“... there is a sudden rapid passage to
a totally new and more comprehensive type of order or organization,
with quite new emergent properties ...”

(Huxley & Huxley 1947)

The Hierarchy Problem Revisted

A new view on the SM of particle physics

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Naturalness, Hierarchy and Fine Tuning
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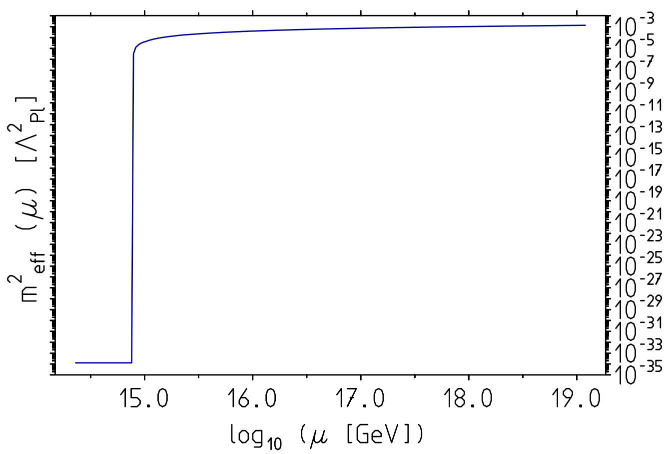
Prelude: Higgs inflation in a Nutshell

You know the SM hierarchy problem?

The renormalized Higgs boson mass is small (at EW scale) the bare one is huge due to radiative corrections going with the UV cutoff assumed to be given by the Planck scale $\Lambda_{\mathrm{Pl}} \sim 10^{19}$ GeV.

$$m^2_{\text{Higgs, bare}} = m^2_{\text{Higgs, ren}} + \delta m^2$$
$$\delta m^2 = \frac{\Lambda^2_{\mathrm{Pl}}}{(16\pi^2)}\, C(\mu)$$



- Is this a problem? Is this unnatural?

- It is a prediction of the SM!

Veltman's "The Infrared - Ultraviolet Connection".

- At low energy we see what we see (what is to be seen): the renormalizable, renormalized SM as it describes close to all we know up to LHC energies.

● What if we go to very very high energies even to the Planck scale?

❒ Close below Planck scale we start to sees the bare theory i.e. a SM with its bare short distance effective parameters, so in particular a very heavy Higgs boson, which can be moving at most very slowly, i.e.

❶ the potential energy

$$\boxed{V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{24}\phi^2}$$ is large

❷ the kinetic energy

$$\boxed{\frac{1}{2}\dot{\phi}^2}$$ is small.

The Higgs boson contributes to energy momentum tensor providing

pressure
energy density

$$\boxed{\begin{aligned} p &= \frac{1}{2}\,\dot{\phi}^2 - V(\phi) \\ \rho &= \frac{1}{2}\,\dot{\phi}^2 + V(\phi) \end{aligned}}$$

❒ As we approach the Planck scale (bare theory): slow–roll condition satisfied

$\frac{1}{2}\,\dot{\phi}^2 \ll V(\phi)$ then $\longrightarrow$ $\boxed{p \approx -V(\phi)\;;\;\; \rho \approx +V(\phi)}$ $\longrightarrow$ $p = -\rho$

$\rho = \rho_\Lambda$ DARK ENERGY! very special equation of state! (only observed through CMB and SN counts, no lab system observation so far).

- The SM Higgs boson in the early universe provides a huge dark energy!

- What does the huge DE do? Provides anti-gravity inflating the universe!

Friedmann equation: $\frac{\mathrm{d}a}{a} = H(t)\,\mathrm{d}t \longrightarrow a(t) = \exp Ht$ exponential growth of the radius $a(t)$ of the universe. $H(t)$ the Hubble constant $H \propto \sqrt{V(\phi)}$. Inflation stops quite quickly as the field decays exponentially. Field equation:
$\ddot{\phi} + 3H\dot{\phi} \simeq -V'(\phi)\,,$ for $V(\phi) \approx \frac{m^2}{2}\,\phi^2$ harmonic oscillator with friction ⇒Gaussian inflation (Planck 2013)

- "flattenization" by inflation: curvature term $k/a^2(t) \sim k\,\exp(-2Ht) \to 0$ ($k = 0, \pm 1$)

- Inflation tunes the total energy density to be that of a flat space, which has a particular value $\rho_{\mathrm{crit}} = \mu^4_{\mathrm{crit}}$ with $\mu_{\mathrm{crit}} = 0.00216\ \mathrm{eV}$!

$\rho_\Lambda = \mu^4_\Lambda$: $\mu_{0,\Lambda} = 0.002\ \mathrm{eV}$ today → approaching $\mu_{\infty,\Lambda} = 0.00216\ \mathrm{eV}$ with time

i.e. the large cosmological constant gets tamed by inflation to be part of the critical flat space density. No cosmological constant problem either?

● Note: inflation is proven to have happened by observation!

Comic Microwave Background (CMB) radiation tells it ✓

● Inflation requires the existence of a scalar field,

⁜ The Higgs field is precisely such a field we need and within the SM it has the properties which promote it to be the inflaton.

Note: the Higgs inflaton is special: almost all properties are known or predicable!

Upshot: I argue that the SM in the Higgs phase does not suffer form a "hierarchy problem" and that similarly the "cosmological constant problem" resolves itself if we understand

the SM as a low energy effective theory
emerging from a cut-off medium at the Planck scale.

I discuss these issues under the condition of a stable Higgs vacuum, by predicting the behavior of the SM when approaching the Planck era at high energies

– bottom-up approach –

All other inflatons put by hand: all predictions are direct consequences of the respective assumptions

SM Higgs inflation sounds pretty simple but in fact is rather subtle,
because of the high sensitivity to the
SM parameters uncertainties and SM higher order effects

Precondition: – a stable Higgs vacuum and a sufficiently large Higgs field at M_{Pl}!
– physics beyond SM should not spoil main features of SM
(i.e. no SUSY, no GUT etc. pretending to solve the hierarchy problem, and/or affecting SM RG pattern substantially) !

Slow-roll inflation in general: Guth, Albrecht, Steinhardt, Linde in 80's mostly top-down approach. Non-minimal GRT approach Zee, ... Shaposnikov et al.

Topics:

- The Hierarchy Problem revisited
- The SM running parameters
- The issue of quadratic divergences in the SM
- The cosmological constant in the SM
- Problems of GRT cosmology if dark energy is absent
- Emergence Paradigm and UV completion: the LEESM
- The Higgs boson is the inflaton!
- Reheating and Baryogenesis
- Conclusion

The Hierarchy Problem revisited

A reminder:“The fate of Infinities”

- Infinities in Physics are the result of idealizations and show up as singularities in formalisms or models.

- A closer look usually reveals infinities to parametrize our ignorance or mark the limitations of our understanding or knowledge.

- Taming the infinities we encounter in the theory of elementary particles i.e. quantum field theories, specifically the Standard Model (SM) by completing with a cutoff, often called the UV–completion of a QFT, is as old as QFT itself although it took 20 years from Dirac 1928 (Dirac hole theory of relativistic electron–photon interaction [preQED]) to Feynman, Schwinger and Tomonaga in 1948 who found how to deal with the large cutoff limit.

- I adopt the scenario of the SM of elementary particles in which ultraviolet singularities which plague the precise non-perturbative definition as well as concrete calculations in quantum field theories are associated with a physical cutoff, represented by the Planck length.

- Thus infinities are replaced by eventually very large but finite numbers, and I will show that sometimes such huge effects are needed in describing reality. Our example is inflation of the early universe.

Limiting scales from the basic fundamental constants: $c, \hbar, G_N$
$\Rightarrow$Relativity and Quantum physics married with Gravity yield

Planck length: $\ell_{\rm Pl} = \sqrt{\frac{\hbar G_N}{c^3}} = 1.616252(81) \times 10^{-33}\ \mathrm{cm}$
Planck time: $t_{\rm Pl} = \ell_{\rm Pl}/c = 5.4 \times 10^{-44}\ \mathrm{sec}$
Planck (energy) scale: $M_{\rm Pl} = \sqrt{\frac{c\hbar}{G_N}} = 1.22 \times 10^{19}$ **GeV**
Planck temperature: $\frac{M_{\rm Pl} c^2}{k_{\rm B}} = \sqrt{\frac{\hbar c^5}{G_N k_{\rm B}^2}} = 1.416786(71) \times 10^{32}\ {}^\circ\mathrm{K}$

- **shortest distance $\ell_{\rm Pl}$ and beginning of time $t_{\rm Pl}$**
- **Planck era energy scale $E_{\rm Pl} = \Lambda_{\rm Pl} \equiv M_{\rm Pl}$ and temperature $T_{\rm Pl}$**

$\boxed{t_{\rm Pl} < t}$ $\cancel{-\infty < t < 0}$

One impact of UV divergences in local QFTs: vacuum energy is in fact

ill-defined in a local continuum QFT as it produces quartically divergent quantum fluctuations.

This is another indication which tells us that local continuum QFT has its limitation and that the need for regularization is actually the need to look at the true system behind it, i.e. the cut-off system is more physical and does not share the problems with infinities which result from the idealization. In any case the framework of a renormalizable QFT, which has been extremely successful in particle physics up to highest accessible energies, is not able to give answers to the questions related to vacuum energy and hence to all questions related to dark energy, accelerated expansion and inflation of the universe.

Such questions can be addressed only in the Low Energy Effective SM (LEESM) “extension” of the local QFT SM, e.g. a lattice implementation of the SM

Remember the upshot of renormalizability and renormalized QFTs:

Renormalization Theorem

In a renormalizable QFT all renormalized quantities as a function of the renormalized parameters and fields in the limit of a large cut-off are finite and devoid of any cut-off relicts!

The Bogoliubov Parasyuk theorem in quantum field theory states that renormalized Green's functions and matrix elements of the scattering matrix (S-matrix) are free of ultraviolet divergences. The theorem specifies a concrete procedure (the Bogoliubov Parasyuk R-operation) for subtraction of divergences in any order of perturbation theory, establishes correctness of this procedure, and guarantees the uniqueness of the obtained results.

i.e. in the low energy world cut-off effects are not accessible to experiments! and a "problem" like the hierarchy problem is not a statement which can be checked to exist in our low energy living.

The hierarchy problem cannot be addressed within the renormalizable, renormalized (like all observables) SM. In this framework all independent parameters are free and have to be supplied from experiment.

In the LEESM "extension" of the SM bare parameter turn into physical parameters of the underlying cut-off system as the "true world" at short distances. Then the hierarchy problem is the problem "tuning to criticality" which concerns the dim < 4 relevant operators , in particular the mass terms:

Our Hierarchy Problem!

In the symmetric phase of the SM, where there is only one mass (the others are forbidden by the known chiral and gauge symmetries), the one in front of the Potential of the Higgs doublet field, the fine tuning to criticality has the form

$$m_0^2(\mu = M_{\mathrm{Pl}}) = m^2(\mu = M_H) + \delta m^2(\mu = M_{\mathrm{Pl}}) \; ; \quad \delta m^2 = \frac{\Lambda^2}{16\pi^2}\, C$$

with a coefficient typically $C = O(1)$. To keep the renormalized mass at some small value, which can be seen at low energy, m_0^2 has to be adjusted to compensate the huge number δm^2 such that about 35 digits must be adjusted in order to get the observed value around the electroweak scale.

One thing is apparent: our fine-tuning relation exhibits quantities (in the LEESM all observable in principle) at very different scales, the renormalized at low energy and the bare at the Planck scale.

- In the Higgs phase:

There is no hierarchy problem in the SM!

It is true that in the relation

$$m^2_{H\,\mathrm{bare}} = m^2_{H\,\mathrm{ren}} + \delta m^2_H$$

both $m^2_{H\,\mathrm{bare}}$ and δm^2_H formally may be expected many many orders of magnitude larger than $m^2_{H\,\mathrm{ren}}$. However, in the broken phase $m^2_{H\,\mathrm{ren}} \propto v^2(\mu_0)$ is $O(v^2)$ not $O(M^2_{\mathrm{Pl}})$, i.e. in the broken phase the Higgs is naturally light. That the Higgs mass likely is $O(M_{\mathrm{Pl}})$ in the symmetric phase is what realistic inflation scenarios are demanding.

In the broken phase, characterized by the non-vanishing Higgs field vacuum expectation value (VEV) $v(\mu)$, all the masses are determined by the well known mass-coupling relations

$$\boxed{\begin{array}{rclcrcl} m^2_W(\mu) & = & \frac{1}{4}\,g^2(\mu)\,v^2(\mu)\;; & \quad & m^2_Z(\mu) & = & \frac{1}{4}\,(g^2(\mu)+g'^2(\mu))\,v^2(\mu)\;; \\ m^2_f(\mu) & = & \frac{1}{2}\,y^2_f(\mu)\,v^2(\mu)\;; & \quad & m^2_H(\mu) & = & \frac{1}{3}\,\lambda(\mu)\,v^2(\mu)\;. \end{array}}$$

Funny enough, the Higgs get its mass from its interaction with its own condensate! and thus gets masses in the same way and in the same ballpark as the other SM species.

❐ Higgs mass cannot by much heavier than the other heavier particles!

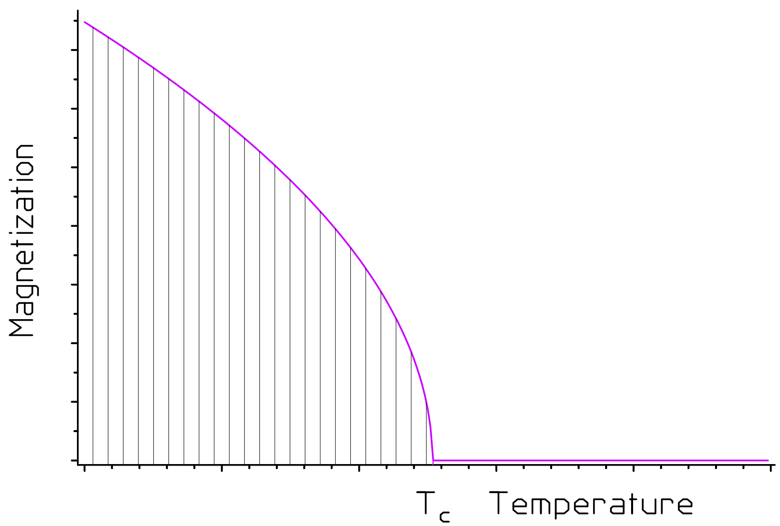
❐ Extreme point of view: all particles have masses $O(M_{\mathrm{Pl}})$ i.e. $v = O(M_{\mathrm{Pl}})$.

This would mean the symmetry is not recovered at the high scale, notion of SSB obsolete! Of course this makes no sense.

- since $v \equiv 0$ above the EW phase transition point, it makes no sense to say that one naturally has to expect $v(\mu = M_{\rm Pl}) = O(M_{\rm Pl})$

- Higgs VEV v is an order parameter resulting form long range collective behavior, can be as small as we like.

Prototype: magnetization in a ferromagnetic spin system



$M = M(T)$ and actually $M(T) \equiv 0$ for $T > T_c$ furthermore $M(T) \to 0$ as $T \underset{\to}{\lesssim} T_c$

Example: Ising ferromagnet in $D = 2$, J n.n. spin coupling

$$H(\sigma) = -J \sum_{<ij>} \sigma_i \sigma_j \; ; \; P_\beta(\sigma) = \frac{\mathrm{e}^{-\beta H(\sigma)}}{Z_\beta} \; ; \; Z_\beta = \sum_\sigma \mathrm{e}^{-\beta H(\sigma)} \, .$$

Here $\beta = \frac{1}{k_B T}$. Onsager Solution: Critical temperature

$$\sinh^2\left(\frac{2J}{k_B T}\right) = 1 \; ; \; T_c = \frac{2J}{k_B \, \ln(1 + \sqrt{2})}$$

Magnetization:

$$M = \left(1 - [\sinh 2\beta J]^{-4}\right)^{\frac{1}{8}} \, ,$$

depending on temperature T and n.n. spin interaction strength J. for more see my 1976 Lausanne Lectures
`http://www-com.physik.hu-berlin.de/~fjeger/LausanneLectures1.pdf`

- $v/M_{\rm Pl} \ll 1$ not unnatural as $v \neq 0$ emerges only below a critical temperature which is not in a simple way related to $M_{\rm Pl}$.

Note the EW scale is set by $v(\mu)$. At low energy $v(0) = 1/(\sqrt{2}G_\mu)^{1/2} \approx 246$ GeV and $v(\mu)$ is monotonically decreasing with increasing μ and vanishing at $\mu_0 \sim 10^{16}$ GeV: $v(\mu) \to 0$ as $\mu \underset{\to}{\lesssim} \mu_0$. The PT point is a point of non-analytic i.e. exhibits singular behavior and physics in the ordered phase and the disordered phase are very different.

Considering a ferromagnet one has to tune the temperature T to criticality in order to find the PT point. What is tuning the temperature to criticality in the SM? The answer: the expansion of the universe, which provides a scan in temperature !!! The maximum value of $v(\mu)$ is achieved at $\mu = 0$, why should the magnitude of $v(0)$ be set by the Planck scale, while when we increase the energy after reaching the symmetric/disordered phase the VEV is actually is vanishing?

This shows that the Higgs boson mass renormalization equation is not a static equation but is subject to a sophisticated dynamics.

- In the symmetric phase at very high energy we see the bare system:

> the Higgs field is a collective field exhibiting an effective mass generated by radiative effects
>
> $$m^2_{\rm bare} \approx \delta m^2 \text{ at } M_{\rm Pl}$$
>
> eliminates fine-tuning problem at all scales!

Many example in condensed matter systems (super conductors etc.).

Astronomy, Astrophysics are unthinkable without the input from laboratory physics in general and particle physics in particular

Now we are at a stage where particle physics has to learn form cosmology; what is required to explain inflation, baryogenesis, nucleosynthesis, CMB patterns, dark matter, etc

In contrast to the old paradigm of an empty vacuum: the ground state of the world is filled with dark energy, Higgs condensate, quark and gluon condensates, which play a key role in the evolution of the universe

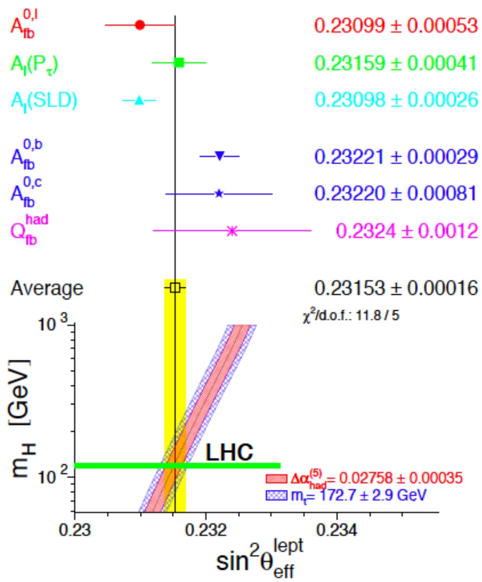
- in fact by reparametrization the cut-off dependence of the preasymptotic theory (renormalizable tail) is completely removed. This implies that from a renormalizable low energy effective theory a cut-off dependence cannot be observable (renormalized theory parametrized in terms of observed parameters)

- in that sense it is nonsensical to say that in the LEET we would naturally expect the Higgs mass to be of the order of the cut-off.

All those working on SM physics, in particular high precision physics and higher order corrections are finally contributing a big deal to a better understanding of the physics of the universe and in particular learning how the cosmos got shaped.

The Higgs boson discovery – the SM completion

Higgs mass found by ATLAS and CMS agrees perfectly with the indirect bounds



LEP 2005 +++ LHC 2012

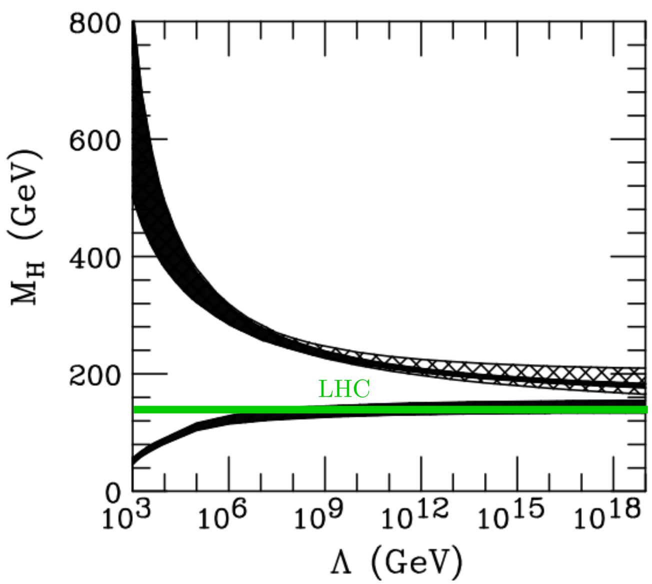
Englert&Higgs Nobel Prize 2013

Higgs mass found in very special mass range 125.9 ± 0.4 GeV

Higgs boson predicted 1964 by Brout, Englert, Higgs – discovered 2012 at LHC by ATLAS&CMS

Common Folklore: SM hierarchy problem (math turned into a dogma)) requires a supersymmetric (SUSY) extension of the SM (no quadratic/quartic divergences) SUSY = infinity killer!

Do we really need new physics? Stability bound of Higgs potential in SM:



$$V = \frac{m^2}{2} H^2 + \frac{\lambda}{24} H^4$$

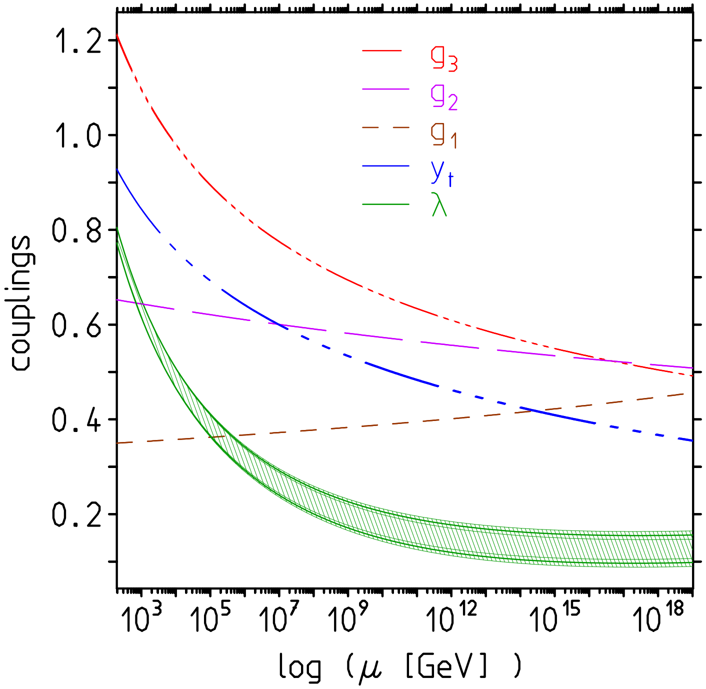
Riesselmann, Hambye 1996

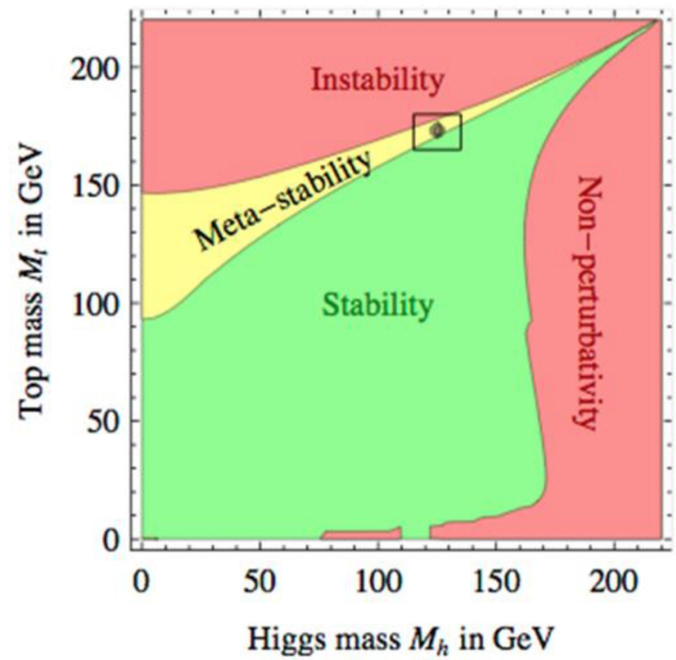
$M_H < 180$ GeV

– first 2-loop analysis, knowing M_t –

SM Higgs remains perturbative up to scale $\Lambda_{\rm Pl}$ if it is light enough (upper bound=avoiding Landau pole) and Higgs potential remains stable ($\lambda > 0$) if Higgs mass is not too light [parameters used: $m_t = 175[150 - 200]$ GeV ; $\alpha_s = 0.118$]

The SM running parameters

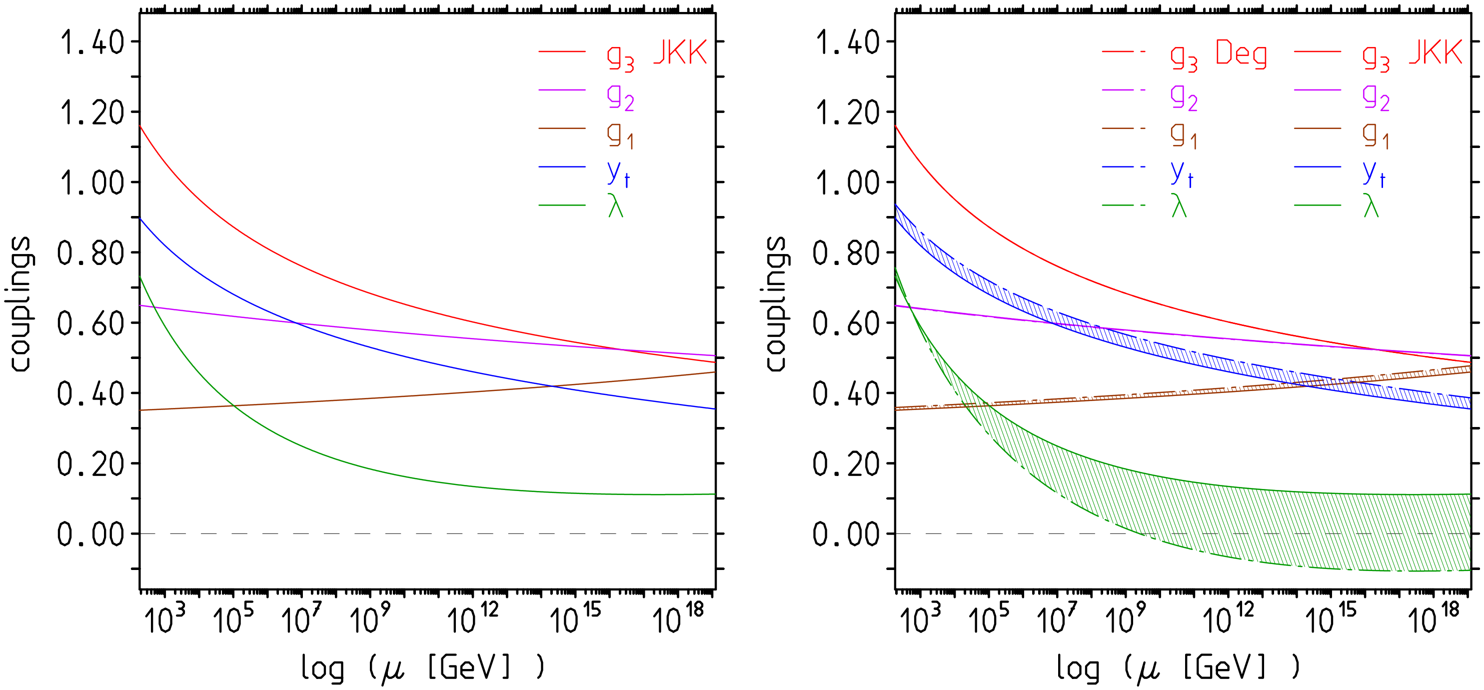




The SM dimensionless couplings in the $\overline{\mathrm{MS}}$ scheme as a function of the renormalization scale for $M_H = 124 - 127$ GeV. Right: Buttazzo et al 13

- perturbation expansion works up to the Planck scale!

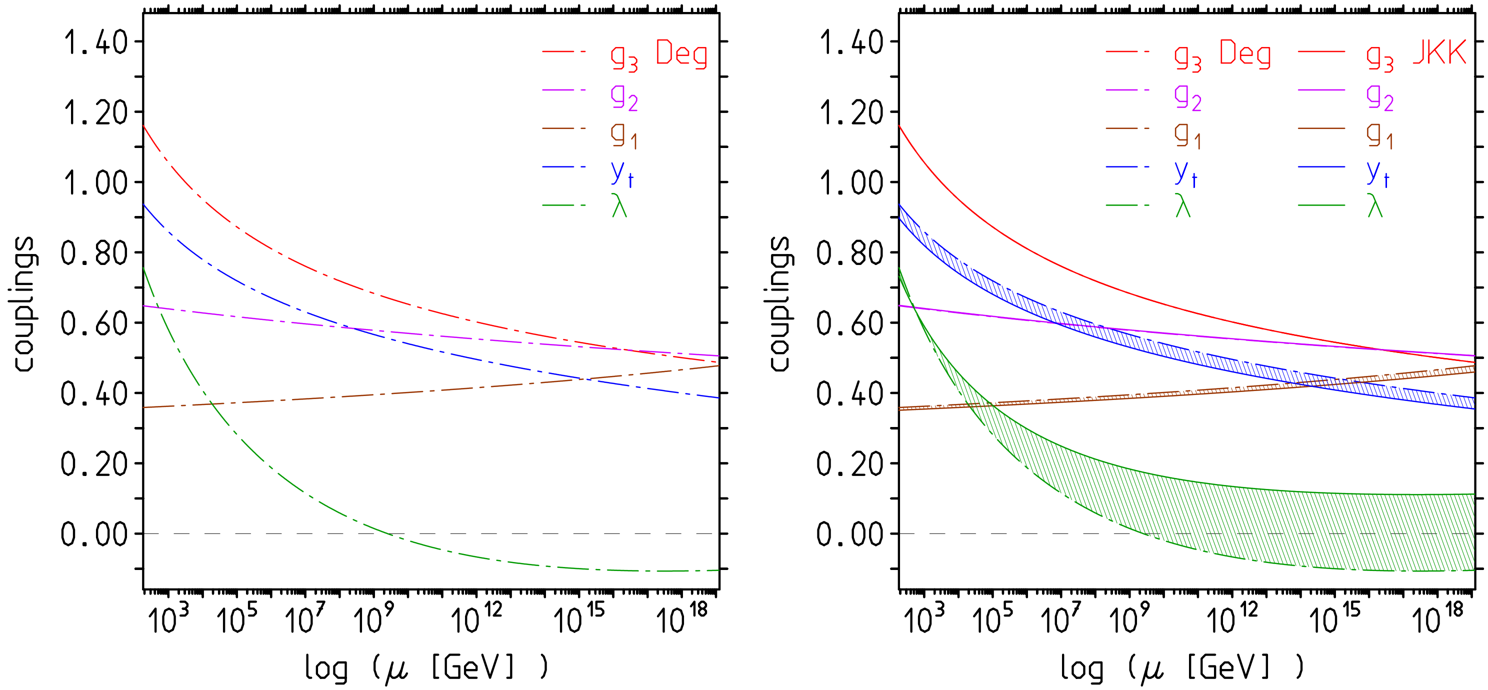
  no Landau pole or other singularities $\Rightarrow$ Higgs potential remains stable!



F.J.,Kalmykov,Kniehl, On-Shell vs $\overline{\mathrm{MS}}$ parameter matching

- the big issue is the very delicate conspiracy between SM couplings: precision determination of parameters more important than ever $\Rightarrow$ the challenge for LHC and ILC/FCC: precision values for λ, y_t and α_s, and for low energy hadron facilities: more precise hadronic cross sections to reduce hadronic uncertainties in $\alpha(M_Z)$ and $\alpha_2(M_Z)$

New gate to precision cosmology of the early universe!



Shaposnikov et al., Degrassi et al. matching

❖ the big issue is the very delicate conspiracy between SM couplings: precision determination of parameters more important than ever $\Rightarrow$ the challenge for LHC and ILC/FCC: precision values for λ, y_t and α_s, and for low energy hadron facilities: more precise hadronic cross sections to reduce hadronic uncertainties in $\alpha(M_Z)$ and $\alpha_2(M_Z)$

New gate to precision cosmology of the early universe!

- perturbation expansion works up to the Planck scale!
  no Landau pole or other singularities, Higgs potential likely remains stable!
- $U(1)_Y$ screening (IR free), $SU(2)_L\,,\ SU(3)_c$ antiscreening (UV free): g_1, g_2, g_3

as expected (standard wisdom)

- Top Yukawa y_t and Higgs λ: screening if standalone (IR free, like QED)

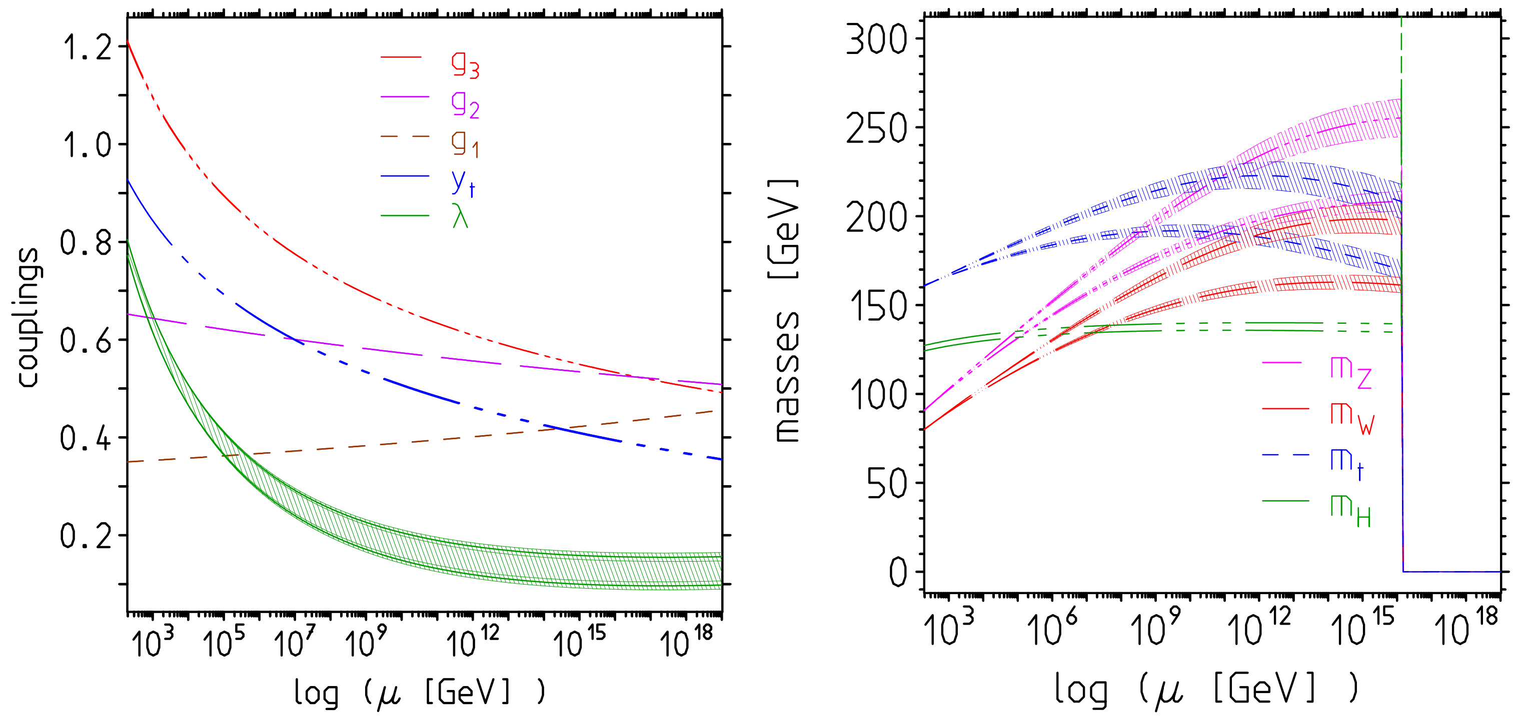
as part of SM, transmutation from IR free to UV free

As SM couplings are as they are: QCD dominance in top Yukawa RG requires $g_3 > \frac{3}{4}\,y_t$, top Yukawa dominance in Higgs RG requires $\lambda < \frac{3\,(\sqrt{5}-1)}{2}\,y_t^2$ in the gaugeless ($g_1, g_2 = 0$) limit.

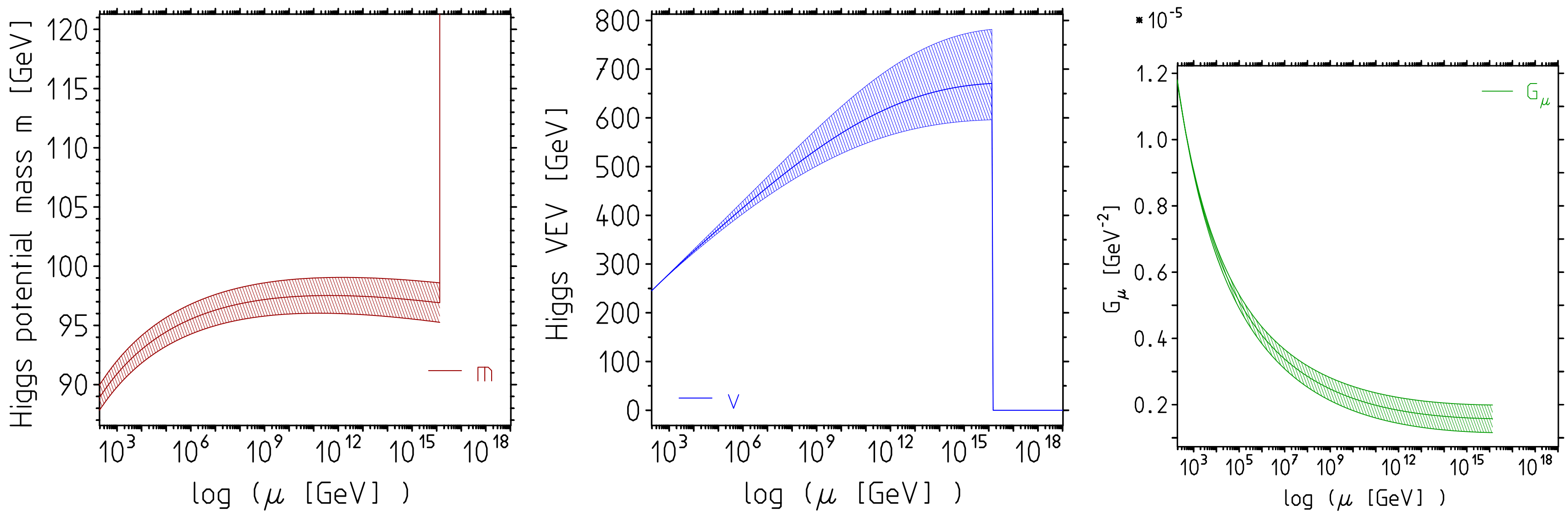
In the focus:

- does Higgs self-coupling stay positive $\lambda > 0$ up to $\Lambda_{\rm Pl}$?
- the key question/problem concerns the size of the top Yukawa coupling y_t
  decides about stability of our world! — [$\lambda = 0$ would be essential singularity!]

Will be decided by:
- more precise input parameters
- better established EW matching conditions



Left: the SM dimensionless couplings in the $\overline{\mathrm{MS}}$ scheme as a function of the renormalization scale. The input parameter uncertainties as given above are exhibited by the line thickness. The green band corresponds to Higgs masses in the range [124-127] GeV. Right: the running $\overline{\mathrm{MS}}$ masses. The shadowed regions show parameter uncertainties , mainly due to the uncertainty in α_s, for a Higgs mass of 124 GeV, higher bands, and for 127 GeV, lower bands. The range also determines the green band for the Higgs mass evolution.



Non-zero dimensional $\overline{\mathrm{MS}}$ running parameters: m, $v = \sqrt{6/\lambda}\, m$ and $G_F = 1/(\sqrt{2}\, v^2)$. Error bands include SM parameter uncertainties and a Higgs mass range 125.5 ± 1.5 GeV which essentially determines the widths of the bands.

- perturbation expansion works up to the Planck scale!
  no Landau pole or other singularities

- Higgs coupling decreases up to the zero of β_λ at $\mu_\lambda \sim 3.5 \times 10^{17}$ GeV, where it is small but still positive and then increases up to $\mu = M_{\mathrm{Pl}}$

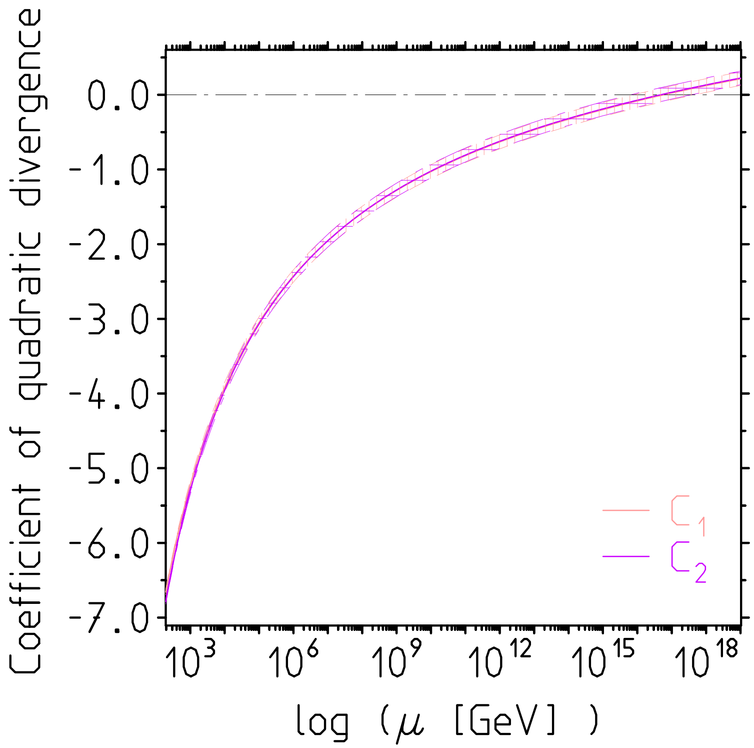
The issue of quadratic divergences in the SM

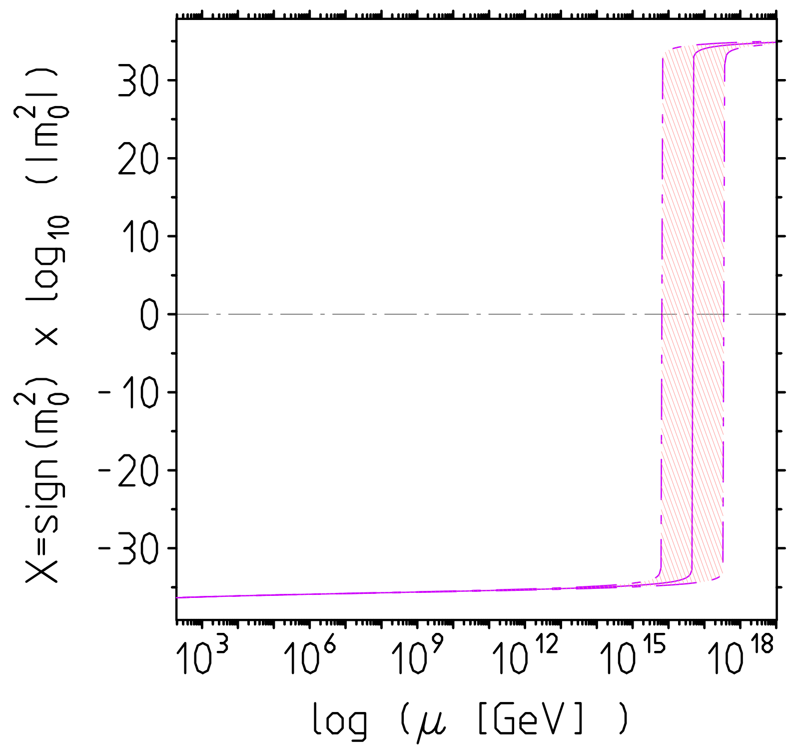
Usual SM "Hierarchy Problem" says Higgs boson mass counterterm represents a huge radiative correction $\propto\ \Lambda_{\rm Pl}^2$, which refers to Veltman's "The Infrared - Ultraviolet Connection". Modulo small lighter fermion contributions, one-loop coefficient function C_1 is given by

$$\delta m_H^2 = \frac{\Lambda_{\rm Pl}^2}{16\pi^2}\, C_1 \ ; \quad C_1 = \frac{6}{v^2}(M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\,\lambda + \frac{3}{2}\,g'^2 + \frac{9}{2}\,g^2 - 12\,y_t^2$$

Key points:

- C_1 is universal and depends on dimensionless gauge, Yukawa and Higgs self-coupling only, the RGs of which are unambiguous.
- Couplings are running!
- the SM for the given running parameters makes a prediction for the bare effective mass parameter in the Higgs potential:





The phase transition in the SM. Left: the zero in C_1 and C_2 for $M_H = 125.9 \pm 0.4$ GeV. Right: shown is $X = \mathrm{sign}(m^2_{\mathrm{bare}}) \times \log_{10}(|m^2_{\mathrm{bare}}|)$, which represents $m^2_{\mathrm{bare}} = \mathrm{sign}(m^2_{\mathrm{bare}}) \times 10^X$.

Jump in vacuum energy: wrong sign and 50 orders of magnitude off Λ_{CMB} !!!

$$V(\phi_0) = -\frac{m^2_{\mathrm{eff}} v^2}{8} = -\frac{\lambda v^4}{24} \sim -9.6 \times 10^8 \ \mathrm{GeV}^4$$

- in the broken phase $m^2_{\rm bare} = \frac{1}{2}\, m^2_{H\,\rm bare}$, which is calculable!

- the coefficient $C_n(\mu)$ exhibits a zero, for $M_H = 126$ GeV at about $\mu_0 \sim 1.4 \times 10^{16}$ GeV, not far below $\mu = M_{\rm Planck}$!!!

- at the zero of the coefficient function the counterterm $\delta m^2 = m^2_{\rm bare} - m^2 = 0$ (m the $\overline{\rm MS}$ mass) vanishes and the bare mass changes sign

- this represents a phase transition (PT), which triggers the Higgs mechanism as well as cosmic inflation

- at the transition point μ_0 we have $\boxed{v_{\rm bare} = v(\mu_0^2)}$, where $v(\mu)$ is the $\overline{\rm MS}$ renormalized VEV

In any case at the zero of the coefficient function there is a phase transition, which corresponds to a restoration of the symmetry in the early universe.

Hot universe $\Rightarrow$ finite temperature effects:

- finite temperature effective potential $V(\phi, T)$:

$$\boxed{T \neq 0}: \; V(\phi,T) = \frac{1}{2}\left(g_T\, T^2 \;\; - \mu^2 \right) \phi^2 + \frac{\lambda}{24}\,\phi^4 + \cdots$$

Usual assumption: Higgs is in the broken phase $\mu^2 > 0$

EW phase transition is taking place when the universe is cooling down below the critical temperature $T_c = \sqrt{\mu^2/g_T}$.

My scenario: above PT at μ_0 SM in symmetric phase $-\mu^2 \to m^2 = (m_H^2 + \delta m_H^2)/2$

$$m^2 \sim \delta m^2 \simeq \frac{M_{\rm Pl}^2}{32\pi^2}\, C(\mu = M_{\rm Pl}) \simeq (0.0295\, M_{\rm Pl})^2 \;, \quad \text{or} \quad m^2(M_{\rm Pl})/M_{\rm Pl}^2 \approx 0.87 \times 10^{-3} \;.$$

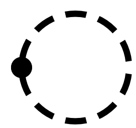
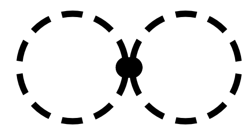
In fact with our value of μ_0 almost no change of phase transition point (see Plot below)

The cosmological constant in the SM

- in symmetric phase Z_2 is a symmetry: $\Phi \to -\Phi$ and $\Phi^+\Phi$ singlet;

$$\langle 0|\Phi^+\Phi|0\rangle = \frac{1}{2}\langle 0|H^2|0\rangle \equiv \frac{1}{2}\,\Xi\ ; \quad \Xi = \frac{\Lambda_{\rm Pl}^2}{16\pi^2}\,.$$

just Higgs self-loops

$\langle H^2\rangle =:$  ; $\langle H^4\rangle = 3\,\left(\langle H^2\rangle\right)^2 =:$ 

$\Rightarrow$ vacuum energy $V(0) = \langle V(\phi)\rangle = \frac{m^2}{2}\,\Xi + \frac{\lambda}{8}\,\Xi^2$; mass shift $m'^2 = m^2 + \frac{\lambda}{2}\,\Xi$

❒ for our values of the $\overline{\rm MS}$ input parameters

$$\mu_0 \approx 1.4\times 10^{16}\ \text{GeV} \to \mu_0' \approx 7.7\times 10^{14}\ \text{GeV}\,,$$

- potential of the fluctuation field $\Delta V(\phi)$.

$\Rightarrow$ quasi-constant vacuum density $V(0)$ representing the cosmological constant

- fluctuation field eq. $3H\dot{\phi} \approx -(m'^2 + \frac{\lambda}{6}\phi^2)\,\phi$, ϕ decays exponentially, must have been very large in the early phase of inflation

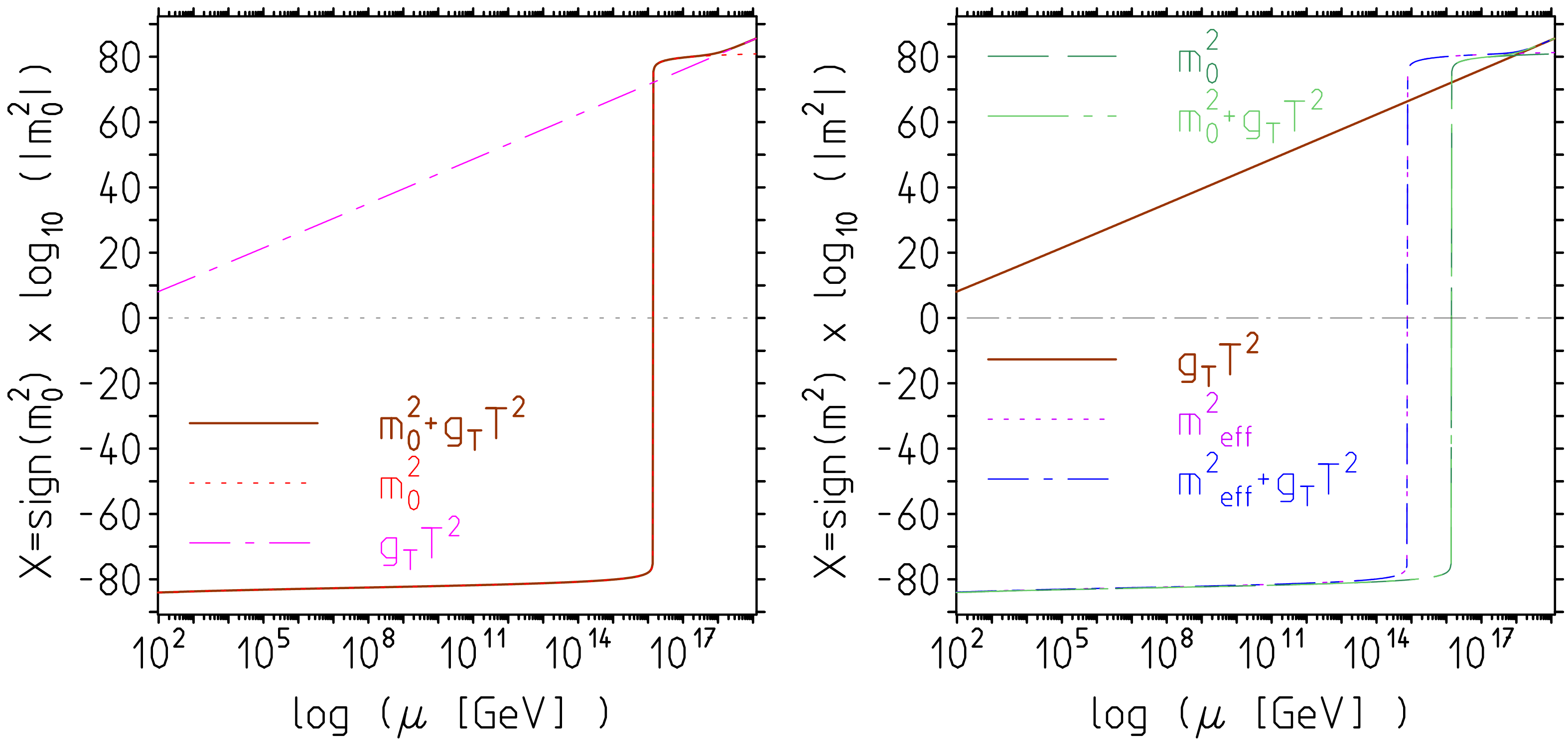
- we adopt $\phi_0 \approx 4.51 M_{\rm Pl}$, big enough to provide sufficient inflation

- $V(0)$ very weakly scale dependent (running couplings): how to get ride of?

- intriguing structure again: the effective CC counterterm has a zero, which again is a point where renormalized and bare quantities are in agreement:

$$\rho_{\Lambda\,\rm bare} = \rho_{\Lambda\,\rm ren} + \frac{M_{\rm Pl}^4}{(16\pi^2)^2}\,X(\mu)$$

with $X(\mu) \simeq 2C(\mu) + \lambda(\mu)$ which has a zero close to the zero of $C(\mu)$ when $2\,C(\mu) = -\lambda(\mu)$.

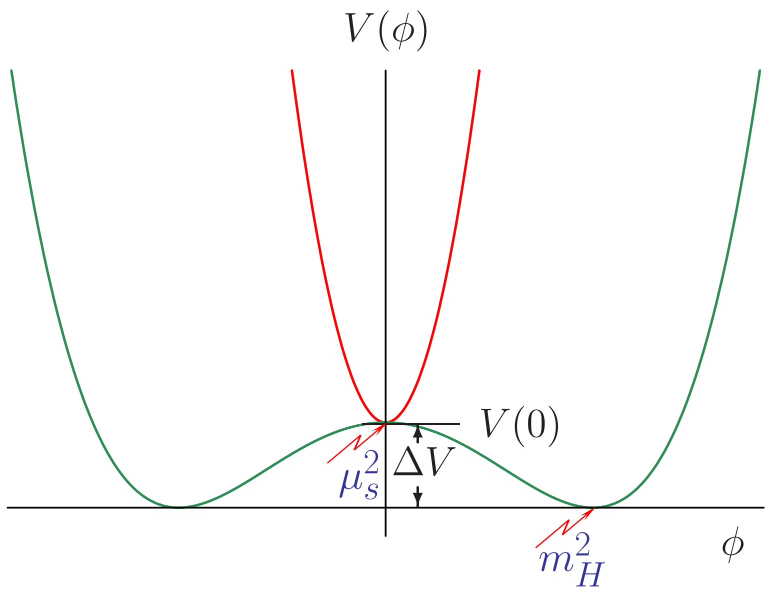


Effect of finite temperature on the phase transition: bare [m^2, C_1] vs effective from vacuum rearrangement [$m'^2, C_1' = C_1 + \lambda$] in case μ_0 sufficiently below $M_{\rm Pl}$ finite temperature effects affect little position of PT; vacuum rearrangement is more efficient:

$$\mu_0 \approx 1.4 \times 10^{16} \text{ GeV} \to \mu_0' \approx 7.7 \times 10^{14} \text{ GeV}\,,$$

❒ SM predicts huge CC at $M_{\rm Pl}$: $\rho_\phi \simeq V(\phi) \sim 2.77\, M_{\rm Pl}^4 \sim 6.13 \times 10^{76}$ GeV^4
how to tame it?

At Higgs transition: $m'^2(\mu < \mu_0') < 0$ vacuum rearrangement of Higgs potential



How can it be: $\boxed{V(0) + V(\phi_0) \sim (0.002 \text{ eV})^4}$??? $\Rightarrow$the zero of $X(\mu)$ makes $\rho_{\Lambda\,\rm bare} = \rho_{\Lambda\,\rm ren}$ to be identified with observed value!

Problems of GRT cosmology if dark energy is absent

- **Flatness problem** i.e. why $\Omega \approx 1$ (although unstable) ? CMB $\Omega_{\mathrm{tot}} = 1.02 \pm 0.02$
- **Horizon problem** finite age t of universe, finite speed of light c: $D_{\mathrm{Hor}} = c\,t$ what we can see at most?

  CMB sky much larger [$d_{t_{\mathrm{CMB}}} \simeq 4 \cdot 10^7\ \ell\mathrm{y}$] than causally connected patch [$D_{\mathrm{CMB}} \simeq 4 \cdot 10^5\ \ell\mathrm{y}$] at t_{CMB} (380 000 yrs), but no such spot shadow seen!

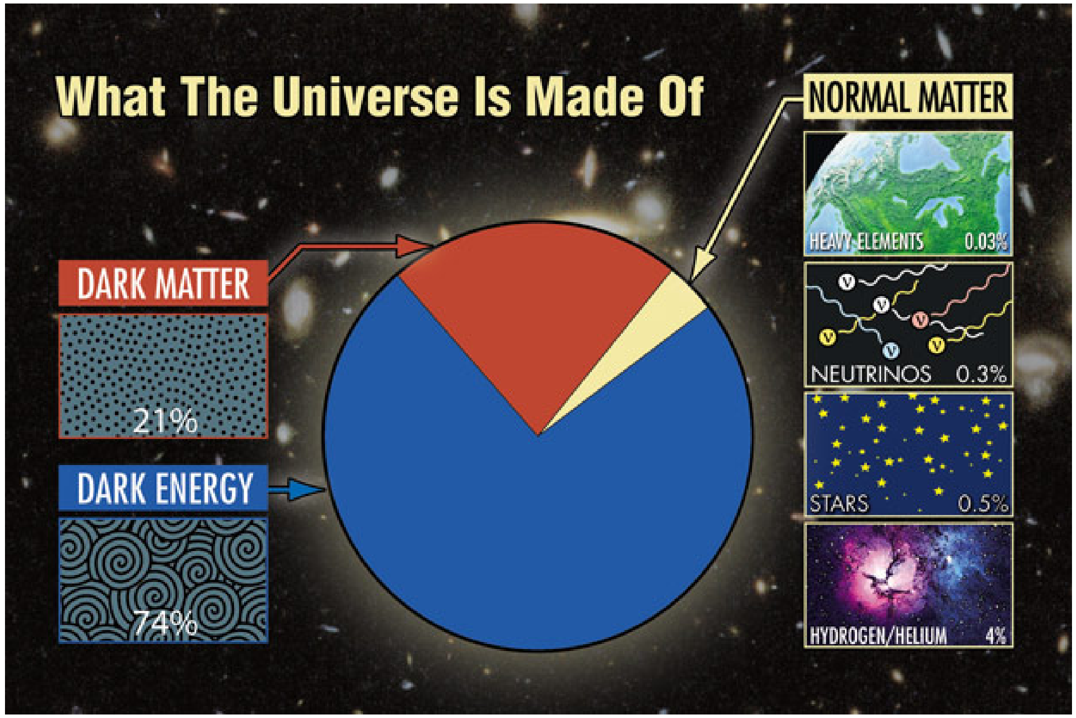
More general: what does it mean homogeneous or isotropic for causally disconnected parts of the universe? Initial value problem required initial data on space-like plane. Data on space-like plane are causally uncorrelated!

- **Problem of fluctuations** magnitude, various components (dark matter, baryons, photons, neutrinos) related: same fractional perturbations
  $\Rightarrow$Planck length ℓ_{Pl} sized quantum fluctuations at Planck time?

As we will see: - $\Omega = 1$ unstable only if not sufficient dark energy!
- dark energy is provided by SM Higgs via $\kappa\, T_{\mu\nu}$
- no extra cosmological constant $+\Lambda\, g_{\mu\nu}$ supplementing $G_{\mu\nu}$
- i.e. all is standard GRT + SM (with minimal UV completion)

$$T^{\mathrm{tot}}_{\mu\nu} = T^{\mathrm{SM}}_{\mu\nu}$$

❒ findings from Cosmic Microwave Background (COBE, WMAP, PLANCK)



❒ the universe is flat! $\Omega_0 \approx 1$. How to get this for any $k = \pm 1, 0$? $\Rightarrow$inflation

$$\boxed{\Omega_0 = \Omega_\Lambda + \Omega_{\mathrm{dark\ matter}} + \Omega_{\mathrm{normal\ matter}} + \Omega_{\mathrm{radiation}}}$$

$$\Omega_\Lambda \simeq 0.74 \ ; \quad \Omega_{\mathrm{dark\ matter}} \simeq 0.21 \ ; \quad \Omega_{\mathrm{normal\ matter}} \simeq 0.05 \ ; \quad \Omega_{\mathrm{radiation}} \simeq 0.003$$

Need inflation: ● need $N \gtrsim 60$, so called e-folds (CMB causal cone)

$$N \equiv \ln \frac{a(t_{\rm end})}{a(t_{\rm initial})} = \int_{t_i}^{t_e} H(t) {\rm d}t \simeq -\frac{8\pi}{M_{\rm Pl}^2} \int_{\phi_i}^{\phi_e} \frac{V}{V'} {\rm d}\phi$$

fixed entirely by scalar potential

I claim: scalar potential = the Higgs potential $V = \frac{m^2}{2} H^2 + \frac{\lambda}{24} H^4$ fixed by SM

It is a bottom-up prediction of the SM, only $\phi(M_{\rm Pl})$ is not fixed [ϕ not an observable at low energy]!

❒ Higgs mechanism = spontaneous $H \to -H$ symmetry breaking!

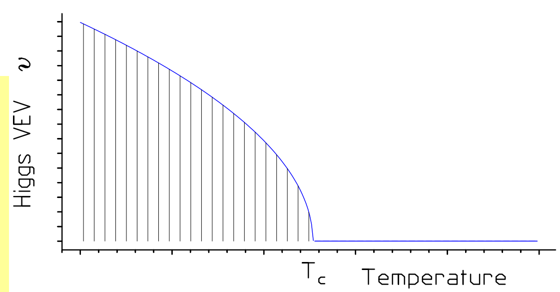
means: symmetry at short distance scale, broken at low energies!

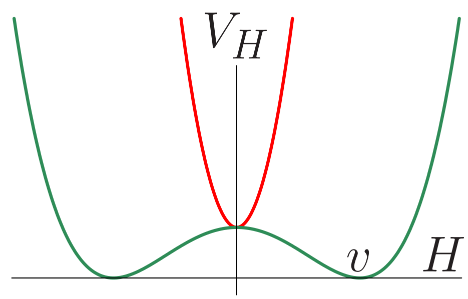
❖ when m^2 changes sign and λ stays positive $\Rightarrow$first order phase transition

❖ vacuum jumps from $v = 0$ to $v \neq 0$

in the SM the PT a consequence of the running of the couplings!

(see below)





Emergence Paradigm and UV completion: the LEESM

The SM is a low energy effective theory of a unknown Planck medium [the "ether"], which exhibits the Planck energy as a physical cutoff: i.e. the SM emerges from a system shaped by gravitation

$$\boxed{\Lambda_{\mathrm{Pl}} = (G_N/c\hbar)^{-1/2} \simeq 1.22 \times 10^{19}\ \mathrm{GeV}}$$

G_N Newton's gravitational constant, c speed of light, $\hbar$ Planck constant

- SM works up to Planck scale, means that in makes sense to consider the SM as the Planck medium seen from far away i.e. the SM is emergent at low energies. Expand in $E/\Lambda_{\mathrm{Pl}} \Rightarrow$ see renormalizable tail only.
- looking at shorter and shorter distances (higher energies) we can see the bare Planck system as it was evolving from the Big Bang! Energy scan in time!
- the tool for accessing early cosmology is the RG solution of SM parameters: we can calculate the bare parameters from the renormalized ones determined at low (accelerator) energies.

❐ In the symmetric phase at very high energy we see the bare system:

the Higgs field is a collective field exhibiting an effective mass generated by radiative effects

$$m^2_{\rm bare} \approx \delta m^2 \text{ at } M_{\rm Pl}$$

eliminates fine-tuning problem at all scales!

Many examples in condensed matter systems, Coleman-Weinberg mechanism

❐ "free lunch" in Low Energy Effective SM (LEESM) scenario:

- renormalizability of long range tail automatic!
- so are all ingredients required by renormalizability:
- non-Abelian gauge symmetries, chiral symmetry, anomaly cancellation, fermion families etc
- last but not least the existence of the Higgs boson!

*** all emergent ***
non-renormalizable stuff
heavily suppressed

The low energy expansion at a glance

	dimension	operator	scaling behavior
hidden world	$\cdot$	∞–many	
	$\cdot$	irrelevant	
$\uparrow$	$\cdot$	operators	
no			
data	$d=6$	$(\Box\phi)^2, (\bar{\psi}\psi)^2, \cdots$	$(E/\Lambda_{\mathrm{Pl}})^2$
$\mid$	$d=5$	$\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi, \cdots$	$(E/\Lambda_{\mathrm{Pl}})$
world as seen			tamed by symmetries
$\mid$	$d=4$	$(\partial\phi)^2, \phi^4, (F_{\mu\nu})^2, \cdots$	$\ln(E/\Lambda_{\mathrm{Pl}})$
experimental	$d=3$	$\phi^3, \bar{\psi}\psi$	$(\Lambda_{\mathrm{Pl}}/E)$
data	$d=2$	$\phi^2, (A_\mu)^2$	$(\Lambda_{\mathrm{Pl}}/E)^2$
$\downarrow$	$d=1$	ϕ	$(\Lambda_{\mathrm{Pl}}/E)^3$

Note: d=6 operators at LHC suppressed by $(E_{\mathrm{LHC}}/\Lambda_{\mathrm{Pl}})^2 \approx 10^{-30}$

$\Rightarrow$ require chiral symmetry, gauge symmetry, $\cdots$??? self-organized!

– just looks symmetric as we cannot see the details –

The Higgs boson is the inflaton!

As inflation is a well established fact (CMB etc), eliminating Flatness, Causality, primordial Fluctuations issues, sufficient dark energy must have been there: the SM Higgs provides it!

❒ in symmetric phase (early universe) bare effective mass and vacuum energy dramatically enhanced by quadratic and quartic cutoff effects

➠ slow-roll inflation condition $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$ satisfied

➠ Higgs potential provides huge dark energy in early universe which triggers inflation

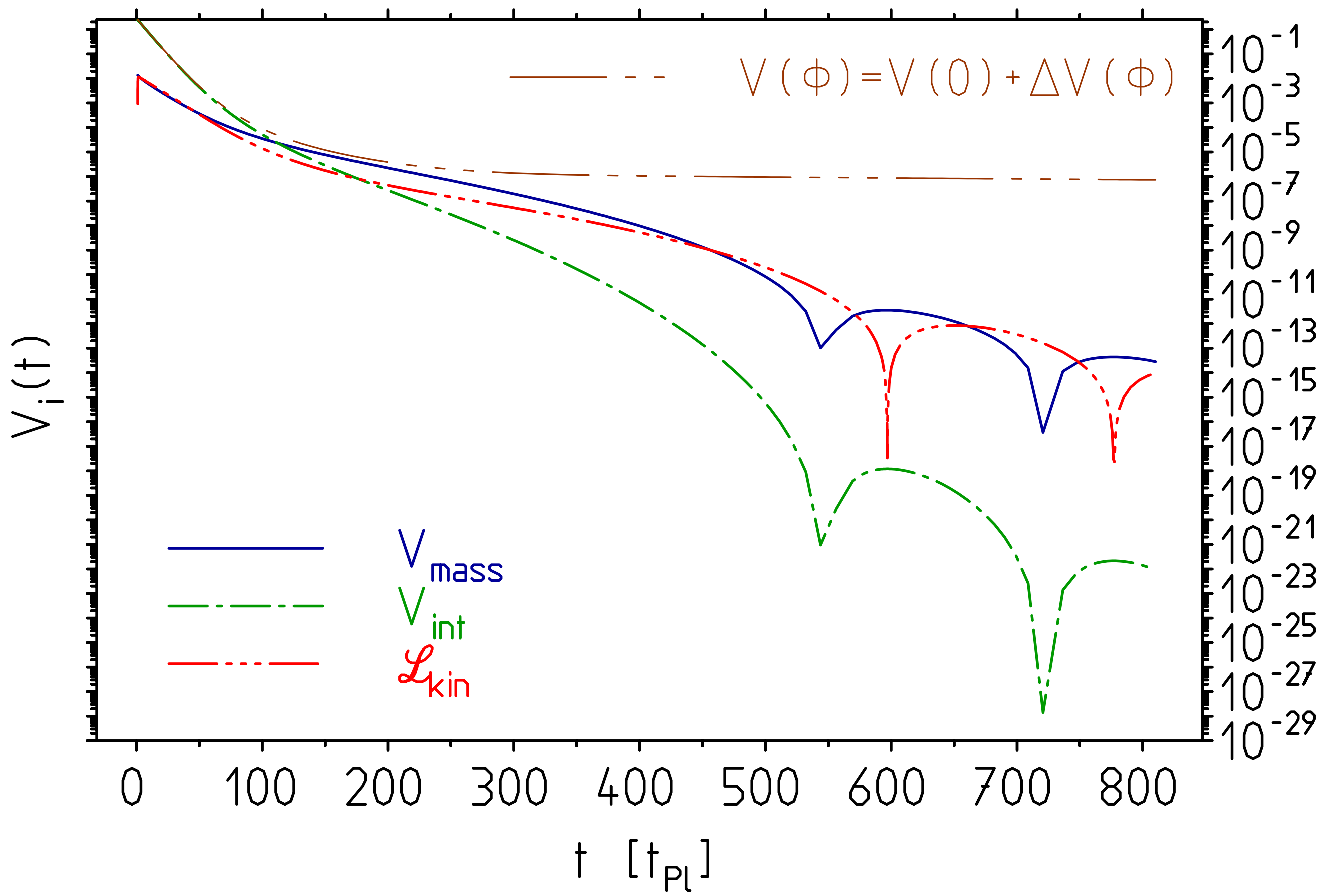
The SM predicts dark energy and inflation!!!

dark energy and inflation are unavoidable consequences of the SM Higgs

(provided new physics does not disturb it substantially)

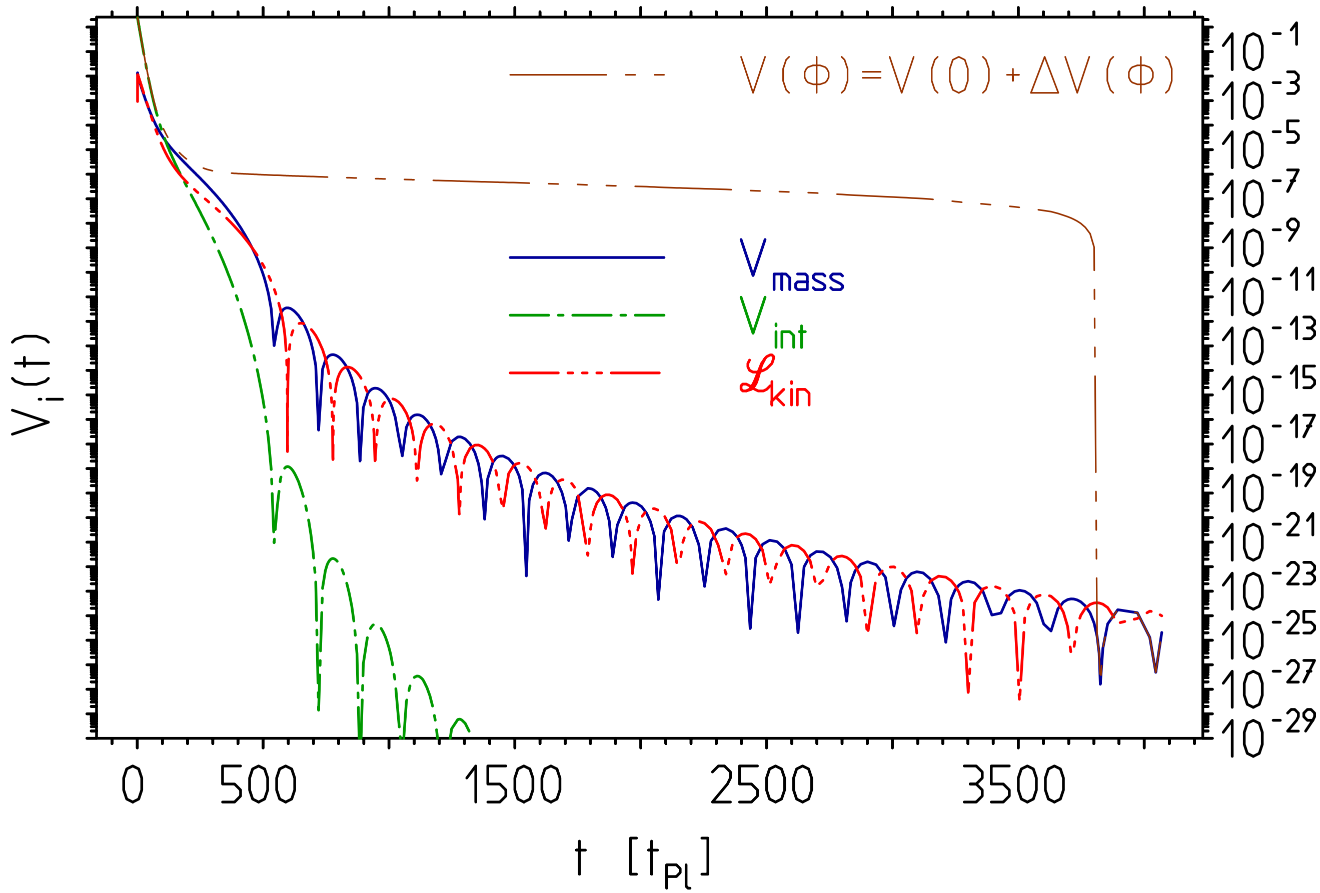
❒ the running of SM parameters triggers the Higgs mechanism

The evolution of the universe before the EW phase transition:



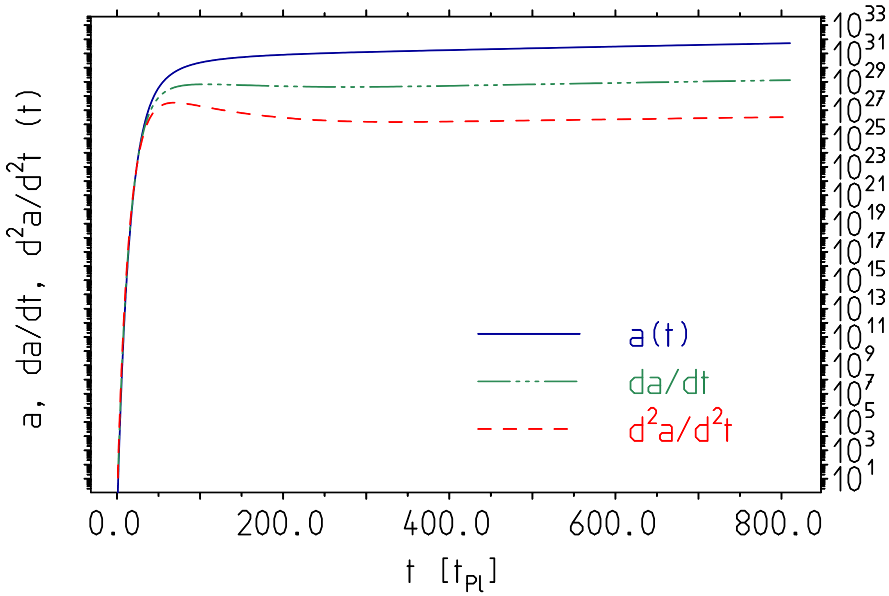
Inflation Times: the mass-, interaction- and kinetic-term of the bare Lagrangian in units of $M_{\rm Pl}^4$ as a function of time.

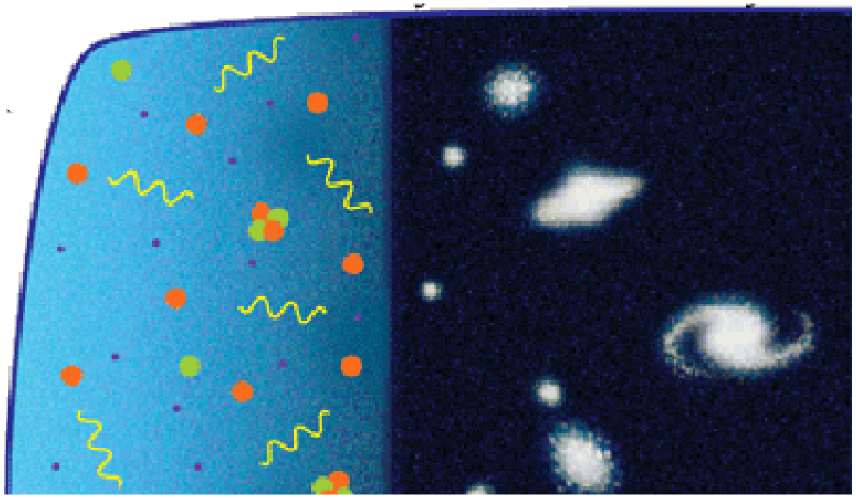
The evolution of the universe before the EW phase transition:



Evolution until symmetry breakdown and vanishing of the CC. After inflation the scene is characterized by a free damped harmonic oscillator behavior.

❍ The inflated expansion in the LEESM





Expansion before the Higgs transition: the FRW radius and its derivatives for $k = 1$ as a function of time, all in units of the Planck mass, i.e. for $M_{\rm Pl} = 1$. Here LEESM versus Artwork.

Reheating and Baryogenesis

❒ inflation: exponential growth = exponential cooling

❒ reheating: pair created heavy states $X, \bar{X}$ in originally hot radiation dominated universe decay into lighter matter states which reheat the universe

❒ baryogenesis: X particles produce particles of different baryon-number B and/or different lepton-number L

Sacharow condition for baryogenesis:

- $\cancel{B}$

❒ small $\cancel{B}$ is natural in LEESM scenario due to the close-by dimension 6 operators Weinberg 1979, Buchmüller, Wyler 1985,Grzadkowski et al 2010

❒ suppressed by $(E/\Lambda_{\mathrm{Pl}})^2$ in the low energy expansion. At the scale of the EW phase transition the Planck suppression factor is 1.3×10^{-6}.

❒ six possible four-fermion operators all $B-L$ conserving!

- $\cancel{C}$, $\cancel{CP}$, out of equilibrium

X is the Higgs! – “unknown” X particles now known very heavy Higgs in symmetric phase of SM: Primordial Planck medium Higgses

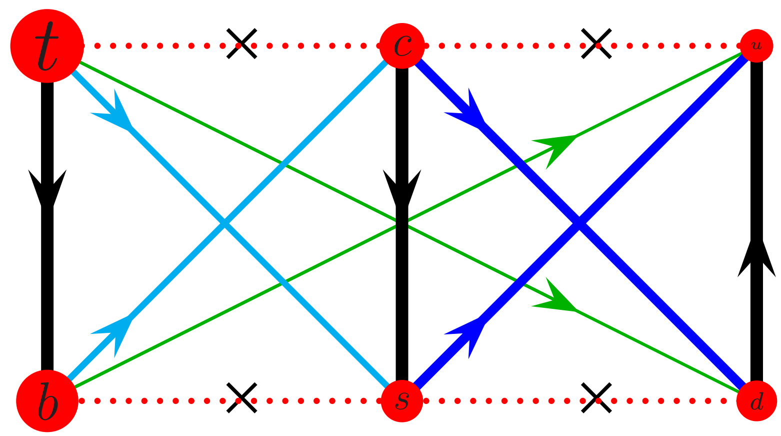
All relevant properties known: mass, width, branching fractions, CP violation properties!

Stages: ❒ $k_BT > m_X$ ⇒thermal equilibrium X production and X decay in balance

❒ $H \approx \Gamma_X$ and $k_BT < m_X$ ⇒X-production suppressed, out of equilibrium

❒ $H \to t\bar{t},\ b\bar{b},\ \cdots$ predominantly (largest Yukawa couplings)

❒ CP violating decays: $H^+ \to t\bar{d}$ [rate $\propto y_t y_d\, V_{td}$] $H^- \to b\bar{u}$ [rate $\propto y_b y_u\, V_{ub}$]
and after EW phase transition: $t \to de^+\nu$ and $b \to ue^-\nu_e$ etc.



Higgses decay into heavy quarks afterwards decaying into light ones

Note: large CP violation in V_{td} and V_{ub} links

Seems we are all descendants of four heavy Higgses via top-bottom stuff!

Baryogenesis most likely a “SM + dim 6 operators” effect!

Conclusion

- The LHC made tremendous step forward in SM physics and cosmology: the discovery of the Higgs boson, which fills the vacuum of the universe first with dark energy and latter with the Higgs condensate, thereby giving mass to quarks leptons and the weak gauge bosons, but also drives inflation, reheating and all that

- Higgs not just the Higgs: its mass about $M_H = 125$ GeV has a very peculiar value!! tailored such that strange exotic phenomena like inflation and likely also the continued accelerated expansion of the universe are a direct consequence of LEESM physics.

➠ ATLAS and CMS results may "revolution" particle physics in an unexpected way, namely showing that the SM has higher self-consistency (conspiracy) than expected and previous arguments for the existence of new physics motivated by the hierarchy "problem" or coupling unification turned out not to be compelling

➠ SM as a low energy effective theory of some cutoff system at $M_{\rm Pl}$ consolidated; crucial point $M_{\rm Pl} >>>> ...$ from what we can see!

➠ change in paradigm:

$\boxed{\text{Natural scenario understands the SM as the "true world" seen from far away}}$

$\Rightarrow$ Methodological approach known from investigating condensed matter systems. (QFT as long distance phenomenon, critical phenomena)
Ken Wilson NP 1982 see Jonathan Bain's Talk

➠cut-offs in particle physics are important to understand early cosmology, i.e. inflation, reheating Baryogenesis and all that

➠ the LEESM scenario, for the given now known parameters, the SM predicts dark energy and inflation, i.e. they are unavoidable

➠ this LEESM scenario is testable! e.g. find SUSY would kill it or find 4th family fermion etc

➠ does not exclude other type of new physics: dark matter, axions (strong CP problem), Majorana neutrinos (see-saw mechanism).

Of course: a lot yet to be understood!

❖ Keep in mind: the Higgs mass miraculously turns out to have a value as it has been expected form vacuum stability. It looks like a tricky conspiracy with other couplings to reach this “purpose”. If it misses to stabilize the vacuum, why does it just miss it almost not?

❖ the big issue is the very delicate conspiracy between SM couplings: precision determination of parameters more important than ever $\Rightarrow$ the challenge for LHC and ILC: precision values for λ, y_t and α_s, and for low energy hadron facilities: more precise hadronic cross sections to reduce hadronic uncertainties in $\alpha(M_Z)$ and $\alpha_2(M_Z)$

- Physics is more than just mathematics. Formal finetuning arguments can easily be misleading. In physics we have to establish relations between measurables. Not everything you may calculate is an observable.

Also: If one scalar can do why should we need two?

In case of additionl scalar. Need proper inclusion of SM Higgs effects in first place!

Imagine...

$\cdots$ a world upside down?

Hello Ether World: we can see you from far far away!

Thanks for your attention!


E ANCHE LA MATEMATICA
$\int x\,dx$
CODICE
CODICE
IN RICERCA DEL MODUS VIVENDI

B. Touschek

Backup Material

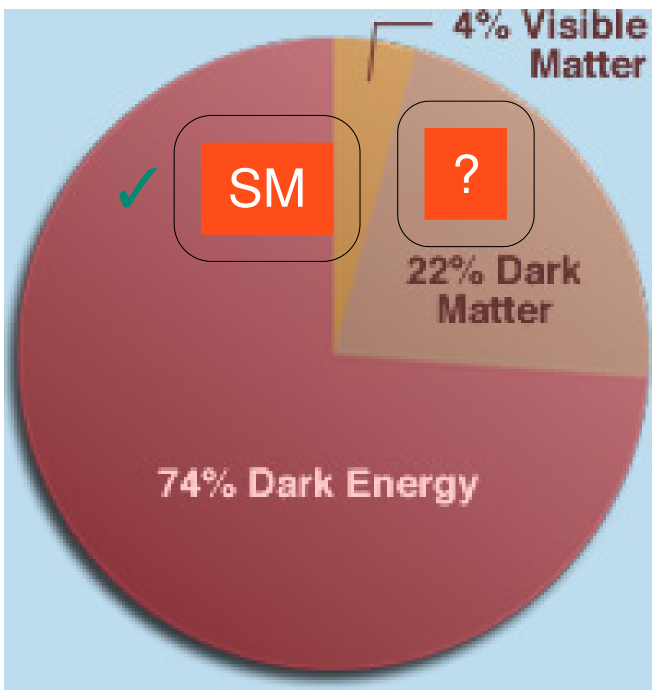
Paths to Physics at the Planck Scale

top-down approach				bottom-up approach
	M–THEORY(BRAIN WORLD)	Energy scale	E–THEORY(REAL WORLD)	
	candidate TOE		"chaotic" system	
	exhibits intrinsic cut-off	Planck scale	with intrinsic cut–off	
	$\downarrow$	$\parallel$		
	STRINGS	10^{19} GeV		
	$\downarrow$		$\uparrow$	
	SUGRA	$\downarrow$	QFT	
	$\downarrow$		$\uparrow$	
	SUSY–GUT	10^{16} GeV		
	$\downarrow$	$\downarrow$	$\uparrow$	
	SUSY	1 TeV	"??SM??"	
	$\searrow$	$\downarrow$	$\nearrow$	
		SM		

symmetry high $\longrightarrow$ $\longrightarrow$ $\longrightarrow$ symmetry low

?? symmetry $\equiv$ blindness for details ??

Last but not least: today's dark energy = relict Higgs vacuum energy?



WHAT IS DARK ENERGY?

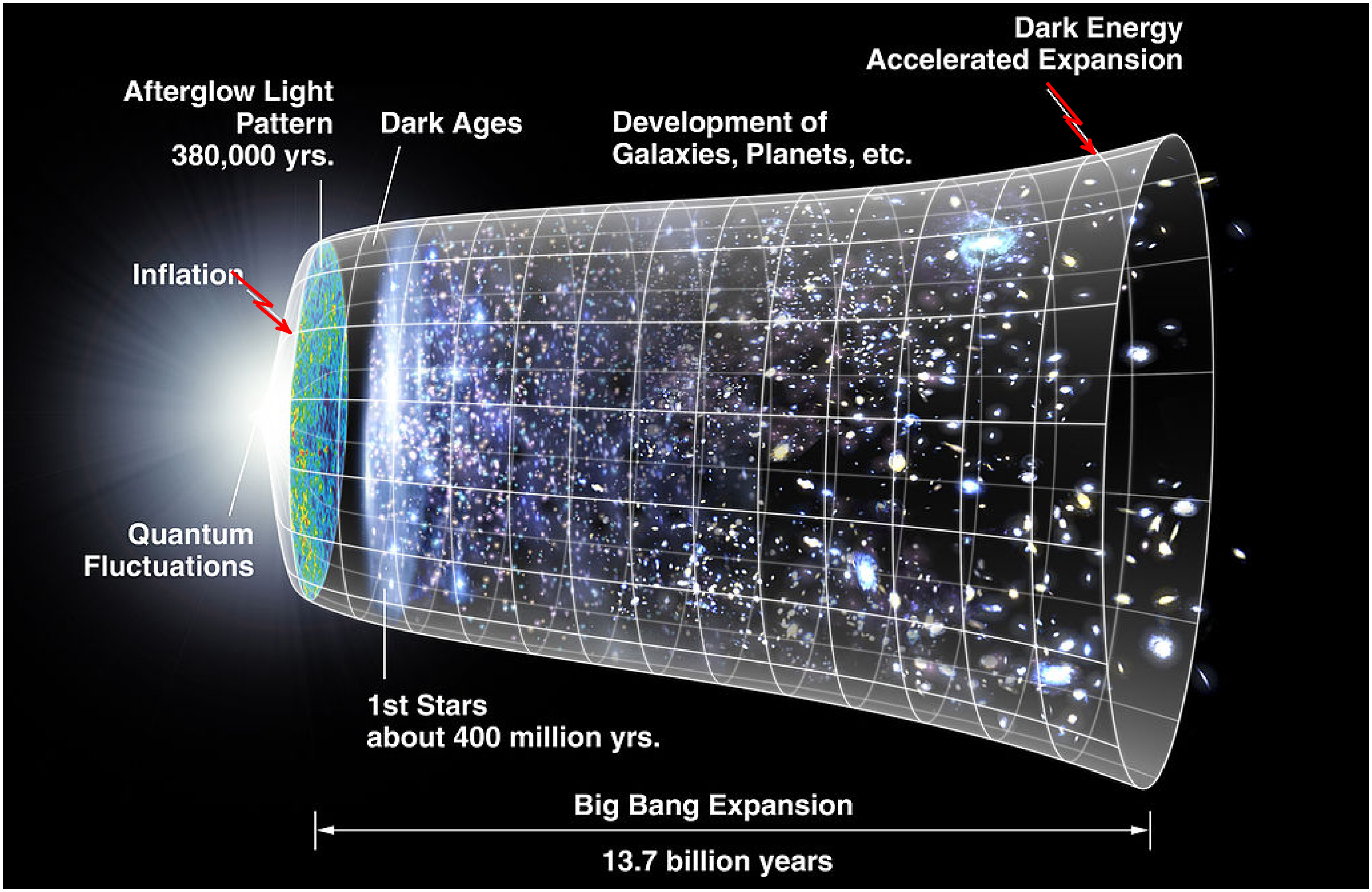
Well, the simple answer is that we don't know.

It seems to contradict many of our understandings about the way the universe works.

. . .

Something from Nothing?

It sounds rather strange that we have no firm idea about what makes up 74% of the universe.



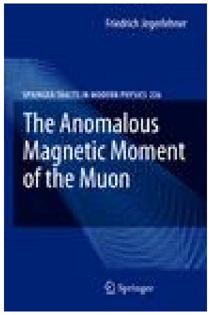
the Higgs at work

Durham and Krakow Lectures:
http://www-com.physik.hu-berlin.de/ fjeger/SMcosmology.html

“The Standard model as a low-energy effective theory: what is triggering the Higgs mechanism?,”
Acta Phys. Polon. B **45** (2014) 1167, [arXiv:1304.7813]

“Higgs inflation and the cosmological constant,”
Acta Phys. Polon. B **45** (2014) 1215, [arXiv:1402.3738]

“The hierarchy problem and the cosmological constant problem in the Standard Model,”
arXiv:1503.00809



New updated and expanded edition
Jegerlehner F., The Anomalous Magnetic Moment of the Muon. Springer Tracts in Modern Physics, Vol 274 (2017). Springer, Cham (693 pages on one number to 8 digits)