The predictive power of the asymptotic safety paradigm for gravity and matter

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PLB 777, 217 (2018), with A. Eichhorn
PRL 121 (2018), **[editor’s suggestion]**, with A. Eichhorn

PLB 782 (2018) 198-201, with A. Eichhorn and C. Wetterich

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Emmy Noether-Programm
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UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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GUTs

SUSY

Higgs

???

Higgs

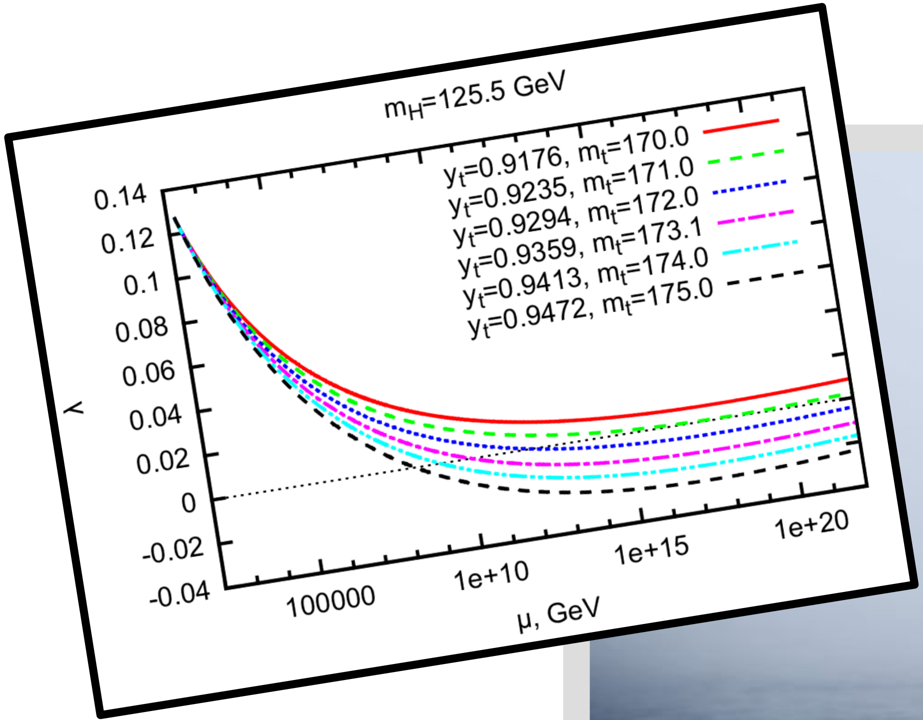
Higgs

hints for

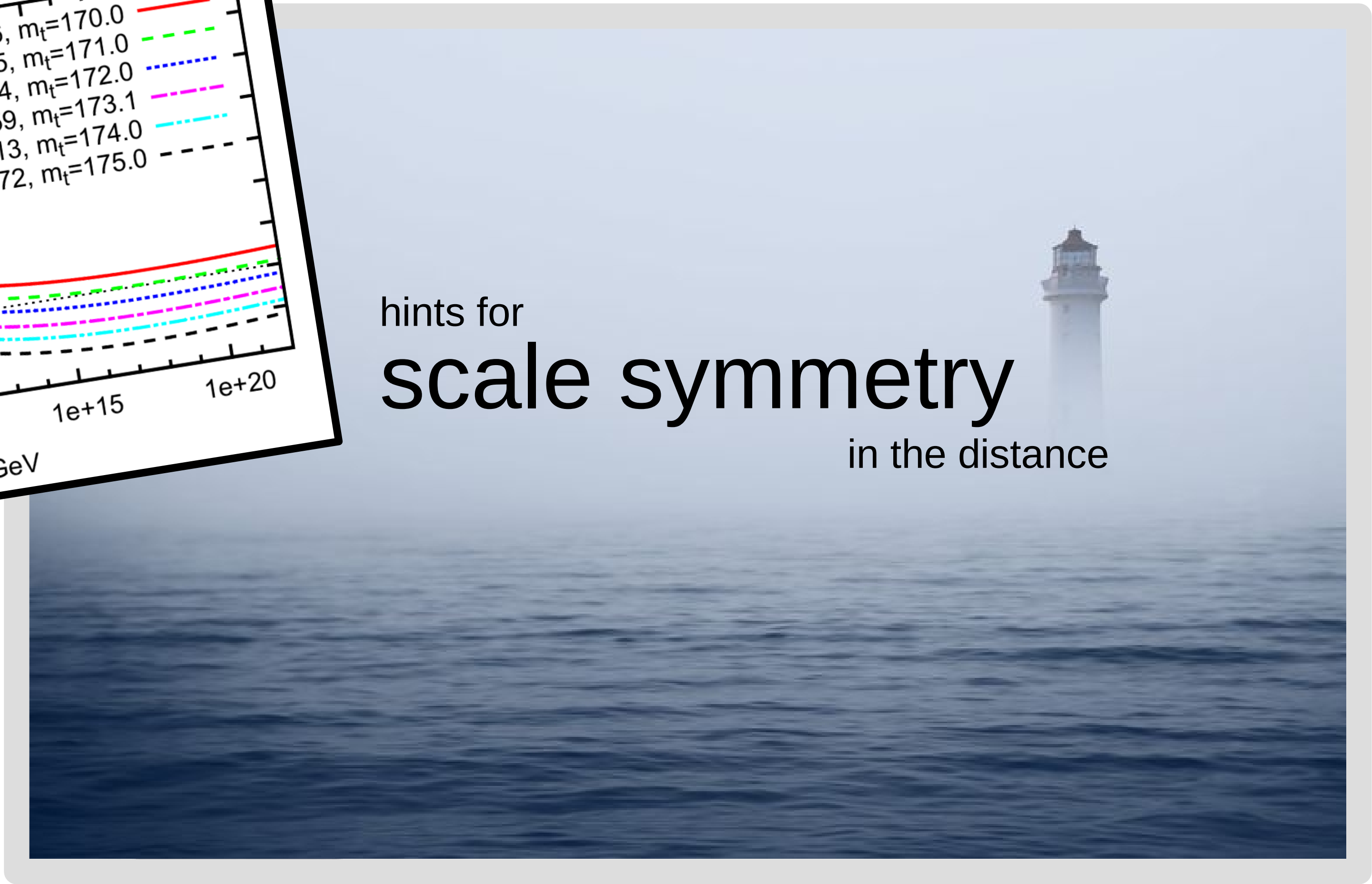
scale symmetry

in the distance

Higgs



Rubio '18



hints for

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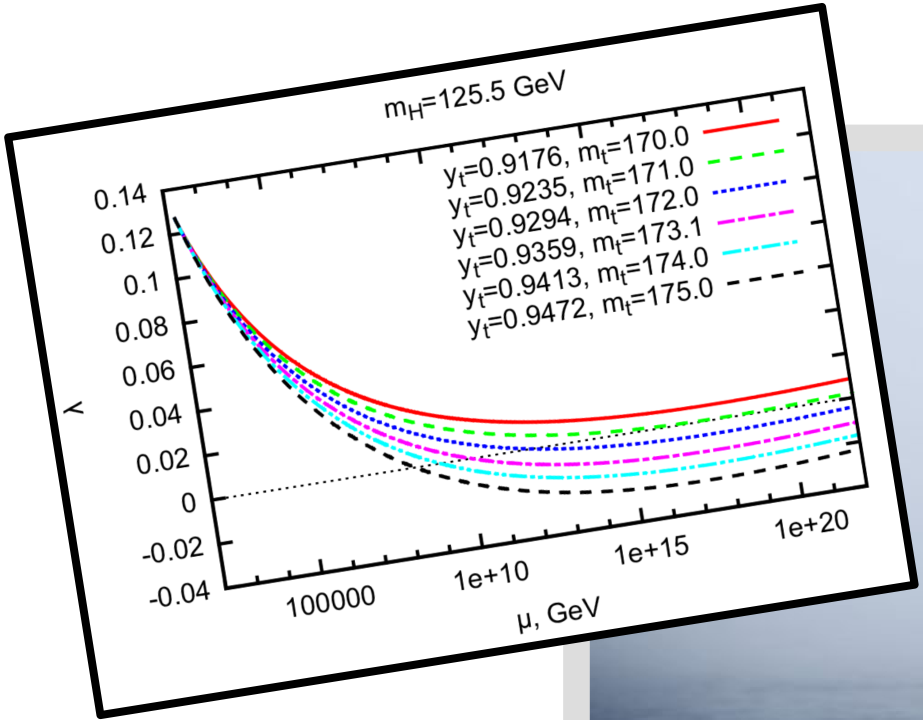
Higgs



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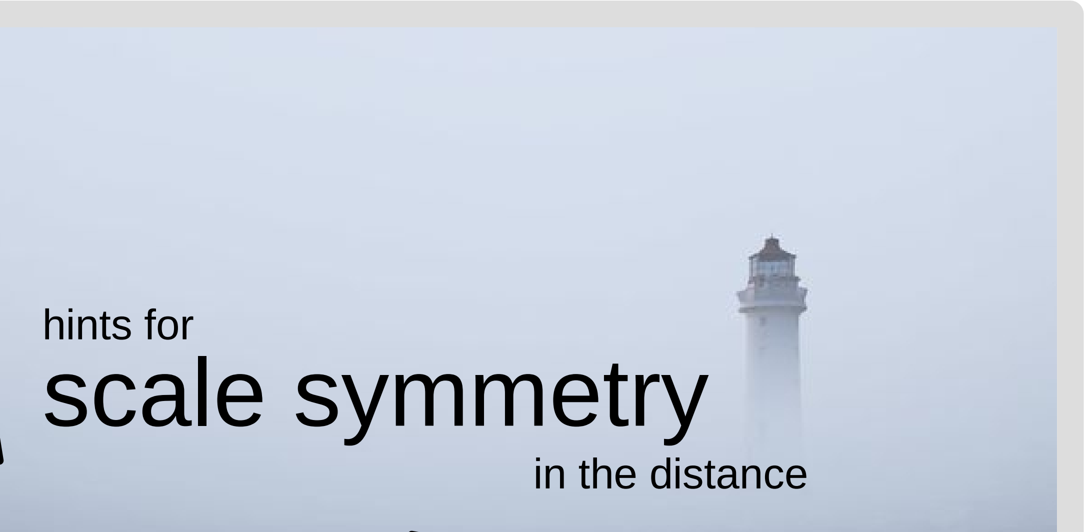

hints for

scale symmetry

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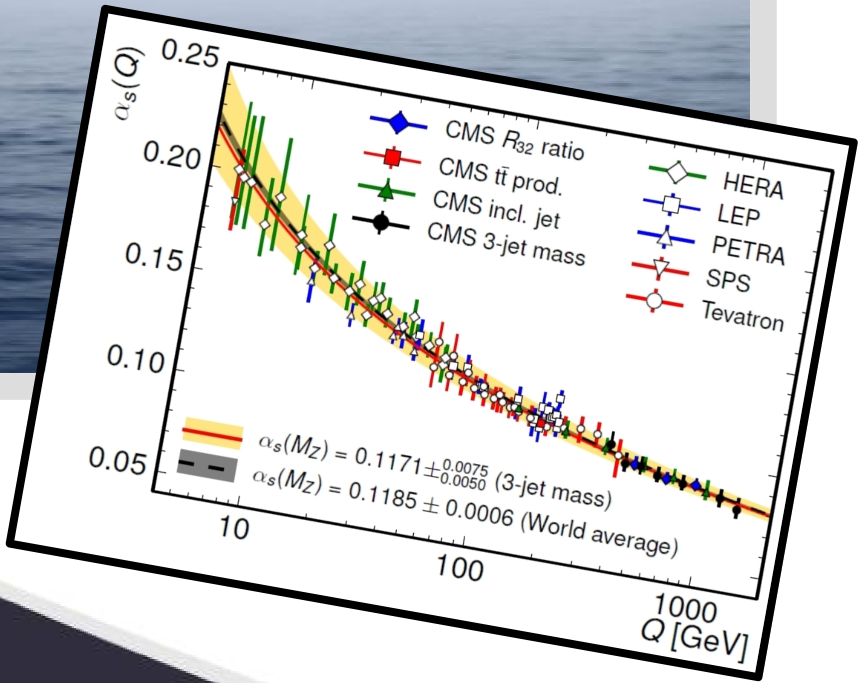
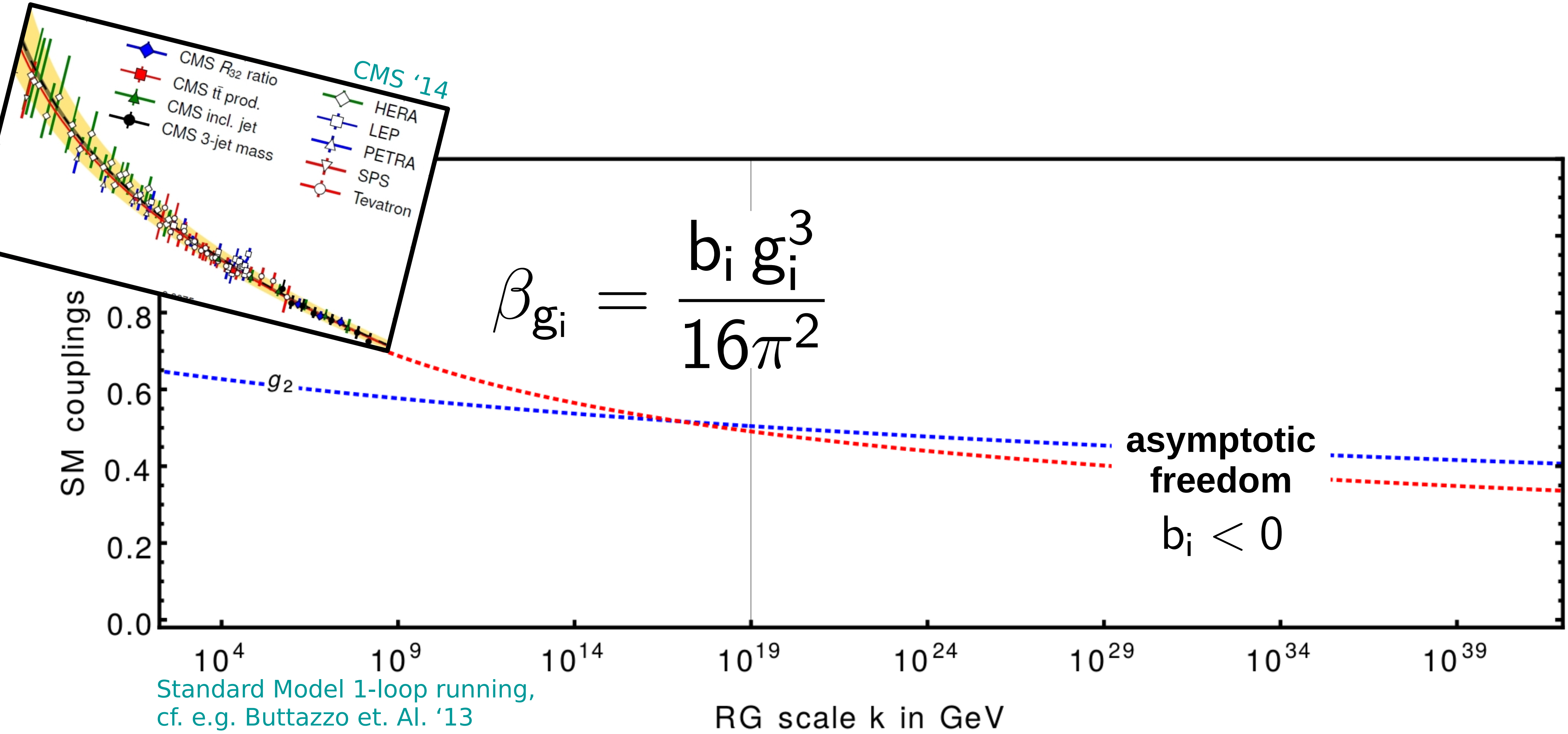


CMS ‘14



CMS ‘14

$$\beta_{g_i} = \frac{b_i\, g_i^3}{16\pi^2}$$

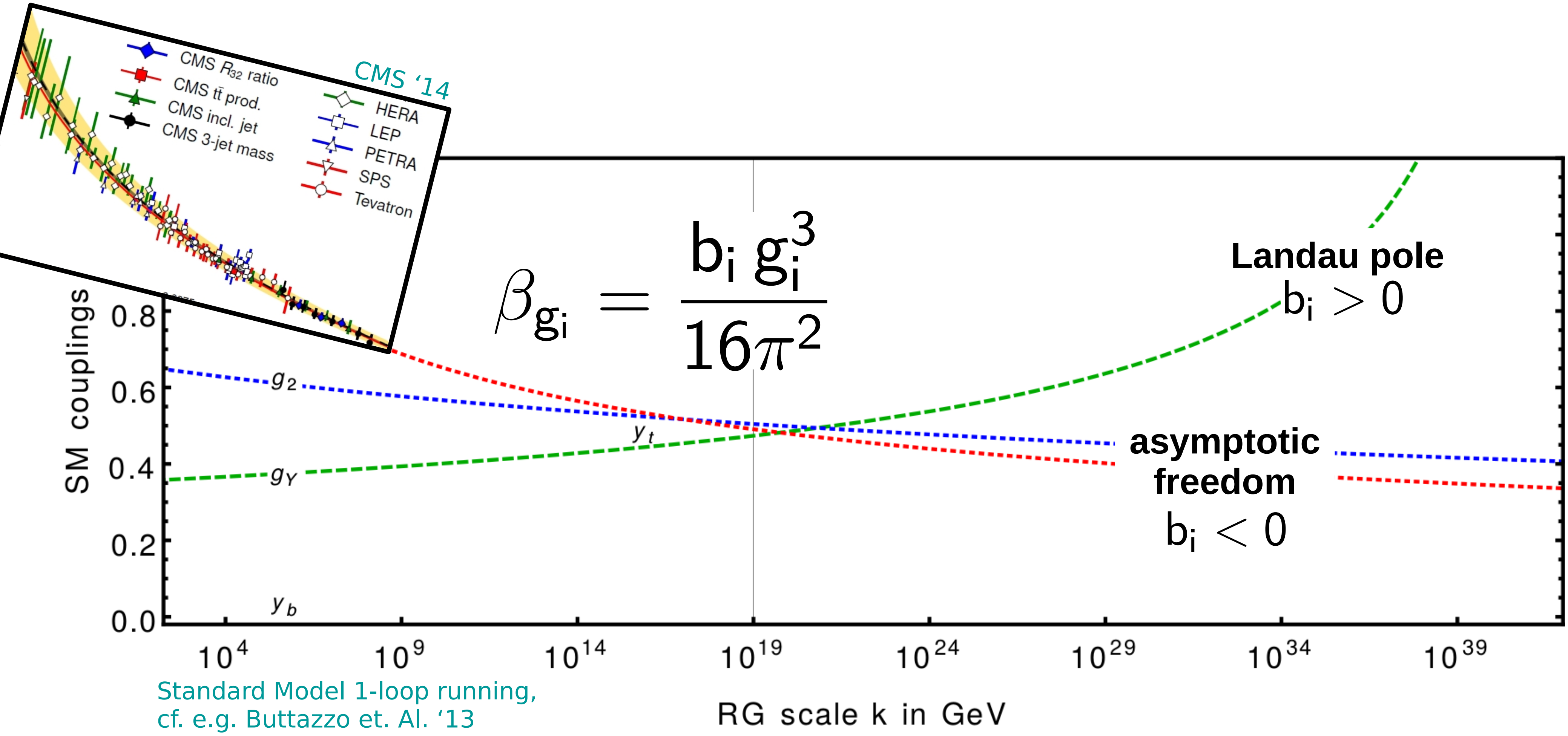
asymptotic freedom

$b_i < 0$

Standard Model 1-loop running,
cf. e.g. Buttazzo et. Al. ‘13

Asymptotic Freedom

scale invariance
at vanishing quantum fluctuations



CMS '14

$$\beta_{g_i} = \frac{b_i\, g_i^3}{16\pi^2}$$

Landau pole

$b_i > 0$

asymptotic freedom

$b_i < 0$

Standard Model 1-loop running,
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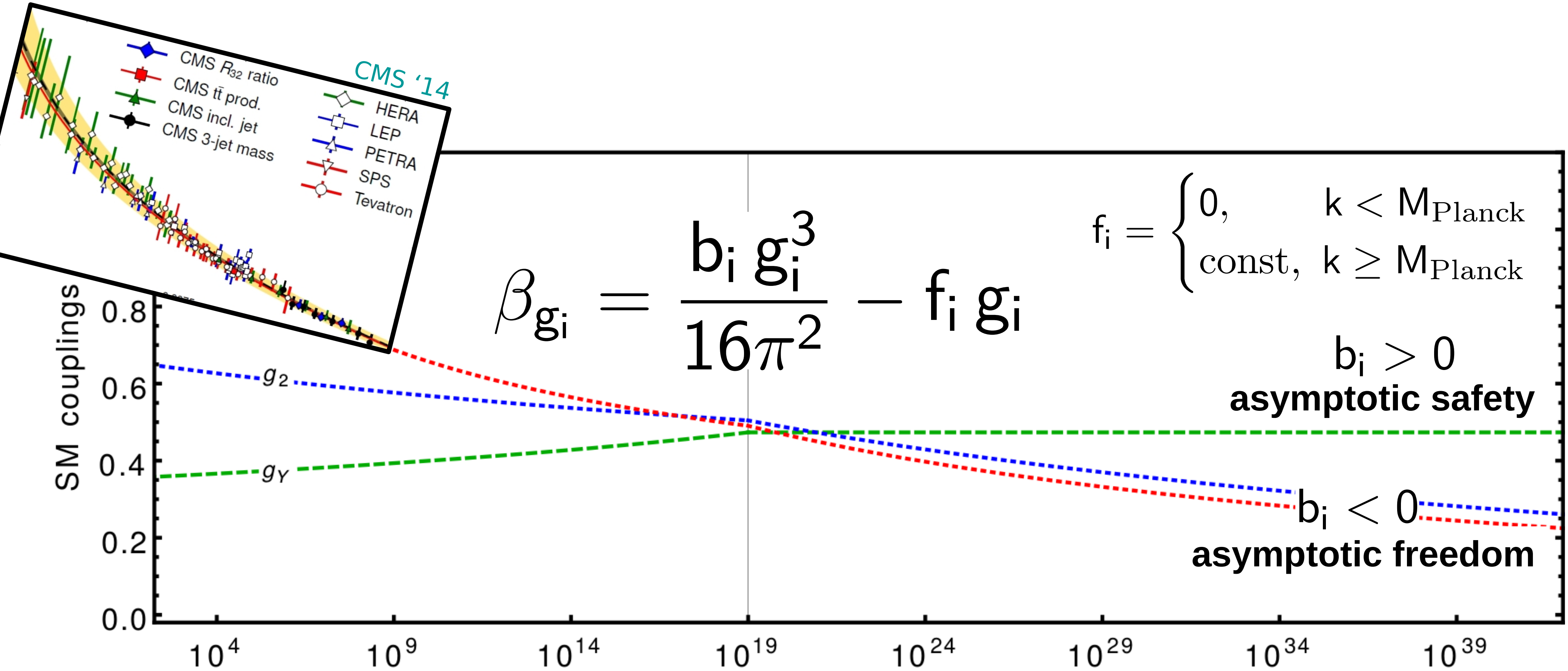

CMS ‘14

$$\beta_{g_i} = \frac{b_i\, g_i^3}{16\pi^2} - f_i\, g_i$$

$$f_i = \begin{cases} 0, & k < M_{\mathrm{Planck}} \\ \mathrm{const}, & k \geq M_{\mathrm{Planck}} \end{cases}$$

$b_i > 0$

asymptotic safety

$b_i < 0$

asymptotic freedom

Standard Model 1-loop running,
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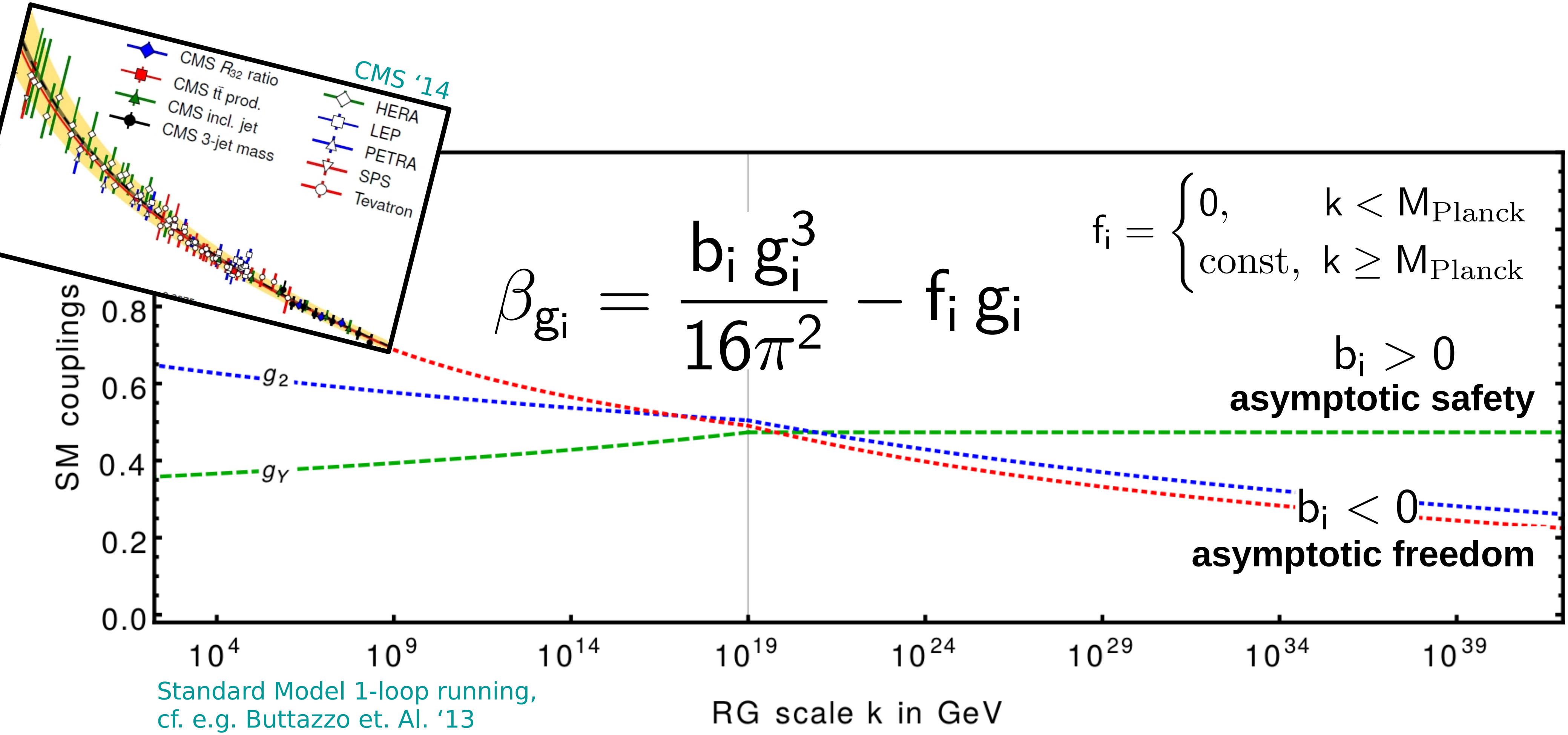

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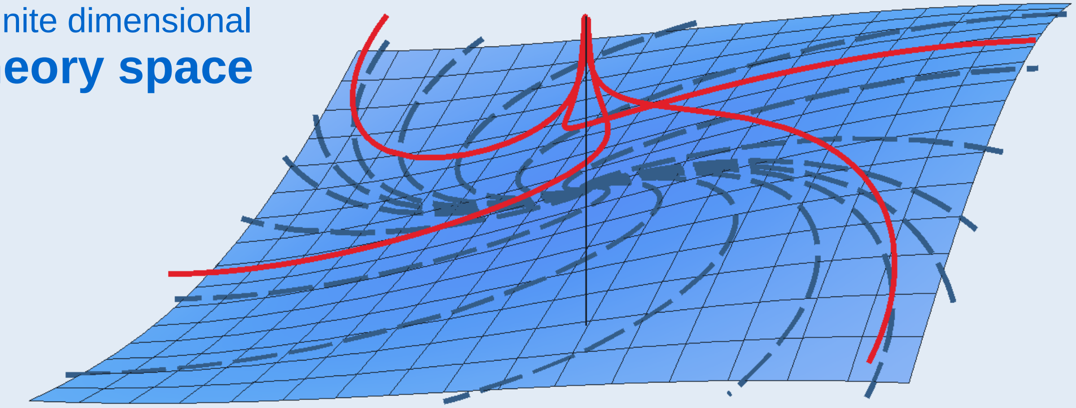
Asymptotic Safety

scale invariance
in presence of quantum fluctuations

Asymptotic safety of quantum gravity

Weinberg '76

infinite dimensional
theory space



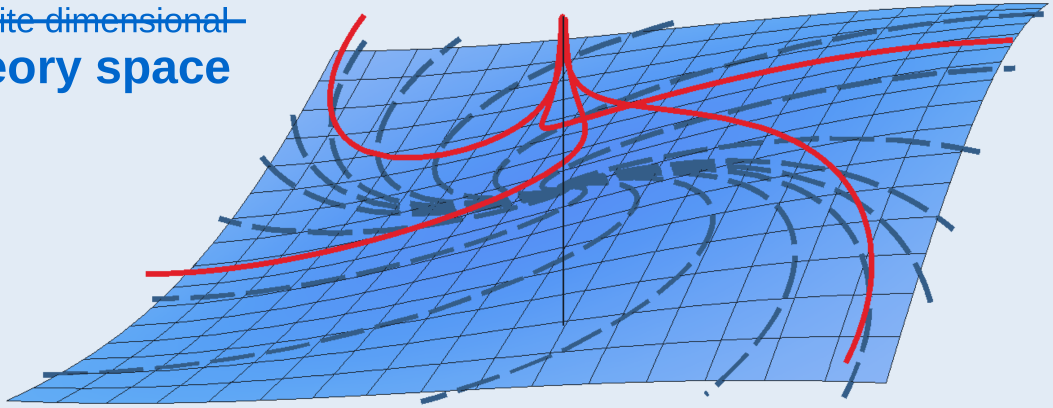
infinite dimensional
theory space

$$S = \frac{-1}{16\pi \bar{G}_N} \int d^4x \, \sqrt{g} \Big[R - 2\bar{\Lambda} + \\ + \bar{a}R^2 + \bar{b}R_{\mu\nu}R^{\mu\nu} + \dots \text{ all terms allowed by symmetry} \Big]$$

Asymptotic safety of quantum gravity

Weinberg '76

truncated
~~infinite dimensional~~
theory space



truncated ~~infinite dimensional~~
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$$\left. + \bar{a}R^2 + \bar{b}R_{\mu\nu}R^{\mu\nu} + \ldots \cancel{\text{ all terms allowed by symmetry}} \right]$$

Asymptotic safety of quantum gravity

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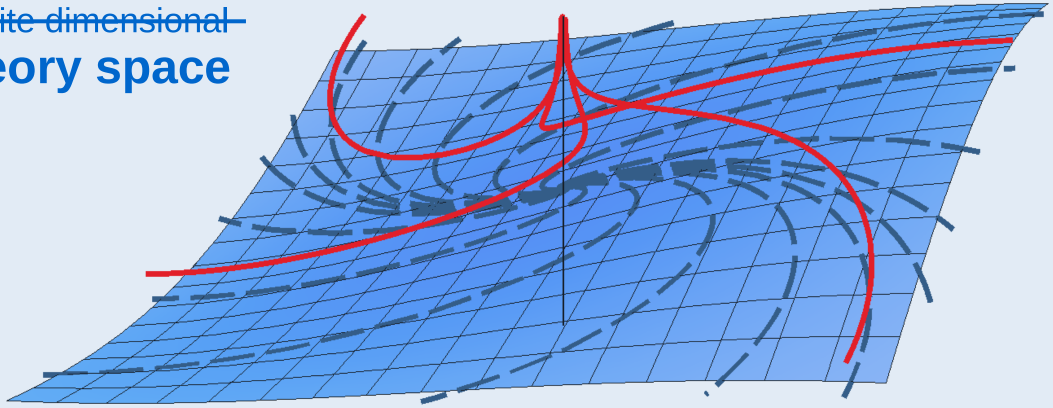

truncated ~~infinite dimensional~~
theory space

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fixed point	symmetry invariants	$\theta > 0$	$\theta < 0$
☑	R	☒	
☑	$\Lambda + R$ Reuter '96	☒	
☑	$R^2 + R_{\mu\nu}R^{\mu\nu}$ Benedetti, Machado, Saueressig '09	☒	☒
☑	$C^{\rho\sigma}_{\mu\nu}C^{\kappa\lambda}_{\rho\sigma}C^{\mu\nu}_{\kappa\lambda}$ Gies, Knorr, Lippoldt, Saueressig '16		☒
☑	R^3 Reuter, Lauscher '02		☒
⋮	⋮		⋮
☑	R^{70}, $R^{\mu\nu\,34}$ Codello, Percacci, Rahmede '07, '08 Machado, Saueressig '07 K. Falls et.Al '13 K. Falls et.Al '18		☒

Asymptotic safety of quantum gravity

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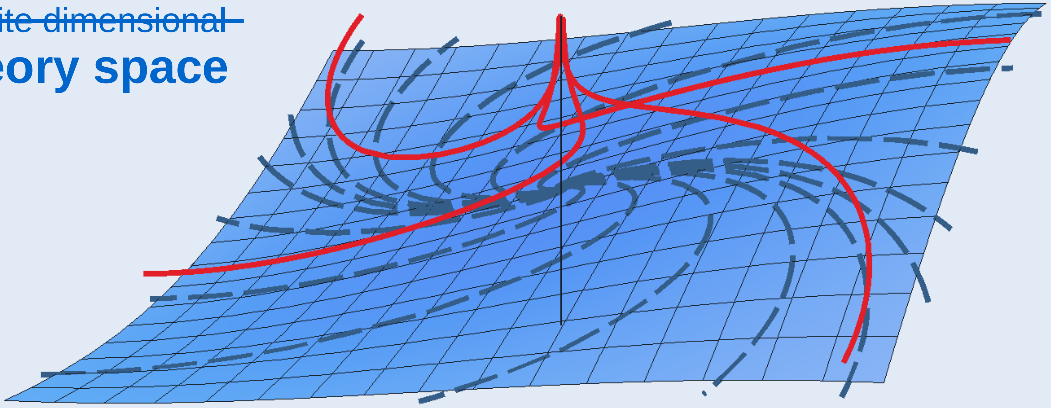

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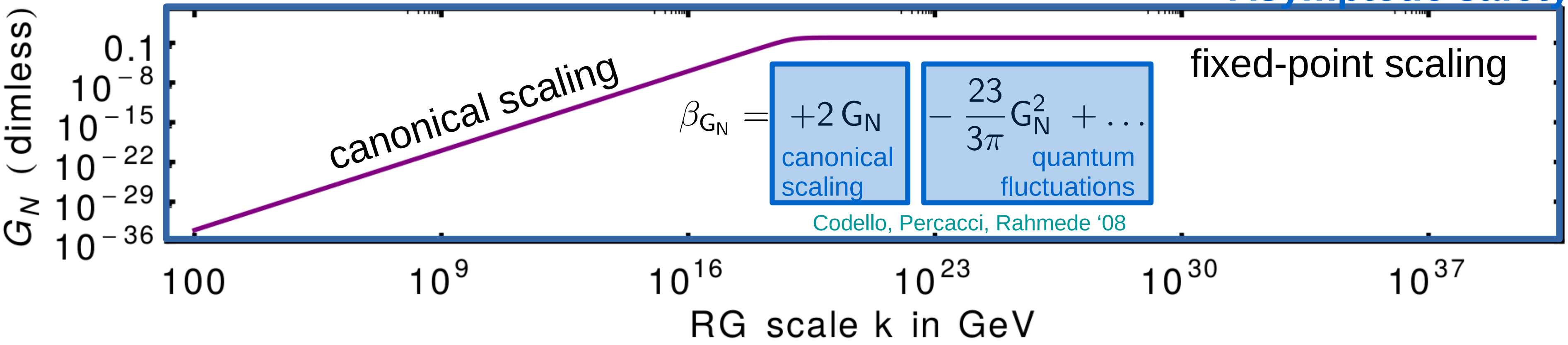
Asymptotic safety



$$\beta_{G_N} = \underbrace{+2\,G_N}_{\text{canonical scaling}} \underbrace{-\frac{23}{3\pi}G_N^2}_{\text{quantum fluctuations}} + \ldots$$

Codello, Percacci, Rahmede '08

$\bar{G}_N$: dimfull

G_N: dimless

Asymptotic safety of quantum gravity

Weinberg '76

	fixed point	symmetry invariants	$\theta > 0$	$\theta < 0$
free parameters	☑	R	☒	
	☑	$\Lambda + R$ Reuter '96	☒	
	☑	$R^2 + R_{\mu\nu}R^{\mu\nu}$ Benedetti, Machado, Saueressig '09	☒	☒
predicted couplings	☑	$C_{\mu\nu}^{\rho\sigma}C_{\rho\sigma}^{\kappa\lambda}C_{\kappa\lambda}^{\mu\nu}$ Gies, Knorr, Lippoldt, Saueressig '16		☒
	☑	R^3 Reuter, Lauscher '02		☒
	⋮	⋮		⋮
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observables

SM and gravity couplings

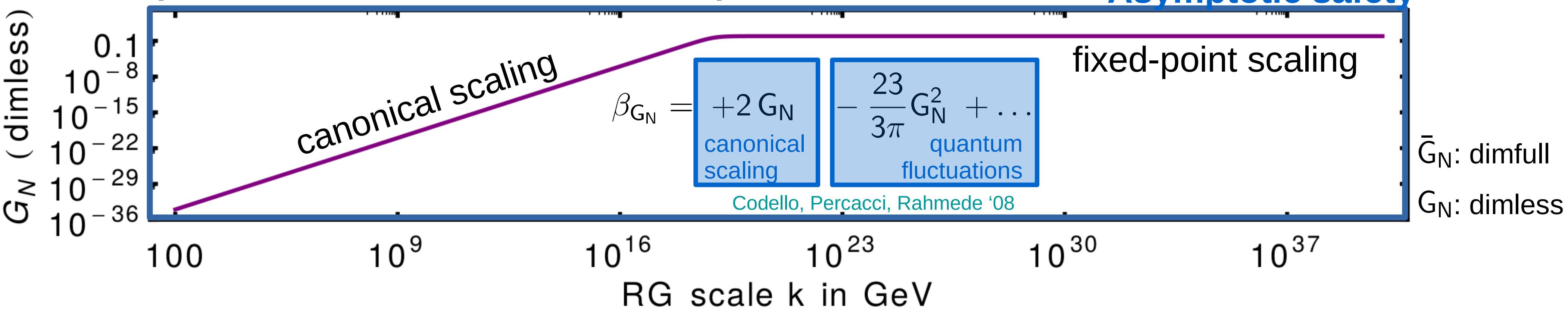
• • •

$$\frac{M_{\mathrm{ew}}}{M_{\mathrm{Planck}}} \approx 10^{-16}$$

electroweak scale

Planck scale

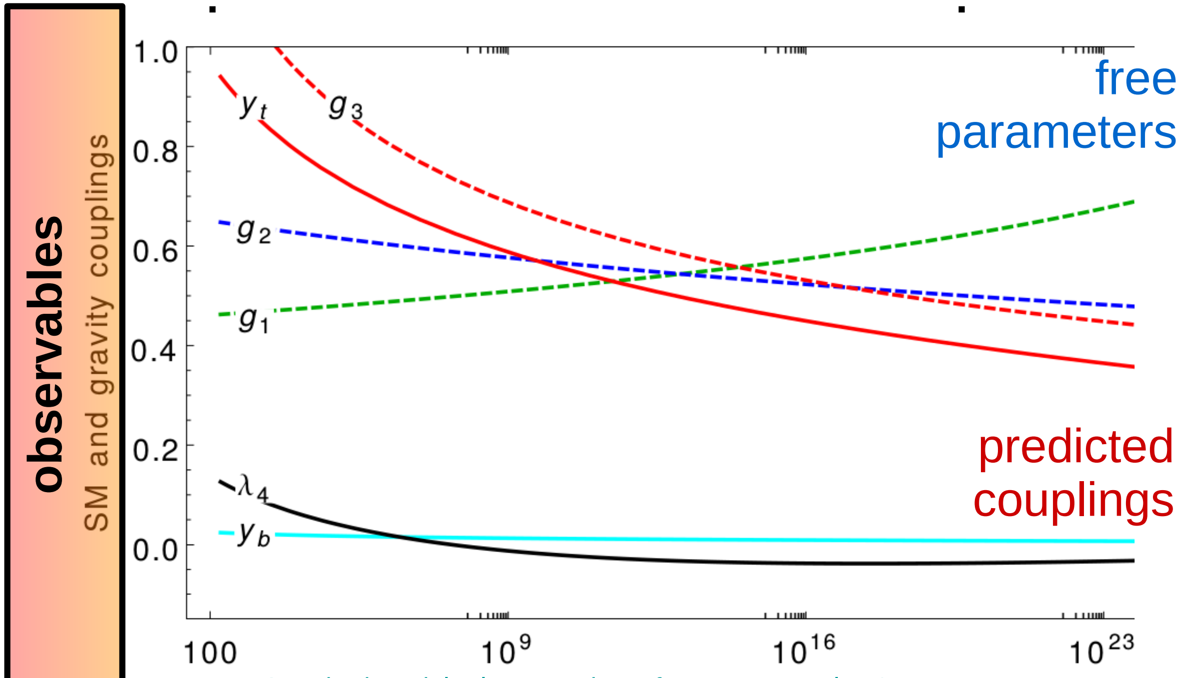
Asymptotic safety



$$\beta_{G_N} = \boxed{+2\,G_N} \boxed{-\frac{23}{3\pi}G_N^2 + \dots}$$

Codello, Percacci, Rahmede '08

Asymptotic safety of quantum gravity



Standard Model 1-loop running, cf. Buttazzo et.Al. '13

electroweak scale

Planck scale

Weinberg '76

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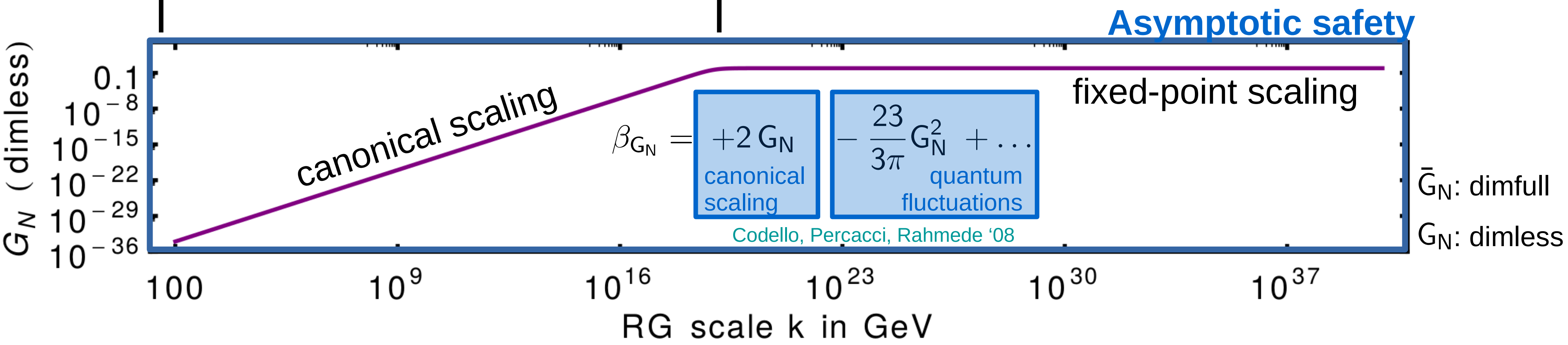

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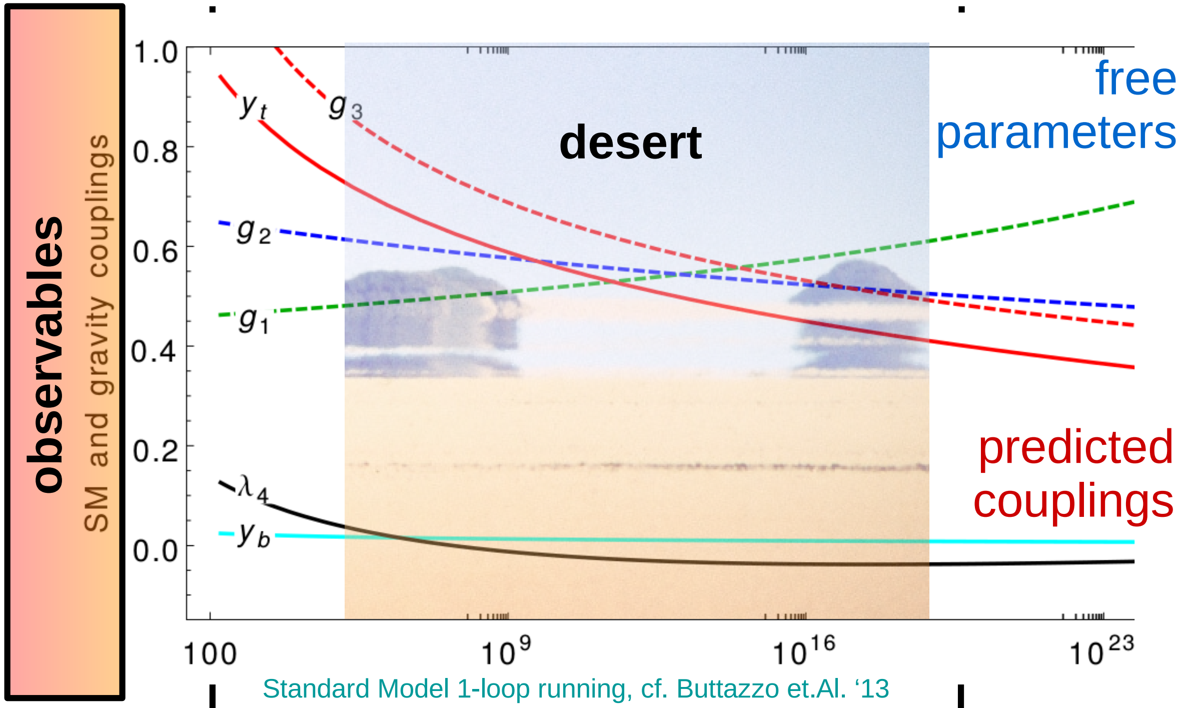

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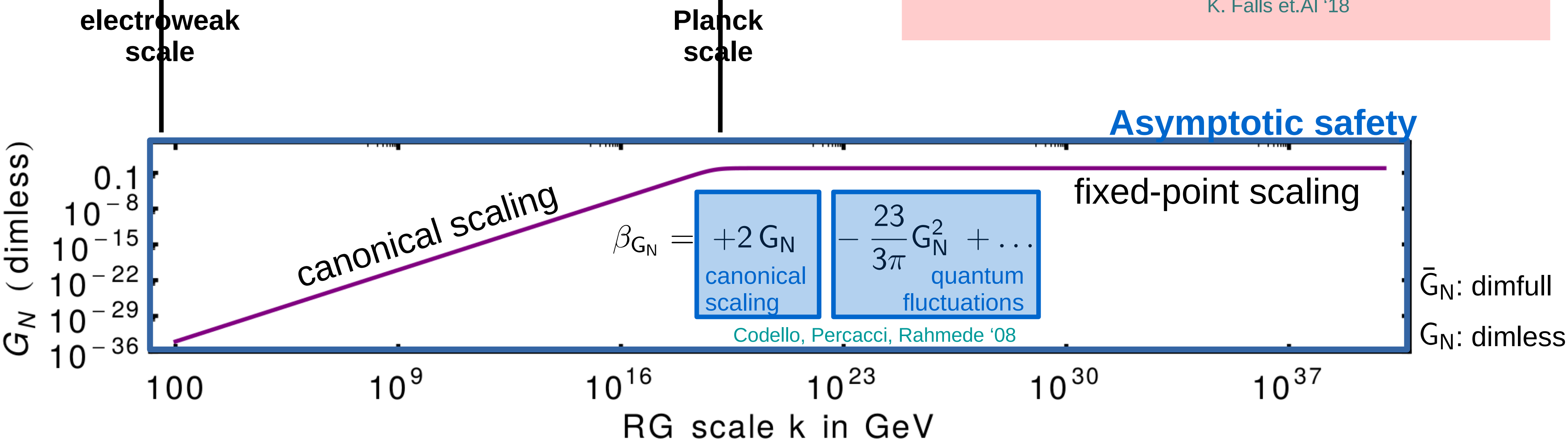

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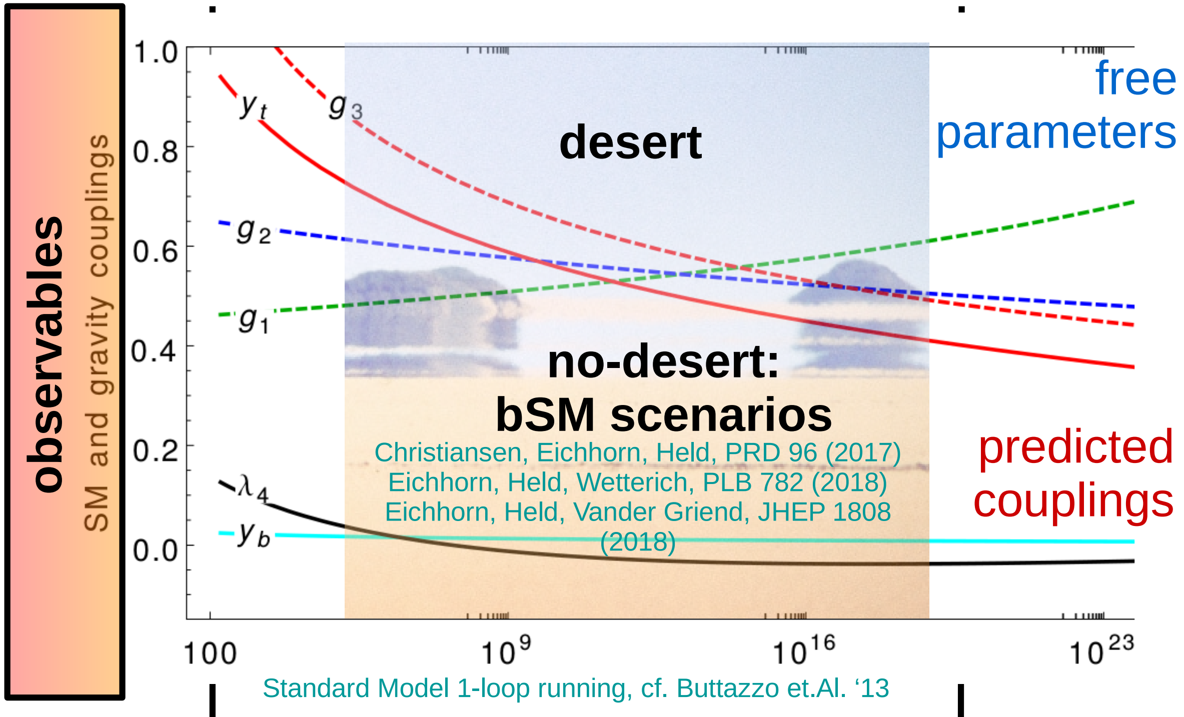
Asymptotic safety of quantum gravity



Christiansen, Eichhorn, Held, PRD 96 (2017)
Eichhorn, Held, Wetterich, PLB 782 (2018)
Eichhorn, Held, Vander Griend, JHEP 1808 (2018)

Standard Model 1-loop running, cf. Buttazzo et.Al. '13

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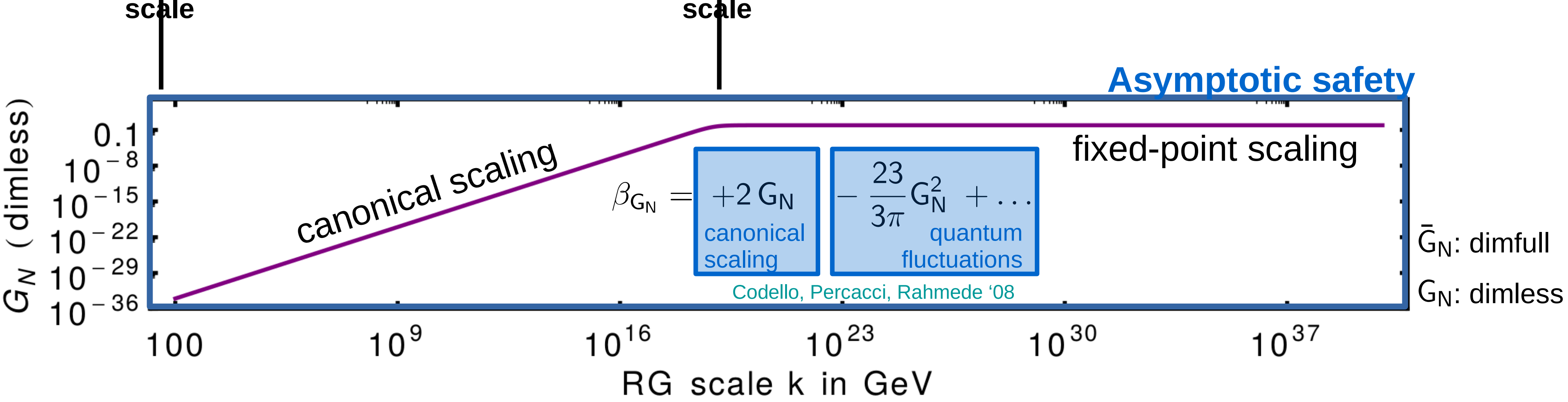
electroweak scale

Planck scale

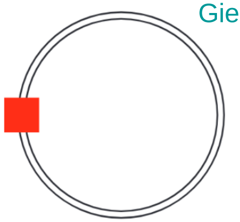


$$\beta_{G_N} = \underbrace{+2\,G_N}_{\text{canonical scaling}} \underbrace{- \frac{23}{3\pi} G_N^2 + \dots}_{\text{quantum fluctuations}}$$

Codello, Percacci, Rahmede '08

Gies ‘06

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\,\partial_t R_k$$



… functional RG …

$$\beta_i = \beta_i^{\mathrm{SM}} - f_i\, g_i$$

$$\beta_G = 2\,G + \mathcal{A}(\Lambda)\,G^2$$

$$\beta_\Lambda = -2\Lambda + \mathcal{A}(\Lambda)\,G\,\Lambda + \mathcal{B}(\Lambda)G$$

Reuter ‘96
Dona, Eichhorn, Percacci ‘13

$$f_g = G\frac{5(1-4\Lambda)}{18\pi(1-2\Lambda)^2}$$

Daum, Harst, Reuter, ‘10
Folkerts, Litim, Pawlowski, ‘12
Christiansen, Eichhorn, ‘17
Christiansen, Litim, Pawlowski, Reichert, ‘17
Eichhorn, Versteegen ‘17

$$f_y = -G\frac{96+\Lambda(-235+\Lambda(103+56\Lambda))}{12\pi(3+2\Lambda(-5+4\Lambda))^2}$$

Griguolo, Percacci ‘95
Percacci, Perini ‘03
Narain, Percacci ‘09

$$f_\lambda = -G\frac{165-8\Lambda\,(61+\Lambda(-49+4\Lambda))}{6\pi\,(3+2\Lambda(-5+4\Lambda))^2}$$

Zanusso, Vacca, Percacci, Zambelli,’10
Oda, Yamada, ‘16
Eichhorn, Held, Pawlowski, ‘16
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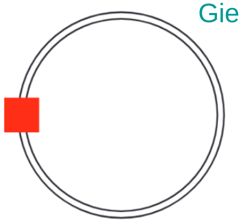

Gies ‘06

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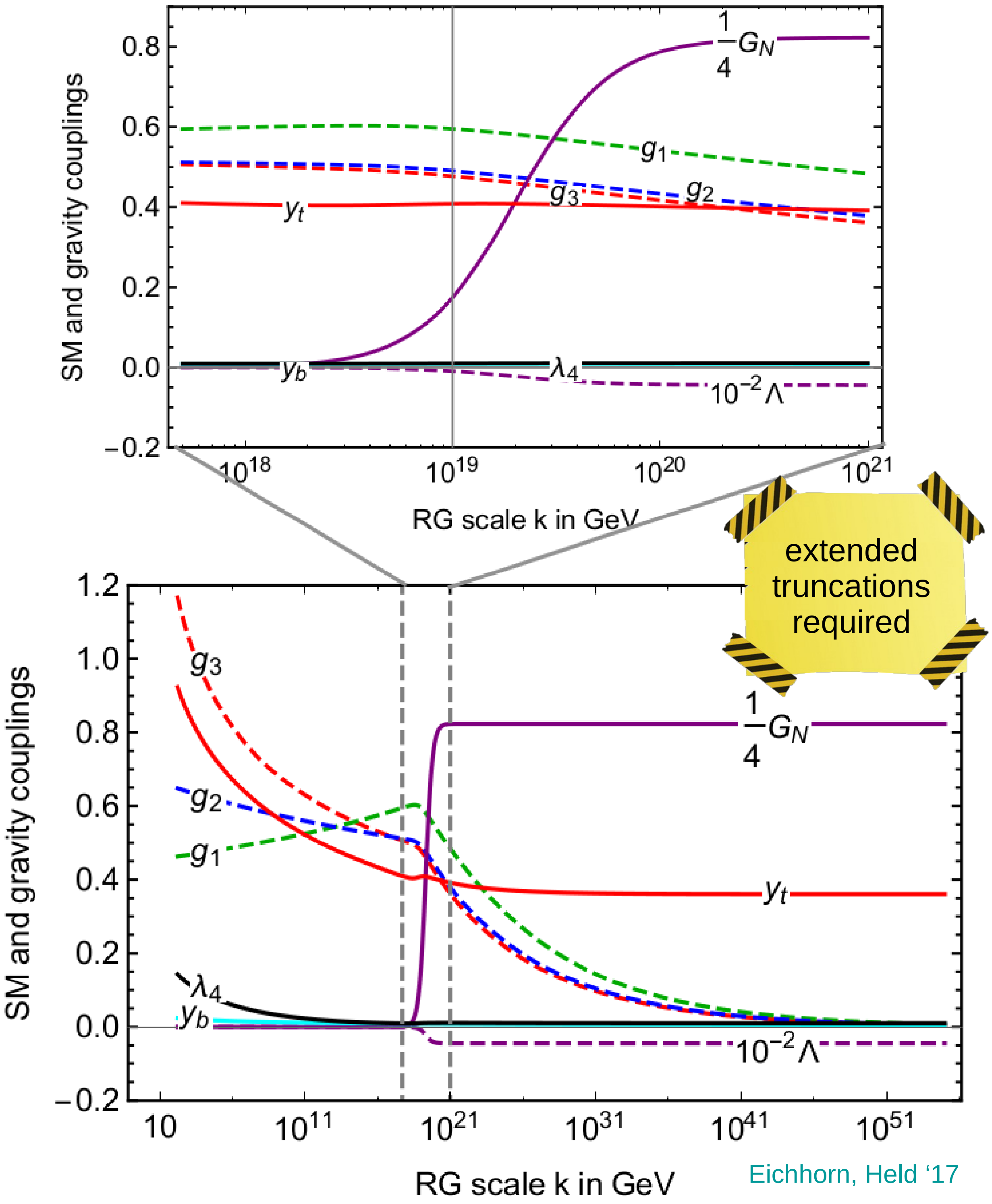
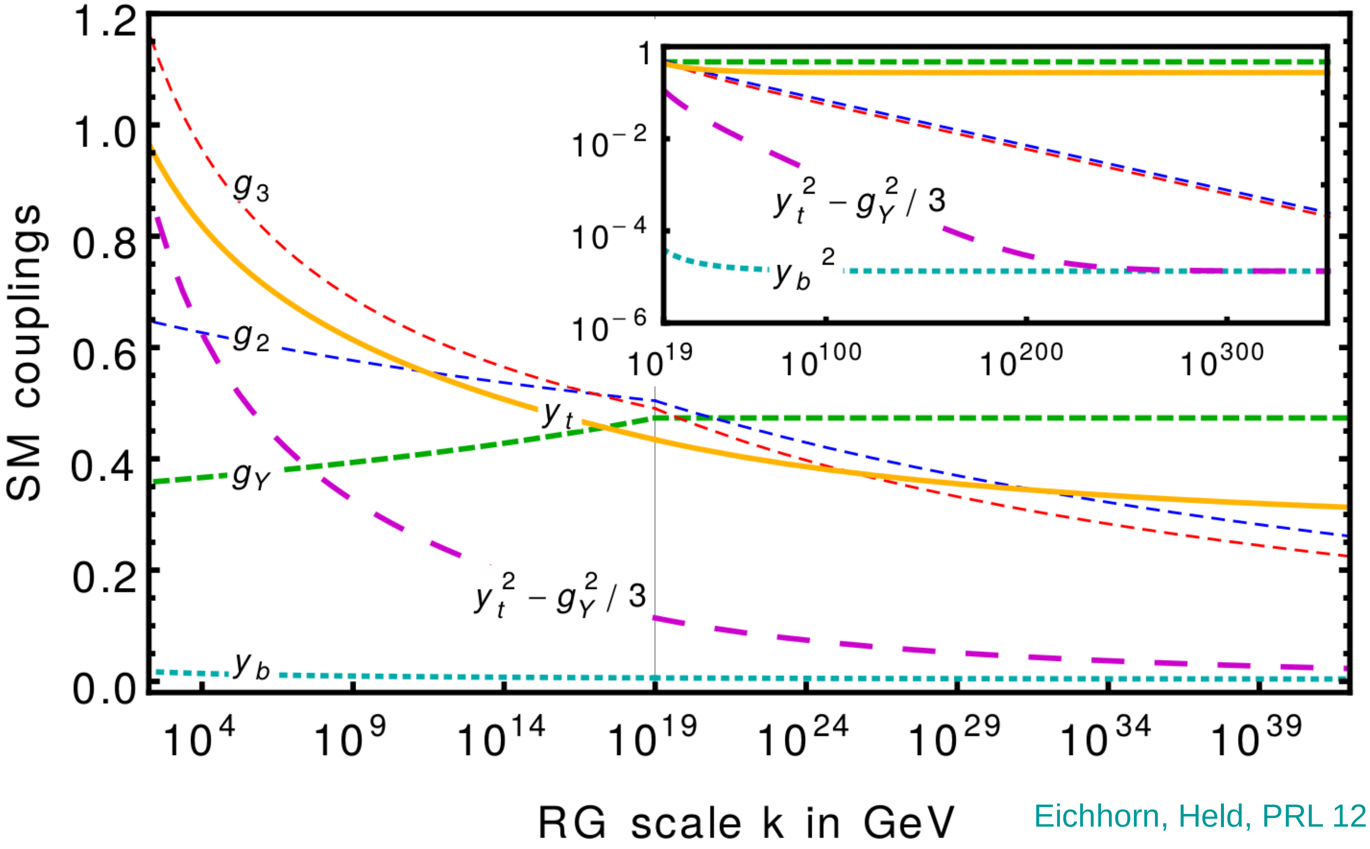


extended
truncations
required

Eichhorn, Held ‘17

Mass difference for charged quarks



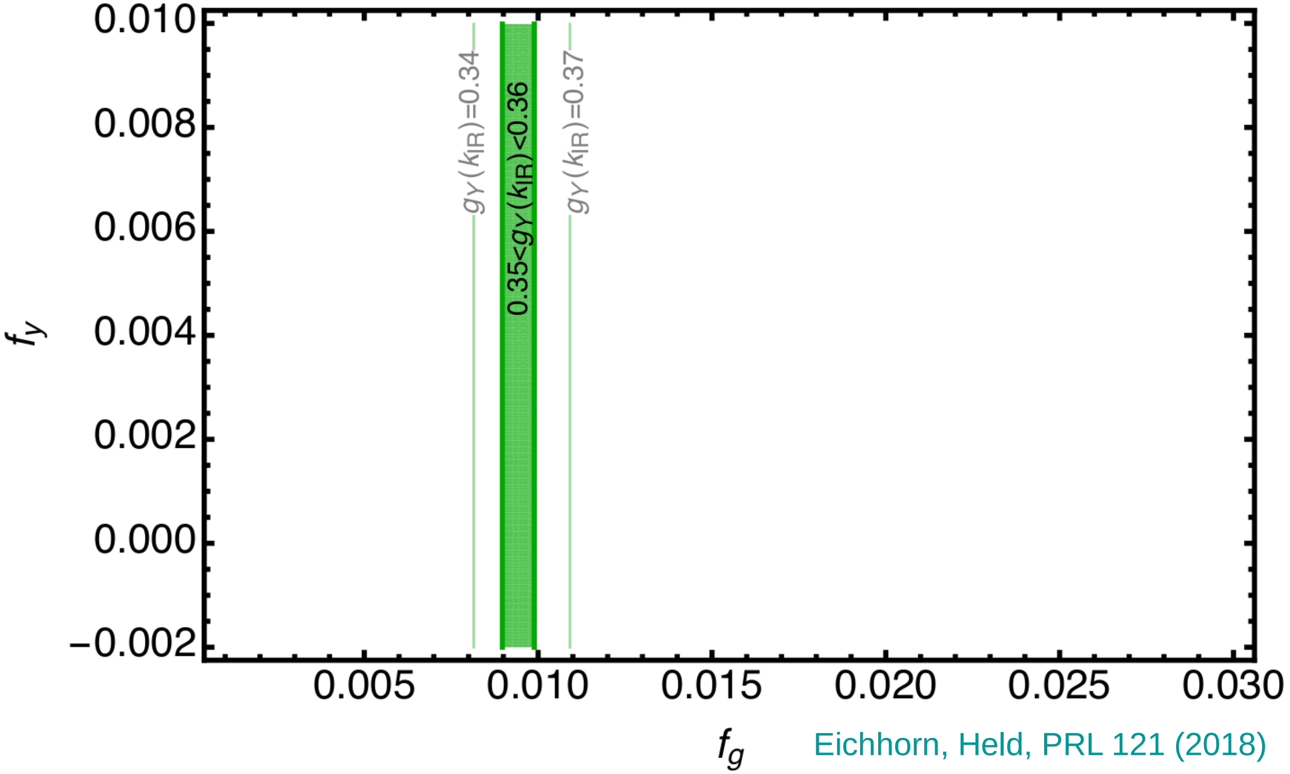
Eichhorn, Held, PRL 121 (2018)

mass difference
from
charge difference

$$\frac{y_{t\,*}^2 - y_{b\,*}^2}{Q_t^2 - Q_b^2} = g_{Y\,*}^2$$

Mass difference for charged quarks

Scale dependence	most predictive fixed point
$\beta_{g_i} = k\partial_k\, g_i(k) = \frac{b_{0,\,i}}{16\pi^2}\, g_i^3 - f_g(G_N, \Lambda)\, g_i$	$g^2_{Y\,*} = \frac{16\pi^2}{b_{0,\,Y}} f_g, \quad g_{2\,*} = 0 = g_{3\,*}$



Eichhorn, Held, PRL 121 (2018)

Mass difference for charged quarks

Scale dependence

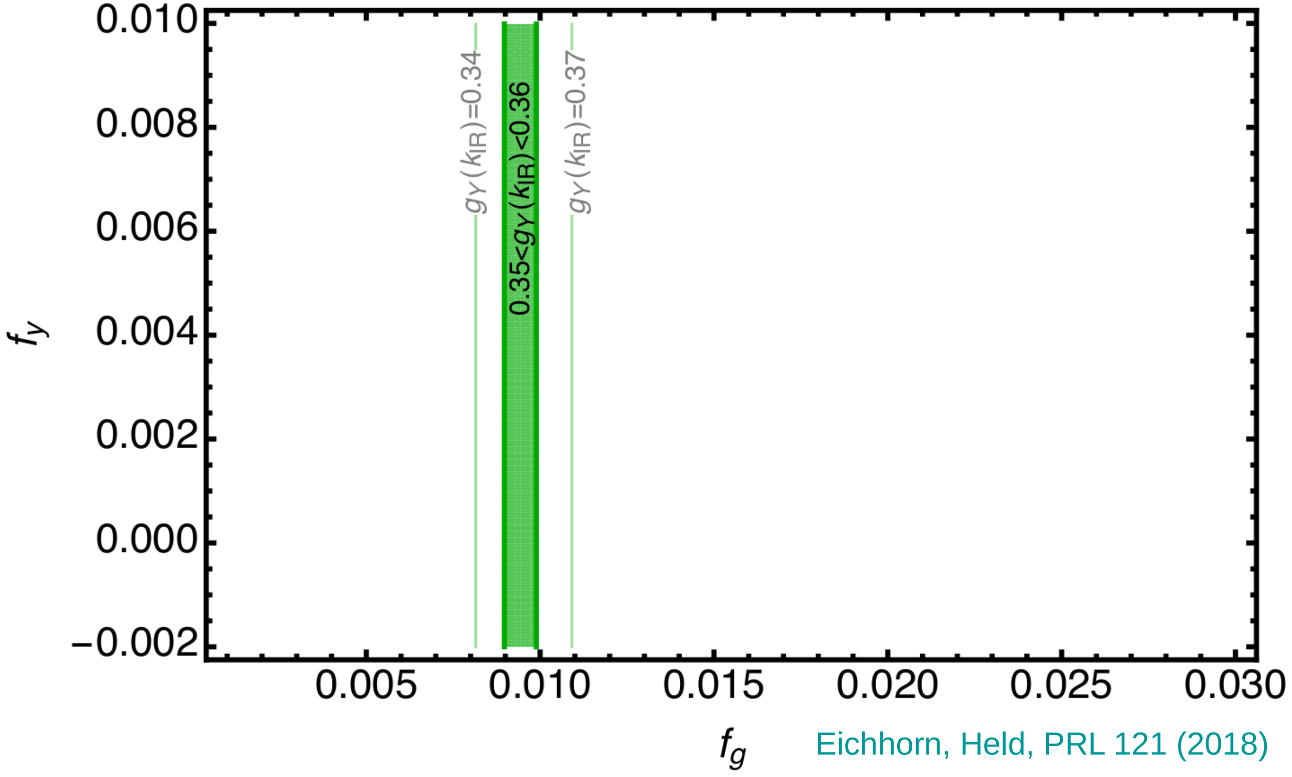
$$\beta_{g_i} = k\partial_k\, g_i(k) = \frac{b_{0,\,i}}{16\pi^2}\, g_i^3 - f_g(G_N, \Lambda)\, g_i$$

$$\beta_{y_t} = \frac{y_t}{16\,\pi^2}\left(\frac{9y_{t\,(b)}^2}{2} - \frac{9}{4}g_2^2 - 8g_3^2\right) - f_y\, y_{t\,(b)} - \frac{3y_t}{16\,\pi^2}\left(Y_Q^2 + Y_t^2\right) g_Y^2$$

most predictive fixed point

$$g_{Y\,*}^2 = \frac{16\pi^2}{b_{0,\,Y}} f_g, \quad g_{2\,*} = 0 = g_{3\,*}$$

$$y_{t\,*}^2 = \frac{8}{3}\pi^2\left(f_y + \frac{3f_g\left(2Y_Q^2 + 3Y_t^2 - Y_b^2\right)}{2\,b_{0,\,Y}}\right)$$



Eichhorn, Held, PRL 121 (2018)

Mass difference for charged quarks

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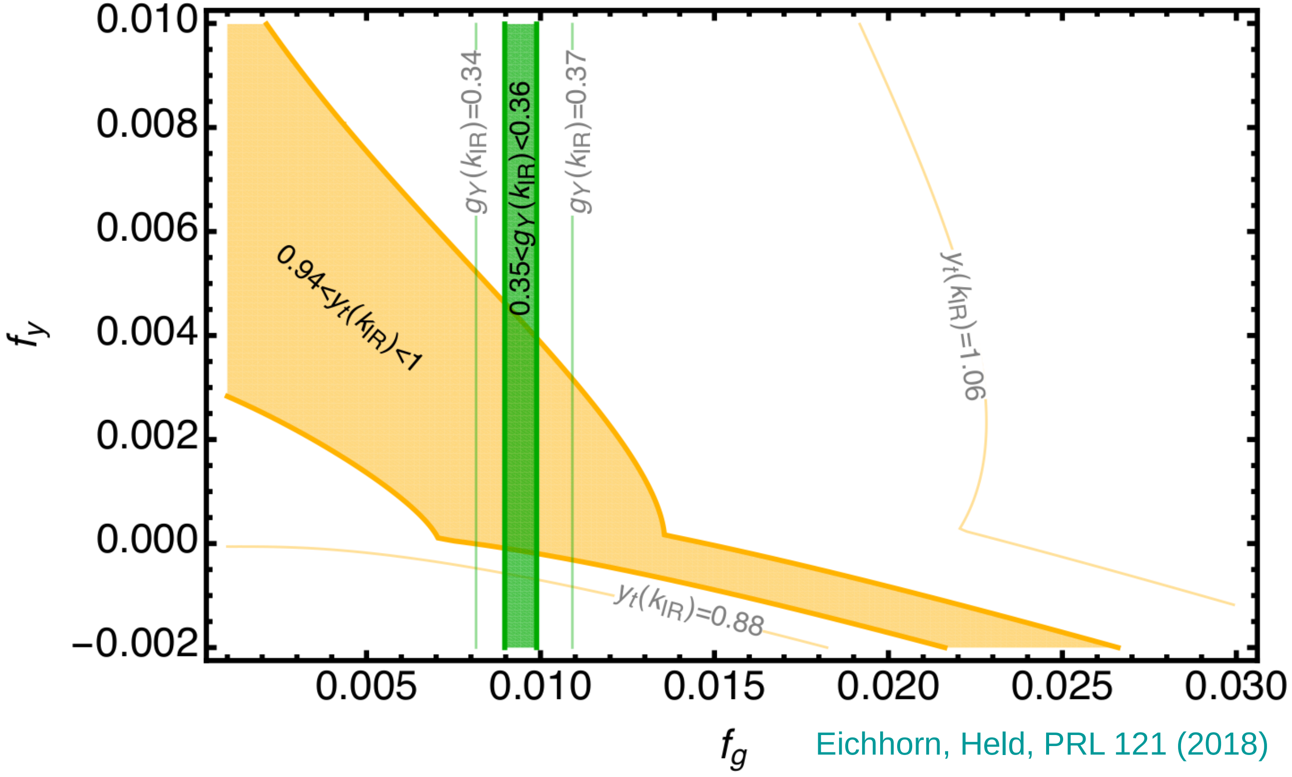

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$$\beta_{y_{t\,(b)}} = \frac{y_{t\,(b)}}{16\,\pi^2}\left(\frac{3y_{b\,(t)}^2}{2} + \frac{9y_{t\,(b)}^2}{2} - \frac{9}{4}g_2^2 - 8g_3^2\right) - f_y\, y_{t\,(b)} - \frac{3y_{t\,(b)}}{16\,\pi^2}\left(Y_Q^2 + Y_{t\,(b)}^2\right) g_Y^2$$

most predictive fixed point

$$g_{Y\,*}^2 = \frac{16\pi^2}{b_{0,\,Y}} f_g, \quad g_{2\,*} = 0 = g_{3\,*}$$

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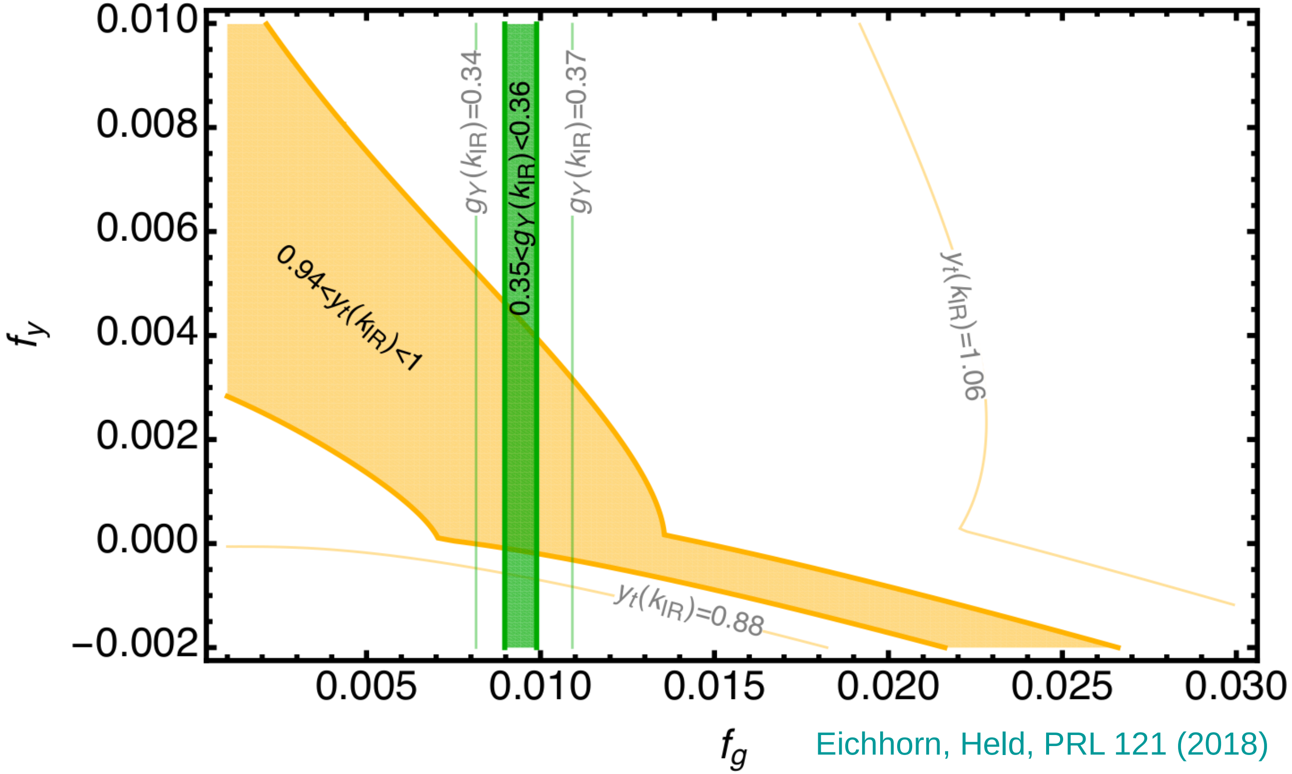

Eichhorn, Held, PRL 121 (2018)

Mass difference for charged quarks

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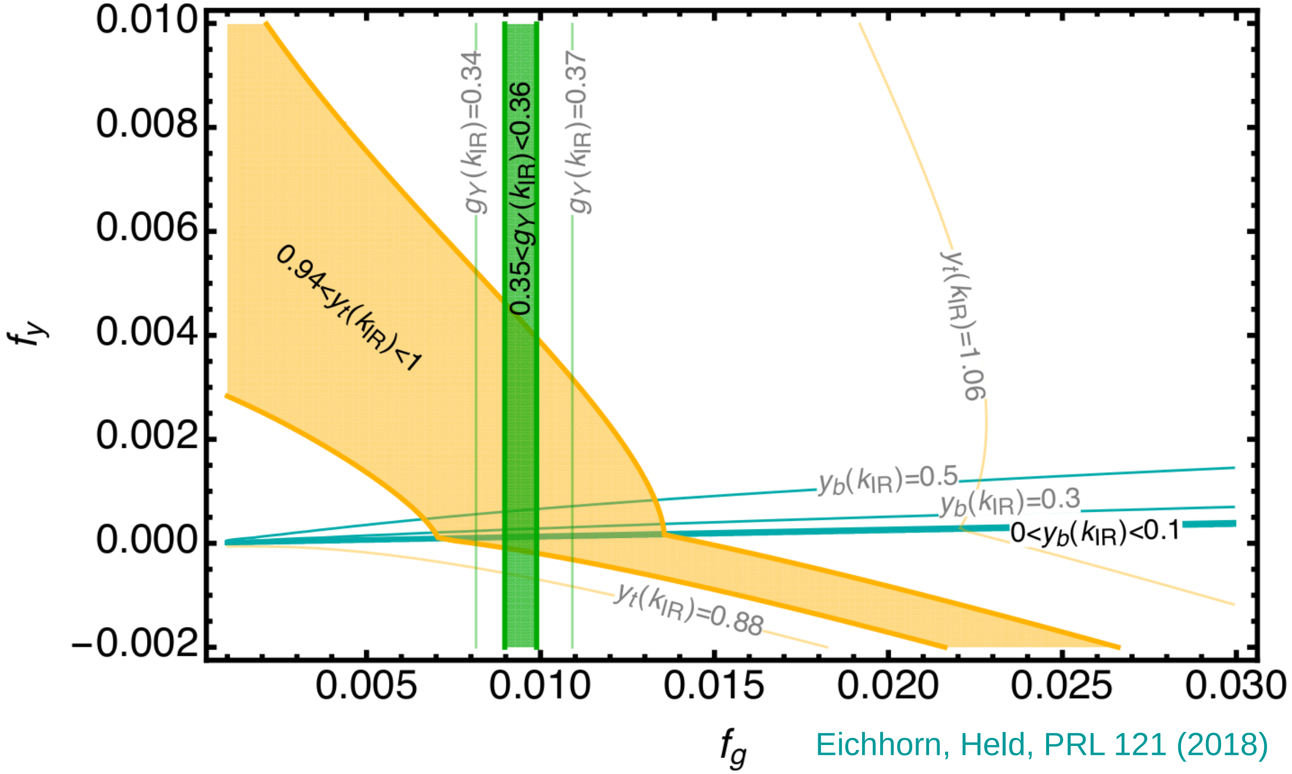

Eichhorn, Held, PRL 121 (2018)

Mass difference for charged quarks

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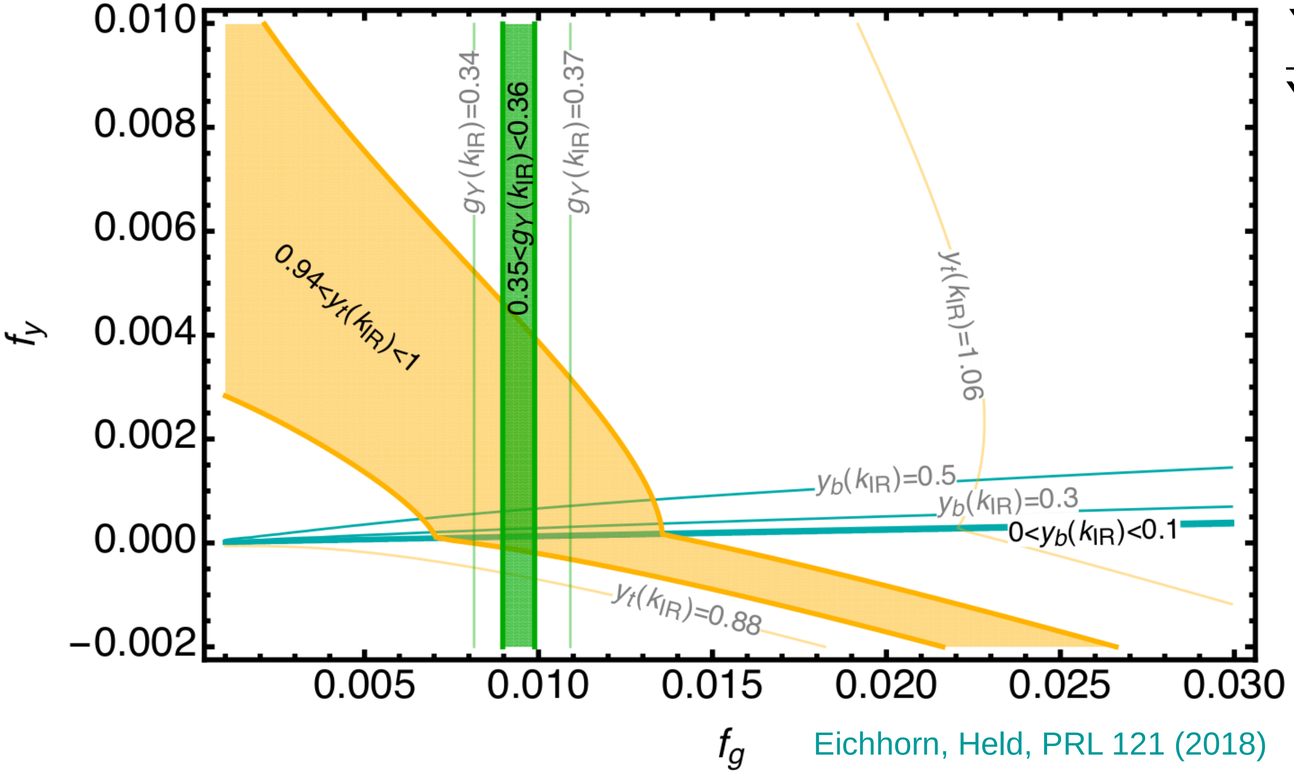
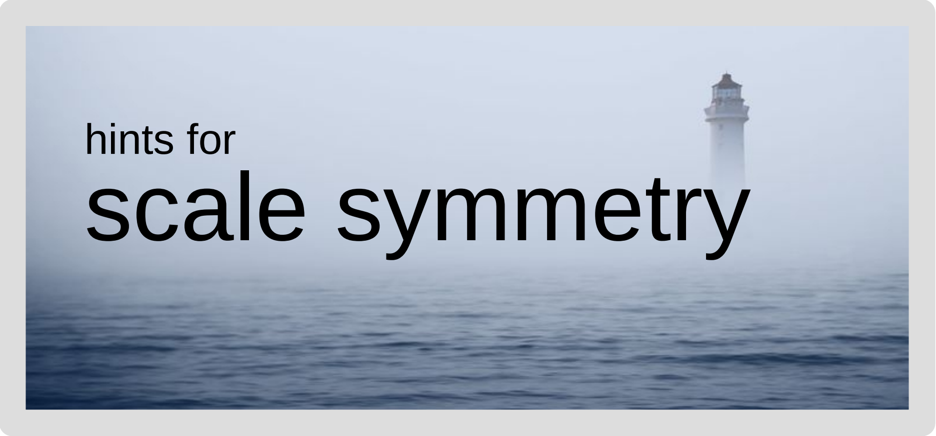


$$\frac{Y_t}{Y_b} = -\frac{1}{2}$$

Eichhorn, Held, PRL 121 (2018)

… in a nutshell ...

- The Standard Model provides hints for **UV scale-symmetry**
- In **asymptotic safety** scale-symmetry implies **enhanced predictive power**



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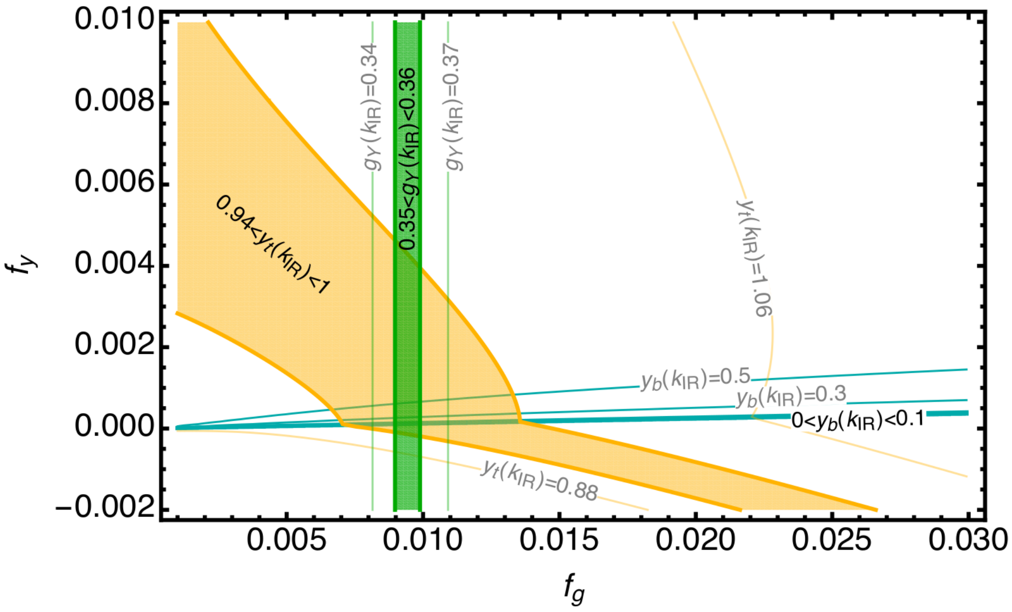
$$(g_{Y,\mathrm{IR}},\, y_{t,\mathrm{IR}},\, y_{b,\mathrm{IR}}) \leftrightarrow (f_g, f_y)$$

Eichhorn, Held, PRL 121 (2018)



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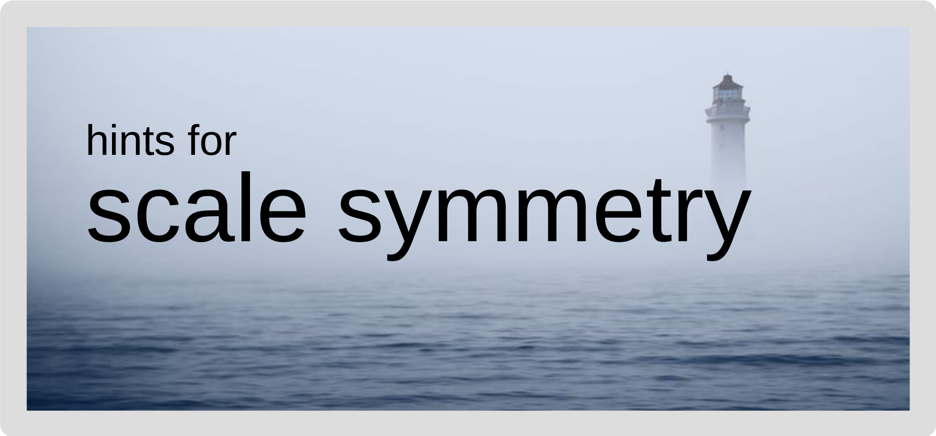

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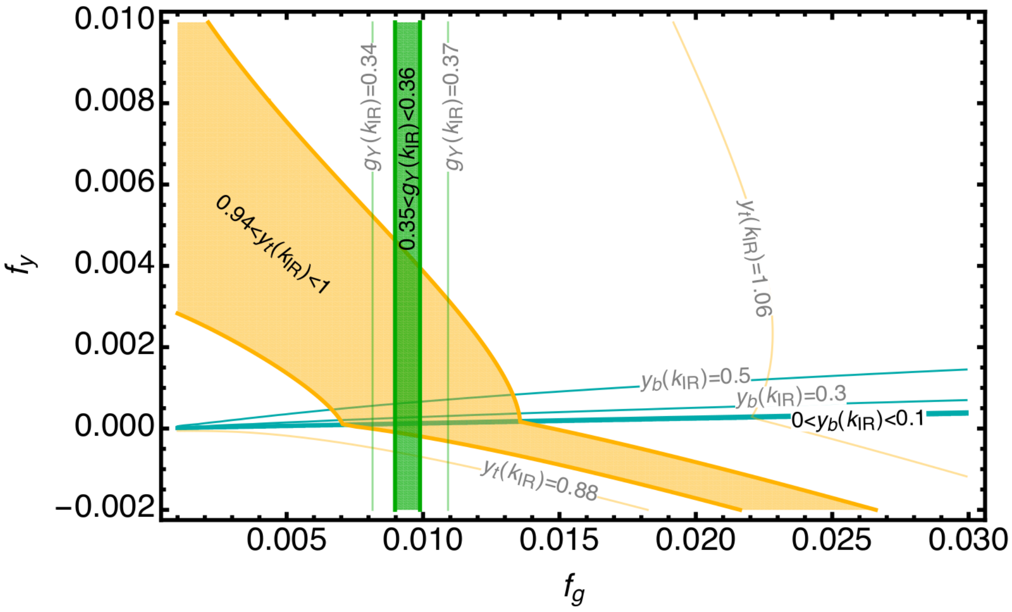
  Eichhorn, Held, PRL 121 (2018)



- Predictive power applies to all **gauge-Yukawa theories**
- **scale-symmetric Planck-scale model building** with perturbative new-physics contributions f_i

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hints for

scale symmetry

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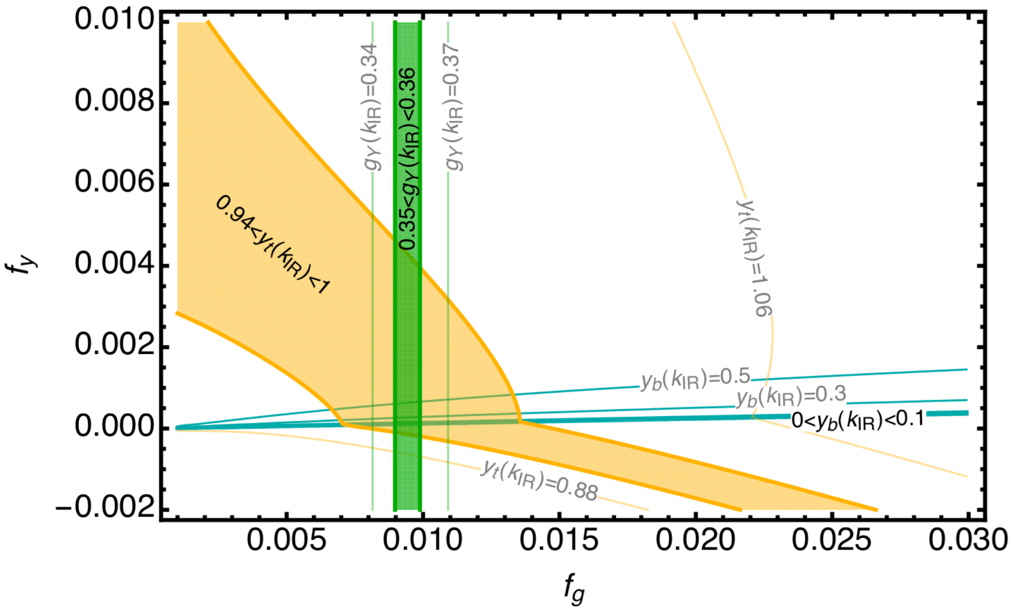

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stay tuned ...

scale symmetry & grand unification
Eichhorn, Held, Wetterich, PLB 782 (2018)
Eichhorn, Held, Wetterich [ongoing work]

scale symmetry & flavor physics
[ongoing work with R Alkofer, A Eichhorn, C Nieto, R Percacci and M Schröfl]

Scale-symmetric
Planck-scale model building

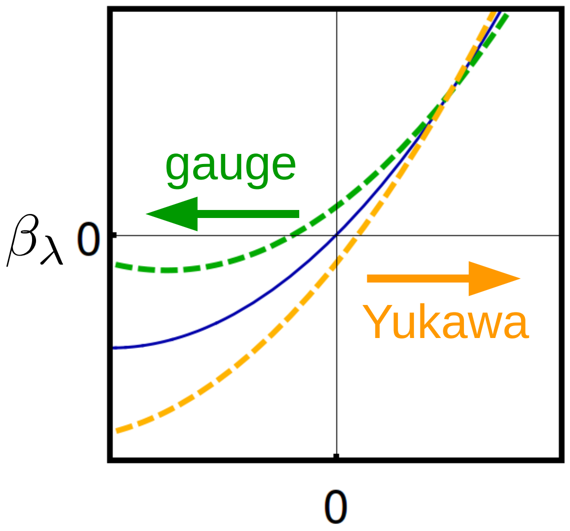
Scale symmetry & grand unification

- running of a general scalar quartic $\Phi_{\rm ijkl}$

Cheng, Eichten, Li ‘73

$$16\pi^2\beta_{\lambda_{\rm ijkl}} = \lambda^2_{\rm [ijkl]_{sym}} - 12S_2(\Phi)\,\alpha\,\lambda_{\rm ijkl} + 3A_{\rm ijkl}\alpha^2$$
$$+ 16\pi^2 f_\lambda\,\lambda_{\rm ijkl}$$

$A_{\rm ijkl} > 0$



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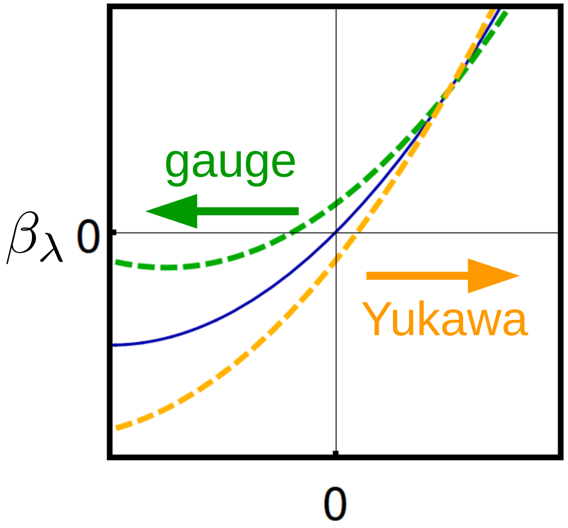

I. **Scale symmetry fixes quartic couplings** at all scales

II. selects the **direction of spontaneous symmetry breaking** as a function of the mass parameter

III. even the **mass-parameter** might be fixed by scale symmetry

see talk by M Yamada

Scale symmetry & CKM mixing

ongoing work, with A Eichhorn,
R Alkofer and M Schröfl,
R Percacci and C Nieto

- diagonalizing Yukawa matrices in the physical basis:

$$Y^u = U_L^\dagger \, \mathcal{Y}^u \, U_R, \quad Y^d = D_L^\dagger \, \mathcal{Y}^u \, D_R, \quad \Rightarrow \quad V = U_L \, D_L^\dagger$$

- parameterization:

$$\underbrace{|V_{ij}|^2 = \begin{bmatrix} X & 1-X \\ 1-X & X \end{bmatrix}}_{\textbf{2-generation}} \qquad \underbrace{|V_{ij}|^2 = \begin{bmatrix} X & Y & 1-X-Y \\ Z & W & 1-Z-W \\ 1-X-Z & 1-Y-W & X+Y+Z+W-1 \end{bmatrix}}_{\textbf{3-generation}}$$

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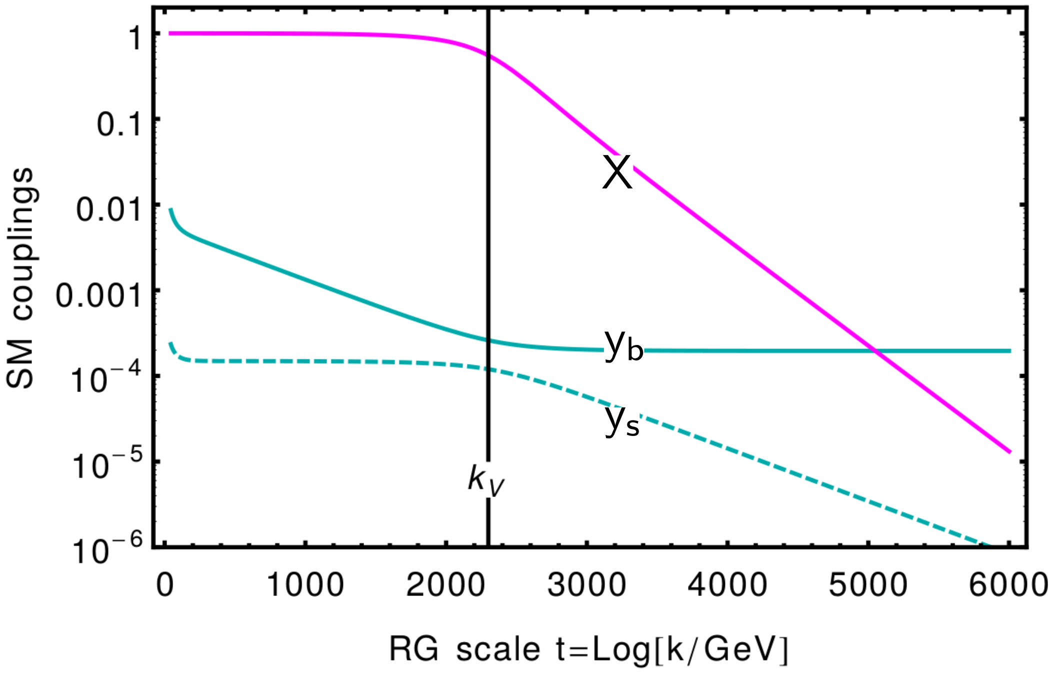
- No-mixing is an **IR-attractive fixed point**

Pendleton, Ross, ‘81



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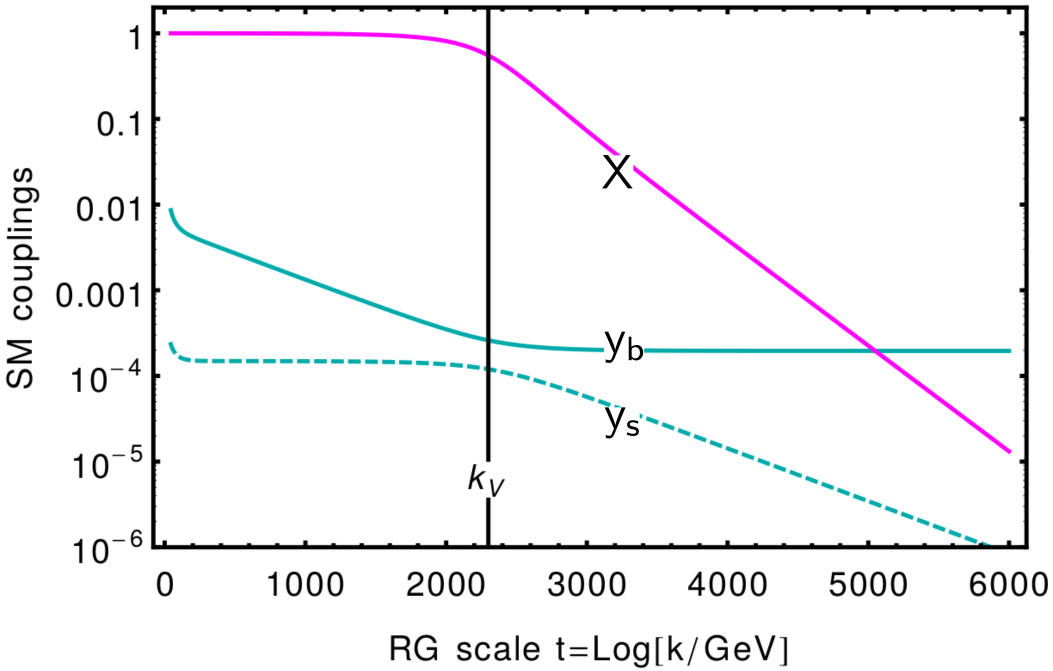

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- again, the Standard Model realizes a **phase transition** from X=0 to X=1 (at least in the 2-generation model)