Asymptotically safe gravity as a guiding light to particle phenomenology

Abhishek Chikkaballi

Based on

JHEP 01(2023) 164 (arXiv:2209.0791), JHEP 11(2023) 224 (arXiv:2308.06114) and arXiv:2407.12086

with K. Kowalska, E. Sessolo, A. Eichhorn

National Center for Nuclear Research (NCBJ)
Warsaw, Poland

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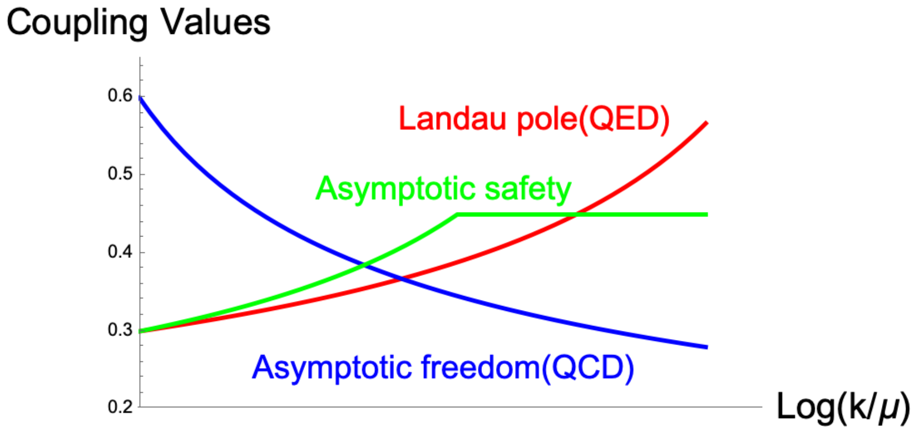
Graduate Physics Seminar

Outline

1. Asymptotic safety framework
2. Predictions and robustness in $U(1)'$ extensions
3. Dynamical mechanism of small y_ν from asymptotic safety
4. SMEFT coefficients from Asymptotically Safe Gravity

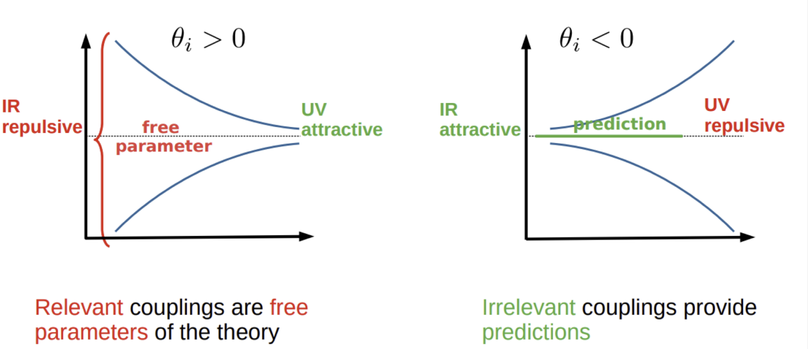
Asymptotic behaviour of the couplings



- UV complete theory: all the couplings approach a fixed point
  $\Longrightarrow$ The theory can be extrapolated to arbitrarily large energy scales

Predictions and free parameters

- Fixed point: where all the couplings stay constant with the changing scale
  - $\beta_i(\{g_i\}) = 0$
- Linearized flow equation near the fixed point
  - Stability matrix: $M_{ij} \equiv \frac{\partial \beta_i}{\partial g_j}\Big|_{\{g_i^*\}} \longrightarrow \{\theta_i\}$ Critical exponents



Asymptotically safe gravity

Einstein-Hilbert action: $\Gamma_k = \frac{1}{16\,\pi\,G_N} \int d^4x \,\sqrt{g}(\Lambda - R)$

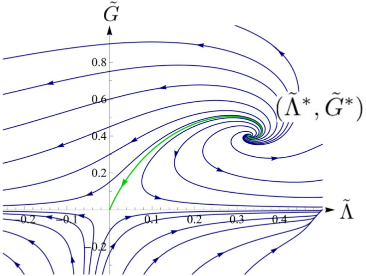
- $dim(G_N) = -2 \longrightarrow$ Perturbatively non-renormalizable:
- Infinitely many counter terms $\longrightarrow$ no predictivity

Asymptotically safe gravity:

- feature interactive UV fixed point
  Reuter '96, Reuter, Saueressig '01, Litim '04, Codello, Percacci, Rahmede '06, Benedetti, Machado, Saueressig '09, Narain, Percacci '09, Manrique, Rechenberger, Saueressig '11, Falls, Litim, Nikolakopoulos '13, Dona', Eichhorn, Percacci '13, Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Zanusso et al. '09
- finite number of relevant directions

  $\longrightarrow$ retains predictivity

Reuter, Saueressig, hep-th/0110054



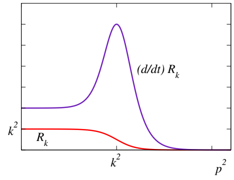
Functional renormalization group

R_k : regulator
Γ_k : scale-dependent effective action

H. Gies, hep-ph/0611146

Wetterich equation: $k\,\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left(\frac{k\,\partial_k R_k}{\Gamma^{(2)}+R_k}\right)$

- Wilsonian integrating out the fluctuations within a momentum shell near $p^2 = k^2$
  $\Longrightarrow$ Free of UV and IR divergencies



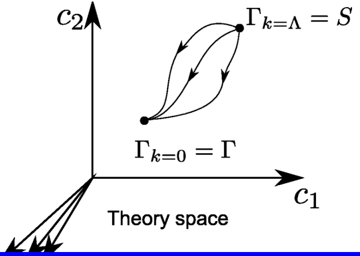
- interpolates between bare action and quantum effective action

- Vertex expansion of effective action:

$$\Gamma_k[\Phi] = \sum_{n\in\mathbb{N}} c^n\,\mathcal{O}^n[\Phi]$$

$$\Longrightarrow \text{k}\ \partial_k \Gamma_k = \sum_{n\in\mathbb{N}} \beta_{c^n}\,\mathcal{O}(\Phi)$$

  - Beta functions are obtained through suitable projection



Gravity affects matter

- Leading order gravity correction to beta functions of gauge ($\{g\}$) and Yukawa couplings ($\{y\}$).

$$\beta_g = \beta_g^{SM+NP} - f_g(\tilde{G}^*, \tilde{\Lambda}^*)\, g$$

universal corrections

$$\beta_y = \beta_y^{SM+NP} - f_y(\tilde{G}^*, \tilde{\Lambda}^*)\, y$$

Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17

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universal corrections

An example of this computation:

A. Eichhorn et. al. 1707.01107, 1604.02041

$$f_g(\tilde{G}_N^*, \tilde{\Lambda}^*) \approx \frac{\tilde{G}_N^*(1-4\tilde{\Lambda}^*)}{4\pi(1-2\tilde{\Lambda}^*)^2}$$

$$f_y(\tilde{G}_N^*, \tilde{\Lambda}^*) \approx \frac{\tilde{G}_N^*\left(-56\tilde{\Lambda}^{*3}-103\tilde{\Lambda}^{*2}+235\tilde{\Lambda}^*-96\right)}{12\pi\left(8\tilde{\Lambda}^*-10\tilde{\Lambda}^*+3\right)^2}$$

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universal corrections

large theoretical uncertainties

Potential consequences

- Reduce Standard Model free parameters.
  (e.g., Eichhorn, Held 1707.01107, Shaposhnikov, Wetterich 0912.0208)
- Predict New Physics couplings.
  (e.g., Kowalska et al., 2209.07971, 2012.15200, 2007.03567)
- Address problem of naturalness.
  (e.g., Resurgence mechanism by Wetterich, Yamada 1612.03069)

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Predictions and robustness in $U(1)'$ extensions

Prediction of New Physics couplings

- $U(1)'$ extensions:

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu} + i\bar{f}\left(\partial^\mu - ig_Y Q_Y \tilde{B}^\mu - ig_{\prime} Q_X \tilde{X}^\mu\right)\gamma_\mu f$$

- Typical experimental constraints $\approx \frac{g_X}{M_{NP}}\mathcal{O}$.

  f_g determines g_X and g_ϵ

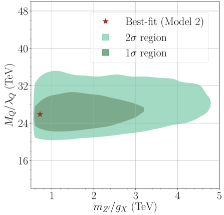
$$g_X = \frac{g_{\prime}}{\sqrt{1-\epsilon^2}}$$

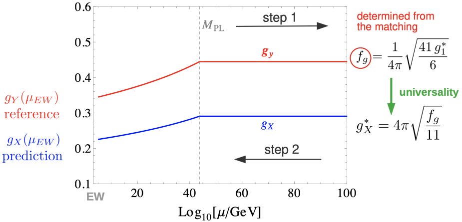
$$g_\epsilon = -\frac{\epsilon\, g_Y}{\sqrt{1-\epsilon^2}}$$

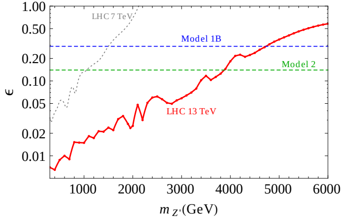
$g_X^* \neq 0$ and $g_\epsilon^* \neq 0$

$\Longrightarrow$ Predict M_{NP}.

AC, W. Kotlarski, K.Kowalska, D. Rizzo, E.M. Sessolo 2209.07971







SM + U(1)$_X$

$$\begin{cases} \dfrac{dg_Y}{dt} = \dfrac{41}{6}\dfrac{g_Y^3}{16\pi^2} - f_g g_Y \\[2mm] \dfrac{dg_X}{dt} = 11\dfrac{g_X^3}{16\pi^2} - f_g g_X \end{cases}$$

Prediction of New Physics couplings

- $U(1)'$ extensions:

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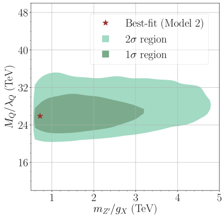
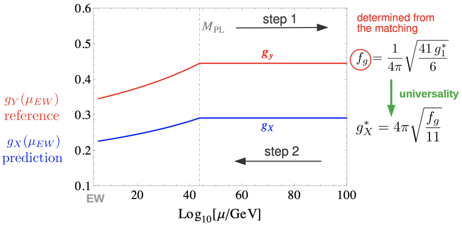
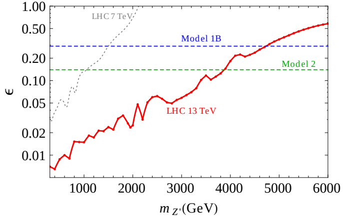






How robust?

(Kotlarski, Kowalska, Rizzo, Sessolo 2304.08959)

- perturbative regime $\longrightarrow$ stable under higher loop corrections
- stable relative to arbitrary Planck scale

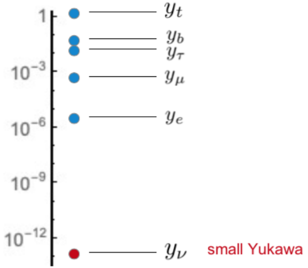
Dynamical mechanism of small y_ν from asymptotic safety

Dirac neutrino:

$$\mathcal{L}_D = -y_\nu^{ij}\,\nu_{R,i}\,(H^c)^\dagger\,L_j + \text{ h.c}$$

$$\implies m_\nu = \frac{y_\nu v_H}{\sqrt{2}}$$

tiny y_ν



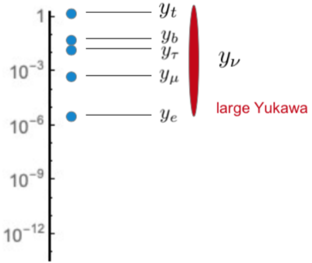
Majorana neutrino:

$$\mathcal{L}_M = \mathcal{L}_D - M_N^{ij}\nu_{R,i}\nu_{R,j} + \text{ h.c}$$

$$\begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \xrightarrow{\text{diagonalize}} m_1\, m_2 \approx m_D^2$$

$$\implies m_\nu = \frac{(y_\nu v_H)^2}{M_N}$$

seesaw mechanism $(y_\nu \approx \mathcal{O}(1)\ )$



Standard Model + Right Handed Neautrinos (SMRHN):

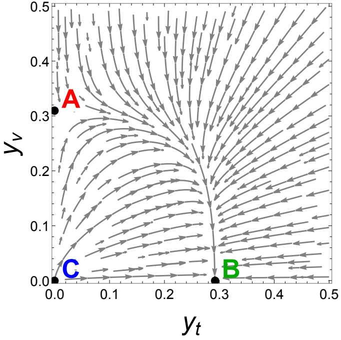
$$\beta_{g_Y} = \frac{1}{16\,\pi^2}\frac{41}{6}g_y^3 - f_g\, g_Y$$

$$\beta_{y_t} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - \frac{17}{12}g_y^2 + y_v^2\right) - f_y\, y_t$$

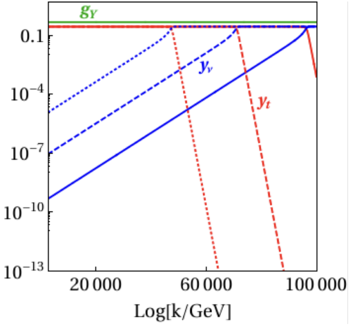
$$\beta_{y_\nu} = \frac{y_\nu}{16\pi^2}\left(3y_t^2 + \frac{5}{2}y_\nu^2 - \frac{3}{4}g_Y^2\right) - f_y\, y_\nu$$

$$y_\nu(t,\kappa) \approx \sqrt{\frac{16\pi^2(f_{\rm crit} - f_y)}{e^{(f_{\rm crit}-f_y)(16\pi^2\kappa - t)} + 5/2}}$$

arrow points the flow towards IR



K.Kowalska, S.Pramanick, E.M. Sessolo, 2204.00866



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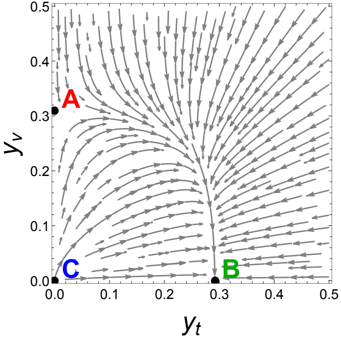

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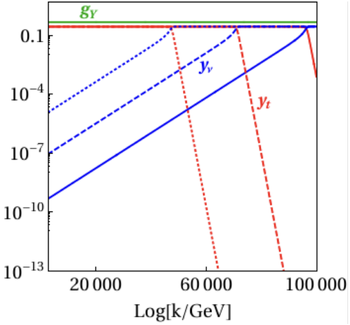
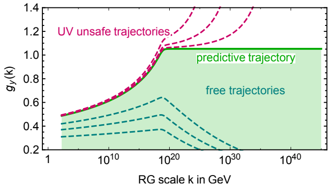


Arbitrarily small Dirac mass without fine-tuning

Connections to gravity: SMRHN

Eichhorn et.al. 1709.07252



- IR attractive fixed-point at $y_\nu^* = 0$ is a crucial condition for this mechanism i.e. $\theta_{y_\nu} \approx \frac{-2}{3} g_Y^{*2} + \frac{3}{2} y_t^{*2} < 0 \implies g_Y^* \neq 0$

$$f_g(\tilde{G}_N^*, \tilde{\Lambda}^*) \approx 0.0097$$

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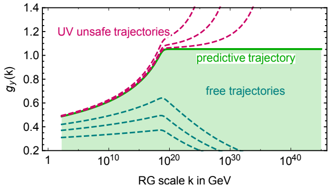

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  $\implies$ narrow range for $(\tilde{G}_N^*, \tilde{\Lambda}^*)$

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$\Longrightarrow$ narrow range for $(\tilde{G}^*_N, \tilde{\Lambda}^*)$

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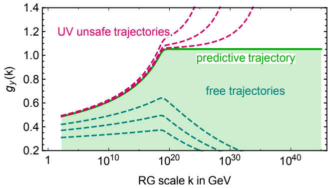
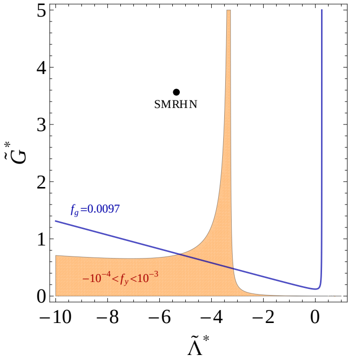


AC, K. Kowalska, E.M. Sessolo 2308.06114

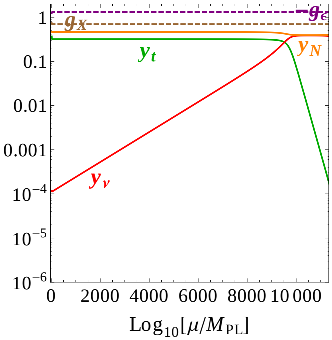


- Gauged $U(1)_{B-L}$ model:

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu} + i\bar{f}\left(\partial^\mu - ig_Y Q_Y \tilde{B}^\mu - ig_{B-L}Q_{B-L}\tilde{X}^\mu\right)\gamma_\mu f$$

- IR-attractive fixed-point at $y_\nu^* = 0$ is possible even if $g_Y^* = 0$ i.e. $f_g \neq 0.0097$

  How? $\theta_{y_\nu} \approx -a g_Y^{*2} - b g_X^{*2} - c g_\epsilon^{*2} + \frac{3}{2} y_t^{*2} < 0$



$$g_X = \frac{g_{B-L}}{\sqrt{1-\epsilon^2}}$$

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$\Longrightarrow g_X^* \neq 0$ and $g_\epsilon^* \neq 0$

f_g determines g_X and g_ϵ

Connections to gravity: U$(1)_{B-L}$ model

- Gauged $U(1)_{B-L}$ model:

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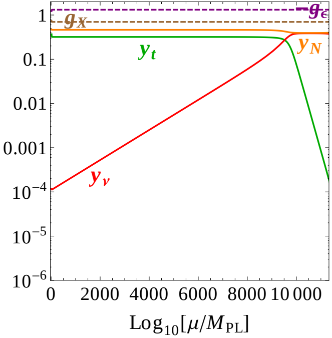
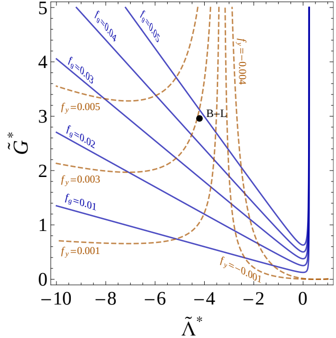


AC, K. Kowalska, E.M. Sessolo 2308.06114



Predictions in the $B - L$ model

- Benchmark points for different f_g and f_y such that
  - IR-attractive fixed-point at $y_\nu^* = 0$
  - Predictions for the New Physics couplings (g_X, g_ϵ, y_N)

$$\mathcal{L}_M = -y_N^{ij} S\, \nu_{R,i}\, \nu_{R,j} + \text{H.c.}$$

	f_g	f_y	g_X^*	g_ϵ^*	y_N^*	$g_X\,(10^{5,7,9}\text{GeV})$	$g_\epsilon\,(10^{5,7,9}\text{GeV})$	$y_N\,(10^{5,7,9}\text{GeV})$
BP1	0.01	0.0005	0.10	-0.55	0.12	0.29, 0.29, 0.30	-0.26, -0.27, -0.28	0.16, 0.16, 0.16
BP2	0.05	-0.005	0.70	-1.32	0.47	0.40, 0.41, 0.44	-0.52, -0.56, -0.61	0.42, 0.44, 0.45
BP3	0.02	-0.0015	0.10	-0.75	0.0	0.12, 0.12, 0.12	-0.33, -0.35, -0.37	0.0
BP4	0.03	-0.004	0.10	0.75	0.0	0.09, 0.09, 0.09	0.23, 0.25, 0.28	0.0

- RGE flow ensures $y_N = 0$; not some global symmetry

Dirac $(y_N = 0)$: BP3, BP4

Majorana $(y_N \neq 0)$: BP1, BP2

- Experimental constrains on kinetic mixing and direct coupling of Z'

$$v_S > 10 \text{ TeV} >> v_H$$

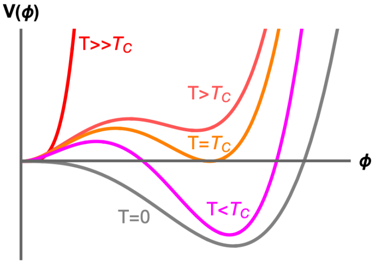
$$\epsilon = \frac{g_\epsilon}{\sqrt{g_Y^2 + g_\epsilon^2}} \approx 0.5 - 0.8$$

SSB through Coleman-Weinberg mechanism

- Since $v_H << v_S$, H and S effectively decouple from each other
- S_{min} through Coleman-Weinberg mechanism

$$V_{tot}(\phi) = V_{CW}(\phi) + V_{thermal}(\phi)\ , \qquad \phi \equiv Re(S)$$

- The Yukawa coupling effect is also included



$$V_{CW}(\phi) = \frac{1}{2} m_S^2(t)\phi^2 + \frac{1}{4}\lambda_2(t)\,\phi^4$$
$$+ \frac{1}{128\,\pi^2}\left[20\lambda_2^2(t) + 96\,g_X^4(t) - 48\,y_N^4(t)\right]\phi^4\left(-\frac{25}{6} + \ln\frac{\phi^2}{\mu^2}\right)$$

$$V_{\rm thermal}(\phi, T) = \frac{T^4}{2\pi^2}\sum n_i J_i\left(\frac{m_i^2(\phi)}{T^2}\right)$$

$$m_{Z'}^2(\phi) = 4\,g_X^2\,\phi^2$$
$$\mathrm{m}_{\nu_R}^2(\phi) = 2\,y_N^2\,\phi^2$$
$$\mathrm{m}_{\phi}^2(\phi) = 3\,\lambda_2\,\phi^2 + m_S^2$$
$$\mathrm{m}_{G}^2(\phi) = \lambda_2\,\phi^2 + m_S^2$$

Gravitational waves from FOPT

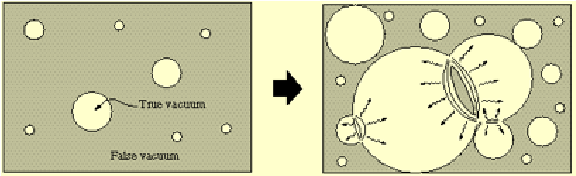
$$V_{eff} \longrightarrow \text{Bubble nucleation}(\Gamma(T)) \longrightarrow \text{Thermal parameters}(\alpha,\, T_{rh},\, \beta) \longrightarrow h^2\Omega(f)$$

Bubble nucleation rate

$\Updownarrow$

depth of potential, barrier between vacua

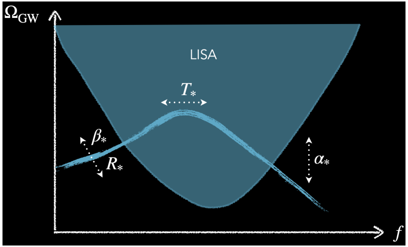
CTC Cambridge Website



The strength of the signal $(h^2\Omega(f))$

$\Updownarrow$

the latent heat, β, T_{rh}



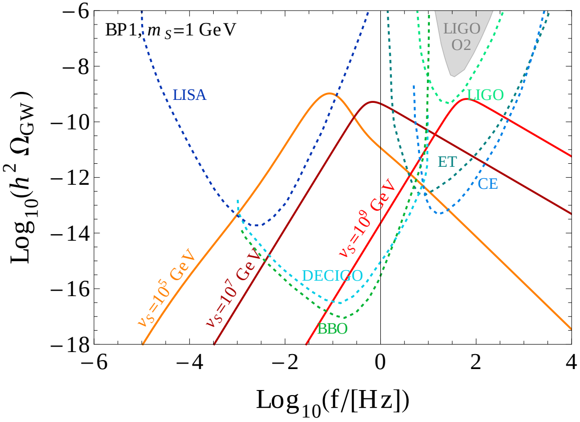
$$\Omega^{peak}(\alpha, \beta, T_{rh})\,,\ f^{peak}(\alpha, \beta, T_{rh})$$

$$\longrightarrow \mathrm{h}^2\Omega(f) = h^2\Omega^{peak} \times \mathcal{F}(f/f^{peak})$$

$m_S^2 \neq 0 \implies$ reduced supercooling, lower barrier

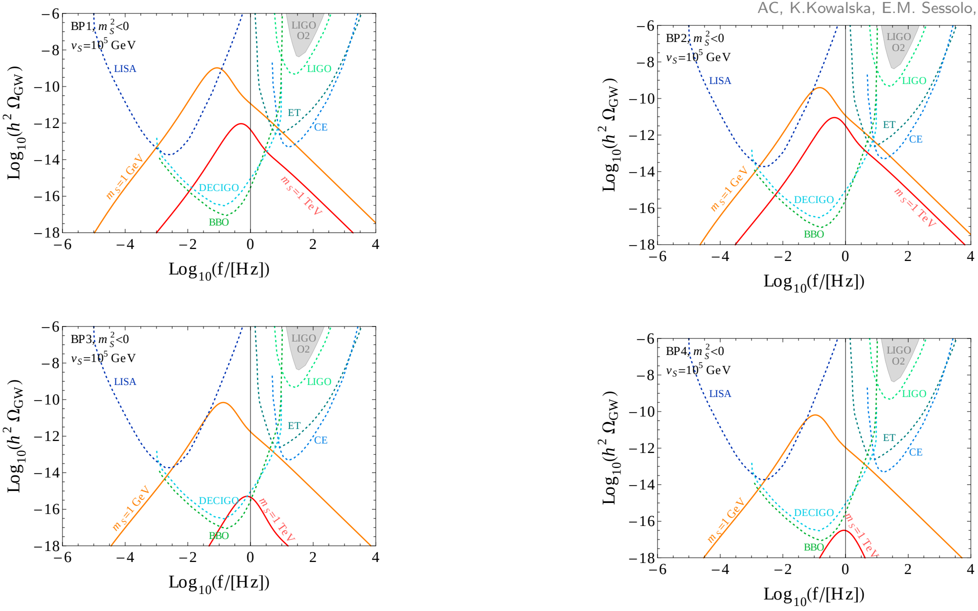
We do have observable GW signals!

AC, K.Kowalska, E.M. Sessolo, 2308.06114



GW signals with $m_S^2 \neq 0$

AC, K.Kowalska, E.M. Sessolo, 2308.06114



But discriminating features are washed out by the strong dependence on mS^2

SMEFT coefficients from Asymptotically Safe Gravity

Effective Field Theories

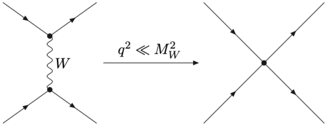
- Effective Field Theory (EFT): Things may appear simpler from a certain distance

A. Falkowski Eur. Phys. J. C (2023) 83:656

Examples:

- General Relativity $\longrightarrow$ Newtoniean gravity
- QCD $\longrightarrow$ nuclear physics
- Electroweak theory $\longrightarrow$ Fermi theory

Buchmüller, Lüdeling hep-ph/0609174



In effective field theories, high-energy physics manifests as contact interactions

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda_{\text{NP}}^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda_{\text{NP}}^4}\mathcal{O}_i^{(8)} + \dots$$

Standard Model Effective Field Theory (SMEFT)

- Preserves the SM gauge symmetry
- model-independent framework for characterizing experimental deviations

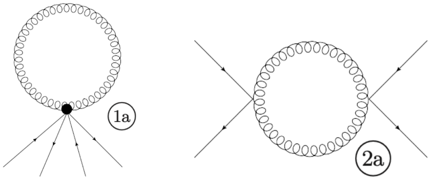
c_i	Operator $(\bar{L}L)(\bar{L}L)$	c_i	Operator $(\bar{R}R)(\bar{R}R)$	c_i	Operator $(\bar{L}L)(\bar{R}R)$
c_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	c_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	c_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$c_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	c_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$c_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	c_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	c_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$c_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	c_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	c_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$c_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	c_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$c_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$c_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$c_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$c_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$c_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$c_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$$S = \frac{1}{16\pi \bar{G}_{\rm N}} \int_x \sqrt{g}(2\bar{\Lambda} - R) \; + \int_x \sqrt{g}\bar{\psi}\gamma^{\mu}\nabla_{\mu}\psi \; + \int_x \sqrt{g}\left[\frac{\bar{\lambda}_+}{2}(\mathcal{V}+\mathcal{A}) + \frac{\bar{\lambda}_-}{2}(\mathcal{V}-\mathcal{A})\right]$$

Spacetime metric fluctuations:

$$g_{\mu\nu} = \delta_{\mu\nu} + \sqrt{\bar{G}_{\sf N}}h_{\mu\nu}$$

Graviton induced interactions:



Fierz-complete basis preserving $\mathsf{SU}(N_{\sf f})_{\sf L} \times \mathsf{SU}(N_{\sf f})_{\sf R}$

$$\mathcal{V} \pm \mathcal{A} = \left(\bar{\psi}\gamma_{\mu}\psi\right)^2 \mp \left(\bar{\psi}\gamma_{\mu}\gamma_5\psi\right)^2$$

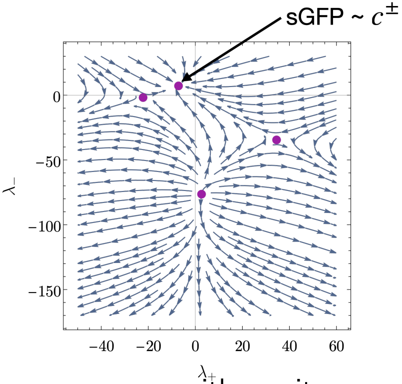
$$\frac{c_i}{M_{Pl}^2} = \bar{\lambda}_- \; , \quad i \in (\bar{L}L)(\bar{L}L), \, (\bar{R}R)(\bar{R}R)$$

$$\frac{c_i}{M_{Pl}^2} = 2\bar{\lambda}_+ \; , \quad i \in (\bar{L}L)(\bar{R}R)$$

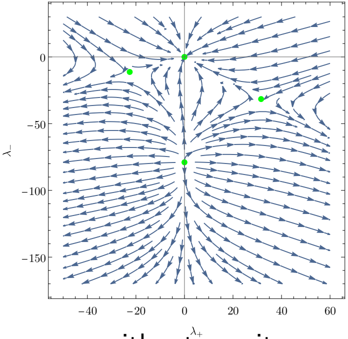
Case 1: Shifted Gaussian Fixed Point and M_{Pl} suppression

Generic form of the beta function: $\beta_{\lambda_\pm} = 2\lambda_\pm + a^\pm \lambda_+ \lambda_- + b^\pm \lambda_\pm h_{ext} + c^\pm h_{ext}^2$

AC, L. Brenner, A. Eichhorn, S. Ray 2407.12086



with gravity



without gravity

IR-attractive fixed point: $\lambda_\pm(k > M_{\text{Pl}}) = \lambda_{\pm,*}|_{\text{sGFP}}$

$$\Longrightarrow |\lambda_\pm(k = M_{\text{LHC}})| \sim \left(\frac{M_{\text{LHC}}}{M_{\text{Pl}}}\right)^2$$

Gravity decouples below M_{Pl}

$$\beta_{\lambda_\pm} \sim 2\lambda_\pm$$

Case 2A: Classical scaling violation

UV attractive fixed point $\longrightarrow$ free parameter at the Planck scale

$$|\lambda_{\pm}(k = M_{\mathsf{Pl}})| = \left(\frac{M_{\mathsf{Pl}}}{M_{\mathsf{LHC}}}\right)^{\delta}$$
$$\Longrightarrow \lambda_{\pm}(k = M_{\mathsf{LHC}}) \approx \lambda_{\pm}(k = M_{\mathsf{Pl}})\,(M_{\mathsf{LHC}}/M_{\mathsf{Pl}})^2 \sim \left(\frac{M_{\mathsf{LHC}}}{M_{\mathsf{Pl}}}\right)^{2-\delta}$$

Violation of naturalness expectation!

But

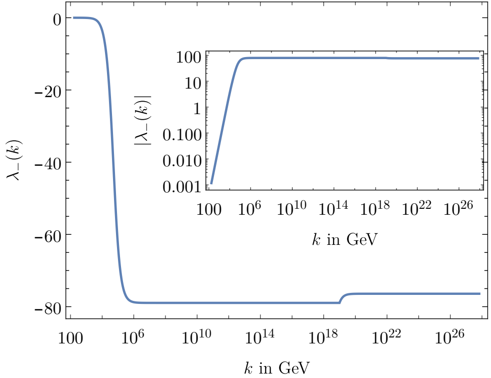
- Flows off to infinity in the IR
- Onset of chiral symmetry breaking close to the Planck scale

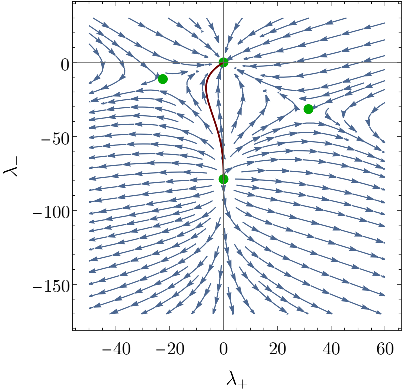
Case 2B: Suppression by $M_{non-pert} << M_{Pl}$

- Effective new scale below M_{Pl} scale

  free parameter at the Planck $|\lambda_{\pm}(k = M_{\text{Pl}})| = \left(\frac{M_{\text{Pl}}}{M'_{\text{NP}}}\right)^2$

  $\implies \lambda_{\pm}(k = M_{\text{LHC}}) \sim \left(\frac{M_{\text{LHC}}}{M'_{\text{NP}}}\right)^2$





effects of dimension-eight operators may not be negligible

Conclusions

- The RGE flow of "irrelevant" couplings from a UV fixed point gives IR predictions
  $\longrightarrow$ U(1) gauge couplings, kinetic mixing, Yukawa couplings
- Asymptotically safe gravity could induce IR-attractive Gaussian fixed point in y_ν
  $\Longrightarrow$ dynamical mechanism to generate arbitrarily small y_ν
- The dynamical mechanism is potentially more in line with QG in B-L model rather than SMRHN
- potentially observable gravitational wave signal from FOPT, but discriminating features of GW spectrum are washed out due to strong dependence on the relevant parameters
- In the most conservative scenario, ASG contribution is unmeasurably small
- Existence of a non-perturbative fixed point at sub-Planckian scales generates new effective scale below the Planck scale
  $\Longrightarrow$ measurable value at the experimental scales
- Dimension-8 operators might not be negligible

Thank you!