Lecture 8:

the SM as a low energy effective theory and its impact on cosmology

Outline of Lecture 8:

③ Summary and outline

Topics:

- ❏ **The Hierarchy Problem revisited**
- ❏ **a new view on naturalness and physics beyond the SM**
- ❏ **an alternate path to new physics?**
- ❏ **open problems**
- ❏ **how to scrutinize SM Higgs inflation**
- ❏ **cold dark matter, what could it be?**
- ❏ **quo vadis particle physics?**

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.**
- **My talk is about taming the infinities we encounter in the theory of elementary particles i.e. quantum field theories.**
- **I discuss a scenario of the Standard Model (SM) of elementary particles in which ultraviolet singularities which plague the precise definition as well as concrete calculations in quantum field theories are associated with a physical cutoff, represented by the Planck length.**

❒ **Thus in my talk 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: $c, \hbar, G_N$

➜ **Relativity and Quantum physics married with Gravity yield**

Planck length: $\ell_{\rm Pl} = \sqrt{\frac{\hbar G_N}{c^3}} = 1.616252(81) \times 10^{-33}$ cm

Planck time: $t_{\rm Pl} = \ell_{\rm Pl}/c = 5.4 \times 10^{-44}$ sec

Planck (energy) scale: $M_{\rm Pl} = \sqrt{\frac{c\hbar}{G_N}} = 1.22 \times 10^{19}$ **GeV**

Planck temperature: $\frac{M_{\rm Pl} c^2}{k_{\rm B}} = \sqrt{\frac{\hbar c^5}{G_N k_{\rm B}^2}} = 1.416786(71) \times 10^{32}$ °K

- **shortest distance** $\ell_{\rm Pl}$ **and beginning of time** $t_{\rm Pl}$ $\boxed{t_{\rm Pl} < t}$ $-\infty < t$
- **highest energy** $E_{\rm Pl} = \Lambda_{\rm Pl} \equiv M_{\rm Pl}$ **and temperature** $T_{\rm Pl}$

One impact of UV divergences in local QTFs: 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 LEESM "extension" of the local QFT 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 divergencies. The theorem specifies a concrete procedure (the Bogoliubov Parasyuk R-operation) for subtraction of divergencies in any order of pertrubation 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 reality.

What about the hierarchy problem?

The hierarchy problem cannot be adressed within the remormalizable, 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 shoert 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

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

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 differnt 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 are 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 $O(M^2_{\mathrm{Planck}})$, i.e. in the broken phase the Higgs is naturally light. That the Higgs mass likely is $O(M_{\mathrm{Planck}})$ in the symmetric phase is what realistic inflation scenarios favor.

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

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

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.

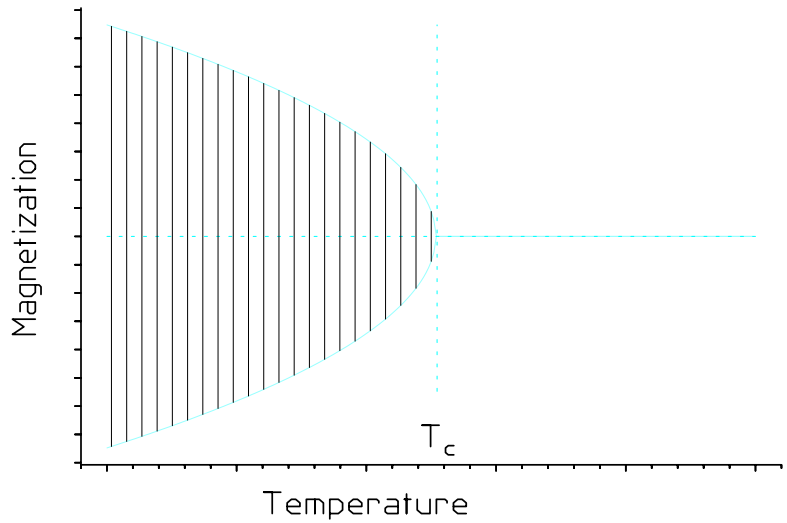
- **Higgs mass cannot by much heavier than the other heavier particles!**

- **Extreme point of view: all particles have masses $O(M_{\rm Pl})$ i.e. $v = O(M_{\rm Pl})$. 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** $T \underset{\to}{<} T_c$

- $v/M_{\rm Pl} \ll 1$ **just means we are close to a 2$^{\rm nd}$ order phase transition point.**

❒ **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.

Astronomy, Astrophysics are unthinkable without the input from laboratory physics

now we are at a stage where particle physics has to learn form cosmology

In contrast to an old paradigm: the ground state of the world is filled with dark energy, Higgs condensate, quark and gluon condensates They 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 to the emergence of the early cosmos.

Inflation works

Flatness, Causality, primordial Fluctuations ➜ Solution:

Inflate the universe

Add an "Inflation term" to the r.h.s of the Friedmann equation, which dominates the very early universe blowing it up such that it looks flat afterwards

Need scalar field $\phi(x)$ $\equiv$ "inflaton" : ➜ inflation term

$$\boxed{\frac{8\pi}{3\,M_{\rm Pl}^2}\left(V(\phi)+\frac{1}{2}\dot{\phi}^2\right)}$$

Means: switch on strong anti-gravitation for an instant [sounds crazy]

Inflation: $a(t)\propto \mathrm{e}^{Ht}\,;\; H=H(t)$ **Hubble constant** $=$ **escape velocity** v**/distance** D

➠ $$\left\|\; N\equiv \ln\frac{a_{\rm end}}{a_{\rm initial}} = H\;(t_e-t_i)\right.$$

$$\rho_\phi = \frac{1}{2}\dot\phi^2 + V(\phi)$$
$$p_\phi = \frac{1}{2}\dot\phi^2 - V(\phi)$$

Equation of state: $w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot\phi^2 - V(\phi)}{\frac{1}{2}\dot\phi^2 + V(\phi)}$

- **small kinetic energy** ➠ $w \longrightarrow -1$

Friedmann equation: $H^2 = \frac{8\pi G_N}{3}\left[V(\phi) + \frac{1}{2}\dot\phi^2\right]$

Field equation: $\ddot\phi + 3H\dot\phi = -V'(\phi)$

- ❒ **Substitute energy density and pressure into Friedmann and fluid equation**
- ❒ **Expansion when potential term dominates**

$$\boxed{\ddot a > 0 \Longleftrightarrow p < -\frac{\rho}{3} \Longleftrightarrow \dot\phi^2 < V(\phi)}$$

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

- **need** $N \gtrsim 60$

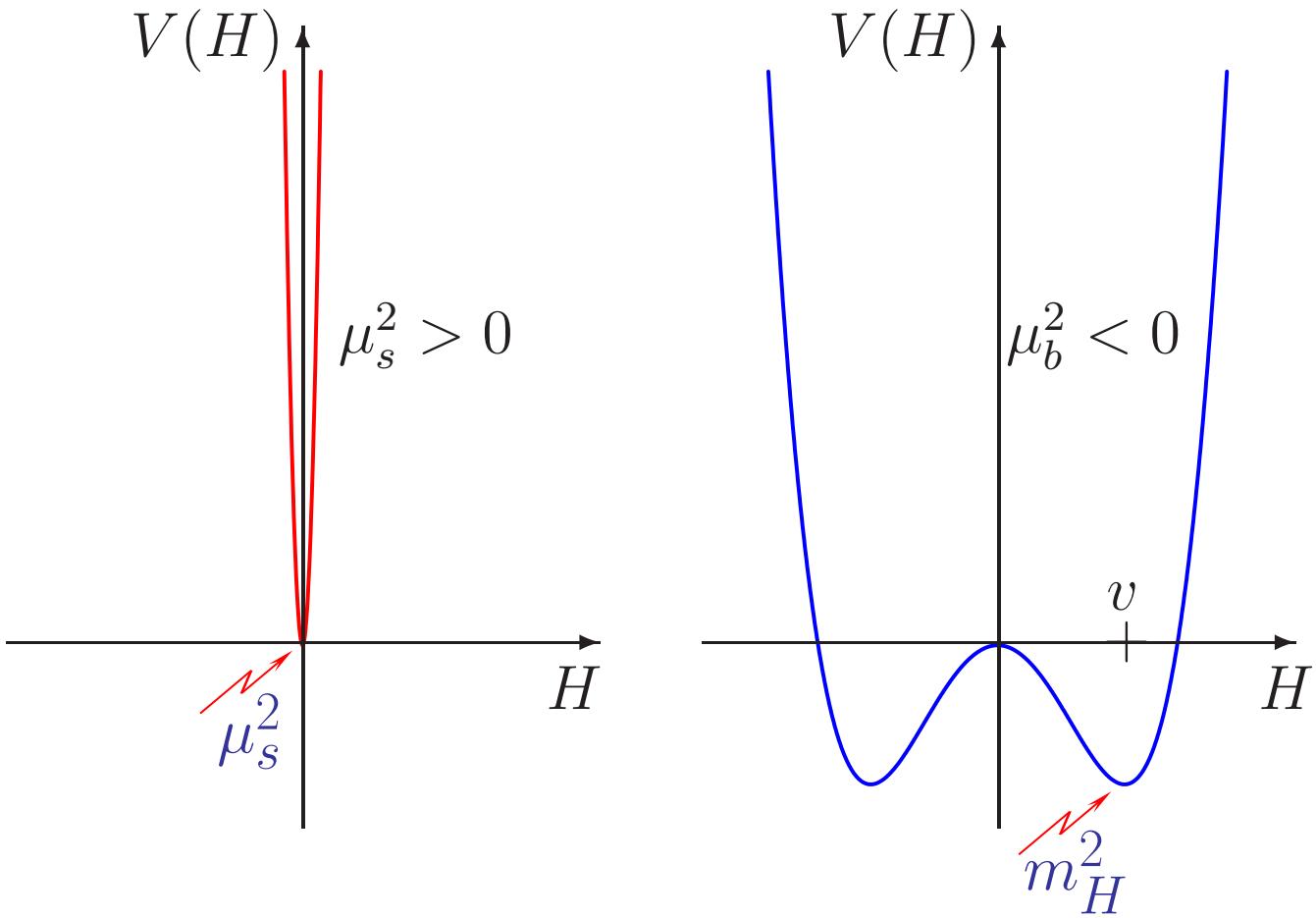
Key object of our interest: **the Higgs potential**

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

❒ **Higgs mechanism**

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

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



Spontaneous breaking of the Z_2 symmetry $H \leftrightarrow -H$. Ground state jumps from $\langle H \rangle = 0$ to $\langle H \rangle = v$

The issue of quadratic divergences in the SM

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

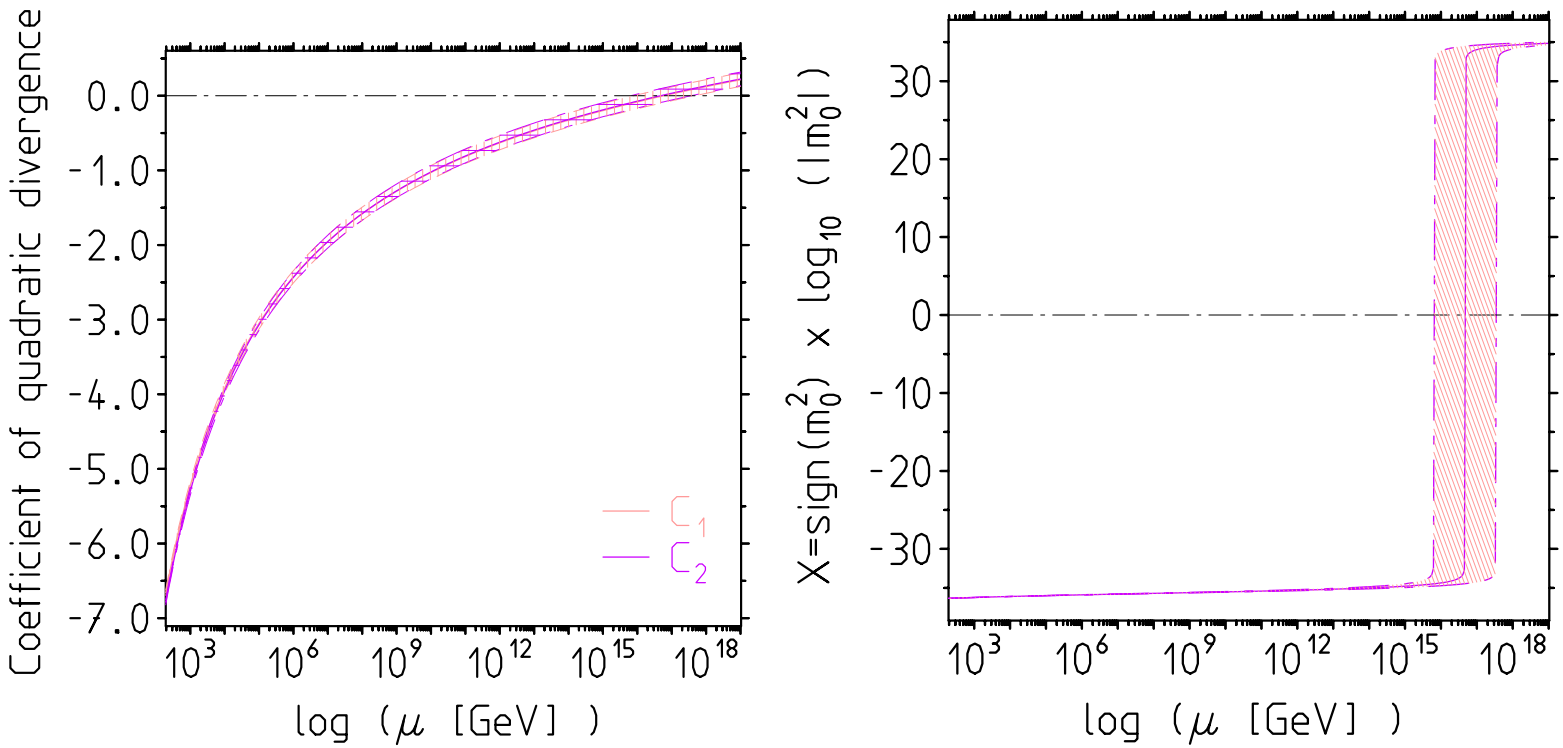
$$\delta m_H^2 = \frac{\Lambda_{\rm Pl}^2}{16\pi^2} C_1 \; ; \quad C_1 = \frac{6}{v^2}(M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\,\lambda + \frac{3}{2} g'^2 + \frac{9}{2} g^2 - 12\, y_t^2$$

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 $X = \mathbf{sign}(m^2_{\rm bare}) \times \log_{10}(|m^2_{\rm bare}|)$, which represents $m^2_{\rm bare} = \mathbf{sign}(m^2_{\rm bare}) \times 10^X$.

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

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

- 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 ➜ finite temperature effects:

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

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

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** $-\mu^2 \to m^2 = (m_H^2 + \delta m_H^2)/2$

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

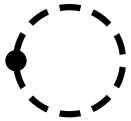
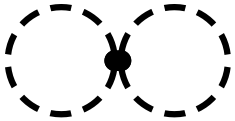
In fact with our value of μ_0 **almost no change of phase transition point (see Plot below)**

The cosmological constant in the SM

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

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

just Higgs self-loops

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

➜ **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**

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

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

➜ **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**

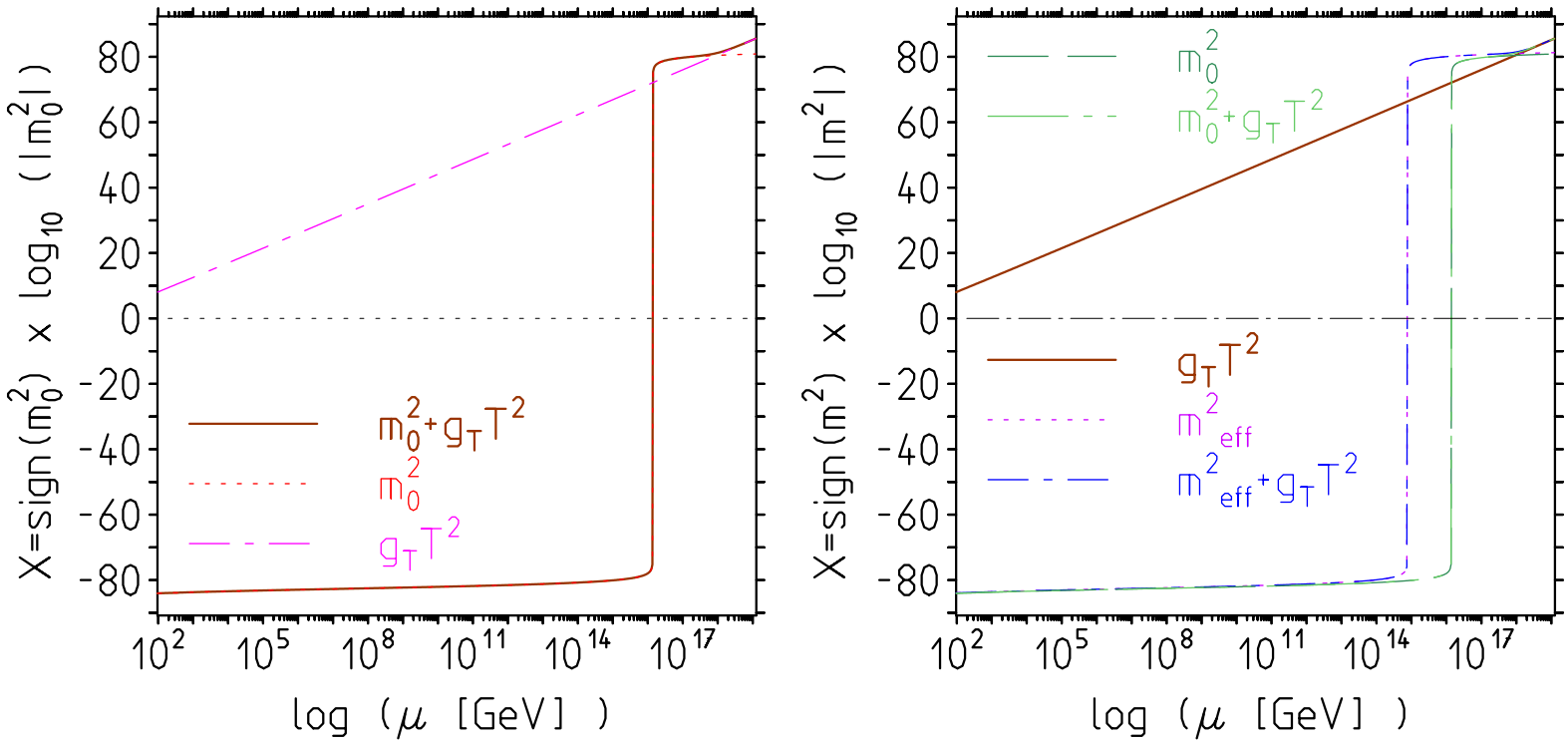
- **we adopt** $\phi_0 \approx 4.51 M_{\rm Pl}$ **, big enough to provide sufficient inflation**

- $V(0)$ **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** $2\,C(\mu) = -\lambda(\mu)$**.**

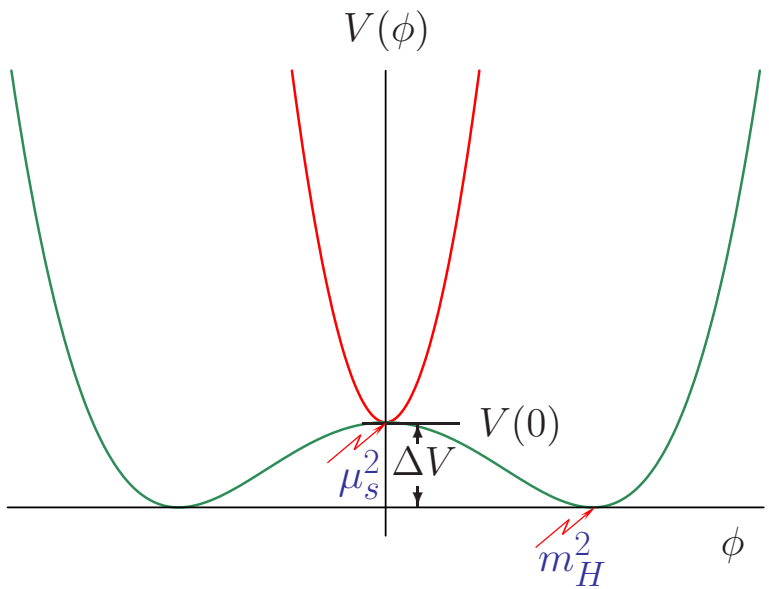


Effect of finite temperature on the phase transition: bare [m^2, C_1] vs effective from vacuum rearrangement [$m'^2, C_1' = C_1 + \lambda$] in case μ_0 sufficiently below $M_{\rm Pl}$ finite temperature effects affect little position of PT; vacuum rearrangement is more efficient:

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

❒ **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: $V(0) + V(\phi_0) \sim (0.002\ \textbf{eV})^4$ **??? ➜ the zero of** $X(\mu)$ **makes** $\rho_{\Lambda\,\rm bare} = \rho_{\Lambda\,\rm ren}$ **to be identified with observed value!**

The Higgs 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

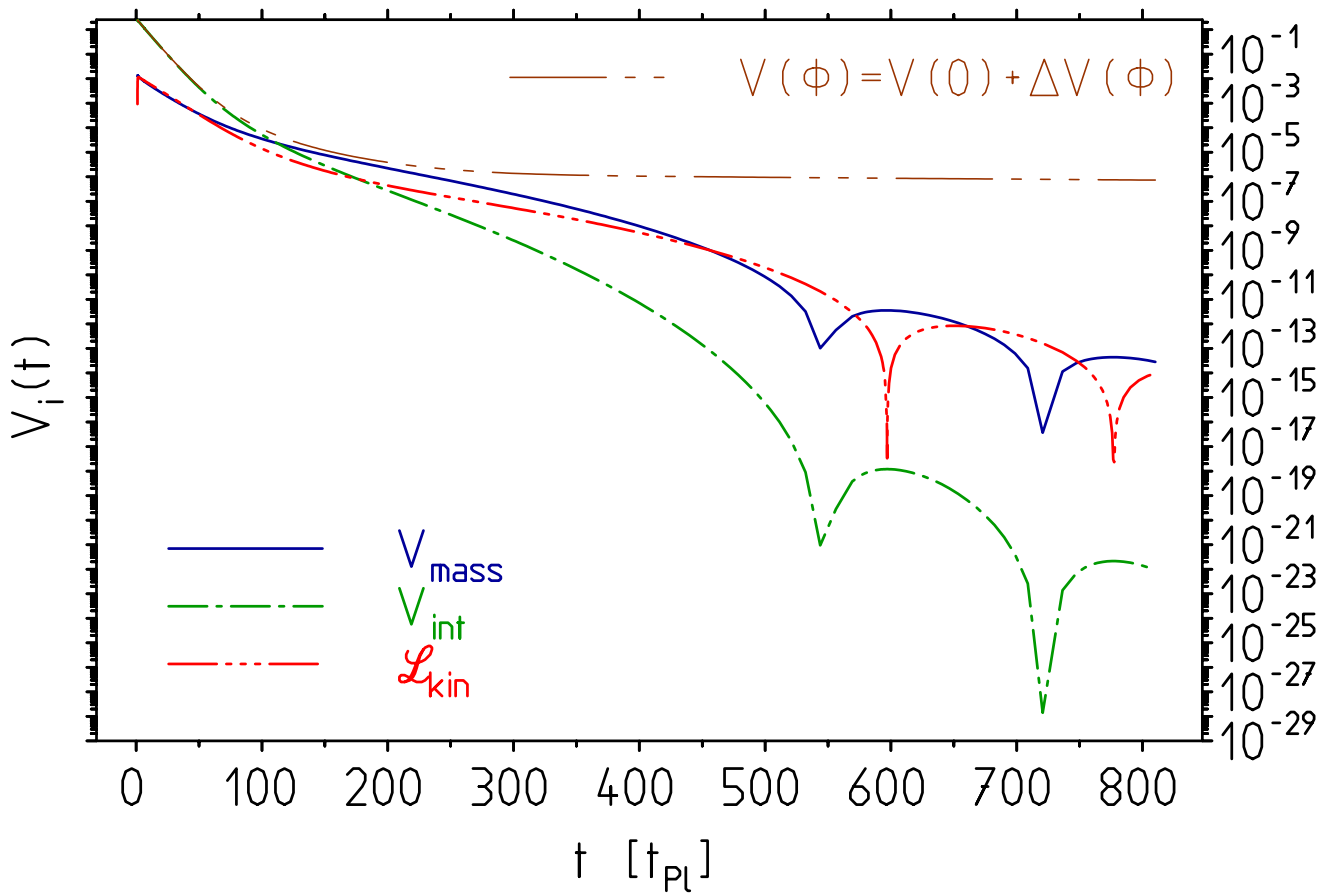
➠ Higgs potential provides huge dark energy in early universe which triggers inflation

The SM predicts dark energy and inflation!!!

dark energy and inflation are unavoidable consequences of the SM Higgs

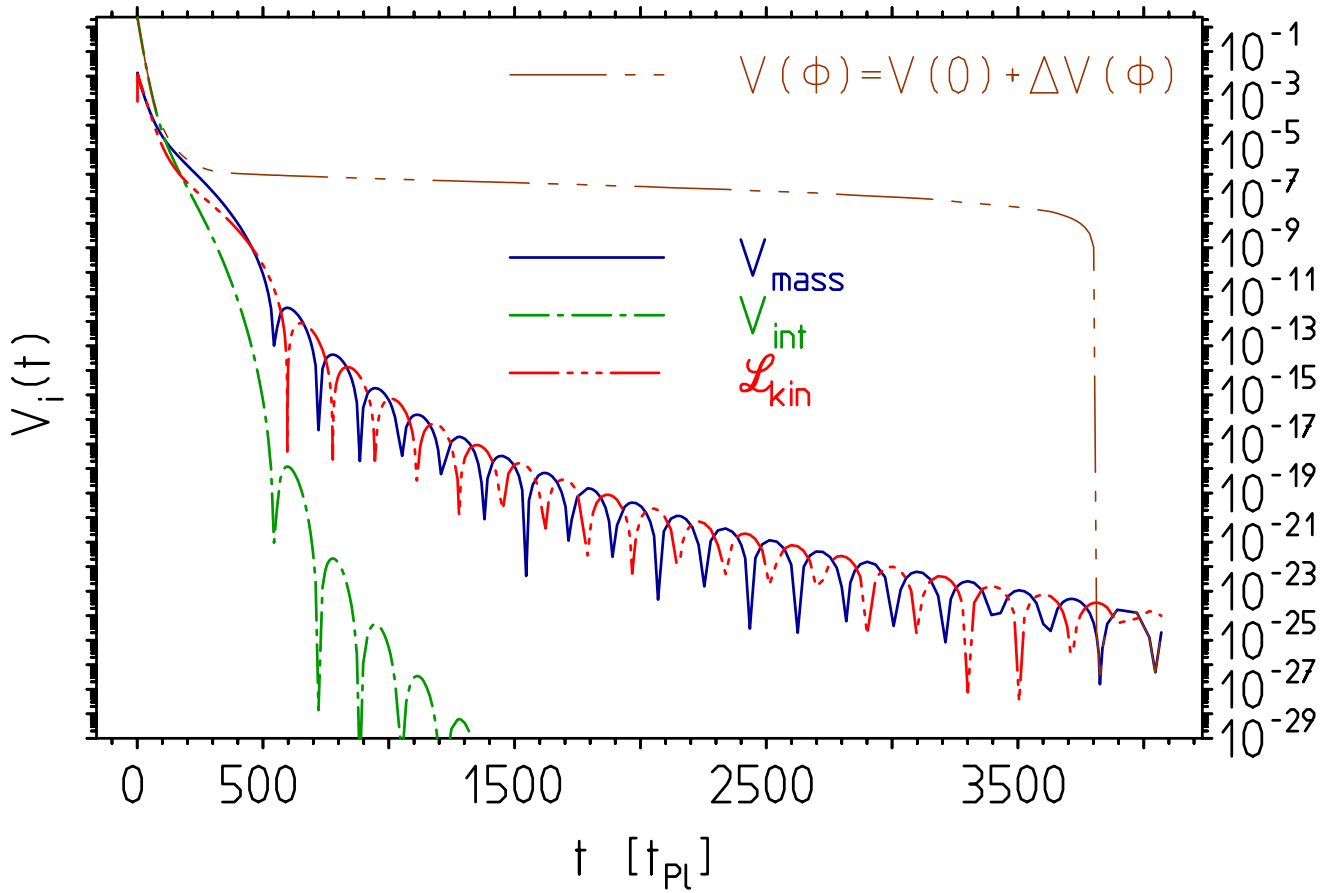
(provided new physics does not disturb it substantially)

The evolution of the universe before the EW phase transition:



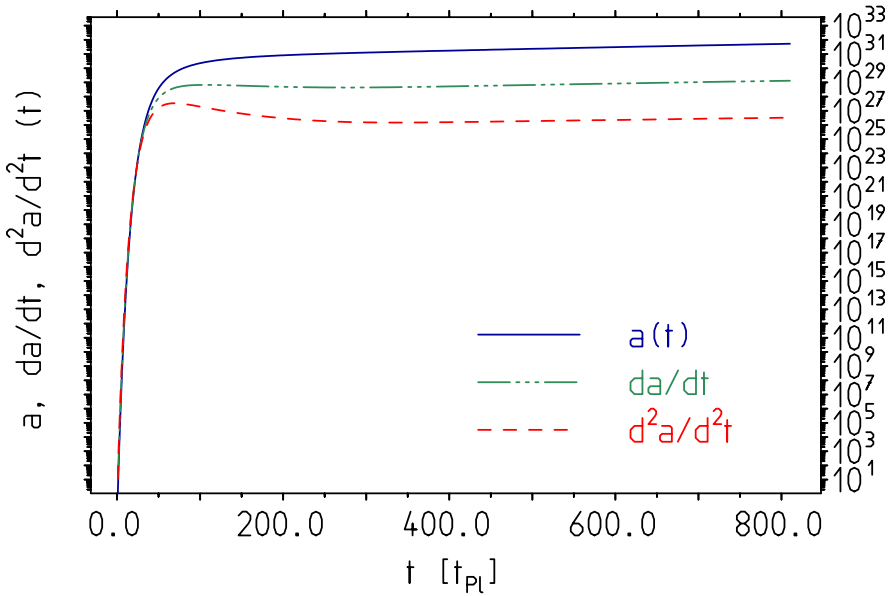
Inflation Times: the mass-, interaction- and kinetic-term of the bare Lagrangian in units of $M_{\rm Pl}^4$ as a function of time.

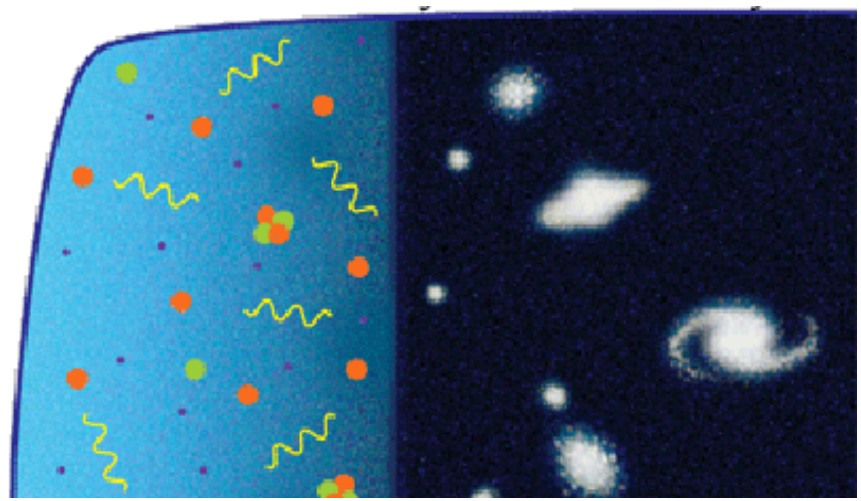
The evolution of the universe before the EW phase transition:



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

"Annihilation Drama of Matter"

10^{-35} sec.

X ??? $\bar{X}$ ... q $\bar{q}$ e^- e^+ ν $\bar{\nu}$ γ

us

$X, \bar{X}$–Decay: $\Rightarrow$

$$\left\{ \begin{array}{lcl} q:\bar{q} & = & 1{,}000\ 000\ 001{:}1 \\ e^-:e^+ & = & 1{,}000\ 000\ 001{:}1 \end{array} \right.$$

10^{-30} sec.

W $\bar{W}$ q $\bar{q}$ e^- e^+ ν $\bar{\nu}$ γ

0.3×10^{-10} sec.

LEP events

$q\bar{q} \to \gamma\gamma$:

10^{-4} sec.

q e^- e^+ ν $\bar{\nu}$ γ

$e^+e^- \to \gamma\gamma$:

1 sec.

q e ν $\bar{\nu}$ γ $\Leftarrow$ CMB

Sacharow condition for baryogenesis:

- $\not{B}$

❒ **small $\not{B}$ is natural in LEESM scenario due to the close-by dimension 6 operators**

Weinberg 1979, Buchmüller, Wyler 1985,Grzadkowski et al 2010

❒ **suppressed by $(E/\Lambda_{\rm Pl})^2$ 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!**

- $\not{C}$, $\not{CP}$, **out of equilibrium**

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

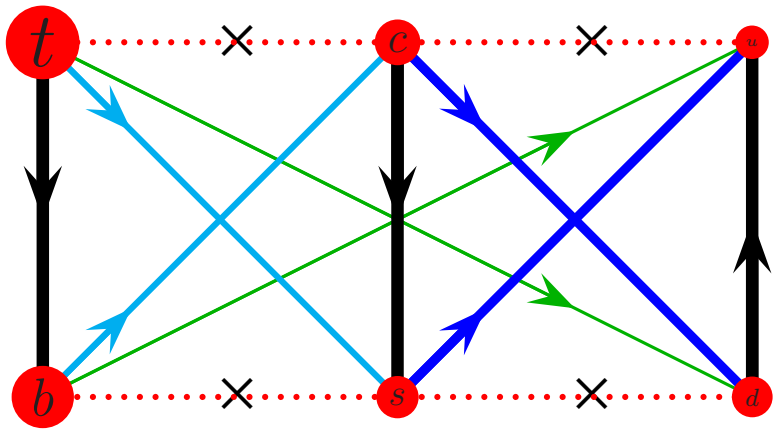
All relevant properties known: mass, width, branching fractions, CP violation properties!

Stages: ❒ $k_B T > m_X$ ➜ **thermal equilibrium X production and X decay in balance**

❒ $H \approx \Gamma_X$ **and** $k_B T < m_X$ ➜ **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:** $t \to d e^+ \nu$ **and** $b \to u e^- \nu_e$ **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!

A hint for the fermion mass hierarchy?

Note: for our existence C and CP violations are mandatory and as we know in a minimal way it only works with 3 families. What is the mass hierarchy good for, which as we know in the SM is a hierarchy of the Yukawa couplings? And why so dramatic? About 7 MeV for the u and d quarks and 173 GeV for the top ($\sim 3.5 \times 10^{-5}$) ? The top must have its coupling in the ballpark of the gauge couplings and the Higgs self-coupling to allow for the competition or conspiracy to stabilize the vacuum. The top is then also produced overwhelmingly in the early universe. In order CP violation can operate at all top matter must decay into lighter species in two steps, and this works most efficiently with a pronounced hierarchy as we know it to be realized. As important for our existence at the end is the inverted ratio $m_u/m_d \sim 0.75 < 1$ vs. $m_t/m_b \sim 40$ "$\gg$" $m_c/m_s \sim 15$ "$\gg$"1. It is important that neutral currents to leading order are absent in the SM, so the hopping has to go via CP violating channels.

Preheating is absent in LEESM Higgs inflation

After inflation stops a phase of reheating must have set in in order not to end up with a universe which would be much emptier than the one we know..

- **inflation ends when the slow-roll conditions are violated and, in our scenario this is the result of the fast diminution of the Higgs field**

- **while the radiation energy decays very fast $\rho_{\rm rad} \propto T^4(t) \propto 1/a^4(t)$, the four heavy Higges essentially supply the dominating part of the energy density at this stage**

- **the energy density of the Higgs system decreases because of the expansion (1$^{\rm st}$ term) and, in fact primarily, because of the decay into other SM particles (2$^{\rm nd}$ term), predominantly "would be heaviest" Fermion pairs. With Γ_ϕ the inflaton width the density evolves as**

$$\dot\rho_\phi + \left(3\,H + \Gamma_\phi\right)\,\rho_\phi = 0\ .$$

Accordingly, the inflaton undergoes damped oscillations and decays into radiation which equilibrates rapidly at a temperature known as the reheat temperature $T_{\rm RH}$.

- **in standard inflation scenarios the inflation is expected also to decay into boson pairs**

In the case of bosons however, one cannot ignore the fact that the inflaton oscillations may give rise to parametric resonance. This is signified by an extremely rapid decay, yielding a distribution of products that is far from equilibrium, and only much later settles down to an equilibrium distribution at energy $T_{\rm RH}$. Such a rapid decay due to parametric resonance is known as preheating (Kofman, Linde, Starobinsky 1994).

- **preheating as a consequence of the decays of the inflaton field into boson pairs, cannot not happen in SM inflation, since triple couplings like HWW or HZZ are absent at tree level in the symmetric phase (in the broken phase triple boson couplings exist and are proportional to the Higgs VEV**

v). **Hence, before the Higgs mechanism takes place, Higgs decays into yet massless gauge bosons are heavily suppressed (absence of bosonic triple couplings or suppresses by lacking phase space). Higgs self-interactions (all quartic in the symmetric phase) between the equal mass heavy Higgses are ineffective as well (phase space suppressed, not matter producing at all).**

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 $M_H = 125.9 \pm 0.4$ 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 may turn out not to be compelling**

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

- **change in paradigm:**

Natural scenario understands the SM as the "true world" seen from far away

➜ **Methodological approach known from investigating condensed matter systems. (QFT as long distance phenomenon, critical phenomena) Wilson NP 1982**

- **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**

Paths to Physics at the Planck Scale

M–THEORY(BRAIN WORLD)	Energy scale	E–THEORY(REAL WORLD)
candidate TOE		"chaotic" system
exhibits intrinsic cut-off	Planck scale	with intrinsic cut–off
↓	$\parallel$	
STRINGS	10^{19} GeV	
↓	↓	↑ QFT
SUGRA		↑
↓		
SUSY–GUT	10^{16} GeV	↑
↓	↓	
SUSY	1 TeV	"??SM??"
↘	↓	↗
	SM	

top-down approach

bottom-up approach

symmetry high $\rightarrow$ $\rightarrow$ $\rightarrow$ symmetry low

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

Keep in mind: the Higgs mass miraculously turns out to have a value as it was 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 Higgs not only provides masses to all SM particles [after the EW phase transition].**
- **For some time at and after the Big Bang the Higgs provides a huge dark energy which inflates the young universe dramatically.**
- **The Higgs likely is the one producing negative pressure and hence blowing continuously energy into the expanding universe up to-date and forever.**

Of course: a lot yet to be understood!

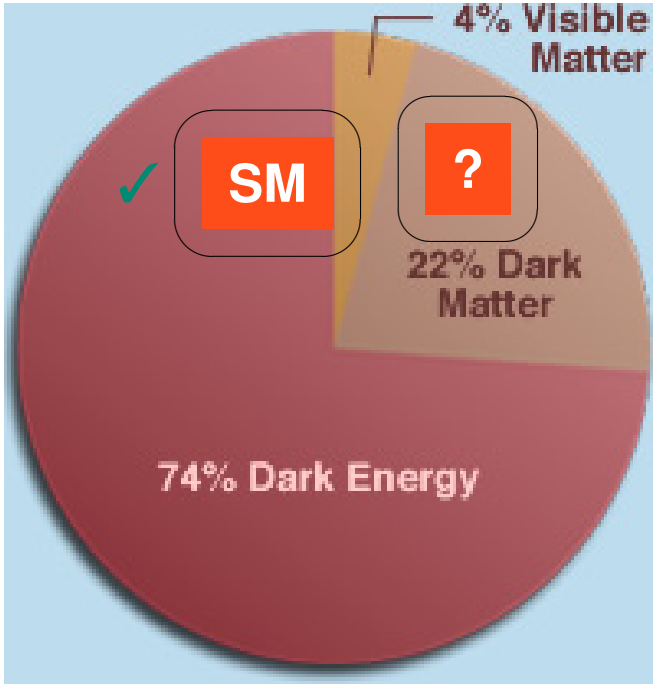
❖ **the big issue is the very delicate conspiracy between SM couplings: precision determination of parameters more important than ever ➜ the challenge for LHC and ILC: precision values for λ, y_t and α_s, and for low energy hadron facilities: more precise hadronic cross sections to reduce hadronic uncertainties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

Imagine...

· · · **a world upside down?**

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

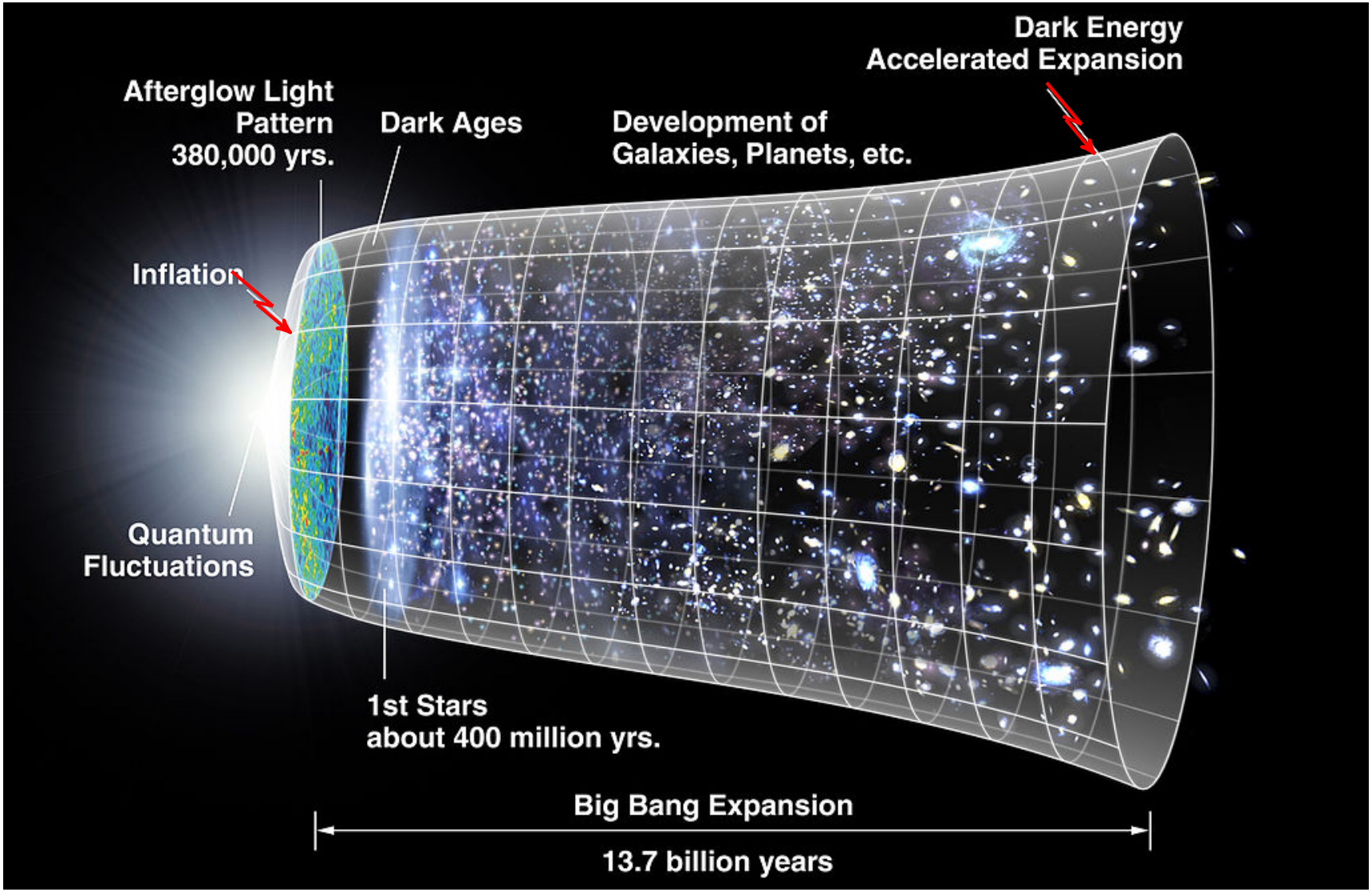
Last but not least: today's dark energy = relict Higgs vacuum energy?



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

Thanks

Thanks for your attention!
Thanks for the kind hospitality at IFJ Krakow!

Dziękuję bardzo!

Down to earth again.

Backup Material

Plenty of questions remain

- Two ways to get rid of massless Yang-Mills fields:
  ❶ Higgs mechansism, SSB of the $SU(2)_L$ via spontaneous beraking of Z_2, provide mass to $SU(2)_L$ gauge fields and the Fermions
  ❷ spontaneous breaking of the chiral $G_F = SU(N_q) \otimes SU(N_q)$, $[G_F, SU(3)_c] = 0$, which is exact before the Higgs mechanism takes place, what is triggering SSB of chiral symmetry? and at what time in the evolution of the Universe? What is the role of the gluon condensate? What that of the quark condensates?
  ❸ How does confinement emerge? Before the Higgs mechanism massive bound states could have been formed (frozzen binding energy)? Aparently not as $m_p \approx m_n \approx 1$ GeV, i.e. hadrons can have formed only very late.

Quark-Gluon Plasma: its Role in Cosmology

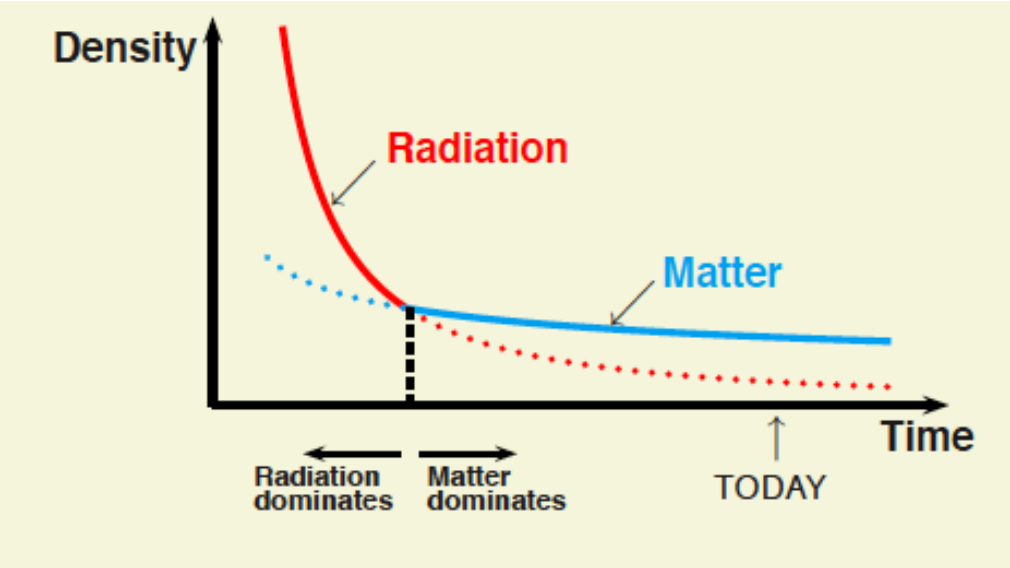
Abstract

On the role of QCD in Cosmology: some time ago the proliferation of hadrons of increasing masses turned the early universe into an unpredictable opaque state. QCD the modern theory of strong interactions of hadrons was bringing new light into the game.

How QCD made early cosmology predictable

Looking back in time in the early history of our universe :

The universe is expanding according to Hubble's law $\text{velocity} = H \times \text{distance}$ (cosmological solutions of Einstein-Friedmann equations). The further we look back in the past, the universe appears to be compressed more and more. We therefore expect the young universe was very dense and hot:



At Start a Light-Flash: ➠ Big-Bang (fireball)

Light quanta very energetic, all matter totally ionized, all nuclei disintegrated.

Elementary particles only!: $\gamma, e^+, e^-, u, \bar{u}, d, \bar{d}, \cdots$

Processes: $2\gamma \leftrightarrow e^+ + e^-$

$2\gamma \leftrightarrow \bar{u} + u, \bar{d} + d$

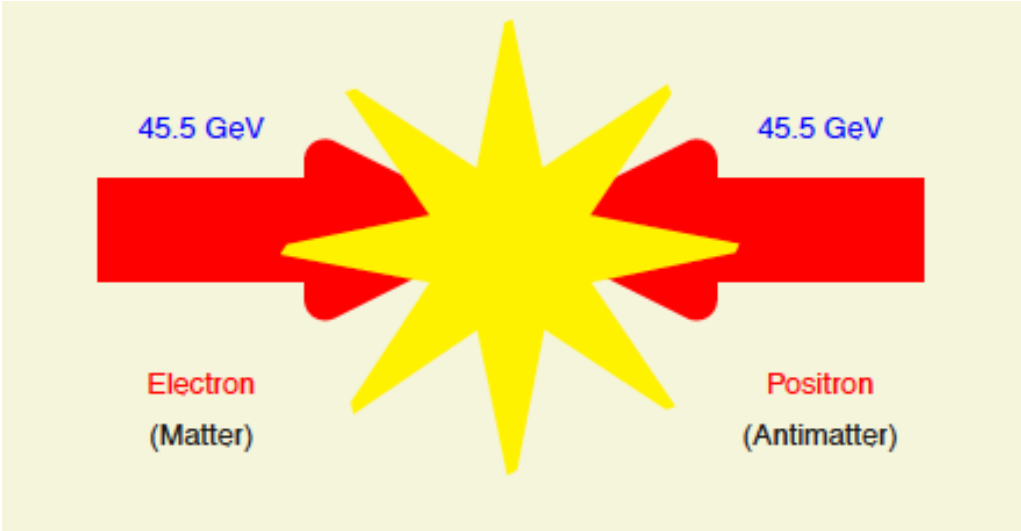
$\vdots$

Particle–Antiparticle Symmetry!

quantum fields in full blossom

☛ Digression into high energy physics: example LEP

e^+e^- Annihilation at LEP



Mini Big Bang !

- What happens in Electron Positron Collisions?

Matter and Antimatter annihilate to pure light or heavy light (Z's), which re-materializes in new forms of matter
(mostly showers of unstable particle).

Science Fiction as Reality!

Theory: Matter ↔ Antimatter Symmetry [Dirac 1928, Andersen 1932, . . .]

To every particle there exists an antiparticle of opposite charge

Nature: in our universe today: antimatter is missing [got lost somehow]!

Energy versus temperature correspondence:

$$\left| \begin{array}{c} 1^\circ\mathrm{K} \equiv 8.6 \times 10^{-5}\mathrm{eV} \\ \text{(Boltzmann constant)} \end{array} \Rightarrow \begin{array}{c} \text{temperature of an event} \\ T \sim 1.8 \times 10^{11} \times T_\odot \end{array} \right|$$

In nature such temperatures only existed in the very early universe:

$$t = \frac{2.4}{\sqrt{g_*(T)}} \left(\frac{1MeV}{kT}\right)^2 \text{sec.}$$

$$\downarrow$$

$$t \sim 0.3 \times 10^{-10} \text{ sec. after B.B.}$$

early universe

$0^\circ\mathrm{K} \equiv -273.15^\circ$ C absolute zero temperature

$T_\odot \simeq 5700^\circ$ K surface temperature of the Sun

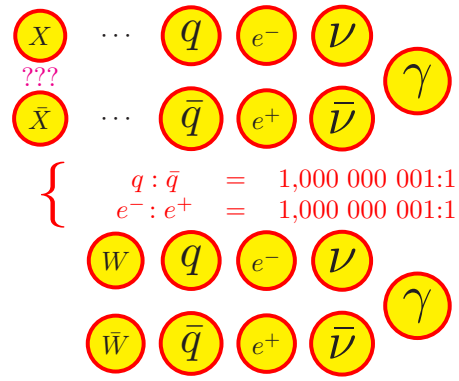
LHC looks further back in time: $t_{\mathrm{LHC}} \sim 1.185 \times 10^{-15}$ seconds A.B.B.

History of the Universe (continuation)

10^{-43} sec.	quantum-chaos
$\vdots$	???
2×10^{-6} sec.	quark-gluon plasma, nucleon–antinucleon annihilation
	Relict: $n_B/n_\gamma \simeq 10^{-9}$ matter visible today
2 sec.	electron–positron annihilation
200 sec.	Helium synthesis
$\rightarrow$	yields more neutrinos ! have tiny masses may contribute substantially to matter density of the universe
400'000 years	Hydrogen recombination
	universe transparent, almost no free charges anymore, photons decouple and cool down further,
500'000 years	from now on matter (neutral atoms) dominates
1 Billion years	stars, galaxies, clusters of galaxies, $\cdots$ form
13.7 Billion years	today

“Annihilation Drama of Matter”

10^{-35} sec.



$X, \bar{X}$–Decay: $\Rightarrow$

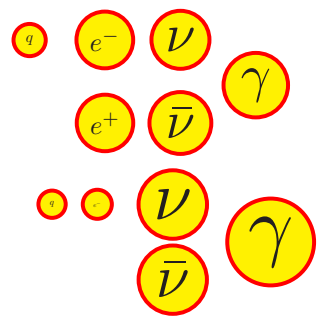
$$\left\{ \begin{array}{lcl} q:\bar{q} & = & 1{,}000\ 000\ 001{:}1 \\ e^-:e^+ & = & 1{,}000\ 000\ 001{:}1 \end{array} \right.$$

10^{-30} sec.

1.2×10^{-15} sec. LHC events

0.3×10^{-10} sec. LEP events

$q\bar{q} \to \gamma\gamma$:

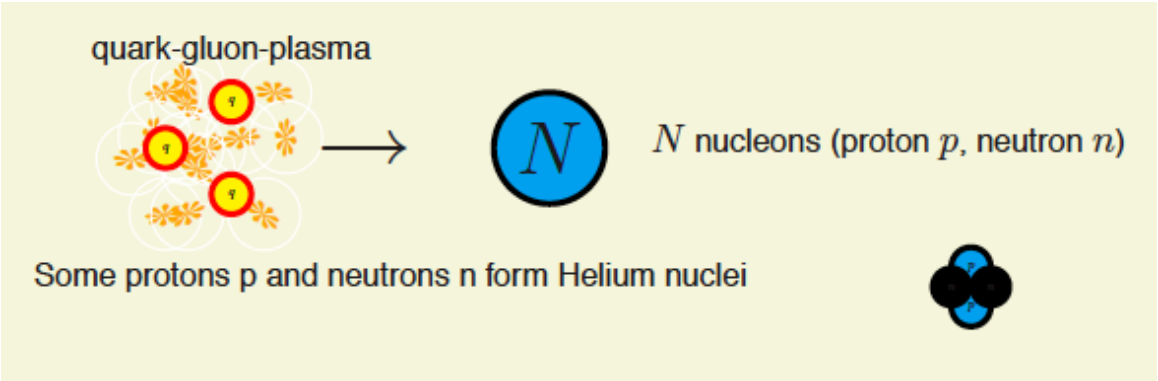


10^{-4} sec.

$e^+e^- \to \gamma\gamma$:

1 sec.

“Nucleo-Synthesis”



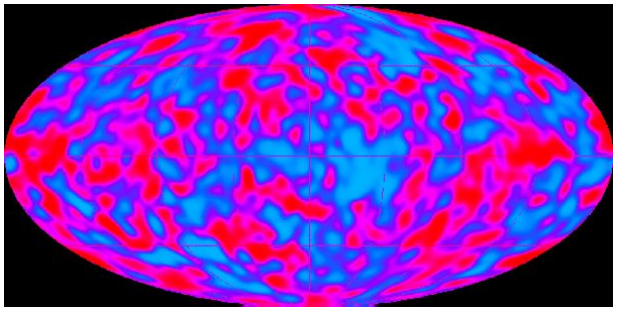
After 400 000 years: light atoms (electrically neutral)

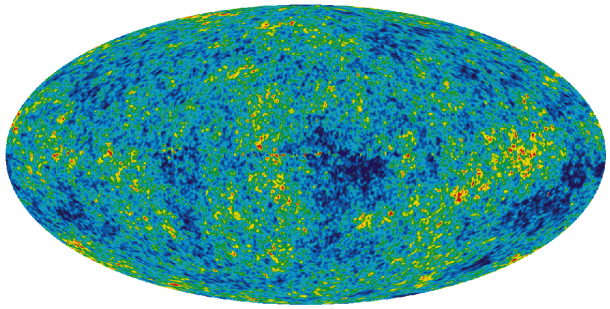
$$H : He \sim 3 : 1$$

together 98% of baryonic matter !

Where are the γ's ?

$\Rightarrow$ Cosmic Microwave Background (today: $T \simeq 2.725^\circ$ K)





Stage	Time	Temperature (Energy)	Description
First	10^{-45} to 10^{-32} sec	Greater than 10^{15} K (100 GeV)	Inflation; generation of density fluctuations
Second	10^{-6} sec	Greater than 10^{12} K (100 MeV)	Quark Soup (QG Plasma)
Third	10^{-4} sec to 3 min	10^{12} to 10^{9} K (0.1 MeV)	Nucleosynthesis; formation of D, He and Li
Fourth	400,000 years	4,000 K (1 eV)	Formation of neutral atoms; radiation decouples
Fifth	1 billion years	20–3 K (1 meV)	Formation of first–generation stars and galaxies
Sixth	3 billion years	20–3 K (1 meV)	Formation of heavy elements by supernovae; Formation of second–generations stars.
Seventh	3–15 billion years	3 K (0.25 meV)	Genesis of planets and LIFE

The Cosmic Calendar

Early Simplicity

Surprisingly, the early universe was much simpler than it is today, for several reasons:

1) Everything was spread out uniformly.
2) Atoms & light were in thermodynamic equilibrium, which is a particularly simple physical state.
3) Changes due to expansion are also simple.

Particle number in Thermal Equilibrium:

$$n_{\substack{\text{Fermions}\\ \text{Bosons}}} = \frac{g}{2\pi^2\hbar^3}\int_{mc^2}^{\infty}\frac{\sqrt{E^2/c^2 - m^2c^2}}{\exp\left(\frac{E-\mu}{kT}\right)\pm 1}\frac{E\,dE}{c^2}$$

Statistical occupation probability (quantum statistics).

Fermions can occupy a state 0- or 1-times (Pauli-Principle),

➠ weight factor $\left(\exp\left(\frac{E-\mu}{kT}\right)+1\right)^{-1}$

Bosons can occupy any state arbitrarily often,

➠ weight factor $\left(\exp\left(\frac{E-\mu}{kT}\right)-1\right)^{-1}$

$\boxed{g \text{ is the spin multiplicity}}$

Limiting cases

In the relativistic limit $(kT \gg mc^2)$ one has

$$
\begin{aligned}
n_{\text{Bosons}} &= \tfrac{4}{3} n_{\text{Fermions}} &&= \frac{\zeta(3)\, g}{\pi^2} \left(\frac{kT}{\hbar c}\right)^3 \\
\epsilon_{\text{Bosons}} &= \tfrac{8}{7} \epsilon_{\text{Fermions}} &&= \frac{\pi^2 g}{30} \left(\frac{kT}{\hbar c}\right)^3 kT \\
s_{\text{Bosons}} &= \tfrac{8}{7} s_{\text{Fermions}} &&= \frac{2\pi^2 g}{45} \left(\frac{kT}{\hbar c}\right)^3 k
\end{aligned}
$$

$$p_{\substack{\text{Fermions}\\ \text{Bosons}}} = \tfrac{1}{3} \epsilon_{\substack{\text{Fermion}\\ \text{Bosons}}}$$

In the non-relativistic limit $(kT \ll mc^2)$ the difference between Fermions and Bosons disappears:

$$n = g \left(\frac{kT}{\hbar c}\right)^3 \sqrt{\left(\frac{mc^2}{2\pi kT}\right)^3} \exp\left(-\frac{mc^2}{kT}\right)$$

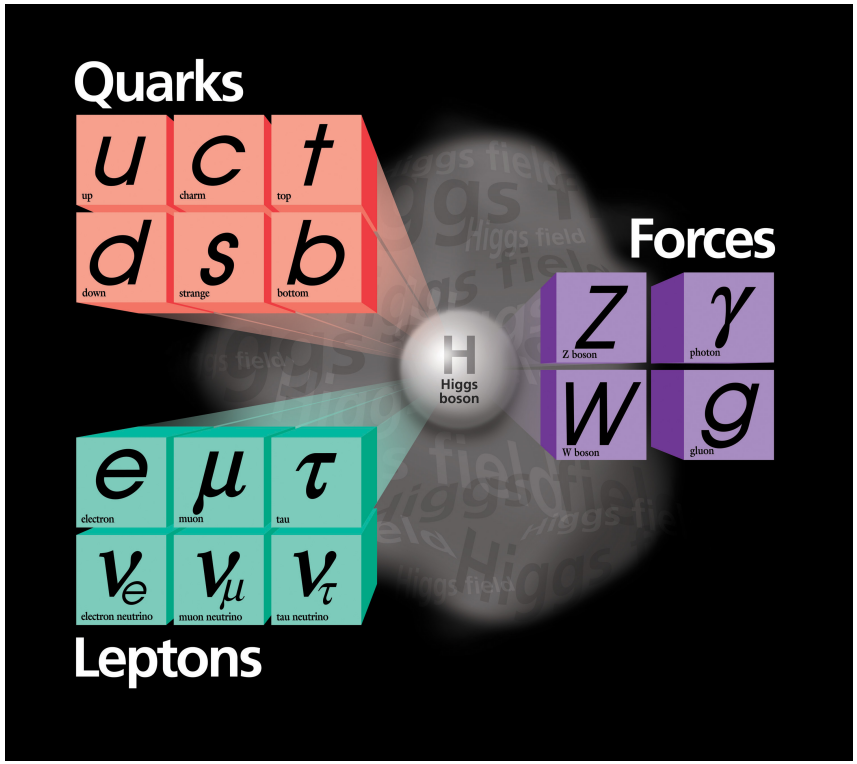
$$s = \frac{mc^2 n}{T}\,, \quad \epsilon = nmc^2\,, \quad p = nkT$$

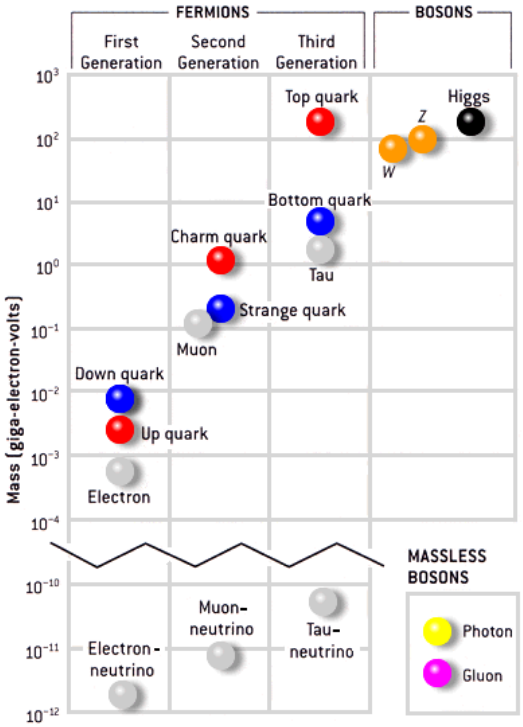
Energy density of the relativistic components: Stefan-Boltzmann law

$$\rho c^2 = \frac{\pi}{30}\, g^* \left(\frac{\hbar c}{kT}\right)^3 kT$$

with g^* the effective number of relativistic degrees of freedom = sum of all contributions of the relativistic particle species.

Scanning the Standard Model from the heavy to the light particles





Leptons	τ^-, τ^+	1776.84 ± 0.171 MeV	spin= $\frac{1}{2}$	$g = 2 \cdot 2 = 4$
	μ^-, μ^+	105.658 MeV		
	e^-, e^+	0.510999 MeV		
				12
Neutrinos	$\nu_\tau, \bar{\nu}_\tau$	< 18.2 MeV	spin= $\frac{1}{2}$	$g = 2$
	$\nu_\mu, \bar{\nu}_\mu$	< 190 keV		
	$\nu_e, \bar{\nu}_e$	< 2 eV		
				6
Weak bosons	$W^\pm$	80.403 ± 0.029 GeV	spin= 1	$g = 3$
	Z	91.1876 ± 0.0021 GeV		
Photon	γ	$0\ (< 6 \times 10^{-17}$ eV$)$		$g = 2$
				11
Higgs	H	> 114.4 GeV	spin= 0	$g = 1$
				1

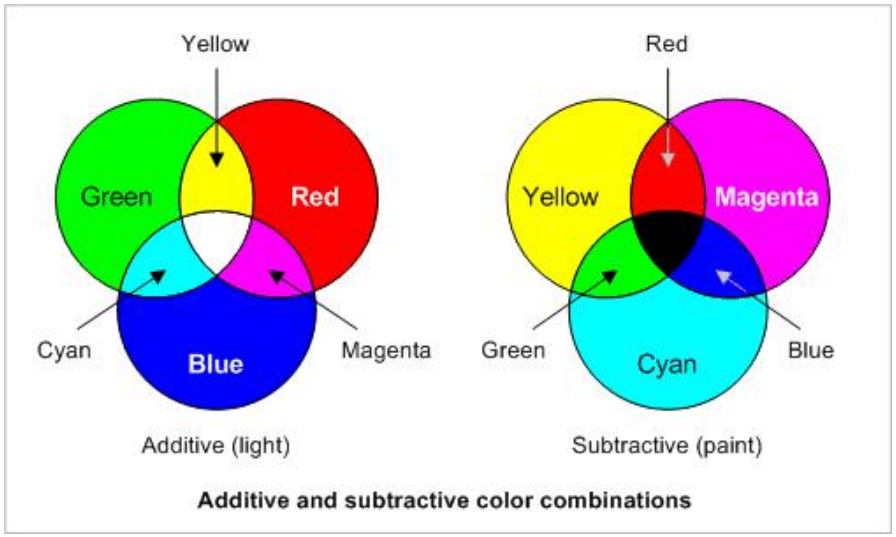
✦✦✦the QCD part ✦✦✦

Quarks	$t, \bar{t}$	171.3 ± 1.6 GeV	spin= $\frac{1}{2}$	$g = 2 \cdot 2 \cdot 3 = 12$
	$b, \bar{b}$	$4.20^{+0.17}_{-0.07}$ GeV	3 colors	
	$c, \bar{c}$	$1.27^{+0.07}_{-0.11}$ GeV		
	$s, \bar{s}$	105^{+25}_{-35} MeV		
	$d, \bar{d}$	$3.5 - 6.0$ MeV		
	$u, \bar{u}$	$1.5 - 3.3$ MeV		
				72
Gluons	8 massless bosons		spin= 1	$g = 2 \cdot 8 = 16$
				16

Remember: QCD = asymptotic freedom

strong interactions = weak at short distances strong at long distances

In nature today: hadrons only = color singlets, [color unobservable!] ➠
Confinement [QCD Gell-Mann, Fritzsch, Leutwyler]



Hadrons are made of Quarks and Gluons

QUARKS are permanently confined inside HADRONS

In early universe: hundreds of hadrons ➠ quark-antiquark-gluon soup [36+36+16]

$$\boxed{\text{All SM}: \; g_f = 72 + 12 + 6 = 90 \; ; \quad g_B = 16 + 11 + 1 = 28}$$

Thus the total energy density

$$\rho(T) = \sum \rho_i(T) = \frac{\pi^2}{30} g_*(T)\, T^4$$

which in general defines an effective number of degrees of freedom $g_*(T)$.

If all particles are ultra relativistic

$$g_*(T) = g_B(t) + \frac{7}{8} g_f(T)$$

with $g_B = \sum_i g_i$ is the sum over relativistic bosons and $g_f = \sum_i g_i$ the sum over the relativistic fermions.

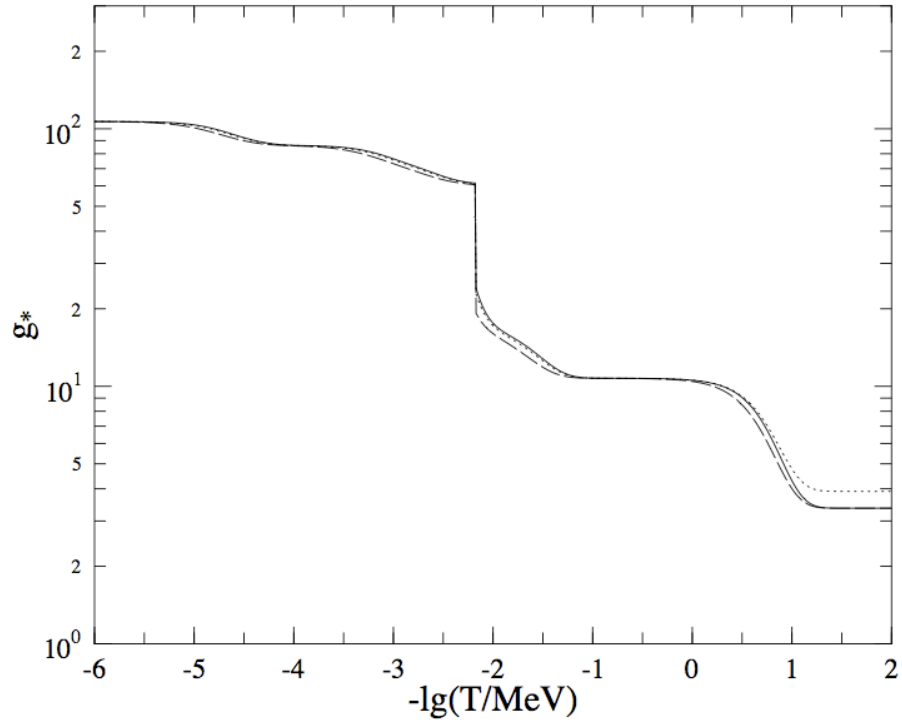
If all SM are relativistically excited we have

$$\boxed{g_*(T) = 106.75}$$

Mass effects can be taken into account as done above for electrons and positrons in the discussion of the e^+e^--annihilation. Mass effects manifest themselves slightly different in energy density ρ, pressure p and entropy density s. Therefore

$$\rho(T) = \frac{\pi^2}{30}\, g_*(T)\, T^4 \;; \quad p(T) = \frac{\pi^2}{90}\, g_{*p}(T)\, T^4 \;; \quad s(T) = \frac{2\,\pi^2}{45}\, g_{*s}(T)\, T^3$$

define slightly different effective numbers of degrees of freedom when masses play a role. Numerical results are shown in the following figure.



The functions $g_*(T)$) (solid), $g_{*p}(T)$ (dashed), and $g_{*s}(T)$ (dotted) calculated for the SM particle content.

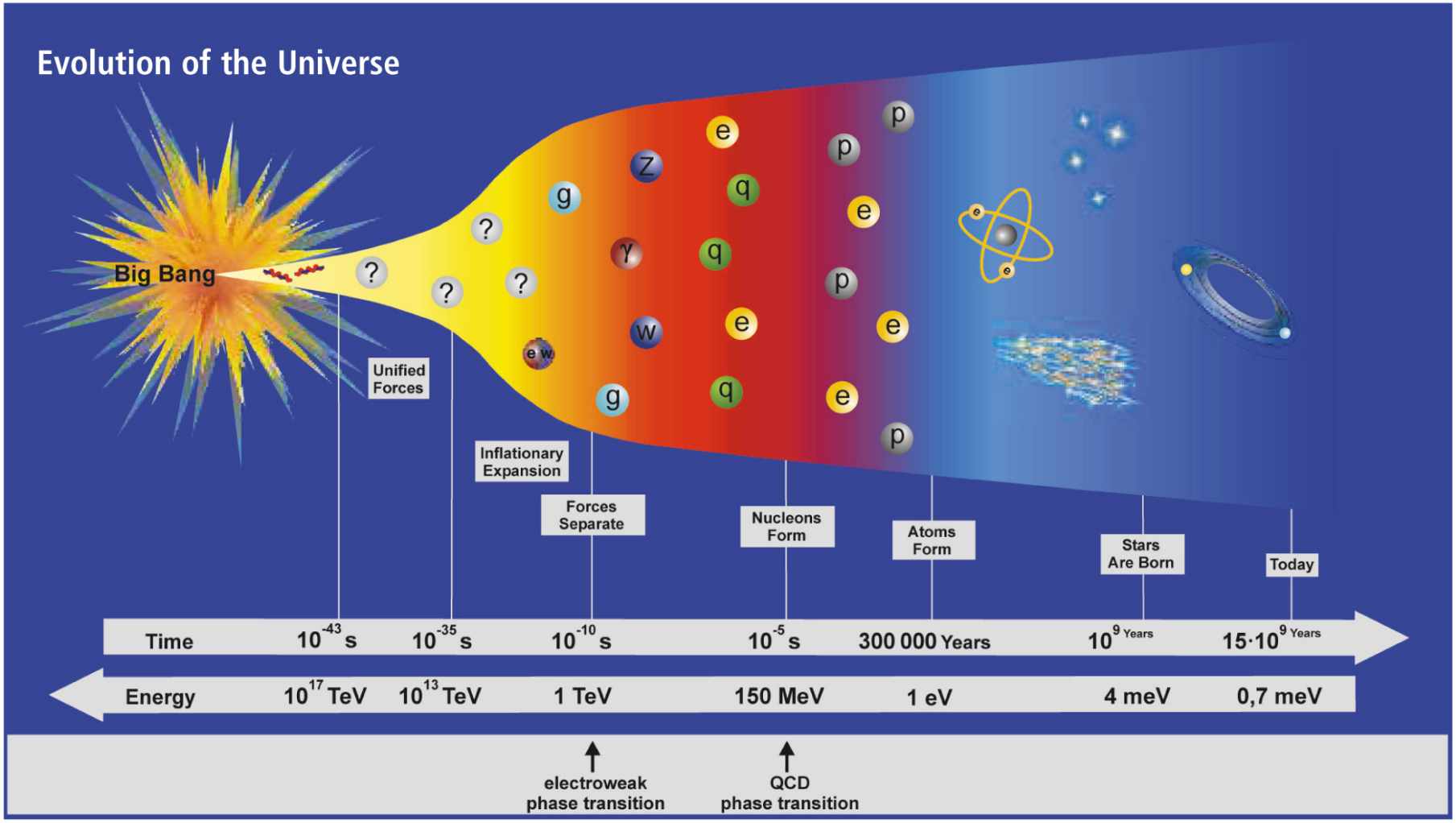
In the following we will often adopt the convention to express temperatures in energy units, as $E = k_{\rm B}\, T$ (hence $1\ ^\circ\!\mathrm{K}\ \sim 8.6 \times 10^{-5}\ \mathrm{eV}$) is a universal relation and as particle physicist we are more familiar with energy units.

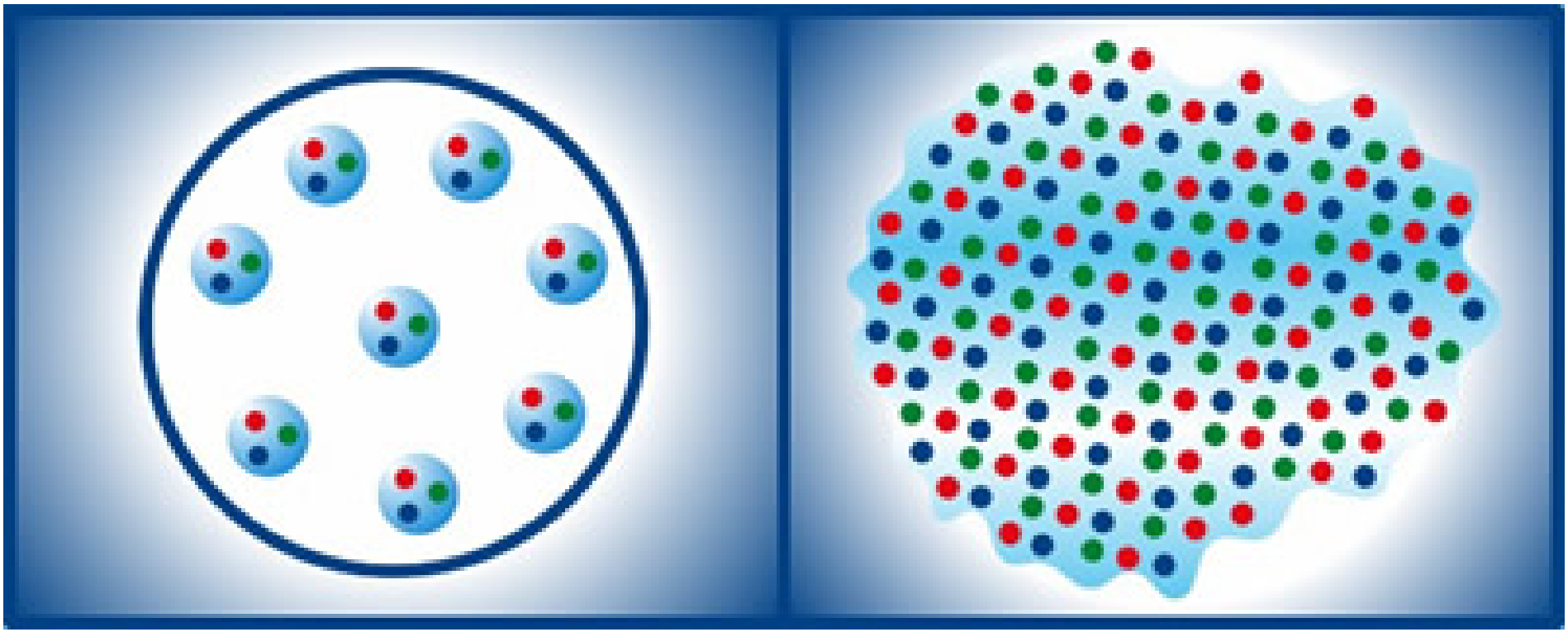
The thermal history of the universe as a scan of the SM:

T	event	$g_*(T)$	comment
~ 200 GeV	all states relativistic	106.75	
~ 100 GeV	EW phase transition	106.75	
< 170 GeV	top annihilation	96.25	
< 80 GeV	$W^\pm, Z, H$ annihilation	86.25	
< 4 GeV	bottom annihilation	75.75	
< 1 GeV	charm, τ annihilation	61.75	
~ 175 MeV	QCD phase transition	17.25	$(u, d, g \to \pi^{\pm,0}, 37 \to 3)$
< 100 MeV	$\pi^\pm, \pi^0, \mu$ annihilate	10.75	$e^\pm, \nu, \bar{\nu}, \gamma$ left
< 500 keV	$e^\pm$ annihilation	7.25	

Time after B.B.: $t = \frac{2.4}{\sqrt{g_*(T)}} \left(\frac{1\ \text{MeV}}{k_B T}\right)^2 \quad \text{sec.}$

Quark-Gluon Plasma: The Stuff of the Early Universe



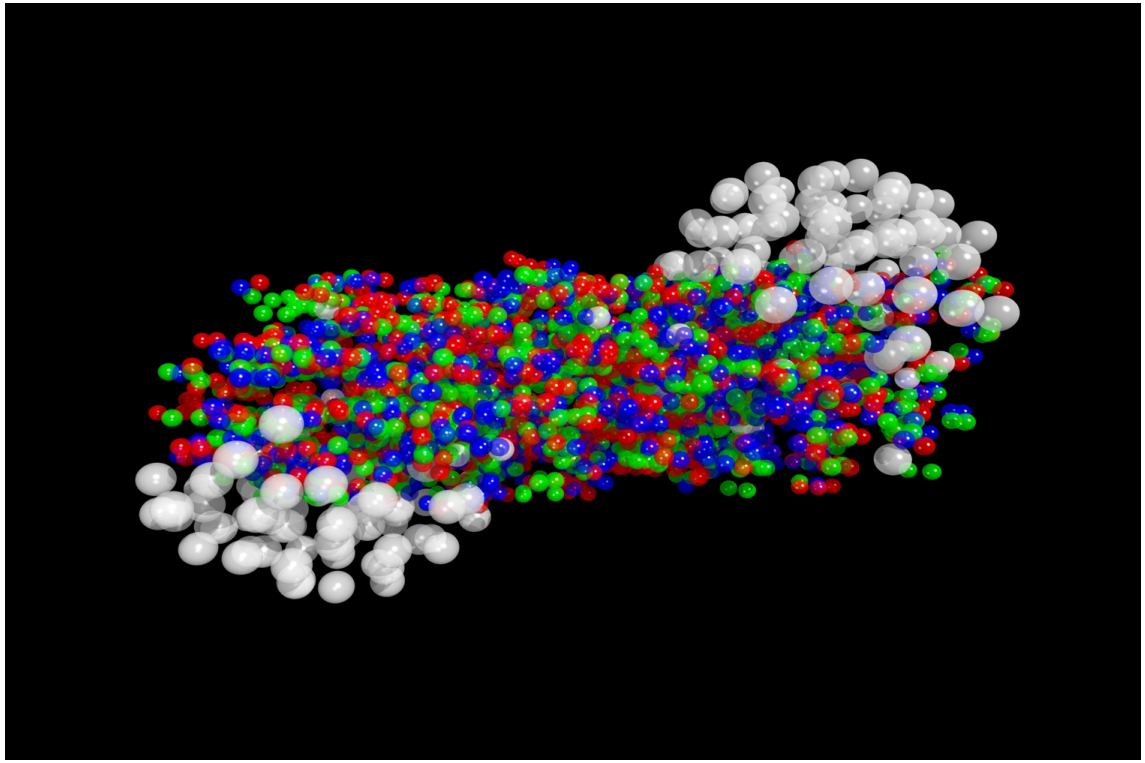


QCD under extreme conditions:

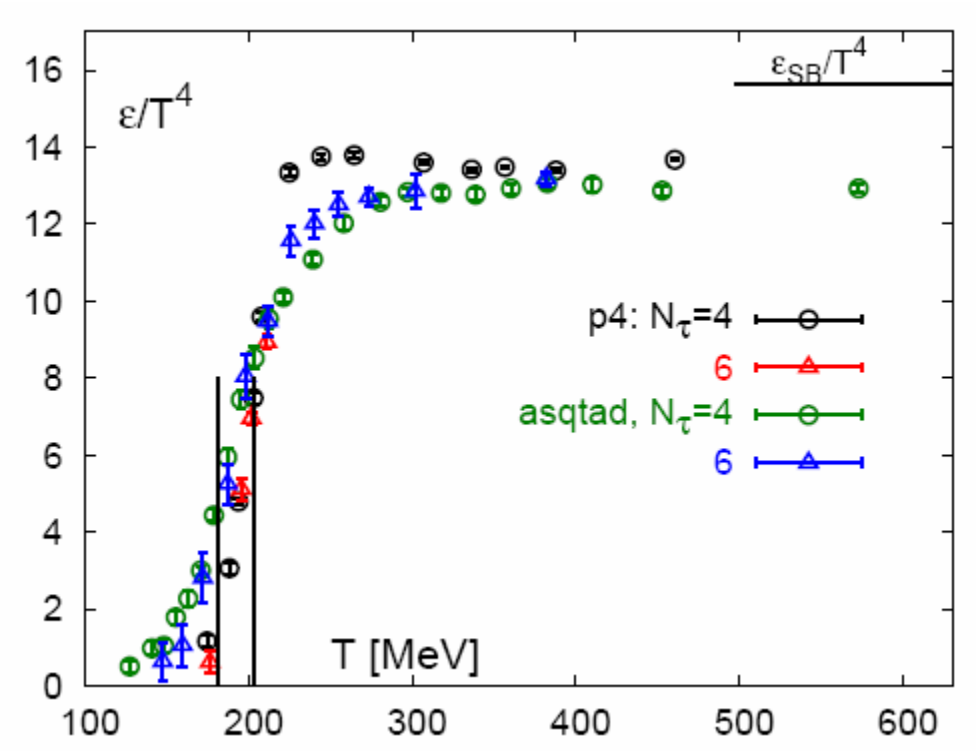
- High temperature matter: early universe
- High density matter: in neuron stars and other supernova remnants

❒ Laboratory test to come: heavy ion collisions RICH/Brookhaven, LHC/Geneva

Nuclei in collision:



QCD phase transition: insulator ↔ metall, hadrons get “ionized”



Physics of the early universe:

➠ Entropy per co-moving volume is conserved

➠ All entropy is in relativistic species Expansion covers many decades in T, so typically either $T \gg m$ (relativistic) or $T \ll m$ (frozen out)

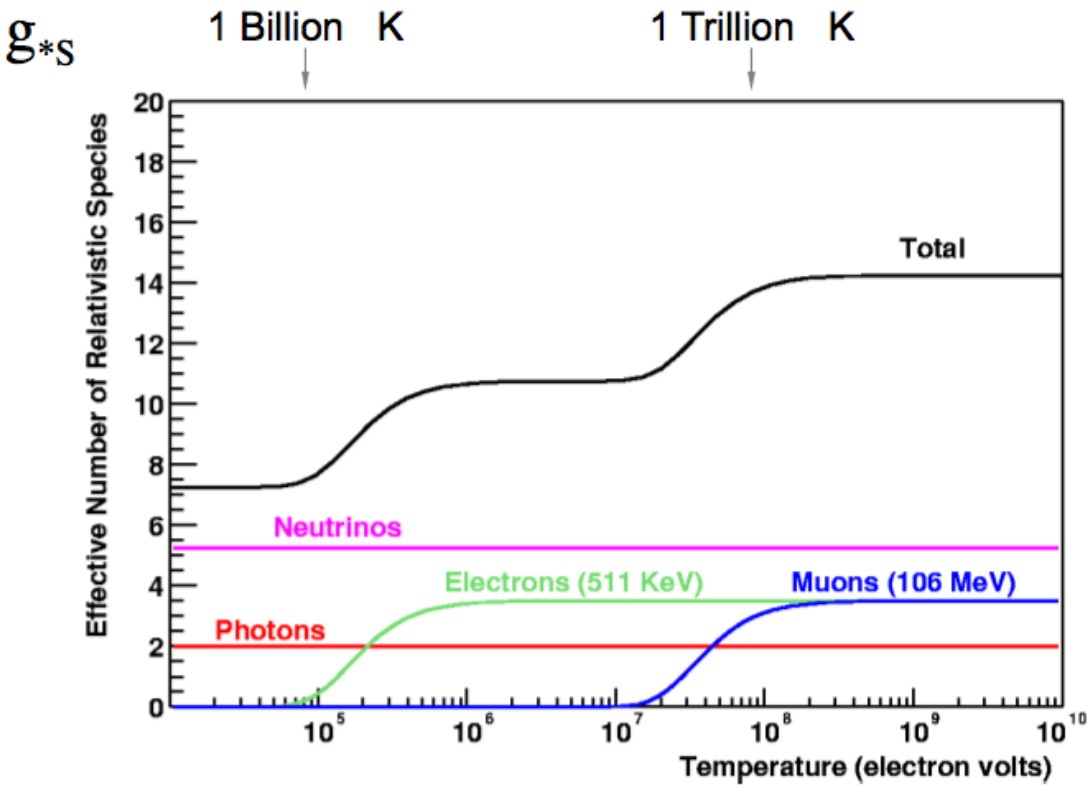
➠ All chemical potentials are negligible

Entropy S in co-moving volume $(D_c)^3$ preserved

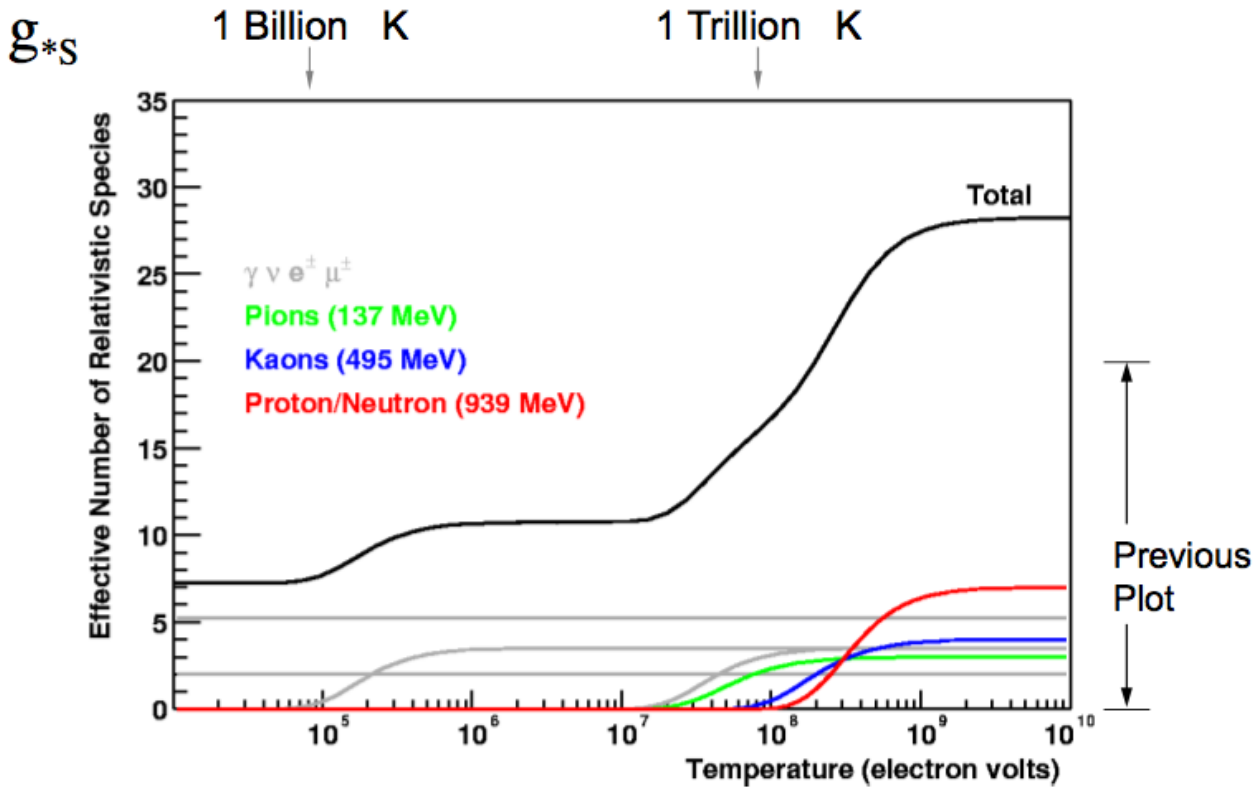
g_{*S} effective number of relativistic species

Entropy density $\frac{S}{V} = \frac{S}{D_c^3}\frac{1}{a^3} = \frac{2p^2}{45} g_S^* \, T^3$

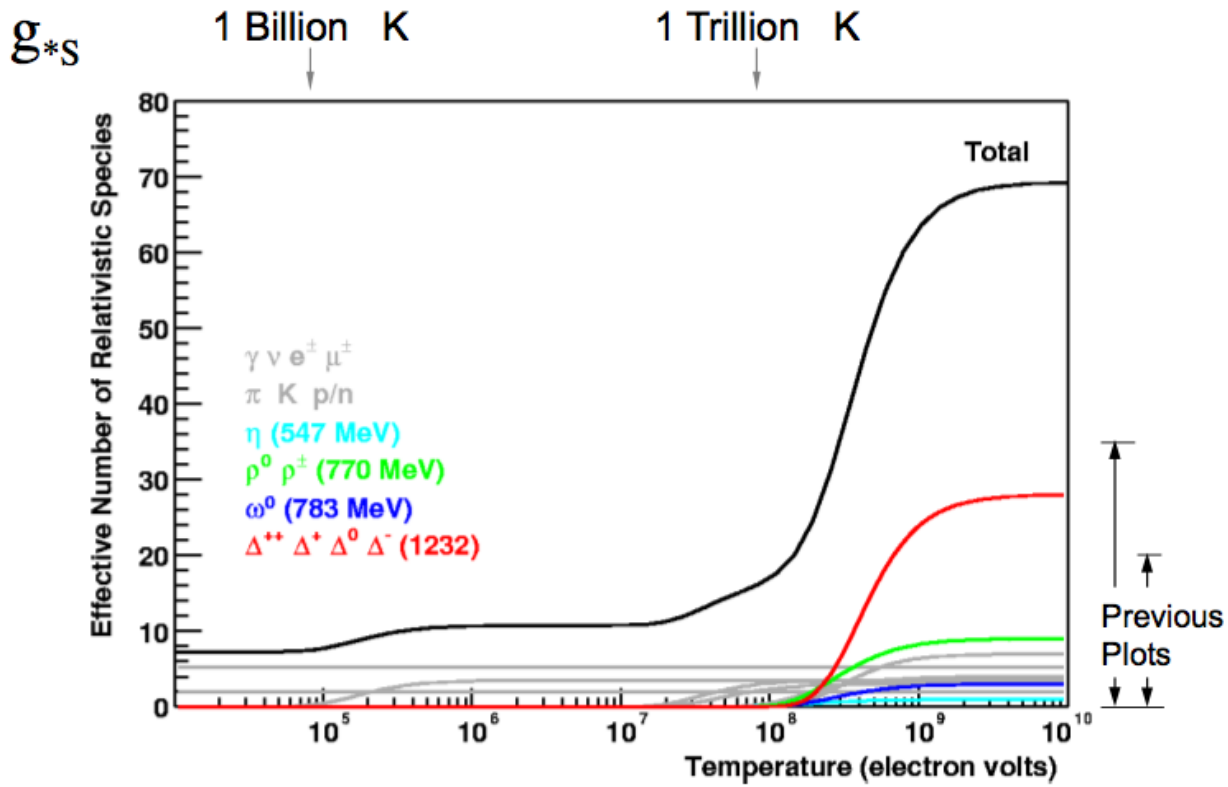
➠ $T = (g_{*S})^{-1/3} \, \frac{1}{a}$; a spacial radius of universe



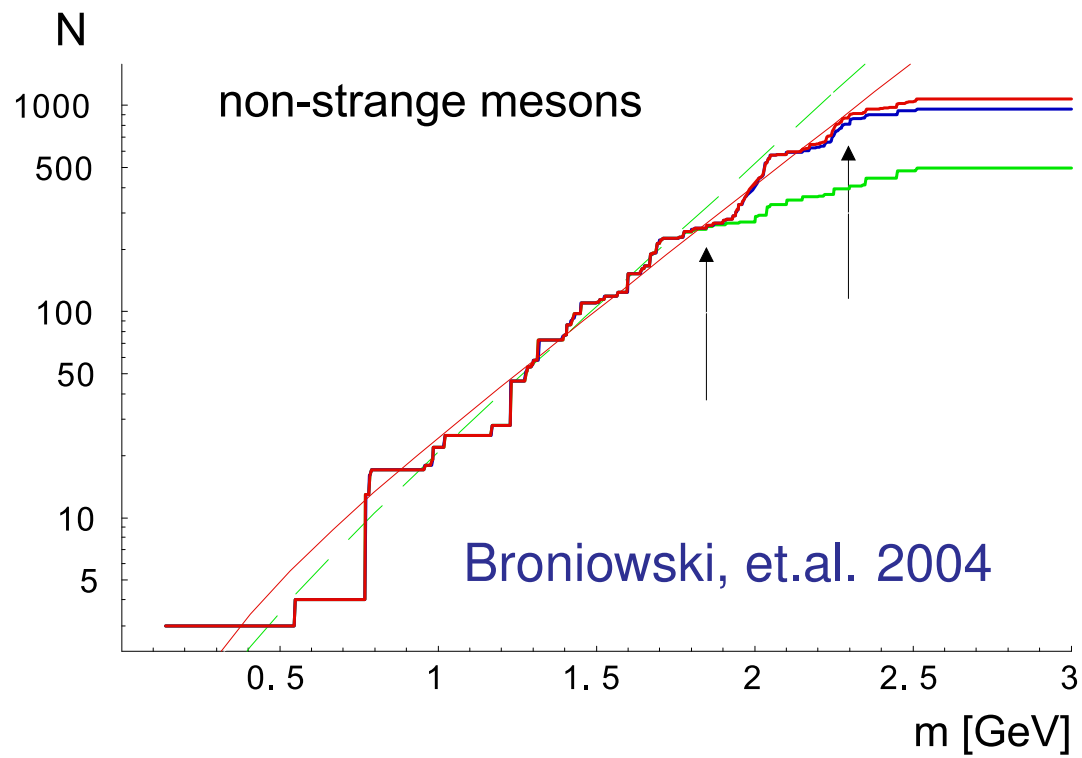
Start with light particles, no strong nuclear force



Now add *hadrons* = feel strong nuclear force



Keep adding more hadrons….



How many hadrons?

Density of hadron mass states dN/dM increases exponentially:

$$\frac{dN}{dM} \sim M^a \exp M/T_{\rm H} \; (T_{\rm H} \sim 2 \times^\circ K = 170 \text{ MeV})$$

QCD to the rescue!

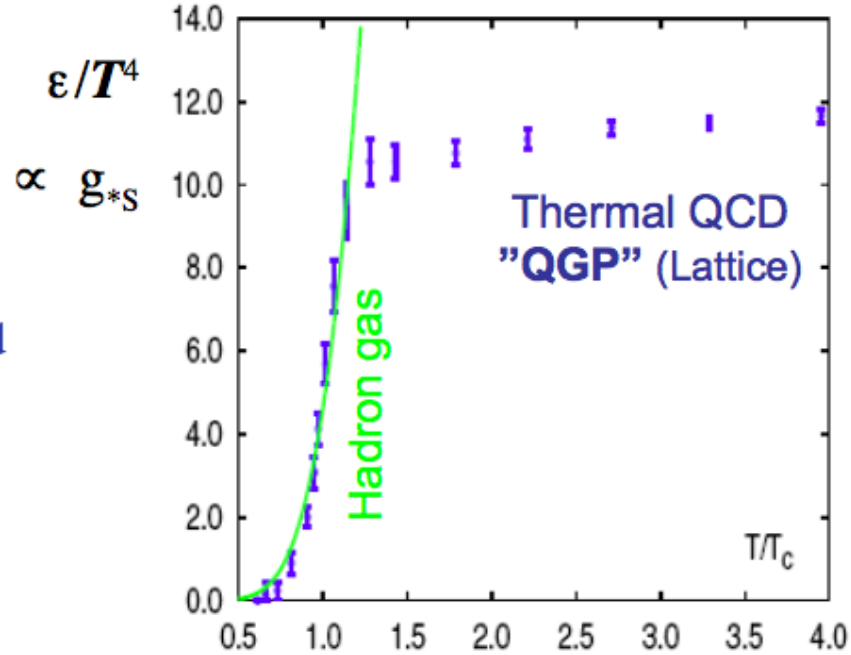
Replace Hadrons (messy and numerous)

by Quarks and Gluons (simple and few)

"In 1972 the early universe seemed hopelessly opaque…conditions of ultrahigh temperatures…produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly…"
Frank Wilczek, Nobel Lecture (RMP 05)

D. Gross
H.D. Politzer
F. Wilczek

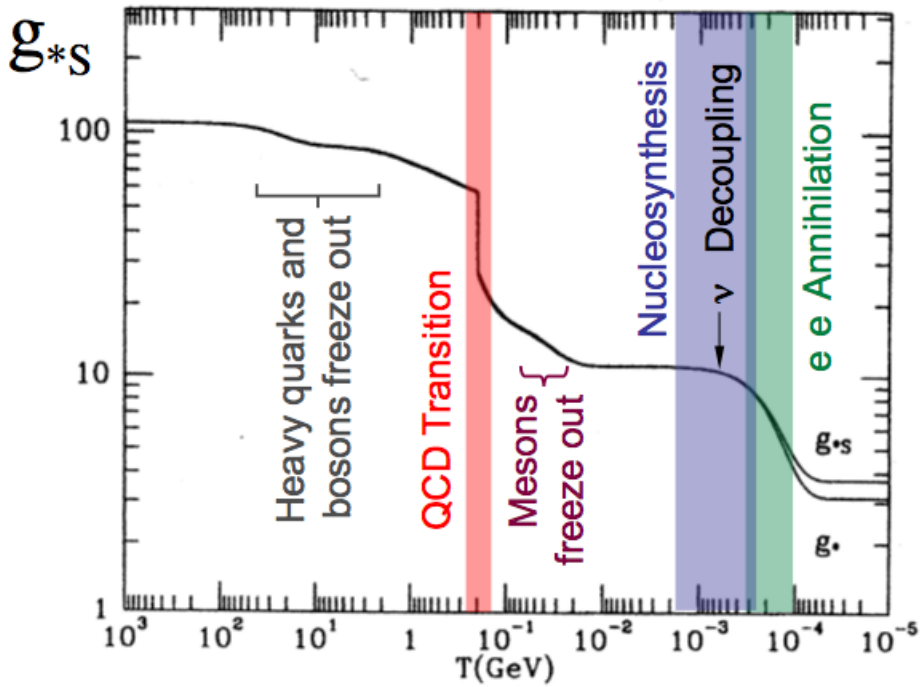
QCD Asymptotic Freedom (1973)



Karsch, Redlich, Tawfik, Eur.Phys.J.**C29**:549-556,2003

from P. Stankus, APS 09

Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted to form a quark-gluon plasma. David Gross, Nobel Lecture (RMP 05)



Kolb & Turner, "The Early Universe"

Cosmological phase transition....

...when the universe cools down below 175 MeV

10^{-5} seconds after the big bang...

Quarks and gluons form baryons and mesons

before: simply not enough volume per particle available

related baryogenesis? hadrons condense (get masses), others phase transitions earlier?

Electroweak phase transition T= 150 GeV ($\sim 1/\sqrt{\sqrt{2}G_F}$ G_F Fermi constant)

$\sim 6 \times 10^{-12}$ seconds after big bang

fermions, W and Z bosons get mass

Standard model: cross over transition baryogenesis if 1st order bubble formation "out of vacuum"

QCD at High temperature, at high T less order more symmetry (magnets crystals):

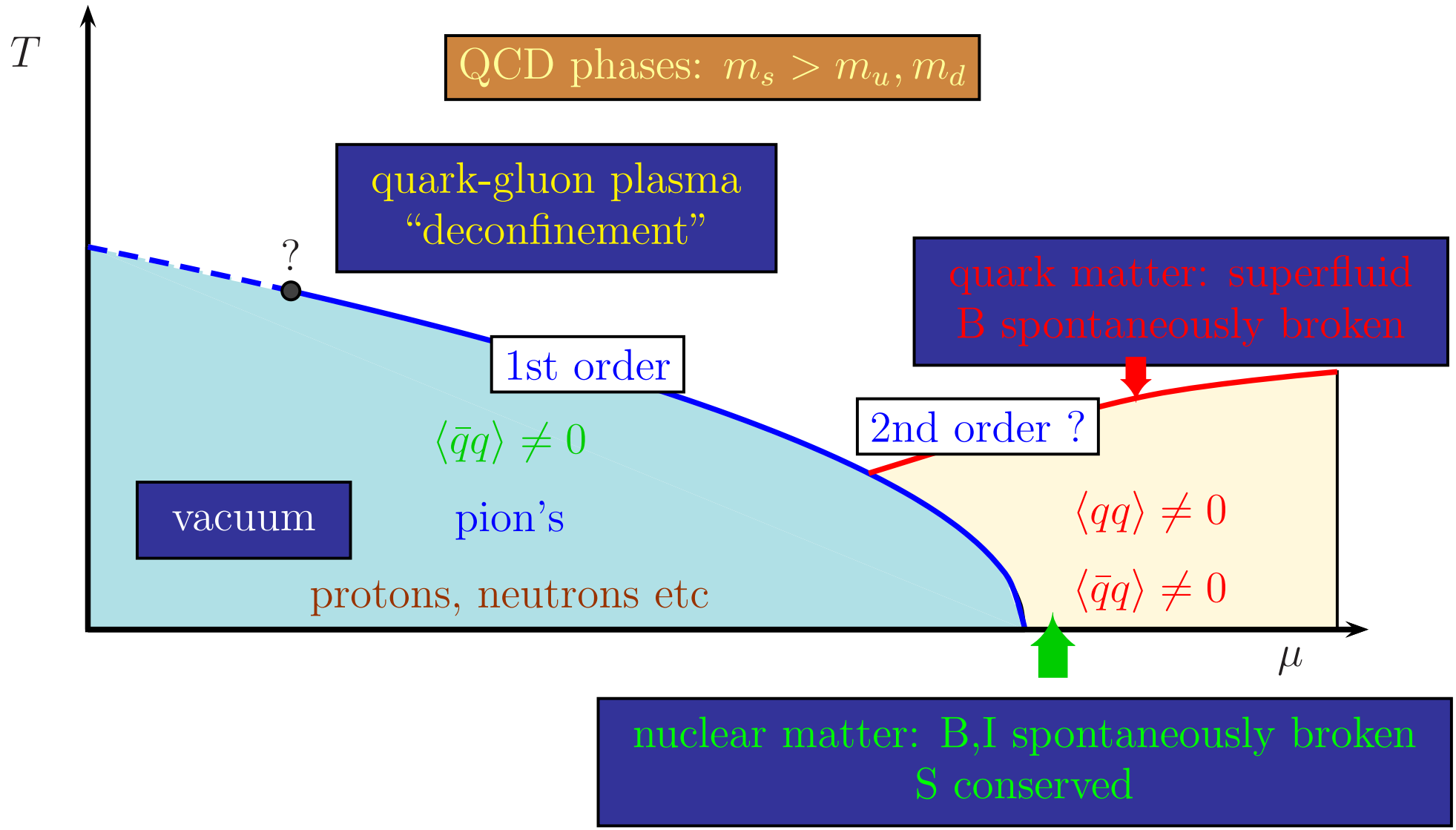
- Quark-gluon plasma
- Chiral symmetry restored (no pions, no quark condensates)
- "Deconfinement" (no linear heavy quark potential at large distances)
- Lattice QCD simulations: both effects happen at the same temperature

QCD - phase transition

Quark-gluon plasma		Hadron gas	
❖ Gluons:	$8 \times 2 = 16$	❖ Light mesons:	8
❖ Quarks:	$9 \times 7/22 = 12.5$	❖ (Pions:	3)
❖ DOF:	28.5	❖ DOF:	8
Chiral symmetry		Chiral symmetry broken	

Large difference in number of degrees of freedom !

Strong increase of density and energy density at T_c !


T
QCD phases: $m_s > m_u, m_d$
quark-gluon plasma
"deconfinement"
?
1st order
quark matter: superfluid
B spontaneously broken
2nd order ?
$\langle \bar{q}q \rangle \neq 0$
vacuum
pion's
$\langle qq \rangle \neq 0$
$\langle \bar{q}q \rangle \neq 0$
protons, neutrons etc
μ
nuclear matter: B,I spontaneously broken
S conserved

❖ Is B broken spontaneously? Could it be responsible for matter-antimatter asymmetry? Likely not: need $B - L$ conserved!

❖ What about dark matter? Is it frozen energy? Is there a phase transition like in baryonic sector? and, and, and ?

Summary

- QCD new type of QFT: particle $\leftrightarrow$ fields intrinsically non-perturbative, confinement & asymptotic freedom

- Baryonic matter (98%) binding energy (induced by interaction, frozen energy, condensed energy bags)

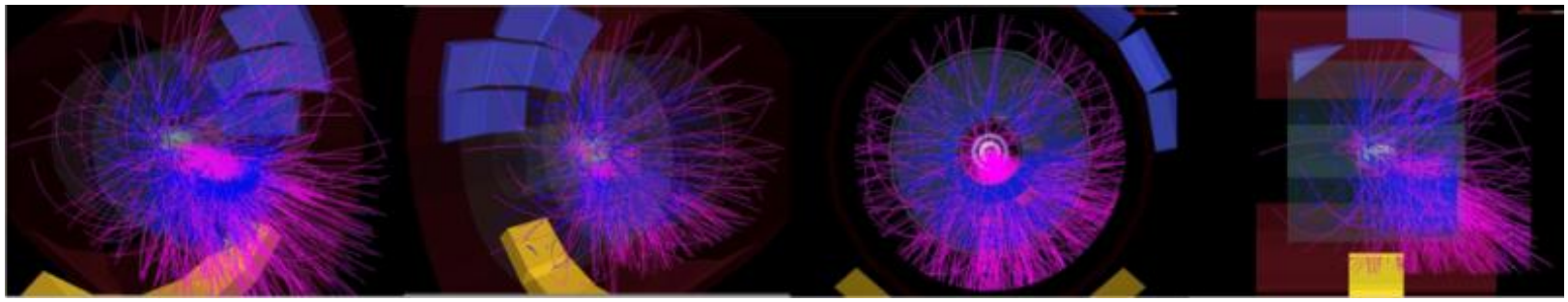
- Debris of hadrons produced at higher and higher energies ends in simple quark-gluon plasma (early universe)

- Extend our understanding of early cosmology from QCD phase transition (175 MeV; about 2×10^{-5} seconds back to the electroweak scale [200 GeV; about 6×10^{-12} seconds A.B.B.])

- To go deeper back in time wait for news from the LHC!

A real new challenge for QCD: the LHC


CERN, Geneva
LHC



- In fact: LHC is designed to look for states and new forms of matter which existed in the early universe but have not yet be seen!

- The big step forward in SM physics and cosmology: the discovery of the Higgs boson, which not only gives mass to quarks leptons and the weak gauge bosons, but also makes the universe look flat today.

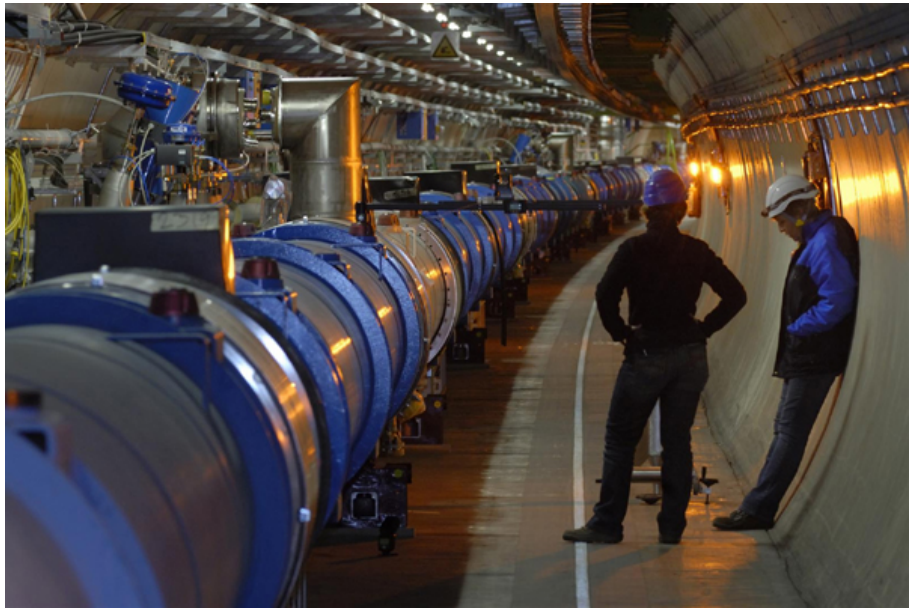
- LHC 27 km beam line: is operated at a temperature of only 1.9 K (-271°C) the coldest spot in the universe and producing hottest spots since 10^{-15} seconds A.B.B.

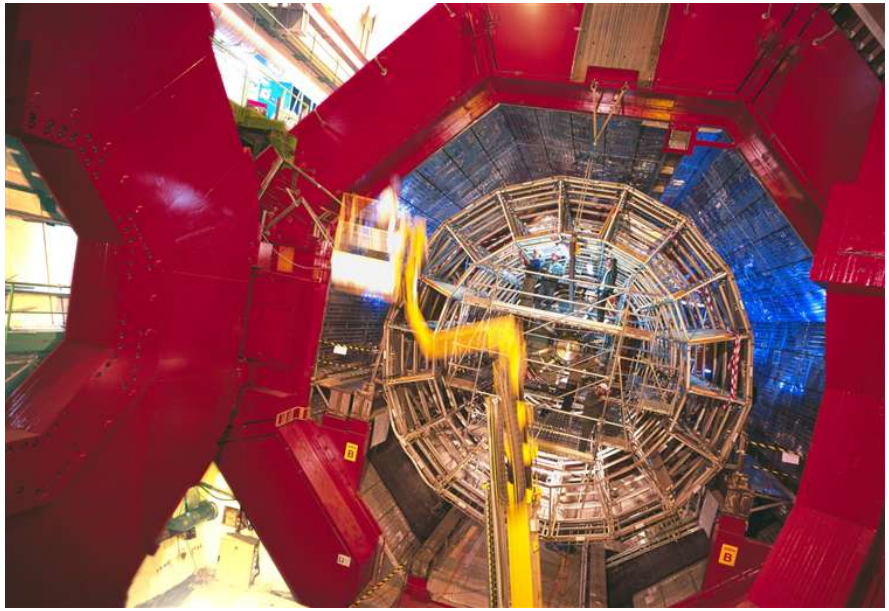
- the QCD quark-gluon plasma is subject to intense investigations at the LHC

ALICE as well as CMS and ATLAS detectors should shed more light on it

✻⋙ ✻⋙ ✻⋙

- The quark-gluon plasma is there and the QCD phase-transition temperature seems to be in accord with the lattice results?





Problem of fine-tuning

Time evolution of the density function:

$$\Omega(t) = \frac{1}{1 - x(t)}$$

$$x(t) = \frac{3k/R^2}{8\pi G\rho}$$

In order that the density today has a value 10 times higher or 10 times lower than the critical value one has to assume that at Planck times the density was coinciding to about 60 digits with the critical value 1.

$$|\Omega(10^{-43}\text{sec.}) - 1| \lesssim 10^{-60} \quad !$$

Solution by Inflation

Cure: add an inflation term, which blows up the early universe, such that it looks flat today:

$$\frac{8\pi}{3m_{Pl}^2}\left(V(\phi) + \frac{1}{2}\dot{\phi}^2\right)$$

to be added to the right hand side of Friedmann's equation (must be the dominating for small times)

"Baryogenesis"

$$n_{\bar{p}}/n_p \simeq 0 \;\; ; \quad n_p/n_\gamma \simeq 10^{-9}$$

Conditions for the possibility of the baryogenesis: (A. Sacharov 1967)

① Baryon number violating processes must exist (B–L violation!)

② CP violation ! Cronin, Fitch 1964 (NP 1980)
(Violation of time-reversal symmetry)
first seen in neutral Kaon decays 0.3% effect, more recently established in B-meson physics $\sim$ 100% effect
CP violation precisely as predicted by SM of elementary
$\Rightarrow$ **B-factories: BaBar and Belle**

③ Thermal far from equilibrium (non-stationary time evolution (as predicted by Friedmann's equations [GRT]))
is true as the universe is expanding

Standard Model of elementary particle physics cannot explain these facts: ➜ NEW PHYSICS REQUIRED likely at energies not yet accessible by experiment (except LHC may reveal new physics and hopefully does)!

GUT'S, SUSY, STRING'S ???

in GUT's: X–bosons and leptoquarks!

$\Rightarrow$ **ATLAS, CMS and LHCB experiments at the LHC**

"Nucleosynthesis"

After baryogenesis and e^+e^--annihilation:

$$n_{\bar{p}}/n_p \simeq 0 \;\; ; \quad n_p/n_\gamma \simeq 10^{-9}$$

At few seconds after B.B. and temperature $T \sim 10^{10}\,^\circ\mathrm{K}$

dropping fast

$n_e = n_p$ and $n_B = n_P + n_n$ conserved

neutrons, protons in thermal equilibrium

$$n + \nu \leftrightharpoons p + e^- \;, \quad n + e^+ \leftrightharpoons p + \bar{\nu} \;, \quad n \leftrightharpoons p + e^- + \bar{\nu}$$

① **Ratio n_n/n_p is given by the Boltzmann equation:**

$$\frac{n_n}{n_p} = \mathrm{e}^{-(m_p - m_n)\,c^2/k_B T}$$

which at $T \sim 10^{10}\,^\circ\mathrm{K}$ gives $n_n/n_p = 0.223$.

② **Below $T \sim 10^{10}\,^\circ\mathrm{K}$, no new neutrons are formed and the ratio is fixed. Yet it is too hot for deuterium to form, so protons and neutrons remain free. The free neutrons decay into protons via β–decay ($n \to p + e^- + \nu_e$, half life 617 seconds). About 4 minutes after B.B. temperature has dropped to $T \sim 10^9\,^\circ\mathrm{K}$, and deuterium can form. At this point, neutron decay has rebalanced the neutron to proton ratio to $n_n/n_p = 0.164$.**

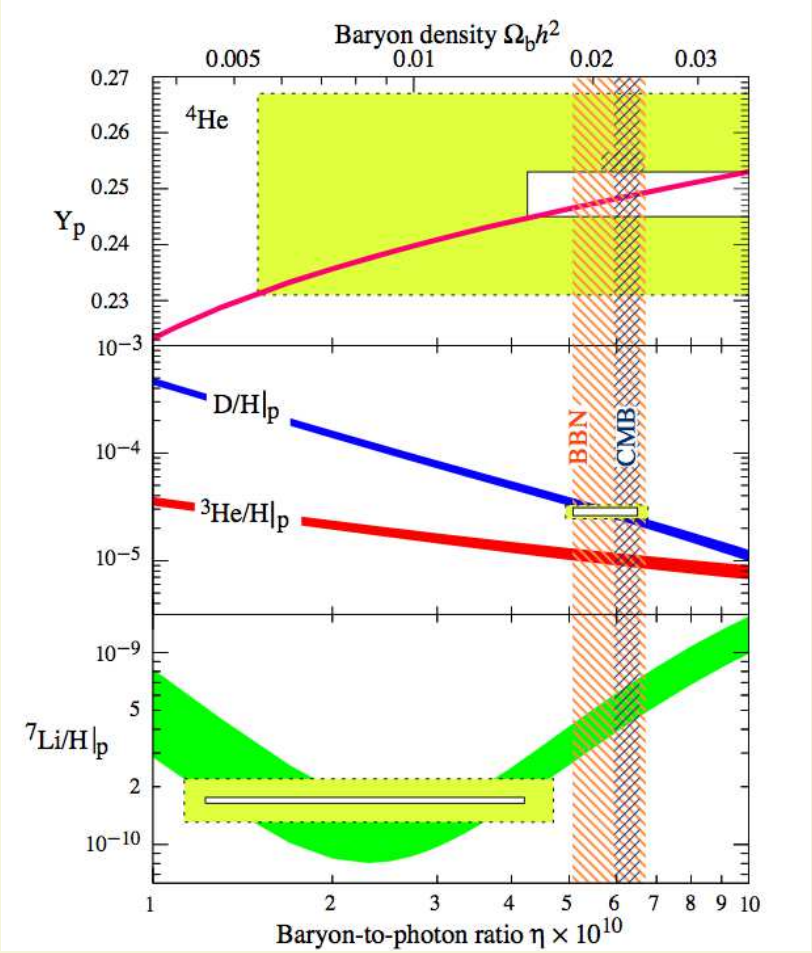
③ **Now time is ready for nucleosynthesis. At $T \sim 10^9\,^\circ\mathrm{K}$, deuterium will survive. So nuclear reactions will form deuterium, tritium, and helium:**

$$p + n \to \text{Deuterium} + n \to \text{Tritium} + p \to He^4$$
$$p + n \to \text{Deuterium} + p \to He^3 + n \to He^4$$

④ **Now per proper volume:** n_{He} **helium,** n_H **hydrogen nuclei: close to all neutrons are in helium:** $n_{He} = n_n/2$, $n_H = n_p - 2\,n_{He} = n_p - n_n \Rightarrow$ **fractional abundance by weight of helium** $Y = 4n_{He}/(4n_{He} + n_H) = 2n_n/(2n_n + n_p - n_n) = 2n_n/(n_p + n_n) = 2x/(1 + x)$, **with** $xn_n/n_p = 0.164$ **at** $T \sim 10^9\,^\circ\mathrm{K}$ **we have** $Y = 0.282$. **Observation close to 25%.**

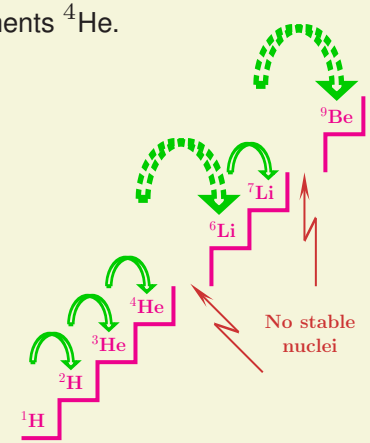
⑤ D **is a steep function of baryon number** $n_B \Rightarrow$ **Baryometer** $\Omega_B = 0.02$

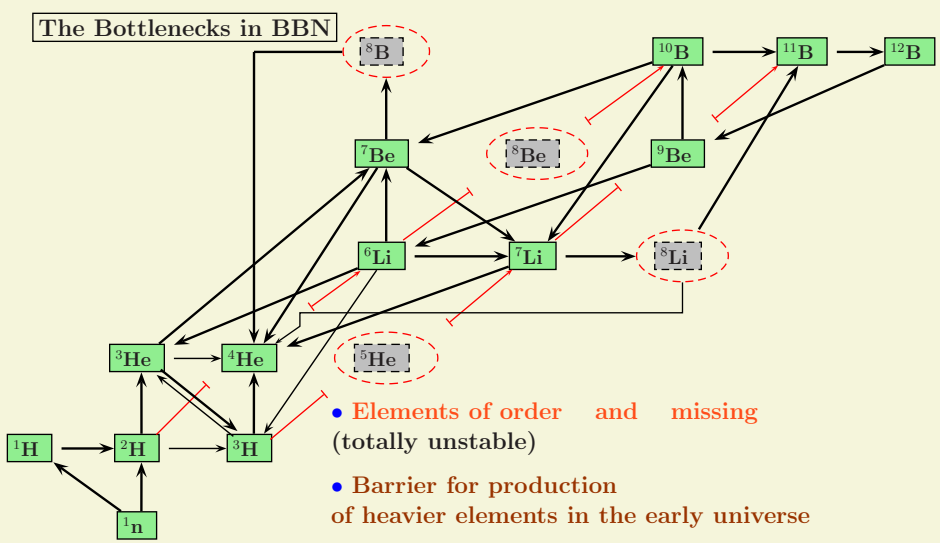
⑥ **Cosmic concordance: one value of** n_B **predicts light element abundances** ^{4}**He, D,** ^{3}**He,** ^{7}**Li rather well and in agreement with value form CMB!**


Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
^{4}He
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{10}$

Under conditions after the B.B. (low density of baryons after baryon antibaryon annihilation) only adding up nucleon by nucleon could be successful. Start of nucleosynthesis hindered by small binding energy of Deuteron [bottleneck]. Formation of D requires low enough temperature (at about $T = 0.1$ MeV) but in the meantime neutrons density decreases by neutrons decaying. At the end most of the remaining neutrons survive bounded in the most sable of the light elements ^{4}He.

The lack of stable elements of masses 5 and 8 makes it very difficult for BBN to progress beyond Lithium and even Helium. Need conditions found in stars for formation of the heavy elements.





- Elements of order and missing (totally unstable)
- Barrier for production of heavier elements in the early universe
- heavy elements must have been produced in stars (extreme temperature and pressure)

The Standard Cosmological Model

- Standard ΛCDM cosmological model is an exceedingly successful phenomenological model
- Rests on three pillars
  - Inflation: sources all structure
  - Cold Dark Matter: causes growth from gravitational instability
  - Cosmological Constant: drives acceleration of expansion that are poorly understood from fundamental physics
- ΛCDM and its generalizations to dark energy and slow-roll inflationary models is highly predictive and hence highly falsifiable.

Wayne Hu's summary

⁕ ⁕ ⁕

The hot Big Bang is supported very well by many facts. The picture of the universe is one of the outstanding intellectual achievements of the 20th century. It bridges physics at smallest scales with physics at largest scales - the cosmic bridge. It involves mysteries about its beginning and leads us into a uncertain future.

⁕ ⁕ ⁕

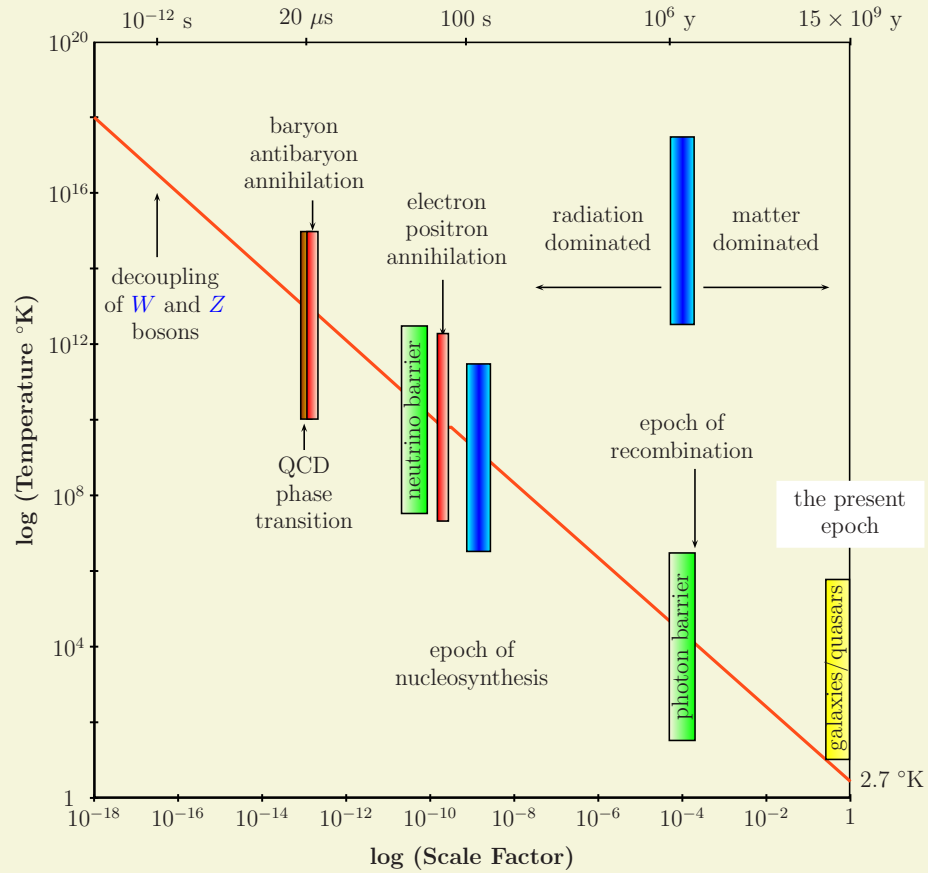
Last but not least: Standard Model of particle physics cannot explain

- **Dark matter,**
- **Baryogenesis [matter vs antimatter asymmetry] (missing B violation, missing amount of CP violation),**
- **Does not explain why cosmological constant is so small**
- **Why universe is flat [Inflation is beyond the SM physics]**

One of today's motivations and a great challenge for high energy particle physics

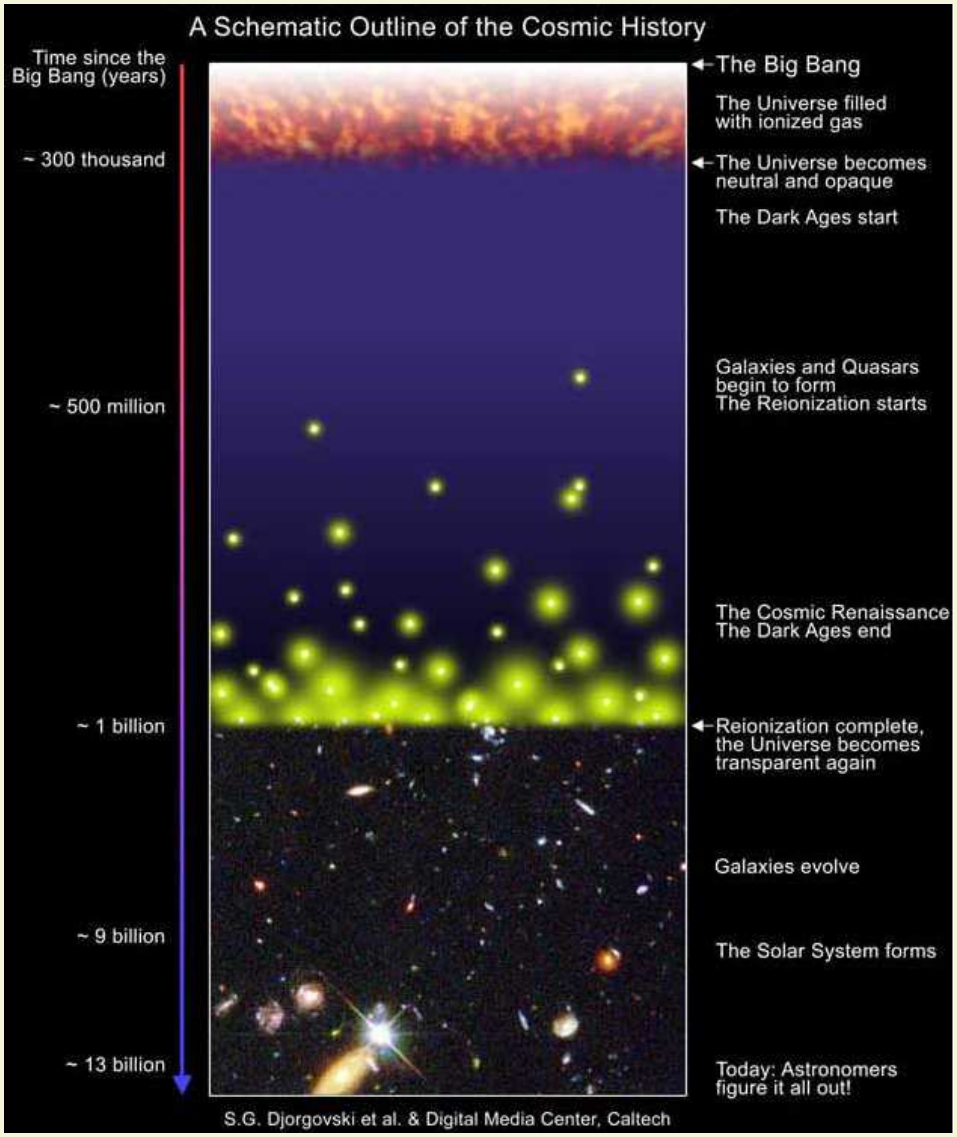
Find what's beyond the SM

● dark matter ● B-violating interactions ● and all that ....



Thermal History

Dark Ages after last scattering (epoch of recombination):
between 150 million to 1 billion years reionization of atoms takes place. The first stars and quasars form from gravitational collapse. The intense radiation they emit reionizes the intergalactic gas (hydrogen) of the surrounding universe. From this point on, most of the universe is composed of plasma. Stars cannot be seen until reionization becomes negligible due to ongoing expansion and decreasing matter density (dilution).



As far as we can see. As close as we can look.

HIGGS INFLATION ENDS HERE

✦✦✦✦✦✦✦✦✦✦✦

Previous ⋘| , this was the last lecture.