Compatibility of quantum gravity and a UV-complete Standard Model

Aaron Held

based on work with
Astrid Eichhorn
1705.02342
1707.01107
… to be continued

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International Seminar on Asymptotic Safety – July 3rd 2017

what's to come ...

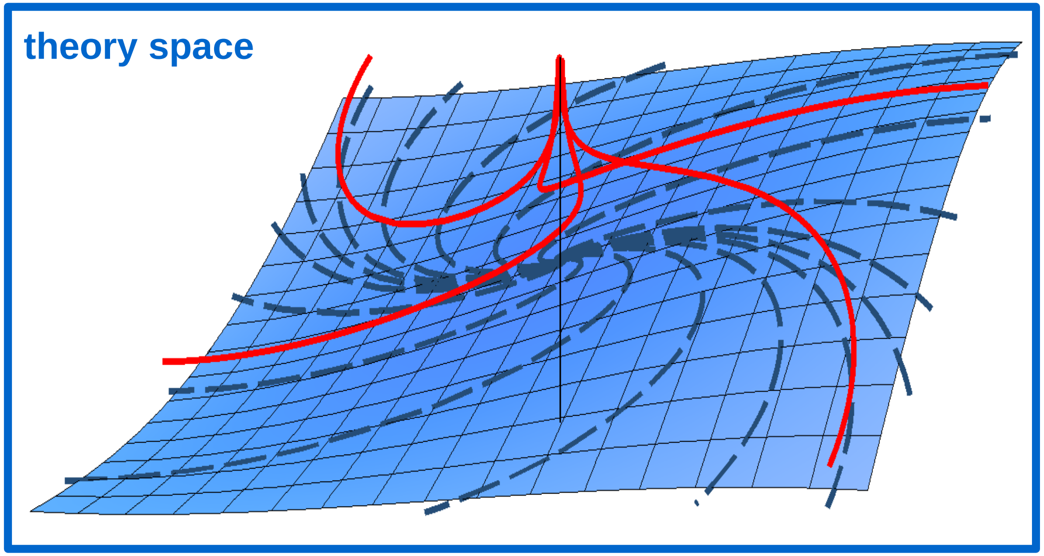
1. **Structure of matter in asymptotic safety: global symmetries**

2. **Weak-gravity bound**

3. **towards a UV-complete Standard Model with enhanced predictivity**

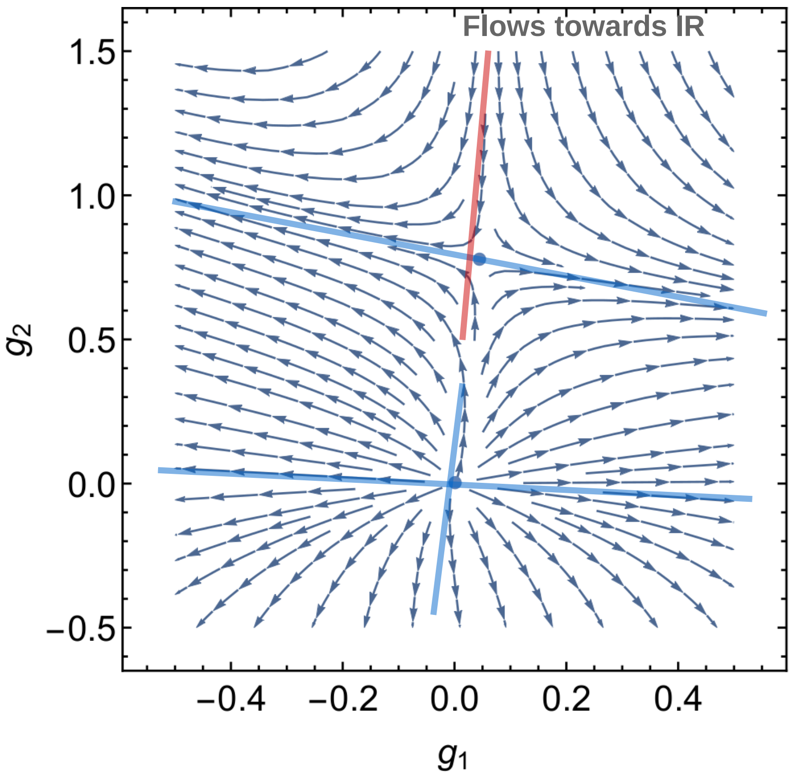
Asymptotic safety: conjecture

Weinberg '79



- existence of a UV fixed point (**fundamental theory**)

$$\beta_{\lambda_i} = 0 \quad \forall\ \lambda_i$$



- finite number of UV-attractive directions (**predictivity**)

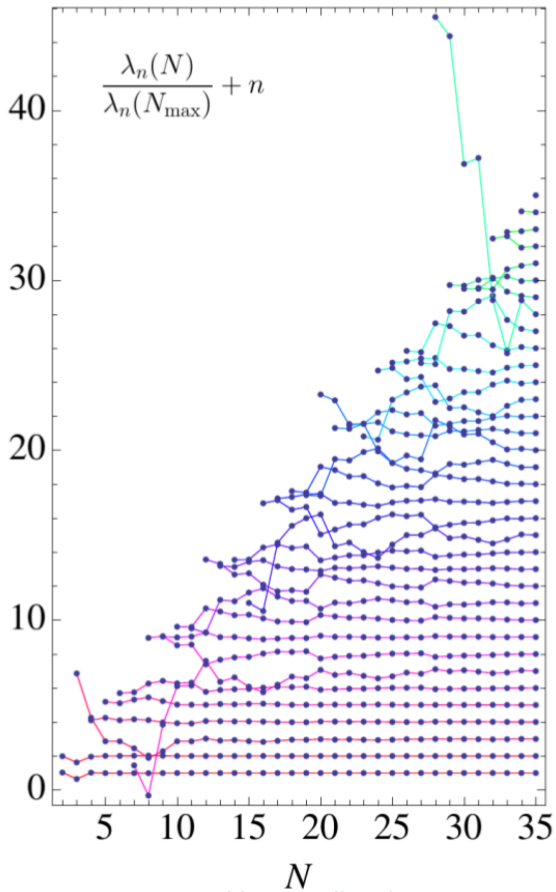
$$\theta_k = -\left[\mathrm{ev}\left(\frac{\partial \beta_{\lambda_i}}{\partial \lambda_j}\right)\right]_k > 0$$

- **UV-attractive** (relevant) direction: needs to be fixed by experiment
- **UV-repulsive** (irrelevant) direction: prediction of asymptotic safety

Asymptotic safety: evidence

C. Wetterich '93
M. Reuter '96

D. Benedetti, P. F. Machado and F. Saueressig '09, 0901.2984
K. Falls, D. F. Litim, K. Nikolakopoulos and C. Rahmede '13, 1301.4191
...



K. Falls, D. F. Litim, K. Nikolakopoulos and C. Rahmede '14, 1410.4815

$f(R)$

$\cdots$

$\lambda_4 R^4$

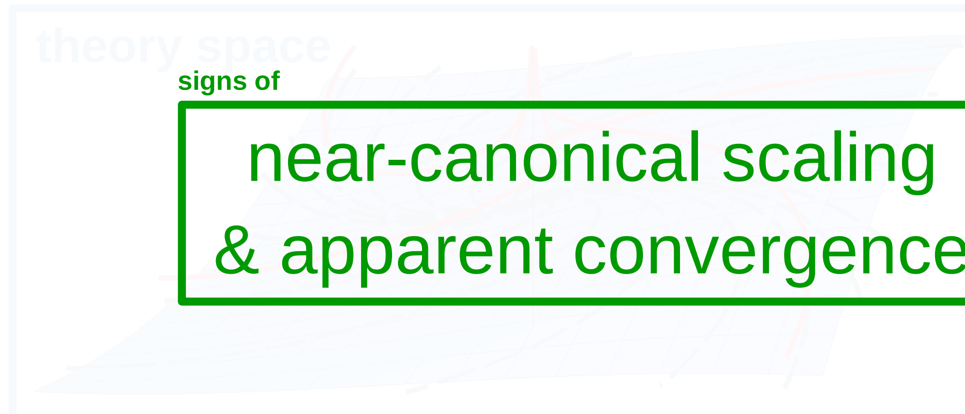
$\lambda_3 R^3$

$\lambda_2 R^2$

$\frac{R}{G_N}$

$\frac{\Lambda}{G_N}$

EINSTEIN-HILBERT: M. Reuter '96
BIMERTIC STUDIES:
D. Becker and M. Reuter '14, 1404.4537
T. Denz, J. M. Pawlowski and M. Reichert '16, 1612.07315
...



signs of

near-canonical scaling & apparent convergence

H. Gies, B. Knorr, S. Lippoldt and F. Saueressig '16, 1601.01800

$\sigma_k C_{\mu\nu}^{\rho\sigma} C_{\rho\sigma}^{\kappa\lambda} C_{\kappa\lambda}^{\mu\nu}$ $\quad c\, R \Box R \quad + 7$ more

$C_{\mu\nu ho\sigma} C^{\mu\nu ho\sigma}$ $\quad b\, R_{\mu\nu} R^{\mu\nu}$

N. Christiansen '16, 1612.06223

What about matter?

1. structure: Gravitationally induced couplings

chiral U(1) symmetry
$\psi \to e^{i\gamma_5\alpha}\psi \quad \bar\psi \to \bar\psi e^{i\gamma_5\alpha}$

U(1) phase symmetry
$\psi \to e^{i\alpha'}\psi \quad \bar\psi \to \bar\psi e^{i\alpha'}$

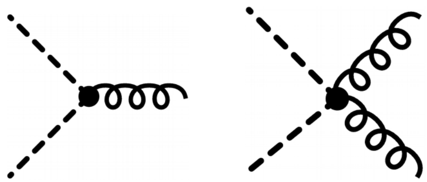
$$S_{\psi\mathrm{kin}} = i \int d^4x \sqrt{\det(g)}\,\left(\bar\psi\gamma^\mu\nabla_\mu\psi\right)$$

scalar Z_2 symmetry
$\phi \to -\phi$

scalar shift symmetry
$\phi \to \phi + a$

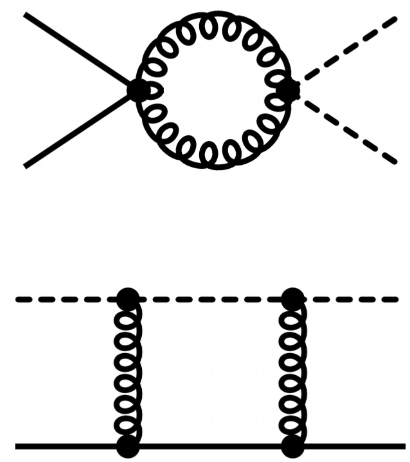
$$S_{\phi\mathrm{kin}} = \frac{1}{2} \int d^4x \sqrt{\det(g)}\,\left(g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right)$$

$\Longrightarrow$



Eichhorn ’12, 1204.0965

gravitational induction



$\sim (G_N)^2$

- gravity **induces all matter interactions sharing the global symmetries** of the matter kinetic terms

$$+\,i\mathcal{X} \int d^4x\sqrt{g}\Big[\overbrace{\left(\bar\psi\gamma^\mu\nabla_\nu\psi - (\nabla_\nu\bar\psi)\gamma^\mu\psi\right)}^{\text{fermion kinetic symmetries}}\overbrace{\left(\partial_\mu\phi\partial^\nu\phi\right)}^{\text{scalar kinetic symmetries}} + \left(\bar\psi\gamma^\mu\nabla_\mu\psi - (\nabla_\mu\bar\psi)\gamma^\mu\psi\right)\left(\partial_\nu\phi\partial^\nu\phi\right)\Big]$$

Eichhorn, Held, Pawlowski ‘16, 1604.02041

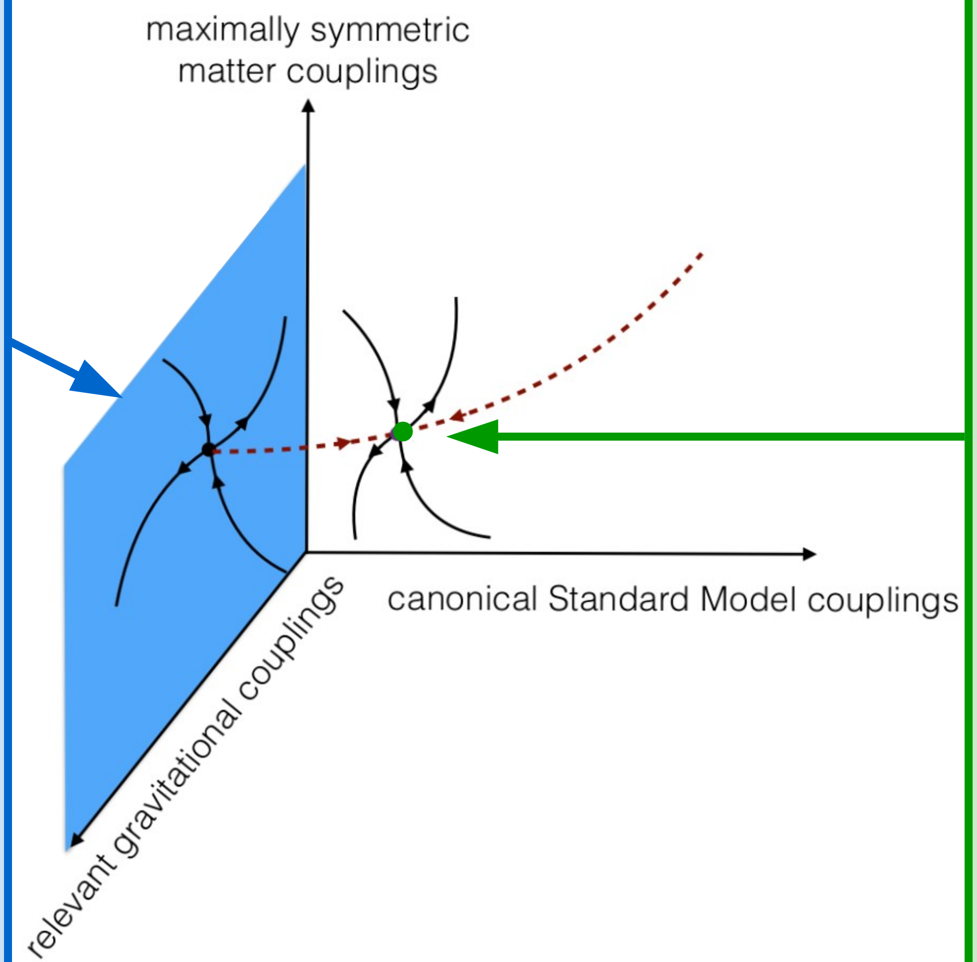
1. structure: Gravitationally induced couplings

	scalars	fermions	gauge fields
scalars	analyzed $\left(\partial_\mu\phi\partial^\mu\phi\right)^2$ Eichhorn '12, 1204.0965	analyzed $\partial_\mu\phi\partial^\mu\phi\,\bar{\psi}\gamma_\nu\nabla^\nu\psi$	conjectured $\partial_\mu\phi\partial^\mu\phi\ \mathrm{F}^2$
fermions		$\left(\bar{\psi}\gamma_\mu\nabla^\mu\psi\right)^2$ Eichhorn and Held '17, 1705.02342 Eichhorn, Held and Pawlowski '16, 1604.02041	conjectured $\bar{\psi}\gamma_\nu\nabla^\nu\psi\ \mathrm{F}^2$
gauge fields			analyzed $\left.\left(\mathrm{F}^2\right)^2\right\vert_{\mathrm{Abelian}}$ Christiansen & Eichhorn, 2017, 1702.07724

1. structure: Gravitationally induced couplings

Scenario A: maximally symmetric

- marginally irrelevant SM couplings becomes **asymptotically free** and **relevant**
- **not predictive** in the SM sector
- higher degree of global symmetry



Eichhorn and Held '17, 1705.02342

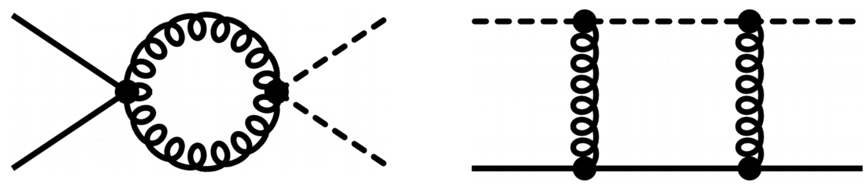
Scenario B: Standard Model symmetries

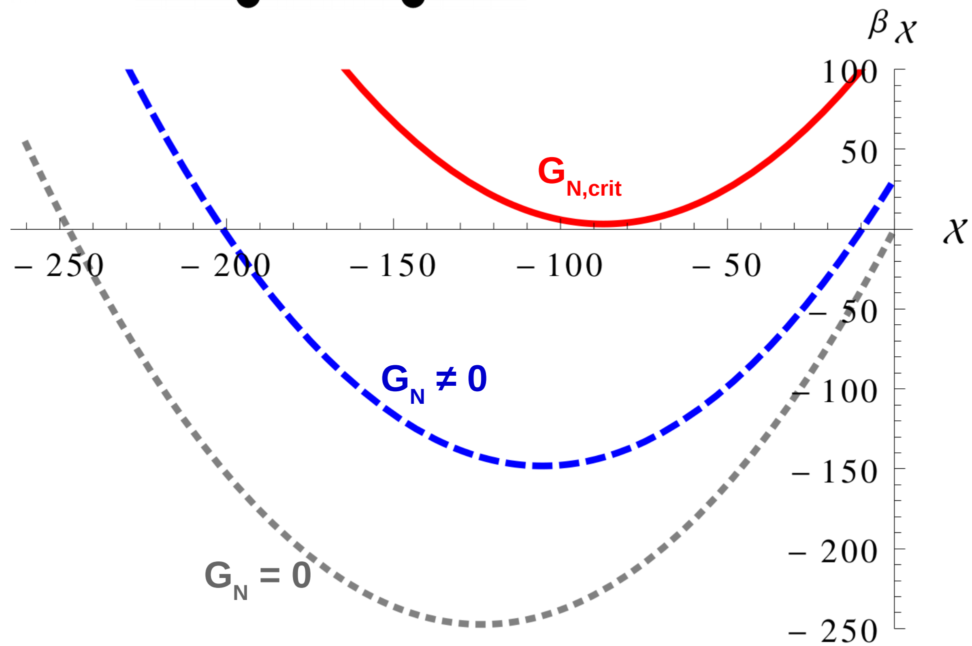
- marginally irrelevant SM coupling becomes **asymptotically safe** and **irrelevant**
- higher **predictive** power than the SM
- non-vanishing SM interactions **partially break global symmetry**
- adds an additional constraint to the relevant directions

2. A weak-gravity bound: conceptual

canonical dimension | pure matter | induced | mixed

$$\beta_{\mathcal{X}} = \underbrace{4\mathcal{X}}_{} + \#_{\mathcal{X}}\mathcal{X}^2 + \boxed{\#_{G1}\, G_N^2} + \#_{G2}\, G_N\, \mathcal{X}$$





Eichhorn, Held, Pawlowski '16, 1604.02041

within truncations

- **Weak gravity bound:**

  Too strong gravity leads to an **unstable matter sector**

2. A weak-gravity bound: cosmological constant

spin-2 mode

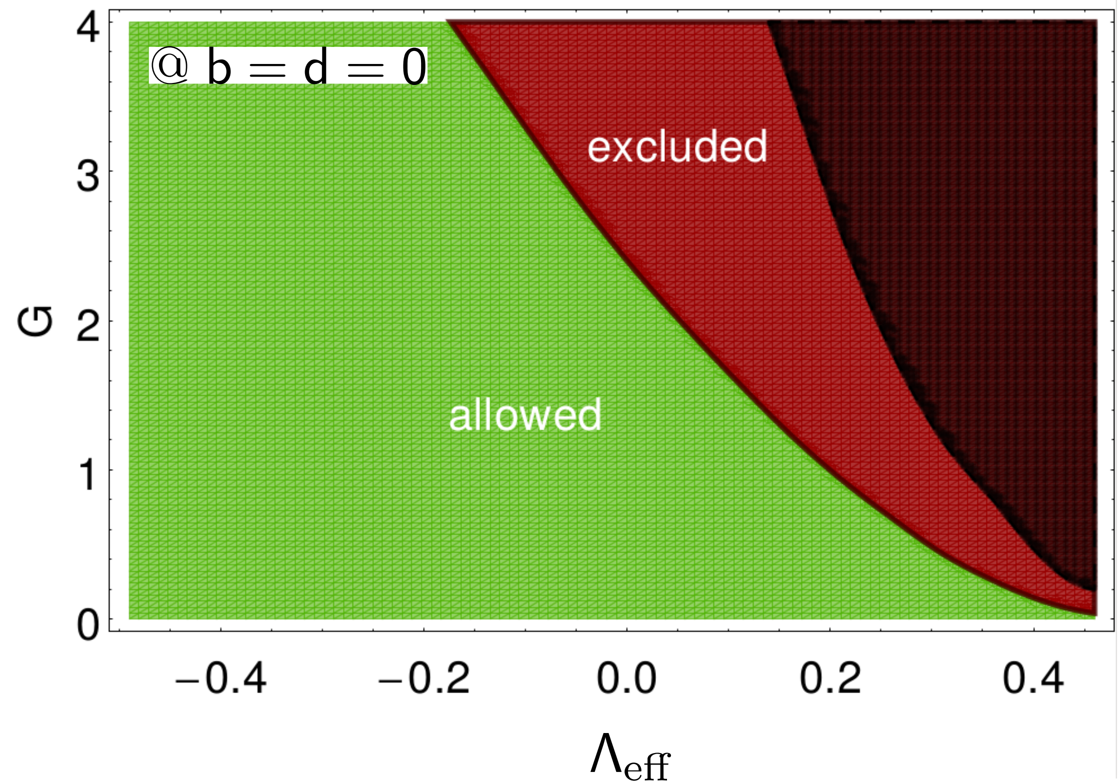
Newton coupling

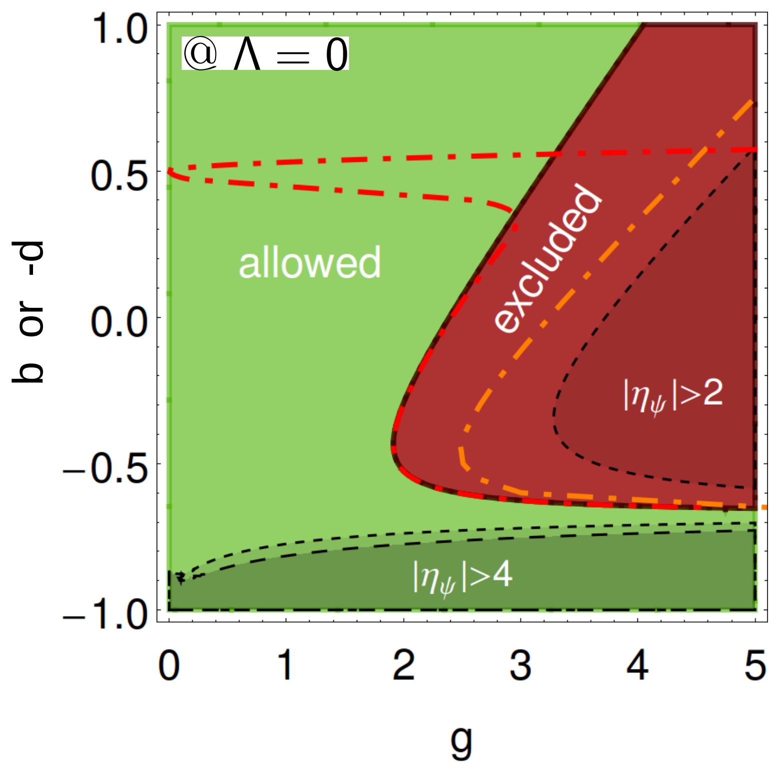
$$\left(\Gamma^{(2)}_{k,\,\mathrm{TT}}\right)^{-1} = \frac{32\pi G}{p^2 - 2\Lambda + bp^4 - dp^6}$$

cosmological constant

$R_{\mu\nu}R^{\mu\nu}$ $R_{\mu\nu}\Box R^{\mu\nu}$

higher curvature couplings





- a large **cosmological constant** works like an **effective mass** that suppressing gravity contributions
- **higher curvature** couplings contribute mass-like in the graviton propagator as well

3. UV-complete SM: triviality problem

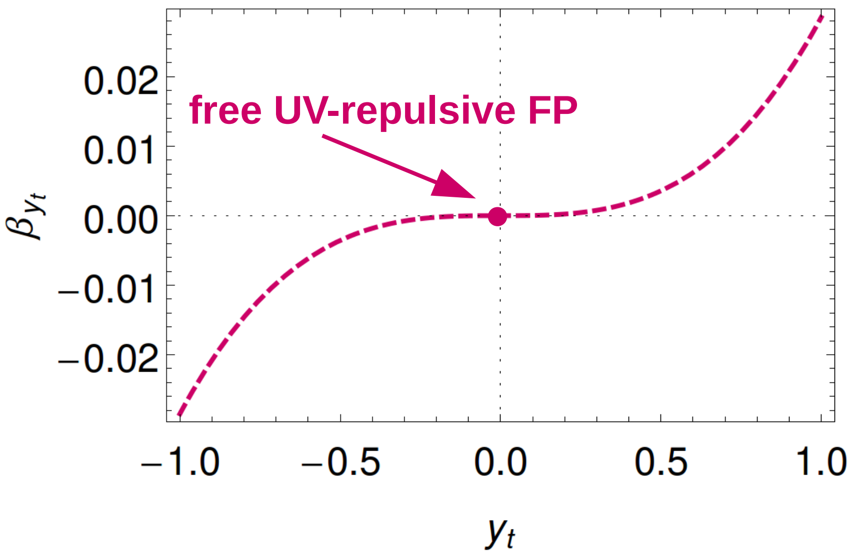
SM exhibits **Landau poles in marginally irrelevant** couplings:

$g_1, \ \lambda_4, \ y_t$

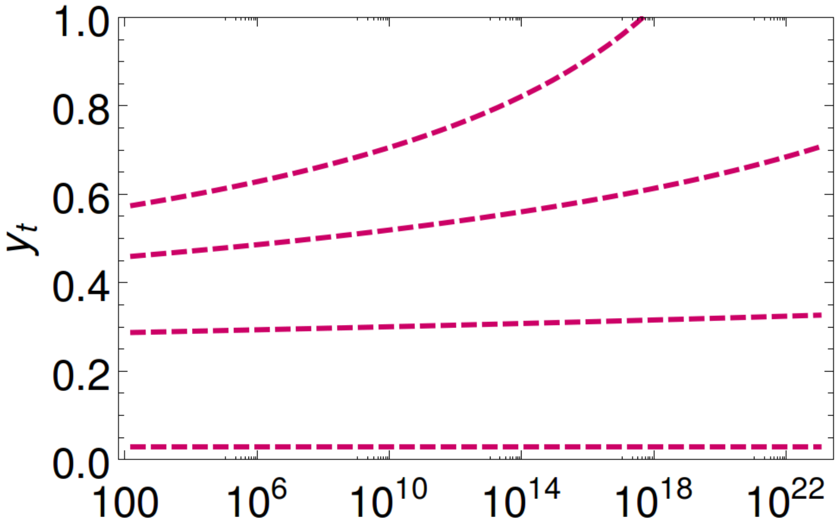
Gell-Mann, Low '54
Maiani, Parisi, Petronzio '78
...

$$\beta_{y_t} = \frac{9}{32\pi^2} y_t^3 + (\text{SM-terms})$$

beta-function



running of the coupling



finite top-mass ($y_t \neq 0$) $\longrightarrow$ **divergence** in the UV

3. UV-complete SM: dimensional reduction

quantum gravity

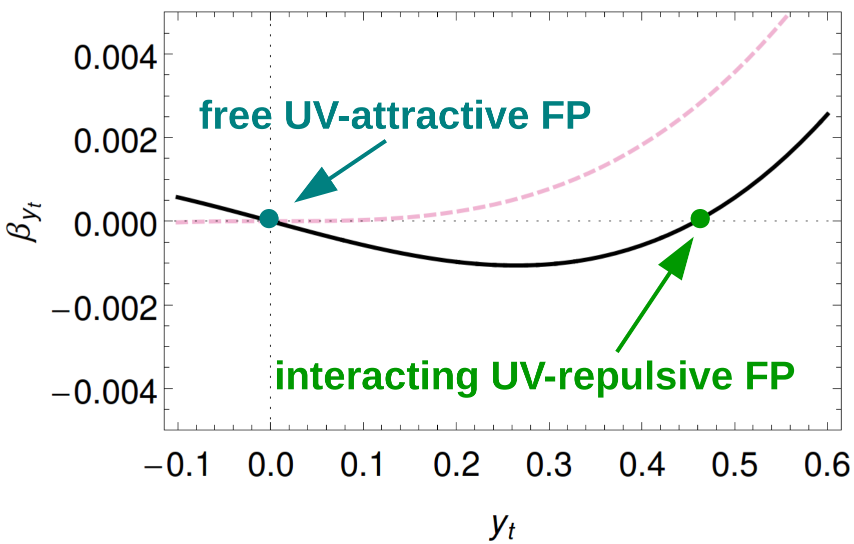
$$\beta_{y_t} = \frac{9}{32\pi^2} y_t^3 + G_N\, y_t\, f_y(\Lambda) + (\text{SM-terms})$$

$$\text{with:} \quad f_y(\Lambda) = \frac{96 + \Lambda(-235 + \Lambda(103 + 56\Lambda))}{12\pi(3 + 2\Lambda(-5 + 4\Lambda))^2} \overset{!}{<} 0$$

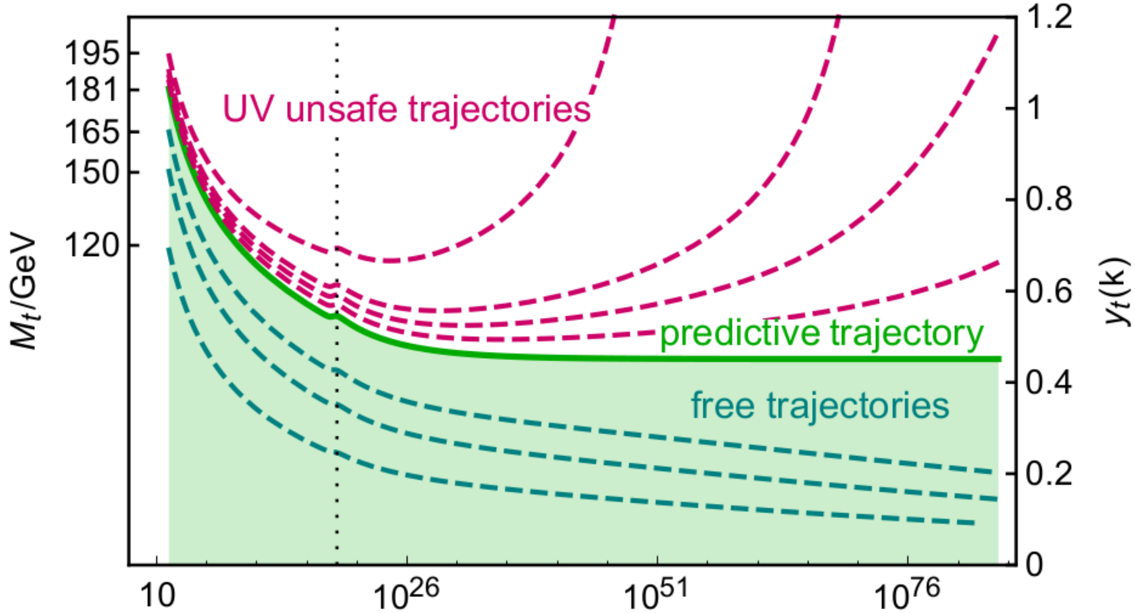
Eichhorn, Held '17, 1705.02342

condition for dimensional reduction

beta-function



running of the coupling



Eichhorn, Held '17, 1707.01107

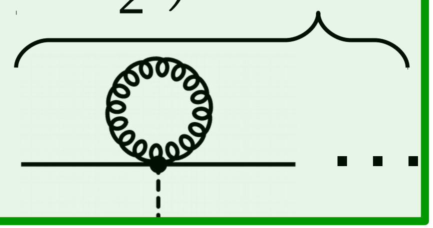
free fixed point: accomodates $M_t < M_{t,crit}$

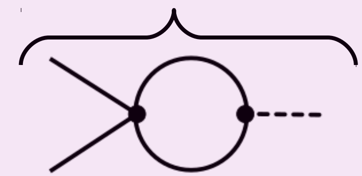
interacting fixed point: unique value for M_t

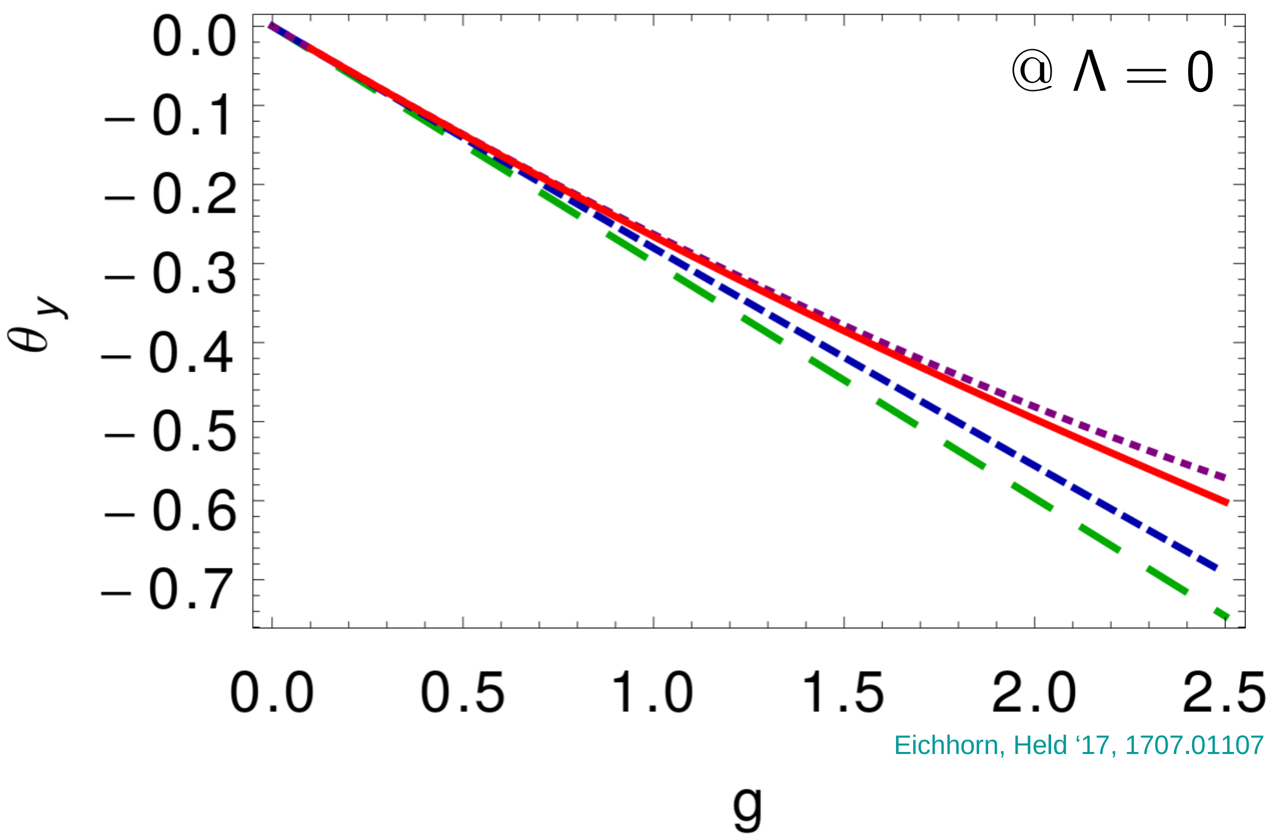
3. UV-complete SM: suppression of matter-mediated effects

direct gravity contributions **matter-mediated**

$$\theta_y = \boxed{-\left(\eta_\psi + \frac{\eta_\phi}{2}\right) - g\,\mathcal{D}_y} \boxed{+\,4\lambda_A \mathcal{M}_y^{\lambda y}}$$







including 4-fermion-mediated
full result
including trace mode
spin-2 mode only

Eichhorn, Held '17, 1707.01107

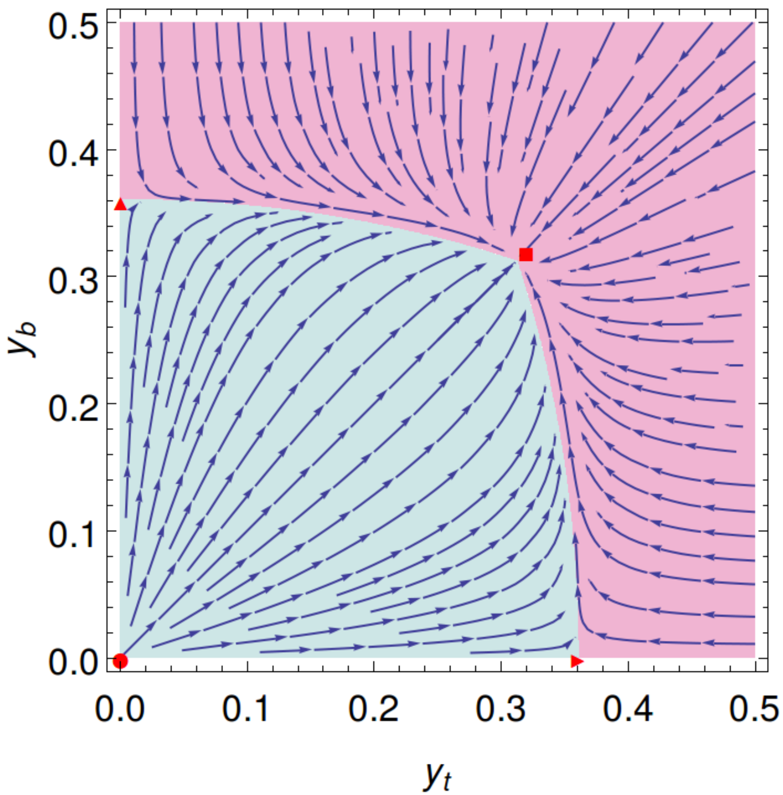
3. UV-complete SM: top-bottom asymmetry

allows for **asymmetric solutions**

$$\beta_{y_t} = \frac{1}{32\pi^2}\left(9y_t^3 + 3y_b^2 y_t\right) + G_N\, y_t\, f_y(\Lambda) + (\text{SM-terms})$$

$$\beta_{y_b} = \frac{1}{32\pi^2}\left(9y_b^3 + 3y_t^2 y_b\right) + G_N\, y_b\, f_y(\Lambda) + (\text{SM-terms})$$

$$\Longrightarrow \quad \boxed{y_t^* = \frac{\sqrt{32}\pi}{3}\sqrt{-G_N^*\, f_y(\Lambda^*)}\,, \qquad y_b^* = 0}$$

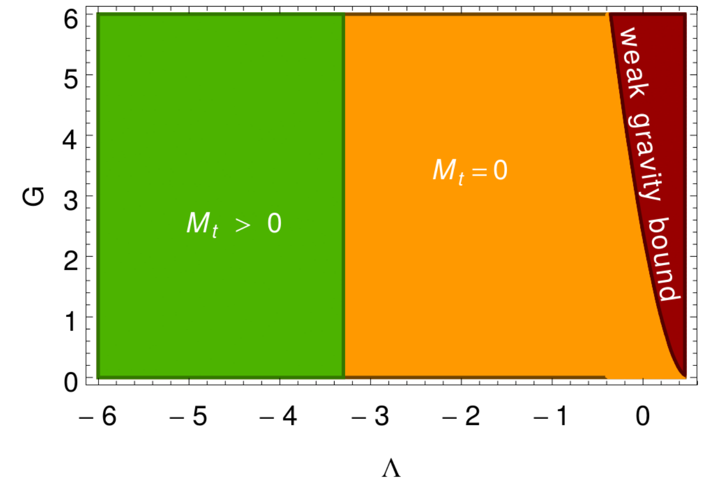


3. UV-complete SM: predicting the top

$$\boxed{y_t^* = \frac{\sqrt{32\pi}}{3}\sqrt{-G_N\, f_y(\Lambda)}\ , \quad y_b^* = 0}$$

with: $f_y(\Lambda) = \dfrac{96 + \Lambda(-235 + \Lambda(103 + 56\Lambda))}{12\pi(3 + 2\Lambda(-5 + 4\Lambda))^2} \overset{!}{<} 0$

Eichhorn, Held '17, 1705.02342



$$G_N^* = \frac{12\pi}{46 - N_W - N_S + 4N_V}$$

$$\Lambda^* = \frac{3}{4}\left(\frac{2 - 2N_W + N_S + 2N_V}{31 - N_W - N_S + 4N_V}\right)$$

simplified form:
P. Donà, A. Eichhorn, R. Percacci '13, 1311.2898

$\Lambda^* \lesssim -3.3$
$\Longleftrightarrow f_y(\Lambda) < 0$

$\Lambda^* \gtrsim -3.3$
$\Longleftrightarrow f_y(\Lambda) > 0$

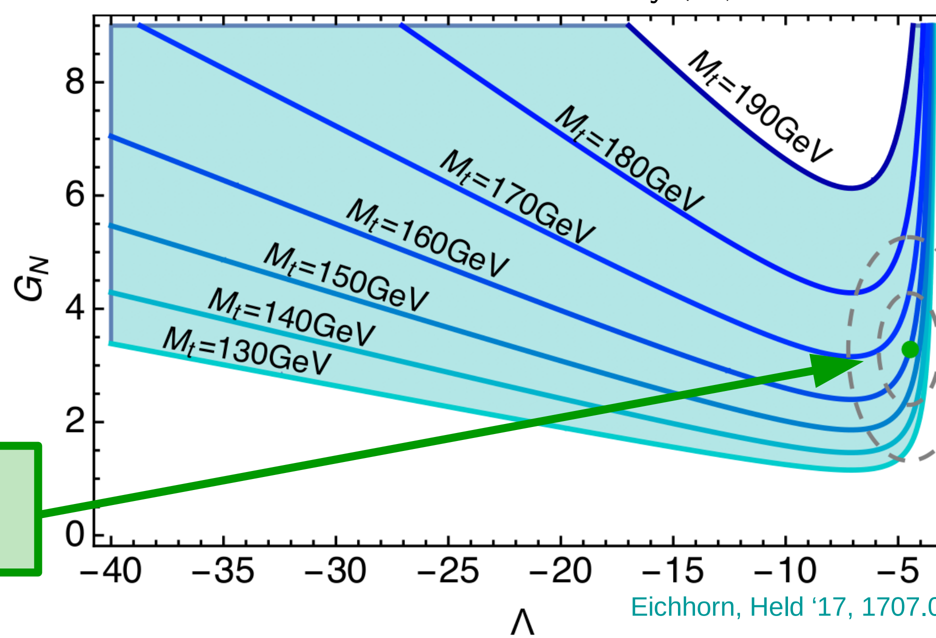
matter content of the SM could push gravity in the **viable regime**

$N_W = 45$: Weyl fermions

$N_S = 4$: scalars

$N_V = 12$: gauge fields

$$\boxed{\Longrightarrow G_N^* = 3.3\ , \quad \Lambda^* = -4.5}$$



only free UV-repulsive FP

in tension with massive fermions

Eichhorn, Held '17, 1707.01107

3. UV-complete SM: predicting the top

Eichhorn, Held '17, 1707.01107

$$y_t^* = \frac{\sqrt{32\pi}}{3}\sqrt{-G_N f_y(\Lambda)}\,, \quad y_b^* = 0$$

with: $f_y(\Lambda) = \dfrac{96 + \Lambda(-235 + \Lambda(103 + 56\Lambda))}{12\pi(3 + 2\Lambda(-5 + 4\Lambda))^2} \overset{!}{<} 0$

Eichhorn, Held '17, 1705.02342

$$G_N^* = \frac{12\pi}{46 - N_W - N_S + 4N_V}$$

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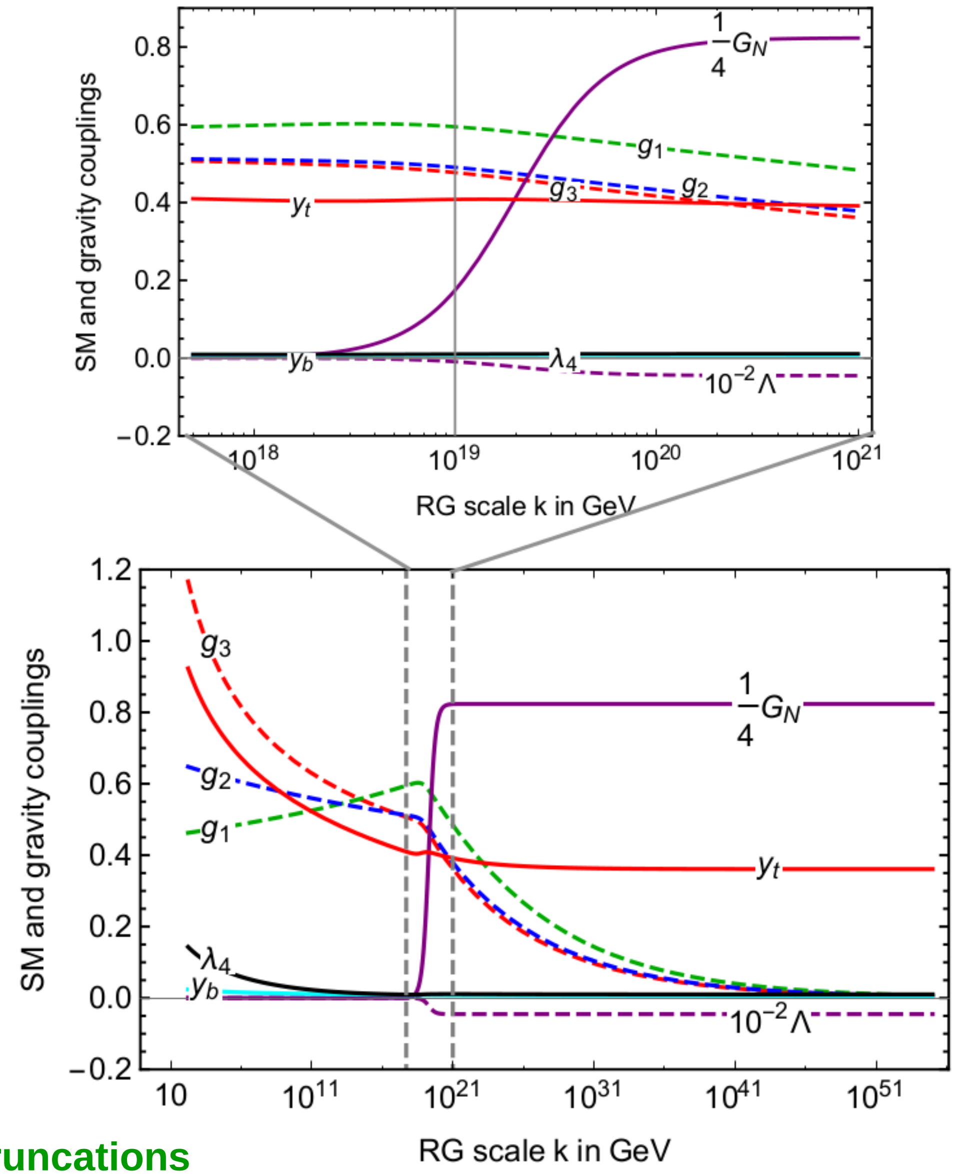
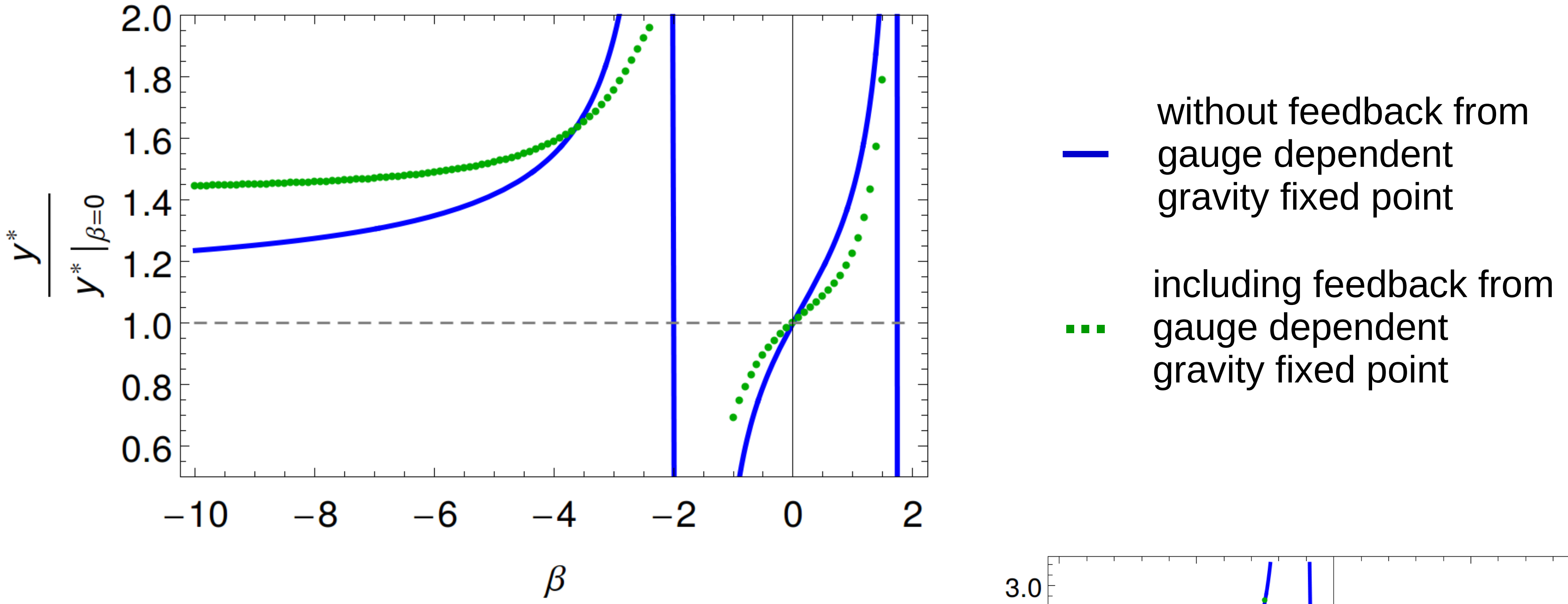


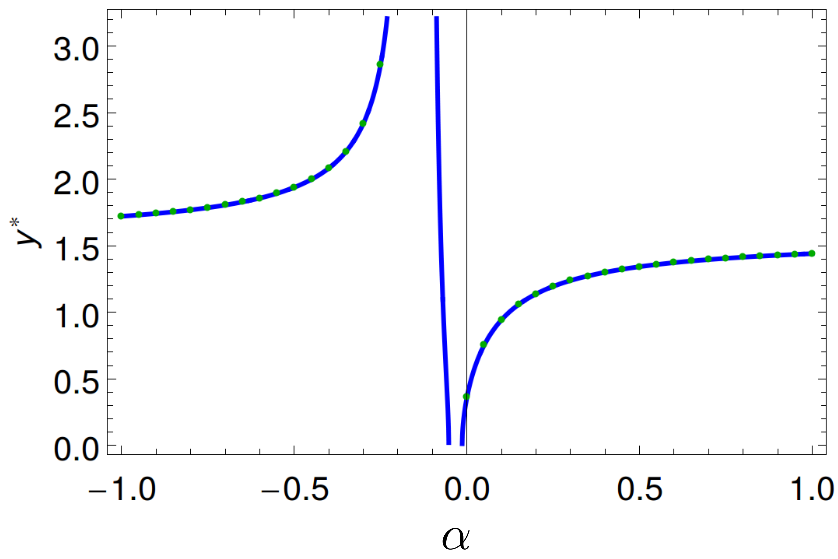
within truncations

predicts a top pole mass of $M_{t,\,pole} \approx 171$ GeV

3. UV-complete SM: gauge dependence



- gauge dependence reduces when taking into account **feedback** effects
- gauge-dependence **away from poles** in the gauge-condition remains mild

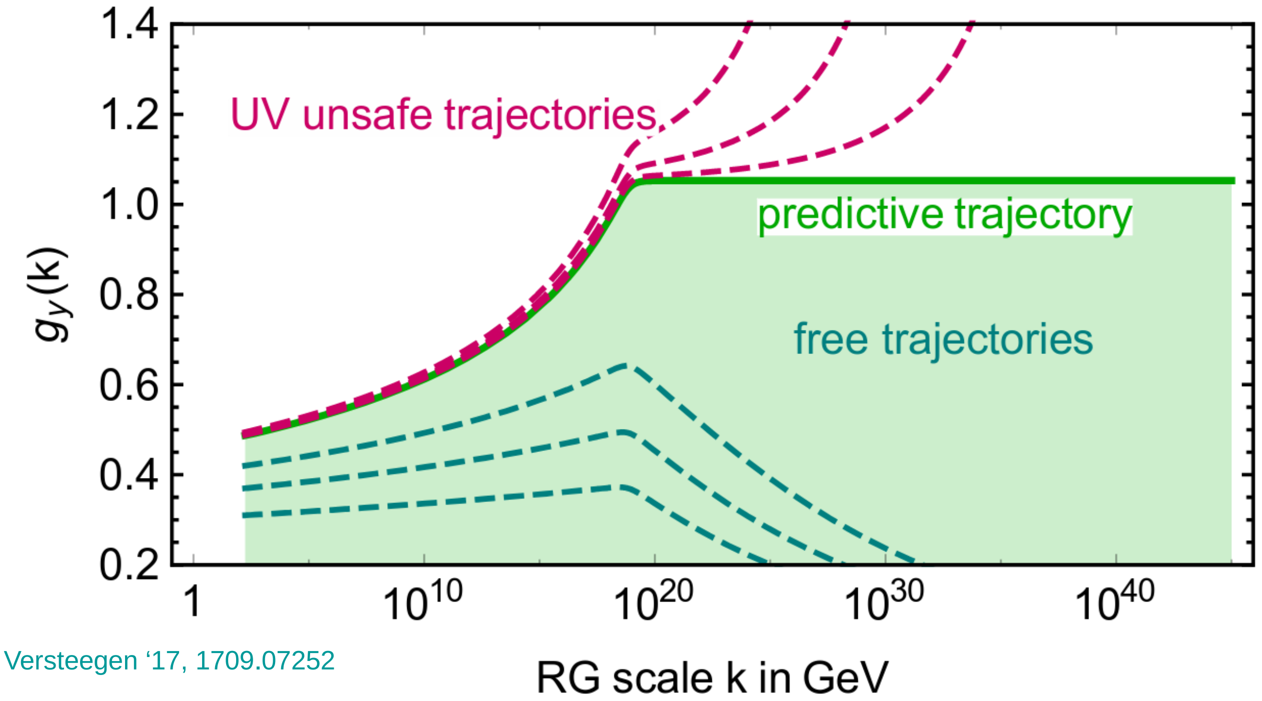


3. outlook: asymptotic safety of the U(1)

Eichhorn, Versteegen '17, 1709.07252

- the same mechanism works in the U(1) hypercharge sector

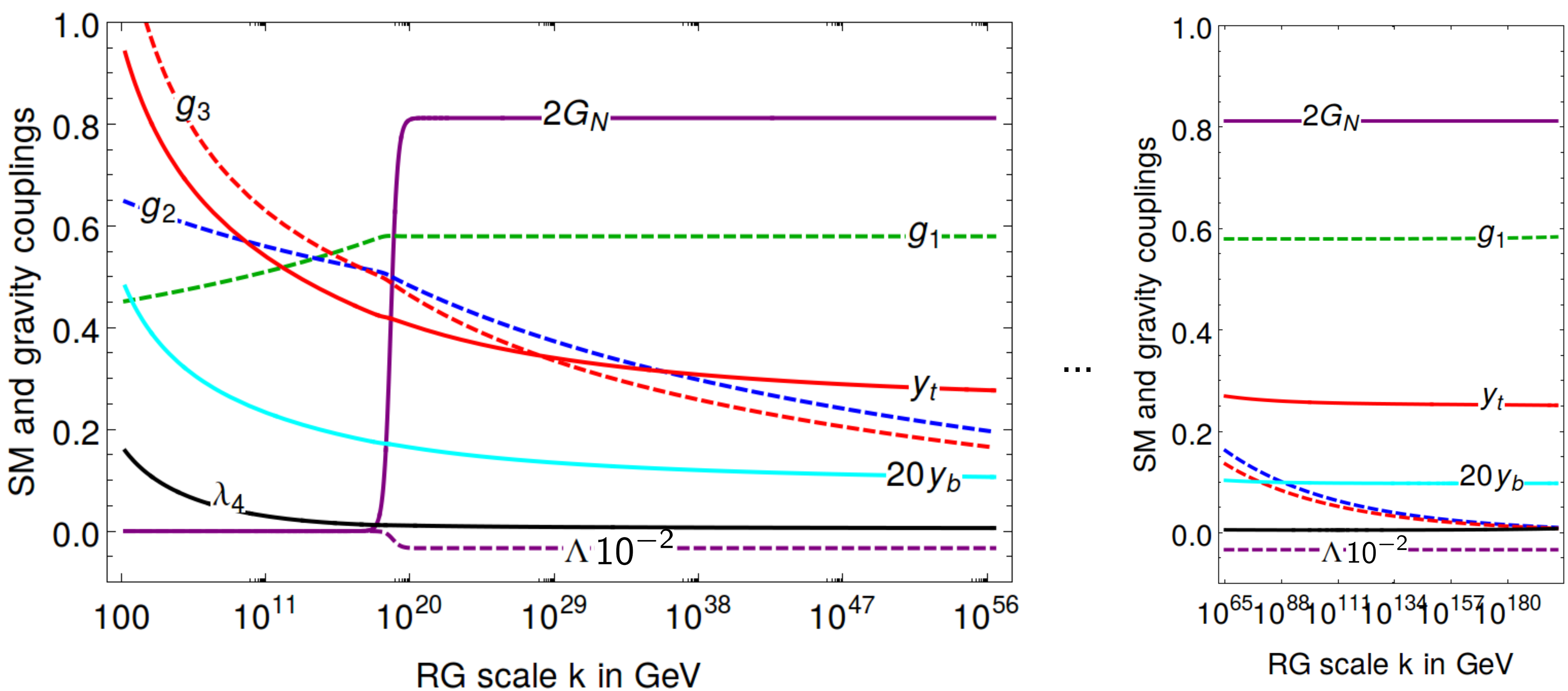
$$\beta_{g_1} = \frac{g_1^3}{16\pi^2}\,\frac{41}{10} - G_N\, g_1\, f_g(\Lambda)$$



Eichhorn, Versteegen '17, 1709.07252

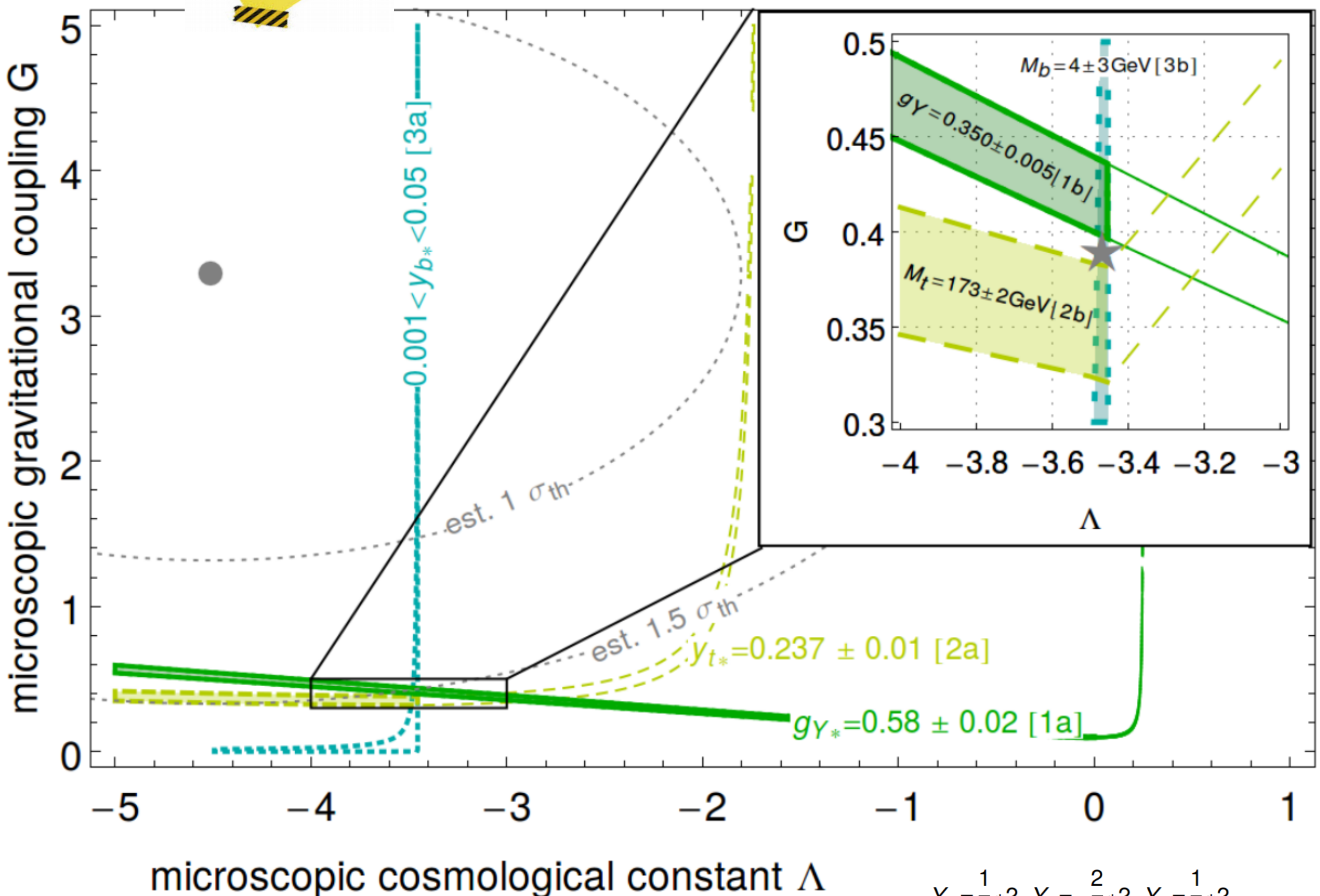
3. outlook: hypercharges

$$
\left.
\begin{aligned}
\beta_{y_t} &= \frac{y_t}{16\pi^2}\left(9y_t^2 + 3y_b^2 - \frac{17}{10}g_1^2\right) + G_N\, y_t\, f_y(\Lambda) + (\text{SM-terms})\\
\beta_{y_b} &= \frac{y_b}{16\pi^2}\left(9y_b^2 + 3y_t^2 - \frac{1}{2}g_1^2\right) + G_N\, y_t\, f_y(\Lambda) + (\text{SM-terms})\\
\beta_{g_1} &= \frac{g_1^3}{16\pi^2}\,\frac{41}{10} - G_N\, g_1\, f_g(\Lambda)
\end{aligned}
\right\} \Rightarrow \boxed{\left(g_1^*,\, y_t^*,\, y_b^*\right)(G_N, \Lambda)}
$$



Eichhorn, Held, in prep.

3. outlook: hypercharges



Theory:

[1a] Eichhorn, Held, 1707.01107 (2017)

[2a] Eichhorn, Versteegen, 1709.07252 (2017)

[3a] Eichhorn, Held, in prep. (2017)

Experiment:

[1b] $g_{Y,exp}$=0.3497 Buttazzo et. Al. (2013)

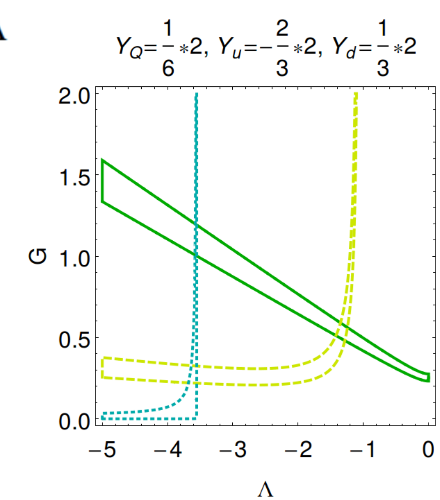
[2b] $M_{t,exp}$=172.35 ± 0.64 CMS, Phys.Rev. D93 (2016)

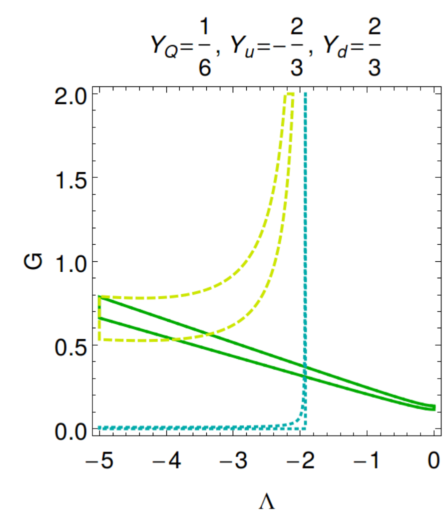
[3b] $M_{b,exp}$=4.18 ± 0.03 PDG, Phys.Rev. D86 (2012)

$$\Rightarrow \boxed{\left(g_1^*,\, y_t^*,\, y_b^*\right)(G_N, \Lambda)}$$

only works for hypercharge ratios of the SM

$$Y_Q = \frac{1}{6},\ Y_u = -\frac{2}{3},\ Y_d = \frac{1}{3}$$





Conclusions

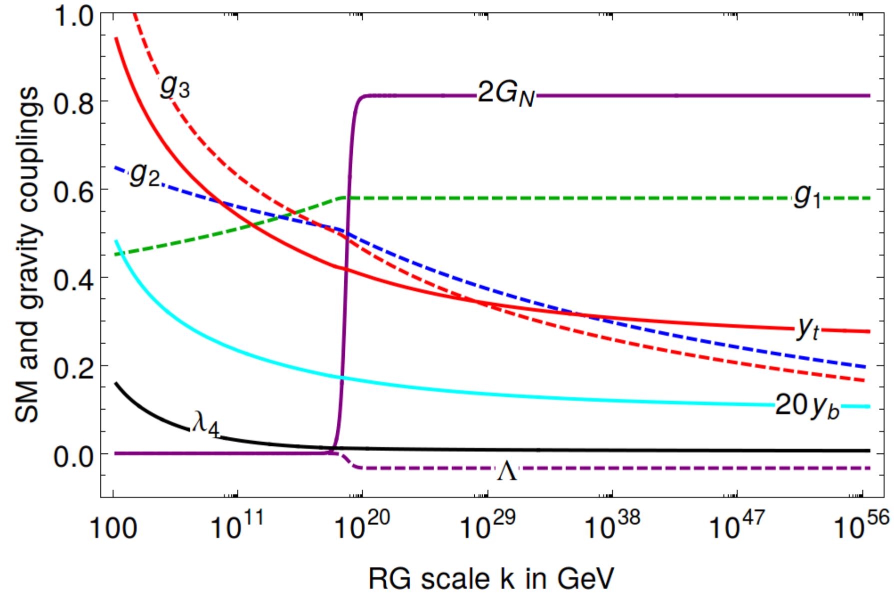
- asymptotically safe quantum gravity could **UV-complete the Standard Model** via dimensional reduction

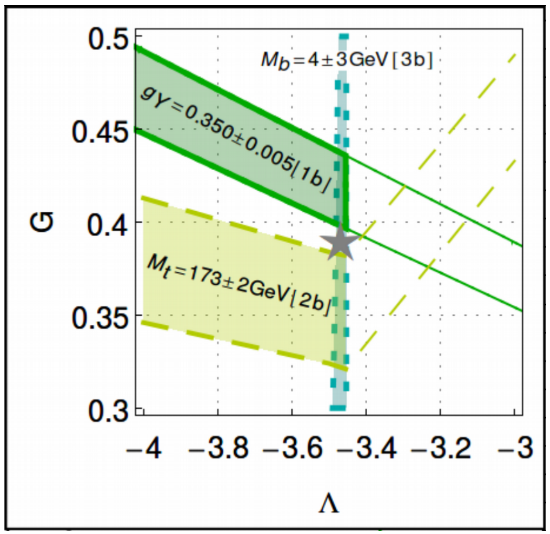
- consistent with a **weak-gravity bound**

- **higher predictive power** than the Standard Model (**fewer** ~~19~~ free parameters) $\mathbf{g_1, M_t, M_b}$

- **convergence** of FP values for microscopic gravity couplings **needs to be studied in the future**

Eichhorn, Held, in prep





Eichhorn, Held, in prep.

Thank you for your attention.