Novel ideas about emergent vacua

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Basic Arguments

Very generally:
- Unified Gauge theories are some of the biggest theoretical achievements of our times.
- Spontaneous symmetry breaking which allows to bridge large scale gaps is a beautiful concept.

Unfortunately the concept does not work for the scalar electroweak Higgs mass. This is the *hierarchy problem*.

However, as 20 years ago
- everything seemed almost correct and
- one was convinced that all masses had to originate in the GUT scale

one dared to accept drastically new concepts like *supersymmetry* or *extra dimensions*.
What changed since then?

- Particle physics and cosmology are no longer considered as separable.
- The meV dark energy scale of cosmology got well established.

As it exactly corresponds to the neutrino mass scale there is no need to directly connect to a GUT mass scale.

It is widely assumed that the dark energy has something to do with the vacuum condensate and it is extremely plausible that such a condensate is responsible for the observed masses.
With the dark energy scale and the GUT scale one has a **two scale situation**.

To understand the spread of fermion masses and to produce intermediate scales is comparatively easy. Combination of powers can produce intermediate scales.

Relations with such power combinations are well established in **chiral perturbation theory**:
There the observed pseudo-scalar meson mass is

\[ M_{\text{pion}}^2 = B_{\text{condensate scale}} \cdot (\text{fermion mass scale}) \]

This relation can be applied to massive bound state of GUT mass constituents

\[ M_{\text{bound}} = (3 \text{ meV} \cdot 10^{16}\text{GeV})^{\frac{1}{2}} = 173\text{ GeV} \]

which is in the vector boson resp. expected mass range of Higgs-like particles.
A possible critique is that the argument seems just to change the context of the hierarchy problem, i.e. that the particle hierarchy problem seems just to merge into a general cosmological one:

- The cosmological constant is taken to correspond to the vacuum energy density caused by a condensate. The properties of the condensate have to somehow reflect the GUT scale of the interactions where presumably it was formed.

- The flatness of the universe requires a non-vanishing, 3 meV cosmological constant.

The mismatch between expectation and observation is $10^{27}$. 
Strictly speaking, this is not a hierarchy problem.

The term hierarchy problem is used if

- from a single available scale derived scales have to be obtained which are non-vanishing but many orders of magnitude away.

In cosmology other scales are available which can bridge the gap. It is easy to envision an evolution in which something like the age of the universe enters.

The expansion of the universe is not linear with age and for dynamical consideration it is better to use the expansion parameter $a$ which is approximately $a \sim t^{0.6}$. 
The central assumption needed is just that there is no additional energy scale available in the evolution.

Usually a decay constant leads to an exponential evolution. Without an additional scale the change of dark energy within a co-moving cell must be linear, i.e. $\epsilon_{\text{vac}}/\epsilon_{\text{GUT}} = \kappa a_{\text{GUT}}/a$ where $\kappa$ is dimensionless and of the order 1.

The observed ratio $\frac{\epsilon_{\text{Vacuum}}(t_0)}{\epsilon_{\text{GUT}}} = 3 \cdot 10^{-28}$ can then be obtained from the age of universe $t_0 = 5 \cdot 10^{46}/M_{\text{GUT}}$ in GUT units as

$$\frac{\epsilon_{\text{Vacuum}}(t_0)}{\epsilon_{\text{GUT}}} = \frac{\kappa}{a} = \frac{\kappa}{(5 \cdot 10^{46})^{0.6}} = \frac{\kappa}{2.2 \cdot 10^{-28}}$$

To the considered accuracy this solves the scale problem.
Cosmological Consideration

The dark energy is small. We do not accept fine-tuning. Without a new scale the energy density of a truly minimal vacuum condensate has to be zero.
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- The observed non-vanishing dark energy means that the unique minimal value is not reached.
- The spontaneous symmetry breaking is replaced by an evolving process.
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Large uncertainties seem unavoidable. It suggests a more or less random 'Emergent' Vacuum state.

A rough history of such a vacuum condensate looks like following:
The condensation starts with chaotically formed bound states when the condensation scale temperature is reached.

These now comparatively massless bound states are formed localized on a condensation scale. They can lose kinetic energy by spreading out in space. In this way they decouple from the hotter rest. Decoupling is here the defining property of "Vacuum".

As they still can radiate of entropy a continuing tumbling down process proceeds to lower and lower energy states. Nowadays they fill the entire space. Quantum mechanical processes created a Vacuum state which is constant on a cosmic scale and coherent.
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Here we will **not attempt to contribute to this difficult problem in a mathematical way.**
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Even without detailed understanding of the emergent Vacuum there are rather unavoidable consequences. It leads on a qualitative level to meaningful consistency checks and testable consequences.
For particle physics an important property of the Vacuum is that it can act as **reservoir**.

It has several consequences. We begin with the most drastic one.
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The Vacuum must be chargeless and spinless. But nothing forbids the Vacuum to contain something like objects with the flavor and color content of **spinless Cooper pairs of antineutrons**.
A repulsive fermionic component might be important for the stability of the condensate.
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The repulsive force of the essentially massless extremely extended fermions leads to an “anti-gravitating” repulsion.
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- The firm limit the unobserved vacuum Cherenkov radiation is not a problem as the fermion density in the Vacuum is too low.
- SU[5] type of antineutron decay can be avoided with a natural choice generation changing technicolor.
Origin of the Extreme Uniformity?

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- The condensate states have to be extremely extended.
- Initial statistical fluctuation augmented by magnetic effects might separate different $U(1)$-charges ($\rightarrow$ Sachs).
- Known condensation often involves replication processes amplifying initial asymmetries over many decades.
- Annihilation processes within the Vacuum radiating into the visible world should purify its antimatter nature.
- The condensation precedes at least part of an inflationary period. In this way a relatively small area can be magnified to extend over essentially our complete horizon.
Expected Non-Uniformities?

Two natural expectations:

- The Vacuum of the past was denser.
- A geometric variation should lead to a “Dipole” - term. There is no reason that the tiny region we originate in happens to have a constant (i.e. extremal) Vacuum density.
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Are there practical consequences?

- All known chiral, fermion and weak vector boson masses increase more or less equally with the condensate density.
- There is one observable:
The fine structure constant $\alpha \propto e^2$ is determined by the $U(1)$ and $SU(2)$ constants at $M_w$ mass scale as

$$\frac{1}{e^2} = \frac{1}{g^2} + \frac{1}{g'^2} = \frac{1}{g_2^2} + \frac{5}{3} \frac{1}{g_1^2}$$

As $1/e^2$ runs more than $1/g^2 + 1/g'^2$ it depends on this $M_w$ which is not fundamental in our scheme. The fine structure constant is smaller in a denser condensate.
A spatial variation ("Australian Vector") was observed by Webb et co-workers.

\[
\Delta \alpha / \alpha \sim B \cos(\Theta) + m
\]

It fixes the scale of the uniformity to 
\[B = 1.1 \pm 0.8 \cdot 10^{-6} \text{ GLyr}^{-1}.\]

The offset \[m = -1.9 \pm 0.8 \cdot 10^{-6}\] just looks in the denser past. Its negative sign confirms the expected increase in \(1/e^2\).

I am aware that the statistical significance is not generally accepted.
As the vacuum is extremely extended the limit $Q \rightarrow 0$ has to be considered.

In the lowest perturbative order a fermion-exchange interaction exists: Relying on a Fierz transformation, it contains a scalar term needed in the limit. There is no other such scalar contribution in lowest order. The concept assumes that higher orders condensate mass effects do not change the basic topological structure.
Both fermions do not have to be identical.
As the Vacuum has to stay neutral the matrix decomposes into 4 separate $3 \times 3$ matrices.
They can be diagonalized and the **CKM matrix** can be obtained in the usual way.
As both flavor do not have to be identical **flavor conservation** can be restored and the apparent flavor changes in the outside world can be attributed to a **reservoir effect** of the Vacuum.
To be clear p.e. the so-called strangeness decay just means that a $d$-quark in the Vacuum is just replaced by an $s$-quark.
Symmetries

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- In the $Q \rightarrow 0$ limit both directions
  
  \[ q_k + (\bar{q}_k)_V \rightarrow q_l + (\bar{q}_l)_V \text{ and } \bar{q}_l + (\bar{q}_k)_V \rightarrow \bar{q}_k + (\bar{q}_l)_V \]

  will be equal. In consequence:

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- However, a $(\bar{q}_i)_V/(q_i)_V$ asymmetry in the Vacuum will differentiate between $q_i + (\bar{q}_i)_V \rightarrow q_j + (\bar{q}_j)_V$ and $\bar{q}_i + (q_i)_V \rightarrow \bar{q}_j + (q_j)_V$. In consequence:

  **CP is not conserved separately** in the outside world.
The vector boson mass arises to lowest order from Compton scattering graphs.

Compton scattering measures the squared charges of Vacuum components.
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’Vacuum’ fluctuations in condensate densities produce the third component of the weak vector bosons. The needed new state arises from an interaction with a scalar phononic excitation:

\[ \text{Diagram showing interaction with a scalar phononic excitation.} \]
The Vacuum has a complicated flavor structure with many possible phononic excitations which couple to the vector bosons and the corresponding fermions in a distinct way. Their masses will be presumably within an order of magnitude of the Weak Boson mass.

In literature such scalars which couple to exactly one fermion type are called ’private Higgs’ particles
Their couplings to *Weak boson and fermion pairs* look like:

For $q_{\text{phonon}}^2 \to 0$ the interactions correspond to the mass term which reflects the corresponding fermion densities in the Vacuum. As for the usual Higgs the couplings to light fermions are suppressed.
The phonon mass should also increase with the fermion masses and phonons coupling to the heavy fermions might be out of reach kinematically.

Considering the coupling strength and the mass the best bet for LHC might be the Higgs coupling to fermions of intermediate masses.

Needed is a broad search for mass peaks. Encouraging but so far not sufficiently significant results exist from Fermilab. They are inspirational.
It is not a beautiful scenario. If correct we can forget the dream about reaching the ‘Theory of Everything’.

However it is not unpersuasive and things fit together in a surprising way on a qualitative level.

Private Higgs at LHC might strongly indicate that an Emergent Vacuum was *nature’s choice*. 
Conclusion

- It is not a beautiful scenario. If correct we can forget the dream about reaching the 'Theory of Everything'.
- However it is not unpersuasive and things fit together in a surprising way on a qualitative level.
- Private Higgs at LHC might strongly indicate that an Emergent Vacuum was nature’s choice.