Naturally small neutrino mass with asymptotic safety and gravitational-wave signatures

Abhishek Chikkaballi

Based on work with

Kamila Kowalska, Enrico Maria Sessolo: 2308.1122

National Center for Nuclear Research (NCBJ)
Warsaw, Poland

12 October 2023

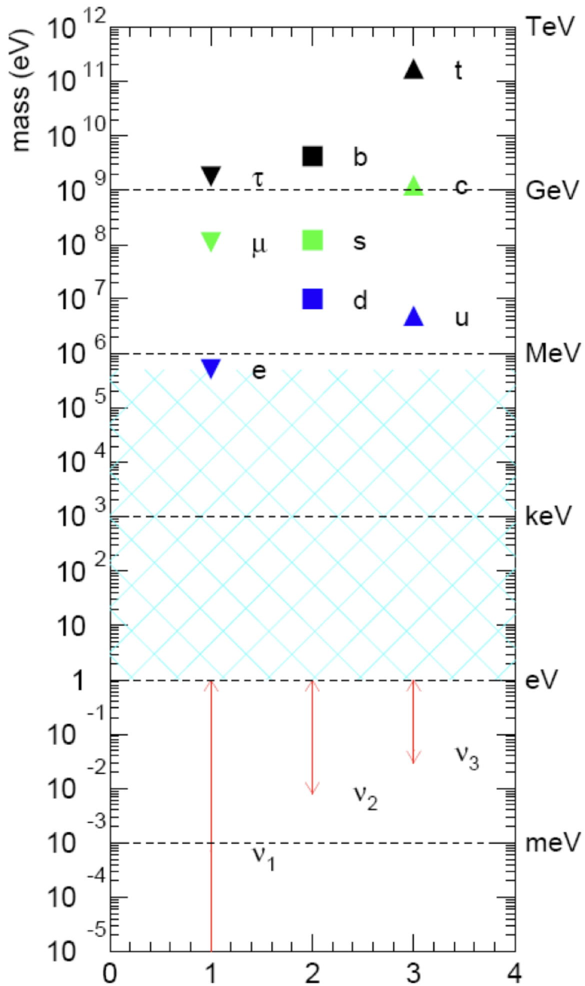
Graduate Physics Seminar

NARODOWE CENTRUM NAUKI

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Motivation

From M. Shaevitz lectures



$$m_\nu \neq 0$$

$$\frac{m_\nu}{m_t} \approx 10^{-12}$$

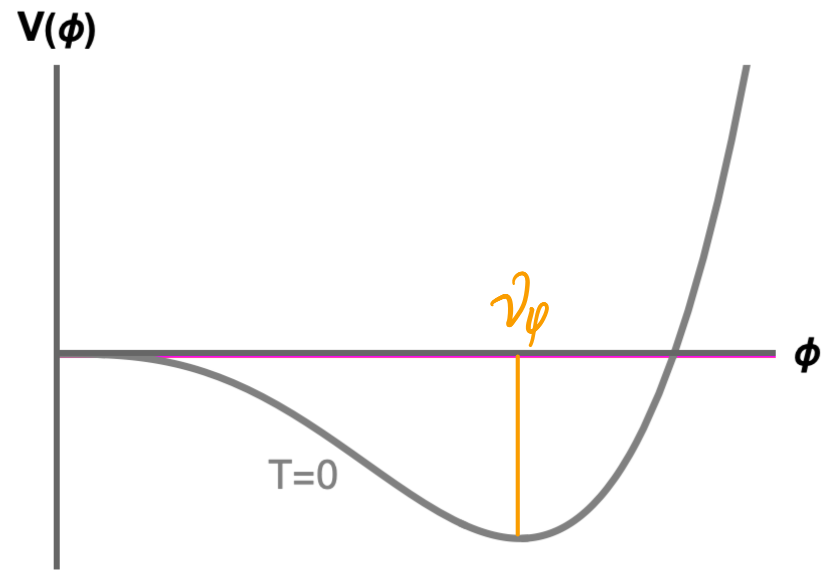
Dirac mass and Majorana mass

Dirac mass: $m_D \, \bar{f}_R f_L$

Majorana mass: $m_M \, \bar{f}_R f_R^C$

Dirac mass: $m_D\, \bar{f}_R f_L$

Majorana mass: $m_M\, \bar{f}_R f_R^C$



- In the Standard Model(SM), symmetries forbid either of these mass terms!

But,

$$y_f\, \bar{f}_R\, \phi\, f_L \xrightarrow[<\phi>=v_\phi]{SSB} y_f\, v_\phi\, \bar{f}_R\, f_L$$

$$\implies m_D = y_f v_\phi$$

- The Yukawa couplings in SM:

$$L_{SM} \supset Y_{ij}^U \bar{Q}_L^i\, H\, u_R^j + Y_{ij}^D \bar{Q}_R^i\, H^\dagger\, d_L^j + \sum Y_i^e \bar{L}_L^i\, H\, e_R^i$$

Dirac mass and Majorana mass

Dirac mass: $m_D\, \bar{f}_R f_L$

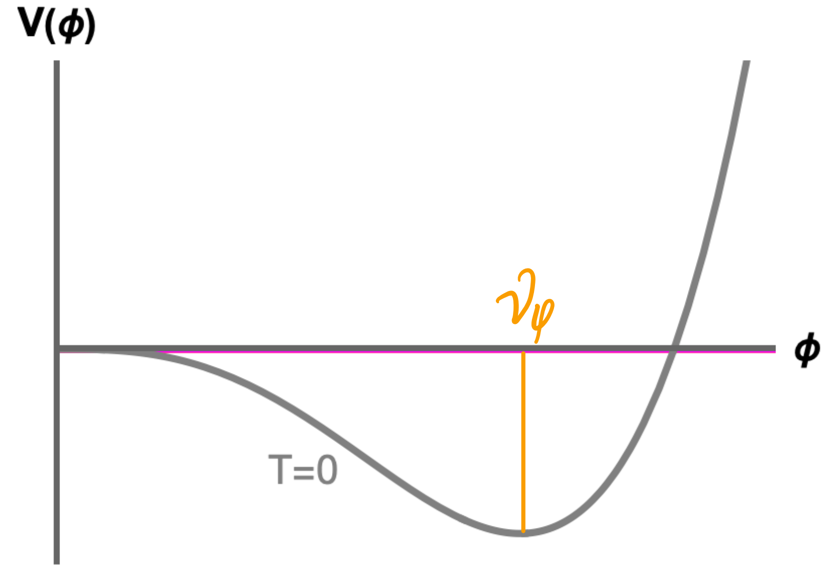
Majorana mass: $m_M\, \bar{f}_R f_R^C$

- In the Standard Model(SM), symmetries forbid either of these mass terms!

But,

$$y_f\, \bar{f}_R\, \phi\, f_L \xrightarrow[<\phi>=v_\phi]{SSB} y_f\, v_\phi\, \bar{f}_R\, f_L$$

$$\implies m_D = y_f v_\phi$$



- The Yukawa couplings in SM:

$$L_{SM} \supset Y^U_{ij}\bar{Q}^i_L\, H\, u^j_R + Y^D_{ij}\bar{Q}^i_R\, H^\dagger\, d^j_L + \sum Y^e_i \bar{L}^i_L\, H\, e^i_R + \sum Y^\nu_i\, \bar{L}^i_L\, H^\dagger\, \nu^i_R$$

y_t $\quad$ y_ν

Seesaw mechanism

- Right-handed neutrinos are invariant under the SM symmetries

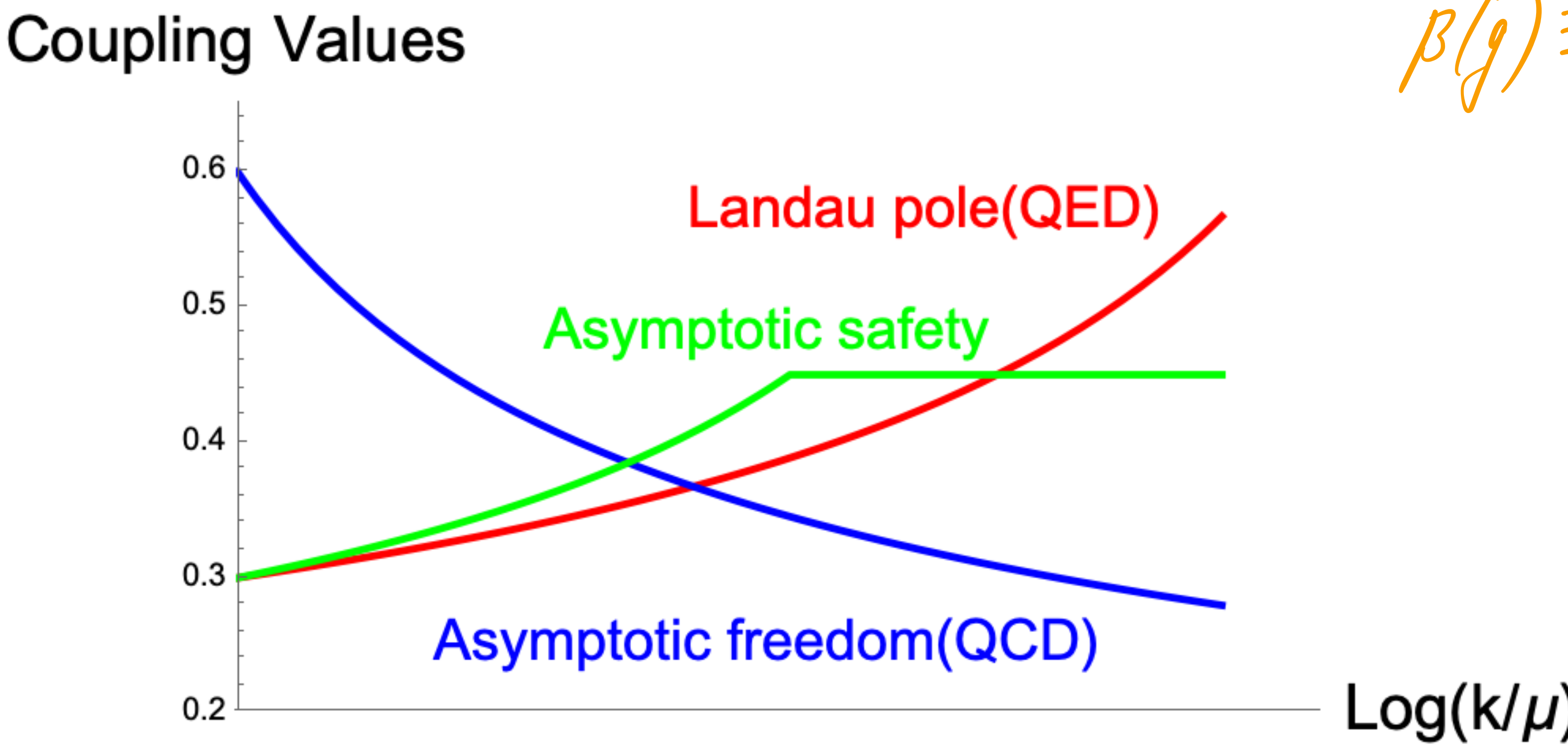
$$\Longrightarrow m_M \bar{\nu}_R \nu_R^C$$

$m_D \sim y_\nu v_\phi$

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

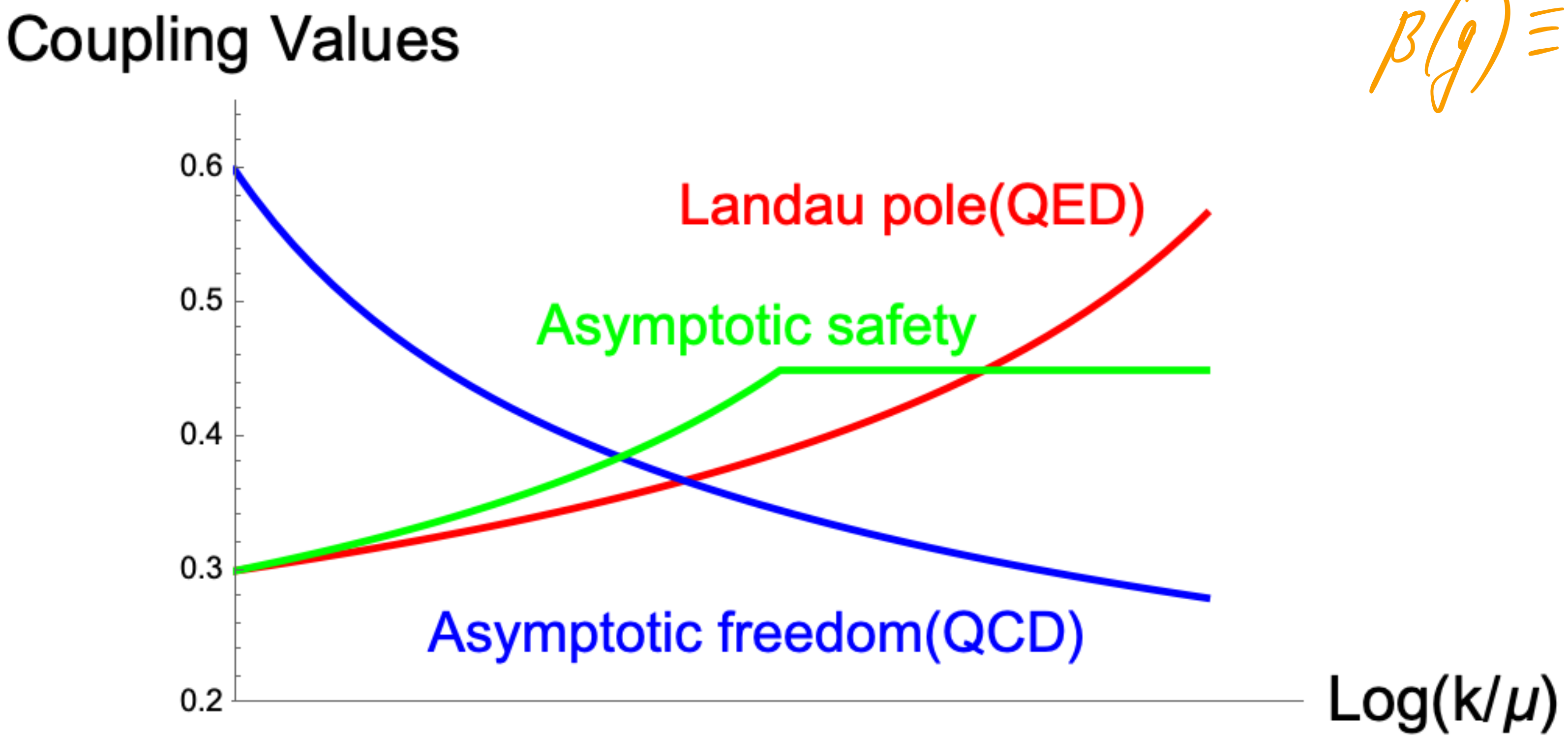
Asymptotic behaviour of the couplings

$$\beta(g) \equiv k\frac{\partial g}{\partial k}$$



Asymptotic behaviour of the couplings

$$\beta(g) \equiv k \frac{\partial g}{\partial k}$$



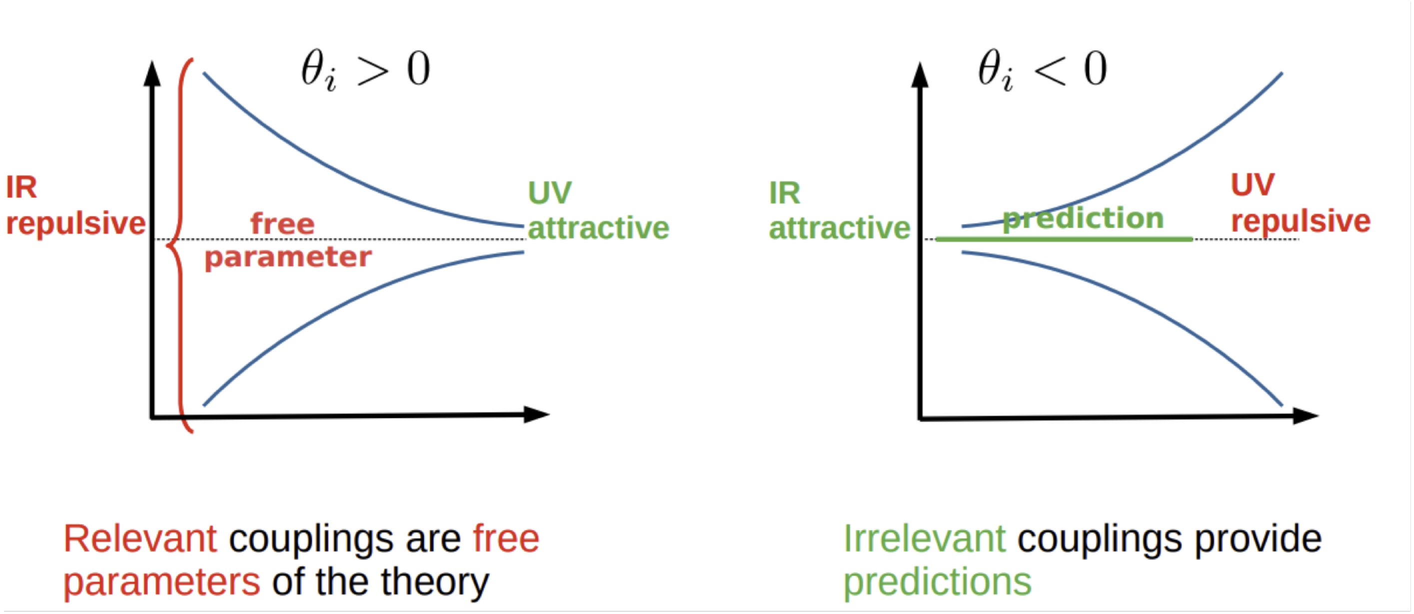
- UV complete theory: all the couplings approach a fixed point
  $\Longrightarrow$ The theory can be extrapolated to infinitely large energy scales

Predictions and free parameters

- Fixed point: where all the couplings stay constant with the changing scale
  - $\beta_i(\{g_i\}) = 0$

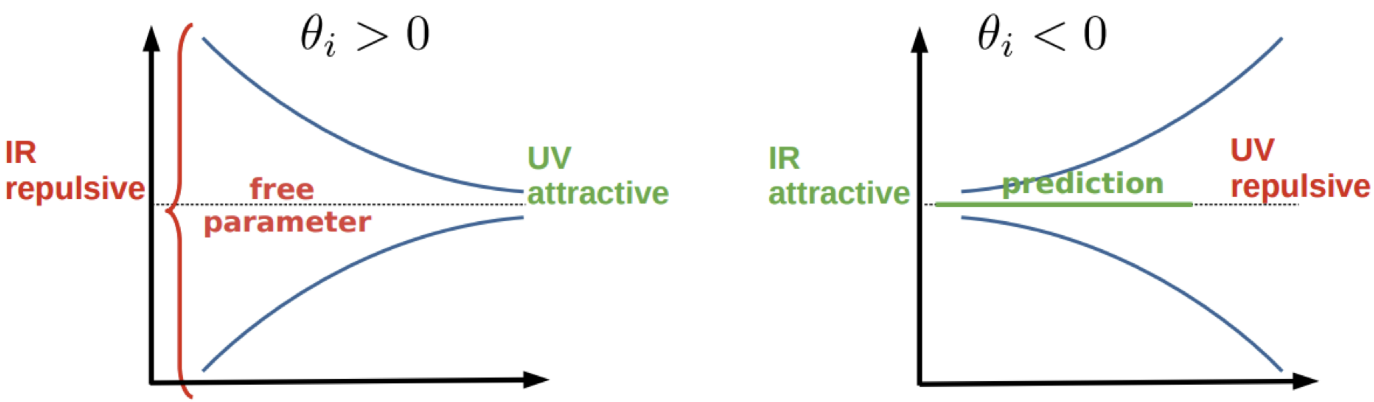
Predictions and free parameters

- 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: $M_{ij} \equiv \left.\frac{\partial \beta_i}{\partial g_j}\right|_{\{g_i^*\}} \longrightarrow \{\theta_i\}$ Critical exponents



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: $M_{ij} \equiv \left.\frac{\partial \beta_i}{\partial g_j}\right|_{\{g_i^*\}} \longrightarrow \{\theta_i\}$ Critical exponents



Relevant couplings are free parameters of the theory

Irrelevant couplings provide predictions

- Choosing free-parameters at the UV boundary fixes the flow of all the couplings

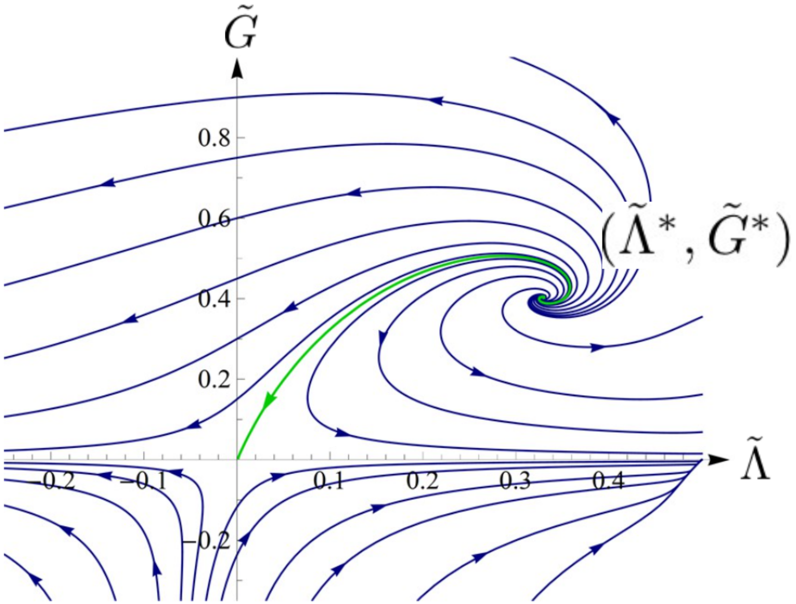
Asymptotically safe gravity

- Einstein-Hilbert action:

$$\Gamma_{EH} = \frac{1}{16\,\pi\,G}\int d^4x\,\sqrt{g}(\Lambda - R)$$

- Applying functional renormalization group methods:

$$\implies \frac{d\tilde{G}}{dt} = 0$$
$$\frac{d\tilde{\Lambda}}{dt} = 0$$



- Gravity could be asymptotically safe
  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 ... many more

Gravity corrections above the Planck scale

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

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

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

Gravity corrections above the Planck scale

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

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

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

- Universal: does not distinguish internal symmeteries
- UV divergencies can be cured
- Improved predictive power

The Majorana mass and the seesaw scale

- Relevant beta functions:

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

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

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

- Fixed-point analysis:

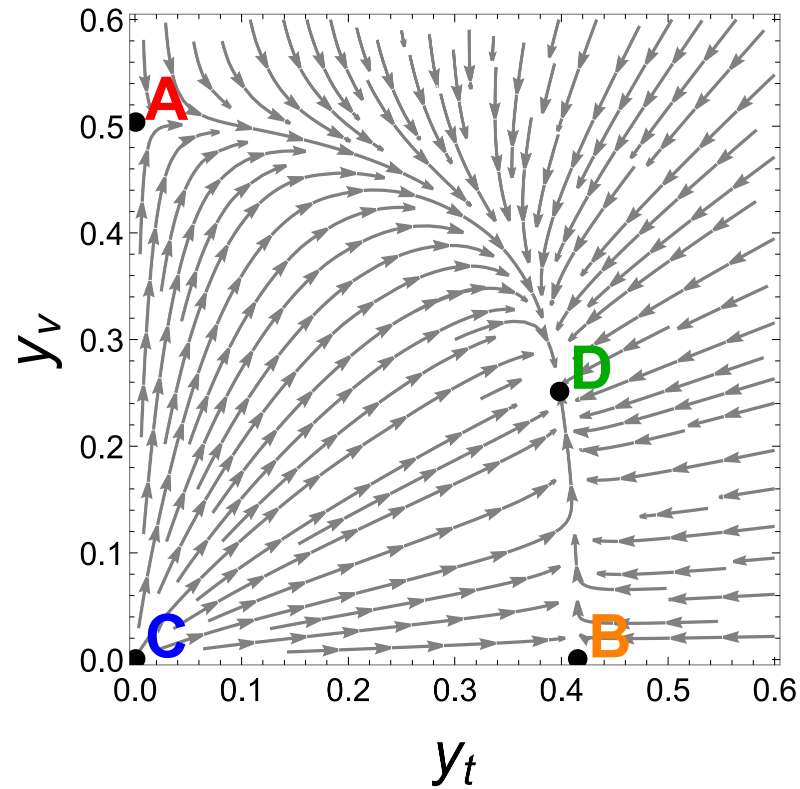
  If $f_y > f_{y,Crit}$

  $\implies$ IR-attractive fixed-point is at:

  $y_\nu^* \neq 0$, $y_t^* \neq 0$

  i.e $\theta_{y_\nu} < 0$ (at $y_\nu^* \neq 0$)

- Majorana mass: $M_\nu \approx \frac{(y_\nu\,v_h)^2}{m_\nu}$



Majorana neutrinos, still prediction of the seesaw scale

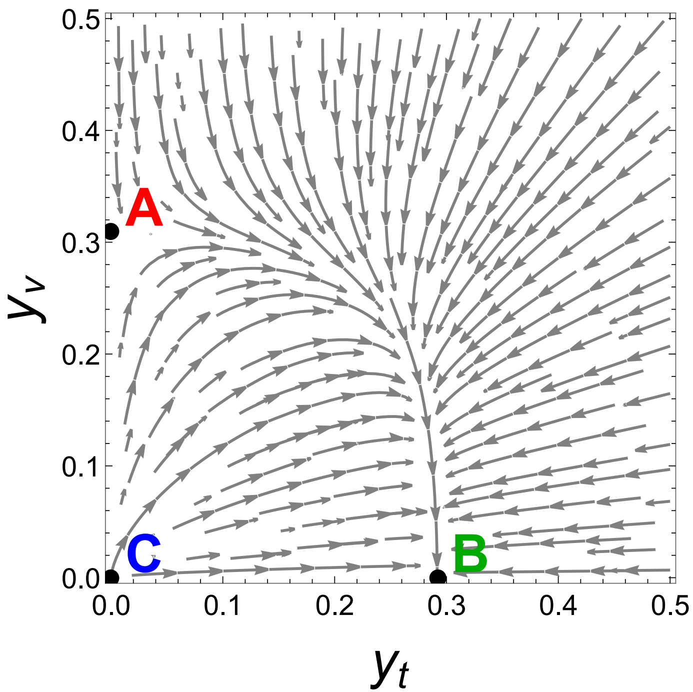
Dynamical mechanism of small neutrino mass

- Fixed point analysis:

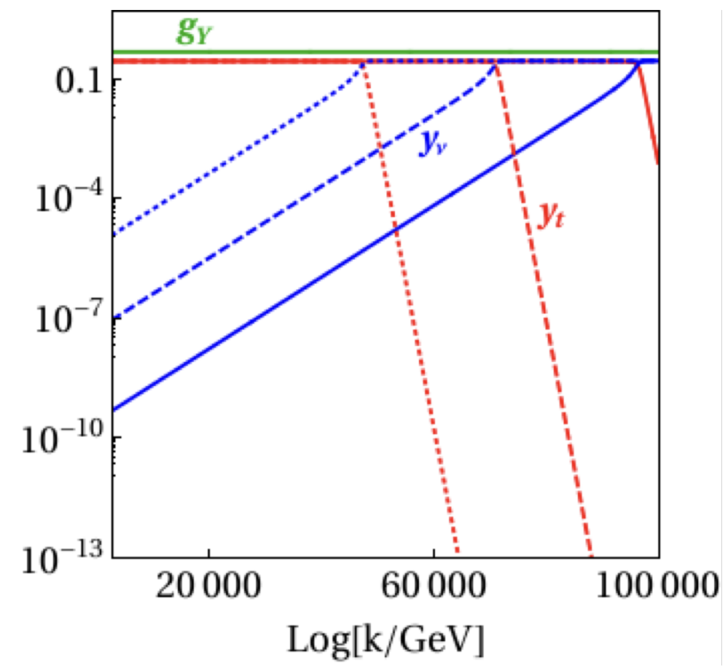
  If $f_y < f_{y,Crit} \approx 8 \times 10^{-4}$

  $\implies$ IR attractive fixed-point at $y_\nu^* = 0$ i.e. $\theta_{y_\nu} < 0$ at $y_\nu^* = 0$

arrow points the flow towards IR



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



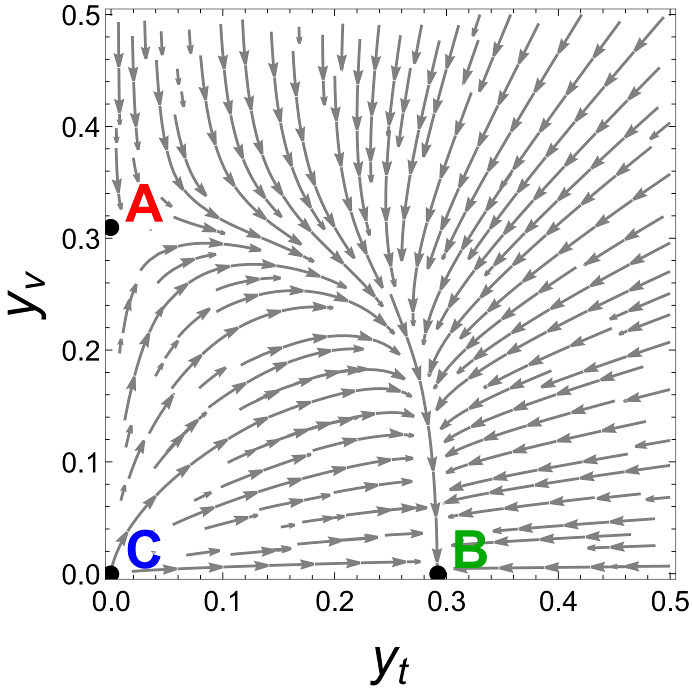
Dynamical mechanism of small neutrino mass

- Fixed point analysis:

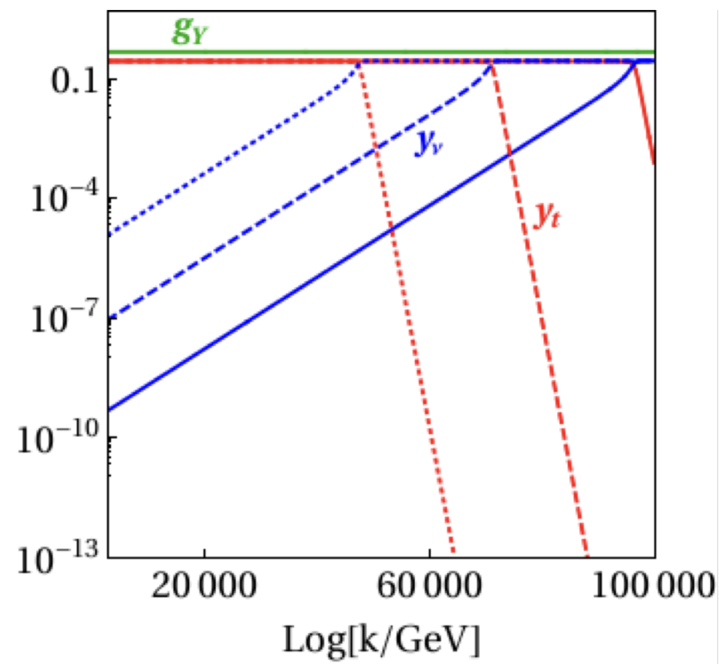
  If $f_y < f_{y,Crit} \approx 8 \times 10^{-4}$

  $\implies$ IR attractive fixed-point at $y_\nu^* = 0$ i.e. $\theta_{y_\nu} < 0$ at $y_\nu^* = 0$

arrow points the flow towards IR



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

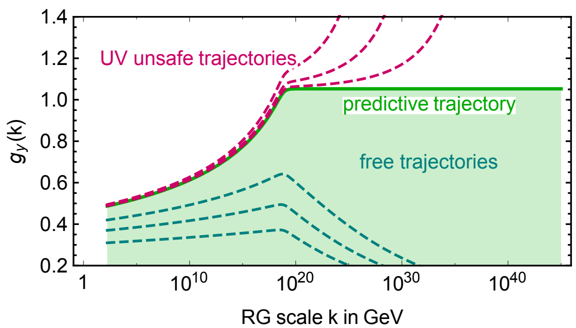


- Dirac mass: $m_\nu \sim y_\nu \nu$

Predicts small Dirac mass without fine-tuning

QG perspective on naturalness of this mechanism in SMRHN

Eichhorn et.al. 1709.07252



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

$$f_g \approx 0.0097$$

QG perspective on naturalness of this mechanism in SMRHN

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

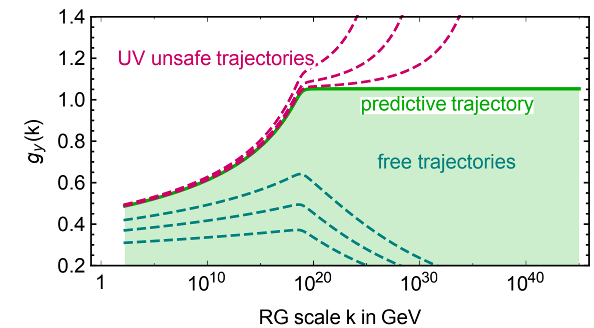
  $$f_g \approx 0.0097$$

- Values of f_g and f_y from asymptotically safe Quantum Gravity (QG)

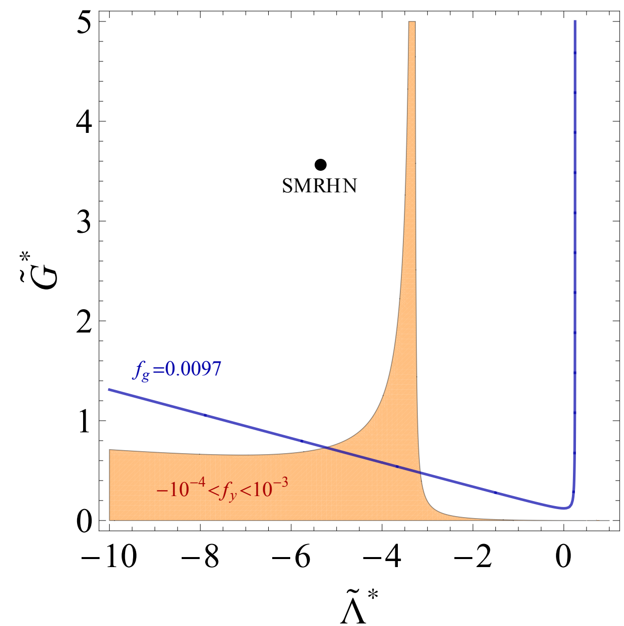
$$f_g(\tilde{G}_N^*, \tilde{\Lambda}^*) \approx \frac{\tilde{G}_N^*(1-4\tilde{\Lambda}^*)}{4\pi(1-2\tilde{\Lambda}^*)^2}$$

$$f_y(\tilde{G}_N^*, \tilde{\Lambda}^*) \approx \left(\frac{\tilde{G}_N^*\left(712\tilde{\Lambda}^{*3}+407\tilde{\Lambda}^{*2}-1391\tilde{\Lambda}^*+561\right)}{60\pi\left(8\tilde{\Lambda}^*-10\tilde{\Lambda}^*+3\right)^2} \right)$$

Eichhorn et.al. 1709.07252



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



QG perspective on naturalness of this mechanism in SMRHN

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

$$f_g \approx 0.0097$$

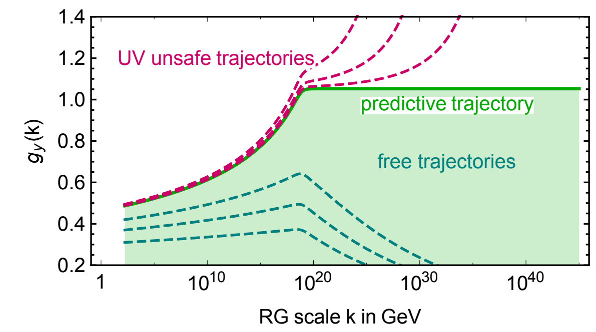
- Values of f_g and f_y from asymptotically safe Quantum Gravity (QG)

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

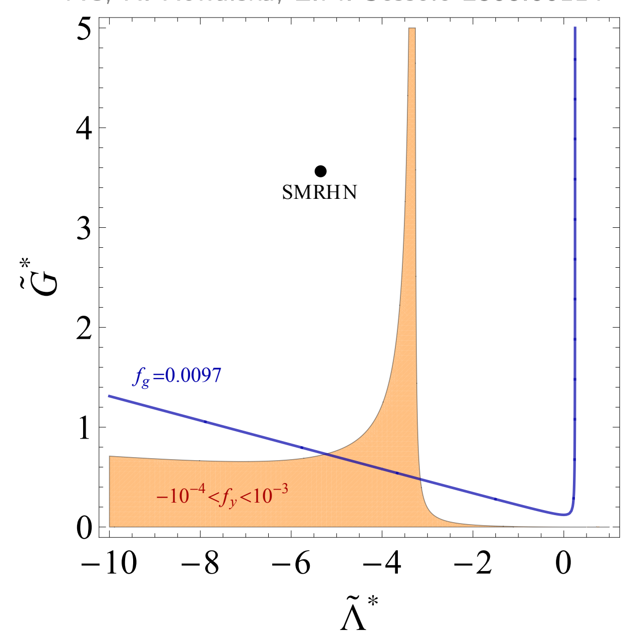
$$f_y(\tilde{G}_N^*, \tilde{\Lambda}^*) \approx \left(\frac{\tilde{G}_N^*\left(712\tilde{\Lambda}^{*3}+407\tilde{\Lambda}^{*2}-1391\tilde{\Lambda}^*+561\right)}{60\pi\left(8\tilde{\Lambda}^*-10\tilde{\Lambda}^*+3\right)^2} \right)$$

- $\tilde{G}_N^*$ and $\tilde{\Lambda}^*$ depend on the number of Dirac fermions, gauge fields, and scalar fields

Eichhorn et.al. 1709.07252



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



QG perspective on naturalness of this mechanism in $B-L$

- 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? If $g_X^* \neq 0$ and $g_\epsilon^* \neq 0$

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

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

$\Longrightarrow$ predicts g_X and g_ϵ

$\Longrightarrow$ larger margin for f_g

QG perspective on naturalness of this mechanism in $B-L$

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

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

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

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

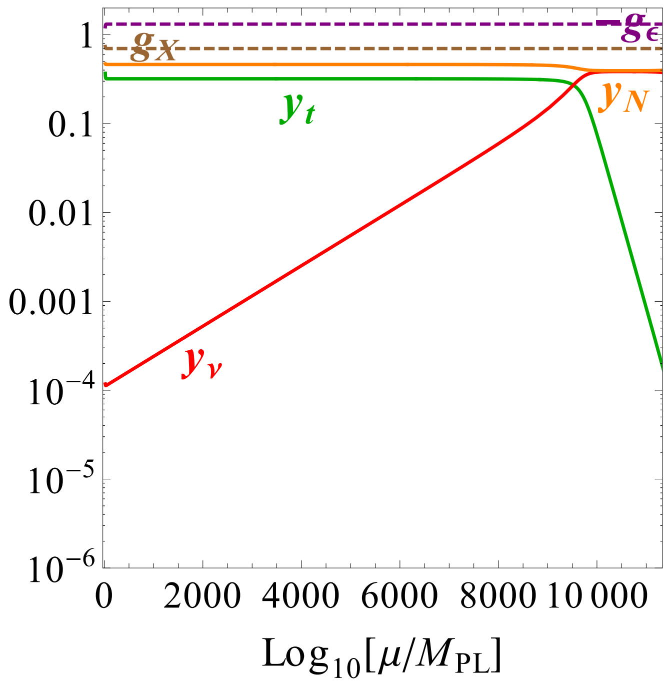
- IR-attractive fixed-point at $y_\nu^* = 0$ is possible even if $g_Y^* = 0$ i.e. $f_g \neq 0.0097$

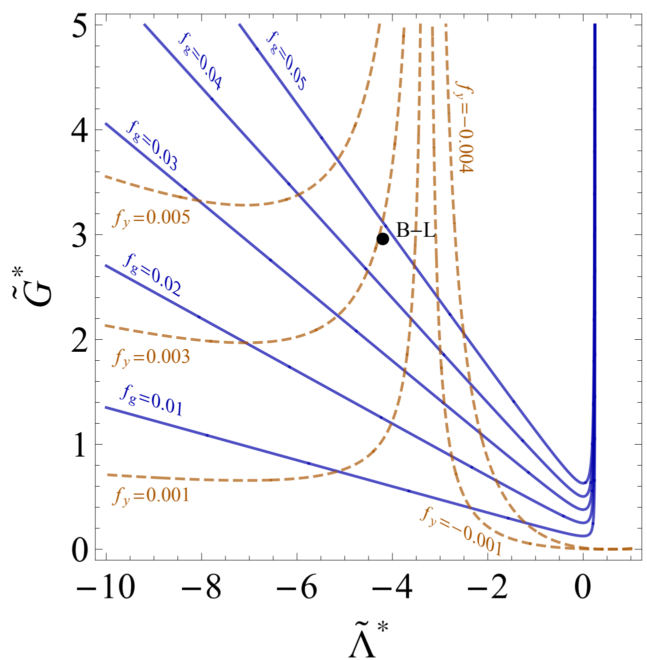
How? If $g_X^* \neq 0$ and $g_\epsilon^* \neq 0$

$\implies$ predicts g_X and g_ϵ

$\implies$ larger margin for f_g

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'

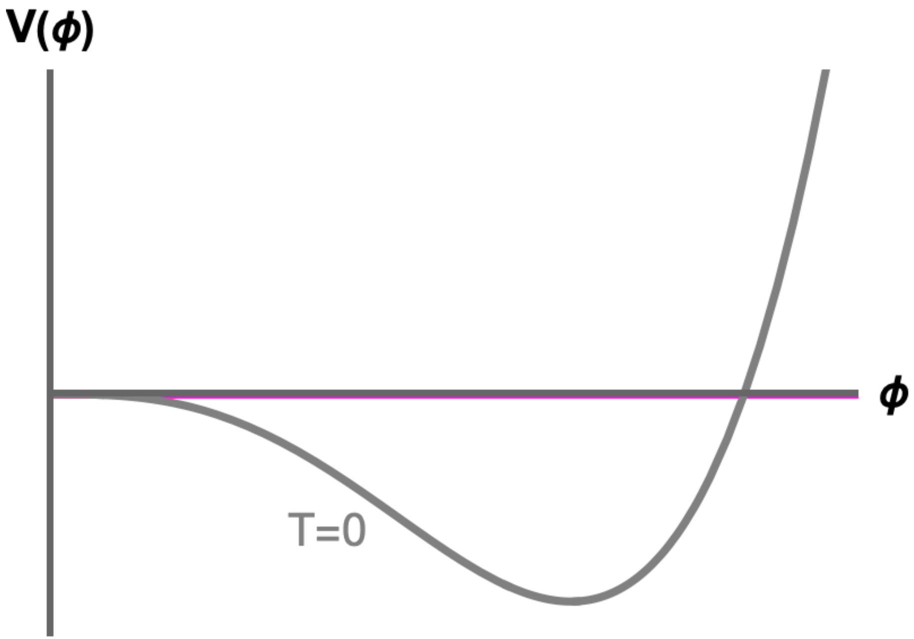
$$\epsilon = \frac{g_\epsilon}{\sqrt{g_Y^2 + g_\epsilon^2}} \approx 0.5 - 0.8$$

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

First-order phase transition and Gravitational waves

- $U(1)_{B-L}$ is spontaneously broken
  - Coleman-Weinberg mechanism is one possible way, which could lead to FOPT

$$V_0(\phi) = -m_\phi^2\phi^2 + \kappa\,\phi^3 + \lambda\phi^4 + ...$$



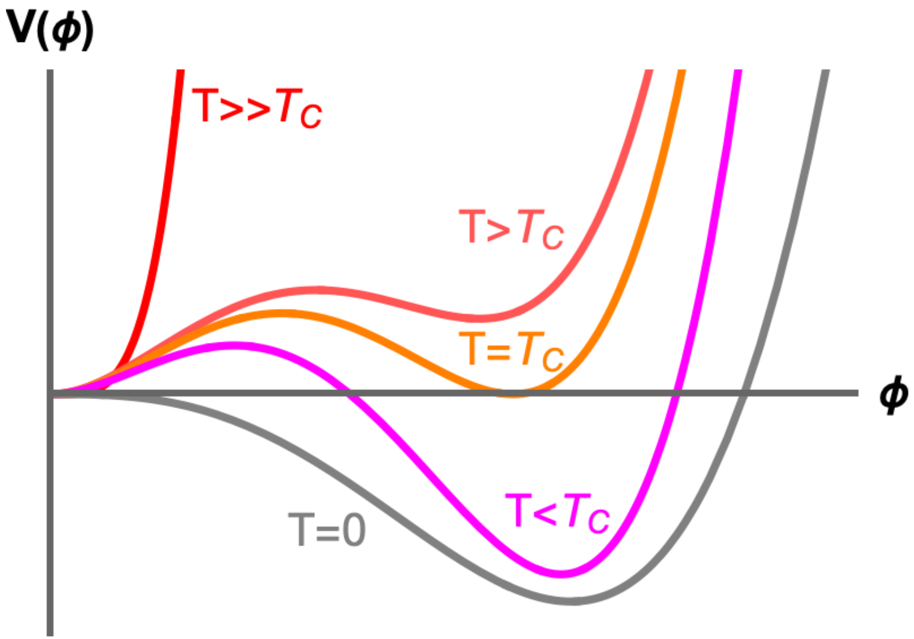
First-order phase transition and Gravitational waves

- $U(1)_{B-L}$ is spontaneously broken
  - Coleman-Weinberg mechanism is one possible way, which could lead to FOPT

$$V_0(\phi) = -m_\phi^2\phi^2 + \kappa\,\phi^3 + \lambda\phi^4 + ...$$

$$V(\phi) = V_0(\phi) + V_{thermal}(\phi)$$

$$V_{thermal}(\phi) \propto T^2$$



First-order phase transition and Gravitational waves

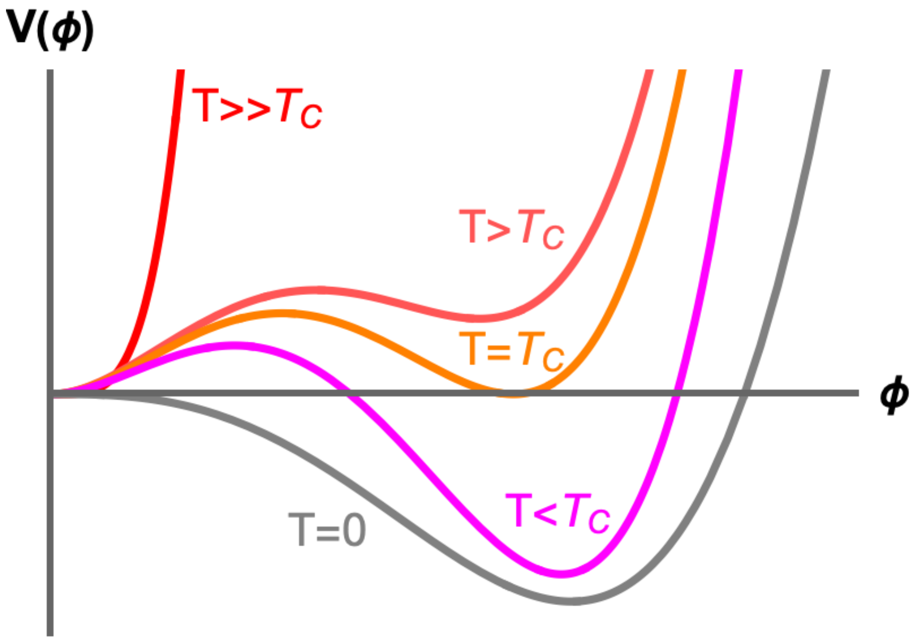
- $U(1)_{B-L}$ is spontaneously broken
  - Coleman-Weinberg mechanism is one possible way, which could lead to FOPT

$$V_0(\phi) = -m_\phi^2\phi^2 + \kappa\,\phi^3 + \lambda\phi^4 + \ldots$$

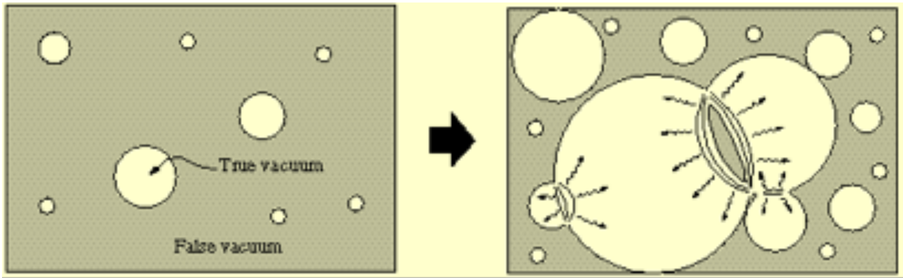
$$V(\phi) = V_0(\phi) + V_{thermal}(\phi)$$

$$V_{thermal}(\phi) \propto T^2$$

Phase transition through true vacuum bubble formation and expansion



CTC Cambridge Website



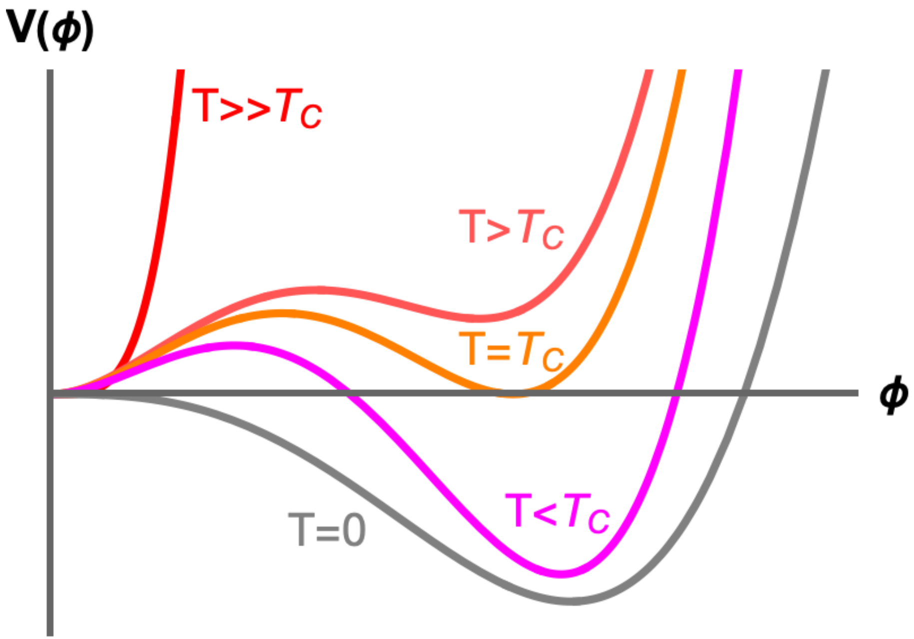
First-order phase transition and Gravitational waves

- $U(1)_{B-L}$ is spontaneously broken
  - Coleman-Weinberg mechanism is one possible way, which could lead to FOPT

$$V_0(\phi) = -m_\phi^2\phi^2 + \kappa\,\phi^3 + \lambda\phi^4 + \ldots$$

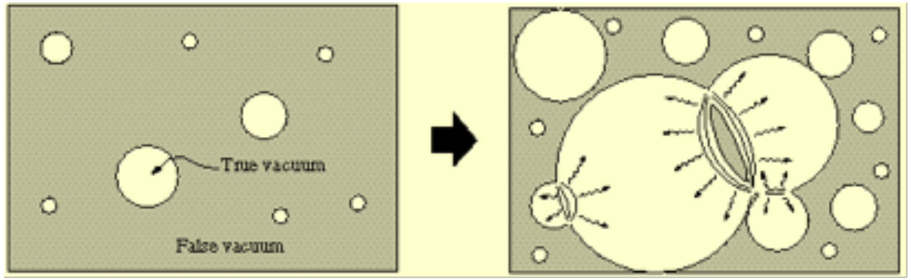
$$V(\phi) = V_0(\phi) + V_{thermal}(\phi)$$

$$V_{thermal}(\phi) \propto T^2$$



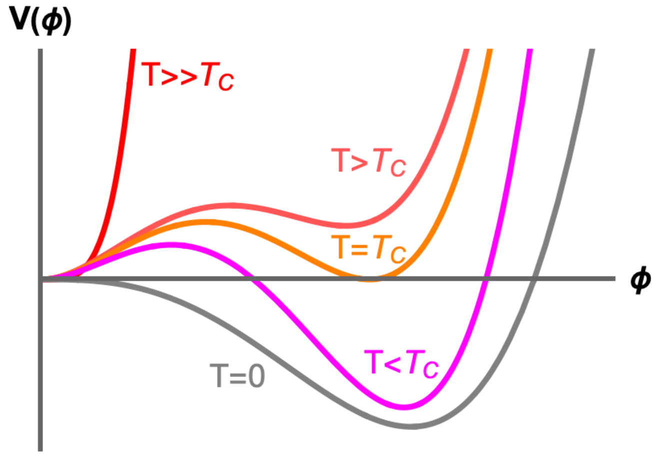
Phase transition through true vacuum bubble formation and expansion

CTC Cambridge Website



Bubble collision breaks spherical symmetry of stress-energy tensor $T_{\mu\nu}$
$\Longrightarrow$ Stochastic gravitational waves

Gravitational waves from FOPT in $B - L$



- Since $v_H << v_S$, the Higgs field effectively decouples
- SSB 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

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

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

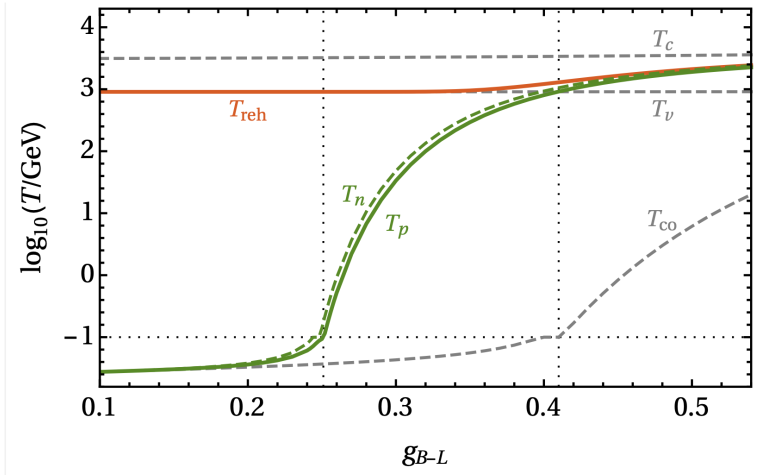
$$m_{Z'}^2(\phi) = 4\, g_X^2\, \phi^2$$
$$\mathrm{m}_{\nu_R}^2(\phi) = 2\, y_N^2\, \phi^2$$
$$\mathrm{m}_{\phi}^2(\phi) = 3\, \lambda_2\, \phi^2 + m_S^2$$
$$\mathrm{m}_{G}^2(\phi) = \lambda_2\, \phi^2 + m_S^2$$

GW signals with scale-invariance ($m_S^2 = 0$)

- If $g_X \lesssim 0.25$, the percolation temperature (T_P) is below QCD phase-transition

	g_X ($10^{5,7,9}$GeV)	y_N ($10^{5,7,9}$GeV)
BP1	0.29, 0.29, 0.30	0.16, 0.16, 0.16
BP2	0.40, 0.41, 0.44	0.42, 0.44, 0.45
BP3	**0.12, 0.12, 0.12**	0.0
BP4	**0.09, 0.09, 0.09**	0.0

C. Marzo, L.Marzola, V.Vaskonen; 1811.11169

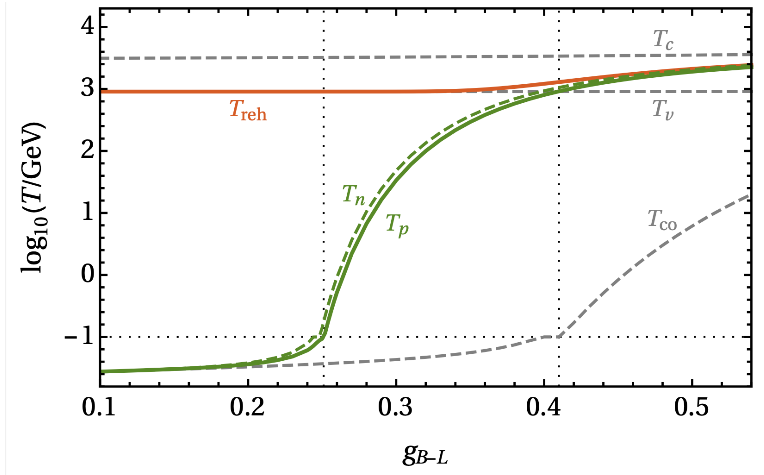


GW signals with scale-invariance ($m_S^2 = 0$)

- If $g_X \lesssim 0.25$, the percolation temperature (T_P) is below QCD phase-transition

	$g_X\ (10^{5,7,9}\mathrm{GeV})$	$y_N\ (10^{5,7,9}\mathrm{GeV})$
BP1	**0.29, 0.29, 0.30**	**0.16, 0.16, 0.16**
BP2	**0.40, 0.41, 0.44**	**0.42, 0.44, 0.45**
BP3	0.12, 0.12, 0.12	0.0
BP4	0.09, 0.09, 0.09	0.0

C. Marzo, L.Marzola, V.Vaskonen; 1811.11169

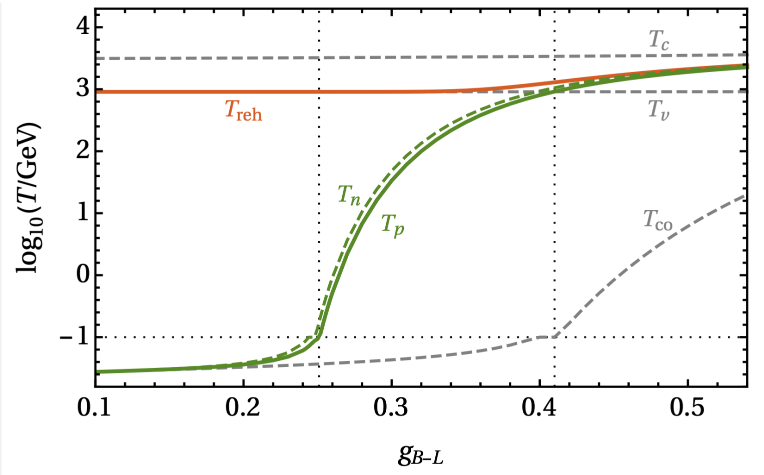


- V_{CW} is shallower when $y_N \neq 0$
  - Nucleation termination condition is not met

GW signals with scale-invariance ($m_S^2 = 0$)

- If $g_X \lesssim 0.25$, the percolation temperature (T_P) is below QCD phase-transition

C. Marzo, L.Marzola, V.Vaskonen; 1811.11169



	$g_X\ (10^{5,7,9}\text{GeV})$	$y_N\ (10^{5,7,9}\text{GeV})$
BP1	**0.29, 0.29, 0.30**	**0.16, 0.16, 0.16**
BP2	**0.40, 0.41, 0.44**	**0.42, 0.44, 0.45**
BP3	0.12, 0.12, 0.12	0.0
BP4	0.09, 0.09, 0.09	0.0

- V_{CW} is shallower when $y_N \neq 0$
  - Nucleation termination condition is not met

No GW signal with $m_S^2 = 0$

QG perspective on scale-invariance

$$\frac{d\tilde{m}_S^2}{dt} \approx (-2 - f_\lambda)\tilde{m}_S^2$$

$$\frac{d\lambda_S}{dt} \approx -f_\lambda \lambda_S + \frac{6}{\pi^2} g_X^{*4}$$

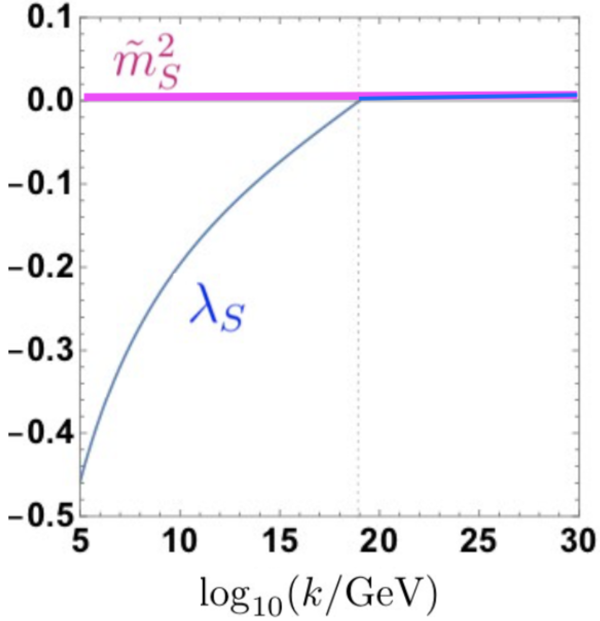
- Gravity corrections to m_S and λ_S. Similar to gauge and Yukawa couplings

QG perspective on scale-invariance

$$\frac{d\tilde{m}_S^2}{dt} \approx (-2 - f_\lambda)\tilde{m}_S^2$$

$$\frac{d\lambda_S}{dt} \approx -f_\lambda \lambda_S + \frac{6}{\pi^2} g_X^{*4}$$

- Gravity corrections to m_S and λ_S. Similar to gauge and Yukawa couplings
  - If $f_\lambda << -2$
    $\implies m_S^{*2} = 0$ and $\theta_{m_S^2} < 0$ (quantum scale invariance)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)

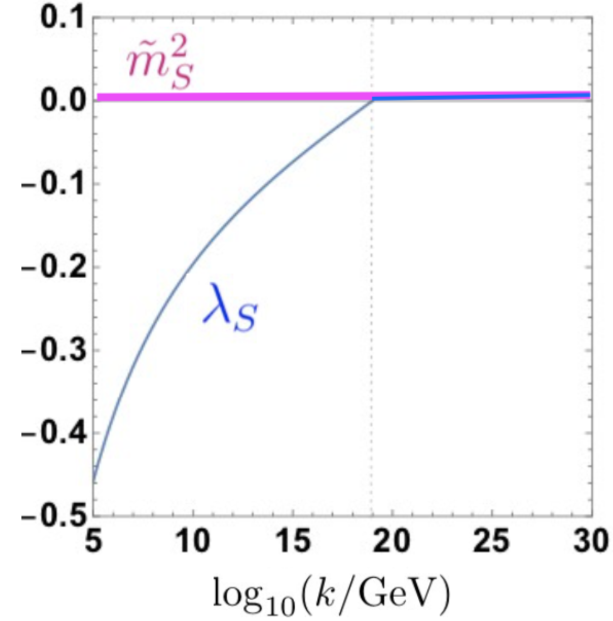


QG perspective on scale-invariance

$$\frac{d\tilde{m}_S^2}{dt} \approx (-2 - f_\lambda)\tilde{m}_S^2$$

$$\frac{d\lambda_S}{dt} \approx -f_\lambda \lambda_S + \frac{6}{\pi^2} g_X^{*4}$$

- Gravity corrections to m_S and λ_S. Similar to gauge and Yukawa couplings
  - If $f_\lambda << -2$
    $\implies m_S^{*2} = 0$ and $\theta_{m_S^2} < 0$ (quantum scale invariance)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)
  - If $-2 < f_\lambda < 0$
    $\implies m_S^{*2} = 0$ but $\theta_{m_S^2} > 0$ (free-parameter)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)

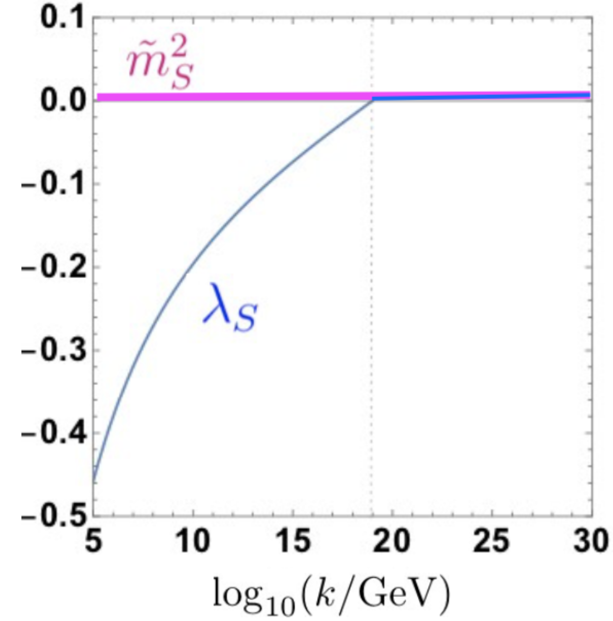


QG perspective on scale-invariance

- Gravity corrections to m_S and λ_S. Similar to gauge and Yukawa couplings
  - If $f_\lambda << -2$
    $\implies m_S^{*2} = 0$ and $\theta_{m_S^2} < 0$ (quantum scale invariance)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)
  - If $-2 < f_\lambda < 0$
    $\implies m_S^{*2} = 0$ but $\theta_{m_S^2} > 0$ (free-parameter)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)
  - If $f_\lambda > 0$
    m_S^2 and λ_S become free-parameters of the theory

$$\frac{d\tilde{m}_S^2}{dt} \approx (-2 - f_\lambda)\tilde{m}_S^2$$

$$\frac{d\lambda_S}{dt} \approx -f_\lambda \lambda_S + \frac{6}{\pi^2} g_X^{*4}$$

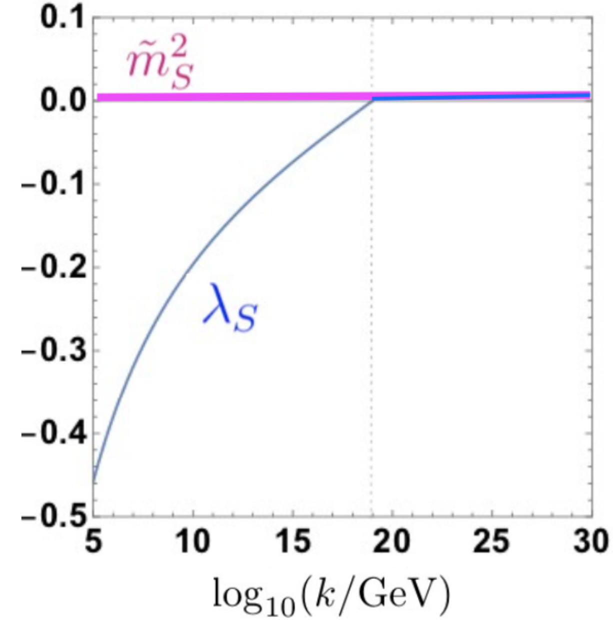


QG perspective on scale-invariance

$$\frac{d\tilde{m}_S^2}{dt} \approx (-2 - f_\lambda)\tilde{m}_S^2$$

$$\frac{d\lambda_S}{dt} \approx -f_\lambda \lambda_S + \frac{6}{\pi^2} g_X^{*4}$$

- Gravity corrections to m_S and λ_S. Similar to gauge and Yukawa couplings
  - If $f_\lambda << -2$
    $\implies m_S^{*2} = 0$ and $\theta_{m_S^2} < 0$ (quantum scale invariance)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)
  - If $-2 < f_\lambda < 0$
    $\implies m_S^{*2} = 0$ but $\theta_{m_S^2} > 0$ (free-parameter)
    $\implies$ But $\lambda_S < 0$ (**destabilizes the vacuum**)
  - If $f_\lambda > 0$
    m_S^2 and λ_S become free-parameters of the theory

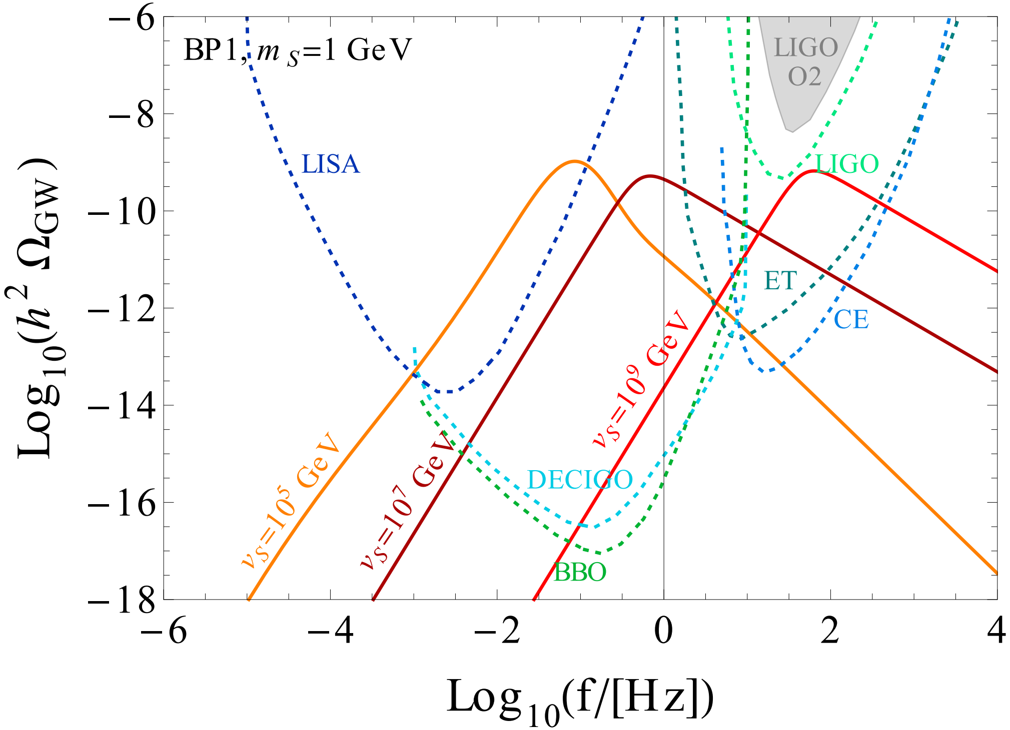


J. M. Pawlowski, M. Reichert, C. Wetterich, and M. Yamada; 1811.11706
A. Pastor-Gutierrez, J. M. Pawlowski, and M. Reichert; 2207.09817

FRG based calculations suggests $f_\lambda < 0$. However, including higher dimensional operators of scalar field and curvature terms could alter this conclusion.

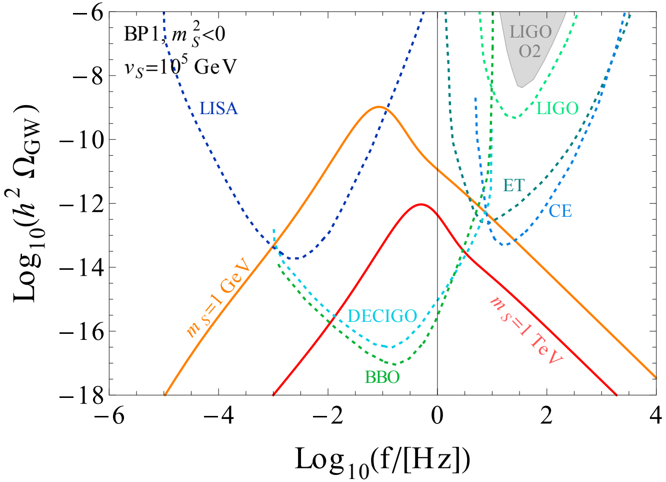
GW with different v_S and $m_S^2 \neq 0$

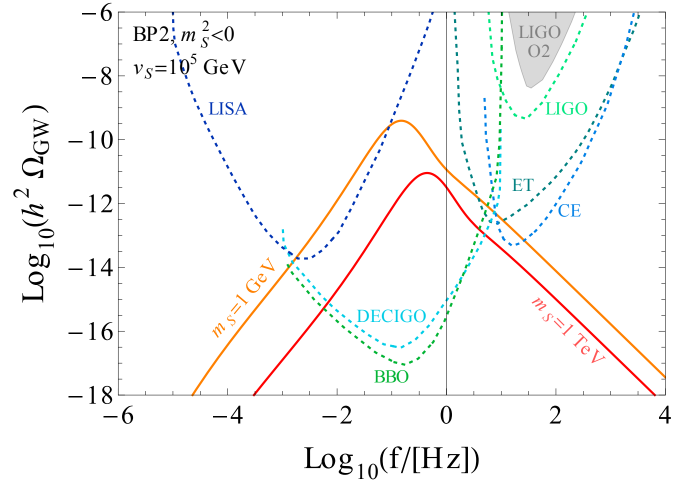
AC, K.Kowalska, E.M. Sessolo, 2308.06114

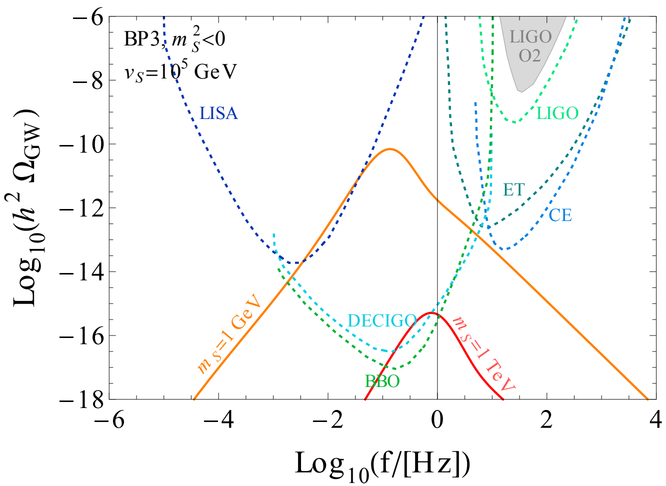


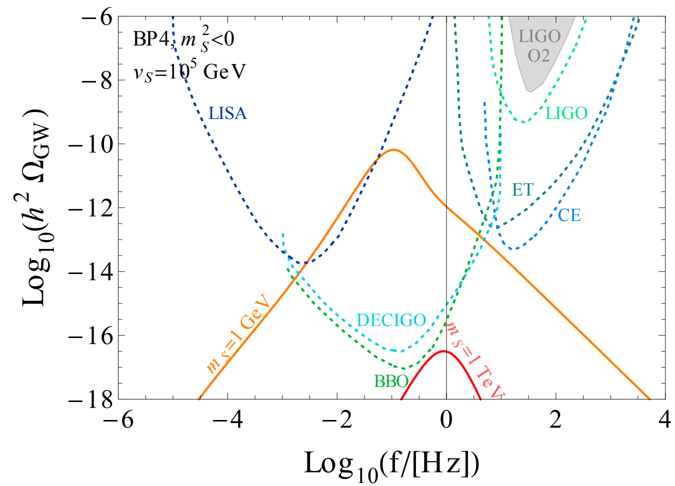
GW signals with $m_S^2 \neq 0$

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









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

Conclusions

- Asymptotically safe gravity could induce IR-attractive Gaussian fixed point $\Longrightarrow$ dynamical mechanism to generate arbitrarily small neutrino mass
- Small Dirac mass appears to arise more naturally in gauged $B - L$ model compared to SMRHN
- Scale invariance of the scalar potential (of S) may be at odds with existing calculations in asymptotically safe quantum gravity
- Observable gravitational wave signal in future space-based interferometers. But discriminating features are obscured due to strong dependence on the mass parameter

Thank you for your attention!