Universal Landau Pole

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Outline:

- **Do we really need asymptotic freedom?**
  Our understanding of quantum gravity suggests that at the Planck scale the usual geometry loses its meaning. Then grand unification in a large non-abelian group naturally endowed with the property of asymptotic freedom may also lose its motivation.

- **Singular unification:**
  an unification of all fundamental interactions at the Planck scale in the form of a **Universal Landau Pole (ULP)**, at which all gauge couplings diverge.

- **Minimal working model of the Universal Landau Pole.**
  The unification is achieved with the addition of fermions with vector gauge couplings coming in multiplets and with hypercharges identical to those of the Standard Model.

- **Stability of the Higgs Potential.**
  The Higgs quartic coupling diverges while the Yukawa couplings vanish.
DO WE REALLY NEED ASYMPTOTIC FREEDOM?

- Simplicity: the less parameters the better $\rightarrow$ unification.

- Asymptotic freedom (flat space-time): the theory is valid up to infinitely high energies.

- BUT what about gravity?

- At the energies of order of Planck scale $M_{Pl} \sim 10^{19}$ GeV gravity becomes strongly coupled, concept of weakly interacting point-like fields looses its meaning!

- Simplicity $+$ pointless geometry $\rightarrow$ singular unification.
SINGULAR UNIFICATION: UNIVERSAL LANDAU POLE

• We propose a singular unification at the Planck scale: one should find such a generalization of the Standard Model, that under the renormalization group flow ALL gauge couplings meet their common Landau pole at the Planck scale.

\[ g_{1,2,3}(\mu) \to \infty \text{ at } \mu \to M_{Pl} \]

• Kinetic terms of ALL gauge fields vanish and they cannot propagate anymore.

\[ \frac{1}{g(\mu)^2} F_{\mu\nu} F^{\mu\nu} \to 0 \text{ at } \mu \to M_{Pl} \]

• ? UV fixed point and dimensional reduction of gauge fields?

\[ F_{\mu\nu} \left( \frac{1}{g(\mu)^2} + \gamma \frac{\Box}{M_{Pl}^2} + \cdots \right) F^{\mu\nu} \to \gamma F_{\mu\nu} \frac{\Box}{M_{Pl}^2} F^{\mu\nu} \text{ at } \mu \to M_{Pl} \]
MINIMAL ULP: REQUIREMENTS

- **Simplicity**: the gauge group of SM $SU(3) \times SU(2) \times U(1)$. We add only fermions. Enlarging the gauge group in principle could be motivated by introduction of a GUT group. However it leads to ULP at $10^{16}$ GeV [see V. A. Rubakov and S. V. Troitsky, hep-ph/0001213, for a review] much smaller than $M_{Pl}$.

- **Higgs sector**: to remain unchanged. If the new particles are described by 4-component spinors with Dirac masses and vector-like gauge interactions $\rightarrow$ no necessity for any Higgs fields. It fits well the recent LHC bounds on the number of generations [see A. Lenz, Adv. High En. Phys. 2013 (2013) 910275 ]

- **NO pathological electric charges** $\rightarrow$ restrictions on the representations of new fermions.

- **Stability**: quartic coupling of the Higgs field self interaction $\lambda$ is always positive under the renormalization group flow. It discriminates a single scenario with four generations.
MINIMAL WORKING ULP: REALIZATION

• **We use Dirac mass terms** \( M \overline{\psi} \psi \) **for new fermions and we are looking for a minimal number of them.**

• **New fermions belong to known representations of gauge group**

  L-quarkons: \( \text{SU}(3) \) - triplets, \( \text{SU}(2) \) - doublets, \( Y = \frac{1}{3} \)

  R-quarkons: \( \text{SU}(3) \) - triplets, \( \text{SU}(2) \) - singlets, \( Y = \frac{4}{3}, \ -\frac{2}{3} \)

  L-leptos: \( \text{SU}(3) \) - singlets, \( \text{SU}(2) \) - doublets, \( Y = -1 \)

  R-leptos: \( \text{SU}(3) \) - singlets, \( \text{SU}(2) \) - singlets, \( Y = -2, \ 0 \)

• **Remark:** L- and R- notations do not imply left and right chiralities! They vector-like relatives.
MINIMAL WORKING ULP: REALIZATION

The only new vertexes appearing in the theory couple Quarkons and Leptos to E-W gauge bosons and gluons.

And at one loop level only beta functions of gauge fields are modified due to presence of these diagramms:
MINIMAL WORKING ULP: THE ANSWER

ULP can be rendered within 4 identical ”generations” of new vector-like massive fermions with different mass scales:

- **At** $5.0 \cdot 10^3$ GeV L-quarkons ($N_{L-\text{quarkon}} = 4$).
- **At** $3.7 \cdot 10^7$ GeV R-quarkons ($N_{R-\text{quarkon}} = 4$).
- **At** $2.6 \cdot 10^{14}$ GeV L and R-leptos ($N_{L-\text{leptos}} = N_{R-\text{leptos}} = 4$).
One(two)-loop RG running of gauge couplings
One(two)-loop RG running of top Yukawa coupling
ON THE STABILITY OF THE HIGGS POTENTIAL

Now we clarify how our vector-like fermions save the Universe from instability, i.e. how they don’t let RG flow to drive the quartic coupling $\lambda(\mu)$ to negative values.

$$\beta^{(1)}_\lambda = \frac{1}{16\pi^2} \left( 24 \lambda^2 - 6 y^4 + \frac{3}{4} g_2^4 + \frac{3}{8} (g_2^2 + g_1^2)^2 ight)$$

$$+ \left(-9 g_2^2 - 3 g_1^2 + 12 y^2\right) \lambda.$$
One(two)-loop RG running of Higgs boson quartic coupling

\[ \lambda = \log_{10} \left( \frac{\mu}{GeV} \right) \]
UV completion

It could well be the case that the onset of gravity corrections renders the ULP non-singular. Indeed gravity being non-renormalizable will require higher-dimensional operators with more derivatives to make the theory finite. In particular, we expect dimension six kinetic terms like

\[
\frac{\gamma}{2M_P^2} \text{tr} (D_\mu W^{\mu\nu} D_\mu W^{\mu\nu}) + \cdots
\]

This would correspond to a renormalization of the gauge coupling induced by gravity of the form

\[
\frac{1}{g^2(p^2)} \simeq \beta_0 \log \frac{m_P^2}{p^2} + \gamma \frac{p^2}{m_P^2}
\]

Thus gravitational corrections may drive the ULP towards a new fixed point [see, for instance, M. E. Shaposhnikov, Theor. Math. Phys. 170, 229 (2012)].
CONCLUSIONS

- An idea of singular unification of ALL gauge interactions at the Planck scale, can be realized in the form of the Universal Landau Pole (ULP).

- The minimal working model of ULP generalization of the SM is constructed.

- Under the RG flow the top Yukawa coupling eventually goes to zero while the quartic coupling has a concordant singularity at the Planck scale. Such a RG behavior saves the Universe from instability problem.
• Yukawa couplings for quarks and leptons run to zero differently: the latter for leptons are diminishing more slowly (due to lack of gluon contribution). Thereby the ULP unification may give a partial resolution of fermion mass hierarchy problem in the range of strong gauge couplings (AEKL, in progress).

• For this problem the two-loop contribution may be essential (in progress).