Title: Asymptotic safety with and without supersymmetry

Date: Jun 05, 2018 10:00 AM

URL: http://pirsa.org/18060010

Abstract: I discuss the state of affairs for asymptotic safety in particle physics with and without supersymmetry.

Charting Fundamental Interactions

Francesco Sannino

Thanks to PI and
Niayesh Afshordi, Astrid Eichhorn & Robert Mann

CP3 Origins
Cosmology & Particle Physics

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?

what is asymptotic safety?

fundamental QFT ⟷ UV fixed point

Wilson '71

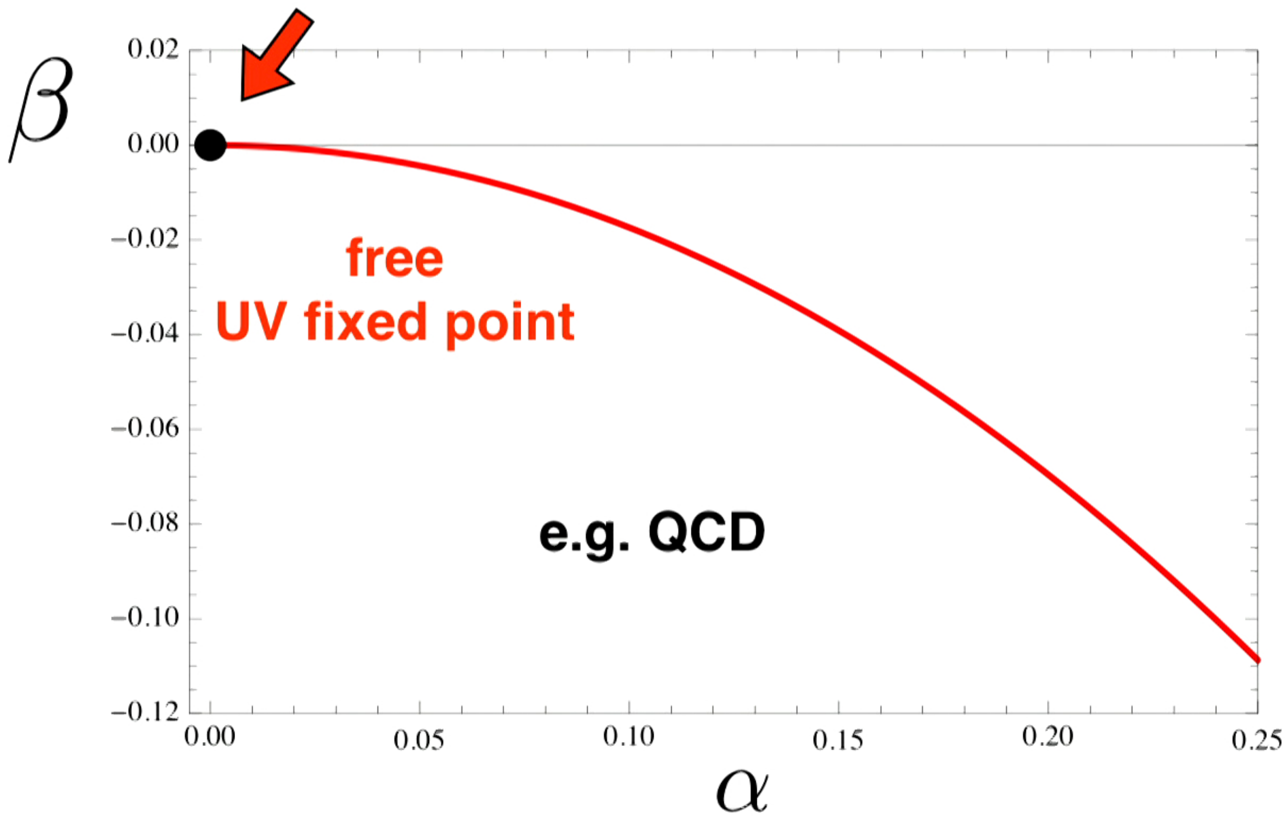
asymptotic freedom ⟷ non-interacting UV fixed point

Gross, Wilzcek '73 , Politzer '73

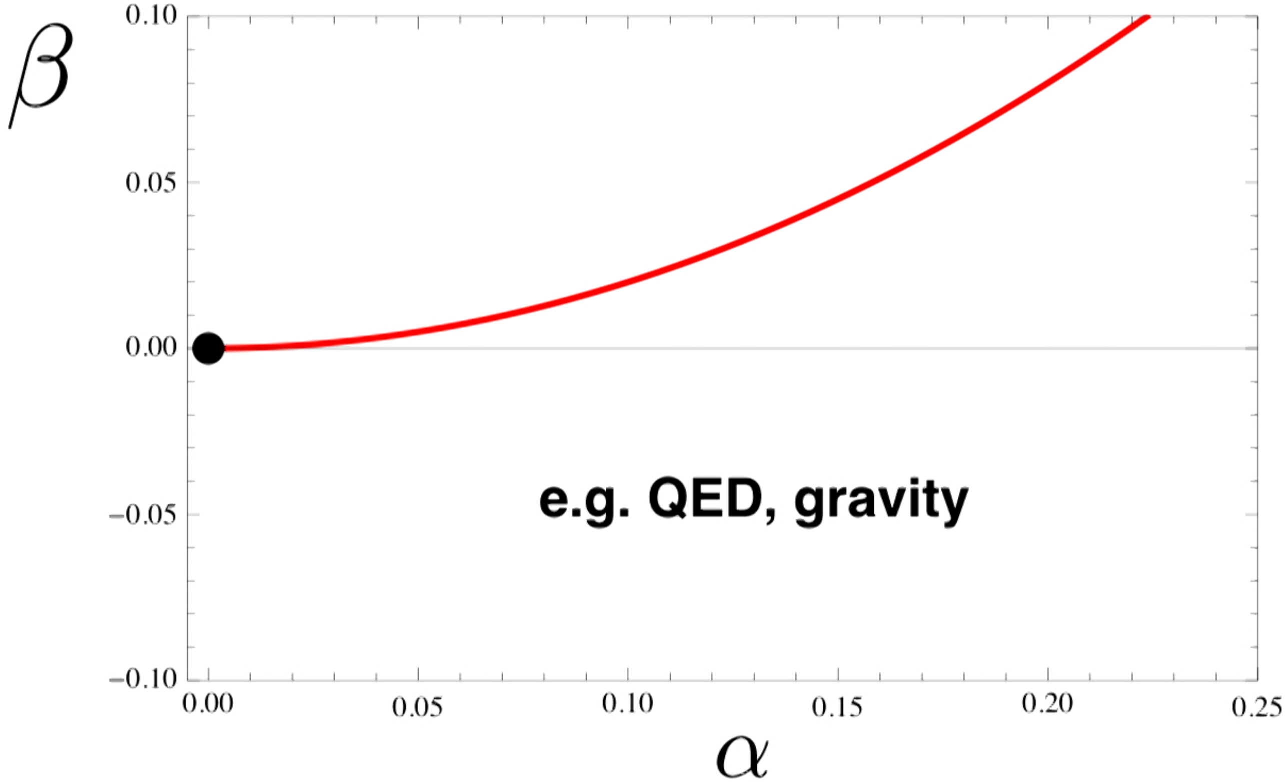
asymptotic safety ⟷ interacting UV fixed point

Weinberg '79

asymptotic freedom



infrared freedom



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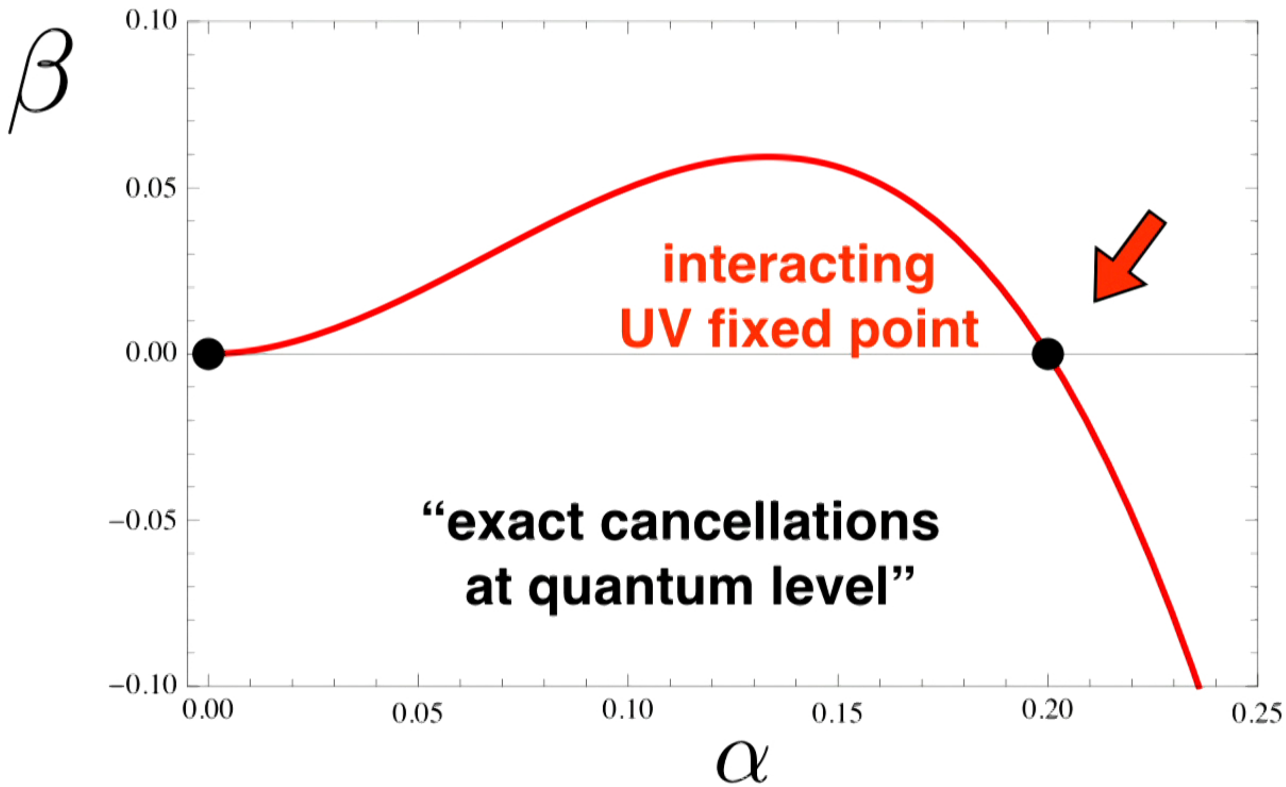
asymptotic safety



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asymptotic safety

quantum gravity in d = 2 + eps	Christensen, Duff '78 Gastmans, Kallosh, Truffin '78 Weinberg '79
3d Gross-Neveu	de Calan, Faria da Veiga, Magnen, de Seneor '91
4d infinite-NF gauge	Palanques-Mestre, Pascual '84 Gracey '96
4d quantum gravity	Reuter '96, Litim '03 **700+ papers**
4d gauge + matter	Litim, Sannino '14 **100+ papers**

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basics of asymptotic safety

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

AD Bond, DF Litim, **Price of Asymptotic Safety,** 1801.08527

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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

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fixed points

gauge theory

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

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competition between matter and gauge fields

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

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

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fixed points

gauge theory

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

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fixed points

gauge theory

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fermions — scalars — 1-loop

$B > 0$ and small: ➡ $C > 0$

Caswell-Banks-Zaks

IR FP

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fixed points

gauge theory

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

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fermions scalars 1-loop

$B < 0$ and small:

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

fixed points

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gauge theory

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fermions — scalars — 1-loop

$B > 0$ and small: $\Rightarrow$ $C > 0$

Caswell-Banks-Zaks

IR FP

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fixed points

gauge theory

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fermions scalars 1-loop

$B < 0$ and small:

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

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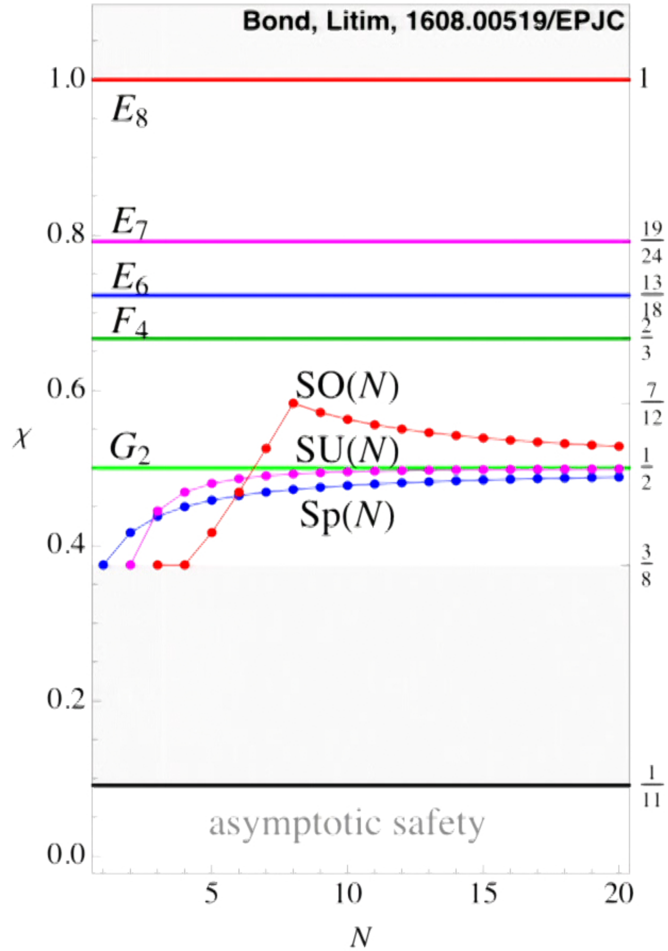
quadratic Casimirs

result:

$$\chi = \frac{\min\ C_2(R)}{C_2(\mathrm{adj})}$$



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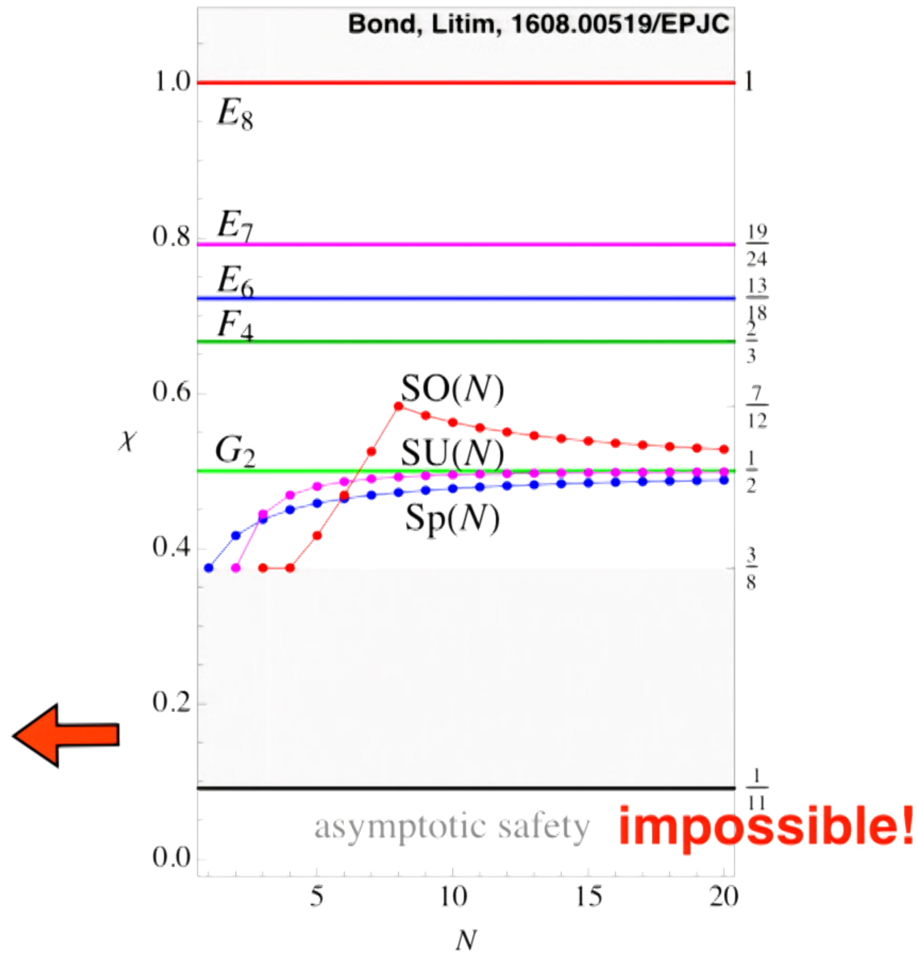
quadratic Casimirs

result:

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

weakly coupled BZ never UV



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asymptotic safety

result

1608.00519/EPJC

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

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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)

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Yukawas and asymptotic safety

gauge Yukawa theory

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y \quad \overset{!}{=} 0 \qquad t = \ln \mu/\Lambda$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y \quad \overset{!}{=} 0 \qquad \alpha_* \ll 1$$

loop coefficients $D, E, F > 0$ in any QFT

Yukawa's **slow down** the running of the gauge

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Yukawas and 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

$$C' = C - \frac{D\,F}{E} < 0$$

$$B < 0$$

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basics of asymptotic safety

summary of fixed points

$(\alpha_g^*, \alpha_y^*) = (0,0)$	Gaussian	UV or IR
$(\alpha_g^*, \alpha_y^*) = \left(\frac{B}{C}, 0\right)$	Banks-Zaks	IR
$(\alpha_g^*, \alpha_y^*) = \left(\frac{B}{C'}, \frac{B}{C'}\frac{F}{E}\right)$	gauge-Yukawa	UV or IR

gauge fields are mandatory

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asymptotic safety

result

1608.00519/EPJC

case	gauge group	matter	Yukawa	asymptotic safety
a)	simple	fermions in irreps	No	No
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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
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

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proofs of asymptotic safety

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

standard model extensions

AD Bond, G Hiller K Kowalska, DF Litim, **Directions for model building from asymptotic safety,** 1702.01727 (JHEP)

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can we drop the gauge fields?

asymptotic freedom

non-abelian gauge fields ➡ AF available

no non-abelian gauge fields ➡ AF **un**available

asymptotic safety

non-abelian gauge fields ➡ AS available

no non-abelian gauge fields ➡ AS **un**available

AD Bond, DF Litim, **Price of Asymptotic Safety,** 1801.08527

No way.

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weak coupling

- **UV complete theories** (free or safe) require non-abelian gauge fields

- **universality class** of any 4D quantum critical point contains gauge fields

"any QFT under pert. control in deep UV or IR asymptotes to a conformal field theory" Polchinski '88
Luty, Polchinski, Rattazzi, '12

- **any** weakly-coupled **4D conformal field theory** contains gauge degrees of freedom

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asymptotic safety with supersymmetry

AD Bond, DF Litim, 1709.06953/PRL

supersymmetry

gauge couplings
Yukawa (superpotential) couplings

no independent scalar couplings

non-renormalisation theorems
superconformal R symmetry

simple vs semi-simple gauge theories

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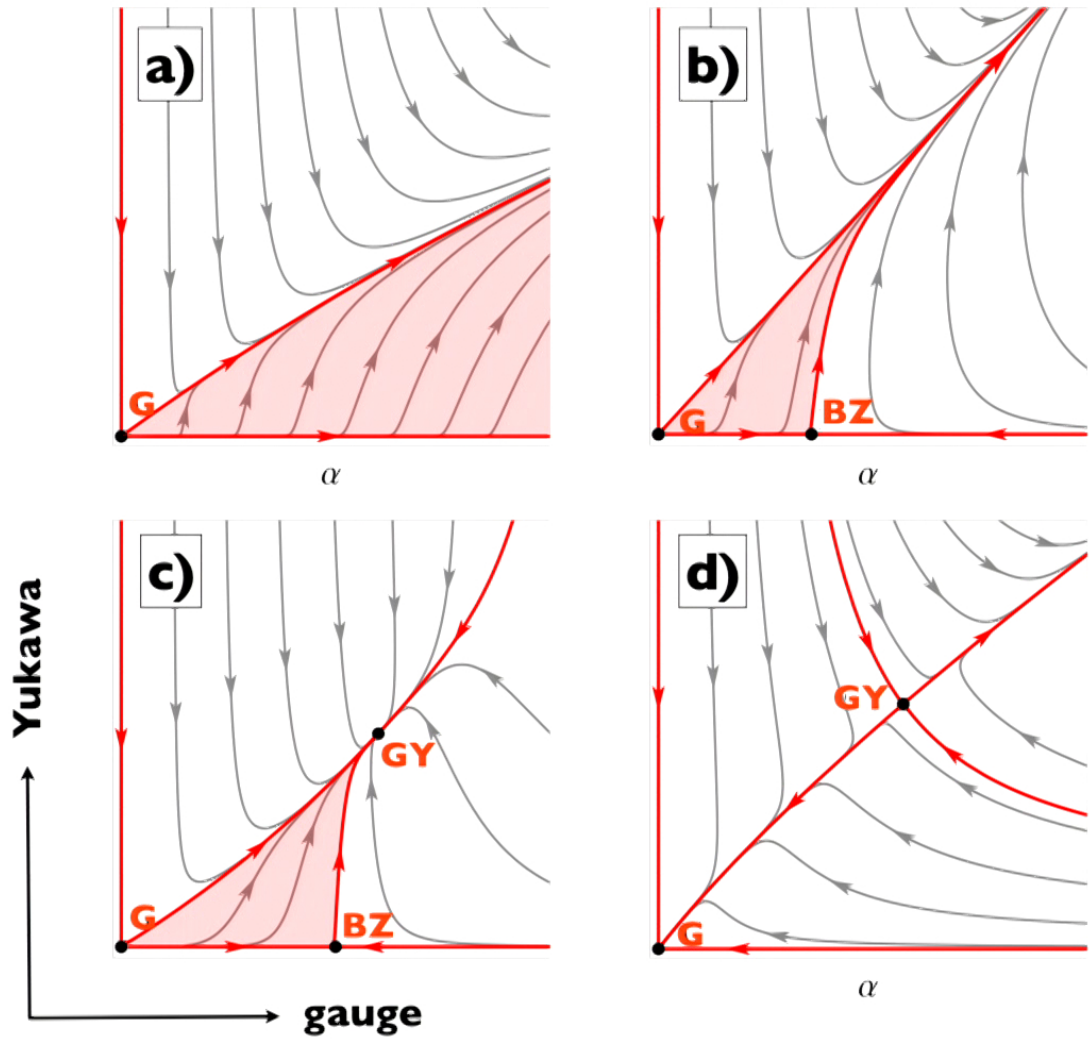
N=0
SUSY



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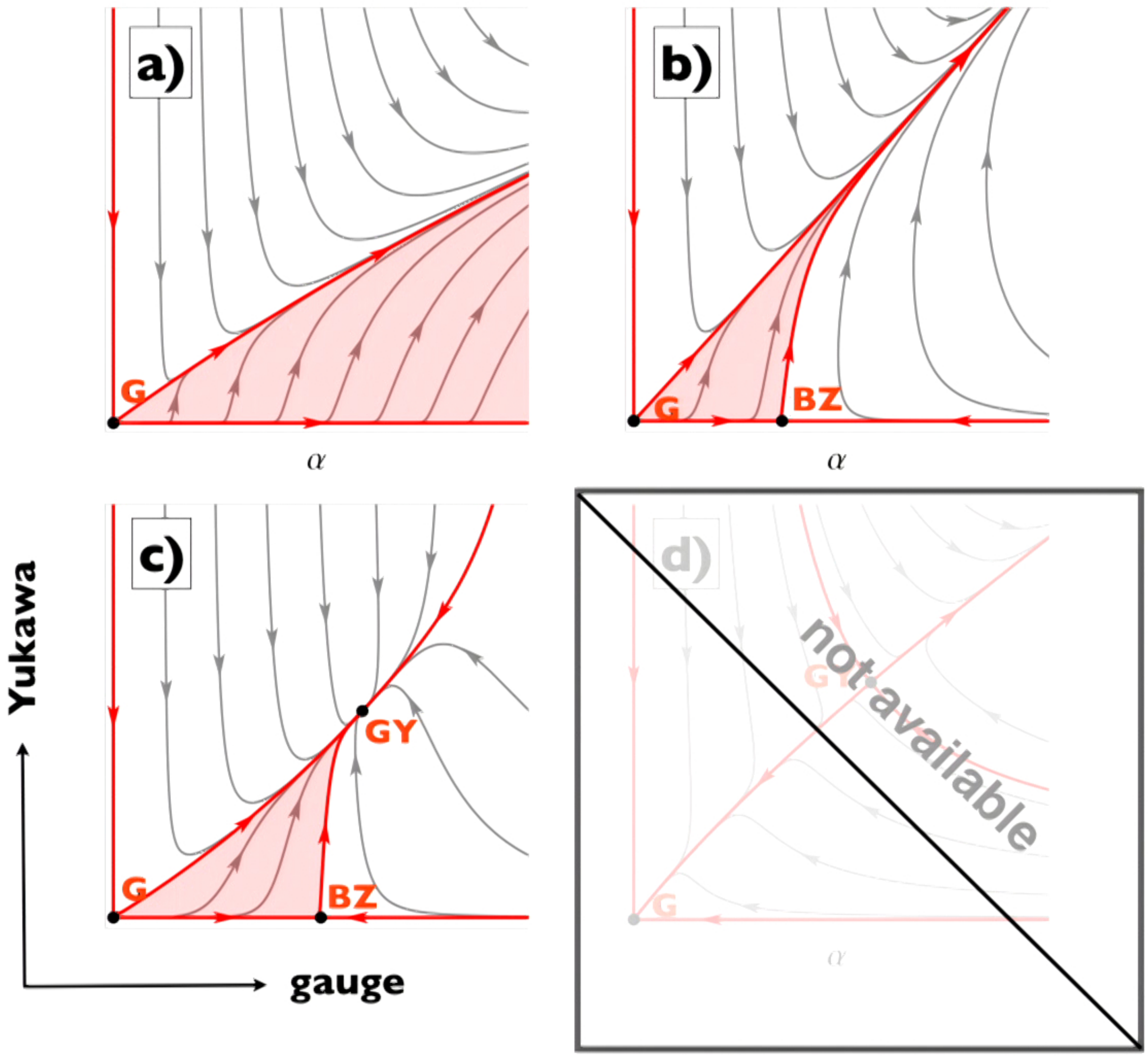
N=1 SUSY



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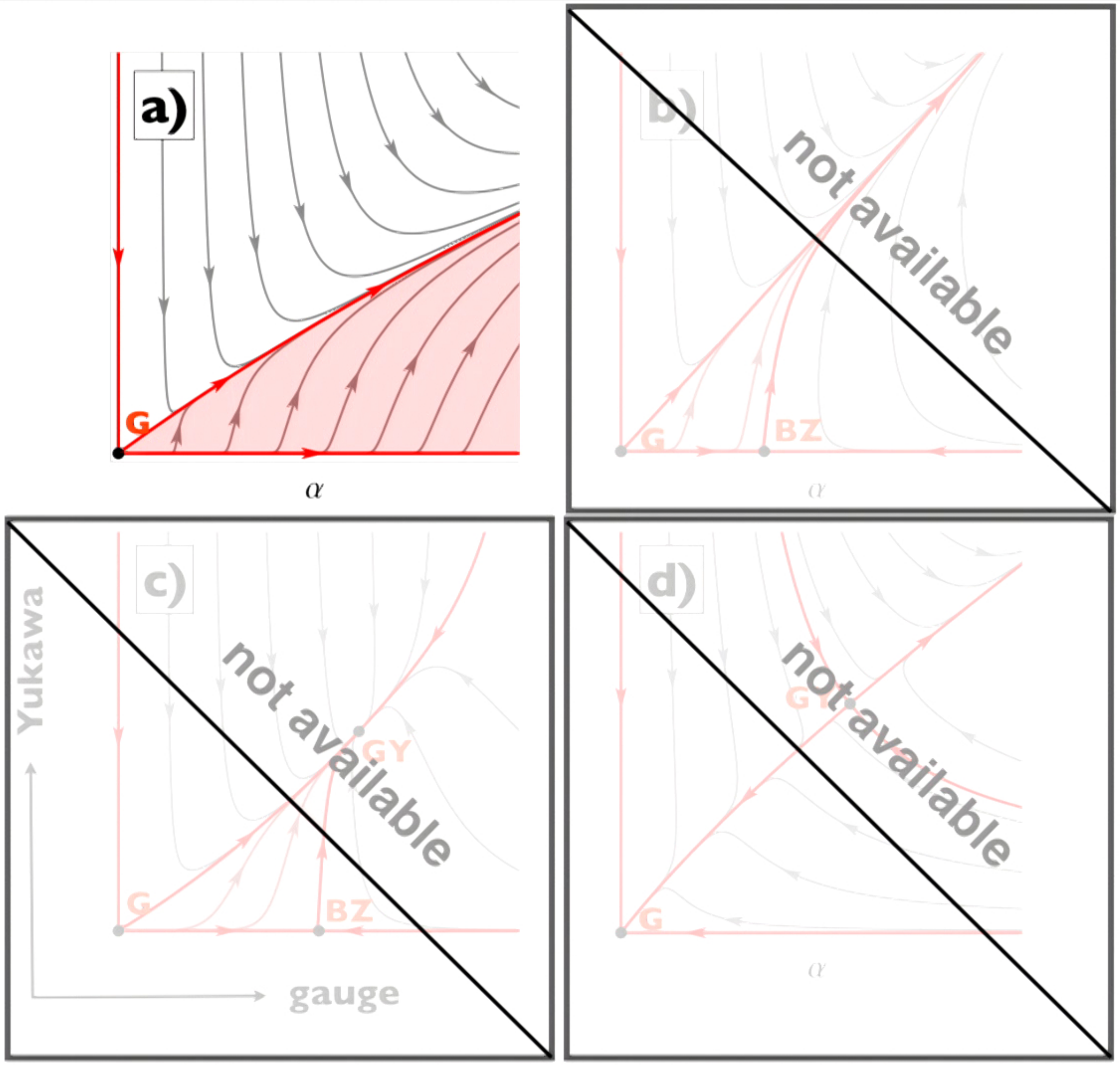
N=2
SUSY



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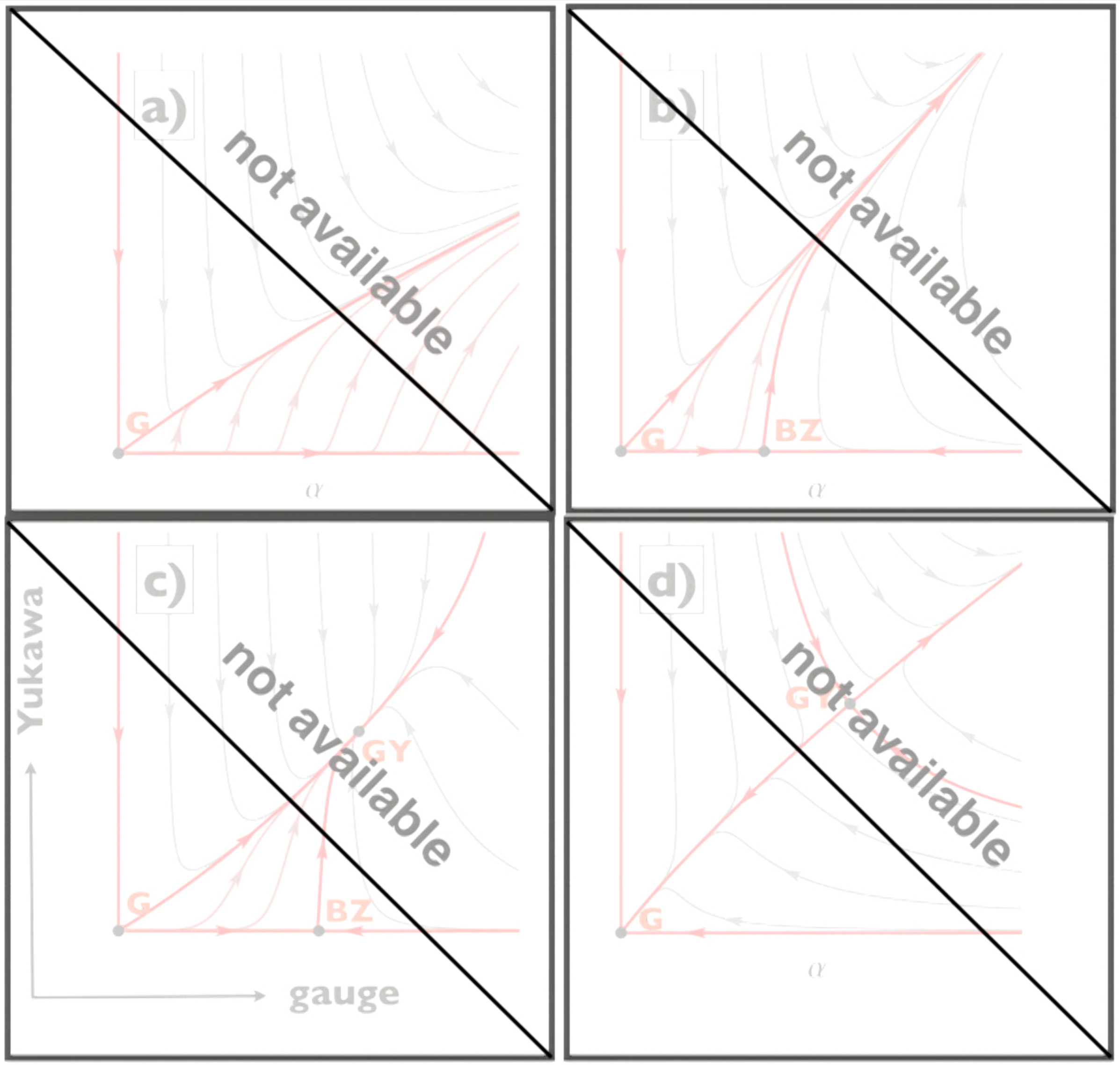
N=4
SUSY



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supersymmetry

semi-simple susy gauge theory

$$SU(N_1) \times SU(N_2)$$

superpotential

$$W = y\,\mathrm{Tr}\big[\psi_L\,\Psi_L\,\chi_L + \psi_R\,\Psi_R\,\chi_R\big]$$

chiral superfields

matter	ψ_L	ψ_R	Ψ_L	Ψ_R	χ_L	χ_R	Q_L	Q_R
$SU(N_1)$	$\overline{\square}$	$\square$	$\square$	$\overline{\square}$	1	1	1	1
$SU(N_2)$	1	1	$\square$	$\overline{\square}$	$\overline{\square}$	$\square$	$\overline{\square}$	$\square$
flavour	N_F	N_F	1	1	N_F	N_F	N_Q	N_Q

Table 1. Chiral matter with gauge charges and multiplicities.

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supersymmetry

parameters

$$R = \frac{N_2}{N_1}\,,$$

$$P = \frac{N_1}{N_2}\,\frac{N_Q + N_1 + N_F - 3N_2}{N_F + N_2 - 3N_1}\,,$$

$$\epsilon = \frac{N_F + N_2 - 3N_1}{N_1}\,.$$

Veneziano limit

$$1 < R < 3\,, \quad P = \text{finite}\,, \quad 0 < |\epsilon| \ll 1\,.$$

strict perturbative control

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supersymmetry

beta functions

$$
\begin{aligned}
\beta_1 &= 2\alpha_1^2\Big[\,\epsilon + 6\alpha_1 + 2R\alpha_2 - 4R(3-R)\alpha_y\Big]\\
\beta_2 &= 2\alpha_2^2\Big[P\epsilon + 6\alpha_2 + \frac{2}{R}\alpha_1 - \frac{4}{R}(3-R)\alpha_y\Big]\\
\beta_y &= 4\alpha_y\Big[2\alpha_y - \alpha_1 - \alpha_2\Big]\,.
\end{aligned}
$$

anomalous dimensions

$$
\begin{aligned}
\gamma_\Psi &= (3-R)\alpha_y - \alpha_1 - \alpha_2\,,\\
\gamma_\psi &= R\,\alpha_y - \alpha_1\,,\\
\gamma_\chi &= \alpha_y - \alpha_2\,,\\
\gamma_Q &= -\alpha_2\,,
\end{aligned}
$$

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supersymmetry

Fixed point	G	BZ_1	BZ_2	GY_1	GY_2	BZ_{12}	GY_{12}
α_1^*	0	$-\frac{\epsilon}{6}$	0	$\frac{-\epsilon}{2(3-3R+R^2)}$	0	$\frac{PR-3}{16}\epsilon$	$\frac{3-4R-2PR^2+PR^3}{(R-1)(9-8R+3R^2)}\frac{\epsilon}{2}$
α_2^*	0	0	$-\frac{P\epsilon}{6}$	0	$\frac{-PR}{4R-3}\frac{\epsilon}{2}$	$\frac{1-3PR}{16R}\epsilon$	$\frac{R-2-3PR+3PR^2-PR^3}{(R-1)(9-8R+3R^2)}\frac{\epsilon}{2}$
α_y^*	0	0	0	$\frac{1}{2}\alpha_1^*$	$\frac{1}{2}\alpha_2^*$	0	$\frac{1}{2}(\alpha_1^* + \alpha_2^*)$

Table 2. The Gaussian (G) and all Banks-Zaks (BZ) and gauge-Yukawa (GY) fixed points to leading order in ϵ.

cases

$$\epsilon < 0 < P$$ **asymptotic freedom**

$$P, \epsilon < 0$$

$$P < 0 < \epsilon$$ **no asymptotic freedom**

$$0 < P, \epsilon$$

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supersymmetry

Fixed point	G	BZ$_1$	BZ$_2$	GY$_1$	GY$_2$	BZ$_{12}$	GY$_{12}$
α_1^*	0	$-\frac{\epsilon}{6}$	0	$\frac{-\epsilon}{2(3-3R+R^2)}$	0	$\frac{PR-3}{16}\epsilon$	$\frac{3-4R-2PR^2+PR^3}{(R-1)(9-8R+3R^2)}\frac{\epsilon}{2}$
α_2^*	0	0	$-\frac{P\epsilon}{6}$	0	$\frac{-PR}{4R-3}\frac{\epsilon}{2}$	$\frac{1-3PR}{16R}\epsilon$	$\frac{R-2-3PR+3PR^2-PR^3}{(R-1)(9-8R+3R^2)}\frac{\epsilon}{2}$
α_y^*	0	0	0	$\frac{1}{2}\alpha_1^*$	$\frac{1}{2}\alpha_2^*$	0	$\frac{1}{2}(\alpha_1^*+\alpha_2^*)$

Table 2. The Gaussian (G) and all Banks-Zaks (BZ) and gauge-Yukawa (GY) fixed points to leading order in ϵ.

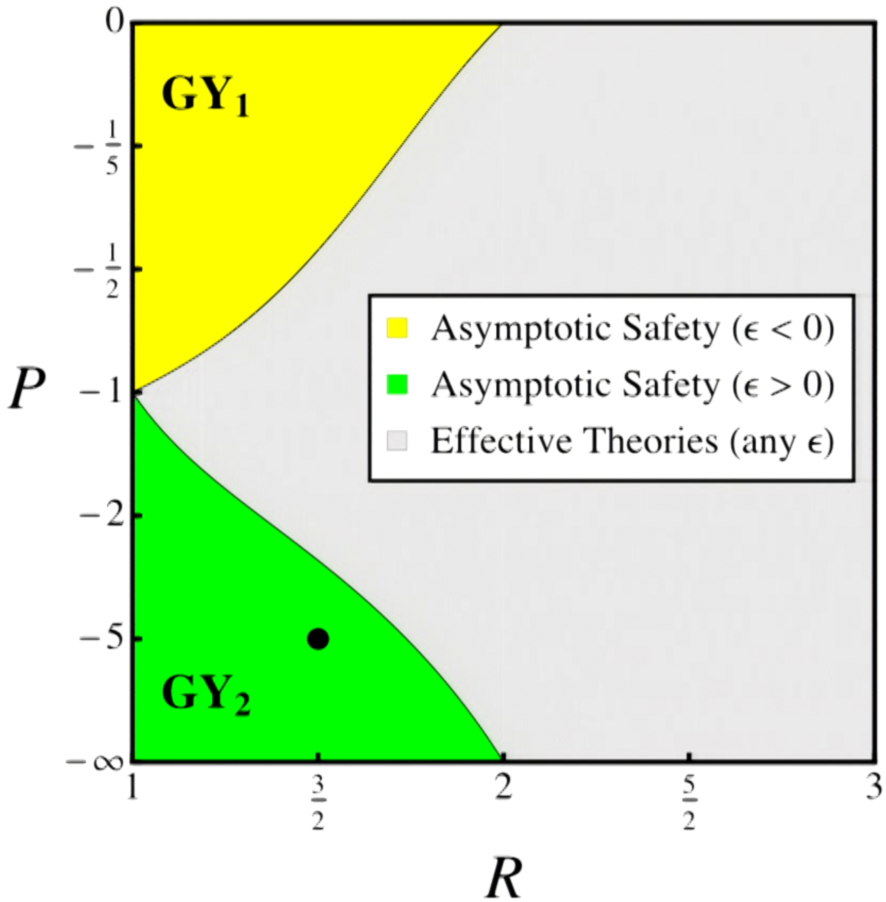
consider $P < 0 < \epsilon$

$$\begin{aligned} \beta_1\big|_{\mathrm{GY}_2} &= -B_{1,\mathrm{eff}}\,\alpha_1^2 + \mathcal{O}(\alpha_1^3)\,, \\ B_{1,\mathrm{eff}} &= -2\epsilon + 2\epsilon\, P/Q_1 \\ Q_1(R) &= (4R-3)/(R^3-2R^2) \end{aligned}$$

interacting UV fixed point if

$$P < Q_1 < 0\,, \quad 1 < R < 2\,, \quad \epsilon > 0$$

asymptotic safety



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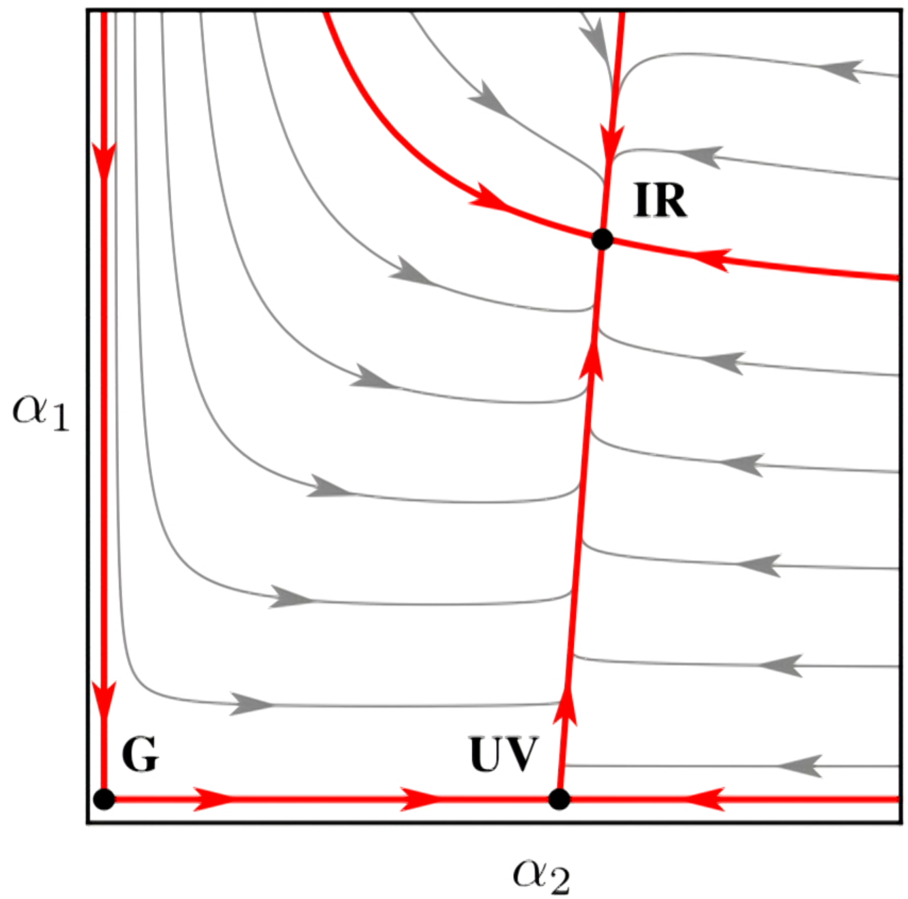
UV-IR crossover



complete
understanding of
asymptotic safety
at weak coupling

works for
simple, **semi-simple**
and **supersymmetric**
gauge theories,
large variety of
fixed points

**window of
opportunities** for
model building,
BSM physics,
dark matter, …

outlook:
asymptotic safety
at strong coupling
w or w/o gravity