Asymptotically safe dark matter with gauged baryon number

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Asymptotic Safety and Quantum Field Theory

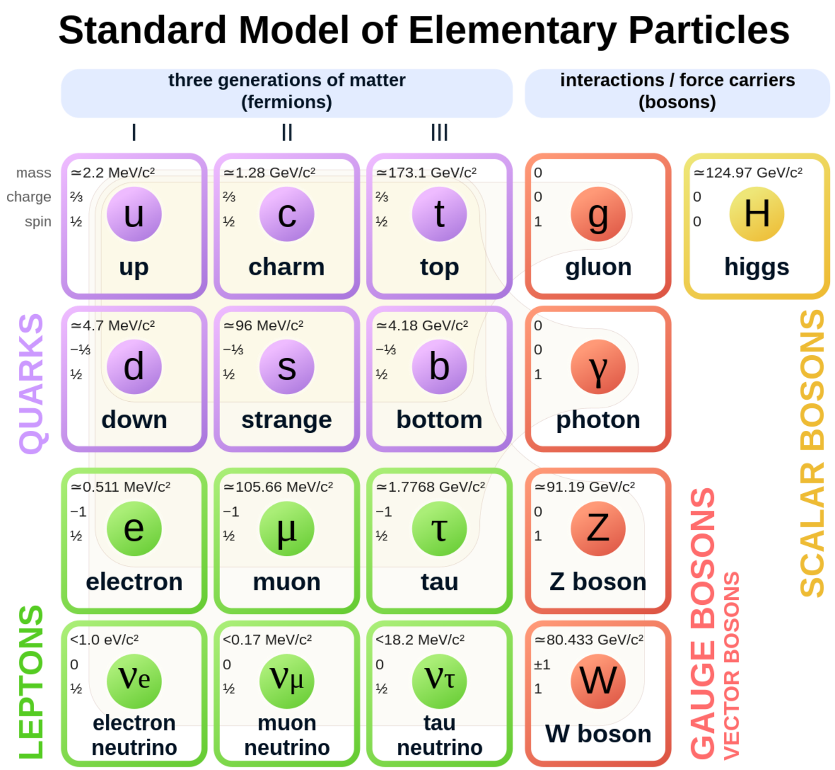
- Asymptotic safety is a framework that can reduce the number of free parameters in a model to only those that can be extrapolated to arbitrarily high energy scales
- Renormalization Group Equations (RGEs) govern the dependence of couplings on energy scale

$$\frac{\mathrm{d}g}{d\log(\mu)} \equiv \beta(g) \equiv \sum_{l=1}^{\infty} \frac{1}{(4\pi)^{2l}} \beta^{(l)}(g)$$

- A theory is asymptotically safe if one or more couplings in the theory flow to non-trivial ultraviolet fixed points and all others flow to zero

Why Extend the Standard Model?

- The hypercharge gauge coupling has a Landau pole (blows up at some scale)
- No dark matter candidate
- Assuring proton stability if quantum gravitational effects violate global symmetries
- <u>Idea:</u> Change the baryon number symmetry from a global symmetry to a gauge symmetry



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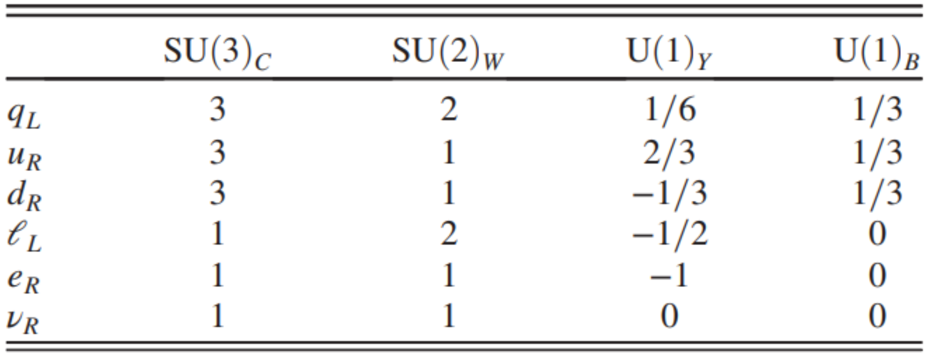
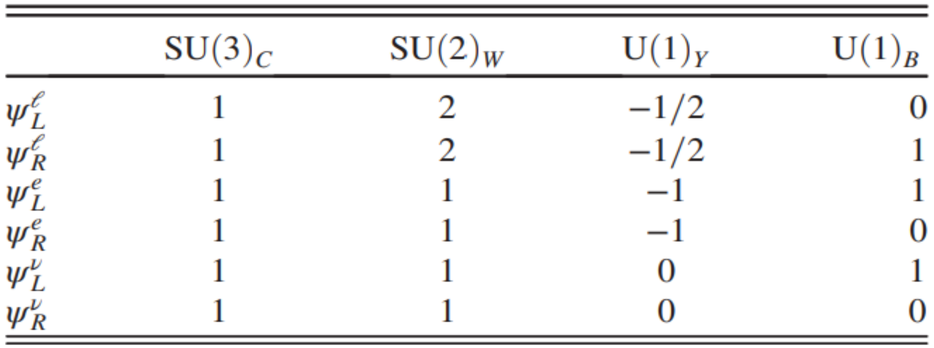
A Gauged Baryon Number Model

- Standard model particles + right-handed neutrinos
- 3 new generations of Dirac, vector-like fermions
- 1 new Dirac, vector-like fermion, χ
- 1 new vector boson
- 1 new complex scalar boson, ϕ
- Kinetic mixing between baryon number and hypercharge



	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
q_L	3	2	1/6	1/3
u_R	3	1	2/3	1/3
d_R	3	1	−1/3	1/3
ℓ_L	1	2	−1/2	0
e_R	1	1	−1	0
ν_R	1	1	0	0



	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
ψ_L^ℓ	1	2	−1/2	0
ψ_R^ℓ	1	2	−1/2	1
ψ_L^e	1	1	−1	1
ψ_R^e	1	1	−1	0
ψ_L^ν	1	1	0	1
ψ_R^ν	1	1	0	0

$\chi_L \sim \chi_R \sim (1, 1, 0, 1/6)$

ϕ is a singlet under the standard model gauge group with baryon number $+1$

Dark Matter Stability

- For all particles (except χ), the baryon number charge is $|Q_B| = 0, \frac{1}{3}, \text{or } 1.$ χ has $Q_B = 1/6$
- $U(1)_B$ phase rotation: $e^{iQ_B(6\pi)}$. All fields are left invariant, but $\chi \rightarrow -\chi$
- This $\mathbb{Z}_2 \subset U(1)_B$ remains unbroken after spontaneous symmetry breaking. It is safe from violation by quantum gravitational effects
- Since χ is the only field odd under this symmetry, its stability is guaranteed

Renormalization Group Equations

- Quantum gravitational effects become important at the Planck scale
- The gauge sector RGEs (1-Loop):

$$\beta^{(1)}(g_1) = \frac{77}{10} g_1^3 - \theta(\mu - M_{Pl})\widehat{f}_g g_1$$

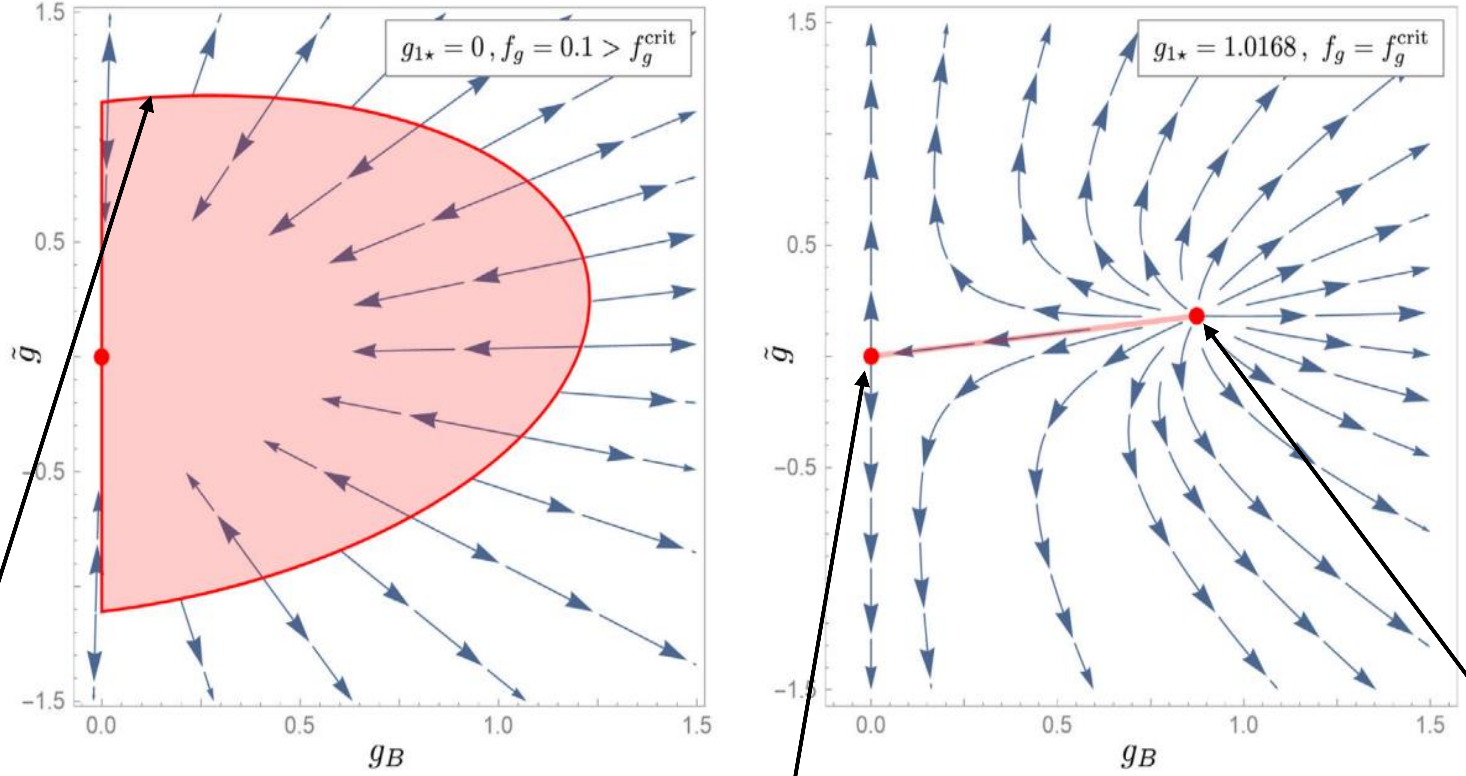
$$\beta^{(1)}(g_B) = 11 g_B^3 + \frac{77}{6} g_B \tilde{g}^2 - \frac{16}{3} g_B^2 \tilde{g} - \theta(\mu - M_{Pl})\widehat{f}_g g_B$$

$$\beta^{(1)}(\tilde{g}) = -\frac{16}{5} g_1^2 g_B - \frac{16}{3} g_B \tilde{g}^2 + \frac{77}{5} g_1^2 \tilde{g} + 11 g_B^2 \tilde{g} + \frac{77}{6} \tilde{g}^3 - \theta(\mu - M_{Pl})\widehat{f}_g \tilde{g}$$

- Ultraviolet fixed points satisfy the conditions:

$$\beta^{(1)}\left(g_{1_*}\right) = \beta^{(1)}\left(g_{B_*}\right) = \beta^{(1)}(\tilde{g}_*) = 0$$

Ultraviolet Fixed Points in the Model



Benchmark Fixed Point: (0.202, 1.136)
At 1 TeV: (0.200, 0.150)

ii

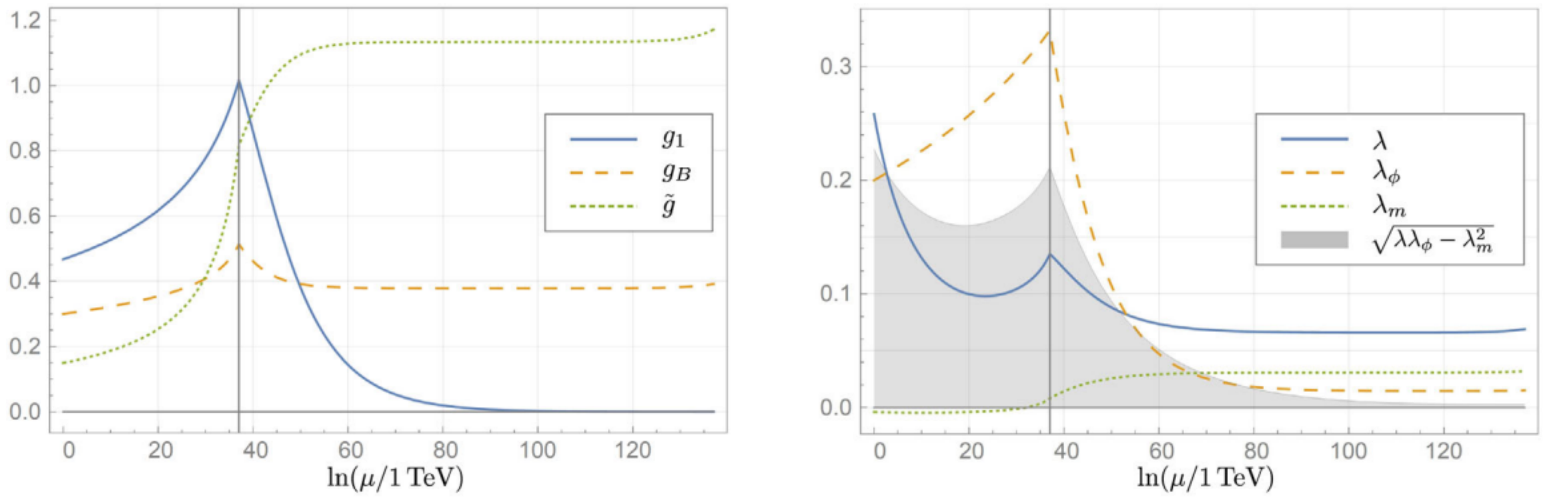
Fixed Point: (0,0)
At 1 TeV: (0.200,0.041)

ib

Fixed Point: (0.871, 0.181)
At 1 TeV: (0.400, 0.083)

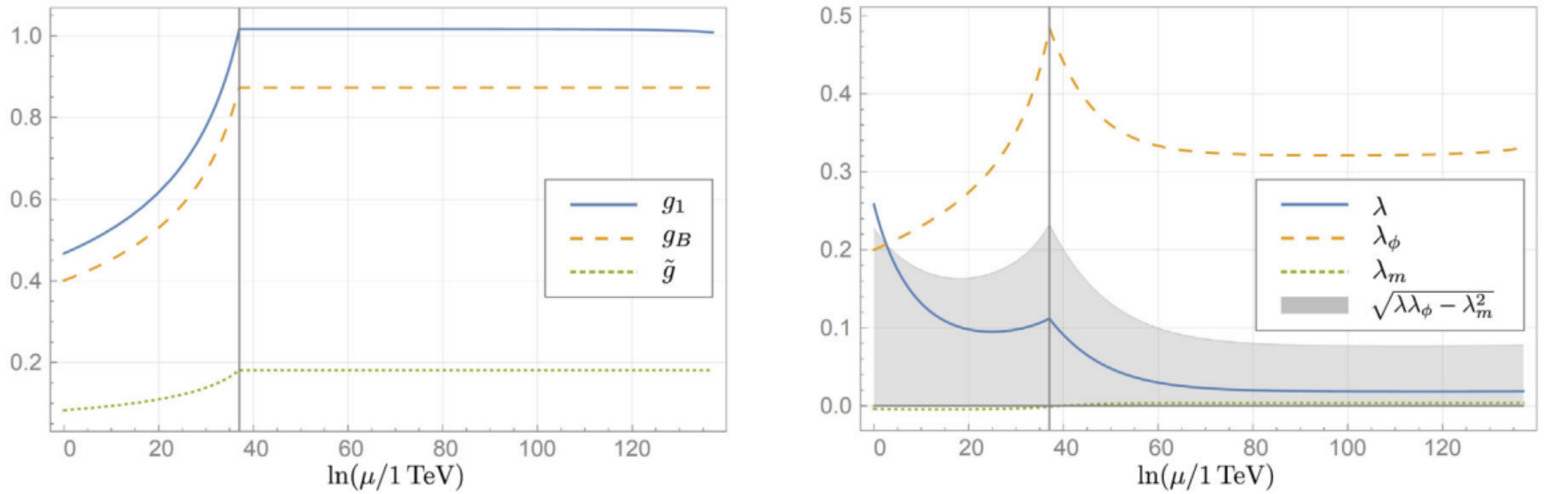
ia

Evolution of Couplings



trivial g_1 fixed point

$\lambda_\star = 0.065$
$\lambda_{\phi\star} = 0.014$
$\lambda_{m\star} = 0.030$



Interacting g_1 fixed point

$\lambda_\star = 0.018$
$\lambda_{\phi\star} = 0.32$
$\lambda_{m\star} = 0.0037$
$g_{1\star} = 1.016$

Dark Matter Relic Density

- A relativistic treatment of the thermally averaged cross section times relative velocity $\sigma(\chi\bar{\chi} \rightarrow f\bar{f})$:

$$\langle \sigma v \rangle = \frac{1}{8m_\chi^4 T K_2^2\left(\frac{m_\chi}{T}\right)} \int_{4m_\chi^2}^{\infty} \mathrm{d}s\, \sigma_{tot} \times (s - 4m_\chi^2)\sqrt{s} K_1\left(\frac{\sqrt{s}}{T}\right)$$

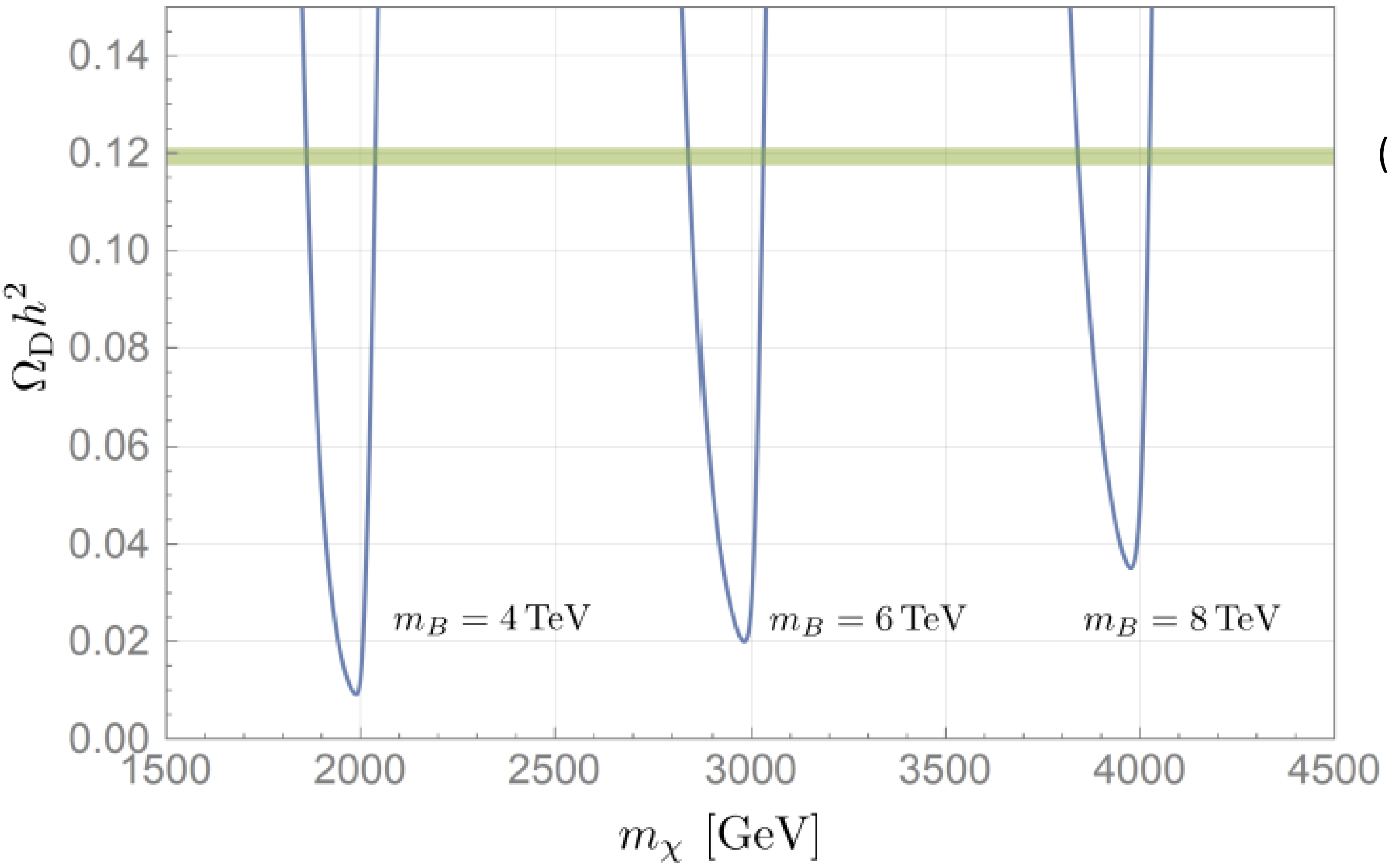
- Dark matter falls out of thermal equilibrium at the freeze-out temperature:

$$\frac{\Gamma}{H(T_f)} \equiv \frac{n_\chi^{EQ}\langle \sigma v \rangle}{H(T_f)} \approx 1$$

- The entropy density to number density ratio is then propagated from the freeze-out temperature to the present temperature:

$$\Omega_{\mathrm{D}} h^2 \approx \frac{2.8 \times 10^8}{\mathrm{GeV}} Y_0\, m_\chi$$

Dark Matter Relic Density

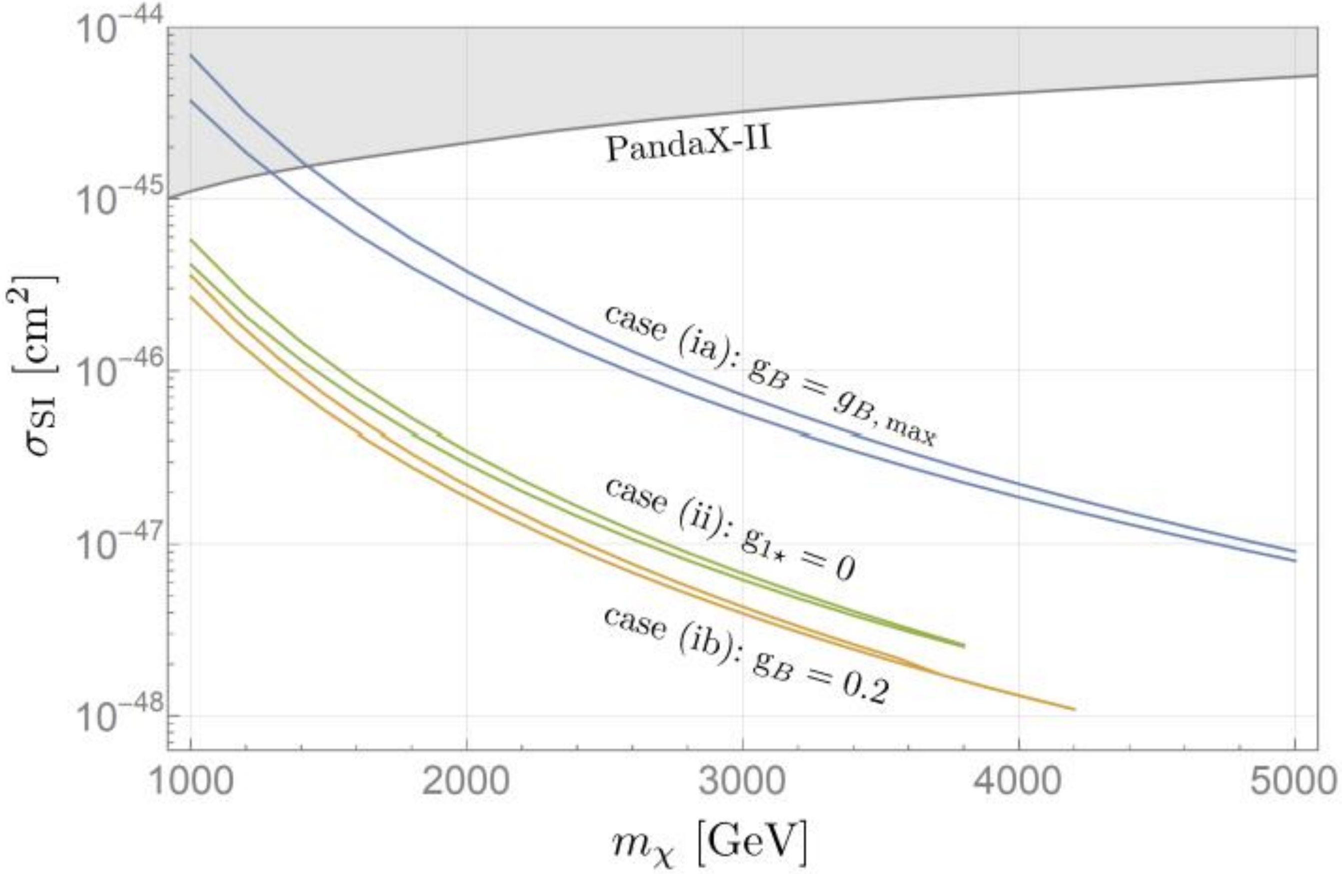


(Planck measurement)

Direct Detection

- $m_B = m_B(m_\chi)$ fixed by the observed relic density within two standard deviations

$$\sigma_{\rm SI} = \frac{g_B^4}{36\,\pi}\frac{\mu_{\chi N}^2}{m_B^4}\left(1 + 0.35\,\frac{\tilde{g}}{g_B}\right)^2$$



Conclusions

1. Gravitational corrections above the Planck scale allow for different fixed-point scenarios in the theory. Requiring asymptotic safety constrains the model's couplings, including the kinetic mixing parameter, and yields a more predictive theory
2. The model includes a stable TeV scale dark matter candidate
3. These models can predict the observed relic density while also remain consistent with direct detection experiments

Stability in the Higgs Sector

- In the standard model, the Higgs vacuum is metastable. Our extension of the standard model changes this analysis

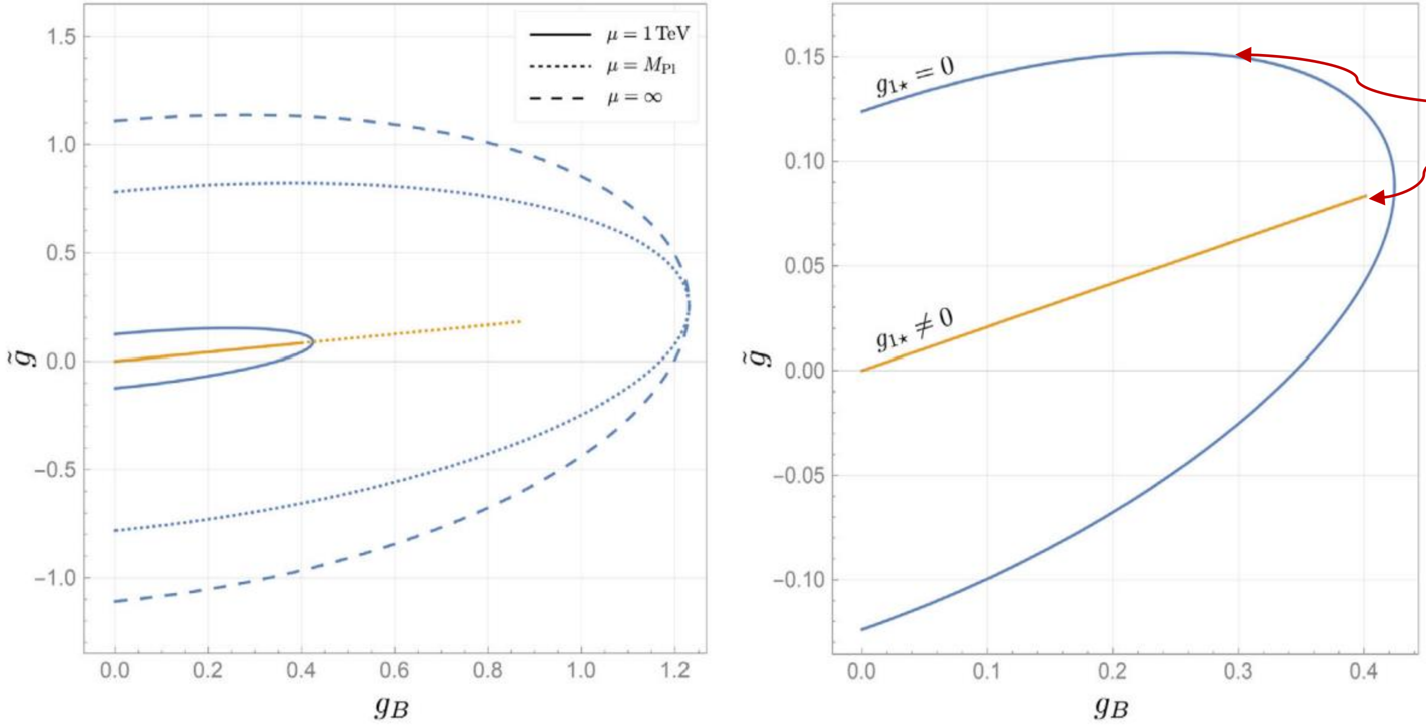
$$V = -m_H^2 H^\dagger H - m_\phi^2 \phi^* \phi + \frac{\lambda}{2}\left[H^\dagger H + \frac{\lambda_m}{\lambda}\phi^*\phi\right]^2 + \frac{\mathfrak{s}}{2\,\lambda}\left[\phi^*\phi\right]^2 \qquad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}\,, \quad \phi = \frac{v_\phi + \varphi}{\sqrt{2}}\,,$$

- After substituting, we find the mass matrix:

$$M^2 = \begin{pmatrix} \lambda\, v^2 & \lambda_m v\, v_\phi \\ \lambda_m v\, v_\phi & \lambda_\phi v_\phi^2 \end{pmatrix} \qquad \det M^2 \equiv m_+^2 m_-^2 = v^2 v_\phi^2 (\lambda\lambda_\phi - \lambda_m^2) \equiv v^2 v_\phi^2 \mathfrak{s}$$

- Thus, we require the quantity: $\mathfrak{s} = \lambda\lambda_\phi - \lambda_m^2 > 0$
- If we also require $\lambda > 0$, then the stability of the scalar potential is guaranteed for large field amplitudes

Couplings and Asymptotic Safety



Consider the following choices of the couplings at 1 TeV ($= \mu_0$):

Case	g_B	$\tilde{g}$	m_B	f_g
$g_{1\star} = 0$:	0.3	0.14988	3 TeV	$0.1\ (> f_g^{\mathrm{crit}})$
$g_{1\star} \neq 0$:	0.40128	0.08338	4.01 TeV	$0.05041\ (= f_g^{\mathrm{crit}})$

$$g_1(\mu_0) = 0.46738, \quad g_2(\mu_0) = 0.63829, \quad g_3(\mu_0) = 1.05737,$$

$$y_t(\mu_0) = 0.85322, \quad y_b(\mu_0) = 0.01388.$$

Measured values of standard model couplings

$$\lambda_\phi(\mu_0) = 0.2, \qquad \lambda_m(\mu_0) = -0.004.$$

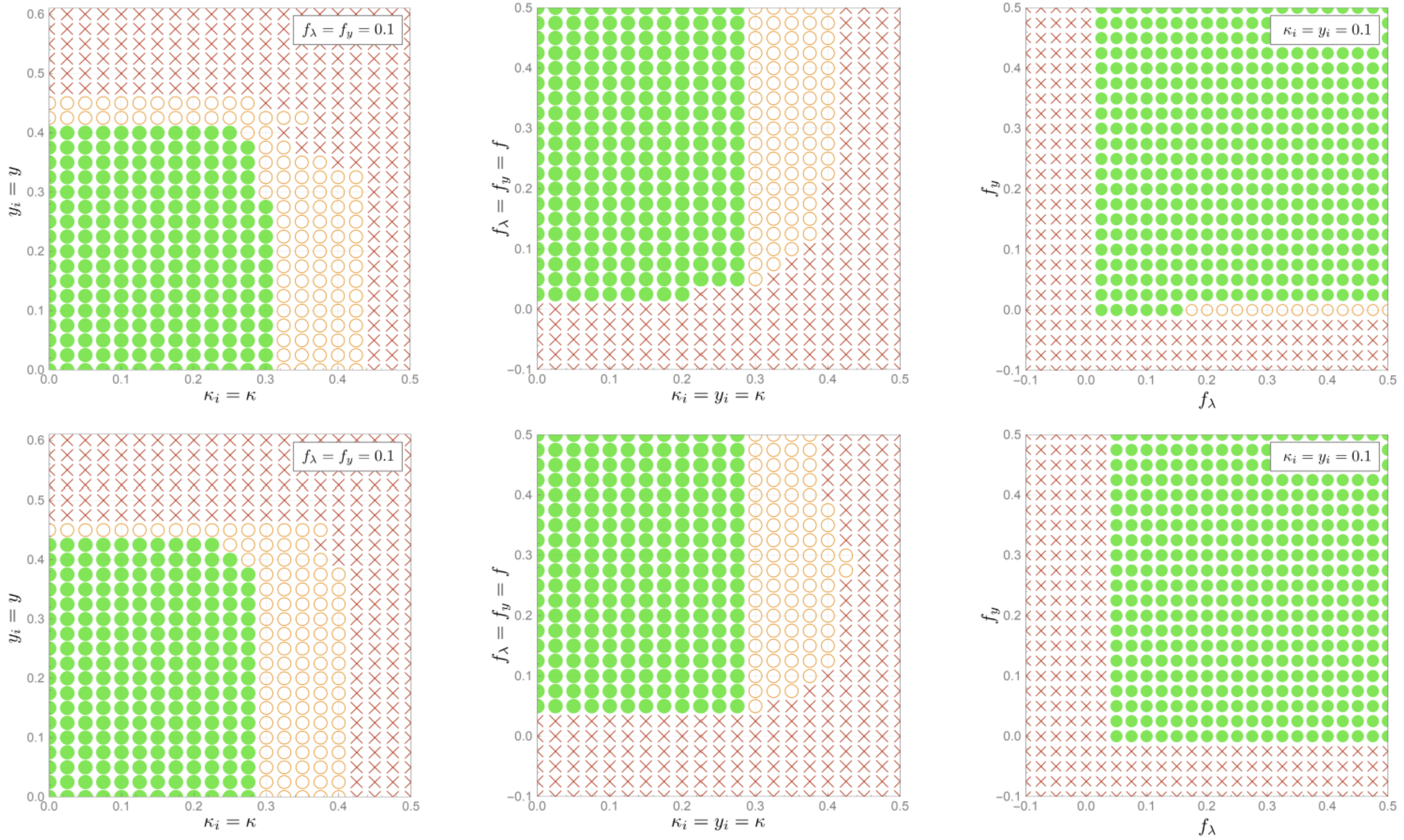
$$\kappa_i(\mu_0) = y_i(\mu_0) = 0.1, \quad i = 1\ldots3,$$

$$f_\lambda = f_y = 0.1.$$

$$v_\phi = 10\ \mathrm{TeV} \qquad v = 246\ \mathrm{GeV}$$

$$m_h = 125\ \mathrm{GeV} \implies \lambda(\mu_0) = 0.25828 \implies m_\phi = 4.472\ \mathrm{TeV}$$

Exploring the Parameter Space



Gaussian
Fixed Point

Interacting
Fixed Point

- These are parameter choices at $\mu_0 = 1$ TeV

References (Cont.):

[26] P. Fileviez Pérez, E. Golias, R. H. Li, C. Murgui and A. D. Plascencia, "Anomaly-free dark matter models," Phys. Rev. D **100**, no. 1, 015017 (2019), arXiv:1904.01017 [hep-ph]; P. Fileviez Perez and A. D. Plascencia, "Theory of Dirac dark matter: Higgs boson decays and EDMs," Phys. Rev. D **105**, no. 9, 095021 (2022), arXiv:2112.02103 [hep-ph].

[27] G. M. Pelaggi, A. D. Plascencia, A. Salvio, F. Sannino, J. Smirnov and A. Strumia, "Asymptotically safe standard model extensions?," Phys. Rev. D **97**, no. 9, 095013 (2018), arXiv:1708.00437 [hep-ph]; R. Mann, J. Meffe, F. Sannino, T. Steele, Z. W. Wang and C. Zhang, "Asymptotically safe standard model via vectorlike fermions," Phys. Rev. Lett. **119**, no.26, 261802 (2017), arXiv:1707.02942 [hep-ph]; O. Antipin, N. A. Dondi, F. Sannino, A. E. Thomsen and Z. W. Wang, "Gauge-Yukawa theories: Beta functions at large N_f," Phys. Rev. D **98**, no.1, 016003 (2018), arXiv:1803.09770 [hep-ph]; E. Molinaro, F. Sannino and Z. W. Wang, "Asymptotically safe Pati-Salam theory," Phys. Rev. D **98**, no. 11, 115007 (2018), arXiv:1807.03669 [hep-ph].

[28] P. Gondolo and G. Gelmini, "Cosmic abundances of stable particles: Improved analysis," Nucl. Phys. B **360**, 145 (1991).

[29] R. L. Workman *et al.* [Particle Data Group], "Review of Particle Physics," Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).

[30] P. Agrawal, Z. Chacko, C. Kilic and R. K. Mishra, "A classification of dark matter candidates with primarily spin-dependent interactions with matter," arXiv:1003.1912 [hep-ph].

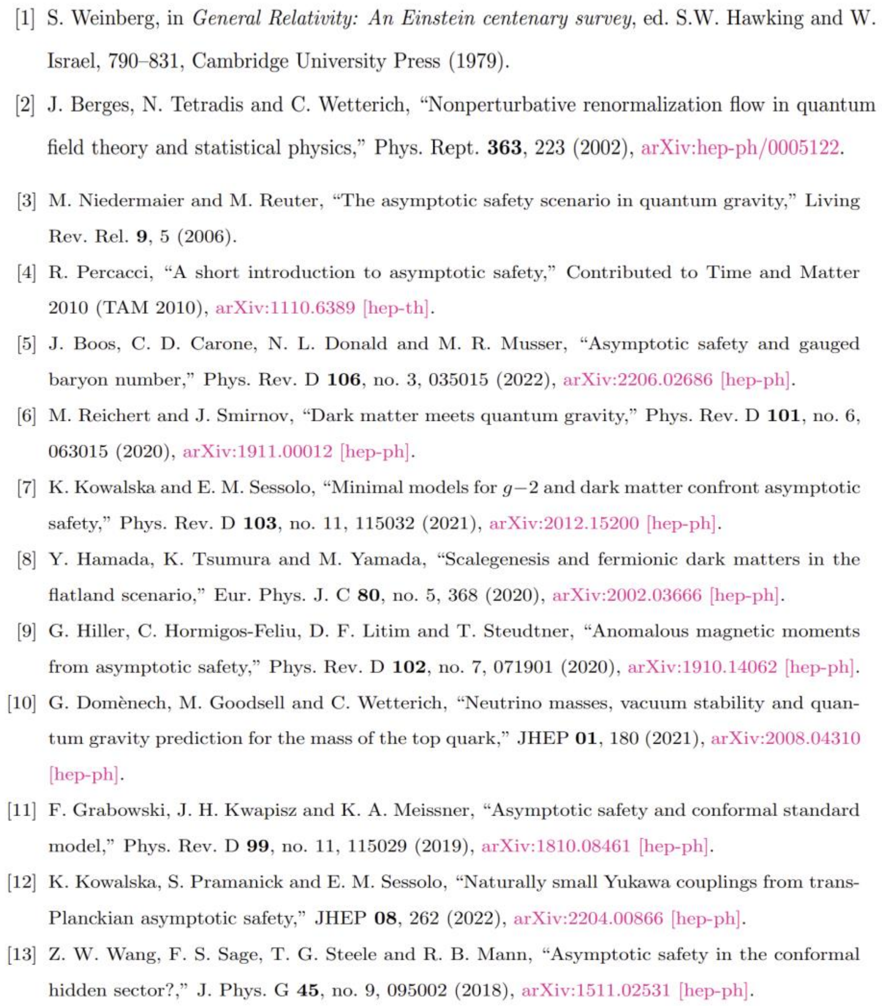
[31] J. M. Cline, G. Dupuis, Z. Liu and W. Xue, "The windows for kinetically mixed Z'-mediated dark matter and the galactic center gamma ray excess," JHEP **08**, 131 (2014), arXiv:1405.7691 [hep-ph].

[32] T. Lin, "TASI lectures on dark matter models and direct detection," arXiv:1904.07915 [hep-ph].

[33] X. Cui *et al.* "Dark matter results from 54-ton-day exposure of PandaX-II experiment," American Physical Society (APS) **119**, no. 18 (2017), arXiv:1708.06917 [hep-ex].

[34] F. Lyonnet, I. Schienbein, F. Staub and A. Wingerter, "PyR@TE: Renormalization group equations for general gauge theories," Comput. Phys. Commun. **185**, 1130-1152 (2014), arXiv:1309.7030 [hep-ph]; F. Lyonnet and I. Schienbein, "PyR@TE 2: A Python tool for computing RGEs at two-loop," Comput. Phys. Commun. **213**, 181–196 (2017), arXiv:1608.07274 [hep-ph]; L. Sartore and I. Schienbein, "PyR@TE 3," Comput. Phys. Commun. **261**, 107819 (2021), arXiv:2007.12700 [hep-ph].

References:



[1] S. Weinberg, in *General Relativity: An Einstein centenary survey*, ed. S.W. Hawking and W. Israel, 790–831, Cambridge University Press (1979).

[2] J. Berges, N. Tetradis and C. Wetterich, "Nonperturbative renormalization flow in quantum field theory and statistical physics," Phys. Rept. **363**, 223 (2002), arXiv:hep-ph/0005122.

[3] M. Niedermaier and M. Reuter, "The asymptotic safety scenario in quantum gravity," Living Rev. Rel. **9**, 5 (2006).

[4] R. Percacci, "A short introduction to asymptotic safety," Contributed to Time and Matter 2010 (TAM 2010), arXiv:1110.6389 [hep-th].

[5] J. Boos, C. D. Carone, N. L. Donald and M. R. Musser, "Asymptotic safety and gauged baryon number," Phys. Rev. D **106**, no. 3, 035015 (2022), arXiv:2206.02686 [hep-ph].

[6] M. Reichert and J. Smirnov, "Dark matter meets quantum gravity," Phys. Rev. D **101**, no. 6, 063015 (2020), arXiv:1911.00012 [hep-ph].

[7] K. Kowalska and E. M. Sessolo, "Minimal models for $g-2$ and dark matter confront asymptotic safety," Phys. Rev. D **103**, no. 11, 115032 (2021), arXiv:2012.15200 [hep-ph].

[8] Y. Hamada, K. Tsumura and M. Yamada, "Scalegenesis and fermionic dark matters in the flatland scenario," Eur. Phys. J. C **80**, no. 5, 368 (2020), arXiv:2002.03666 [hep-ph].

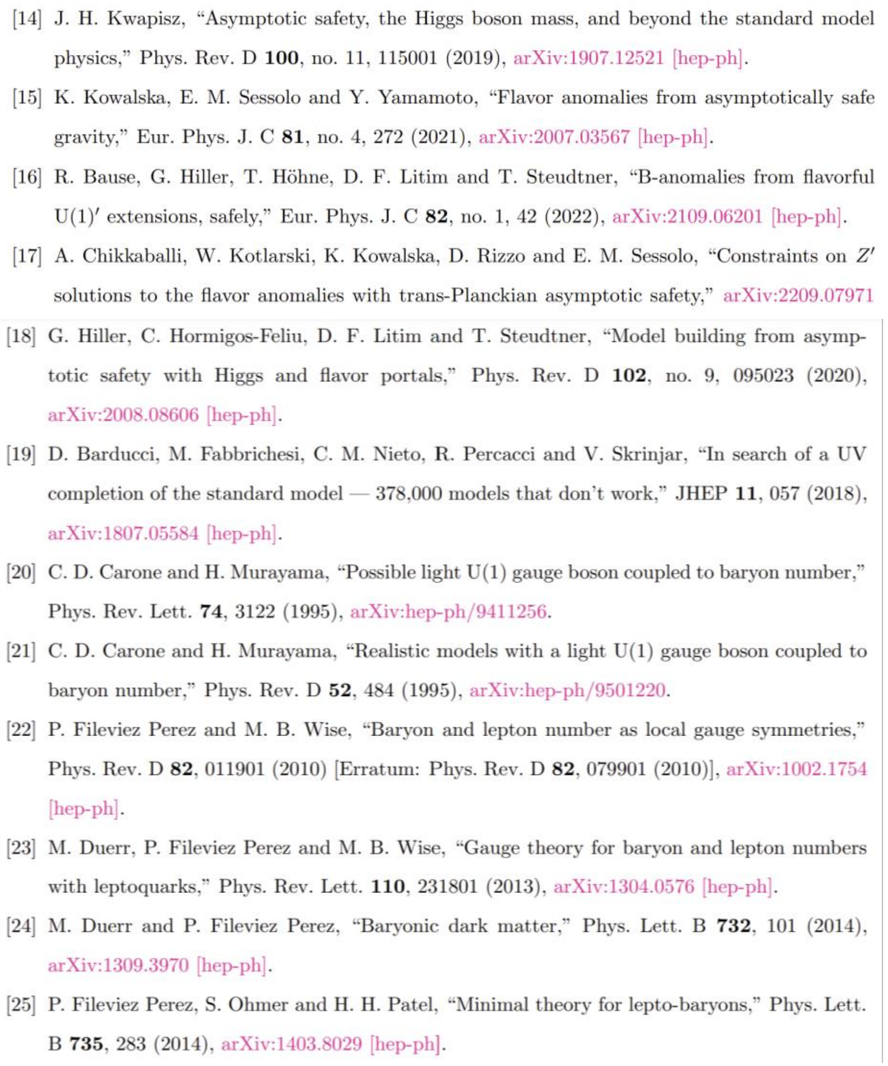
[9] G. Hiller, C. Hormigos-Feliu, D. F. Litim and T. Steudtner, "Anomalous magnetic moments from asymptotic safety," Phys. Rev. D **102**, no. 7, 071901 (2020), arXiv:1910.14062 [hep-ph].

[10] G. Domènech, M. Goodsell and C. Wetterich, "Neutrino masses, vacuum stability and quantum gravity prediction for the mass of the top quark," JHEP **01**, 180 (2021), arXiv:2008.04310 [hep-ph].

[11] F. Grabowski, J. H. Kwapisz and K. A. Meissner, "Asymptotic safety and conformal standard model," Phys. Rev. D **99**, no. 11, 115029 (2019), arXiv:1810.08461 [hep-ph].

[12] K. Kowalska, S. Pramanick and E. M. Sessolo, "Naturally small Yukawa couplings from trans-Planckian asymptotic safety," JHEP **08**, 262 (2022), arXiv:2204.00866 [hep-ph].

[13] Z. W. Wang, F. S. Sage, T. G. Steele and R. B. Mann, "Asymptotic safety in the conformal hidden sector?," J. Phys. G **45**, no. 9, 095002 (2018), arXiv:1511.02531 [hep-ph].



[14] J. H. Kwapisz, "Asymptotic safety, the Higgs boson mass, and beyond the standard model physics," Phys. Rev. D **100**, no. 11, 115001 (2019), arXiv:1907.12521 [hep-ph].

[15] K. Kowalska, E. M. Sessolo and Y. Yamamoto, "Flavor anomalies from asymptotically safe gravity," Eur. Phys. J. C **81**, no. 4, 272 (2021), arXiv:2007.03567 [hep-ph].

[16] R. Bause, G. Hiller, T. Höhne, D. F. Litim and T. Steudtner, "B-anomalies from flavorful U$(1)'$ extensions, safely," Eur. Phys. J. C **82**, no. 1, 42 (2022), arXiv:2109.06201 [hep-ph].

[17] A. Chikkaballi, W. Kotlarski, K. Kowalska, D. Rizzo and E. M. Sessolo, "Constraints on Z' solutions to the flavor anomalies with trans-Planckian asymptotic safety," arXiv:2209.07971

[18] G. Hiller, C. Hormigos-Feliu, D. F. Litim and T. Steudtner, "Model building from asymptotic safety with Higgs and flavor portals," Phys. Rev. D **102**, no. 9, 095023 (2020), arXiv:2008.08606 [hep-ph].

[19] D. Barducci, M. Fabbrichesi, C. M. Nieto, R. Percacci and V. Skrinjar, "In search of a UV completion of the standard model — 378,000 models that don't work," JHEP **11**, 057 (2018), arXiv:1807.05584 [hep-ph].

[20] C. D. Carone and H. Murayama, "Possible light U(1) gauge boson coupled to baryon number," Phys. Rev. Lett. **74**, 3122 (1995), arXiv:hep-ph/9411256.

[21] C. D. Carone and H. Murayama, "Realistic models with a light U(1) gauge boson coupled to baryon number," Phys. Rev. D **52**, 484 (1995), arXiv:hep-ph/9501220.

[22] P. Fileviez Perez and M. B. Wise, "Baryon and lepton number as local gauge symmetries," Phys. Rev. D **82**, 011901 (2010) [Erratum: Phys. Rev. D **82**, 079901 (2010)], arXiv:1002.1754 [hep-ph].

[23] M. Duerr, P. Fileviez Perez and M. B. Wise, "Gauge theory for baryon and lepton numbers with leptoquarks," Phys. Rev. Lett. **110**, 231801 (2013), arXiv:1304.0576 [hep-ph].

[24] M. Duerr and P. Fileviez Perez, "Baryonic dark matter," Phys. Lett. B **732**, 101 (2014), arXiv:1309.3970 [hep-ph].

[25] P. Fileviez Perez, S. Ohmer and H. H. Patel, "Minimal theory for lepto-baryons," Phys. Lett. B **735**, 283 (2014), arXiv:1403.8029 [hep-ph].