TRIUMF

Effective field theory breakdown of varying coupling constants

Carlos Henrique de Lima

arxiv:2411.xxxx

Dark Interactions 2024

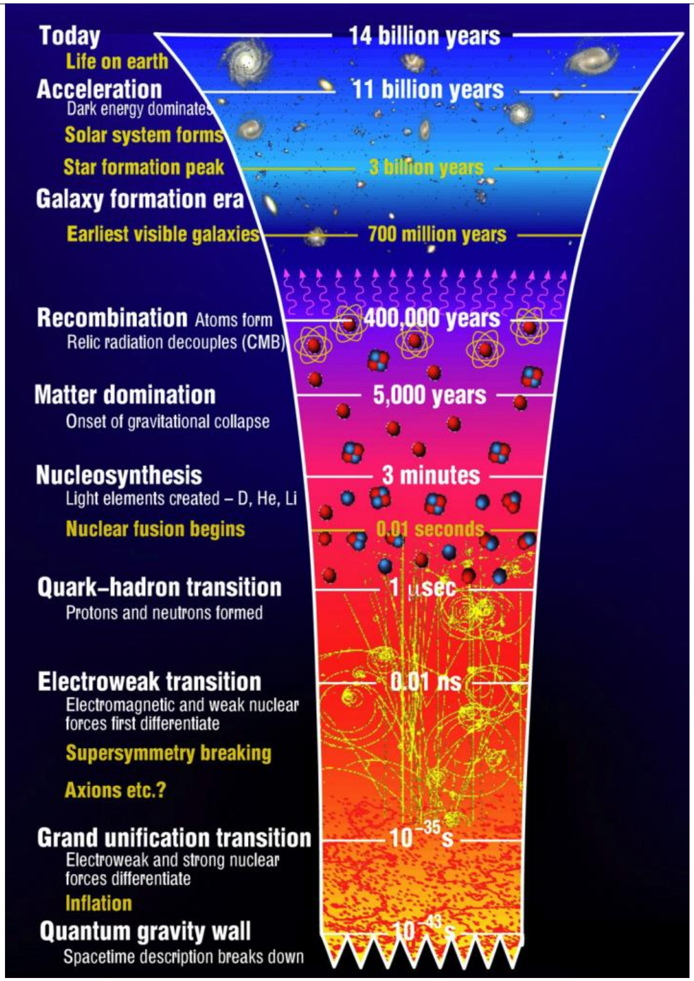
In collaboration with: Michael Shamma, David McKeen and David Morrissey

Motivation

- Little is known from the period before electroweak phase transition

- The dynamics of the early universe could have been **drastically different** than the standard cosmological history.

- The **strength of the interactions** could be significantly different probing new phases of matter.



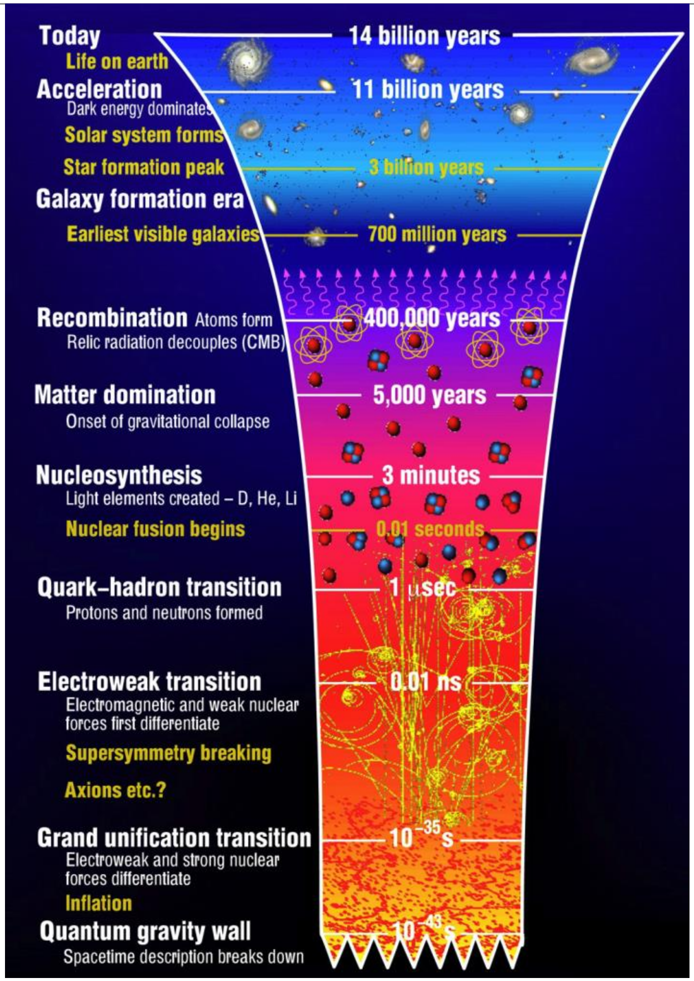
Stephen Hawking Centre for Theoretical Cosmology

Motivation

- Drastic changes on fundamental couplings can trigger these nonstandard phases.

- How can we describe these scenarios with **dynamically changing couplings**?

- How **consistent** are these scenarios and what can we learn for model building this class of dark sectors?



Stephen Hawking Centre for Theoretical Cosmology

Standard picture of varying coupling constants

Low energy EFT

- Focus on **SU(N)** gauge coupling

- In most scenarios a **singlet field** is introduced with an induced interaction to the SU(N) gauge boson

$$\mathcal{L} \supset \frac{c_5}{2}\frac{\phi}{\Lambda}\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

- The low energy description in this scenario has only **one additional degree of freedom**.

- Highly motivated by many UV completions: Higgs-like, dilaton, extra dimensions/string theory

Low energy EFT

- In this picture a **nontrivial dynamics** of ϕ would create a nontrivial profile for the gauge coupling:

$$\mathcal{L} \subset -\frac{1}{2}\left(\frac{1}{g^2} - c_5\frac{\phi}{\Lambda}\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

- We can define then the commonly used **field-dependent coupling**:

$$\frac{1}{g_{\mathrm{eff}}^2} = \frac{1}{g^2} - c_5\frac{\langle\phi\rangle}{\Lambda}$$

Low energy EFT

- Drastic changes of couplings implies $\langle\phi\rangle \sim \Lambda$, is this description complete?

$$\mathcal{L} \subset -\frac{1}{2}\left(\frac{1}{g^2} - c_5\frac{\phi}{\Lambda}\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

Low energy EFT

- Drastic changes of couplings implies **$\langle\phi\rangle \sim \Lambda$**, is this description complete?

$$\mathcal{L} \supset -\frac{1}{2}\left(\frac{1}{g^2} - c_5\frac{\phi}{\Lambda}\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

- NO! **The EFT breaks down on this regime**!

$$\mathcal{L} \supset -\frac{1}{2}\left(\frac{1}{g^2} - \sum_n c_n\left(\frac{\phi}{\Lambda}\right)^n\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

- Can we still say something meaningful on this regime? **We need to go to the UV**

UV completions and their low energies

Generic UV completion

- **Rules**:
  - The low energies is described by **4d QFT**, including the approach to the UV scale.
  - The low energy must contain **only** the singlet ϕ.
  - To generate the higher-dimensional operator, whatever is on the loop must be **charged under SU(N)**.

UV completion with heavy charged states

- Let us assume one heavy vector-like fermion in a representation R of an SU(N) gauge theory with mass M_F generated by a real singlet field ϕ

- The theory has two distinct phases:
  - **Low energy** with only gauge field and the singlet
  - **High energy** with gauge field, singlet and the heavy fermion.

UV completion with heavy charged states

- Considering the effect of the heavy fermion, we have a contribution to the field strength renormalization of the gauge field and can describe the UV and IR theory by the following lagrangians

$$\mathcal{L}_{UV} = -\frac{1}{2}\left(\frac{1}{g(M_F)^2} - \frac{1}{8\pi^2}\beta^0(F)\ln\left(\frac{M_F}{\mu}\right)\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

$$\mathcal{L}_{IR} = -\frac{1}{2}\left(\frac{1}{g(M_F)^2} - \frac{1}{8\pi^2}\beta^0(0)\ln\left(\frac{\mu}{M_F}\right)\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

$$\beta_F(g) = -\frac{g^3}{(4\pi)^2}\left(\frac{11}{3}N - \frac{2}{3}S_2(F)\right) = -\frac{g^3}{(4\pi)^2}\beta^0(F)$$

UV completion with heavy charged states

- The interaction between the singlet and the gauge boson can be recovered at one-loop by the following identification

$$M_F \to M_F\left(1+\frac{\phi}{\langle\phi\rangle}\right)$$

- We obtain the low energy interaction between the singlet and the gauge field

$$\mathcal{L}_{EFT} = -\frac{1}{2}\left(\frac{1}{g(M_F)^2} - \frac{1}{8\pi^2}\beta^0(F)\ln\left(1+\frac{\phi}{\langle\phi\rangle}\right)\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

$$\beta_F(g) = -\frac{g^3}{(4\pi)^2}\left(\frac{11}{3}N - \frac{2}{3}S_2(F)\right) = -\frac{g^3}{(4\pi)^2}\beta^0(F)$$

UV completion with heavy charged states

- We recover the dimension-5 operator for small fluctuations, but higher-order operators appear on equal footing for large fluctuations

$$\mathcal{L}_{EFT} = -\frac{1}{2}\left(\frac{1}{g(M_F)^2} - \frac{1}{8\pi^2}\beta^0(F)\ln\left(1+\frac{\phi}{\langle\phi\rangle}\right)\right)\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right)$$

- Given a nontrivial dynamics of the singlet field, the changes are entirely described by a **dynamical RG equation with changing thresholds**!

Can we have early weak confinement?

SU(2) example: Early weak confinement

- What if the weak interaction were strong in the early universe?

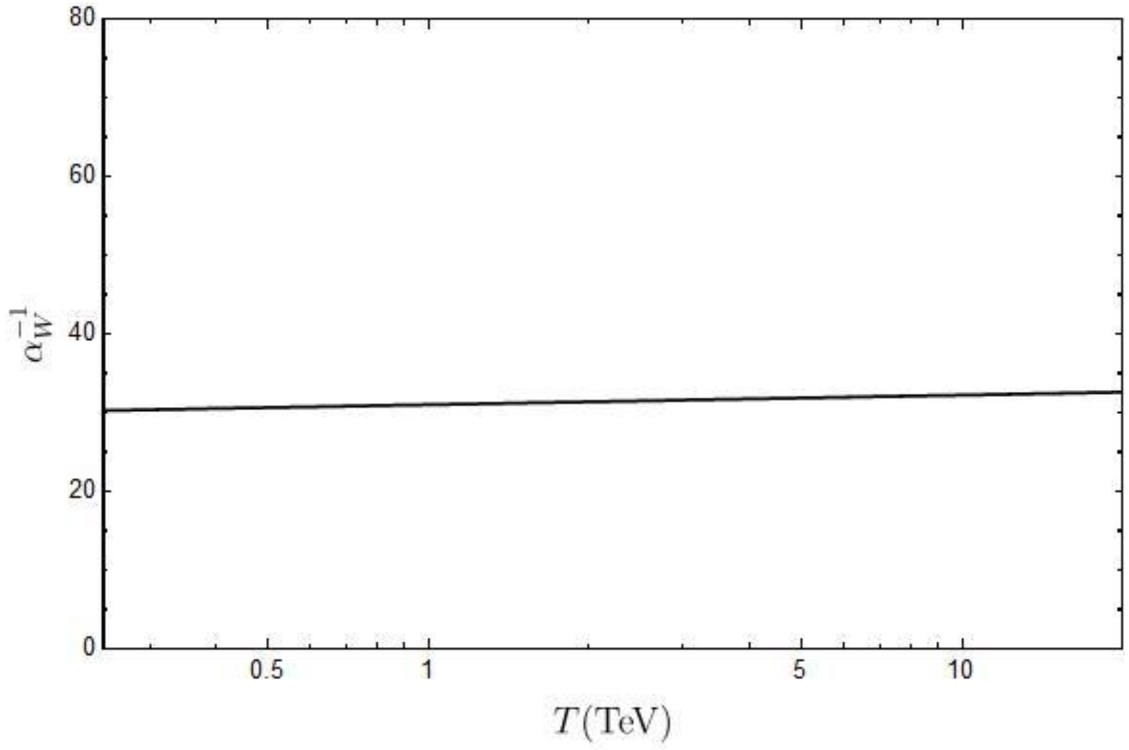
- Let us work out how this could be implemented and the differences between the linear expectation vs full EFT

- Consider a generic framework where we are free to change the singlet vev to whatever value that we want.

L.F. Abbott, E.Farhi **1981**
Sebastian A.R. Ellis, Seyda Ipek, Graham White **2019**
Joshua Berger, Andrew J. Long, Jessica Turner **2019**
Nakarin Lohitsiri, David Tong, **2019**
Jessica N. Howard, Seyda Ipek, Tim M.P. Tait, Jessica Turner **2022**

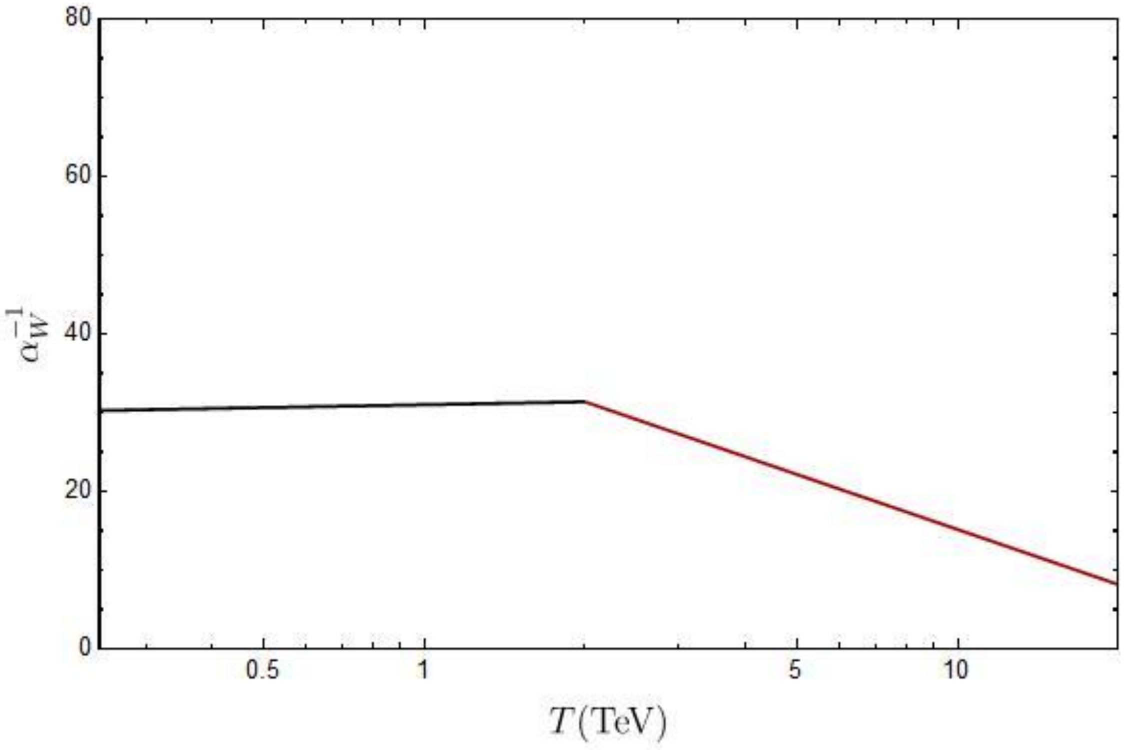
SU(2) example: Early weak confinement

- **SM** running of $\alpha_W = \frac{g^2}{4\pi}$



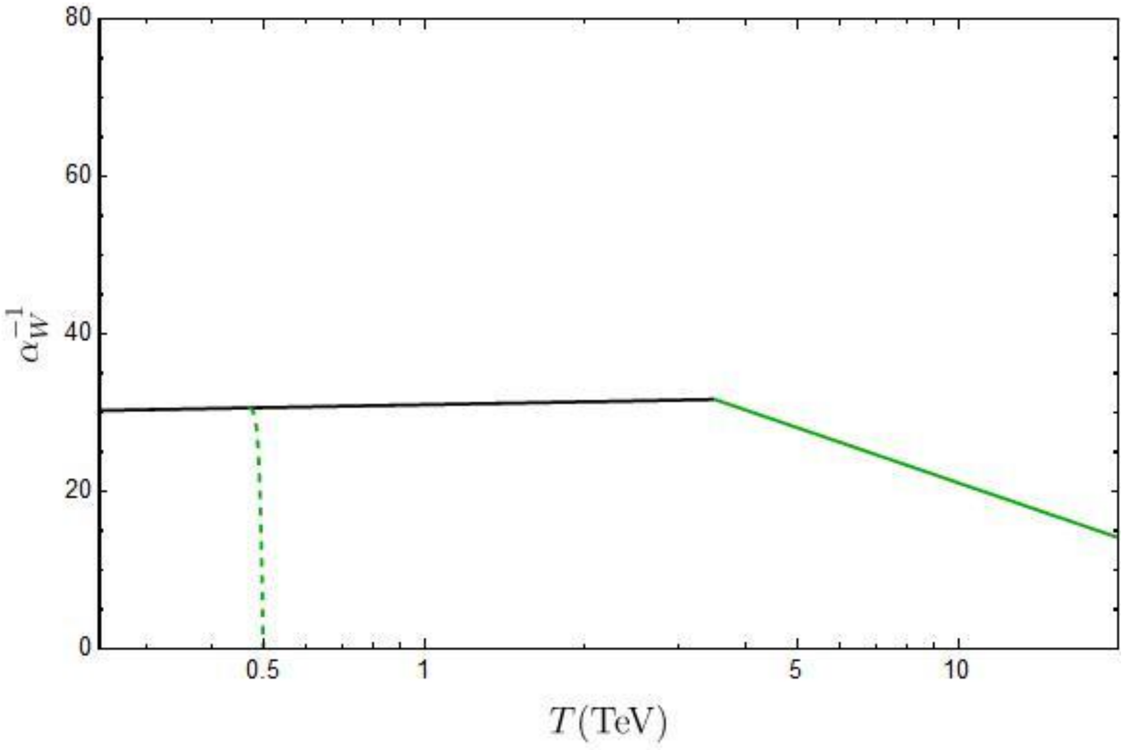
SU(2) example: Early weak confinement

- Scenario with 100 fundamental vector-like fermions at 2 TeV



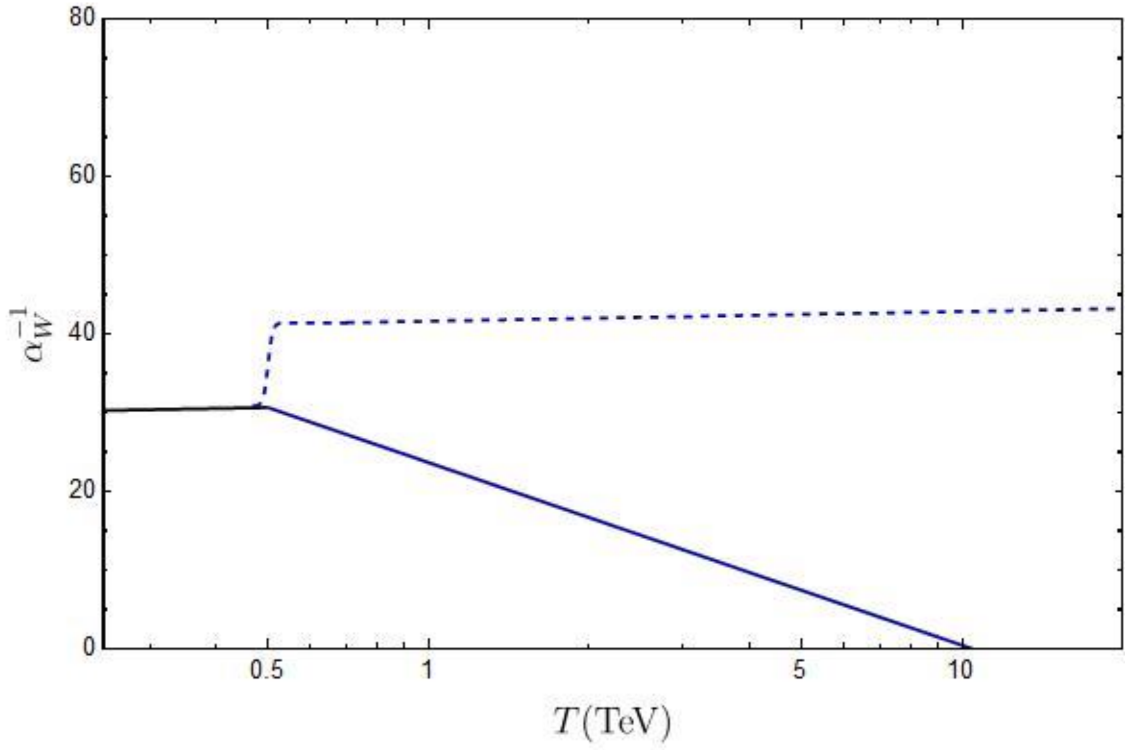
SU(2) example: Early weak confinement

- Dynamical transition of $\langle\phi\rangle$ for **positive** values
 (linear expectation in dashed vs all EFT in solid)



SU(2) example: Early weak confinement

- Dynamical transition of $\langle\phi\rangle$ for **negative** values (linear expectation in dashed vs all EFT in solid)



Conclusion

- We have shown that nontrivial dynamics of the singlet field connected to a gauge field are entirely described by a **dynamical RG equation with changing thresholds**

- In the SU(2) scenario we have seen that the linear expectation is **completely different** than the full calculation

- In general, if you want to change the coupling drastically, it is necessary to introduce **a lot of new states** which can mess up other things!

Thank You