations	$\hbar$
energy scale	μ
couplings	$\alpha(\mu)$

running couplings

quantum fluctuations modify interactions
couplings depend on energy

$$\mu \frac{d\alpha}{d\mu} = \beta(\alpha)$$

fluctuations	$\hbar$
energy scale	μ
couplings	$\alpha(\mu)$

QFT provides us with

predictions into regions where we cannot (yet) make measurements

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

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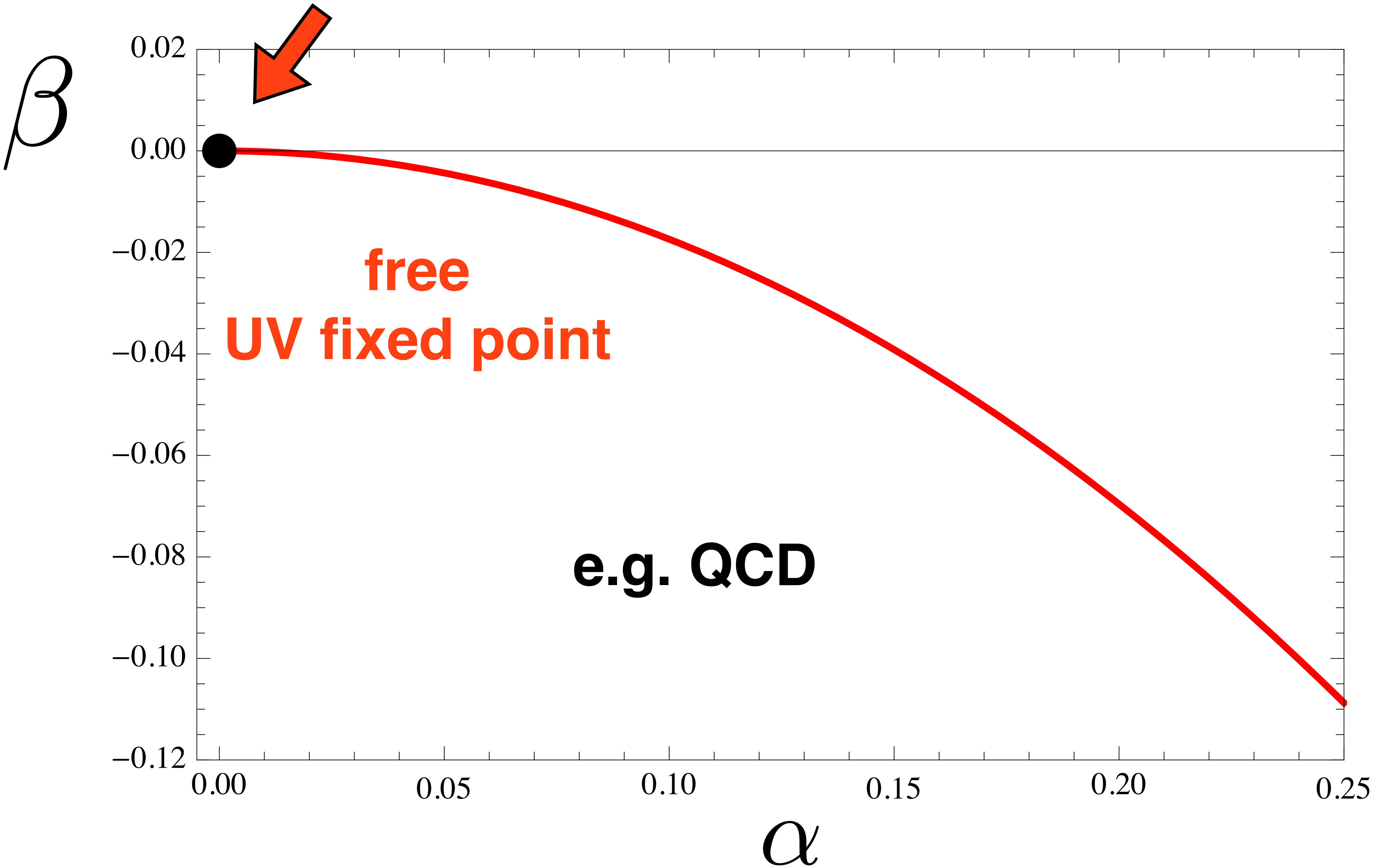
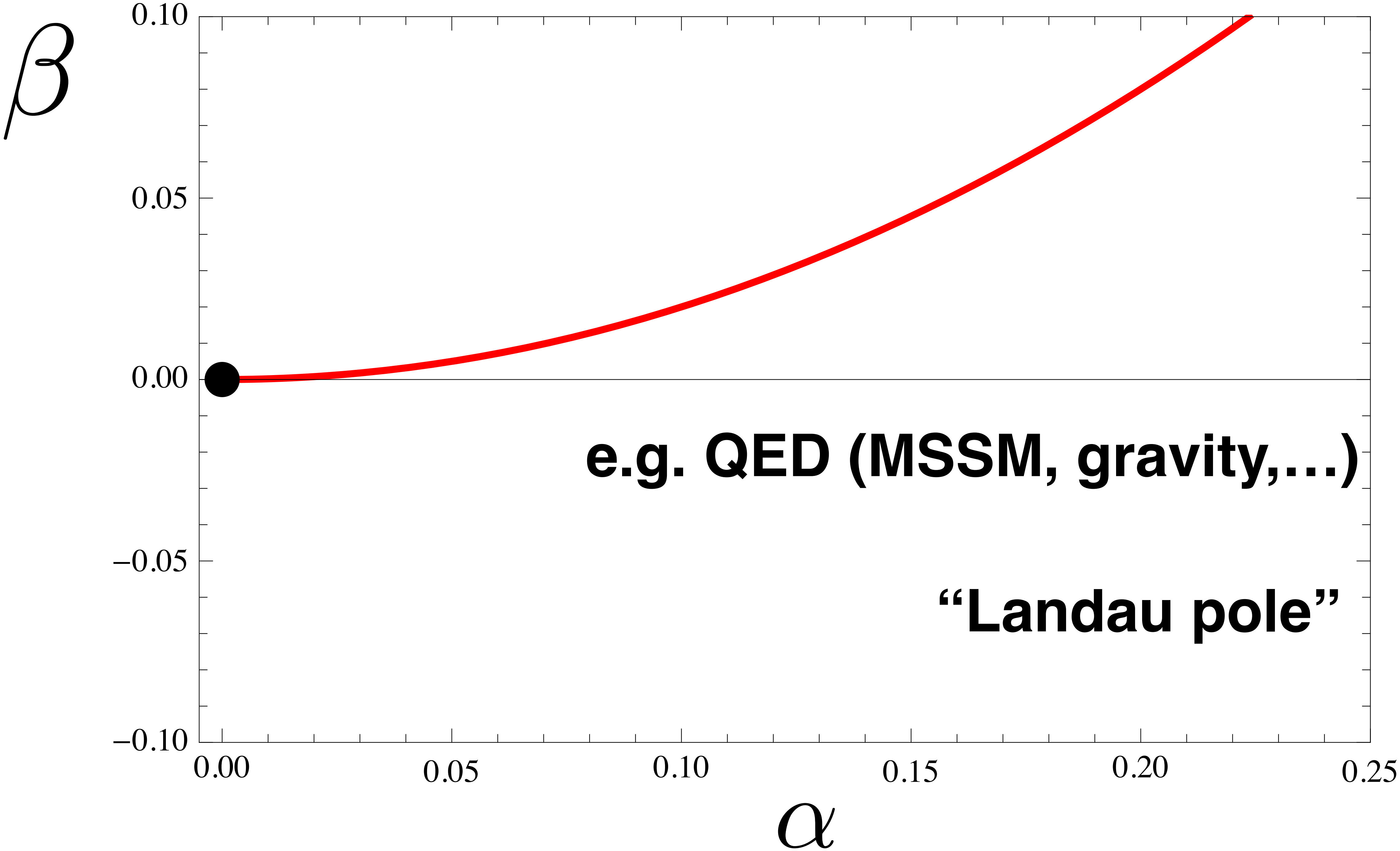
asymptotic freedom



infrared freedom



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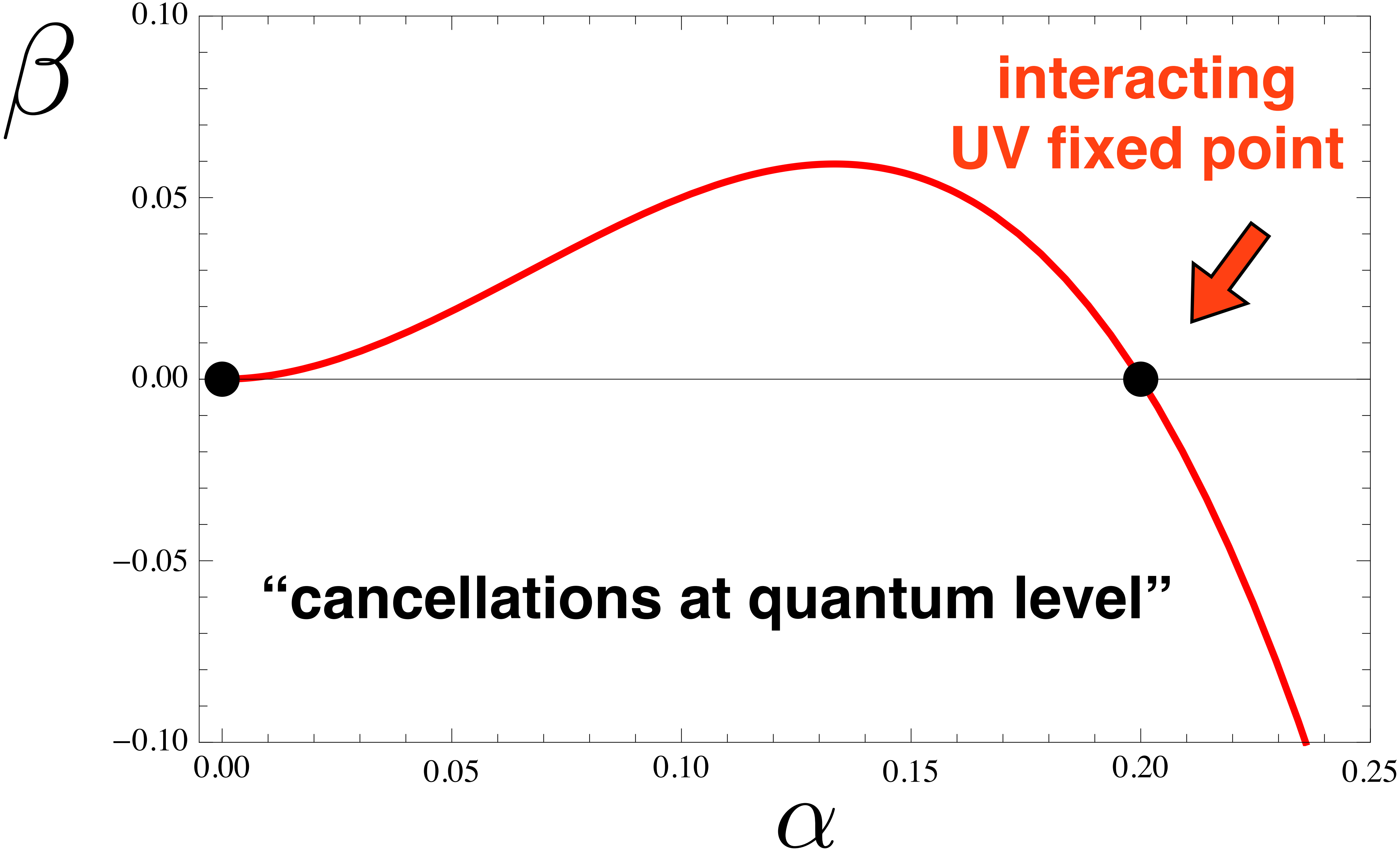
asymptotic safety



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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

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path integral

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

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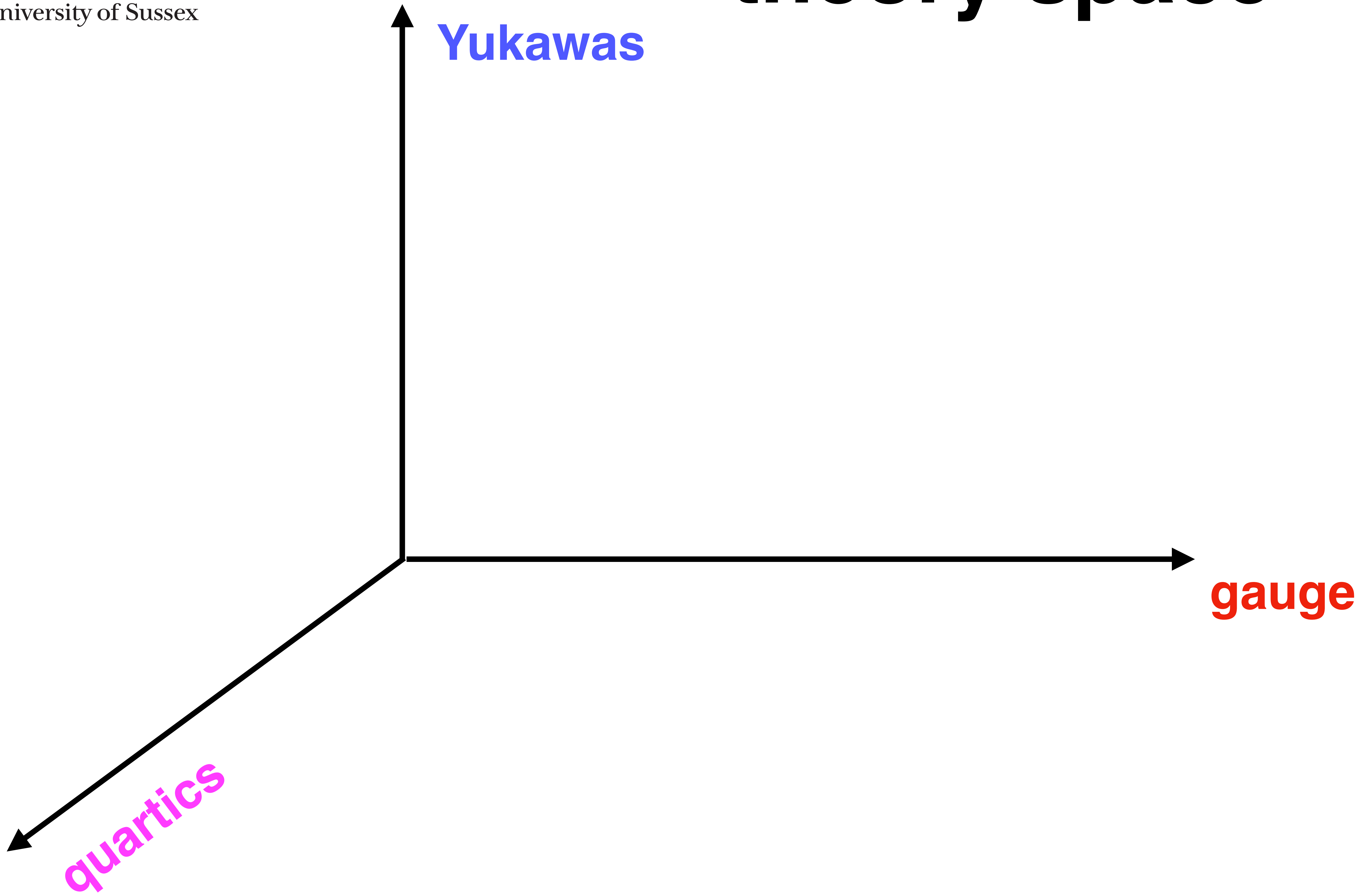
$$L = \frac{1}{4g_a^2}\,{\rm Tr}\,F^a_{\mu\nu}F^{\mu\nu}_a + i\psi_I \not{D}\psi_I + \frac{1}{2}(D_\mu\phi^A)^2$$
$$+\frac{1}{2}Y^A{}_{IJ}\phi^A\,\psi_I\,\xi\,\psi_J + \frac{1}{4!}\lambda_{ABCD}\phi^A\phi^B\phi^C\phi^D$$

gauge

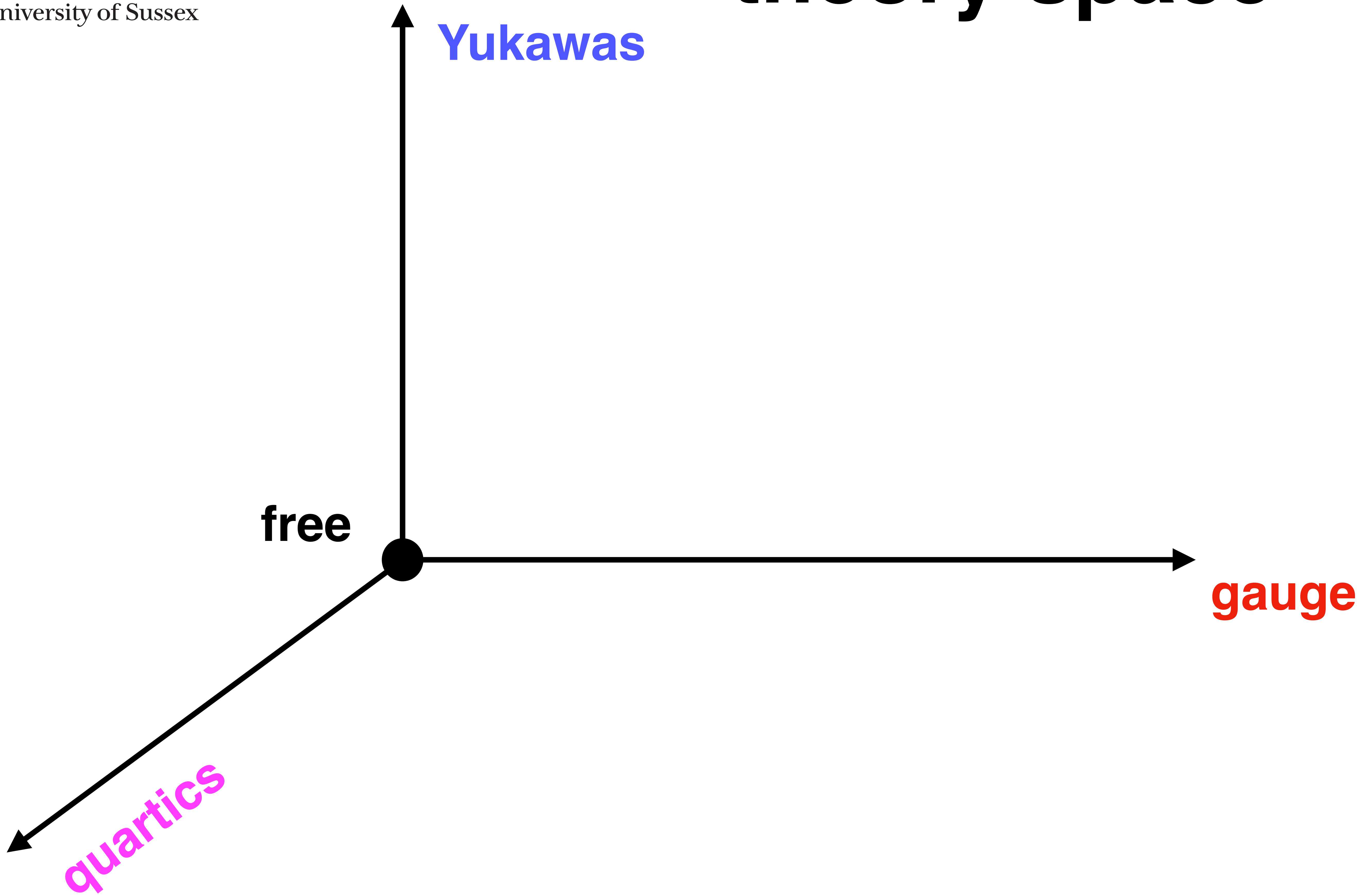
Yukawa

quartics

“theory space”



“theory space”



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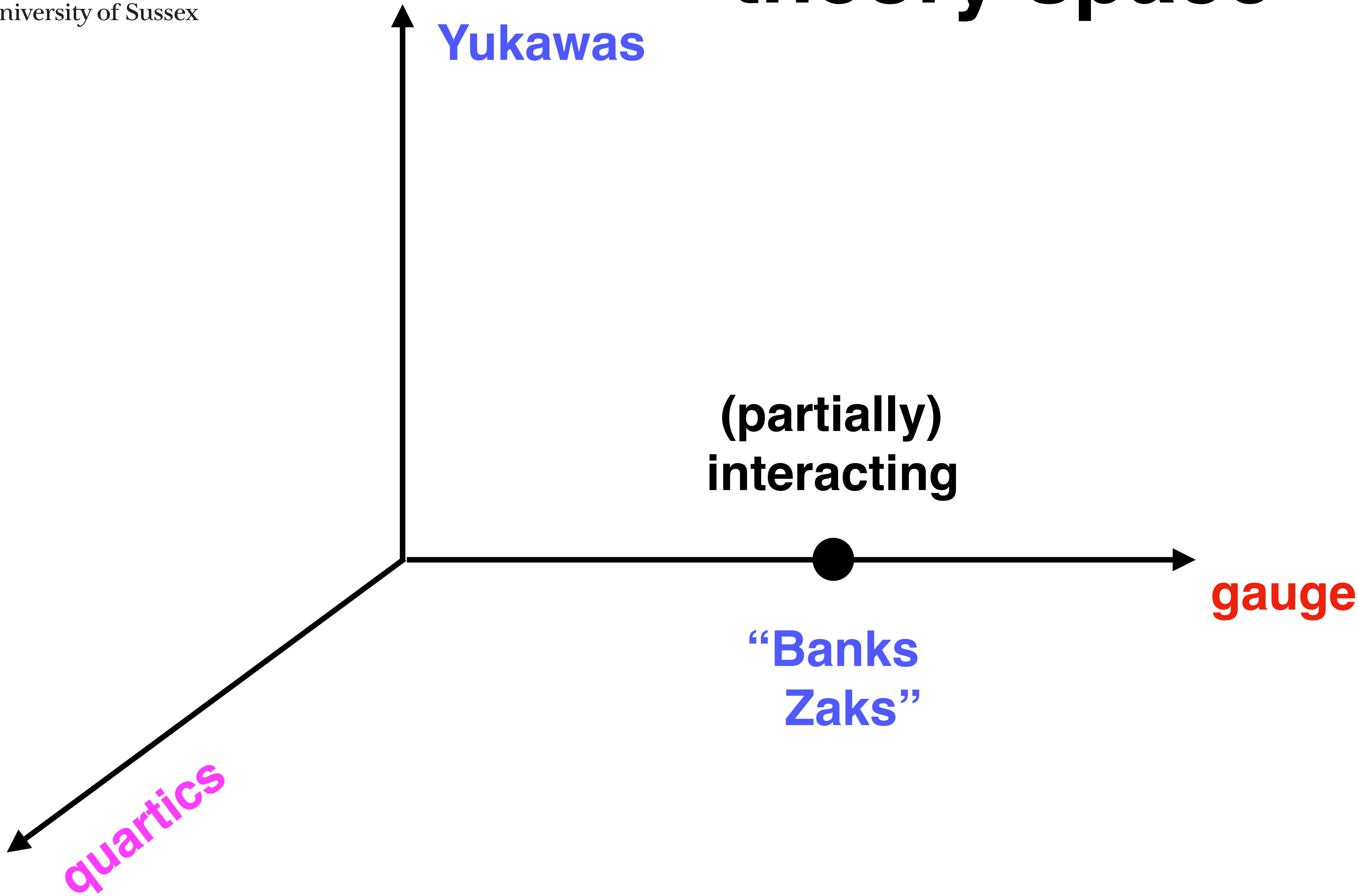

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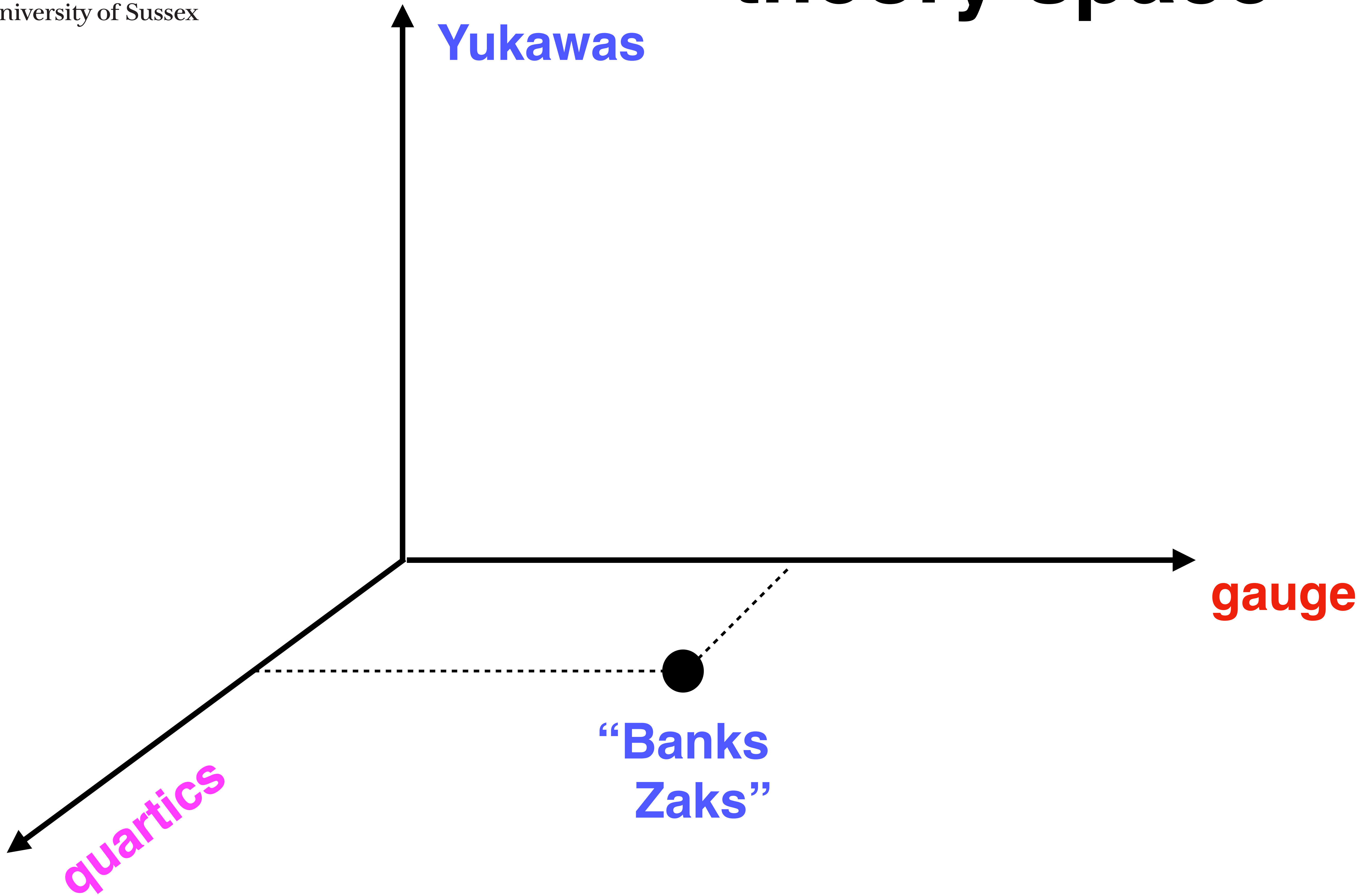

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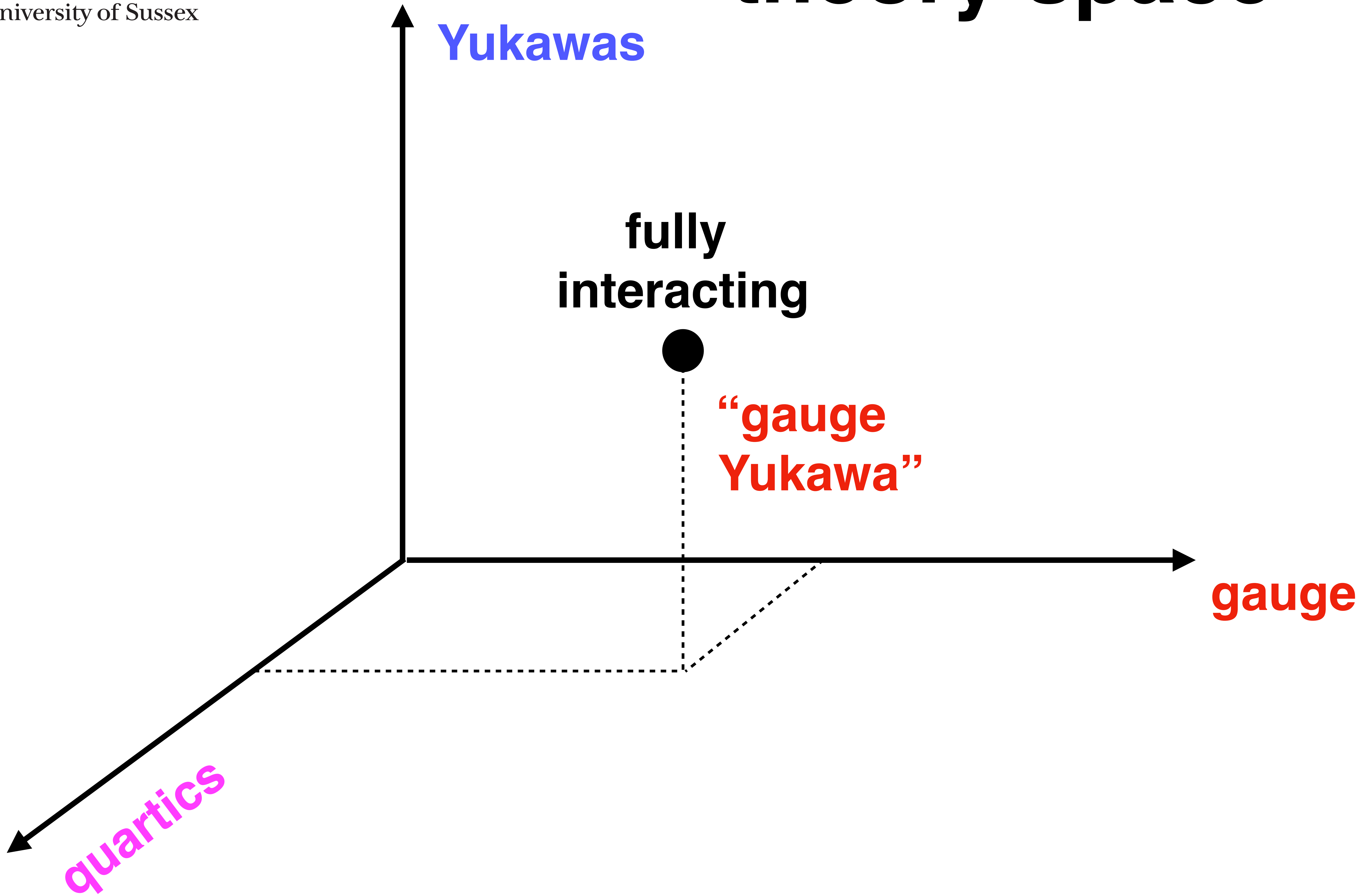

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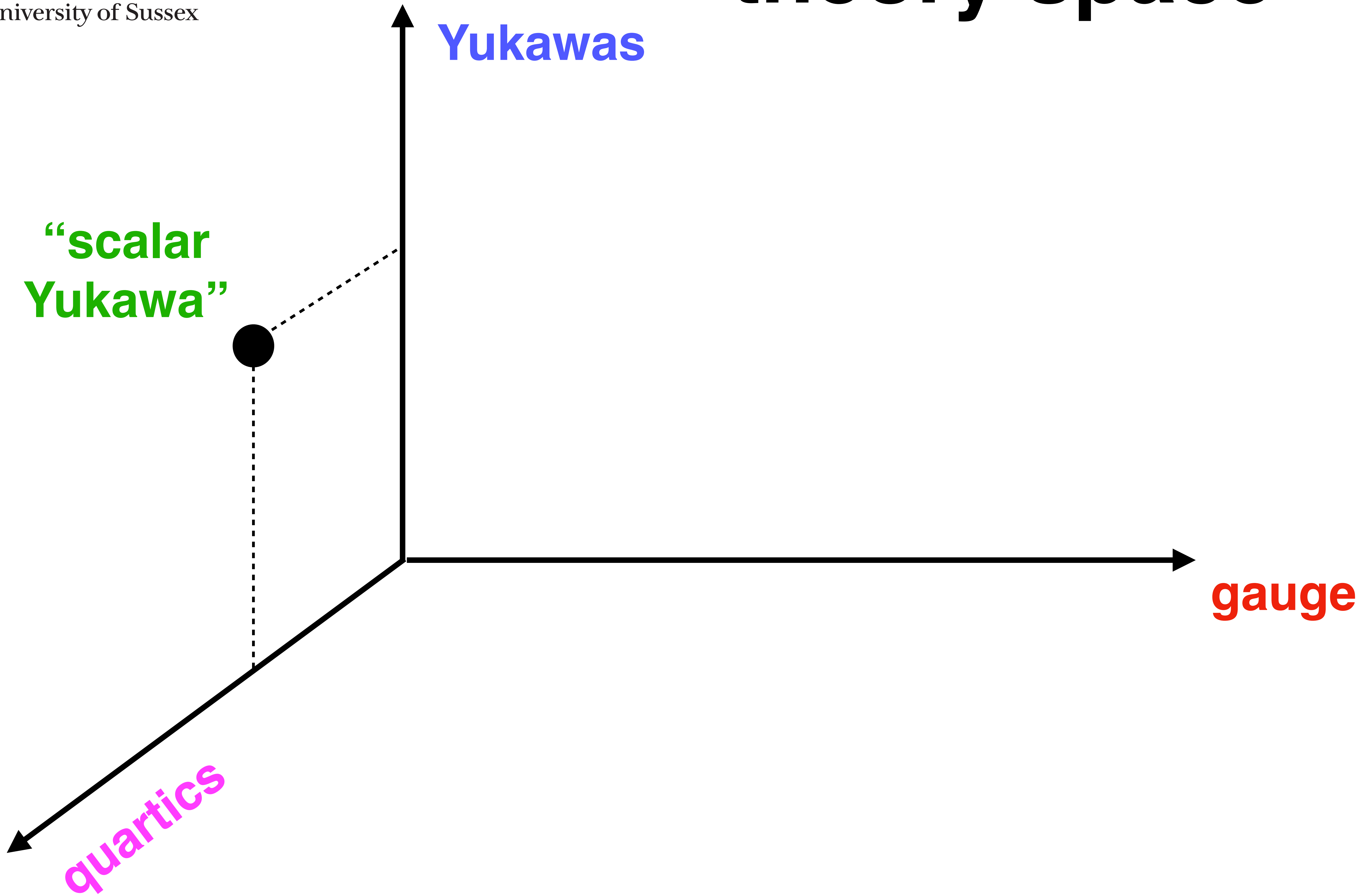

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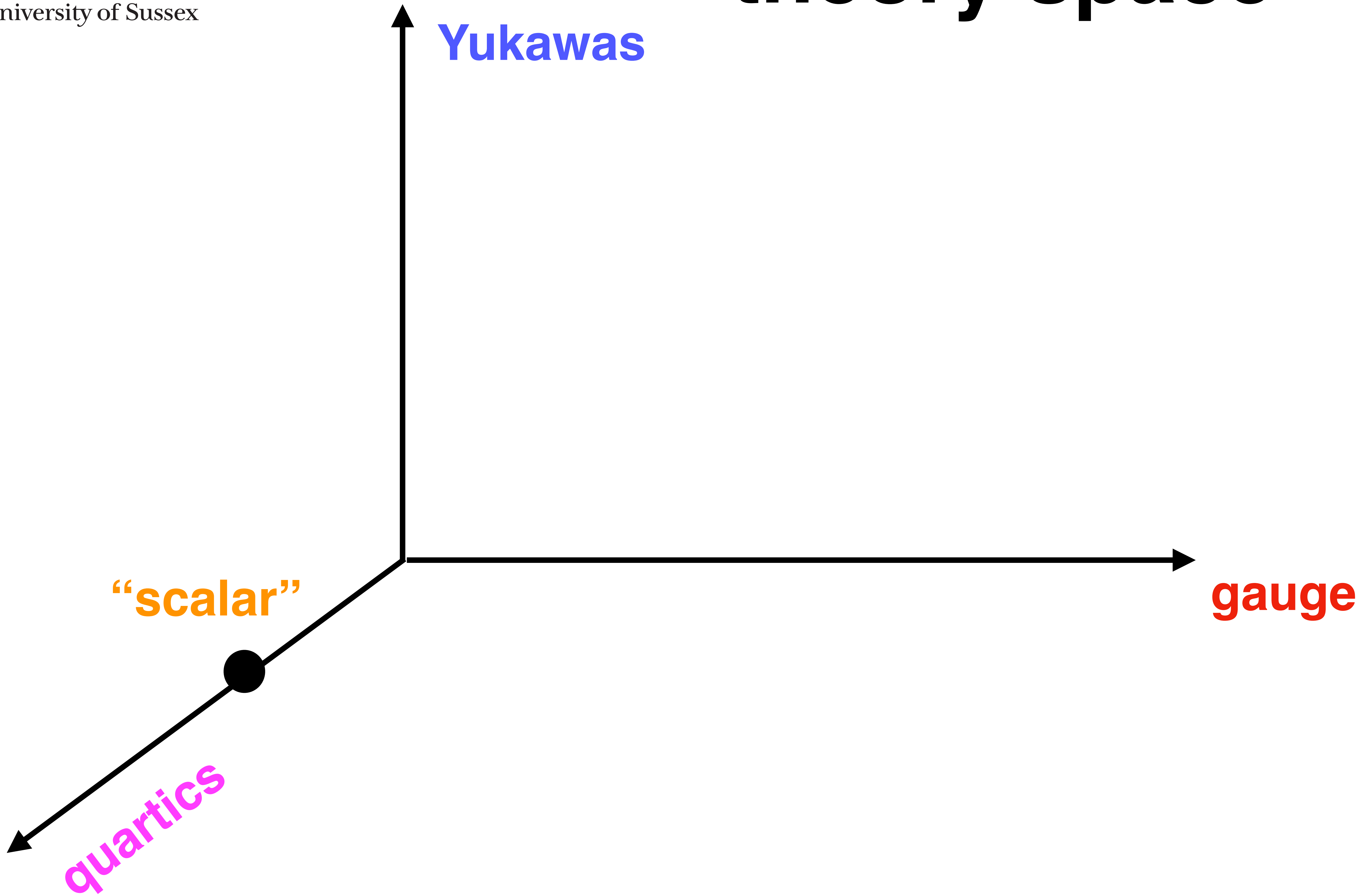
“theory space”



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“theory space”

interacting fixed points

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

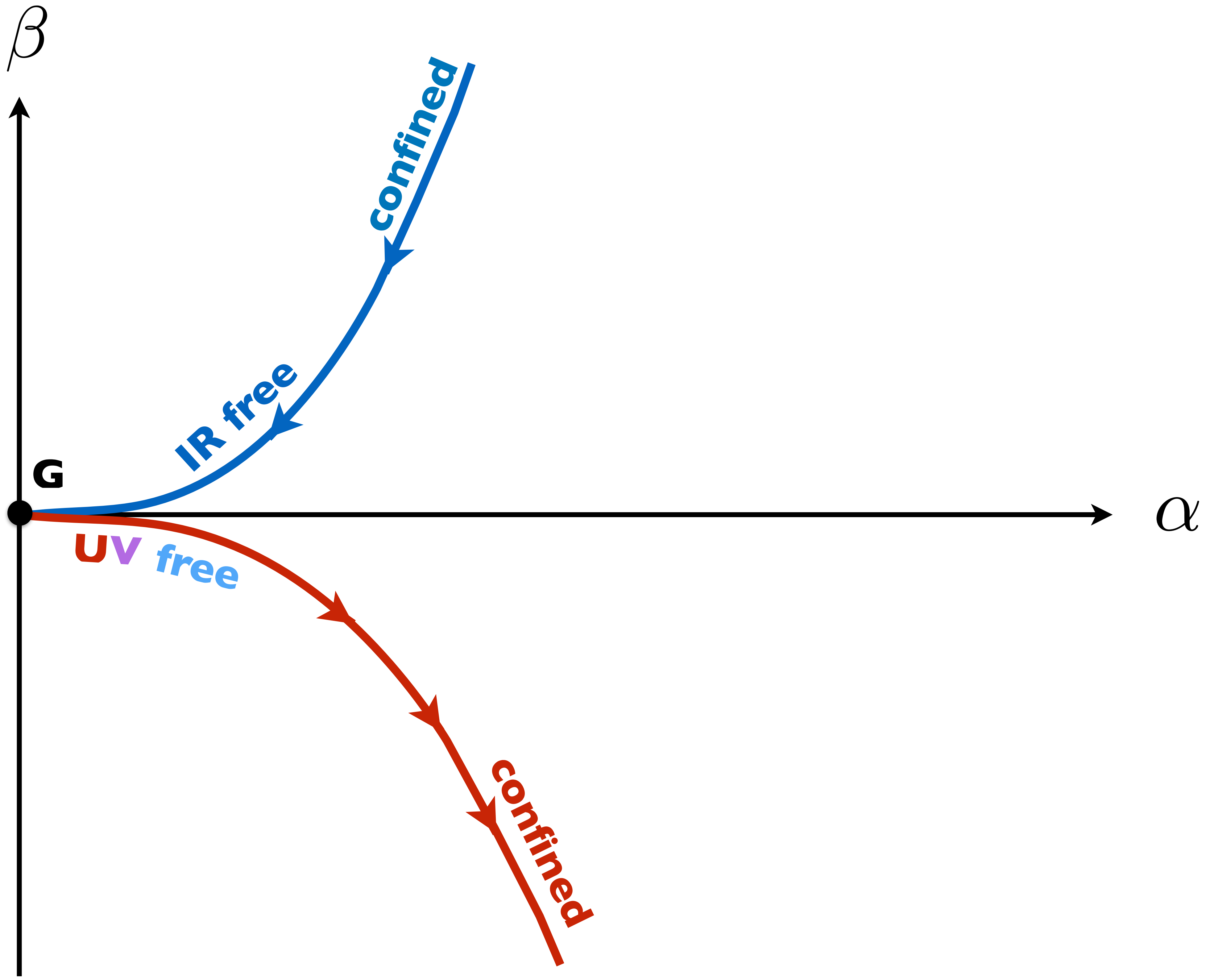
scalar Yukawa

Banks Zaks

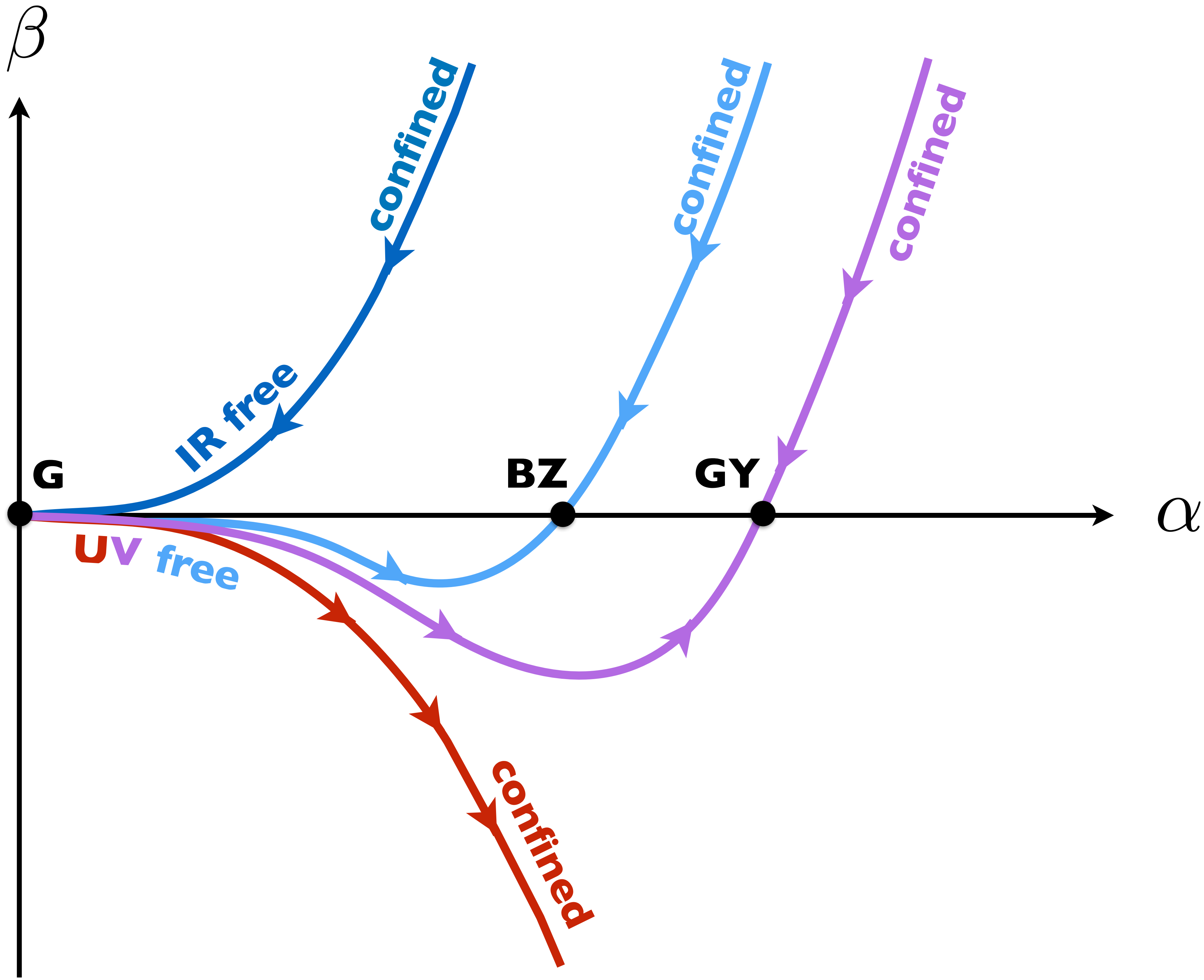
gauge Yukawa

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

renormalisation group



renormalisation group



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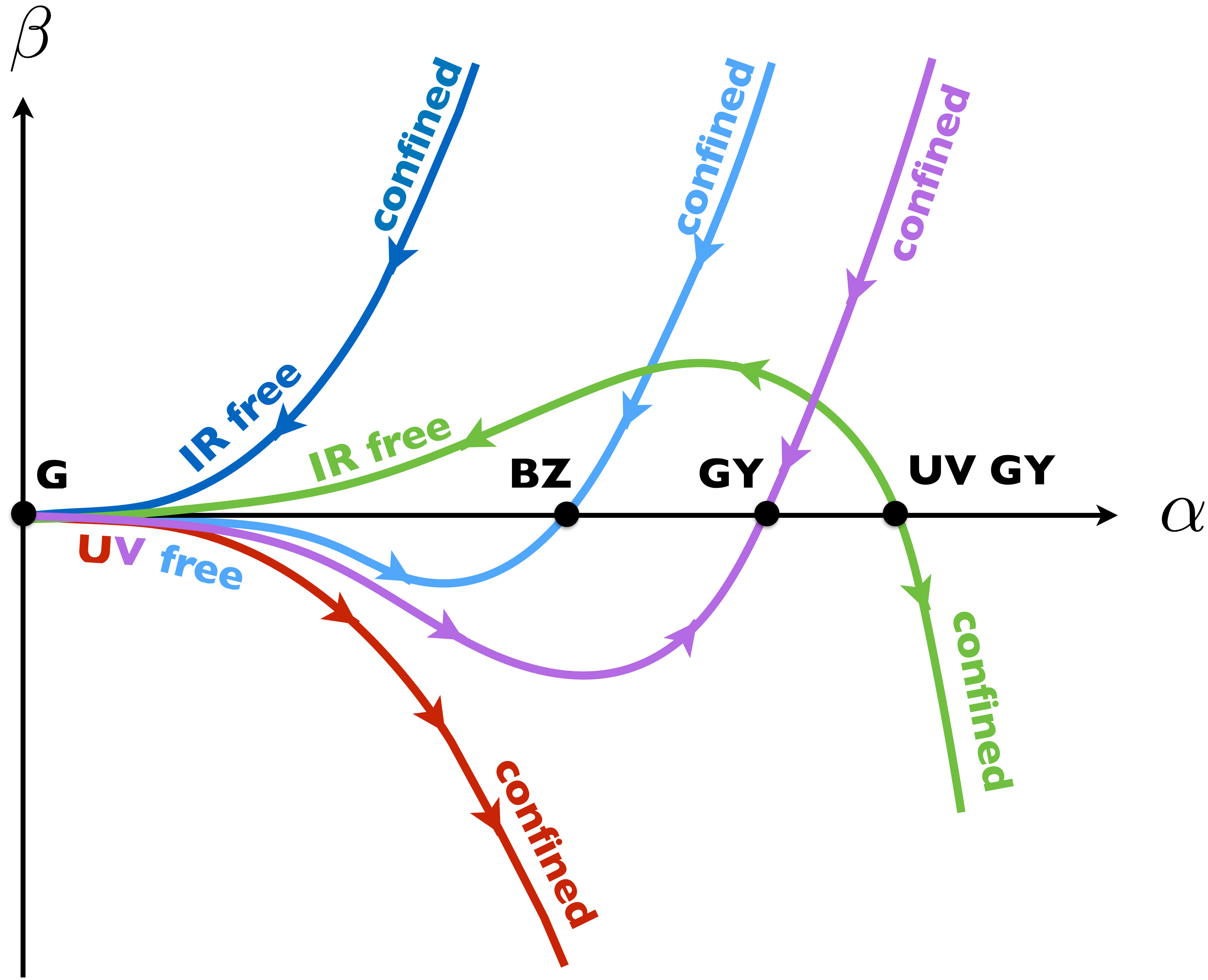

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“theory space”

	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 & no go theorems

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)
AD Bond, DF Litim, T Steudtner, **Asymptotic safety with Majorana fermions and new large N equivalences** 1911.11168

semi-simple 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 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** 1905.11020, **Anomalous magnetic moments from asymptotic safety** 1910.14062
Model building from asymptotic safety with Higgs and flavour portals 2008.08606

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why no UV BZ?

gauge coupling

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

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

competition between matter and gauge fields

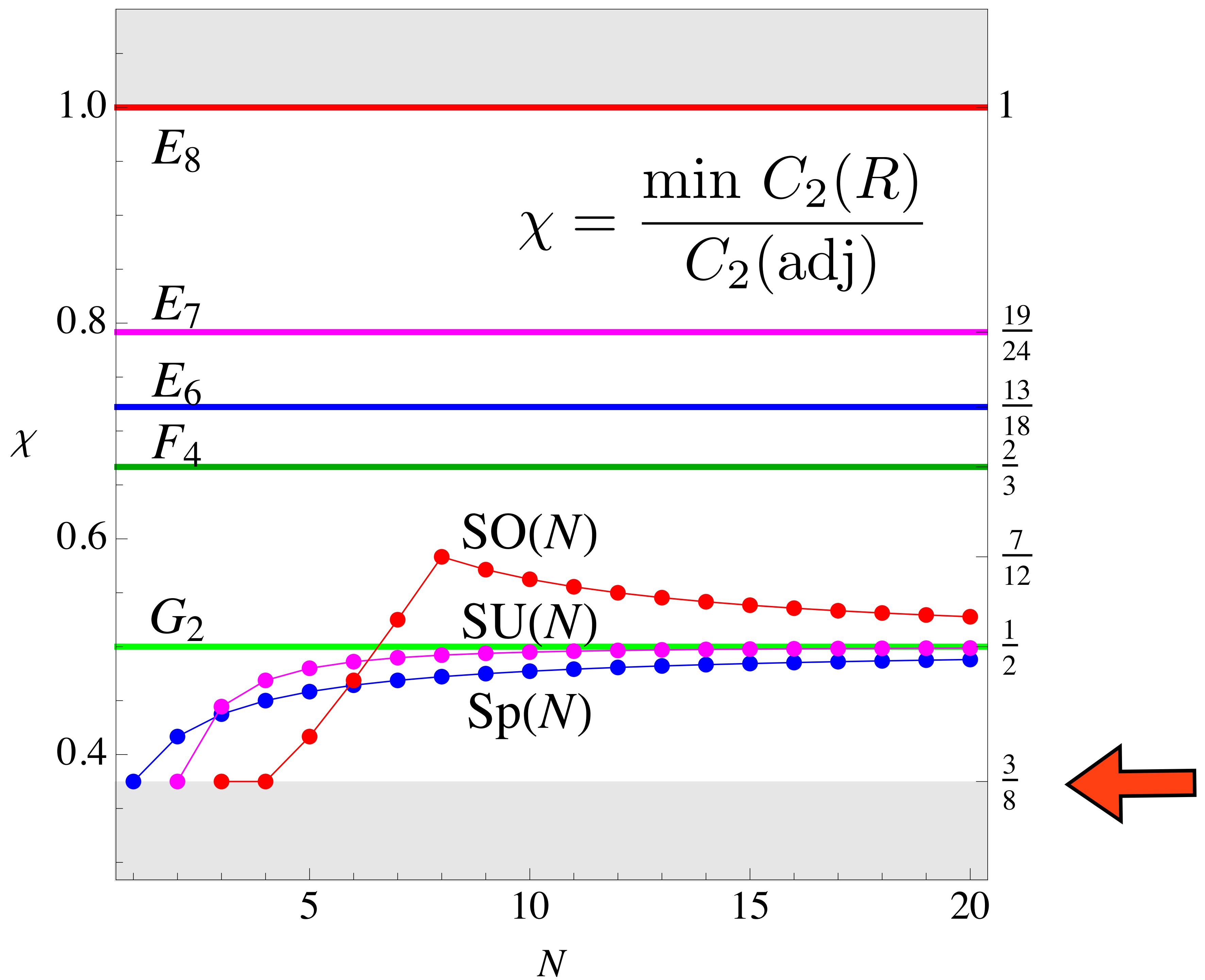
UV BZ requires $\quad B < 0, C < 0$

necessary condition

$$\chi = \frac{\min\, C_2(R)}{C_2(\mathrm{adj})} < \frac{1}{11}$$

impossible!

here's why.



Bond, Litim, 1608.00519/EPJC

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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here's why.

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

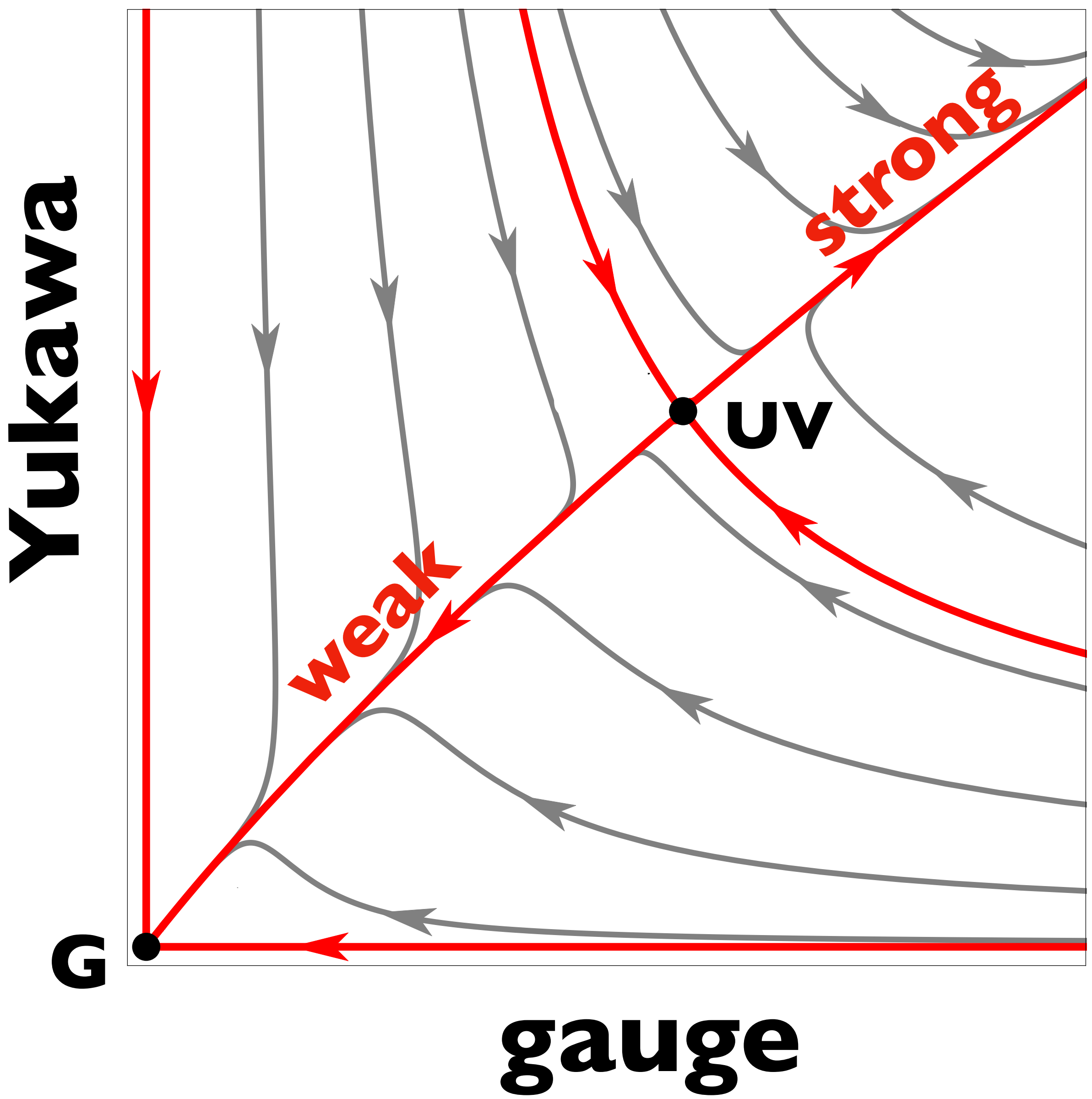
$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

one loop   gauge   Yukawa

Yukawas *always* slow down the running of gauge couplings

templates with SU/SO/Sp



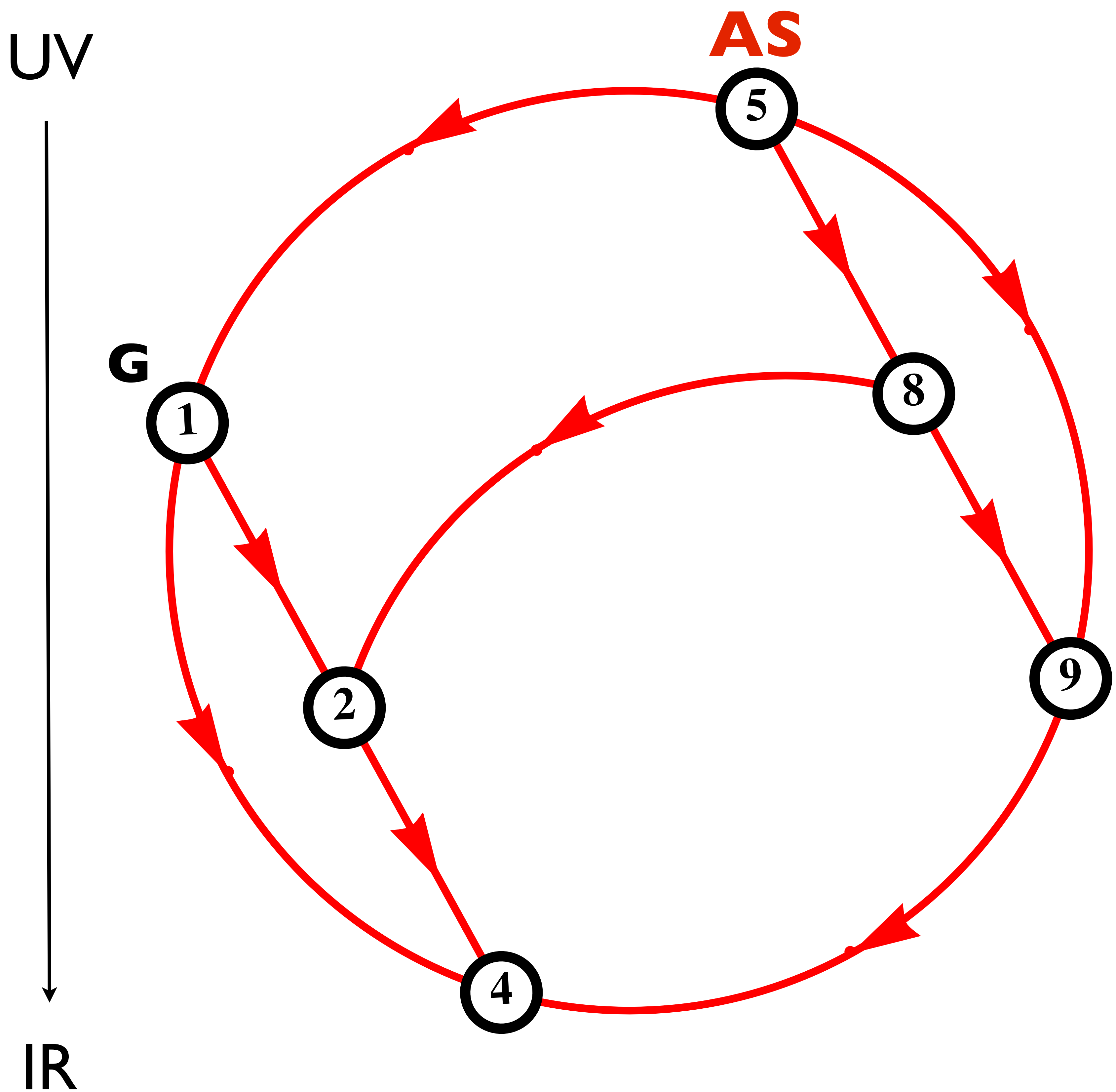
SU(N) + Diracs
+ mesons

SO(N) + Majoranas
+ mesons

Sp(N) + Majoranas
+ mesons

DF Litim, F Sannino, **Asymptotic safety guaranteed,** 1406.2337
AD Bond, DF Litim, G Medina Vazquez, T Steudtner, **Conformal window for asymptotic safety**, 1710.07615
AD Bond, DF Litim, T Steudtner, **Asymptotic safety with Majorana fermions and new large N equivalences** 1911.11168

semi-simple template



SU(N) x SU(M)
+ Diracs
+ mesons

2 gauge
2 Yukawas
5 quartics

various FPs

AD Bond, DF Litim, **More Asymptotic Safety Guaranteed,** 1707.04217

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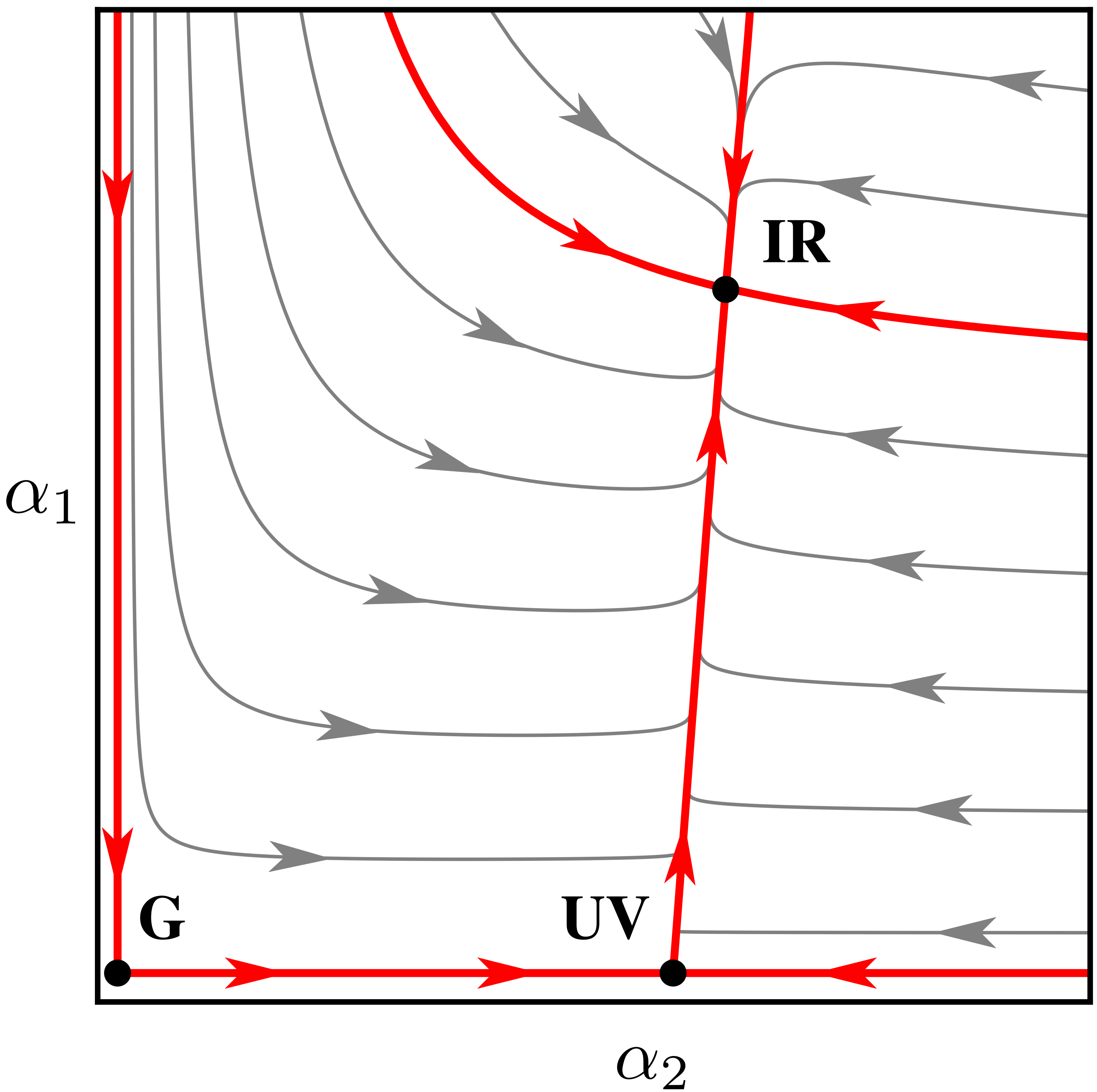
templates for SUSY



SU(N) x SU(M)
+ chiral superfields
+ superpotential

"Susy enhances predictivity"

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

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overview

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]

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**

implications

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- 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**

⇒ new territory **"beyond BSM"** 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

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

beyond BSM

…inspired by asymptotic safety

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 1905.11020
Anomalous magnetic moments from asymptotic safety 1910.14062
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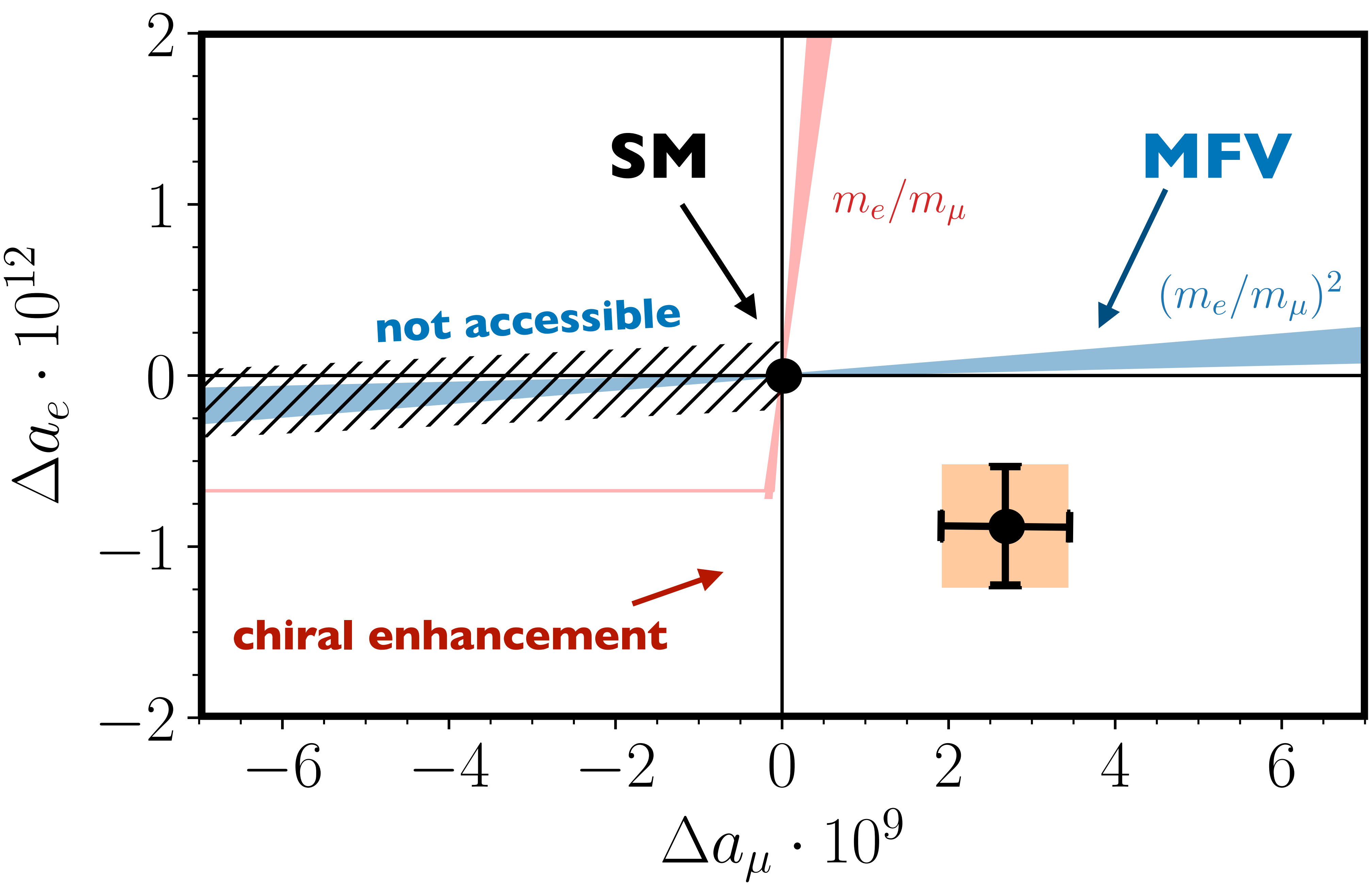
anomalous magnetic moments

a puzzle...

$$\Delta a_\mu \equiv a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 268(63)(43) \cdot 10^{-11}$$

$$\Delta a_e \equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = -88(28)(23) \cdot 10^{-14}$$

anomalous magnetic moments



intriguing…

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anomalous magnetic moments

what's the new physics?

to date: 25 BSM models can explain the data

24 of them treat electrons and muons differently
i.e. lepton universality manifestly broken

beyond BSM

BSM models inspired by asymptotic safety:

new vector-like BSM fermions + scalars
new Yukawas + portal interactions

$$\boxed{y\,\mathrm{Tr}\left[\overline{\psi}_L S \psi_R\right]} + \boxed{\kappa\,\overline{L} H \psi_R + \kappa'\,\mathrm{Tr}[\overline{E} S^\dagger \psi_L]}$$

BSM matter **SM matter**

lepton universality intact

beyond BSM

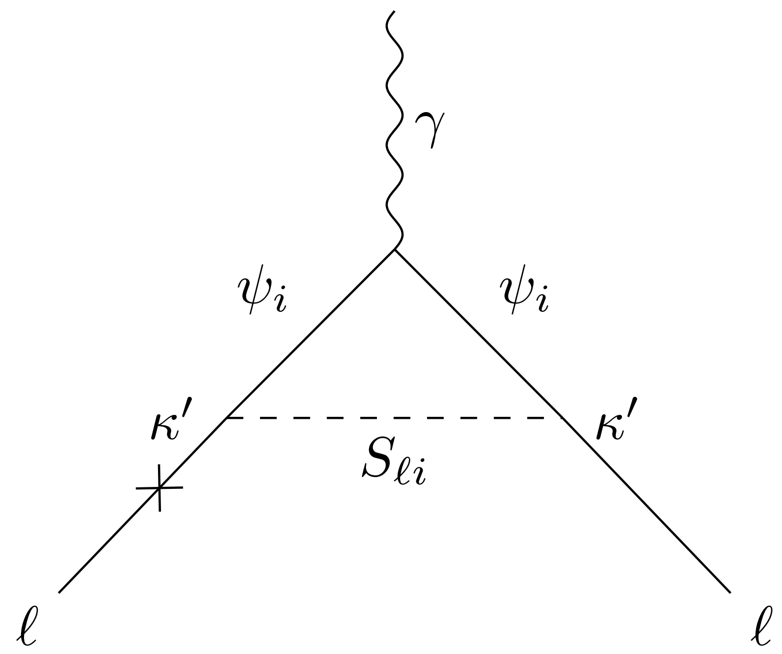
new vector-like BSM fermions + scalars
new Yukawas + portal interactions

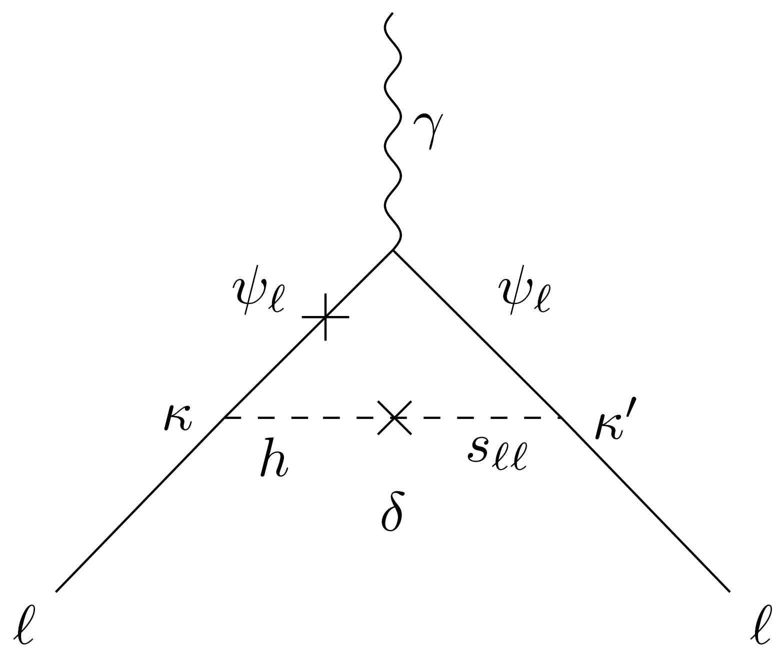
$$\boxed{y\,\mathrm{Tr}\,[\overline{\psi}_L S \psi_R]} + \boxed{\kappa\,\overline{L} H \psi_R + \kappa'\,\mathrm{Tr}[\overline{E} S^\dagger \psi_L]}$$

feature: **BSM Yukawas can explain anomalous magnetic moments**

beyond BSM

new vector-like BSM fermions + scalars
new Yukawas + portal interactions





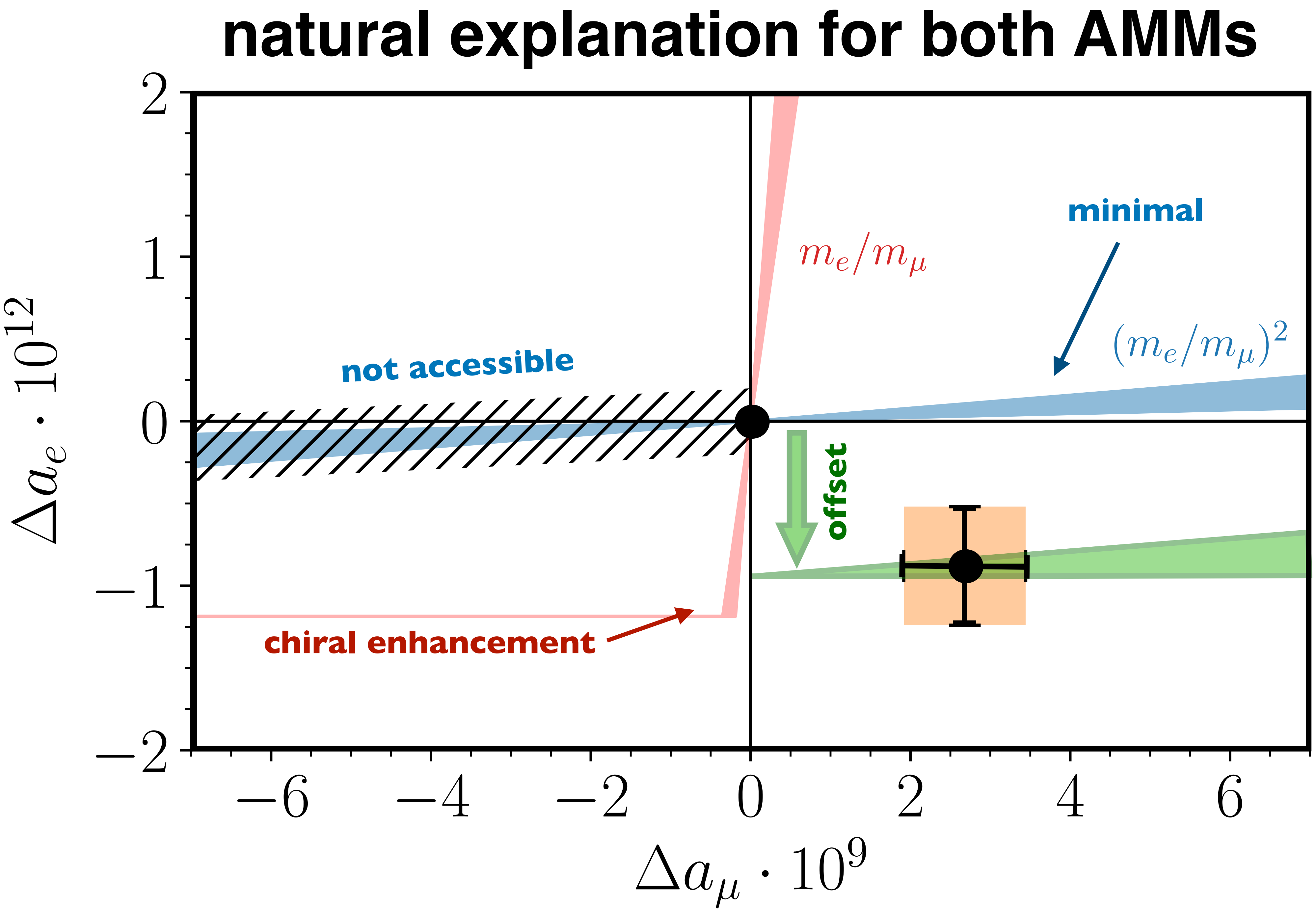
"minimal"

$$\sim (m_e/m_\mu)^2$$

"chirally enhanced"

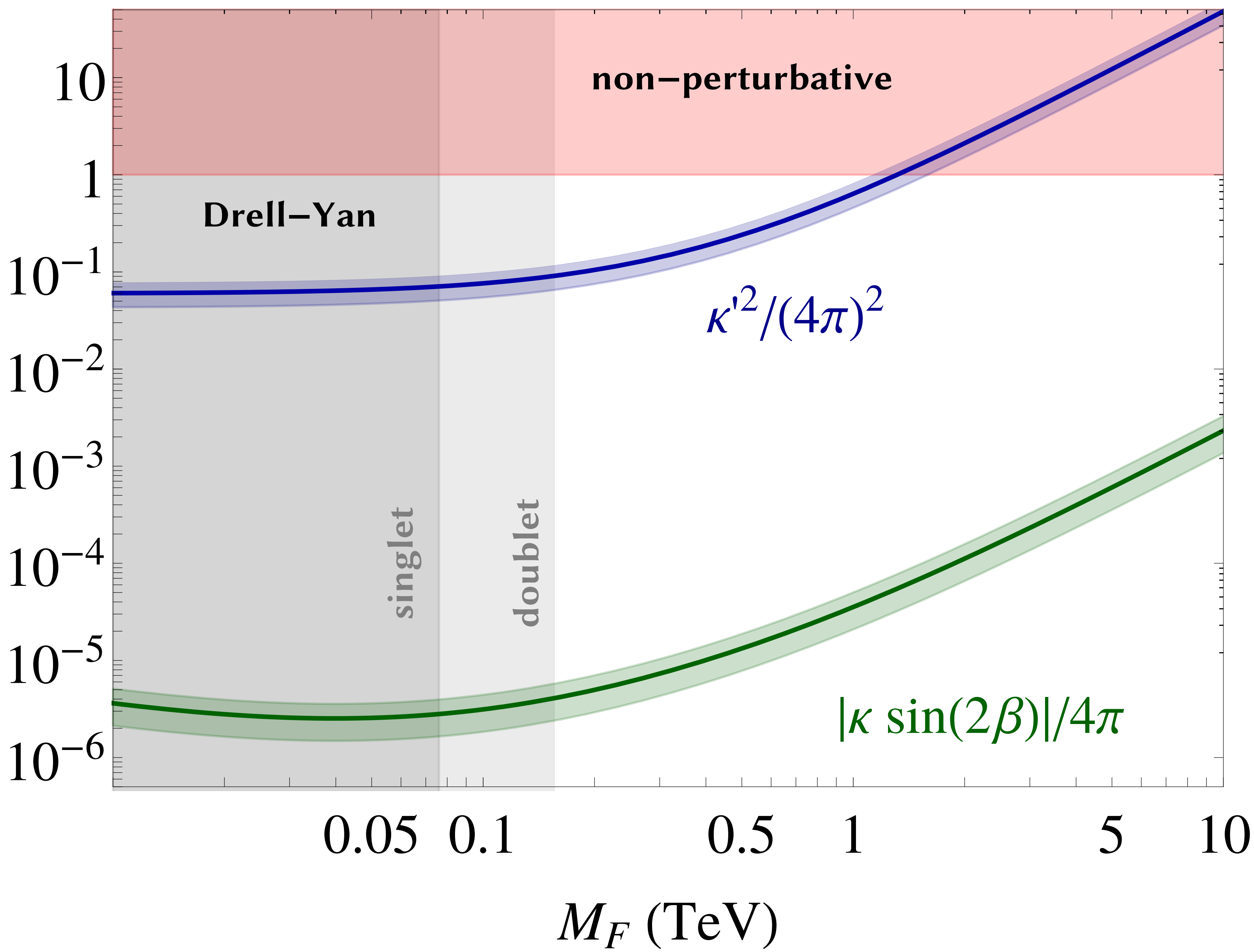
$$\sim (m_e/m_\mu)$$

beyond BSM


natural explanation for both AMMs
m_e/m_μ
minimal
$(m_e/m_\mu)^2$
not accessible
offset
chiral enhancement
$\Delta a_e \cdot 10^{12}$
$\Delta a_\mu \cdot 10^9$
2
1
0
−1
−2
−6
−4
−2
0
2
4
6

beyond BSM

constraints



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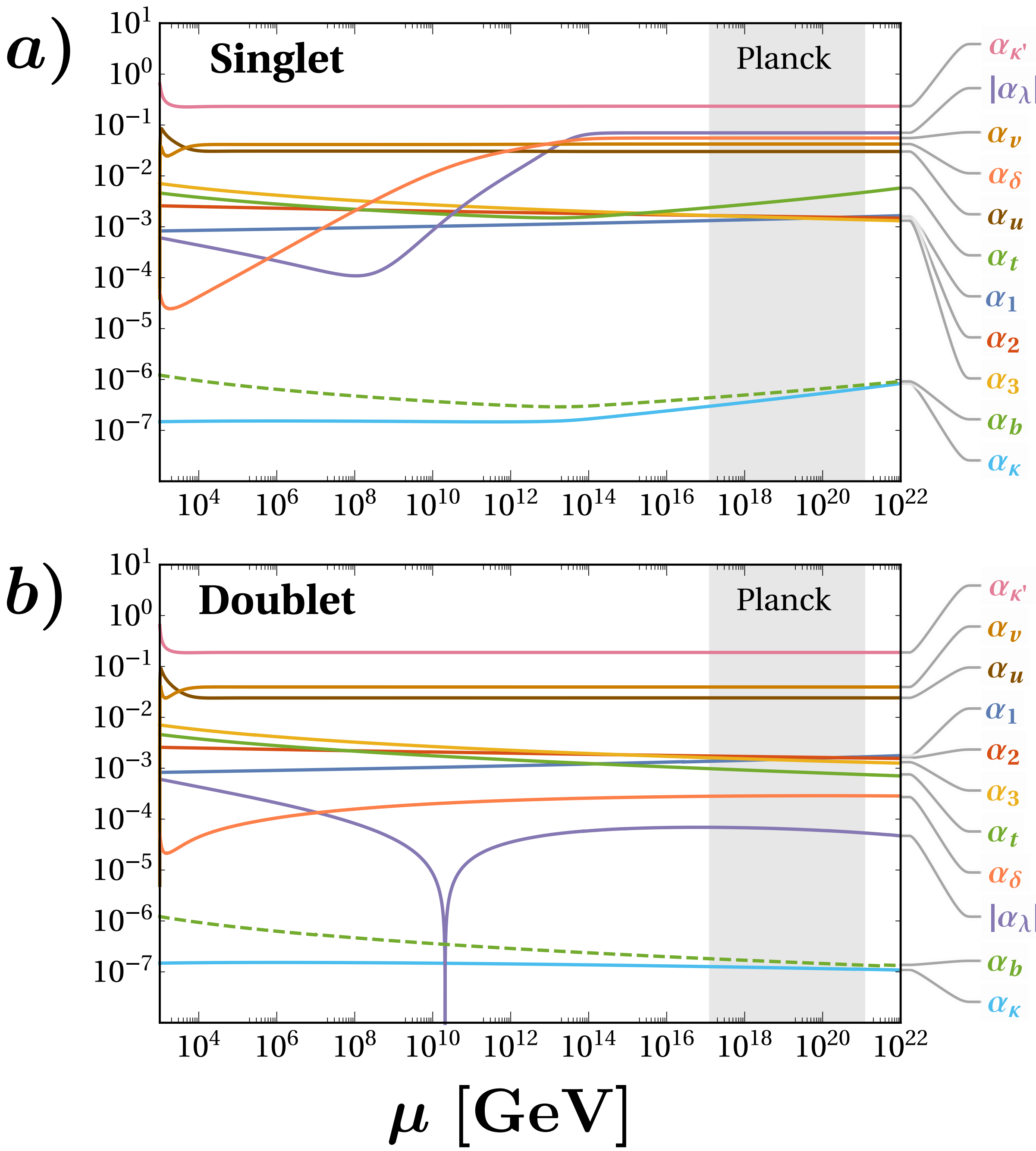
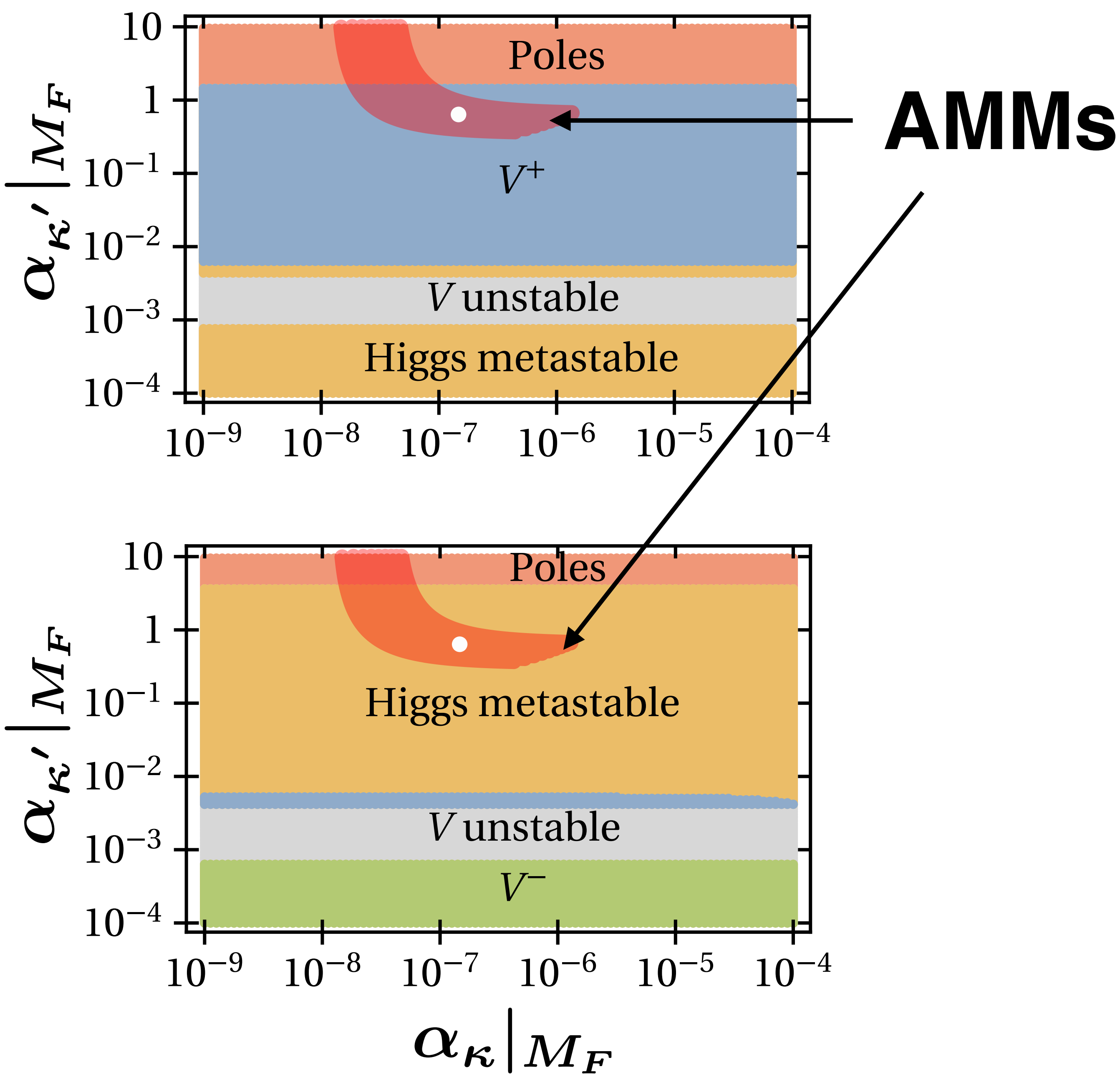
beyond BSM

asymptotic safety





G Hiller, C Hermigos-Feliu, DF Litim, T Steudtner, **Anomalous magnetic moments from asymptotic safety** 1910.14062

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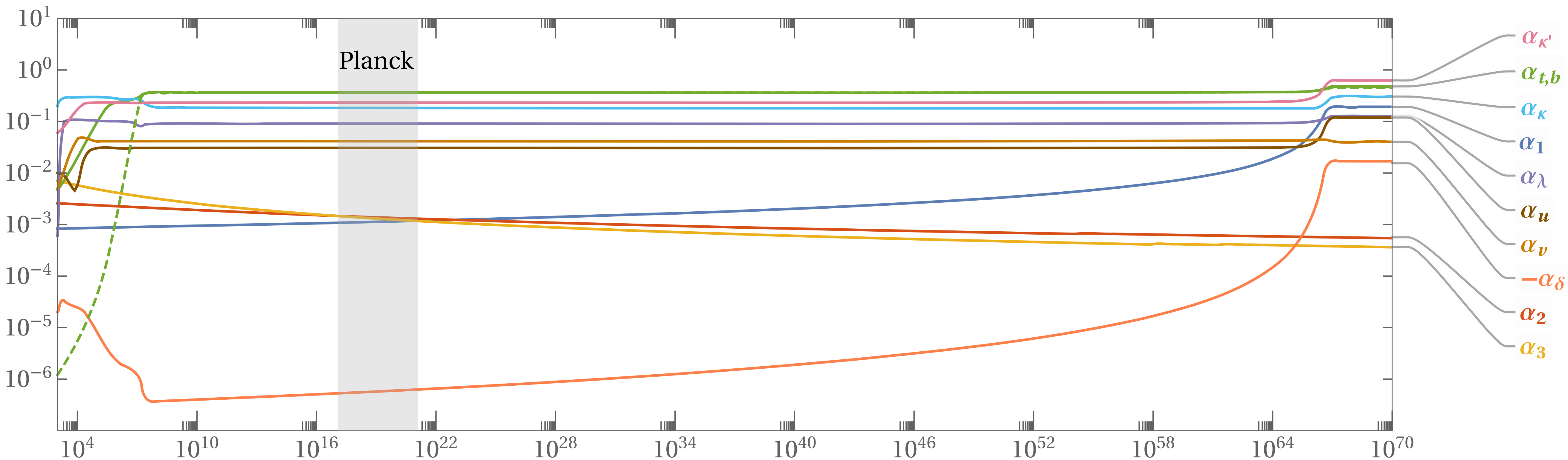
beyond BSM



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beyond BSM

BSM models inspired by asymptotic safety

AMMs are explained naturally for wide range of parameters

more features: compatible with lepton universality
prediction for tau AMM

can be tested at colliders

G Hiller, C Hermigos-Feliu, DF Litim, T Steudtner, **Anomalous magnetic moments from asymptotic safety** 1910.14062

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asymptotic safety

in 4d 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**

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

perturbatively non-renormalisable

interacting fixed point may require **strong** coupling and **large** anomalous dimensions

Weinberg, '79
Stelle '77

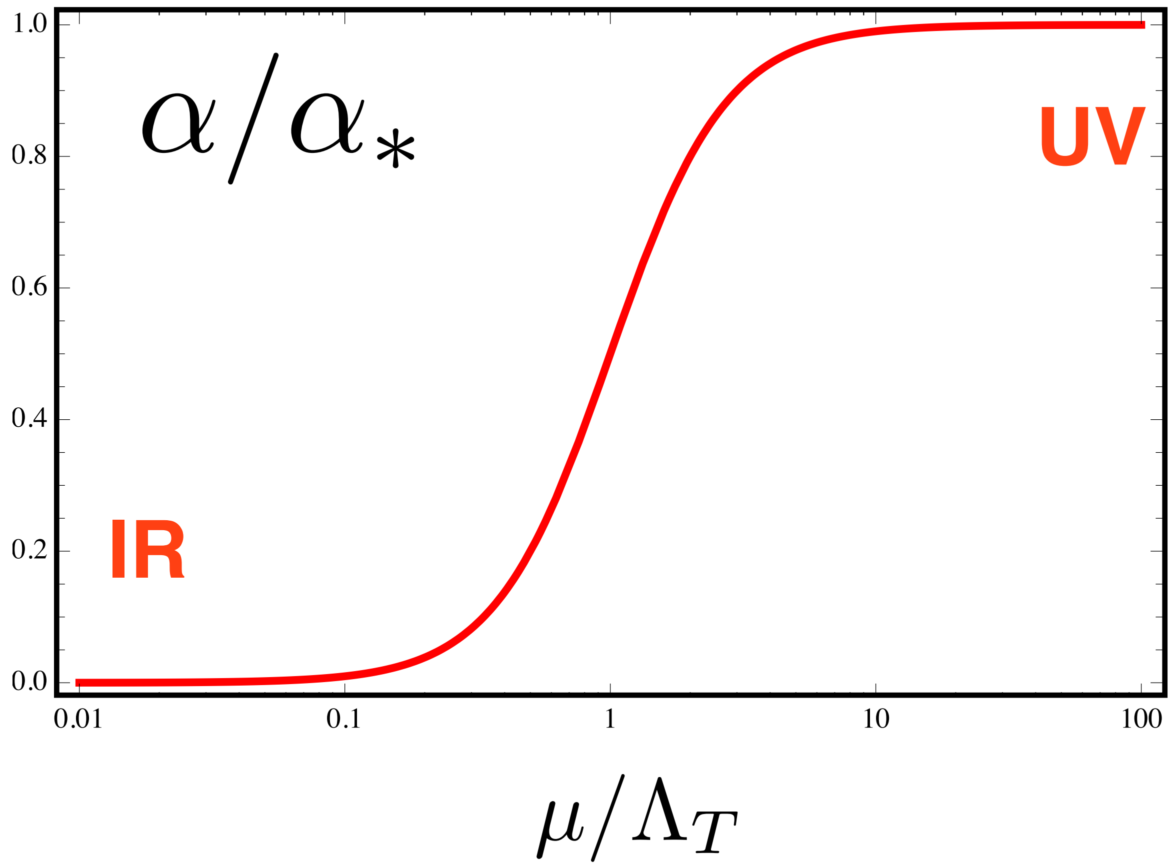
why it ‘might’ work…

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

$G(\mu) \approx G_N$

classical GR

IR fixed point implies classical GR



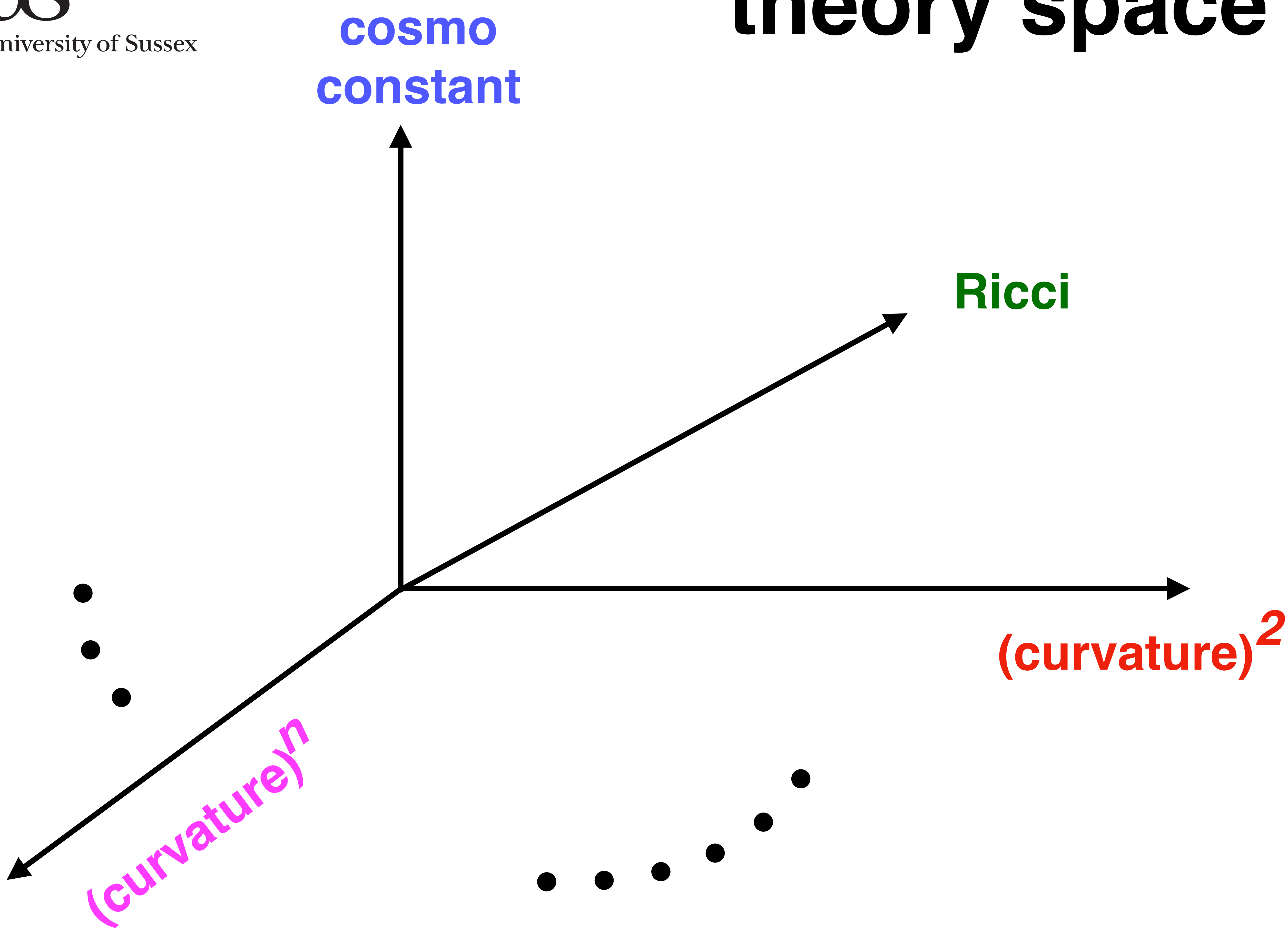
$G(\mu) \approx \dfrac{\alpha_*}{\mu^{D-2}}$

quantum GR

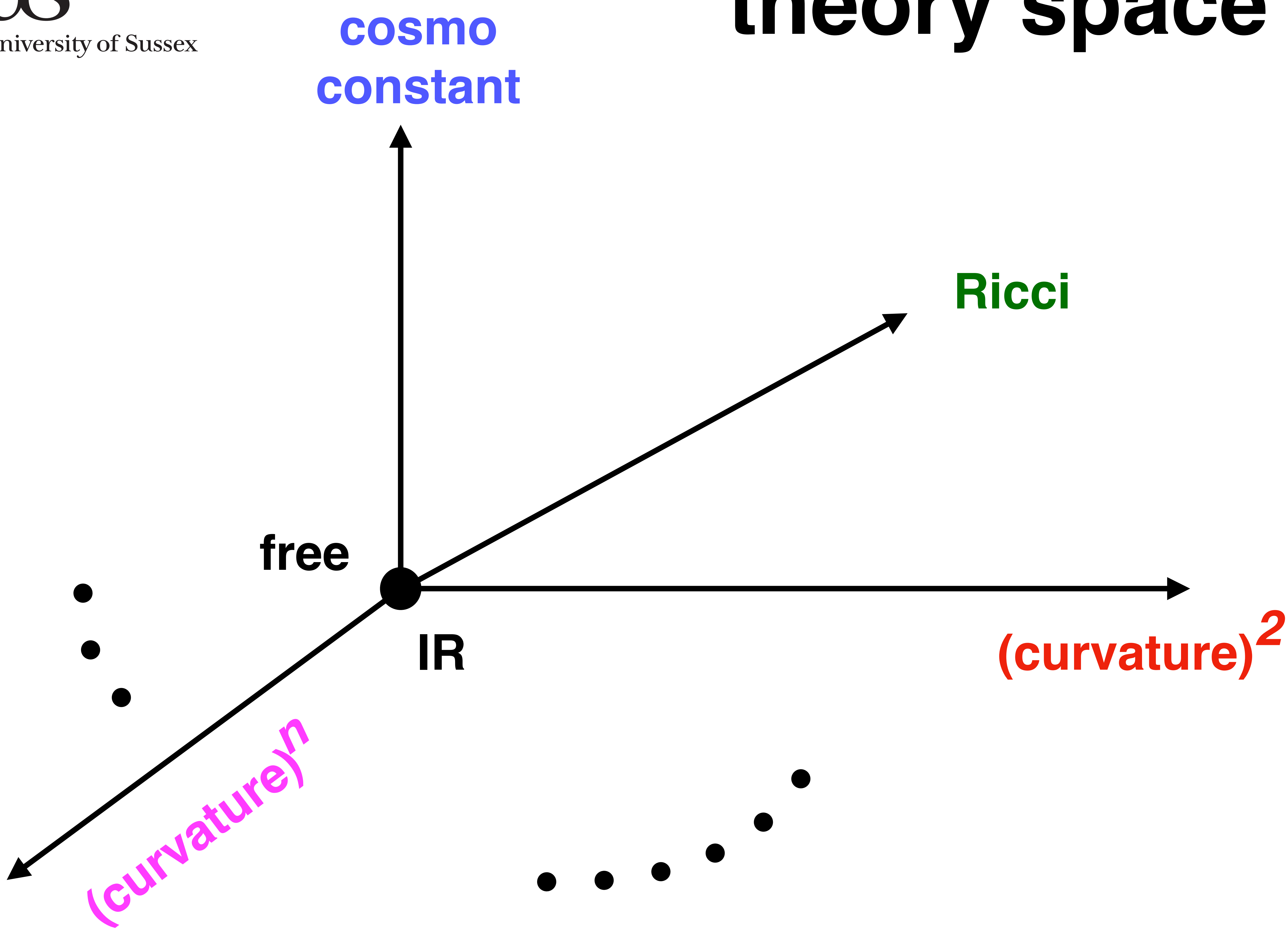
UV fixed point implies ‘weak gravity’

Litim, ’03, ‘06

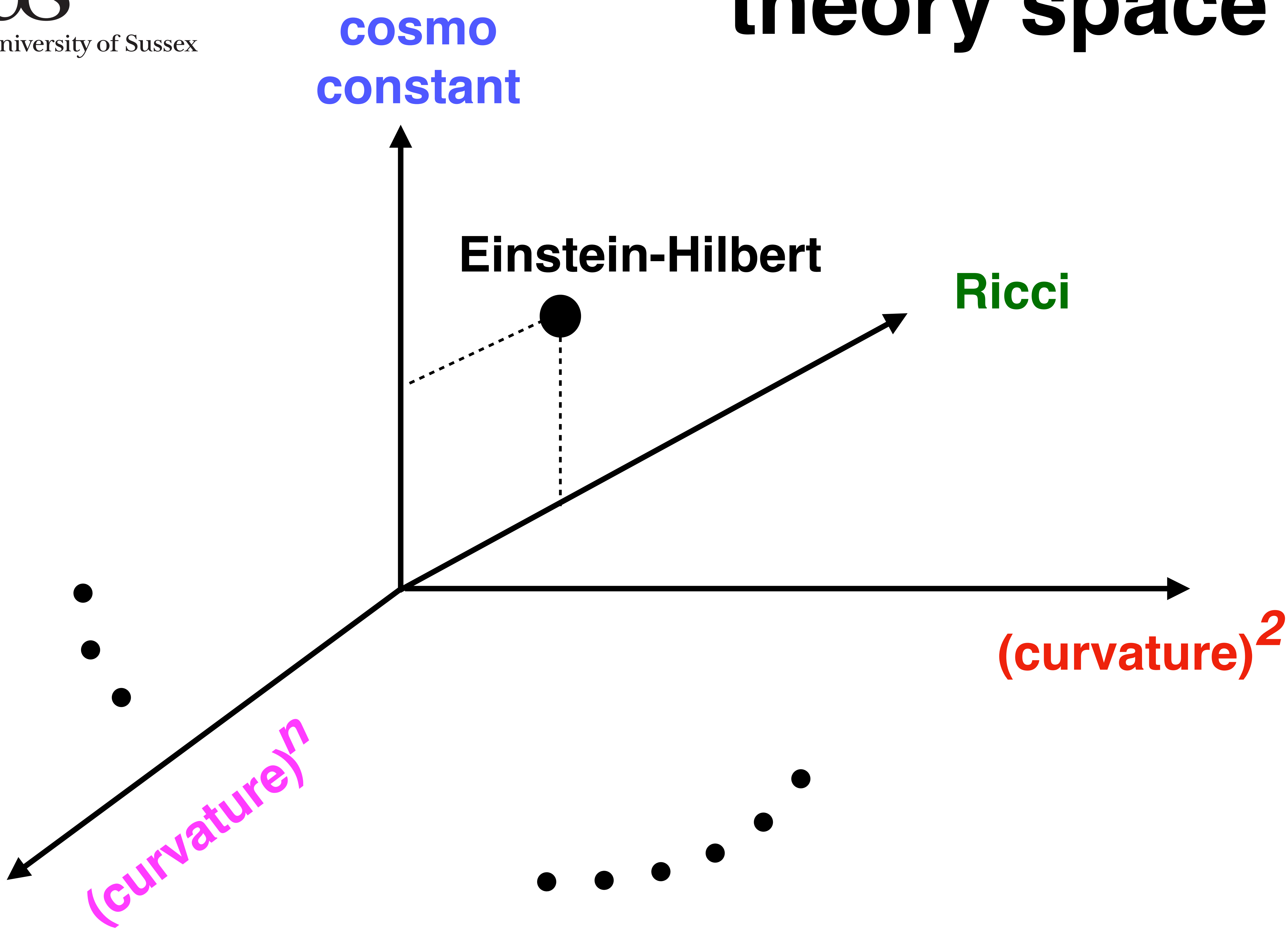
“theory space”



“theory space”



“theory space”



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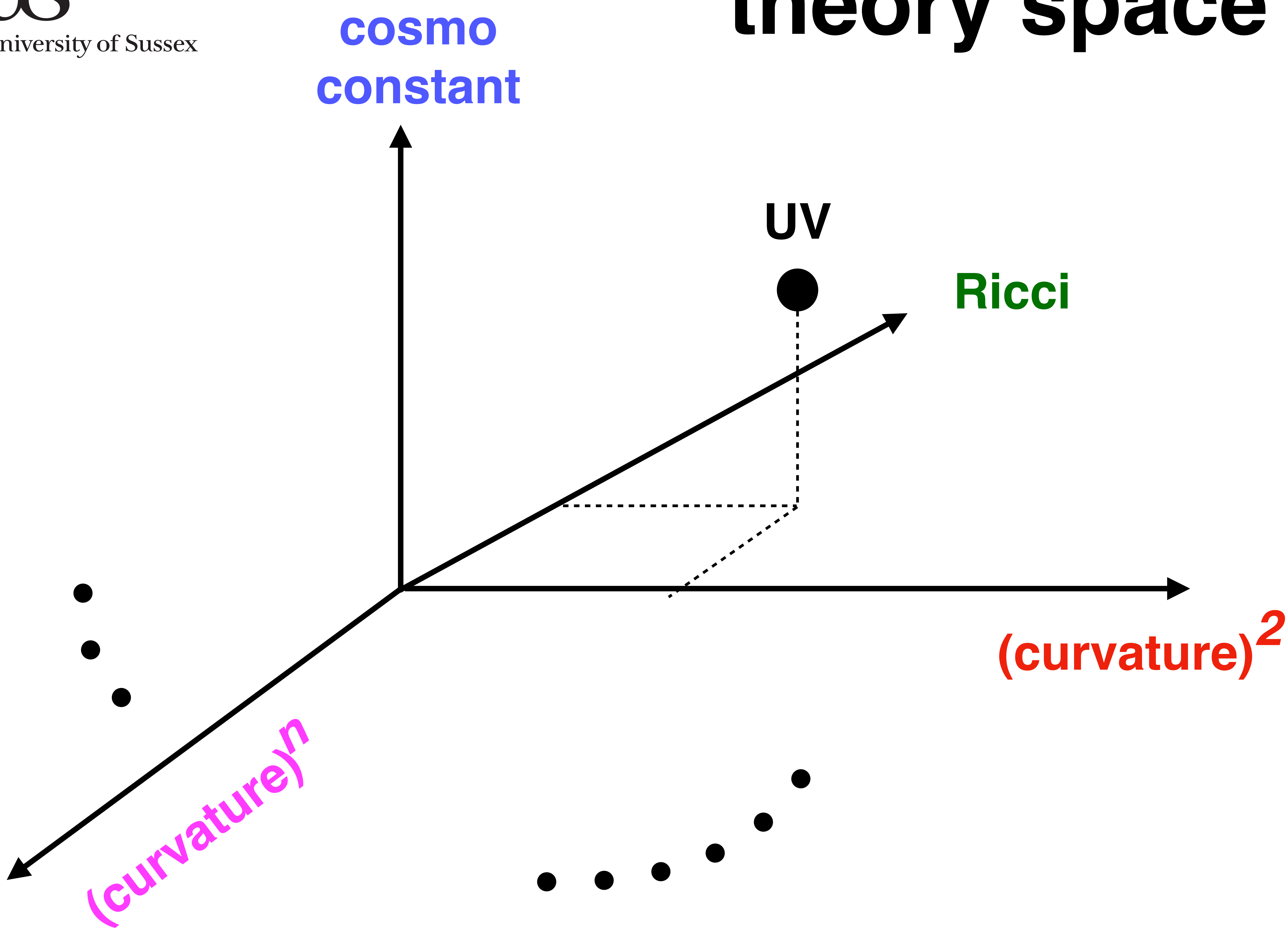

template: Ricci scalars

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 $D = 2(N-1)$

template: Ricci scalars

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 $D = 2(N-1)$

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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Ricci scalars

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 '03

$N = 3$ Reuter, Lauscher '01

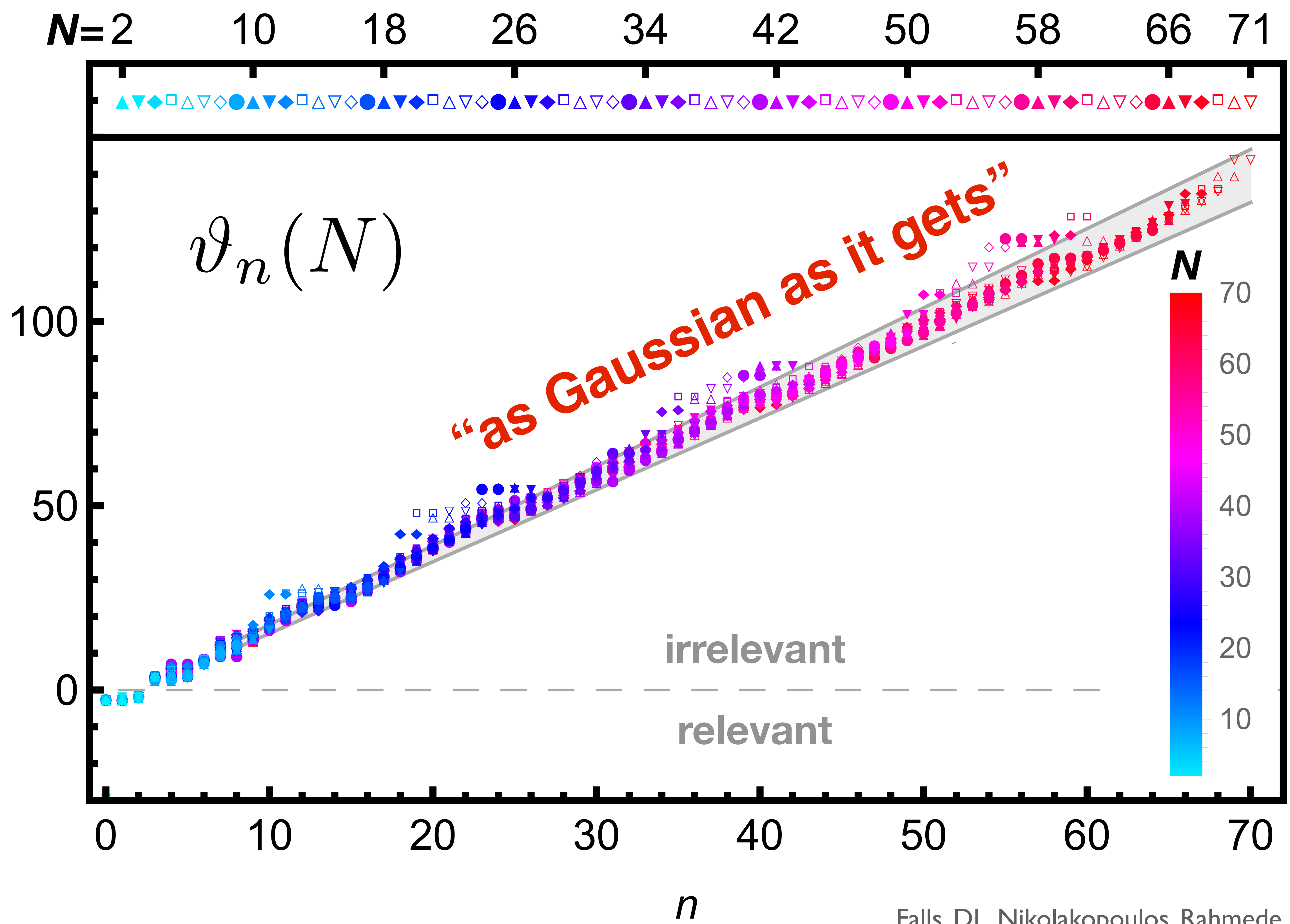
$N = 7$ Codello, Percacci, Rahmede '07

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

$N = 35$ Falls, Litim, Nikolakopoulos, Rahmede '13, '14, '16

$N = 71$ Falls, Litim, Schroeder '18

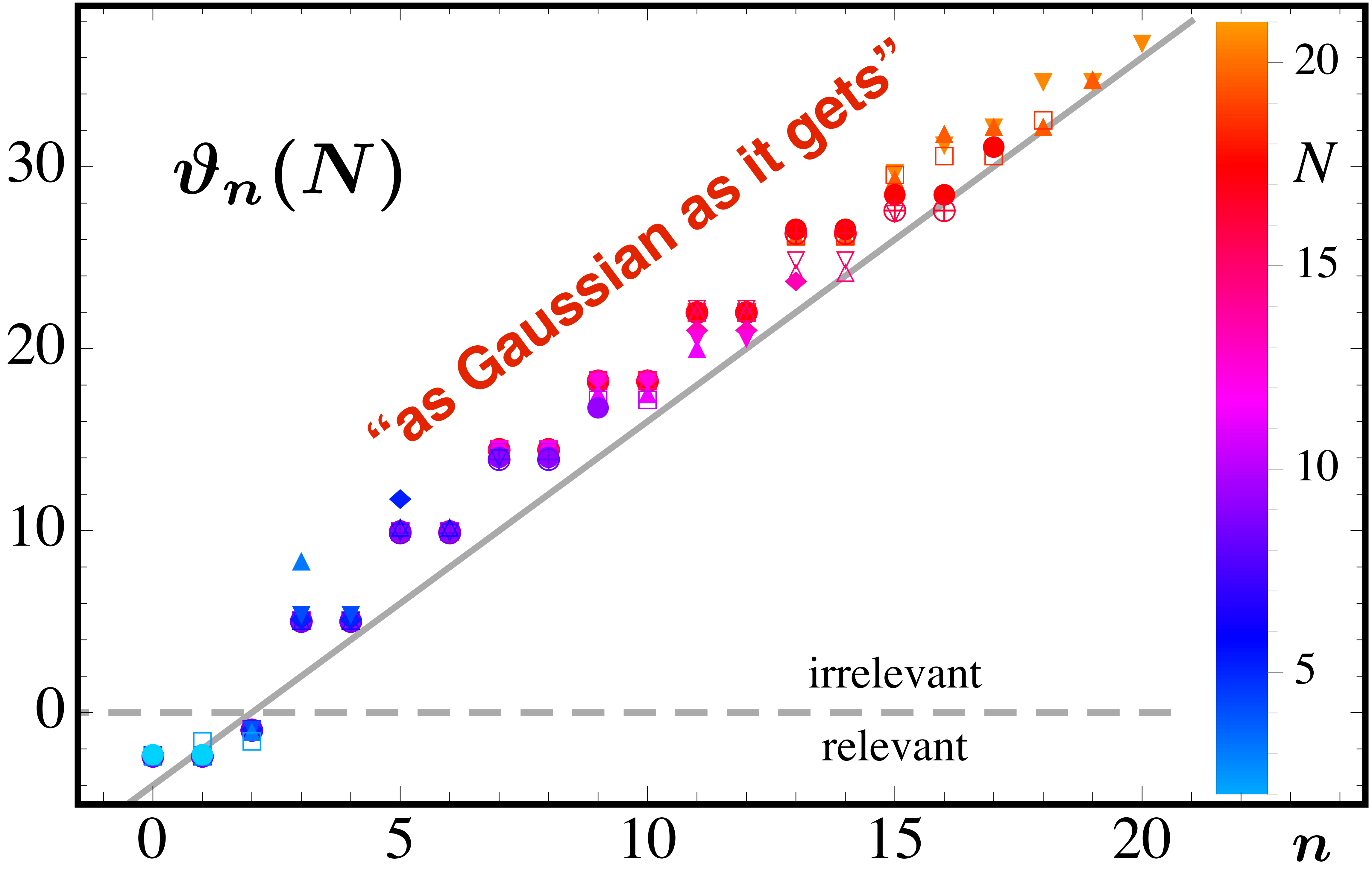
Ricci scalars



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

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

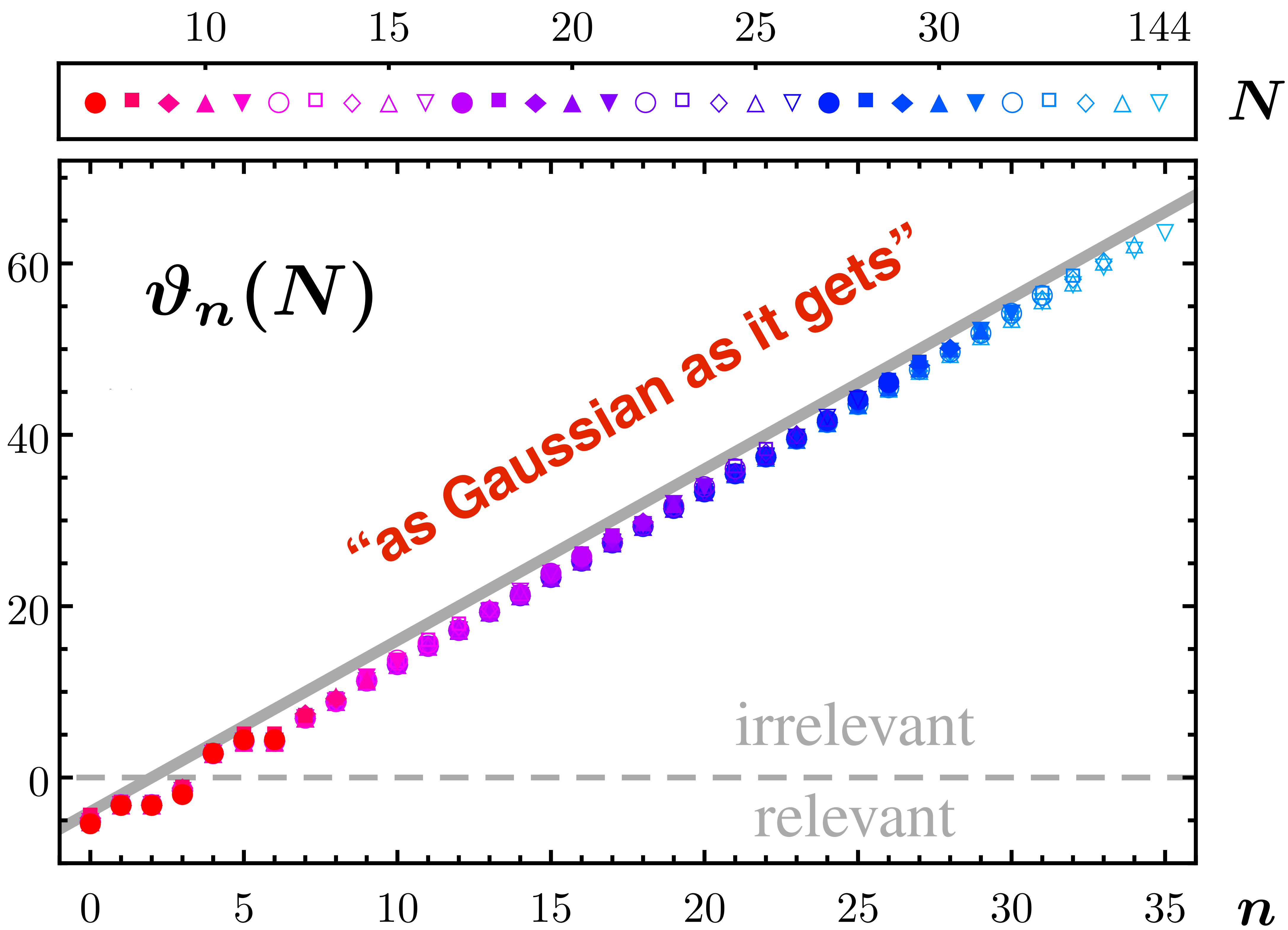
Ricci tensors



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

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

Riemann



Yannick Kluth, DF Litim, **Fixed points of quantum gravity and the dimensionality of the UV critical surface,** 2008.09181

beyond EH

asymptotic safety for gravity

systematic (bootstrap) search strategy

inclusion of higher order curvature interactions
strong circumstantial evidence for FP

more features: signatures of weak coupling
dS solutions

next steps: find hidden small parameter?
include matter !

conclusions

rigorous asymptotic safety in 4d ordinary QFTs

- weak coupling: theorems, templates, links with CFTs
- new directions for BSM
- strong coupling?

evidence for asymptotic safety in 4d quantum gravity

- signatures for weak coupling and near-Gaussianity
- small parameter?
- systematic inclusion of matter?

...stay tuned