The beginning of all sciences
is the astonishment that things are
the way they are

Aristoteles

The Higgs boson as Inflaton

A new view on the SM of particle physics

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Kitzbühel Humboldt Kolleg, June 29, 2016

Cosmology, Cosmological Constant and Dark Energy

- Cosmology shaped by Einstein gravity $G_{\mu\nu} = \kappa\, T_{\mu\nu}$ +
  - Weyl's postulate (radiation and matter (galaxies etc) on cosmological scales behave as ideal fluids)
  - Cosmological principle (isotropy of space [homogeneity a consequence])

  $\Rightarrow$fix the form of the metric and of the energy-momentum tensor:

1. The metric (3-spaces of constant curvature $k = \pm 1, 0$ [closed,flat,open])

$$\boxed{\mathrm{d}s^2 = (c\mathrm{d}t)^2 - a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\,\mathrm{d}\Omega^2\right)}$$

where in the comoving frame $\mathrm{d}s = c\,\mathrm{d}t$ with t the cosmic time

2. The energy-momentum tensor

$$\boxed{T^{\mu\nu} = (\rho(t) + p(t))\,(t)\,u^\mu u^\nu - p(t)\,g^{\mu\nu}\;;\quad u^\mu \doteq \frac{\mathrm{d}x^\mu}{\mathrm{d}s}}$$

Need $\rho(t)$ energy density and $p(t)$ pressure to get $a(t)$ radius of the universe

Einstein [CC $\Lambda = 0$]: curved geometry $\leftrightarrow$ matter [empty space $\leftrightarrow$ flat space]

3. Special form energy-momentum tensor $p(t) = -\rho(t)$??? "Dark Energy" only

$$\boxed{T^{\mu\nu} = \rho(t)\, g^{\mu\nu}}$$

Peculiar dark energy equation of state: $w = p/\rho = -1$ no known physical system exhibits such strange behavior as anti-gravity!

WHAT IS DARK ENERGY? Well, the simple answer is that we don't know.

First introduced by Einstein as "Cosmological Constant" (CC) as part of the geometry, [where empty space appears curved,] in order to get stationary universe.

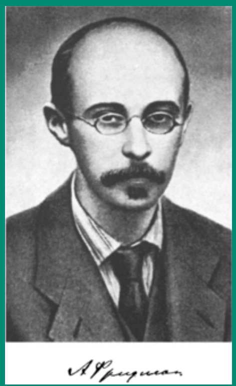
$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = \kappa \; T_{\mu\nu}$$

Einstein Tensor $\Leftrightarrow$ geometry of space-time

Gravitational interaction strength $\kappa = \frac{8\pi G_N}{3c^2}$

Energy-Momentum Tensor $\Leftrightarrow$ deriving from the Lagrangian of the SM

Cosmological solution: universe as a fluid of galaxies $\Rightarrow$Friedmann-Equations:



$$3\,\frac{\dot{a}^2+kc^2}{c^2a^2} - \Lambda = \kappa\,\rho$$

$$-\frac{2\,\ddot{a}a+\dot{a}^2+kc^2}{c^2a^2} + \Lambda = \kappa\,p$$

$a(t)$ Robertson-Walker radius of the universe

Λ Cosmological Constant

- universe must be expanding, **Big Bang**, and has finite age t
- Hubble's law [galaxies: $velocity_{\text{recession}} = H\,Distance$], H Hubble constant
- temperature, energy density, pressure huge at begin, decreasing with time

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu}\, R \quad = \quad \kappa \quad (T_{\mu\nu} + \rho_\Lambda\, g_{\mu\nu}) \quad = \kappa\, T^{\mathrm{tot}}_{\mu\nu} \;\; ; \; \rho_\Lambda = \Lambda/\kappa$$

Einstein Tensor $\Leftrightarrow$ geometry of space-time

Gravitational interaction strength $\kappa = \frac{8\pi G_N}{3c^2}$

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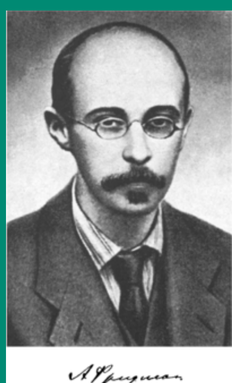


$$3\, \frac{\dot{a}^2 + kc^2}{c^2 a^2} \quad = \quad \kappa\, (\rho + \rho_\Lambda)$$

$$-\, \frac{2\, \ddot{a} a + \dot{a}^2 + kc^2}{c^2 a^2} \quad = \quad \kappa\, (p + p_\Lambda)$$

$a(t)$ Robertson-Walker radius of the universe

$p_\Lambda = -\rho_\Lambda$ Dark Energy

- ❒ universe must be expanding, **Big Bang**, and has finite age t
- ❒ Hubble's law [galaxies: $velocity_{\mathrm{recession}} = H\, Distance$], H Hubble constant
- ❒ temperature, energy density, pressure huge at begin, decreasing with time

Problems of GRT cosmology if dark energy absent:

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

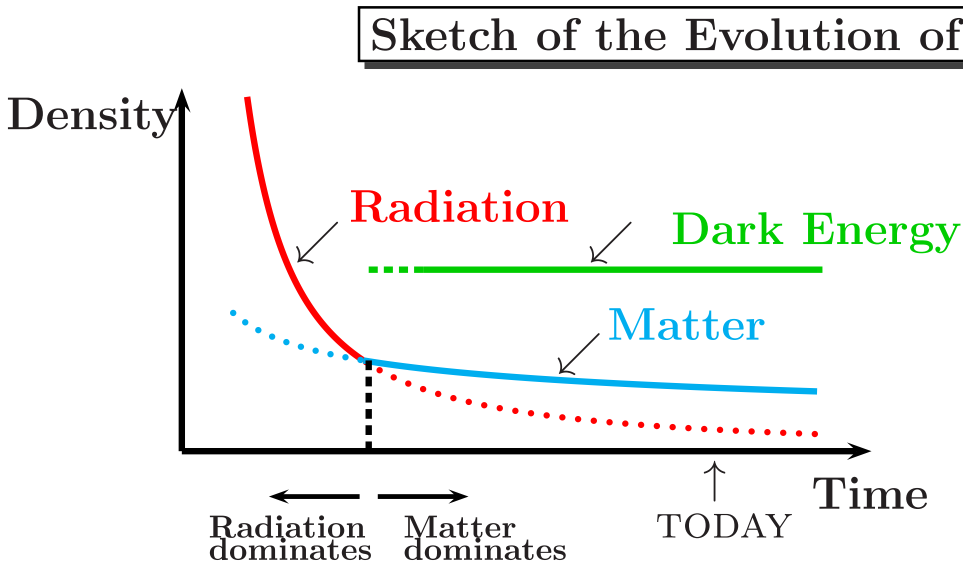
  CMB sky much larger [$d_{t_{\rm CMB}} \simeq 4 \cdot 10^7\ \ell{\rm y}$] than causally connected patch [$D_{\rm CMB} \simeq 4 \cdot 10^5\ \ell{\rm y}$] at $t_{\rm CMB}$ (380 000 yrs), but no such spot shadow seen!

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 $\ell_{\rm Pl}$ sized quantum fluctuations at Planck time?

As we will see: - $\Omega \doteq \rho/\rho_{\rm crit} = 1$ 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)

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



At Start ➠ **a Light-Flash!**
- high density
- high temperature

$\Rightarrow$ radiation dominates!

Late Times ➠ Dark Energy only

all other stuff dilutes into nothing!

unless universe recontracts $[k = +1]$

Forms of energy:

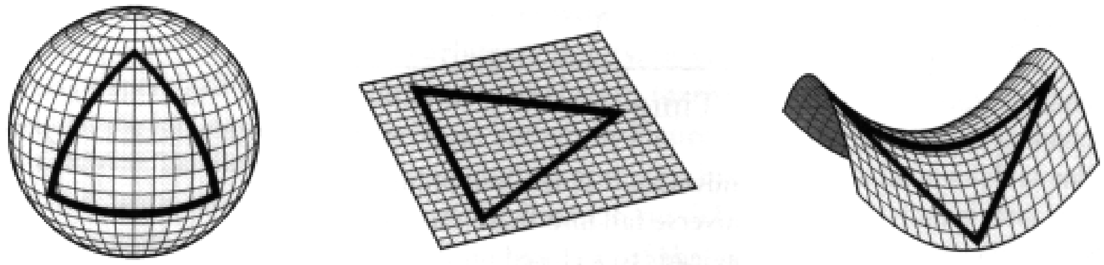
❒ radiation: photons, highly relativistic particles $p_{\text{rad}} = \rho_{\text{rad}}/3$

❒ normal and dark matter (non-relativistic, dilute) $p_{\text{matter}} \simeq 0\,,\;\; \rho_{\text{matter}} > 0$

❒ dark energy (cosmological constant) $p_{\text{vac}} = -\rho_{\text{vac}} < 0$

Note: Radiation $\rho_{\text{rad}} \propto 1/a(t)^4$, Matter $\rho_{\text{mat}} \propto 1/a(t)^3$, Dark Energy $\rho_\Lambda \propto a(t)^0$

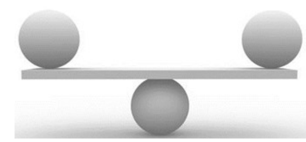
much matter recontraction | border case | little matter expanding forever



Curvature: closed $k = 1$ $[\Omega_0 > 1]$, flat $k = 0$ $[\Omega_0 = 1]$ and open $k = -1$ $[\Omega_0 < 1]$

Interesting fact: flat space geometry $\Leftrightarrow$ specific critical density, “very unstable”

$$\boxed{\rho_{0,\mathrm{crit}} = \rho_{\mathrm{EdS}} = \frac{3H_0^2}{8\pi G_N} = 1.878 \times 10^{-29}\, h^2\, \mathrm{gr/cm}^3,}$$

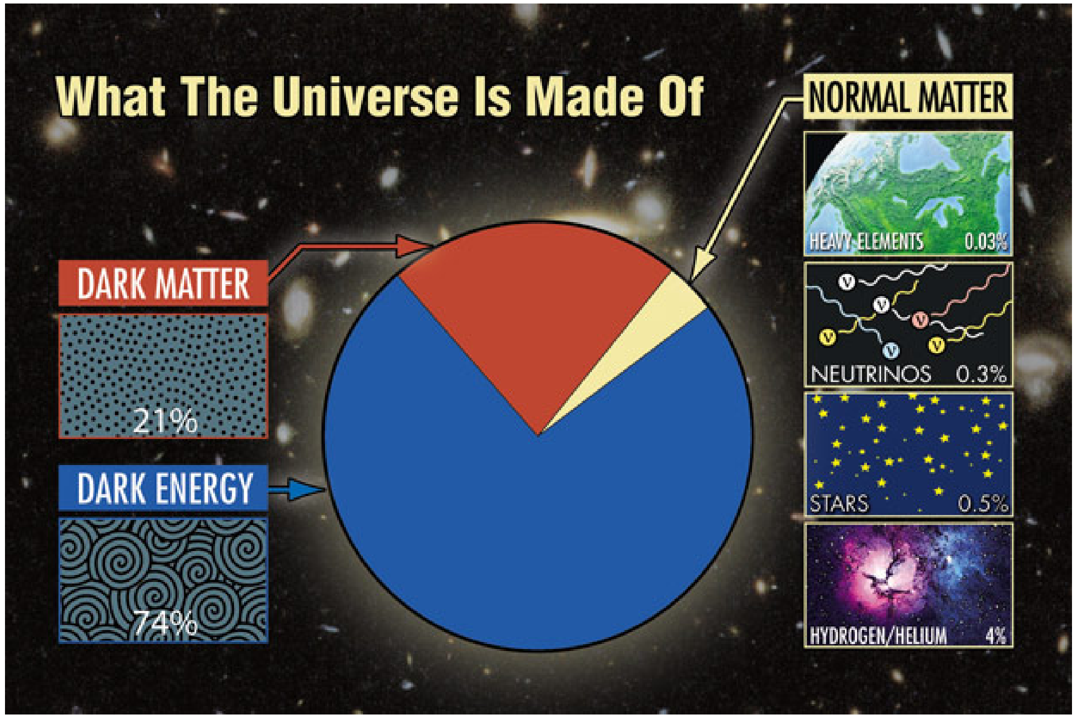


where H_0 is the present Hubble constant, and h its value in units of 100 km s^{-1} Mpc^{-1}. Ω expresses the energy density in units of $\rho_{0,\mathrm{crit}}$. Thus the present density ρ_0 is represented by

$$\Omega_0 = \rho_0/\rho_{0,\mathrm{crit}}$$

Dark energy will turn repulsive state into an attractor!

- 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

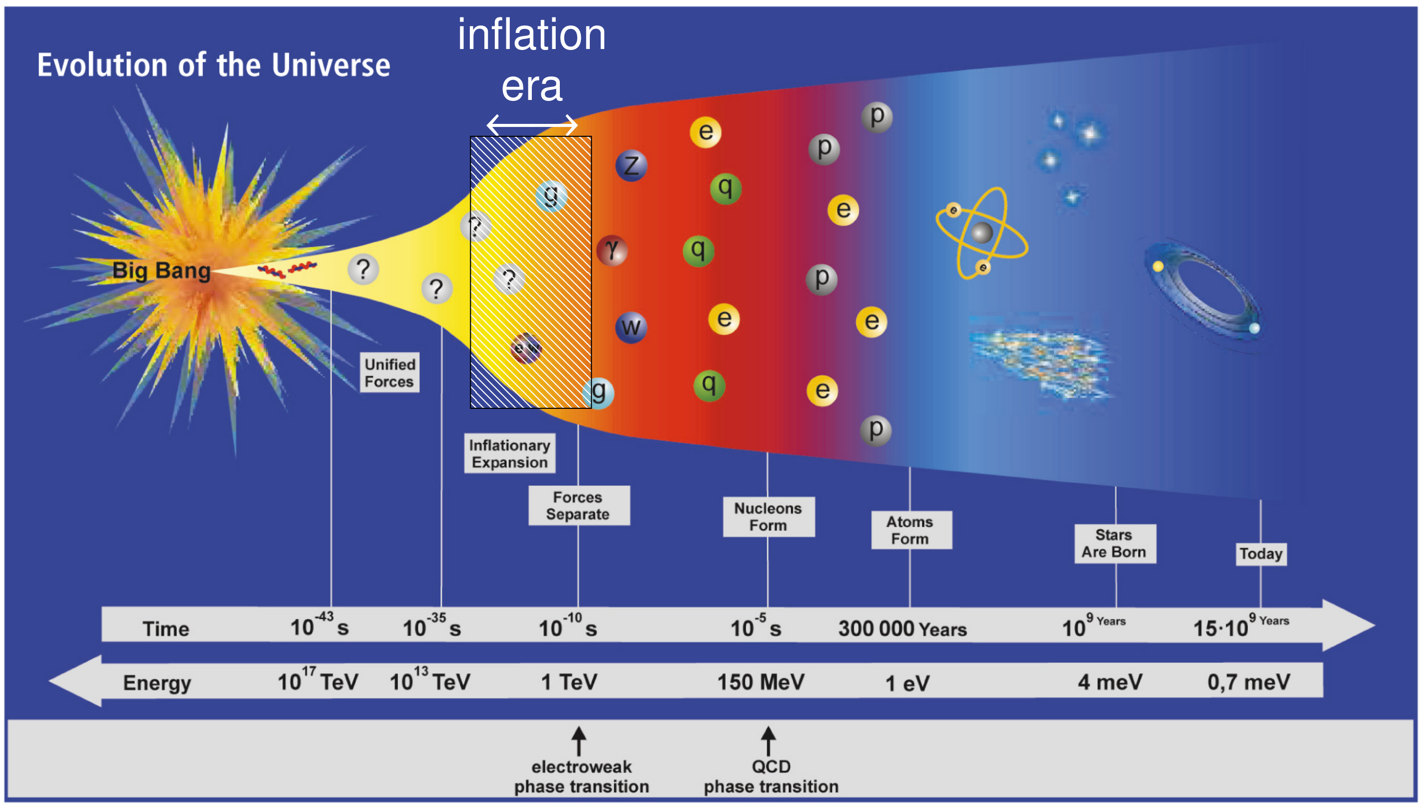
$$\boxed{\Omega_0 = \Omega_\Lambda + \Omega_{\rm dark\ matter} + \Omega_{\rm normal\ matter} + \Omega_{\rm radiation}}$$

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

Inflation

Need inflation! universe must blow up exponentially for a very short period, such that we see it to be flat! [switch on anti-gravity for very short period of time]

Need scalar field, which can do it! A. Guth 1980



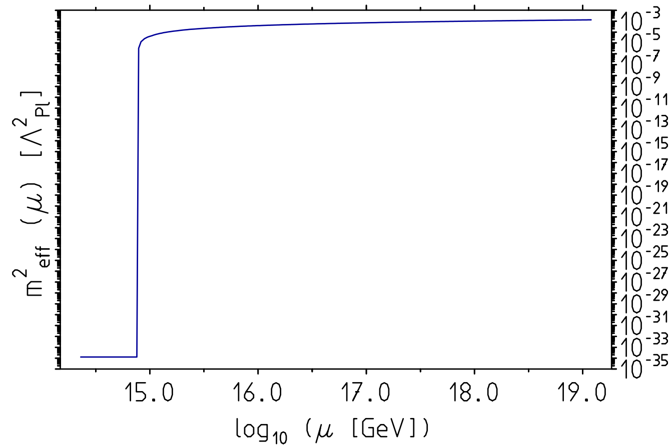
Higgs inflation in a Nutshell

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 $\Lambda_{\rm Pl} \sim 10^{19}$ GeV.

$$m^2_{\rm Higgs,\ bare} = m^2_{\rm Higgs,\ ren} + \delta m^2$$

$$\delta m^2 = \frac{\Lambda^2_{\rm Pl}}{(16\pi^2)}\, C(\mu)$$



- Is this a problem? Is this unnatural?
- It is a prediction of the SM!

- 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

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

- 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! no other system exhibits such strange equation of state!

● 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!

Friedman 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)

● the Higgs boson is the inflaton!

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

$\rho_\Lambda = \mu_\Lambda^4$: $\mu_{0,\Lambda} = 0.002\ \mathrm{eV}$ 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!

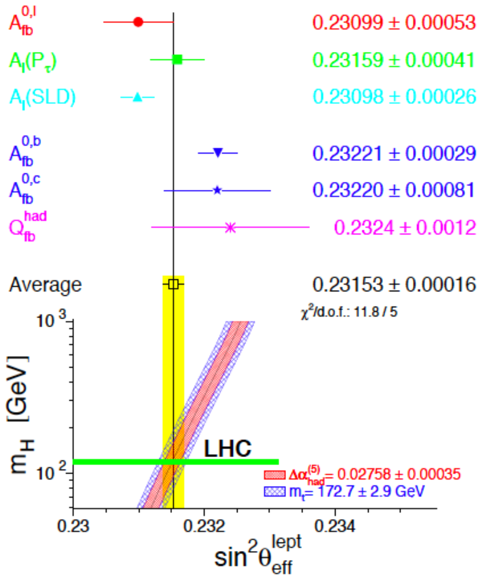
All other inflatons put by hand: all predictions are direct consequences of the respective assumptions

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}!

The Higgs boson discovery – the SM completion

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



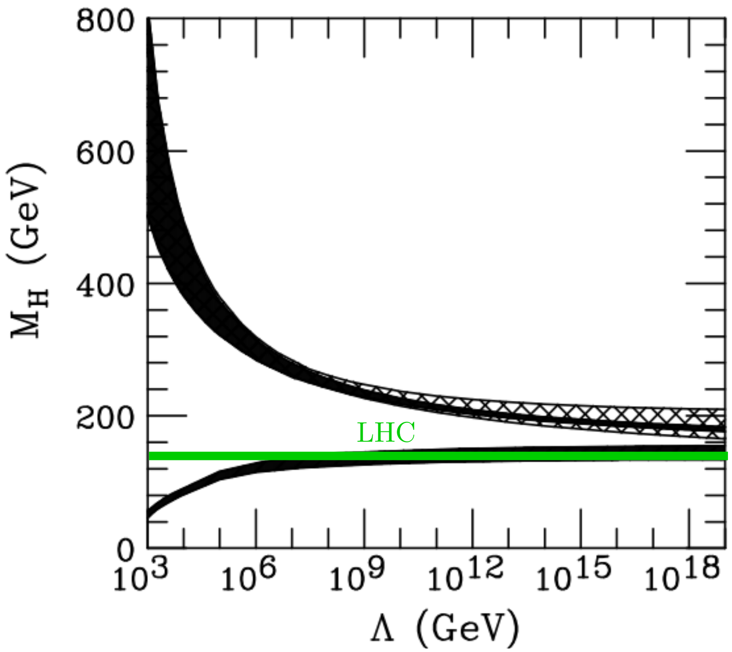
LEP 2005 +++ LHC 2012 Englert&Higgs Nobel Prize 2013

Higgs mass found in very special mass range 125.2 ± 0.4 GeV

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

Common Folklore: SM hierarchy problem 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:



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

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 ; $\alpha_s = 0.118$]

Basic parameters: gauge couplings $g' = g_1$, $g = g_2$, g_3, top quark Yukawa coupling y_t, Higgs self-coupling λ and Higgs VEV v, besides smaller Yukawas.
Note: $1/(\sqrt{2}v^2) = G_F$ is the Fermi constant! [$v = \left(\sqrt{2}G_F\right)^{-1/2}$]

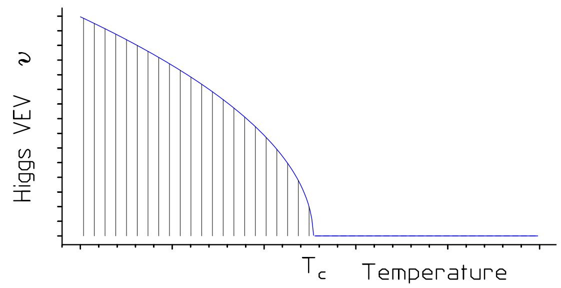
Key object of our interest: the Higgs potential

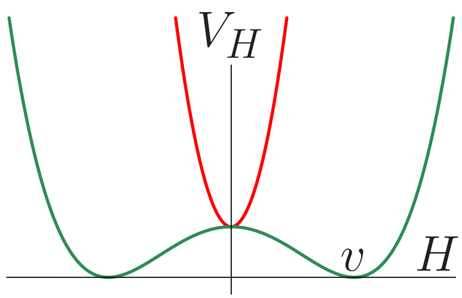
$$\boxed{V = \frac{m^2}{2} H^2 + \frac{\lambda}{24} H^4}$$

❖ when m^2 changes sign and λ stays positive ⇒first order phase transition

❒ Higgs mechanism = spontaneous $H \to -H$ symmetry breaking!
means: symmetry at short distance scale, broken at low energies!

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





SSB $\Rightarrow$ mass $\propto$ interaction strength $\times$ Higgs VEV v

$$\begin{array}{llllll} M_W^2 & = & \frac{1}{4}\, g^2\, v^2\;; & M_Z^2 & = & \frac{1}{4}\,(g^2+g'^2)\, v^2\;; \\ m_f^2 & = & \frac{1}{2}\, y_f^2\, v^2\;; & M_H^2 & = & \frac{1}{3}\,\lambda\, v^2 \end{array}$$

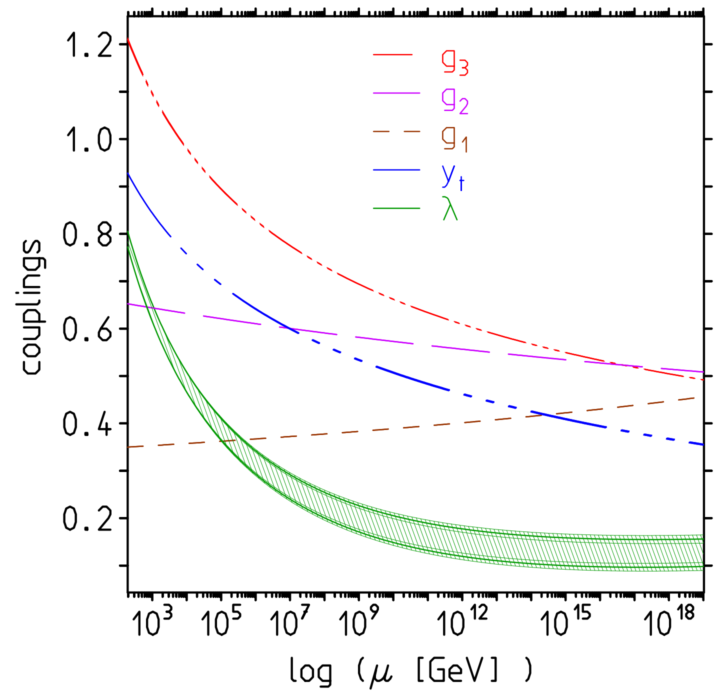
Measure masses predict couplings: $M_W,\ M_Z,\ M_H,\ M_t \Rightarrow g,\ g',\ \lambda,\ y_t$

Effective parameters depend on renormalization scale μ [normalization reference energy!], scale at which ultraviolet (UV) singularities are subtracted

- running couplings change substantially with energy and hence as a function of time during evolution of the universe!
- high energy behavior governed by $\overline{\mathrm{MS}}$ Renormalization Group (RG) [$E \gg M_i$]
- key input matching conditions between $\overline{\mathrm{MS}}$ and physical parameters !
- running well established for electromagnetic $\alpha_{\rm em}$ and strong coupling α_s: $\alpha_{\rm em}$ screening, α_s anti-screening (Asymptotic Freedom)

The SM running parameters

The SM dimensionless couplings in the $\overline{\mathrm{MS}}$ scheme as a function of the renormalization scale for $M_H = 124\text{–}127$ GeV. On-Shell vs $\overline{\mathrm{MS}}$ parameter matching: F.J., Kalmykow, Kniehl: PLB 2013
Issue: $M_t^{\mathrm{exp}} \to y_t(M_t)^{\overline{\mathrm{MS}}}$



- perturbation expansion works up to the Planck scale!
  no Landau pole or other singularities $\Rightarrow$ Higgs potential remains stable!
- Window to SM cosmology – inflation, reheating etc.!

The Role of Quadratic Divergences in the SM

Veltman 1978 [NP 1999] modulo small lighter fermion contributions, one-loop coefficient function C_1 is given by

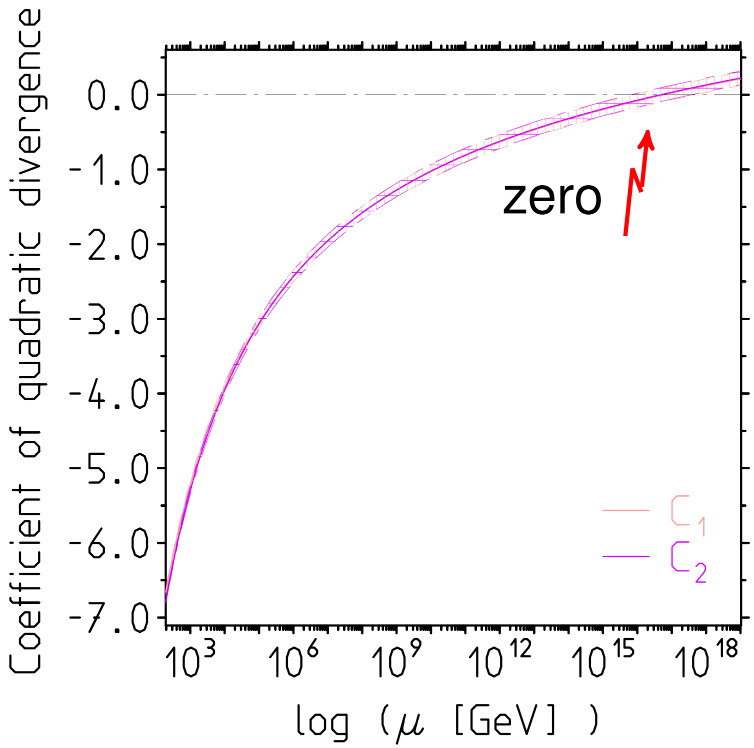
$$\delta m_H^2 = \frac{\Lambda_{\rm Pl}^2}{16\pi^2}\, C_1 \;;\quad C_1 = 2\,\lambda + \tfrac{3}{2}\, g'^2 + \tfrac{9}{2}\, g^2 - 12\, y_t^2$$

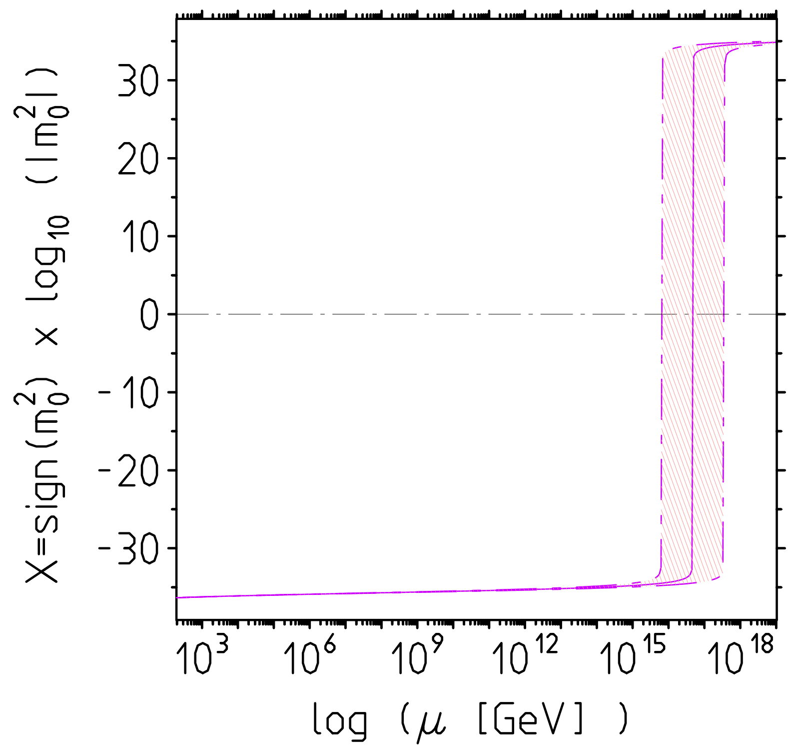
Key points:

- C_1 is universal and depends on dimensionless gauge, Yukawa and Higgs self-coupling only, the RGs of which are unambiguous.
  At two loops $C_2 \approx C_1$ numerically [Hamada et al 2013] stable under RCs!

- Couplings are running! $C_i = C_i(\mu)$

- the SM for the given running parameters makes a prediction for the bare effective mass parameter in the Higgs potential:





The Higgs phase transition in the SM [for $M_H = 125.9 \pm 0.4$ GeV].

$$\boxed{m^2_{\rm bare} = \text{sign}(m^2_{\rm bare}) \times 10^X}$$

Jump in vacuum energy: wrong sign and 50 orders of magnitude off $\Lambda_{\rm CMB}$!!!

$$\Delta V(\phi_0) = -\frac{m^2_{\rm eff} v^2}{8} = -\frac{\lambda\, v^4}{24} \sim -(176.0 \text{ GeV})^4$$

$\Rightarrow$one version of CC problem

- 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 as $\boxed{V(\phi) \gg \dot{\phi}^2}$ for $\mu > \mu_0$

➠ at the transition point μ_0 we have $\boxed{v_{\rm bare} = v(\mu_0^2)\ ; \quad m_{H\,{\rm bare}} = m_H(\mu_0^2)}$, where $v(\mu^2)$ 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.

Is the renormalized Higgs mass a free parameter?

- In fact: given SM parameters besides m_H, vacuum stability requires to take a value in the stability window!

More precisely:

Higgs mass and top quark mass must conspire with other SM masses such that in the gaugeless limit at one loop:

1. AF top Yukawa: $\beta_{y_t}(g, g', y_t, \lambda) < 0$,
   requires QCD dominance $g_3 > \frac{3}{4}\, y_t$
2. AF Higgs self-coupling: $\beta_\lambda(g, g', y_t, \lambda) < 0$,
   requires TOP dominance $\frac{3\,(\sqrt{5}-1)}{2}\, y_t^2 > \lambda$
3. Vacuum stability $\lambda(\mu) > 0$ up to $M_{\rm Pl}$.

- Higgs mass constrined to narrow window! (antropic principle)

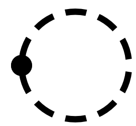
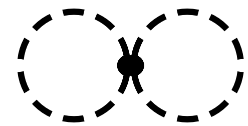
- Emergence paradigm: renormalizable low energy SM as UV completed SM as seen from far far away ($E <<< M_{\rm Pl}$)!

The Cosmological Constant in the SM

- SM vacuum energy in symmetric phase $\rho_{\Lambda\,\mathrm{bare}} = V(0) = \langle V(\phi) \rangle = \frac{m^2}{2}\,\Xi + \frac{\lambda}{8}\,\Xi^2$;
- in symmetric phase $SU(2)$ is a symmetry: $\Phi \to -U(\omega)\Phi$ and $\Phi^+\Phi$ singlet;

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

just Higgs self-loops

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

$\Rightarrow$ mass shift $m'^2 = m^2 + \frac{\lambda}{2}\,\Xi \quad \Rightarrow \quad \mu_0 \approx 1.4 \times 10^{16}$ GeV $\to \mu_0' \approx 7.7 \times 10^{14}$ GeV ,

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

$\Rightarrow$ $H \simeq \ell\,\sqrt{V(0) + \Delta V}$ at M_{Pl} we expect $\phi_0 = O(M_{\mathrm{Pl}})$ i.e. at start $\Delta V(\phi) \gg V(0)$

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

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

- need $\phi_0 \approx 4.51 M_{\rm Pl}$, big enough to provide sufficient inflation. Note: this is the only free parameter in SM inflation, the Higgs field is not an observable in the renormalized low energy world (laboratory/accelerator physics).

Decay patterns:

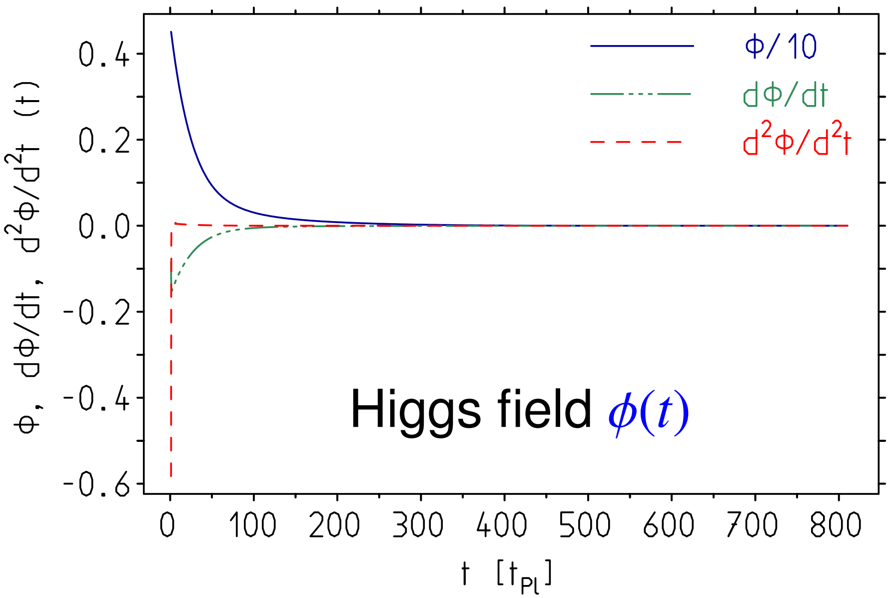
$$\phi(t) = \phi_0 \, \exp\{-E_0\,(t-t_0)\}\,, \;\; E_0 \approx \frac{\sqrt{2\lambda}}{3\,\sqrt{3}\ell}\,, \;\; \approx 4.3 \times 10^{17}\ \text{GeV}\,, \;\; V_{\rm int} \gg V_{\rm mass}$$

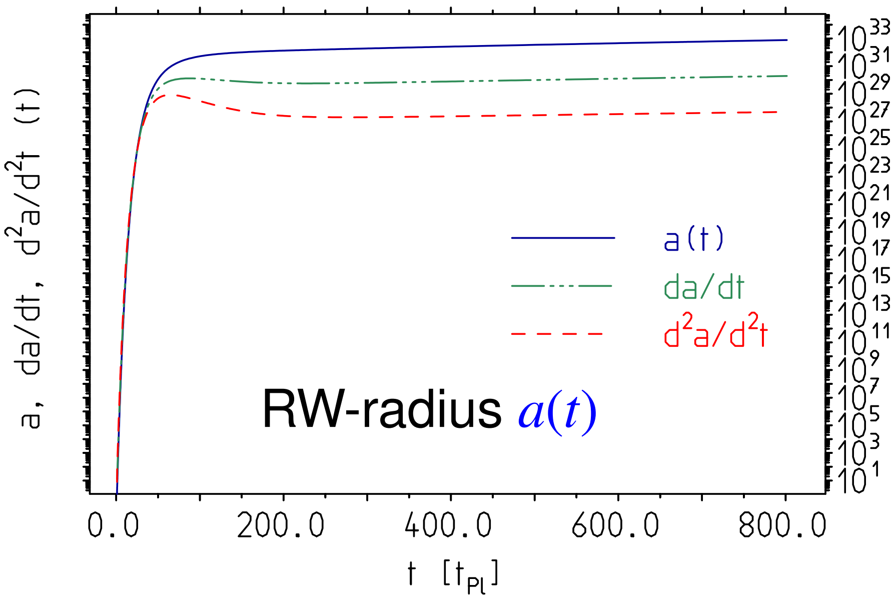
soon mass term dominates, in fact $V(0)$ and $V_{\rm mass}$ are comparable before $V(0)$ dominates and $H \approx \ell\,\sqrt{V(0)}$ and

$$\phi(t) = \phi_0 \, \exp\{-E_0\,(t-t_0)\}\,, \;\; E \approx \frac{m^2}{3\ell\,\sqrt{V(0)}} \approx 6.6 \times 10^{17}\ \text{GeV}\,, \;\; V_{\rm mass} \gg V_{\rm int}$$

Note: if no CC ($V(0) \approx 0$) as assumed usually

$$\phi(t) = \phi_0 - X_0\,(t-t_0)\,, \;\; X_0 \approx \frac{\sqrt{2}m}{3\ell} \approx 7.2 \times 10^{35}\ \text{GeV}^2\,, \;\; V_{\rm mass} \gg V_{\rm int}$$





Note: the Hubble constant in our scenario, in the symmetric phase, during the radiation dominated era is given by (Stefan-Boltzmann law)

$$\boxed{H = \ell\,\sqrt{\rho_{\rm rad}} \simeq 1.66\,(k_BT)^2\,\sqrt{102.75}\,M_{\rm Pl}^{-1}}$$

such that at Planck time (SM predicted)

$$\boxed{H_i \simeq 16.83\,M_{\rm Pl}\;.}$$

i.e. trans-Planckian $\phi_0 \sim 5M_{\rm Pl}$ is not unnatural!

Note: inflation stops because of the extremely fast decay of the Higgs field ($t_{\rm end} \lesssim 100\,t_{\rm Pl}$)

How to get rid of the huge CC?

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

Note total energy density as a function of time

$$\boxed{\rho(t) = \rho_{0,\mathrm{crit}} \left\{\Omega_\Lambda + \Omega_{0,\mathrm{k}}\,(a_0/a(t))^2 + \Omega_{0,\mathrm{mat}}\,(a_0/a(t))^3 + \Omega_{0,\mathrm{rad}}\,(a_0/a(t))^4\right\}}$$

reflects a present-day snapshot. Cosmological constant is constant! Not quite!

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

$$\boxed{\rho_{\Lambda\,\mathrm{bare}} = \rho_{\Lambda\,\mathrm{ren}} + \frac{M_{\mathrm{Pl}}^4}{(16\pi^2)^2}\,X(\mu)\;;\quad X(\mu) \simeq 2C(\mu) + \lambda(\mu) = 5\,\lambda + 3\,g'^2 + 9\,g^2 - 24\,y_t^2}$$

with $X(\mu)$ exhibiting a zero close to the zero of $C(\mu)$
when $2\,C(\mu) = -\lambda(\mu)$, which happens at

$$\mu_{\mathrm{CC}} \approx 3.1 \times 10^{15}\ \mathrm{GeV}$$

in between $\mu_0 \approx 1.4 \times 10^{16}$ GeV and $\mu_0' \approx 7.7 \times 10^{14}$ GeV .

Again we find a matching point between low energy and high energy world:

$$\boxed{\rho_{\Lambda\,\mathrm{bare}} = \rho_{\Lambda\,\mathrm{ren}}}$$

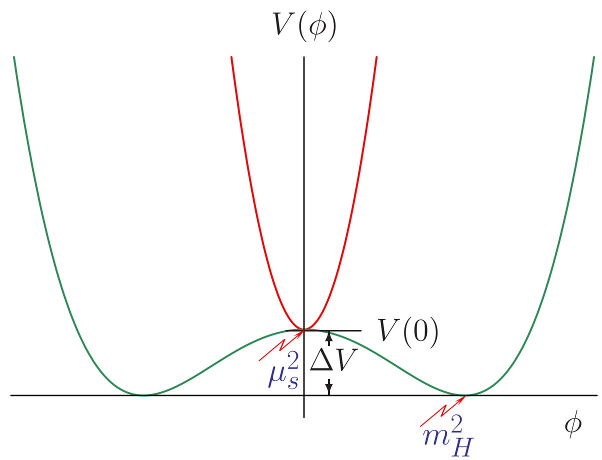
where memory of quartic Planck scale enhancement gets lost!

Has there been a cosmological constant problem?

Crucial point $X = 2C + \lambda$ acquires positive bosonic contribution and negative fermionic ones, with different scale dependence. X can change a lot (pass a zero), while individual couplings are weakly scale dependent $y_t(M_Z)/y_t(M_{\mathrm{Pl}}) \sim 2.7$ biggest, $g_1(M_Z)/g_1(M_{\mathrm{Pl}}) \sim 0.76$ smallest.

- SM predicts huge CC at M_{Pl}: $\rho_\phi \simeq V(\phi) \sim 2.77\, M_{\mathrm{Pl}}^4 \sim \left(1.57 \times 10^{19}\ \mathrm{GeV}\right)^4$ how to tame it?

At Higgs transition: $m'^2(\mu < \mu'_0) < 0$ vacuum rearrangement of Higgs potential



How can it be: $\boxed{V(0) + \Delta V \sim (0.002\ \mathrm{eV})^4}$???

The zero $X(\mu_{\mathrm{CC}}) = 0$ provides part of the answer as it makes $\rho_{\Lambda\,\mathrm{bare}} = \rho_{\Lambda\,\mathrm{ren}}$ to be identified with the observed value?

Can be naturally small, since Λ_{Pl}^4 term nullified at matching point.

Note: in principle, like the Higgs mass in the LEESM, also $\rho_{\Lambda\,\mathrm{ren}}$ is expected to be a free parameter to be fixed by experiment.

Not quite! there is a big difference: inflation forces $\rho_{\rm tot}(t) \approx \rho_{0,\rm crit} = \rm constant$ after inflation era

$$\boxed{\Omega_{\rm tot} = \Omega_\Lambda + \Omega_{\rm mat} + \Omega_{\rm rad} = \Omega_\Lambda + \Omega_{0,\rm k}\,(a_0/a(t))^2 + \Omega_{0,\rm mat}\,(a_0/a(t))^3 + \Omega_{0,\rm rad}\,(a_0/a(t))^4 \approx 1}$$

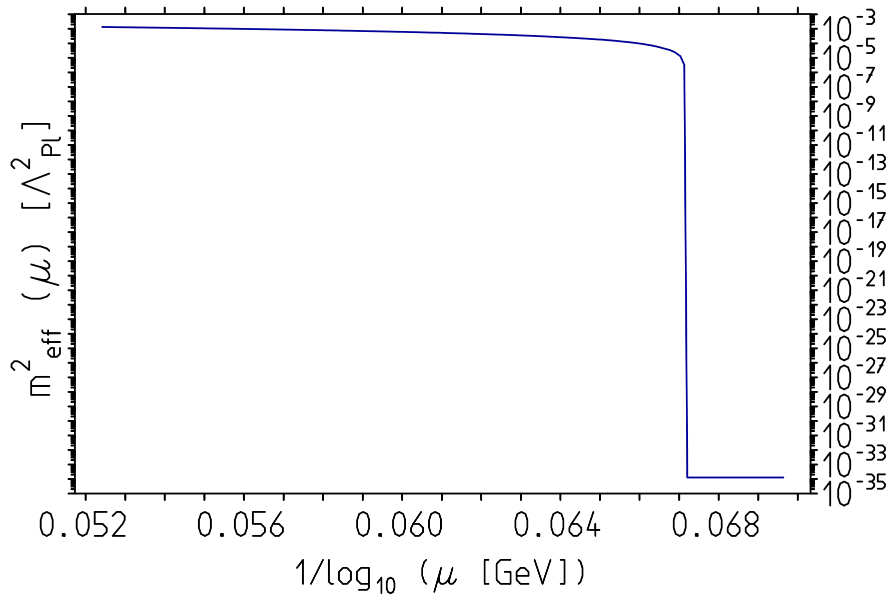
and since $1 > \Omega_{\rm mat},\ \Omega_{\rm rad} > 0$ actually Ω_Λ is fixed once we know dark matter, baryonic matter and the radiation density:

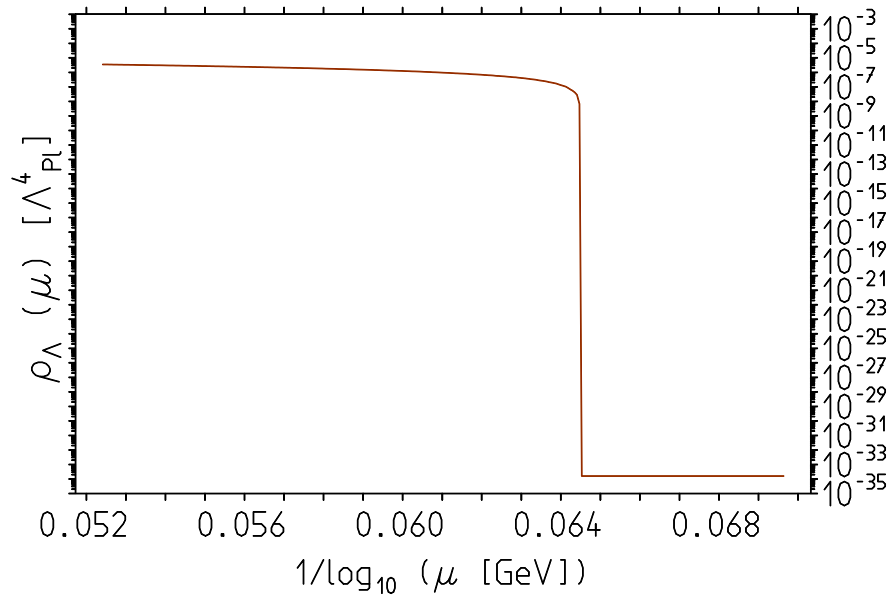
$$\boxed{\Omega_\Lambda = 1 - \Omega_{\rm mat} - \Omega_{\rm rad}}$$

So, where is the miracle to have CC of the magnitude of the critical density of a flat universe? Also this then is a prediction of the LEESM!

Note that $\Omega_{\rm tot} = 1$ requires Ω_Λ to be a function of t, up to negligible terms,

$$\Omega_\Lambda \to \Omega_\Lambda(t) \approx 1 - (\Omega_{0,\rm dark\ mat} + \Omega_{0,\rm baryonic\ mat})\ (a_0/a(t))^3 \to 1\ ;\quad t \to \infty$$





effective Higgs mass square

effective dark energy density

in units of $\Lambda_{\rm Pl}$, for $\mu < \mu_{\rm CC}$ we display $\rho_\Lambda[\text{GeV}^4] \times 10^{13}$ as predicted by SM

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

Remark: $\Omega_\Lambda(t)$ includes besides the large positive $V(0)$ also negative contributions from vacuum condensates, like $\Delta\Omega_{\rm EW}$ from the Higgs mechanism and $\Delta\Omega_{\rm QCD}$ from the chiral phase transition.

The Higgs Boson is the Inflaton!

- after electroweak PT, at the zeros of quadratic and quartic "divergences", memory of cutoff lost: renormalized low energy parameters match bare parameters

- 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)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Dark Energy: The Biggest Mystery in the Universe

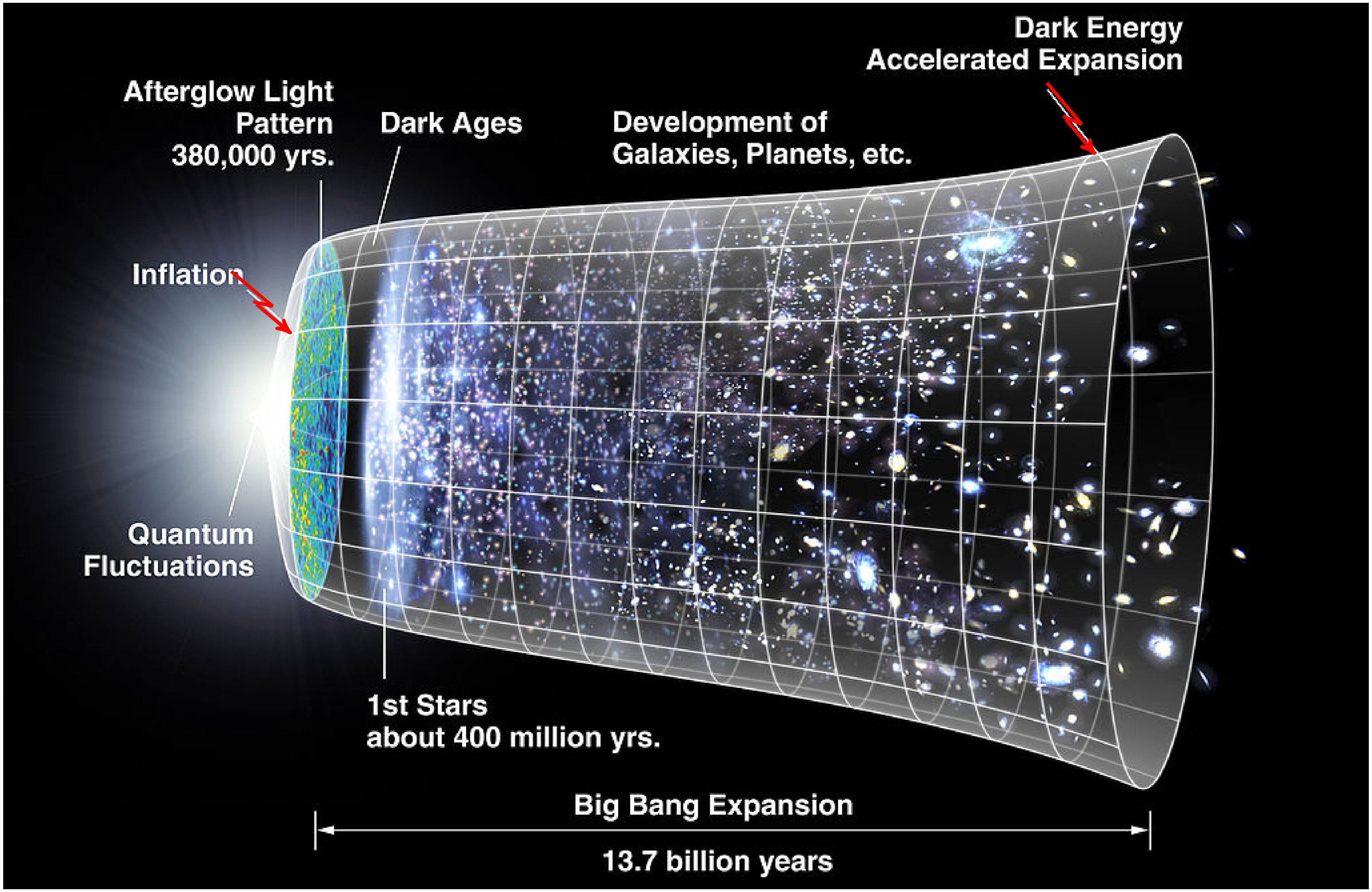
Unless you accept the SM supplemented with a physical cutoff!

Thanks

Thanks for your attention!


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

B. Touschek



the Higgs at work

Backup Slides: 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

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

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 $E/\Lambda_{\rm Pl} \Rightarrow$ 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.

- Why M_{Pl} as physical UV cutoff and not some other new physics scale?

i.) M_{Pl} is the only known fundamental cutoff (other possible new physics scales are hypothetical at best),

ii.) specific Higgs mass value found actually opens a window up to M_{Pl}

iii.) The cosmological constant problem in the SM is associated with the Higgs system, which is the only SM field “talking” directly to gravity and M_{Pl} is the scale intrinsic to gravity.

The low energy expansion at a glance

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

hidden world

world as seen

tamed by symmetries

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

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

– just looks symmetric as we cannot see the details –

❒ 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

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

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

Need vacuum stability and Higgs phase transition below M_{Pl}.

My evaluation of $\overline{\mathrm{MS}}$ parameters revealed Vacuum Stability

Although other evaluations of the matching conditions seem to favor the meta-stability of the electroweak vacuum within the experimental and theoretical uncertainties, one should not exclude the possibility that other experiments and improved matching conditions will be able to establish the absolute stability of Standard Model in the future.

Shaposhnikov et al. `arXiv:1412.3811` say about Vacuum Stability

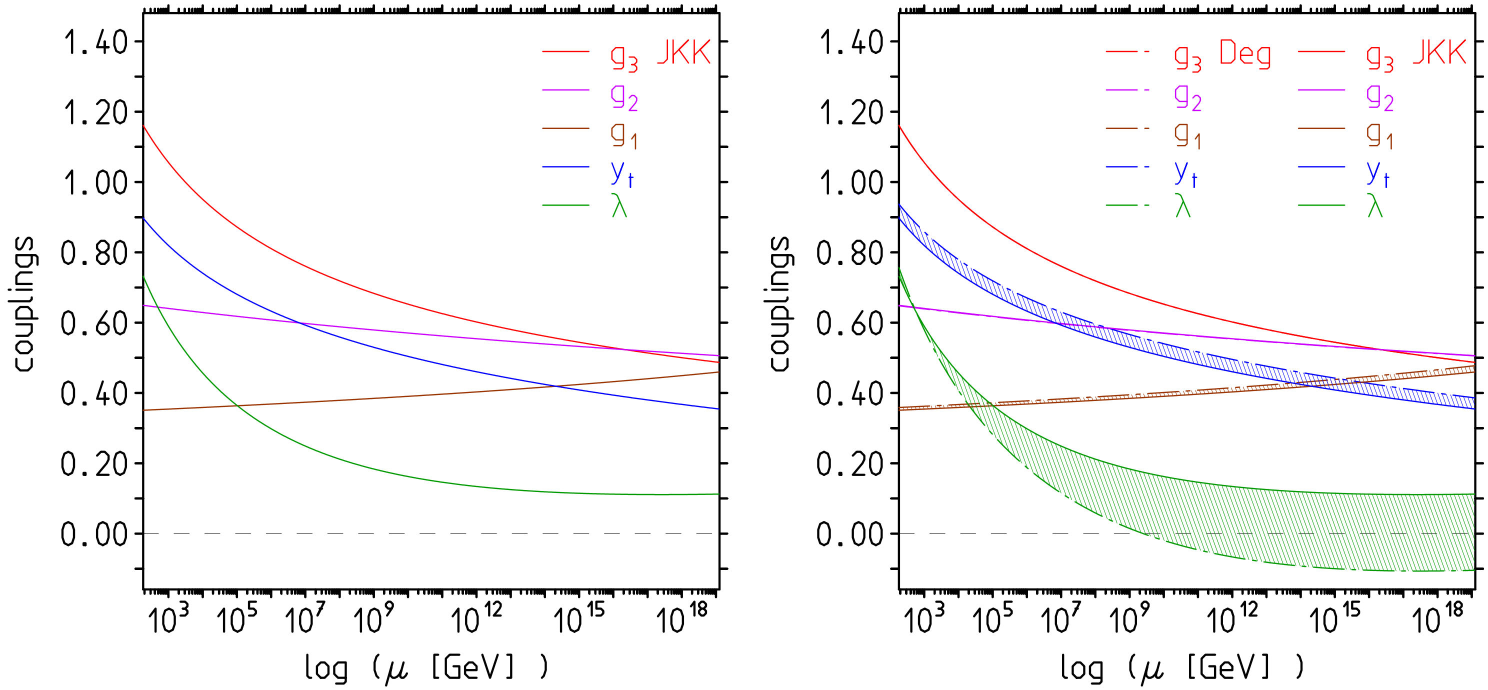
Although the present experimental data are perfectly consistent with the absolute stability of Standard Model within the experimental and theoretical uncertainties, one should not exclude the possibility that other experiments will be able to establish the meta-stability of the electroweak vacuum in the future.

- So what is “new”?
  Take hierarchy problem argument serious, SM should exhibit Higgs mass of Planck scale order (what is true in the symmetric phase),
  as well as vacuum energy of order Λ^4_{Pl}, but do not try to eliminate them by imposing supersymmetry or what else, just take the SM regularized by the Planck cutoff as it is.

➠ inflation seems to be strong indication that quadratic and quartic cutoff enhancements are real, as predicted by LatticeSM for instance, i.e.

Power divergences of local QFT are not the problem they are the solution!

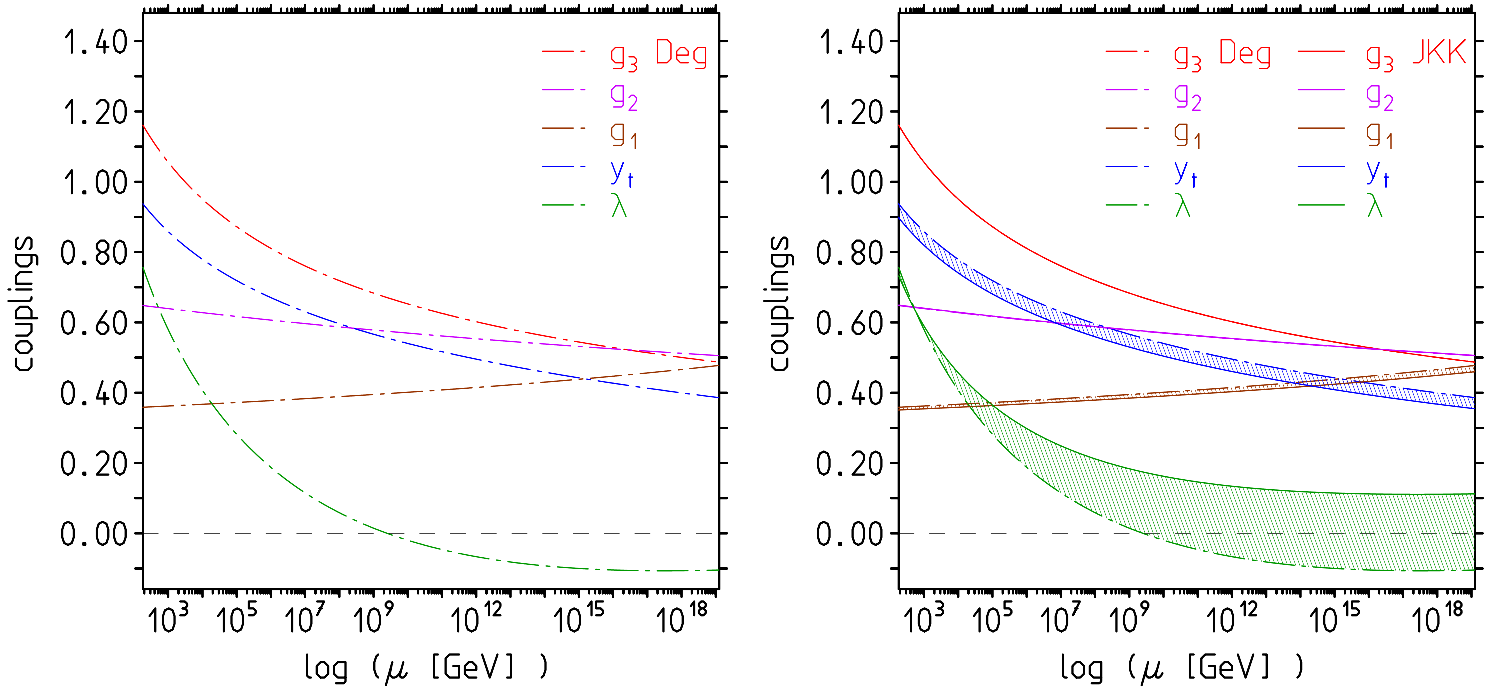
- New physics: still must exist
  ❶ cold dark matter
  ❷ axions as required by strong CP problem
  ❸ singlet neutrino puzzle (Majorana vs Dirac) and likely more $\cdots$,
  however, NP should not kill huge effects in quadratic and quartic cutoff sensitive terms and it should not deteriorate gross pattern of the running of the SM couplings. As most Yukawa couplings (besides y_t).



F.J.,Kalmykow,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!

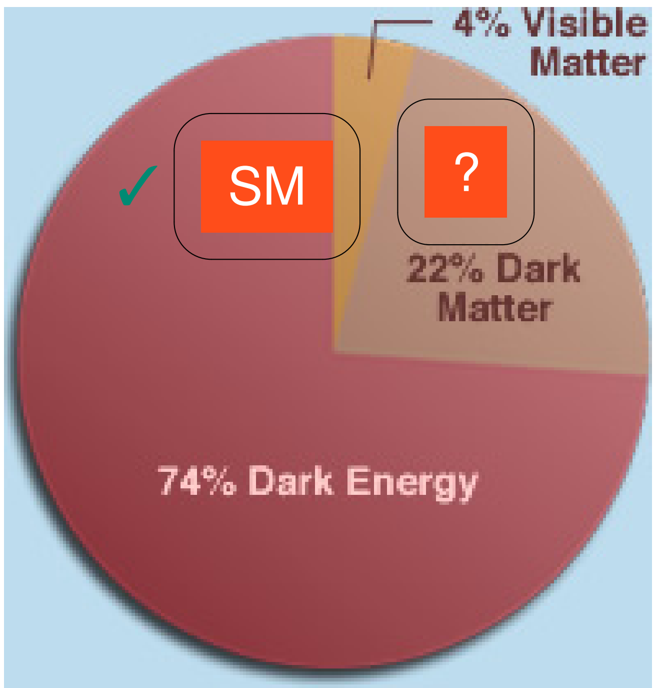


Shaposnikov et al., Degrassi et al. matching

- 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!

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.

Asked questions:

- does SM physics extend up to the Planck scale?
- do we need new physics beyond the SM to understand the early universe?
- does the SM collapse if there is no new physics?

"collapse": Higgs potential gets unstable below the Planck scale; actually several groups claim to have proven vacuum stability break down at 3σ level!
Shaposhnikov et al, Degrassi et al, Maina, Hamada et al, ...

Scenario this talk: Higgs vacuum remains stable up and beyond the Planck scale
$\Rightarrow$seem to say we do not need new physics affecting the evolution of SM couplings to investigate properties of the early universe. 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

Paths to Physics at the Planck Scale

top-down 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
↑	‖	
STRINGS	10^{19} GeV	
↑		↓
SUGRA	↓	QFT
↑		↓
SUSY–GUT	10^{16} GeV	
↑	↓	↓
SUSY	1 TeV	“??SM??”
↖	↓	↙
soft SB only	SM	SB soft at low/hard at high energies

bottom-up approach

symmetry low → → → symmetry high

?? symmetry ≡ blindness for details ??

the closer you look the more you can see when approaching the cut-off scale

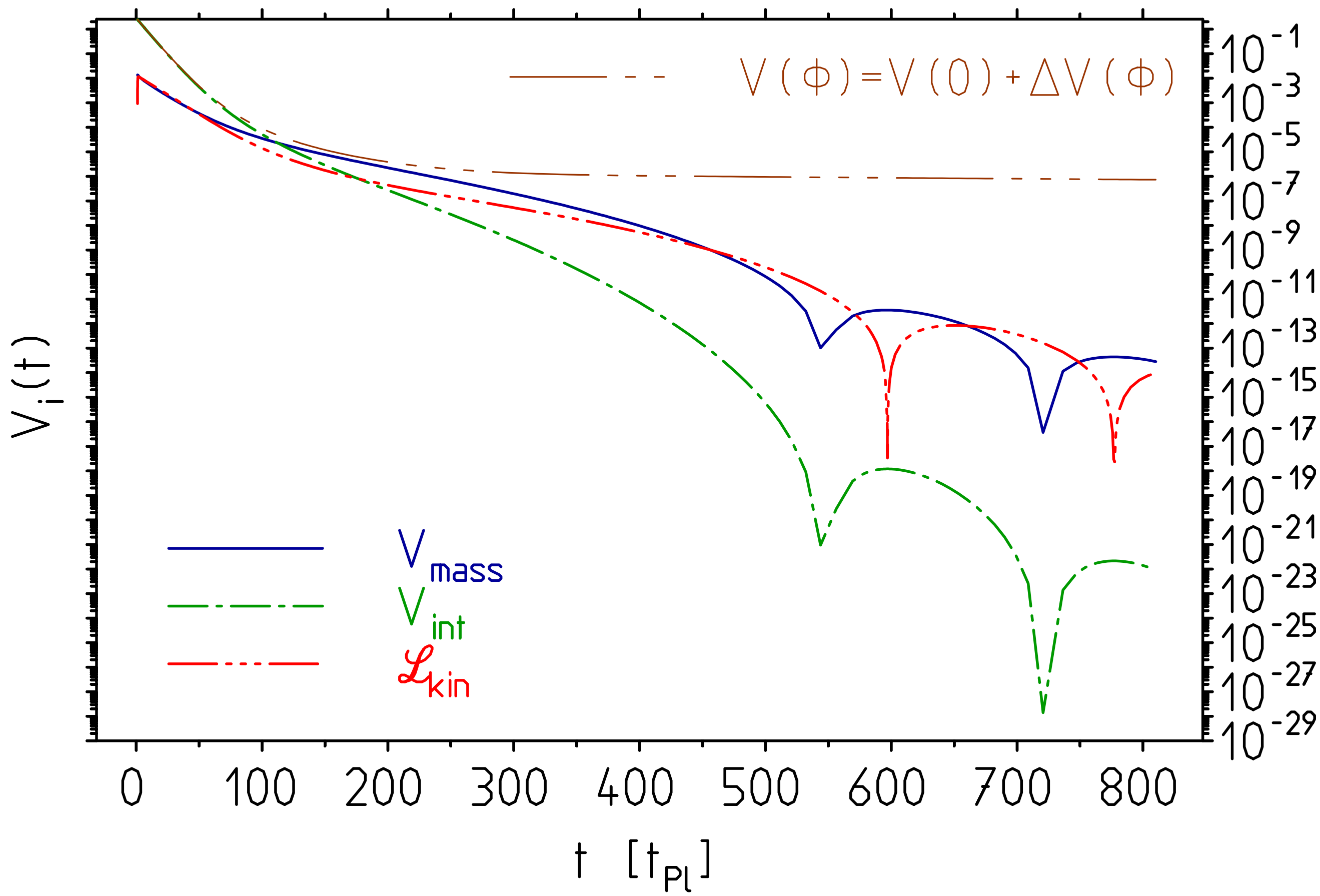
Comparison of $\overline{\text{MS}}$ parameters at various scales: Running couplings for $M_H = 126$ GeV and $\mu_0 \simeq 1.4 \times 10^{16}$ GeV.

	my findings				Degrassi et al. 2013	
coupling \ scale	M_Z	M_t	μ_0	$M_{\rm Pl}$	M_t	$M_{\rm Pl}$
g_3	1.2200	1.1644	0.5271	0.4886	1.1644	0.4873
g_2	0.6530	0.6496	0.5249	0.5068	0.6483	0.5057
g_1	0.3497	0.3509	0.4333	0.4589	0.3587	0.4777
y_t	0.9347	0.9002	0.3872	0.3510	0.9399	0.3823
$\sqrt{\lambda}$	0.8983	0.8586	0.3732	0.3749	0.8733	i 0.1131
λ	0.8070	0.7373	0.1393	0.1405	0.7626	- 0.0128

Most groups find just unstable vacuum at about $\mu \sim 10^9$ GeV! [not independent, same $\overline{\text{MS}}$ input]

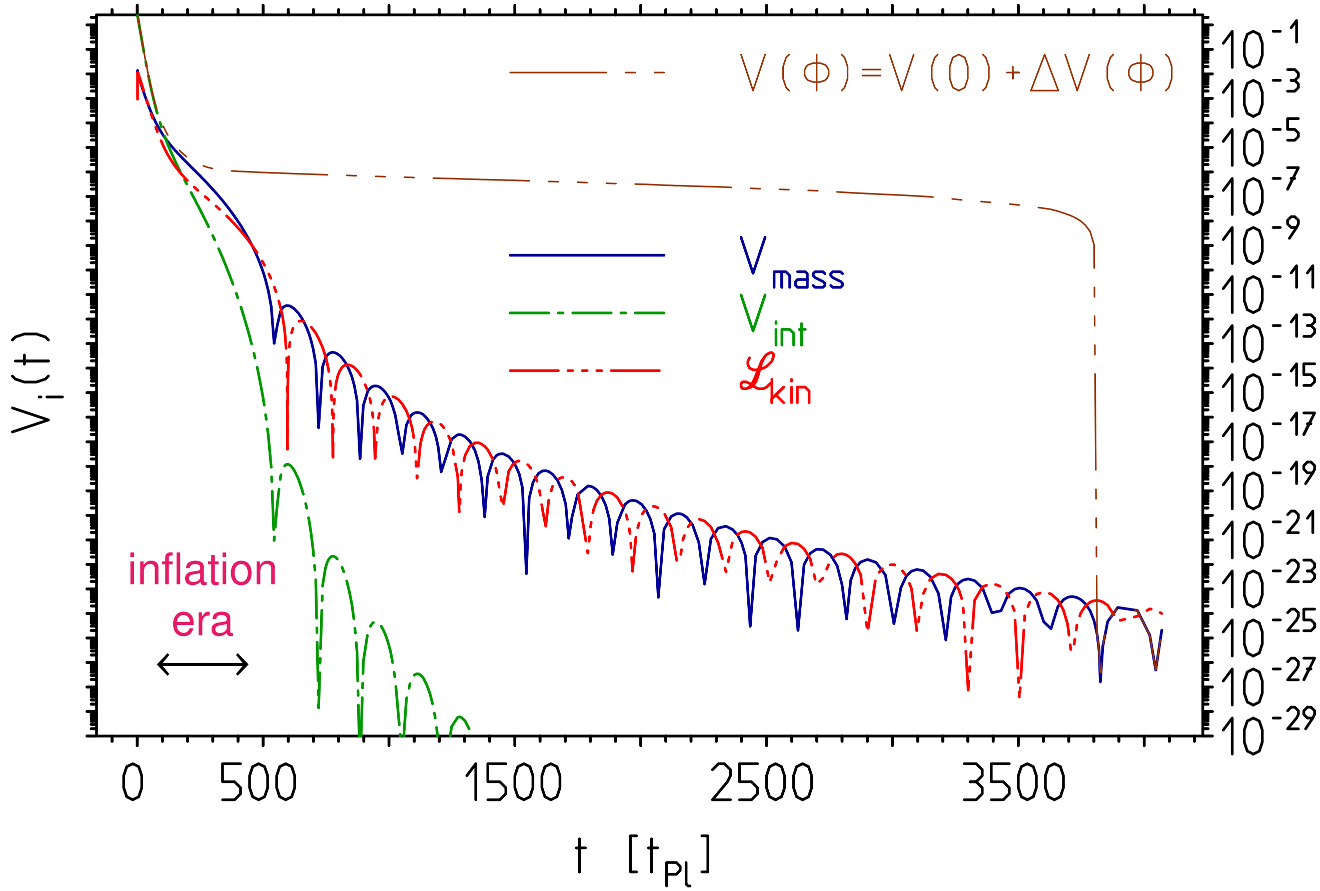
Note: $\lambda = 0$ is an essential singularity and the theory cannot be extended beyond a possible zero of λ: remind $v = \sqrt{6m^2/\lambda}$!!! i.e. $v(\lambda) \to \infty$ as $\lambda \to 0$
besides the Higgs mass $m_H = \sqrt{2}\, m$ all masses $m_i \propto g_i\, v \to \infty$ different cosmology

The evolution of the universe before the EW phase transition:



Inflation epoch ($t \lesssim 450\, t_{\mathrm{Pl}}$): the mass-, interaction- and kinetic-term of the bare Lagrangian in units of M_{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 quasi-free damped harmonic oscillator behavior (reheating phase).

References:

“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 [hep-ph]].

“The hierarchy problem of the electroweak Standard Model revisited,” arXiv:1305.6652 [hep-ph] also arXiv:1503.00809 [hep-ph]

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

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

see also: “The Vector Boson and Graviton Propagators in the Presence of Multipole Forces,” Helv. Phys. Acta **51** (1978) 783.