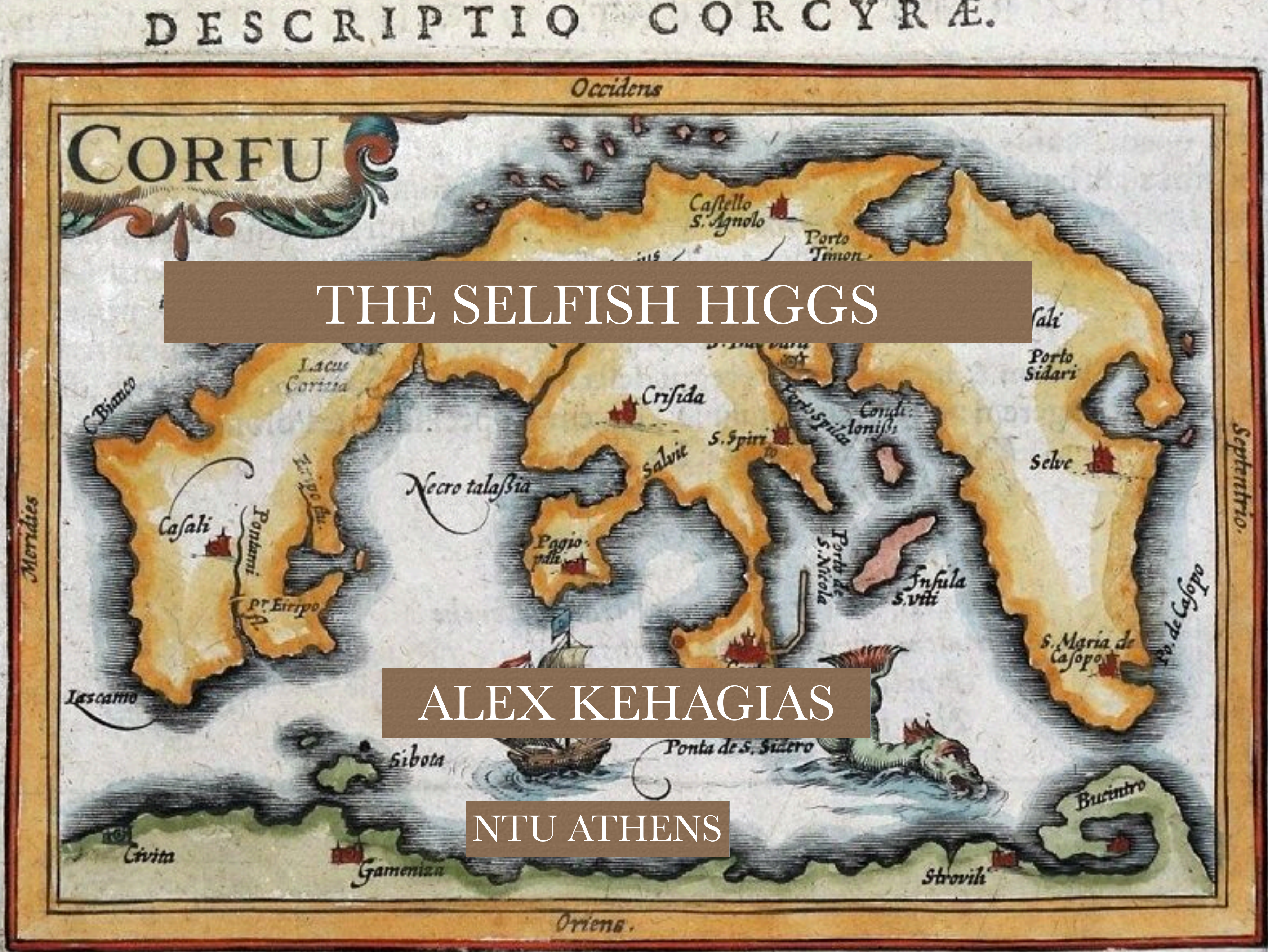
THE SELFISH HIGGS

ALEX KEHAGIAS

NTU ATHENS



Work in collaboration with Gian Giudice and Toni Riotto.

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Introduction

Our story starts with the observation that the ratio between the Fermi constant G_F and the Newton constant G_N, which characterize respectively the strengths of the weak and gravitational forces, is a very large number[2] [10]

$$\frac{G_F \hbar^2}{G_N c^2} = 1.738\ 59(15) \times 10^{33}. \quad (1)$$

This is an unnatural large number and our target is to understand why the Electroweak scale is so far from the Planck scale, i.e., why the Higgs vev is small.

In physics, **naturalness** is the property that the dimensionless ratios between free parameters or physical constants appearing in a physical theory should take values "of order 1" and that free parameters are not fine-tuned. That is, a natural theory would have parameter ratios with values like 2.34 rather than 2.34 x 10.000 or 2.34/10.000.

For example only on dimensional grounds we may write that the period of a pendulum should be

$$T \sim (l/g)^{1/2}$$

It turns out that

$$\frac{T}{(l/g)^{1/2}} = 2\pi$$

The large number of the Fermi constant to Newton constant is not the only large number we are aware of. Let me recall another unnatural large number, namely that of the Planck mass square to the Cosmological Constant Λ:

$$\frac{M_p^2}{\Lambda} \approx 10^{120}$$

Various ideas have been proposed to explain this large number with more or less fantasy. Among them I can recall:

1) Adjustment mechanisms (mainly by scalars),
2) Extra dimensions, (braneworld,…)
3) Modified gravity (unimodular, …),
4) Scanning of CC,
5) …..

I will discuss briefly the last possibility, the scanning of the CC, since it is related to the solution we propose for the smallness of the EW scale.

For the scanning of the CC, one needs to make the CC dynamical. But how can you make the CC dynamical? The CC may be attributed to a 3-form field. The action is

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\ldots - \frac{1}{2\cdot 4!}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma} \right) + \mathcal{S}_{\rm membrane}.$$

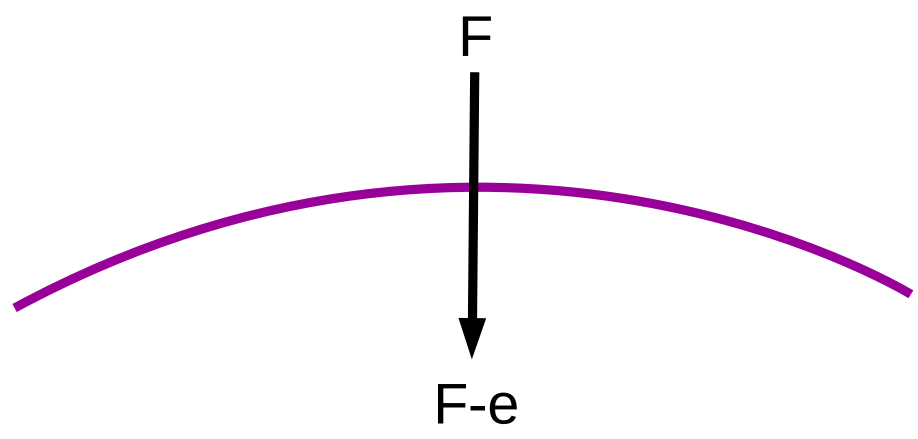
$$\mathcal{S}_{membrane} = -m\int d^3\xi\sqrt{-{}^{(3)}g} + \frac{e}{3!}\int d^3\xi\; A_{\mu\nu\rho}\frac{\partial x^\mu}{\partial \xi^a}\frac{\partial x^\nu}{\partial \xi^b}\frac{\partial x^\rho}{\partial \xi^c}\epsilon^{abc}$$

$$F_{\mu\nu\rho\sigma} = \partial_\mu A_{\nu\rho\sigma} + \text{cyclic}$$

The three-form is non-propagating :

$$F_{\mu\nu\rho\sigma} = F\epsilon_{\mu\nu\rho\sigma}$$

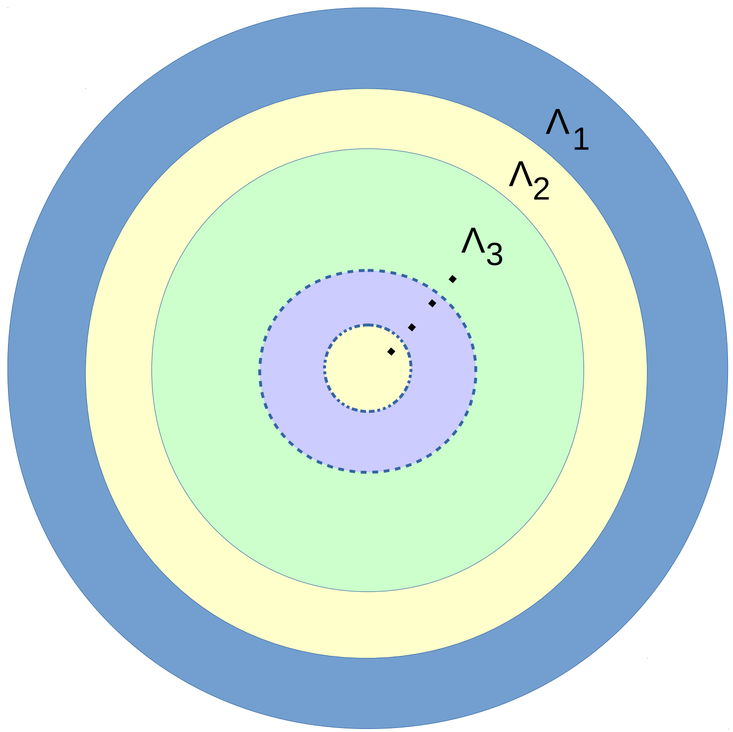
From the field equations, F is piecewise constant: it will jump by one unit of e (charge) any time we cross a membrane

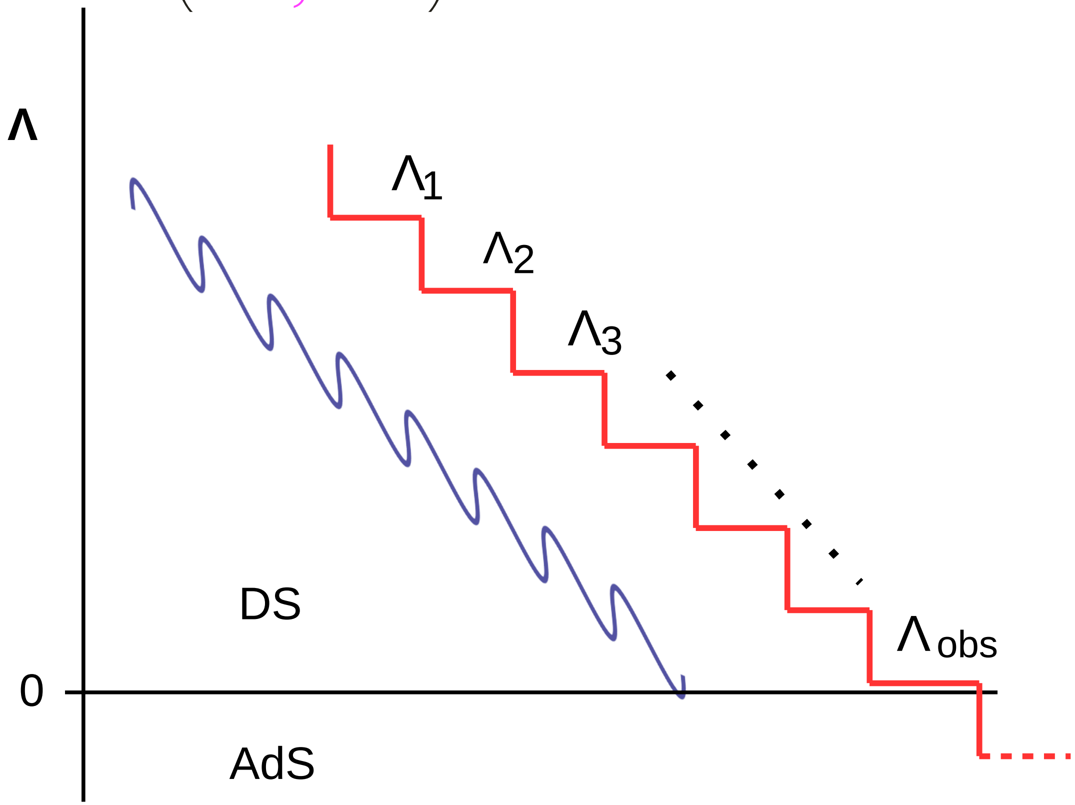


So it contributes like a CC in the effective action

$$\mathcal{S}_{eff} = \int d^4x\sqrt{-g}\left(\ldots - \mathbf{\Lambda}\right), \quad \mathbf{\Lambda} = \frac{1}{2}F^2$$

Dynamical Relaxation: The CC is the vev of a non-dynamical field (3-form). This field has no propagating DoF but it does contribute to vacuum energy. It can have though different values in different regions with different CC. The vacuum is therefore filled with bubbles and the CC is scanned and relaxes to the observed value through consecutive bubble nucleation (BT, BP)



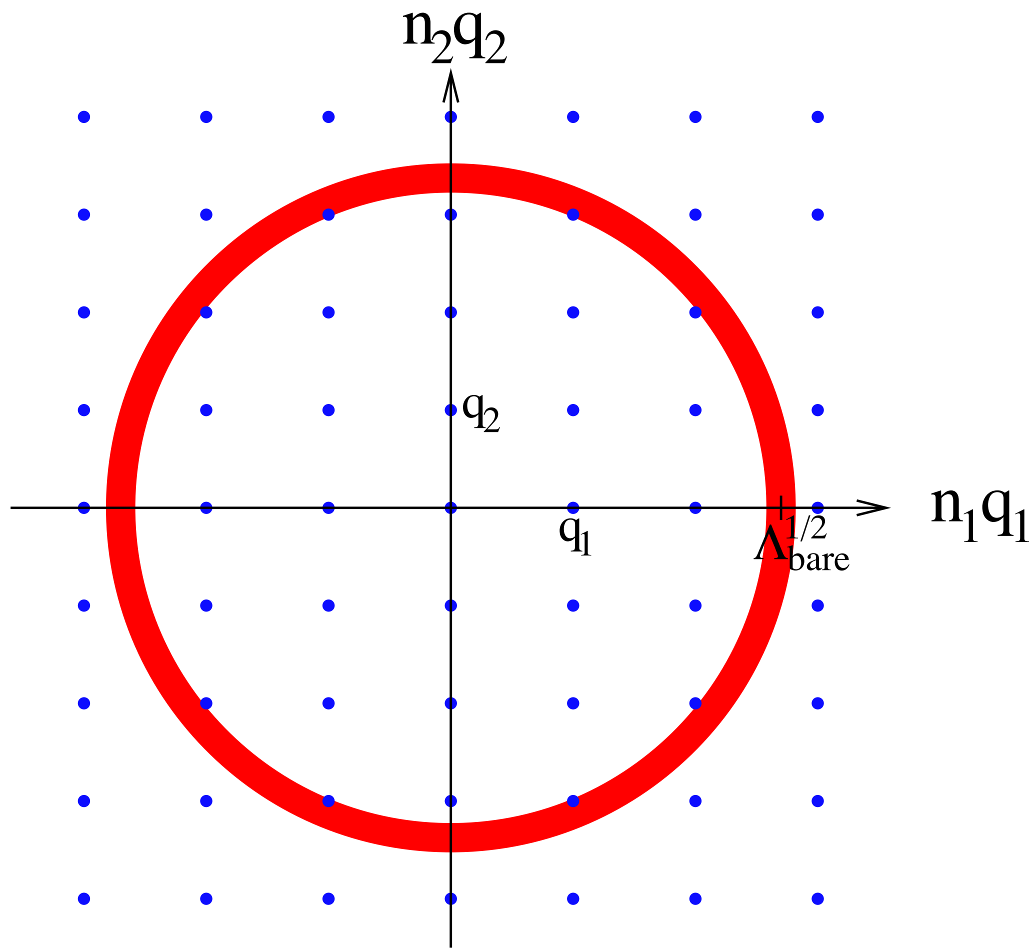


This is the original proposal of Brown-Teitelboim. However it does not work basically for two reasons:

A) **Gap Problem**: the BT mechanism requires an energy spacing which is infinitesimal compared to the scales of microphysics.

B) **Empty Universe Problem**: the BT process involves spontaneous membrane nucleation in a prolonged de Sitter phase. One would expect this to lead to an empty universe.

These problems are solved in the Bousso-Polchinski picture: Use of many-three-forms with fluxes filling a Euclidean grid.



For the empty universe problem reheating with a scalar (inflaton).

The ingredients for the relaxation of the CC in the BP scenario are :

1) a large number of discrete vacuum states,

2) a small fraction of them have a small CC.

3) There is an inflaton

4) Using Weinberg's bound on values of the CC consistent with galaxy formation, BP argue that only those states with CC consistent with observation will have living organisms in them to observe the value of the CC.

5) BP solved the empty universe problem with the inflaton, which is displaced from its minimum due to thermal fluctuations in the penultimate state of very large CC and then slow-rolls in the final state with a small CC and reheats the Universe.

How this mechanism works in a SUSY framework?

The CC is connected to the SUSY breaking scale and the gravitino mass. A basic question to answer is how to keep SUSY breaking scale high and still have a tiny CC.

SUSY scanning

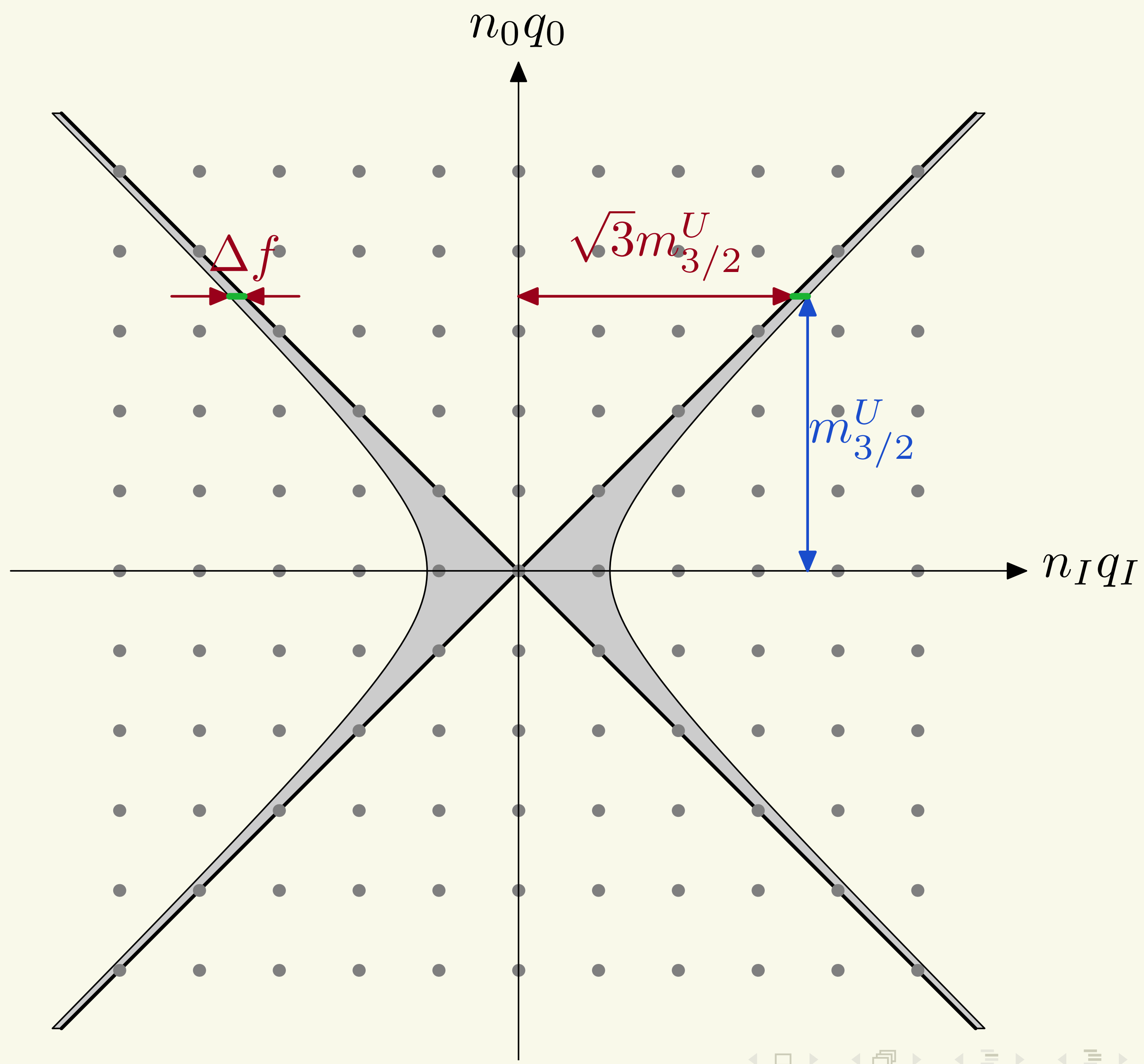
There is an interesting interplay between the scanning of the cosmological constant, the supersymmetry breaking scale and the gravitino mass in supergravity. This is due to the fact that there are two competitive contributions to the CC in sugra:

1) a positive one proportional to the square of the supersymmetry breaking scale f, and

2) a negative one from the square of the gravitino mass, so that

$$\Lambda = f^2 - 3\, m_{3/2}^2 \, .$$

Euclidean lattice $\longrightarrow$ Lorentzian lattice



$n_0 q_0$
$n_I q_I$
Δf
$\sqrt{3} m^U_{3/2}$
$m^U_{3/2}$

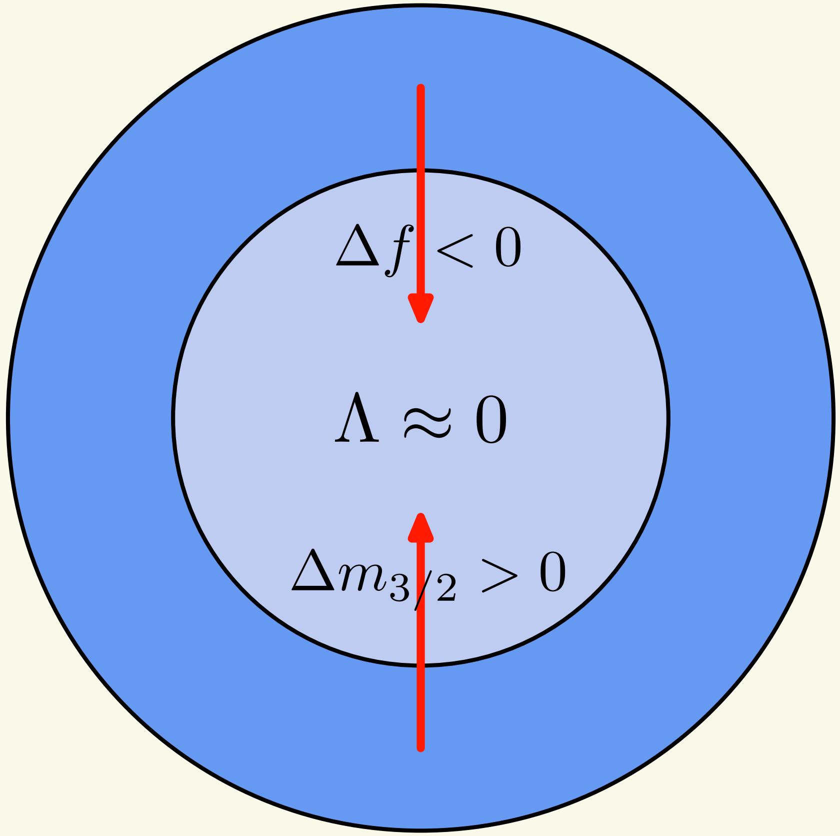


Figure: A schematic view.

HIGGS NATURALNESS

In traditional solutions of Higgs naturalness based on weak-scale dynamics (technicolor, supersymmetry, composite Higgs, etc.), it is common to disregard the analogous naturalness problem of the CC. This may be viewed as an acceptable working hypothesis because one can always postulate that the dynamics of the Higgs and the cosmological constant are completely unrelated. However, this hypothesis is hardly defendable in the context of cosmological selection solutions, which generally involve a landscape of values for the Higgs mass. Whatever makes the Higgs mass scan almost necessarily contributes to the energy density of the system and therefore the cosmological constant must scan as well. Thus, the first observation is that:

Any solution to Higgs naturalness based on cosmological selection must simultaneously address the problem of the CC.

The second observation, generic of mechanisms based on cosmological selection, is related to the the landscape:

The presence of a dynamical landscape not only offers a natural setup for anthropic arguments, but makes statistical or environmental considerations almost unavoidable.

When dealing with selection mechanisms based on cosmological evolution, anthropic arguments look as motivated as natural selection in biological evolution. To emphasise the similarity with the role of evolution in biology we called our mechanism ***Selfish Higgs***, since the Higgs acts as an anthropic selector for the emergence of a fairly unique non-empty universe.

The selection criterion that singles out our universe among the multitude of possibilities is purely anthropic, but rather mild:

A universe can be `non-empty' only when the CC and the Higgs mass are close to critical values around zero.

The result that the cosmological constant must lie within a small interval around zero follows from Weinberg's well-known considerations. The novel ingredient of the Selfish Higgs is the feature that:

Only a Higgs near the critical point for EW breaking is capable of igniting the start of inflation by driving the inflaton field away from its true minimum.

How to implement the scanning of the EW scale?

So far we have seen how the CC can be set to its measured value by the BT and BP scenario. Can we also say something about the smallness of the Higgs vev?

We have seen that the membranes are nucleated by the three-form field. If this field exists, then it is expected to couple also to the Standard Model fields as well. The coupling should be gauge invariant and dimension 4. Although, we can not write any operator satisfying these requirements involving fermions or gauge fields, one can write a gauge invariant coupling of the three-form to the Higgs.

The SM Lagrangian coupled to the three-form is:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}D_\mu H^\dagger D^\mu H - V + \cdots\right) + S_A + S_\mathrm{b},$$

where

$$S_A = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2\cdot 4!}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}\right) - T\int \mathrm{d}^3\xi\sqrt{-{}^{(3)}g} + \frac{e}{3!}\int \mathrm{d}^3\xi\ A_{\mu\nu\rho}\frac{\partial x^\mu}{\partial \xi^a}\frac{\partial x^\nu}{\partial \xi^b}\frac{\partial x^\rho}{\partial \xi^c}\epsilon^{abc}$$

$$S_\mathrm{b} = \int \mathrm{d}^4x\sqrt{-g}\ \partial_\mu\left(\frac{1}{3!}F^{\mu\nu\rho\sigma}A_{\nu\rho\sigma} - \frac{g}{2\cdot 3!}\epsilon^{\mu\nu\rho\sigma}A_{\nu\rho\sigma}|H|^2\right),$$

$$V_H = -\left(M^2 + \frac{y}{24}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\right)|H|^2 + \lambda|H|^4$$

If we write $F_{\mu\nu\rho\sigma} = f \epsilon_{\mu\nu\rho\sigma}$

the equations of motion are:

$$\epsilon^{\mu\nu\rho\sigma}\partial_\mu\left(f - \frac{g}{2}h^2\right) = -e\int \mathrm{d}^3\xi\ \delta^4\left(x - x(\xi)\right)\ \frac{\partial x^\nu}{\partial \xi^a}\frac{\partial x^\rho}{\partial \xi^b}\frac{\partial x^\sigma}{\partial \xi^c}\epsilon^{abc}\,,$$

$$\Box h = \left(-M_0^2 + yf\right)h + \lambda h^3\,.$$

Let us focus on the constant-field vacuum configuration:

$V_H = \mu_{\mathrm{H}}^2 \,|\,\mathrm{H}\,|^2 + \lambda \,|\,\mathrm{H}\,|^4$

$$\langle h \rangle = v$$

The Higgs mass parameter in $V_H = \mu_{\mathrm{H}}^2 \,|\,\mathrm{H}\,|^2 + \lambda \,|\,\mathrm{H}\,|^4$ is then:

$$\mu_{\mathrm{H}}^2 = -\mathrm{M}^2 + yf$$

From the equations above we learn that, when a membrane is nucleated, f and h are constant on both sides of the membrane wall, but there is a jump in their values across the wall

$$\Delta f - \frac{y}{2}\Delta v^2 = e$$

This condition leads to the quantisation condition:

$$f - \frac{y}{2}v^2 = e\,n\,, \quad n \in \mathbb{Z}$$

The cosmological constant Λ and the Higgs mass parameter μ_H^2 (defined such that the Higgs potential is $V_H = \mu_H^2|H|^2 + \lambda|H|^4$) corresponding to the solutions labelled by the integer n are given by

$$\begin{cases} \Lambda = -\Lambda_0 + \frac{e^2 n^2}{2} \\ \mu_H^2 = -M^2 + y\, e\, n \end{cases} \qquad \text{for } n > n_c \ \ \text{(unbroken phase)}$$

and

$$\begin{cases} \Lambda = -\Lambda_0 + \frac{\lambda e^2 n^2 + y M^2 e\, n - M^4/2}{y^2 + 2\lambda} \\ \mu_H^2 = \frac{2\lambda(y\, e\, n - M^2)}{y^2+2\lambda} \end{cases} \qquad \text{for } n \leq n_c \ \ \text{(broken phase)}\,.$$

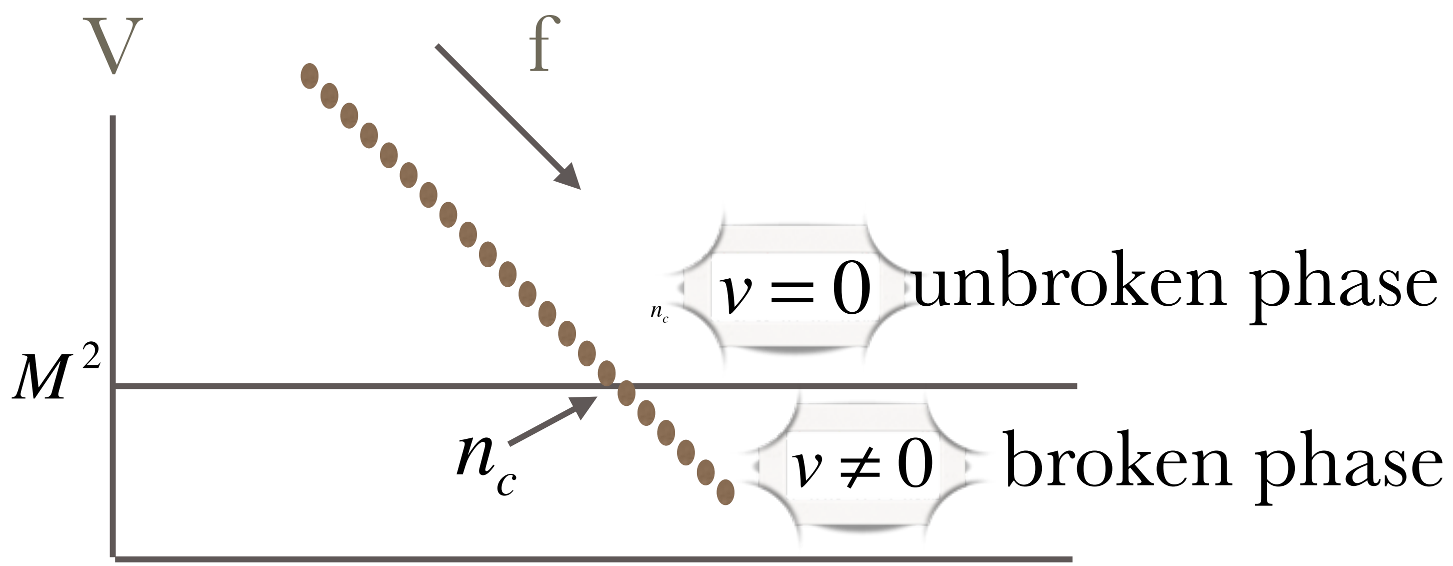
The important observation for the Selfish Higgs is that the coupled system four-form/Higgs leads to a landscape of possible background solutions, on which both the cosmological constant and the Higgs mass parameter vary. However, Λ and μ_H^2 do not scan independently, but remain correlated as n changes.

Scanning Higgs mass with spontaneous membrane nucleation

The four-form has no dynamics at the classical level, although it can attain different field configurations labelled by the integer n. Quantum mechanically, these configurations are unstable and can tunnel into each other through non-perturbative effects. Starting from a spacetime region with charge n, a membrane can be spontaneously created encompassing a subregion in which the field is in the $(n-1)$ configuration. The energy stored in the membrane tension is taken from the energy gain of lowering the field by one charge unit. The tunnelling probability between two consecutive configurations in dS space is given by

$$\mathcal{P}(n+1 \to n) \approx \exp\left(-\frac{24\pi^2 M_P^4}{\Lambda_{n+1}}\right) ,$$

for $\Lambda_{n+1} \ll T^2/M_P^2$. At the last stages of evolution, when the effective cosmological constant is very small, the tunnelling transitions are extremely slow and all corresponding universes have a viable metastable nature.



V
f
M^2
n_c
$v = 0$ unbroken phase
$v \neq 0$ broken phase

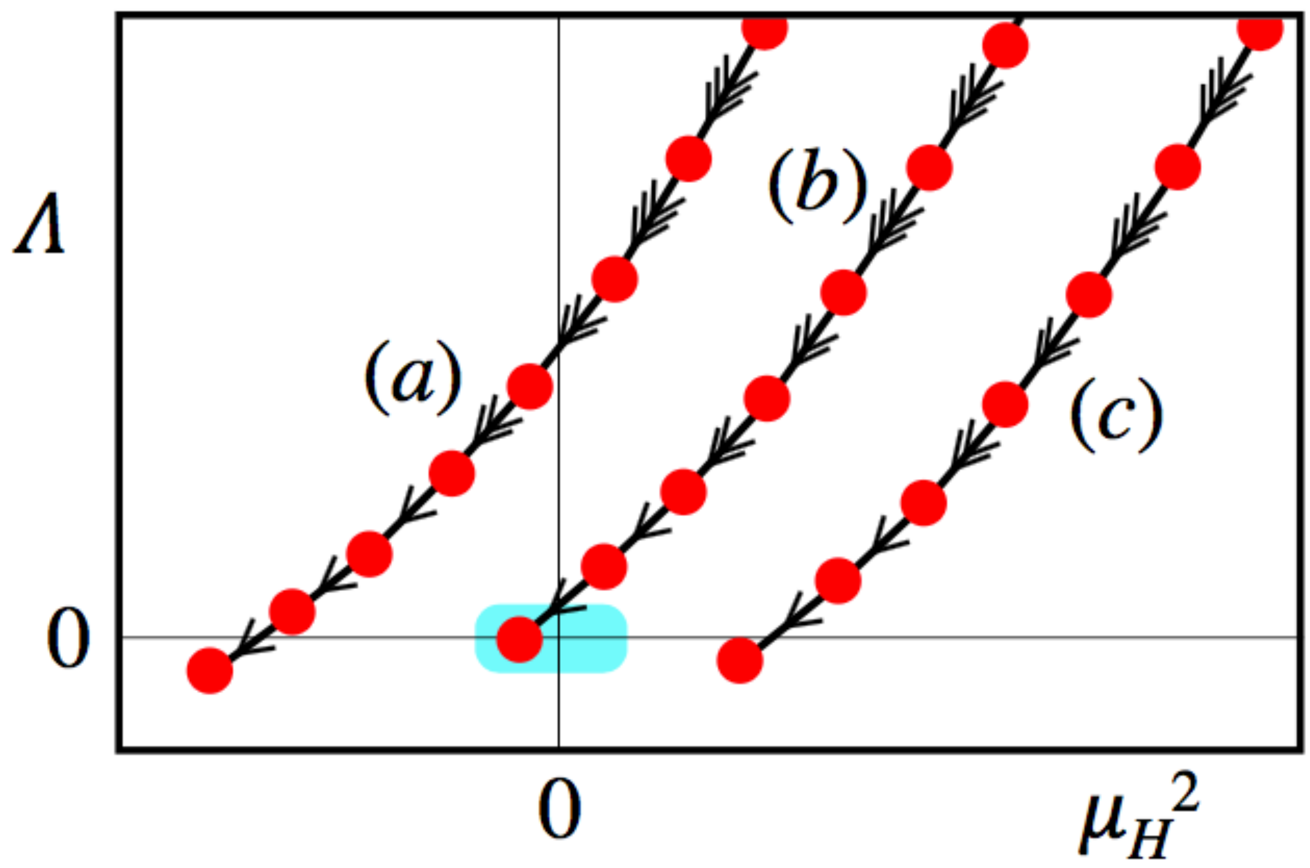
Due to the linear dependence on n, the scanning of μ_H^2 occurs through uniform steps

$$\Delta\mu_H^2 \equiv \mu_H^2(n+1) - \mu_H^2(n) = y\,e\,,$$

which do not involve quantities parametrically equal to the cutoff scale. A crucial assumption of the Selfish Higgs is that these steps are of the order of the weak scale

$$y\,e = \mathcal{O}(m_h^2)\,,$$

where $m_h = 125$ GeV is the physical Higgs boson mass.



Sketch of possible trajectories in the plane of cosmological constant (Λ) and Higgs mass squared parameter (μ_H^2) coming from the evolution of four-form configurations. Transitions become exponentially slow as Λ is reduced and typically come to a halt after the first jump into AdS or Minkowski. The condition $\Lambda \approx 0$ can be reached with EW symmetry in the broken phase (a), unbroken phase (c), or near-critical (b). The coloured region shows the area selected by the Selfish Higgs.

It turns out that out of the multitude of universes generated by the random process of brane nucleation, only those with small $|\Lambda|$ and $|\mu_H^2|$ are 'non-empty'. In these special universes, brane nucleation leads to the production of SM particles that will rapidly thermalise creating a bath with weak-scale temperature. However, these universes do not have the right properties to resemble our own for at least two reasons.

- First, the nucleated bubbles with $\Lambda \approx 0$ will expand and asymptotically fill up a very large fraction of space, but cannot percolate in the expanding dS environment in which they are immersed. This is problematic because a single bubble has size $H^{-1} \sim M_P/T^2$ and entropy density $s \sim T^3$, so that its total entropy $S \sim M_P^3/v^3 \sim 10^{48}$ is insufficient to contain our universe, whose present entropy inside the horizon is about 10^{88}.

- The second problem is that the nucleated bubbles do not have the density perturbations needed to seed structure formation. As usual, these problems can be solved with a stage of inflation.

As usual, these problems can be solved by INFLATION

Inflation is ignited by thermal effects.

I will not present specific models, but only point out that a thermal origin for inflation can be fairly generic. To react to temperature effects, the inflaton must have a mass less than the weak scale and be sufficiently coupled to SM particles.

CONCLUSIONS

The Selfish Higgs is a mechanism that selects a small cosmological constant and small Higgs mass as the only possibility to have a non-empty universe. In other words, the Selfish Higgs is an evolutionary process leading to a fairly unique universe that contains something rather than nothing.

The theory is described by

- a four form $F_{\mu\nu\rho\sigma}$,
- the SM couled to the four-form and
- an inflaton.

The four-form is naturally coupled to the SM Higgs and leads to a landscape where the cosmological constant and the Higgs mass vary in a correlated way. Universes with large positive or negative cosmological constant are ruled out because they cannot support structures, as argued by Weinberg. Out of the universes with $\Lambda \approx 0$, only those with small μ_H^2 can be populated by matter and radiation, while all others remain empty.