

# UV-Completion by Classicalization.

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with:

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Fundamental physics is about understanding nature on various length-scales.

Some important examples are:

Hubble length ( $10^{28}$  cm),

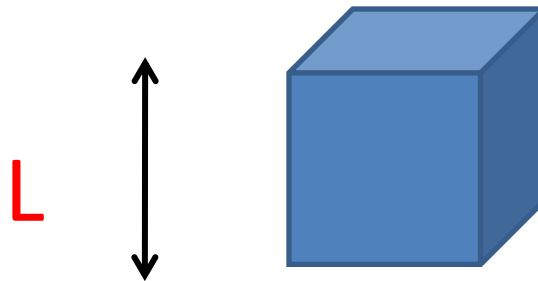
QCD-length ( $10^{-14}$  cm),

Weak-length ( $10^{-16}$  cm), ...

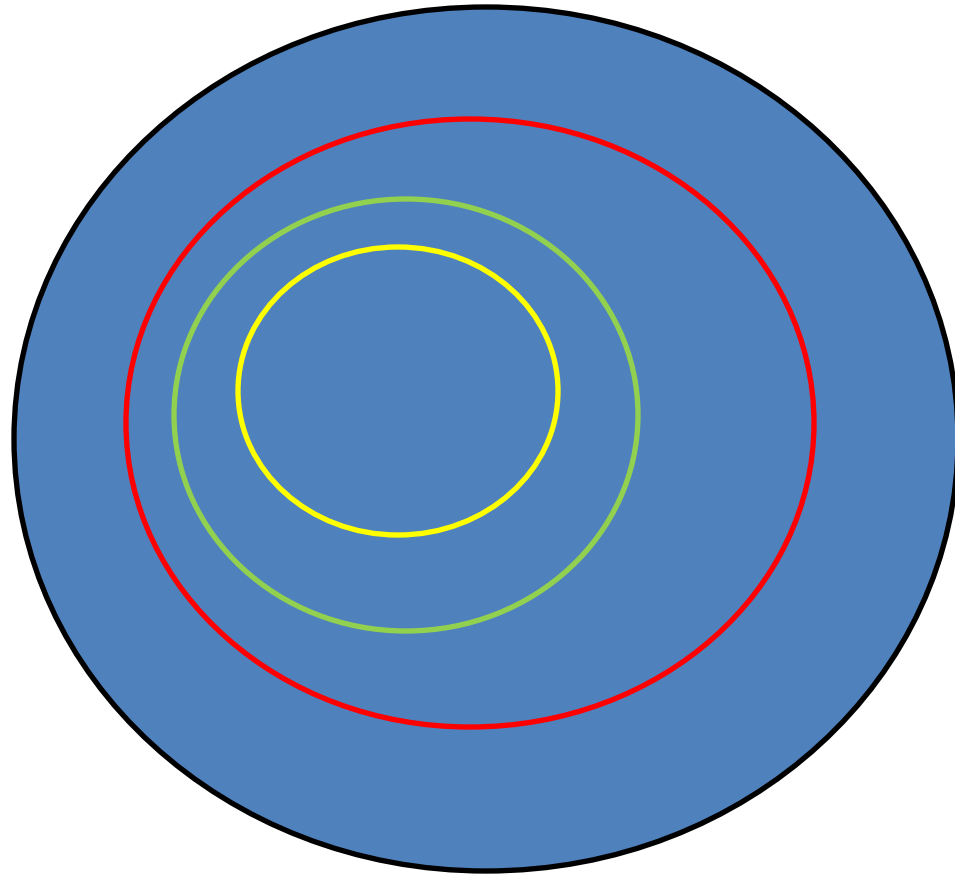
and the shortest length scale of nature,  $L_*$



At any given length-scale we describe nature in terms of an effective (field) theory valid at distances larger than a certain cutoff length,  $L$ . This length marks a size of a black box beyond which a given theory has to be replaced by a more powerful microscopic theory capable of resolving sub-structure at distances shorter than  $L$ .



Theories, describing nature at different length-scales, are embedded in one another like Russian dolls



Usual (**Wilsonian**) picture of UV-completion assumes that such embedding has no end:

**With enough energy, one can resolve nature at arbitrarily-short length-scales.**

In this talk we are going to suggest an alternative possibility:

Certain theories incorporate the notion of a **shortest** length  **$L_*$** , beyond which no Wilsonian UV-completion exists.

Instead, at high energies theory **self-completes** itself by **classicalization**.

In such a theory a very high energy scattering is dominated by formation of **big classical** object, **Classicalons**.

So, a high-energy physics becomes **a long-distance** physics.

We suggest that one example of theory self-completed in this way is **Einstein's gravity**.

**Gravity provides a shortest length of nature**

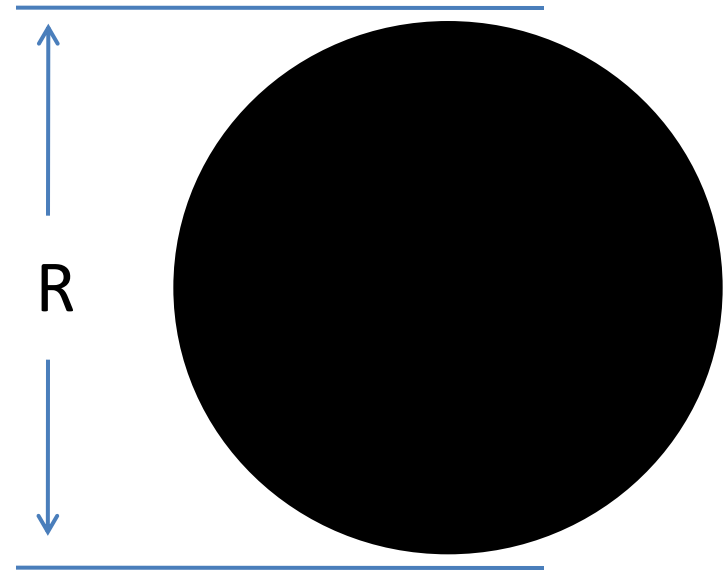
$$L_* = L_p = 1/M_p ,$$

**beyond which length-scales cannot be resolved in principle.**

The reason is simple. To resolve a distance  $L$ , one needs a microscope. Any microscope puts at least energy  $E = 1/L$ , within that distance. But energy gravitates, and when gravitational **Schwarzschild** radius exceeds  $L$ ,

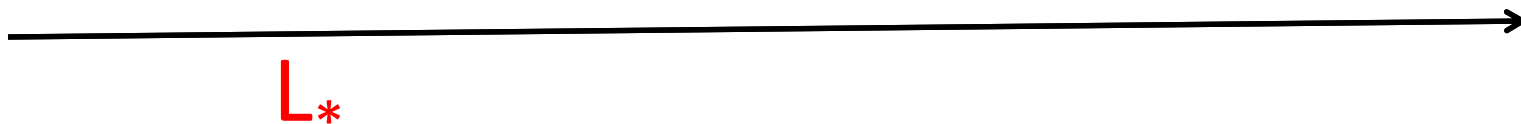
$$R = L_p^2/L > L,$$

the entire microscope collapses into a **classical black hole**!



Which becomes larger with the growing energy. Thus, harder we try to improve resolution of our microscope, worse it becomes.

Usual (Wilsonian) approach to UV-completion of non-renormalizable theories, with a cutoff length  $L_*$ , is to integrate-in some weakly-coupled new physics.





Our idea is to suggest an alternative, in which a theory “refuses” to get localized down to short distances, and instead of becoming **short and quantum**, becomes **large and classical**.

This can happen in theories that are (self)-sourced by **energy** (e.g., containing gravity or Nambu-Goldstone bosons).

In this case, the high-energy scattering is dominated by production of classical configurations (**classicalons**) of a certain bosonic field (**classicalizer**):

**Theory classicalizes**

In remaining 15 min, let me give you a general sense of this idea.

In a generic theory cross section can be written as a geometric cross section

$$\sigma \sim r_*(E)^2$$

where  $r_*(E)$  is a **classical radius, not containing any dependence on  $\hbar$ .**

$r_*(E)$  can be defined as a distance down to which, at given center of mass energy  $E$ , particles propagate freely, without experiencing any significant interaction.

But, if a classical  $r_*$ -radius can be defined in any theory, what determines **classicality** of a given theory?

In a generic weakly-coupled theory,  $r_*$  is a **classical radius**, but it is much shorter than the other relevant quantum length-scales in the problem.

For example, in Thomson scattering the role of  $r_*$  is played by the classical radius of electron,

$$r_* = r_e = e^2 / m_e ,$$

but system is **quantum** because it is much shorter than relevant quantum length in the problem, the Compton wave-length of electron.

Another example is the gravitational Schwarzschild radius of electron,

$$r_S = m_e L_p^2 ,$$

where  $L_p = 10^{-33}\text{cm}$  is the Planck length.

Although  $r_S$  is a classical radius, electron is not a classical gravitating system, because  $r_S$  is much shorter than the Compton wave-length of electron,

$$r_S \ll 1/m_e ,$$

The crucial point is, that in classicalizing theories  $r_*(E)$ -radius grows with  $E$ ,

and becomes much larger than any relevant quantum scale in the problem.

At this point the system Classicalizes!

To be short, consider (a tree-level) scattering  
in two theories,

$$L = (\partial\phi)^2 - \lambda\phi^4$$

and

$$L = (\partial\phi)^2 + L_*^4 (\partial\phi)^4$$

In both theories cross section can be written  
as

$$\sigma \sim r_*^2,$$

where,  $r_*$  is distance at which the correction  
to a free-wave becomes significant:

$$\phi = \phi_0 + \phi_1$$

where  $\phi_0$  is a free wave and  $\phi_1$  is a  
correction due to scattering.

In  $\phi^4$ -theory we have  $r_* = \lambda/E$ , and

$$\sigma = (\lambda/E)^2$$

On the other hand in

$$L = (\partial\phi)^2 + L_*^4(\partial\phi)^4,$$

story is very different, because  $\phi_1$  is sourced by the energy of  $\phi_0$ .

Let at  $t=-\infty$  and  $r = \infty$ ,  $\phi_0$  be a free collapsing in-wave of a huge center of mass energy  $E$  and very small occupation number. Because of energy self-sourcing,

$$\partial^2 \phi_1 = -L_*^4 \partial(\partial\phi_0(\partial\phi_0)^2)$$

scattering takes place at a macroscopic classical distance

$$r_* = L_* (EL_*)^{1/3}$$



For example, take

$$\phi_0 = A [\exp((t+r)/a)^2 ]/r ,$$

where  $E = A^2 / a$  .

Then, for  $r \gg a$ ,

$$\phi_1 = A \Theta(t-r) [r_*^3 / (r(t-r)^3)]$$

In other words, the energy of the initial **few** hard quanta is converted into **many** soft quanta of momentum  $1/r_*$  !

Let us summarize what happened.

By scattering very energetic particles, we thought that we could probe very short distances, such as  $1/E$  (or at least,  $L_*$ ).

Instead, the scattering took place at a **macroscopic classical** distance,

$$r_* = L_* (EL_*)^{1/3} \gg L_* \gg 1/E$$

At this distance  $\phi_1$  becomes same order as  $\phi_0$ , and we simply cannot deny, that scattering took place.

The free-waves refuse to get localized:

Theory **classicalizes!**

An immediate consequence is, that  $2 \rightarrow 2$  scattering takes place via very low momentum-transfer:

$$A_{2 \rightarrow 2} \sim (L_*/r_*)^{4/3}$$

The dominant process is

$2 \rightarrow$  classicalon  $\rightarrow$  many

The total cross section becomes geometric

$$\sigma = r_* (E)^2 = L_*^2 (EL_*)^{2/3}$$

What does classicalization teach us about gravity?

Systems considered here share the bare essentials with gravity:  
existence of a **classical length** that grows with energy.

In this sense, gravity is an **universal** classicalizer :

2 → **Black Hole** → many

From the point of view of unitarization, this is  
no different than

2 → **Classicalon** → many

Other peculiarities of the Black hole physics, such as entropy  
and (approximate) thermality, can be understood as  
accompanying properties of classicaliation.

To see this, do exactly the same scattering with

$$\phi_0 = A [\exp((t+r)/a)^2 ]/r,$$

where again  $E = A^2 / a$ , but instead of self-coupling now couple  $\phi$  to gravity.

The role of  $\phi_1$  is now played by graviton  $h_{\mu\nu}$ .

Now, for  $r \gg a$ , we have

$$h_{00} = \Theta(t+r) \ln(r-t) [r_* / r]$$

$$\text{Where } r_* = E L_p^2$$

Thus, black hole formation is nothing but classicalization with the radius given by **Schwarzschild!**

This result demystifies the origin of the black hole entropy, and tells us, that it is simply given by the number of soft quanta, which make up the classicalon configuration.

Number of such soft quanta is :

$$N = (r_* E)$$

which for a black hole case,  $r_* = E L_p^2$  ,  
gives **Bekenstein Entropy**.

This is not surprising, since the number of states is exponentially sensitive to the number of particles making up a given classicalon.

By now, we understand, that black holes have no choice, they must have Bekenstein entropy, not just because they have horizon, but because they are classicalons made out of many soft quanta

$$N = (r_* E) .$$

This notion of entropy is equally applicable to any classicalon!

So, what is **essential** for unitarization is **classicalization**: Any consistent theory that in high energy scattering is dominated by

2  $\rightarrow$  **Anything Classical**  $\rightarrow$  many

can (should) unitarize by classicalization.

This notion of entropy becomes less and less useful for small  $N$ . E.g., micro Black Holes (e.g., the ones that may be produced at LHC), **will not** have time to forget their origin, and therefore **cannot** carry a well-defined entropy.

Micro black holes will be **qualitatively indistinguishable** from classical resonances predicted by other classicalizing theories.



An example of a prediction:

Applying idea of classicalization to longitudinal WW-scattering:

$$A_{2 \rightarrow 2} \sim (\sqrt{s}/V)^{4/9}$$

and

$$\sigma = V^{-2} (\sqrt{s} 250 / V)^{2/3}$$

where  $V = 250 \text{ GeV}$

Above  $V$ , scattering is dominated by production of **classicalon** resonances.

Of course, there are many questions:

- 1) Does it work?
- 2) Is GR self-UV-completed by classicalization?
- 3) What does it mean from conventional point of view (in terms of degrees of freedom) to be classicalized?
- 4) What are the pheno-applications: Higgsless SM? Yet another solution to the Hierarchy Problem?.....

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