Phenomenology with trans-Planckian asymptotic safety

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in collaboration with

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E. M. Sessolo, Y. Yamamoto

Eur.Phys.J.C 81 (2021) 4, 272 (arXiv: 2007.03567)
Phys. Rev. D 103, 115032 (2021) (arXiv: 2012.15200)
JHEP 01 (2023) 164 (arXiv: 2209.07971)
Eur.Phys.J.C 83 (2023) 7, 644 (arXiv: 2304.08959)

Workshop on Standard Model and Beyond, Corfu
31.08.2023

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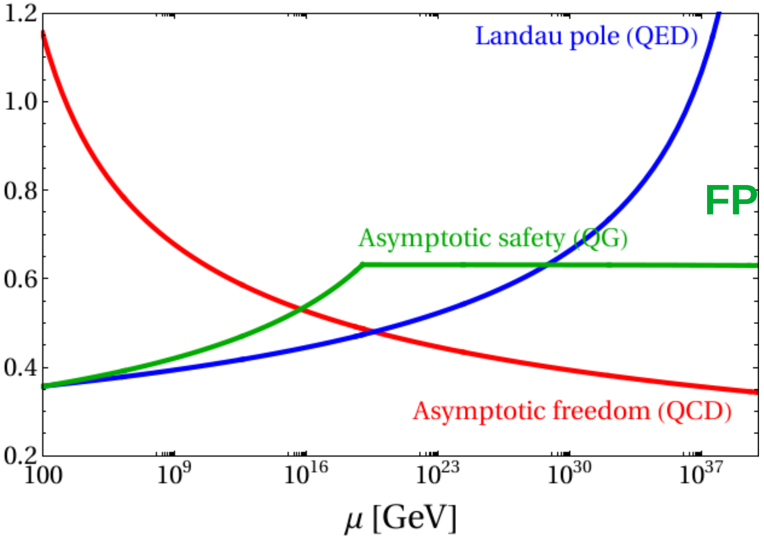
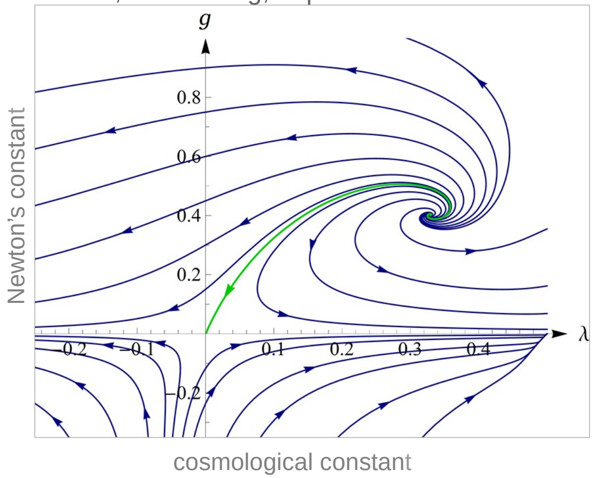
Asymptotic safety in a nutshell

Looking for hints from the UV for the IR model buidling

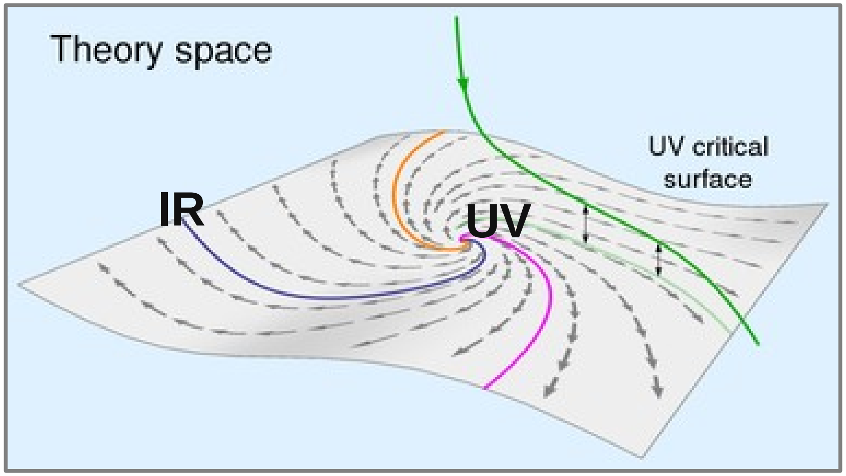


AS defines UV boundary conditions

Reuter, Saueressig, hep-th/0110054



AS inspired by quantum gravity



from Wikipedia (created by Andreas Nink)

Transmitted to the IR by the RGE flow

Trans-Planckian AS with matter

Gravity affects matter:

RGE system coupled to gravity

Modification to RGEs @ $k > M_{\mathrm{Pl}}$

$$\beta_g = \beta_g^{\mathrm{SM+NP}} - \boxed{g\, f_g}$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}} - \boxed{y\, f_y}$$

$$\beta_\lambda = \beta_\lambda^{\mathrm{SM+NP}} - \boxed{\lambda\, f_\lambda}$$

Quantum-gravitational contribution
(in principle via FRG)

[Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al.* '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16,Wetterich, Yamada '16, Hamada, Yamada '17, Pawlowski et al. '18, Eichhorn, Versteegen '17, Eichhorn, Held '17-'18 ...]

EXAMPLE : U(1) + Φ + E-H:

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

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FRG calculation of f_i has very large uncertainties ...

(truncation in number of operators, cut-off scheme dependence, higher-order loop corrections in matter)

[Lauscher, Reuter '02, Codello, Percacci, Rahmede '07-'08, Benedetti, Machado, Saueressig '09, Narain, Percacci '09, Dona', Eichhorn, Percacci '13, Falls, Litim, Schroeder '18, ...]

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Due to universality of *f*$_i$, existance of a FP is enough to get predictions for **irrelevant couplings**

Similar approach*: see, eg.,* Eichhorn, Held, 1707.01107, 1803.04027; Reichert, Smirnov, 1911.00012; Alkofer *et al.* 2003.08401, KK, Sessolo, Yamamoto, 2007.03567; KK, Sessolo, 2012.15200, Boos, Carone, Donald, Musser, 2006.02686

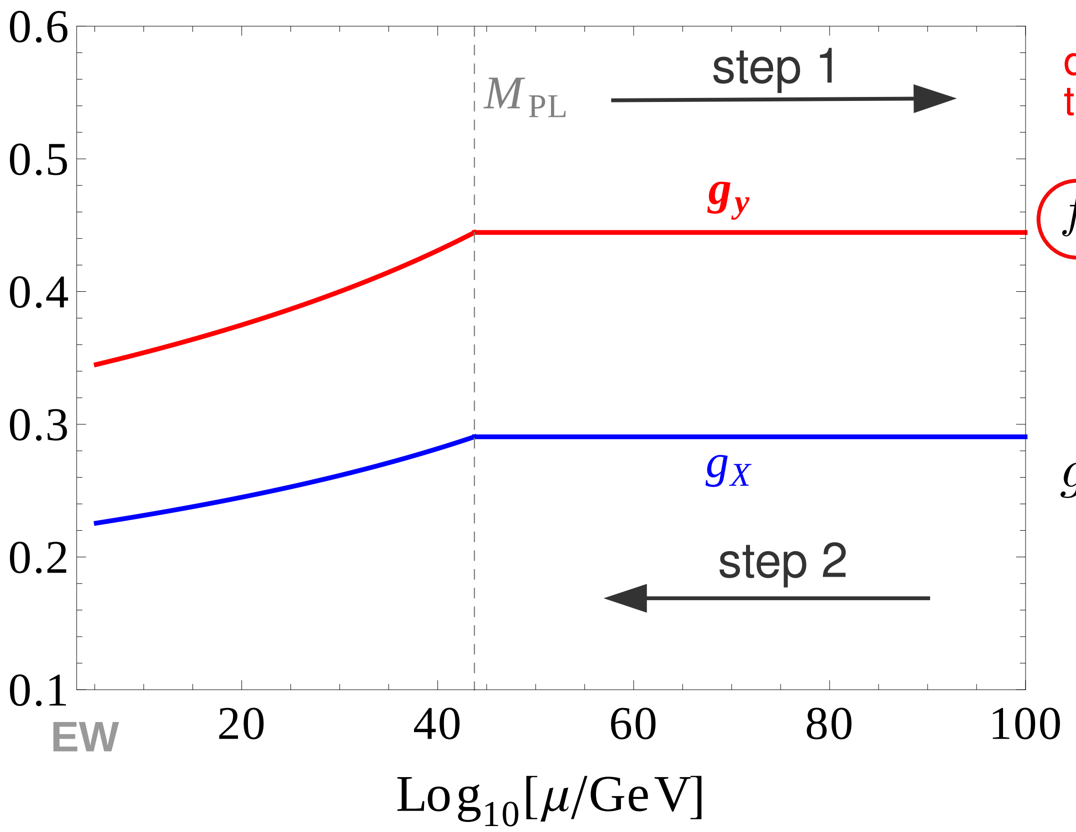
Strategy of getting predictions from AS

illustrative example:

SM + U(1)$_X$
$$\begin{cases} \dfrac{dg_Y}{dt} = \dfrac{41}{6}\dfrac{g_Y^3}{16\pi^2} - f_g g_Y \\ \dfrac{dg_X}{dt} = 11\dfrac{g_X^3}{16\pi^2} - f_g g_X \end{cases}$$

$g_Y(\mu_{EW})$
reference

$g_X(\mu_{EW})$
prediction



determined from
the matching

$$\boxed{f_g} = \frac{1}{4\pi}\sqrt{\frac{41\, g_1^*}{6}}$$

universality

$$g_X^* = 4\pi\sqrt{\frac{f_g}{11}}$$

Predictions for NP from AS

New Physics

fixed point for dimensionless NP couplings

NP couplings irrelevant
predictions in IR

Experimental anomaly

$$\frac{\mathcal{C}_{\text{NP}}}{\Lambda^n} \approx \frac{c_i c_j}{m_{\text{NP}}^n} \times \text{loop factor}$$

Predictions for NP masses

(relevant parameters not constrained by AS)

AS leads to specific and testable signatures

Predictions from AS: muon (g-2)

Measured value at BNL (2006):

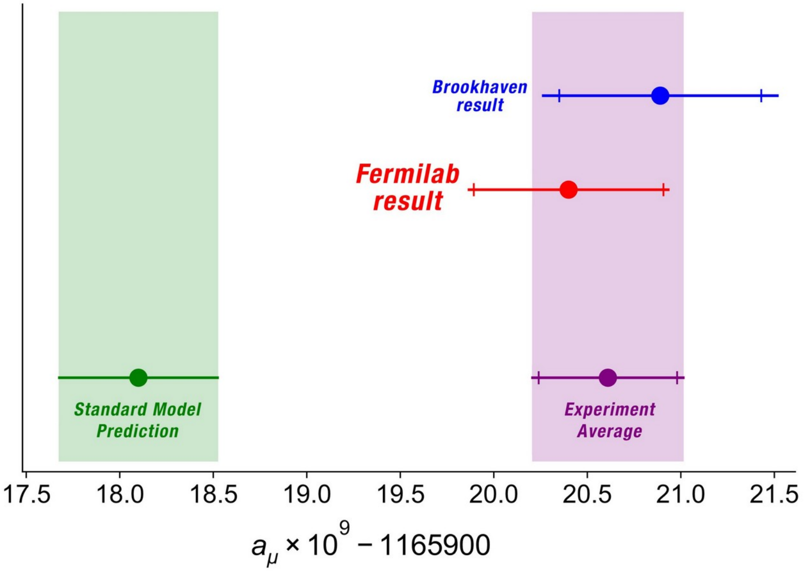
Bennet *et al*, Phys. Rev. D 73 (2006) 072003 (hep-ex/0602035)

$$a_\mu^{\mathrm{BNL}} = (116592089 \pm 63) \times 10^{-11}$$

Measured value at FNAL (2021,2023):

Muon g-2 Collaboration, Phys. Rev. Lett. 126 (2021) 141801
D. P. Aguillard et al. (Muon g-2) (2023), arXiv:2308.06230

$$a_\mu^{\mathrm{FNAL}} = (116592055 \pm 24) \times 10^{-11}$$



$$\boxed{\Delta\, a_\mu = (24.9 \pm 4.8) \times 10^{-10}}$$

discrepancy at ~ 5.1 σ

Calls for a NP explanation...

… although stay tuned for the lattice results

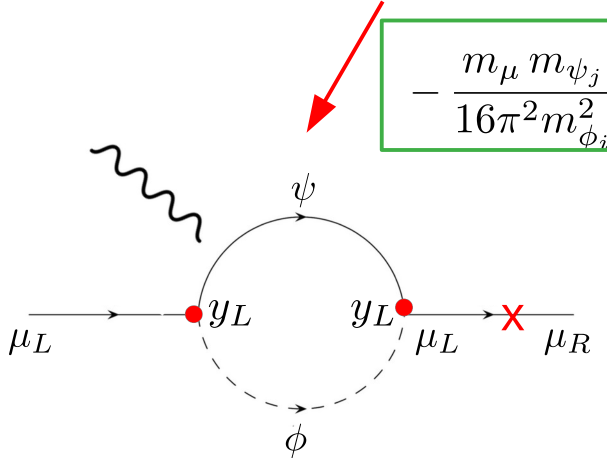
Predictions from AS: muon (g-2)

1-loop contribution from scalar(s) ϕ_i and VL fermions ψ_j

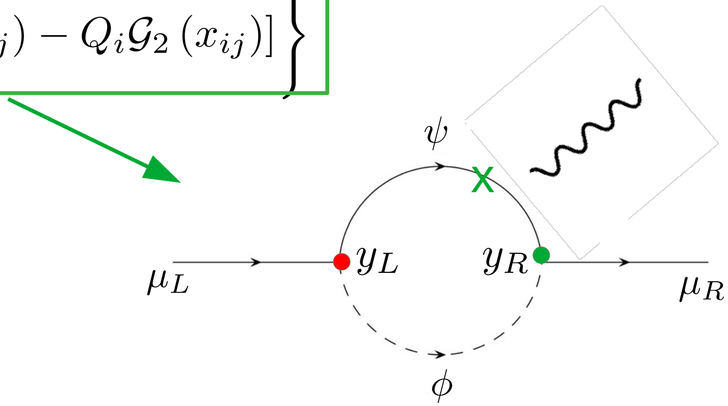
$$\delta(g-2)_\mu = \sum_{i,j}\left\{\boxed{-\frac{m_\mu^2}{16\pi^2 m_{\phi_i}^2}\left(|y_L^{ij\mu}|^2+|y_R^{ij\mu}|^2\right)\left[Q_j\mathcal{F}_1\left(x_{ij}\right)-Q_i\mathcal{G}_1\left(x_{ij}\right)\right]}\right.$$

$$\left.\boxed{-\frac{m_\mu\, m_{\psi_j}}{16\pi^2 m_{\phi_i}^2}\mathrm{Re}\left(y_L^{ij\mu}y_R^{ij\mu*}\right)\left[Q_j\mathcal{F}_2\left(x_{ij}\right)-Q_i\mathcal{G}_2\left(x_{ij}\right)\right]}\right\}$$

$x_{ij} = m_{\psi_j}^2/m_{\phi_i}^2$



- minimal: 1 VL lepton and 1 scalar
- $m_\psi,\, m_\phi \sim \mathcal{O}(100\,\mathrm{GeV})$
- Yukawa couplings > 1
- **excluded by the LHC** see P. Athron et al., 2104.03691 for the most recent results
- **Landau Pole** e.g. KK. E.Sessolo, 1707.00753



- 2 VL + 1 S or 1 VL + 2 S needed
- parametrically enhanced
- LHC bounds easily avoided...

… but PS largely unconstrained

Predictions from AS: muon (g-2)

KK, E.M.Sessolo (PRD ’21, arXiv: 2012.15200)

minimal SM extension: two <u>different</u> VL leptons + extra scalar

extra assumption: a DM particle and a symmetry to stabilize it

$$\mathcal{L}_{\rm NP} \supset \left(Y_R\, \mu_R E' S + Y_L\, F' S^{\dagger} l_{\mu} + Y_1\, E\, h^{\dagger} F + Y_2\, F' h\, E' + \mathrm{H.c.}\right)$$

Minimally coupled to QG above the Planck scale

$$\frac{dg_Y}{dt} = \frac{g_Y^3}{16\pi^2} B_Y - \underline{f_g\, g_Y}$$

$$\frac{dy_t}{dt} = \frac{1}{16\pi^2}\left[\frac{9}{2} y_t^2 + C_1 (Y_1^2 + Y_2^2) - \frac{17}{12} g_Y^2 - \frac{9}{4} g_2^2 - 8 g_3^2\right] y_t - \underline{f_y\, y_t}$$

$$\frac{dY_1}{dt} = \frac{1}{16\pi^2}\left[3y_t^2 + C_3\, Y_2^2 + \frac{5}{2} C_1\, Y_1^2 + C_6\, Y_L^2 + C_7\, Y_R^2 - G_Y\, g_Y^2 - G_2\, g_2^2\right] Y_1 - f_y\, Y_1$$

$$\frac{dY_2}{dt} = \frac{1}{16\pi^2}\left\{\left[3y_t^2 + \frac{5}{2} C_1\, Y_2^2 + C_3\, Y_1^2 + C_4\, Y_L^2 + \frac{1}{2} Y_R^2 - G_Y\, g_Y^2 - G_2\, g_2^2\right] Y_2 + C_5\, y_\mu\, Y_L\, Y_R\right\} - f_y\, Y_2$$

$$\frac{dY_L}{dt} = \frac{1}{16\pi^2}\left\{\left[C_4\, Y_2^2 + C_6\, Y_1^2 + C_8\, Y_L^2 + C_9\, Y_R^2 + \frac{1}{2} y_\mu^2 - H_Y\, g_Y^2 - H_2\, g_2^2\right] Y_L + C_5\, y_\mu\, Y_R\, Y_2\right\} - f_y\, Y_L$$

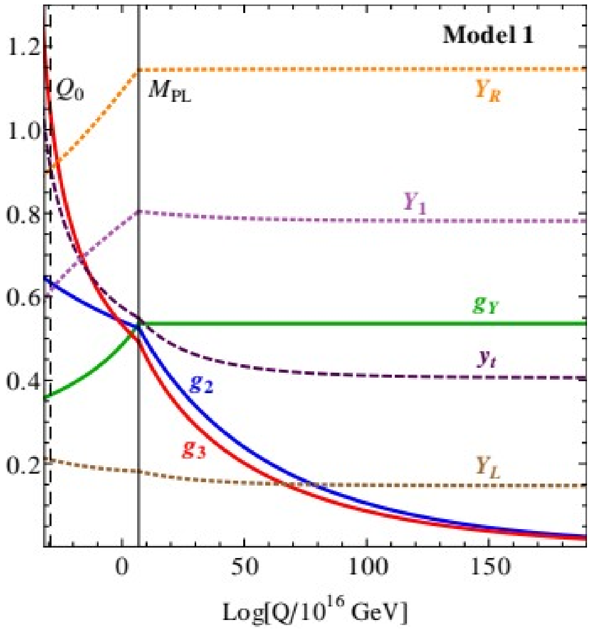
$$\frac{dY_R}{dt} = \frac{1}{16\pi^2}\left\{\left[Y_2^2 + 2\, C_7\, Y_1^2 + 2\, C_9\, Y_L^2 + C_{10}\, Y_R^2 + y_\mu^2 - J_Y\, g_Y^2 - J_2\, g_2^2\right] Y_R + 2\, C_5\, y_\mu\, Y_L\, Y_2\right\} - f_y\, Y_R$$

Predictions from AS: muon (g-2)

KK, E.M.Sessolo (PRD ’21, arXiv: 2012.15200)

IR predictions ←

	$Y_L(Q_0)$	$Y_R(Q_0)$	$Y_1(Q_0)$	$Y_2(Q_0)$
M_1	0.21	0.91	0.62	9×10^{-4}
M_2	0.65	0.59	0.03	6×10^{-4}
M_3	0.01	0.77	0.18	3×10^{-5}
M_6	0.04	0.78	0.65	9×10^{-5}
M_{10}	0.98	0.87	0.03	1×10^{-3}



UV fixed point

$$Y_R^* \neq 0$$

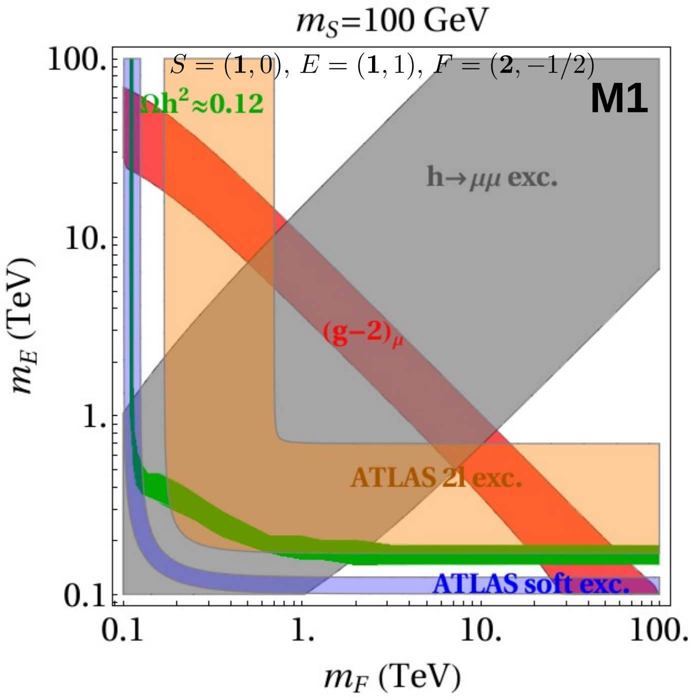
$$Y_1^* \neq 0$$

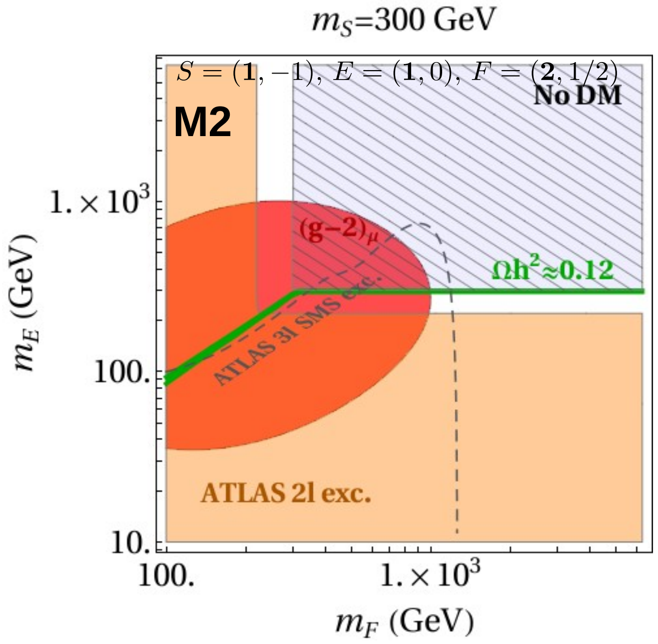
$$g_Y^* = 4\pi\sqrt{\frac{f_g}{B_Y}}$$

$$y_t^* = F(f_g, f_y)$$

$$Y_L^* \neq 0$$

free parameters: $m_S,\ m_E,\ m_F$





1) Fundamentally different and testable signatures.

Entirely consequence of asymptotic safety.

2) Relevant parameters constrained.

Other BSM predictions can be made...

- **anomalies in *b* → *s***

  KK, E.M.Sessolo, Y.Yamamoto,
  Eur.Phys.J.C 81 (2021) 4, 272

  A.Chikkaballi, W. Kotlarski, KK, D.Rizzo, E.M.Sessolo,
  JHEP 01 (2023) 164

- **anomalies in *b* → *c***

  KK, E.M.Sessolo, Y.Yamamoto,
  Eur.Phys.J.C 81 (2021) 4, 272

- **neutrino masses**

  KK, S.Pramaick, E.M.Sessolo,
  JHEP 08 (2022) 262

  A.Chikkaballi, KK, E.M.Sessolo,
  arXiv: 2308.06114

Also gravitational wave signals!

E.Sessolo's talk

- **dark matter, baryon number, ALPs, GWs**

  see eg. Reichert, Smirnov, 1803.04027; Grabowski, Kwapisz, Meissner, 1810.08461; Hamada, Tsumura, Yamada, 2002.03666, Eichhorn, Pauly, 2005.03661; de Brito, Eichhorn, Lino dos Santos, 2112.08972, Boos, Carone, Donald, Musser, 2206.02686, 2209.14268, Eichhorn, dos Santos, Miqueleto, 2306.17718, ….

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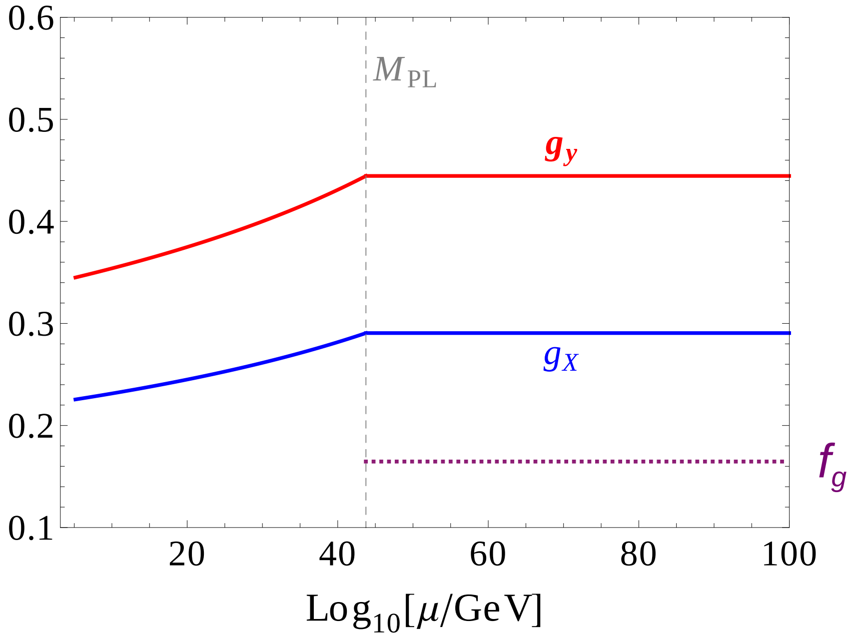
Predictions for NP - assumptions

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC ’23, arXiv: 2304.08959

- 1-loop matter RGEs
- Planck scale set at 10^{19} GeV
- Gravity parameters *f* are constant
- Gravity decouples instantaneously



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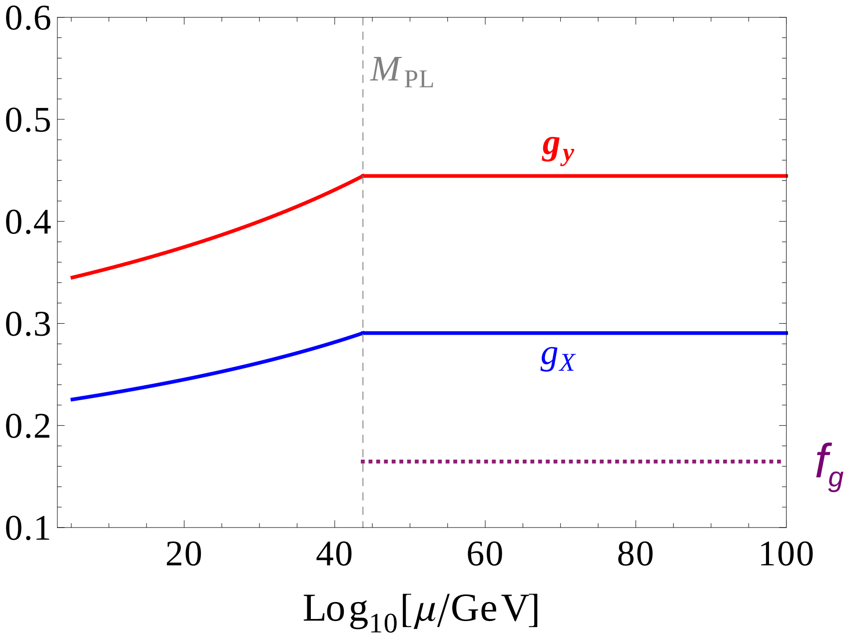
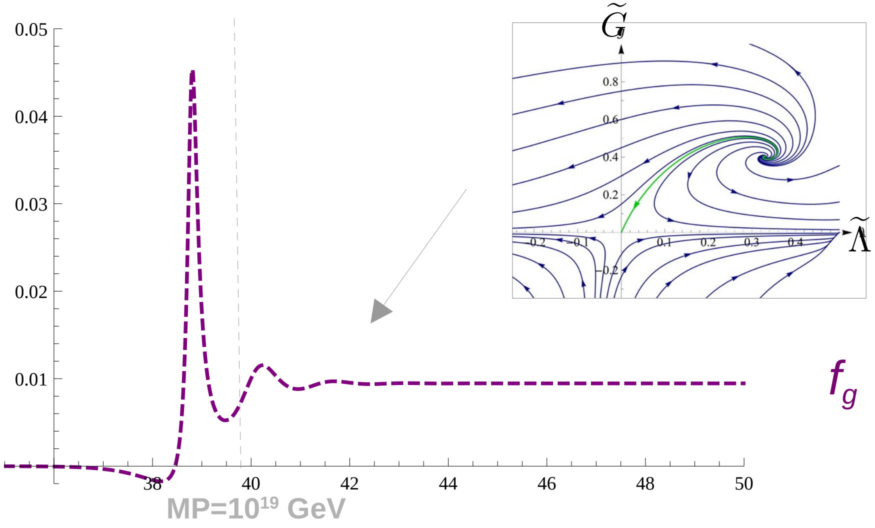


But in FRG:

eg. EH truncation, α=0, β=1 g.f
A. Eichhorn, F. Versteegen, JHEP 01 (2018) 030

$$f_g(t) = \tilde{G}(t)\frac{1-4\tilde{\Lambda}(t)}{4\pi\left(1-2\tilde{\Lambda}(t)\right)^2}$$



Let’s drop the assumptions...

Uncertainties – gauge sector

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

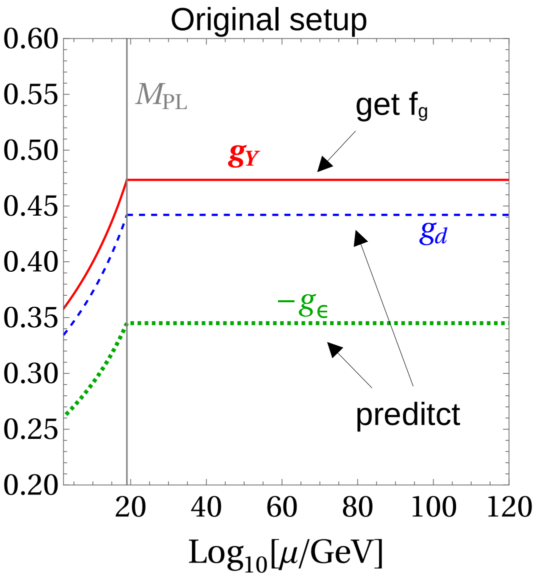
eg. $U(1)_Y \times U(1)_D$

Recall B-L from E.Sessolo's talk

$$\frac{dg_Y}{dt} = \frac{1}{16\pi^2}\overbrace{\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right)}^{\tilde{b}_Y} g_Y^3 - g_Y\, f_g(t)$$

$$\frac{dg_d}{dt} = \frac{1}{16\pi^2}\left[\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right) g_d g_\epsilon^2 + \left(b_d + \Pi^{(d)}_{n\geq 2}\right) g_d^3 + \left(b_\epsilon + \Pi^{(\epsilon)}_{n\geq 2}\right) g_d^2 g_\epsilon\right] - g_d\, f_g(t)$$

$$\frac{dg_\epsilon}{dt} = \frac{1}{16\pi^2}\left[\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right)\left(g_\epsilon^3 + 2g_Y^2 g_\epsilon\right) + \left(b_d + \Pi^{(d)}_{n\geq 2}\right) g_d^2 g_\epsilon \right.$$
$$\left. + \left(b_\epsilon + \Pi^{(\epsilon)}_{n\geq 2}\right)\left(g_Y^2 g_d + g_d g_\epsilon^2\right)\right] - g_\epsilon\, f_g(t)$$



The coupling ratios do not depend on f_g

(due to the universality of QG)

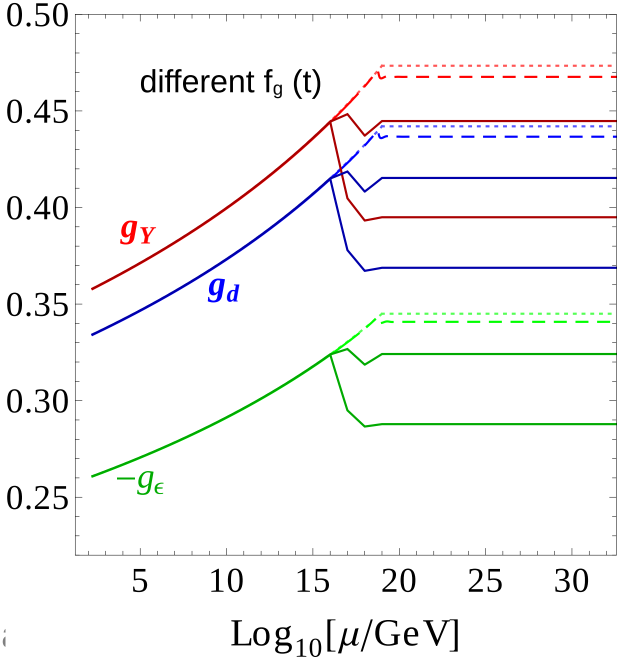
$$\frac{g_d^*}{g_Y^*}(n\ \text{loops}) \approx \frac{2\tilde{b}_Y}{\sqrt{4\tilde{b}_Y\tilde{b}_d - \tilde{b}_\epsilon^2}}$$

$$\frac{g_\epsilon^*}{g_Y^*}(n\ \text{loops}) \approx -\frac{\tilde{b}_\epsilon}{\sqrt{4\tilde{b}_Y\tilde{b}_d - \tilde{b}_\epsilon^2}}$$

Invariant of the RGE flow

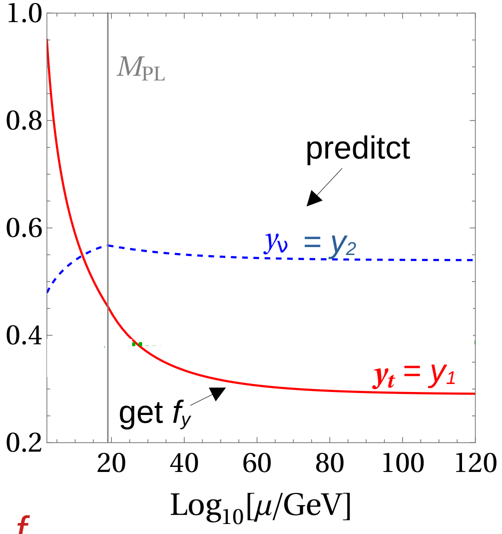
PREDICTIONS VERY STABLE

δg ≤ 0.1%



Uncertainties – Yukawa sector

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC ’23, arXiv: 2304.08959



<u>2-Yukawa system</u>

$$\frac{dy_1}{dt} = \frac{y_1}{16\pi^2}\left(a_1^{(1)} y_1^2 + a_2^{(1)} y_2^2 - a'^{(1)} g_1^2 + \sum_{n\geq 2}\Pi_n^{(1)}\right) - y_1 f_y(t)$$

$$\frac{dy_2}{dt} = \frac{y_2}{16\pi^2}\left(a_1^{(2)} y_1^2 + a_2^{(2)} y_2^2 - a'^{(2)} g_1^2 + \sum_{n\geq 2}\Pi_n^{(2)}\right) - y_2 f_y(t)$$

The FP ratio y_2 to y_1 depends on FP of other couplings

$$\frac{y_2^*}{y_1^*}(1\ \mathrm{loop}) \approx \left[\overbrace{\frac{\left(a_1^{(2)} - a_1^{(1)}\right) + \left(a'^{(1)} - a'^{(2)}\right) g_1^{*2}/y_1^{*2}}{a_2^{(1)} - a_2^{(2)}}}^{\text{fixed } f_g \text{ and } f_y} + \overbrace{\frac{\left(a_1^{(2)} - a_1^{(1)}\right)\delta y_1^{*2} + \left(a'^{(1)} - a'^{(2)}\right)\delta g_1^{*2}}{y_1^{*2}\left(a_2^{(1)} - a_2^{(2)}\right)}}^{\text{shift due to the running } f_g,\ f_y}\right]^{1/2}$$

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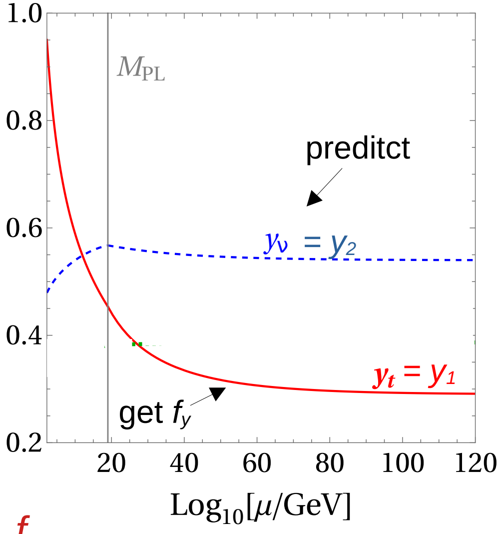

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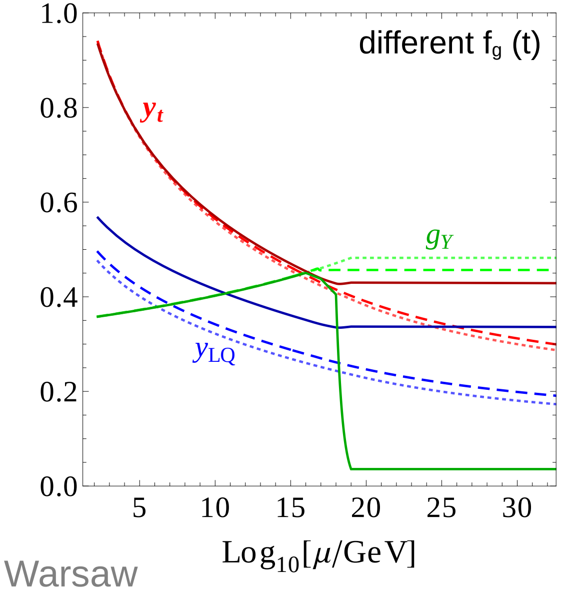
eg. LQ S_3 model:

$$\mathcal{L} \supset -Y_{\rm LQ}\, Q^T \tilde{\epsilon} S_3\, L + \text{H.c.}$$



PREDICTION UNSTABLE ...

Uncertainties – Yukawa sector

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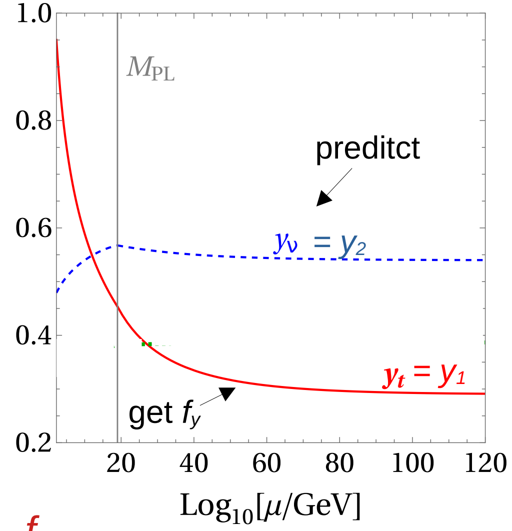


$$\frac{dy_1}{dt} = \frac{y_1}{16\pi^2}\left(a_1^{(1)} y_1^2 + a_2^{(1)} y_2^2 - a'^{(1)} g_1^2 + \sum_{n\geq 2}\Pi_n^{(1)}\right) - y_1 f_y(t)$$

$$\frac{dy_2}{dt} = \frac{y_2}{16\pi^2}\left(a_1^{(2)} y_1^2 + a_2^{(2)} y_2^2 - a'^{(2)} g_1^2 + \sum_{n\geq 2}\Pi_n^{(2)}\right) - y_2 f_y(t)$$

The FP ratio y_2 to y_1 depends on FP of other couplings

$$\frac{y_2^*}{y_1^*}(1\ \text{loop}) \approx \left[\overbrace{\frac{\left(a_1^{(2)} - a_1^{(1)}\right) + \left(a'^{(1)} - a'^{(2)}\right) g_1^{*2}/y_1^{*2}}{a_2^{(1)} - a_2^{(2)}}}^{\text{fixed } f_g \text{ and } f_y} + \overbrace{\frac{\left(a_1^{(2)} - a_1^{(1)}\right)\delta y_1^{*2} + \left(a'^{(1)} - a'^{(2)}\right)\delta g_1^{*2}}{y_1^{*2}\left(a_2^{(1)} - a_2^{(2)}\right)}}^{\text{shift due to the running } f_g,\ f_y}\right]^{1/2}$$

eg. LQ S_3 model:

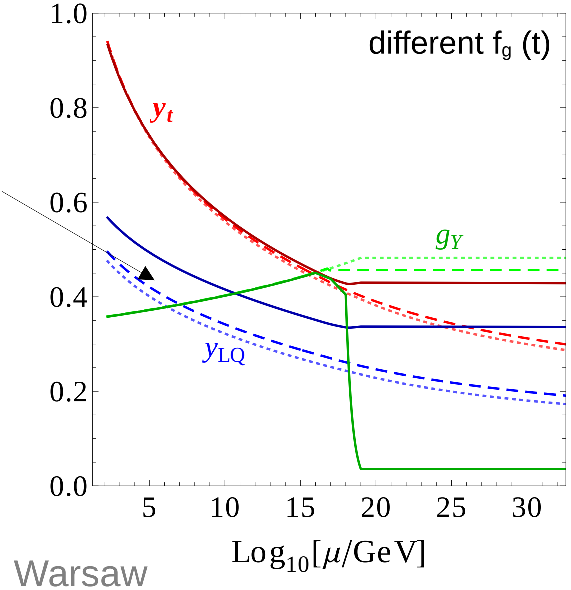
$$\mathcal{L} \supset -Y_{\text{LQ}}\, Q^T \tilde{\epsilon} S_3\, L + \text{H.c.}$$

... but not so much in FRG

... IR focusing helps

PREDICTION UNSTABLE ...

δy ≤ 20%



Conclusions

- Trans-Planckian AS is a **very predictive UV framework.** Applications for SM and NP.
- **AS predictions** in the **gauge sector** are **stable** under higher-order corrections and running of the gravity parameters.
- **Uncertainties** of the AS predictions in **the Yukawa sector** do **not exceed 20%**.
- Flavor anomalies, *g-2* anomaly, dark matter, etc. can lead to very **testable signatures**.