About the role of the Higgs boson in the early universe

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Outline of Talk:

- Introduction
- The Standard Model completed
- The SM running parameters
- Is the Standard Model sick?
- Emergence Paradigm
- Gravitation and Cosmological Models
- The Cosmic Microwave Background
- Inflation
- The issue of quadratic divergences in the SM
- The cosmological constant in the SM
- The Higgs is the inflaton!
- Reheating and baryogenesis
- What about the hierarchy problem?
- Conclusion

Introduction

"Four Infinity"

My talk is anti-infinity!

- 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, 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: $c, \hbar, G_N$

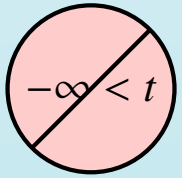
$\Rightarrow$Relativity and Quantum physics married with Gravity yield

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

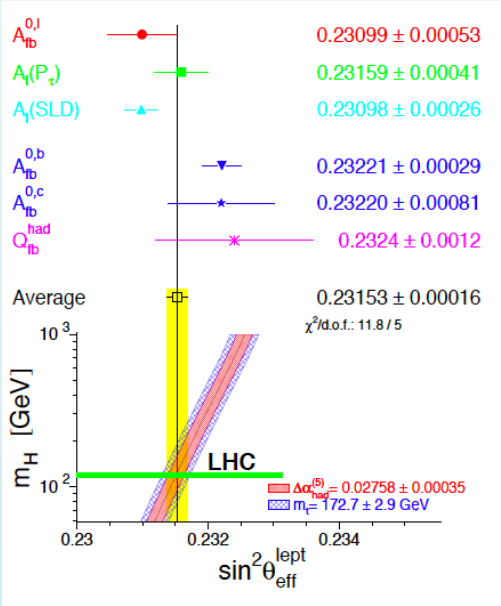
Planck temperature: $\frac{M_{\rm Pl}c^2}{k_{\rm B}} = \sqrt{\frac{\hbar c^5}{G_N k_{\rm B}^2}} = 1.416786(71) \times 10^{32}$ °K

- shortest distance $\ell_{\rm Pl}$ and beginning of time $t_{\rm Pl}$ $\boxed{t_{\rm Pl} < t}$ 

- highest energy $E_{\rm Pl} = \Lambda_{\rm Pl} \equiv M_{\rm Pl}$ and temperature $T_{\rm Pl}$

✌ LHC ATLAS&CMS Higgs discovered ⇒ the SM completion

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



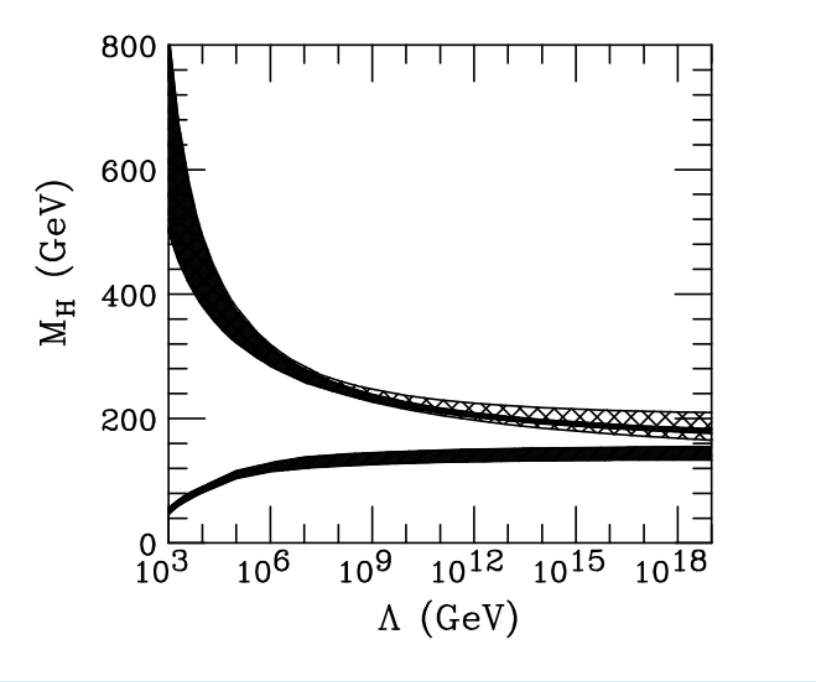
LEP 2005 +++ LHC 2012

Englert&Higgs Nobel Prize 2013

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

Common Folklore: hierarchy problem requires supersymmetry (SUSY) extension of the SM (no quadratic/quartic divergences) SUSY = infinity killer!

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



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

Riesselmann, Hambye 1996

$M_H < 180$ GeV

– first 2-loop analysis, knowing M_t –

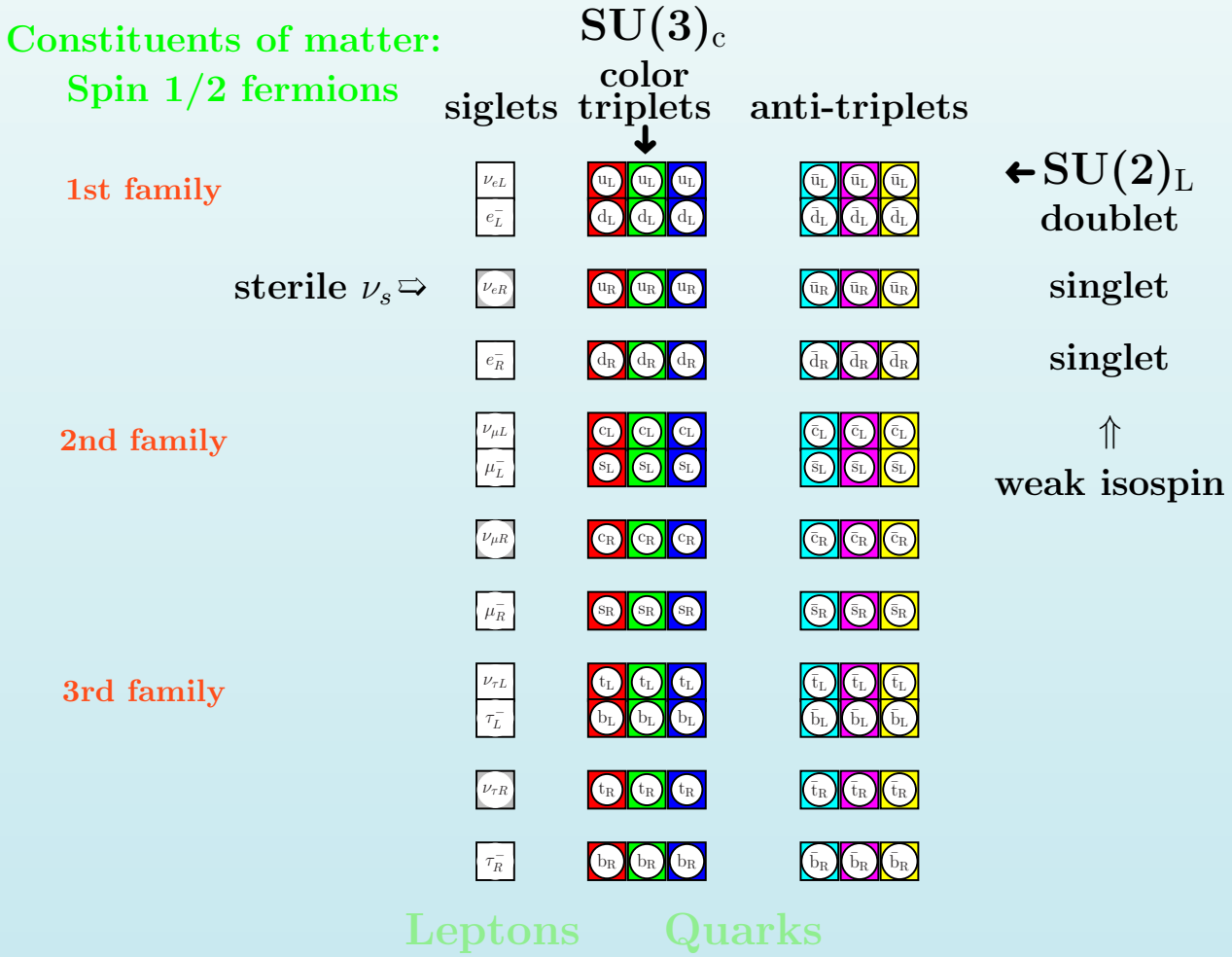
SM Higgs remains perturbative up to scale Λ if it is light enough (upper bound=avoiding Landau pole) and Higgs potential remains stable ($\lambda > 0$) if Higgs mass is not too light [parameters used: $m_t = 175[150 - 200]$ GeV ; $\alpha_s = 0.118]$

The Higgs is special!

- the Higgs boson was invented 1964 by Higgs, Englert and others to formulate a renormalizable theory of weak interactions
- the secret behind: all particle masses are dynamically generated by spontaneous symmetry breaking (SSB) [Higgs mechanism]
- one needs one scalar field ≡ Higgs field, which develops a finite constant vacuum expectation value (VEV) v [vacuum condensate]

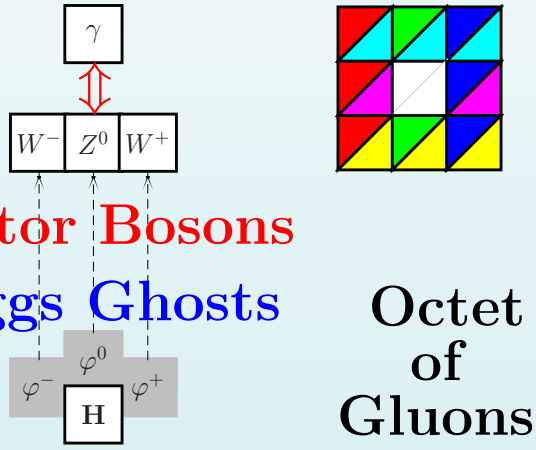
  ⇒originally massless particles must move in a ground state filled with Bose condensate such that particles appear to have a mass.

The Standard Model completed



Carrier of Forces:
Spin 1 Gauge Bosons

Photon



Octet of Gluons

"Cooper Pairs":
Spin 0 Higgs Boson

Higgs mechanism: breaking weak isospin spontaneously

weak bosons W, Z and all fermions get masses

$m_i \propto y_i\, v$; $v = \langle H \rangle > \simeq 246.21$ **GeV**; $G_{\rm Fermi} = \frac{1}{\sqrt{2}v^2}$ **(radioactivity)**

Before Higgs mechanism [symmetric phase]: $W^\pm, Z$ and all fermions massless
Higgs "ghosts" $\phi^\pm, \phi^0$ heavy physical degenerate with the Higgs!

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

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

$$
\begin{aligned}
m_W^2(\mu) &= \frac{1}{4} g^2(\mu)\, v^2(\mu)\ ; \quad m_Z^2(\mu) = \frac{1}{4}\left(g^2(\mu) + g'^2(\mu)\right) v^2(\mu)\ ; \\
m_f^2(\mu) &= \frac{1}{2} y_f^2(\mu)\, v^2(\mu)\ ; \quad m_H^2(\mu) = \frac{1}{3} \lambda(\mu)\, v^2(\mu)\ .
\end{aligned}
$$

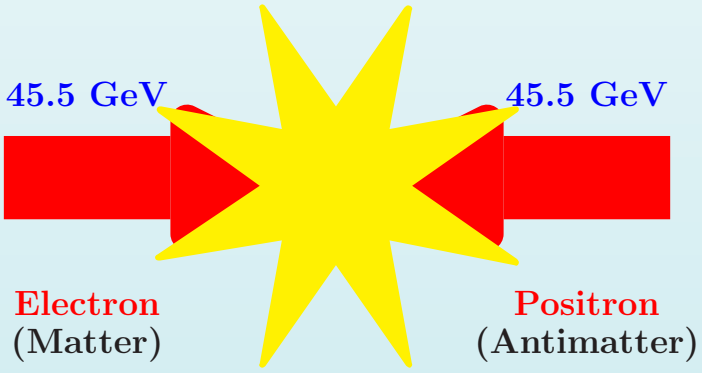
Effective parameters depend on renormalization scale μ [normalization reference energy!], scale at which ultraviolet (UV) singularities are subtracted

energy scale $\leftrightarrow$ center of mass energy of a physical process

e.g. at Large Electron Positron Collider [LEP] (pre LHC e^+e^- storage ring)

The Cosmic Bridge

e^+e^- Annihilation at LEP



$$E = 2m_{\rm eff}c^2$$

Mini Big Bang !

Energy versus temperature correspondence:

$$1^\circ\text{K} \equiv 8.6 \times 10^{-5} \text{ eV}$$
(Boltzmann constant k_B)
$$\downarrow$$
temperature of an event
$$T \sim 1.8 \times 10^{11} \times T_\odot$$

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

$$t = \frac{2.4}{\sqrt{g^*(T)}} \left(\frac{1MeV}{k_B T}\right)^2 \text{ sec.}$$
$$\downarrow$$
$t \sim 0.3 \times 10^{-10}$ sec. after B.B.
early universe

$0^\circ\text{K} \equiv -273.15^\circ$ C absolute zero temperature
$T_\odot \simeq 5700^\circ$ K surface temperature of the Sun

$g*(T)$ number of highly relativistic degrees of freedom at given T

Collider	energy		temperature	time after B.B.
LEP I:	$E_{cm} \sim 100$ GeV	$\Rightarrow$	1.16×10^{15} °K	$t_{\rm LEPI} \sim 2.58 \times 10^{-11}$ seconds
LEP II:	$E_{cm} \sim 200$ GeV	$\Rightarrow$	2.33×10^{15} °K	$t_{\rm LEPII} \sim 6.46 \times 10^{-12}$ seconds
LHC :	$E_{cm} \sim 14$ TeV	$\Rightarrow$	1.63×10^{17} °K	$t_{\rm LHC} \sim 1.185 \times 10^{-15}$ seconds

The key question: does SM physics describe physics up to the Planck scale?

or do we need new physics beyond the SM to understand the early universe or does the SM collapse if there is no new physics?

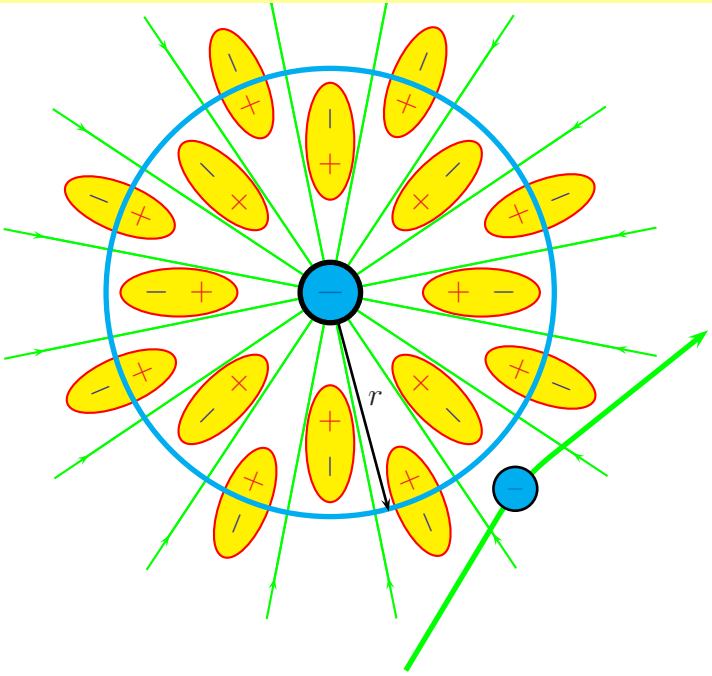
"collapse": Higgs potential gets instable below the Planck scale; actually several groups claim to have proven vacuum stability break down!
Shaposhnikov et al, Degrassi et al, Maina, Hamada et al, ...

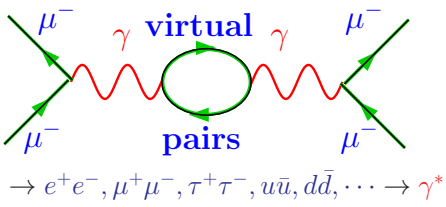
Alternative scenario: Higgs vacuum remains stable up and beyond the Planck scale $\Rightarrow$seem to say we do not need new physics affecting the evolution of SM couplings to investigate properties of the early universe. In the focus:

- does Higgs self-coupling stay positive $\lambda > 0$ up to $\Lambda_{\rm Pl}$
- the key question the size of the top Yukawa coupling y_t

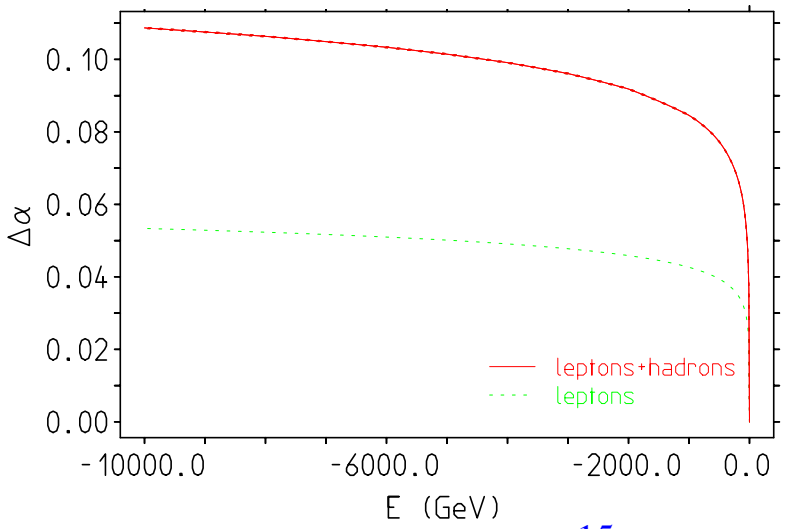
  decides about stability of our world! — [$\lambda = 0$ would be essential singularity!]

Running parameters $\alpha_{\rm em}$ and α_s





$\gamma^* \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, u\bar{u}, d\bar{d}, \cdots \to \gamma^*$



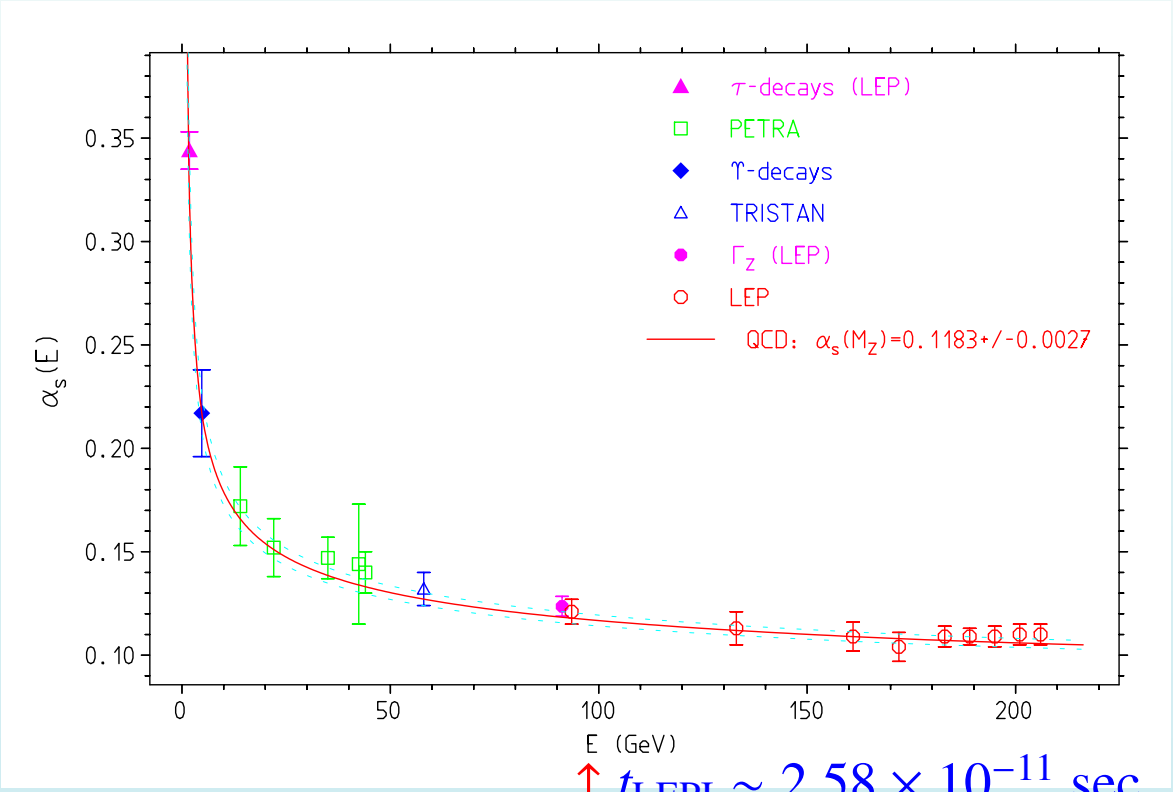
$\uparrow t_{\rm LHC} \sim 1.66 \times 10^{-15}$ sec

In a collision of impact energy E the effective charge is the charge contained in the sphere of radius $r \simeq 1/E$, which due to vacuum polarization is larger than the classical charge seen in a large sphere ($r \to \infty$)

$\Rightarrow$ *charge screening* (charge renormalization) running charge.

electromagnetic interaction strength decreases with distance

- non-Abelian gauge theories responsible for weak [local $SU(2)$ symmetry] and strong [local $SU(3)$ symmetry] interactions are anti-screening
  ≡ Asymptotic Freedom (AF) Gross, Wilczek, Politzer NP 2004

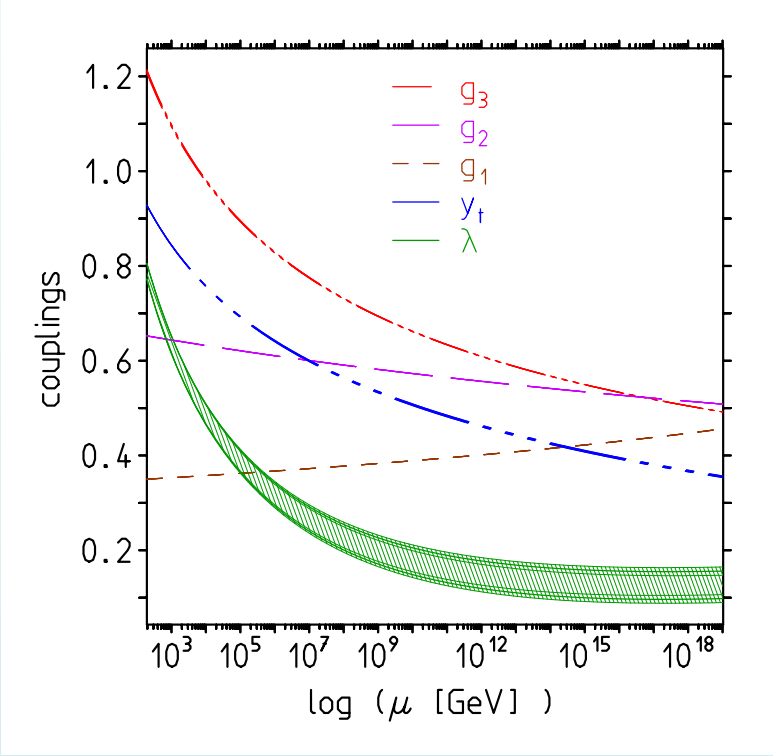


$\uparrow t_{\rm LEPI} \sim 2.58 \times 10^{-11}$ sec

A compilation of strong interaction coupling α_s measurements. The lowest point shown is at the τ lepton mass $M_\tau = 1.78$ GeV where $\alpha_s(M_\tau) = 0.322 \pm 0.030$

strong interaction strength increases with distance

The SM running parameters



The SM dimensionless couplings in the $\overline{\rm MS}$ scheme as a function of the renormalization scale for $M_H = 124 - 127$ GeV.

- perturbation expansion works up to the Planck scale!

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

- $U(1)_Y$ screening (IR free), $SU(2)_L$, $SU(3)_c$ antiscreening (UV free) [asymptotic freedom (AF)] – g_1, g_2, g_3

  Right – as expected

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

  Wrong!!! – transmutation from IR free to AF

- running top Yukawa QCD takes over: IR free $\Rightarrow$UV free
- running Higgs self-coupling top Yukawa takes over: IR free $\Rightarrow$UV free
- Higgs coupling decreases up to the zero of β_λ at $\mu_\lambda \sim 3.5 \times 10^{17}$ GeV, where it is small but still positive and then increases up to $\mu = \Lambda_{\rm Pl}$

Is the Standard Model sick?

The issue of the quadratic and quartic divergences: in a QFT quantities are affected by radiative correction (RC) (e.g. RC make couplings running) [quantum corrections]. In perturbation theory RC's are infinite if we do not regularize the theory. One class of regularizations: introduce a ultraviolet cutoff Λ, then corrections are finite for finite cutoff, result useful if energy scale of predicted quantity is $E \ll \Lambda$. i.e. low energy behavior or equivalent the long distance properties then are well predictable.

Basic problem: Quantum fields are operator valued distributions and local field products are ill-defined: $\phi^2(x) = \lim_{y\to x} \phi(y)\,\phi(x)$ limit singular [short distance singularity $\sim$ ultraviolet (high energy) singularity]

While logarithmic singularities are well controllable by RG methods (running effective parameters), power singularities are more severe [relevant parameters, fine tuning problems] in condensed matter physics adjusted for criticality (e.g. tuning to critical temperature)

In particle physics symmetries are tuning masses to be absent (long range stuff): fermions by chiral symmetry, spin 1 vector bosons by gauge symmetries !

And the Higgs (scalars)?

In SM before symmetry is broken by the Higgs mechanism: all particles massless except the Higgses. Actually – only two quantities show up severe power-like UV singularities

The SM's naturalness problems and fine-tuning problems

- the Higgs mass: [note bare parameters parametrize the Lagrangian]

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

with a coefficient typically $C = O(1)$. To keep the renormalized mass at the observed small value $m_{\text{ren}} = O(100\ \text{GeV})$, m^2_{bare} has to be tuned to compensate the huge term δm^2: about 35 digits must be adjusted in order to get the observed

value.

Hierarchy Problem!

❒ the vacuum energy density:

$$\rho_{\text{vac, bare}} = \rho_{\text{vac, ren}} + \delta\rho \; ; \quad \delta\rho = \frac{\Lambda_{\text{Pl}}^4}{(16\pi^2)^2} X(\mu)$$

SM predicts huge CC at Λ_{Pl}:

$$\rho_{\text{vac, bare}} \simeq V(0) + \Delta V(\phi) \sim 2.77\, \Lambda_{\text{Pl}}^4 \sim 6.13 \times 10^{76}\ \text{GeV}^4 \quad \text{vs. } \rho_{\text{vac}} = (0.002\ \text{eV})^4 \text{ today}$$

Cosmological Constant Problem!

Note: the only trouble maker is the Higgs!

Emergence Paradigm

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

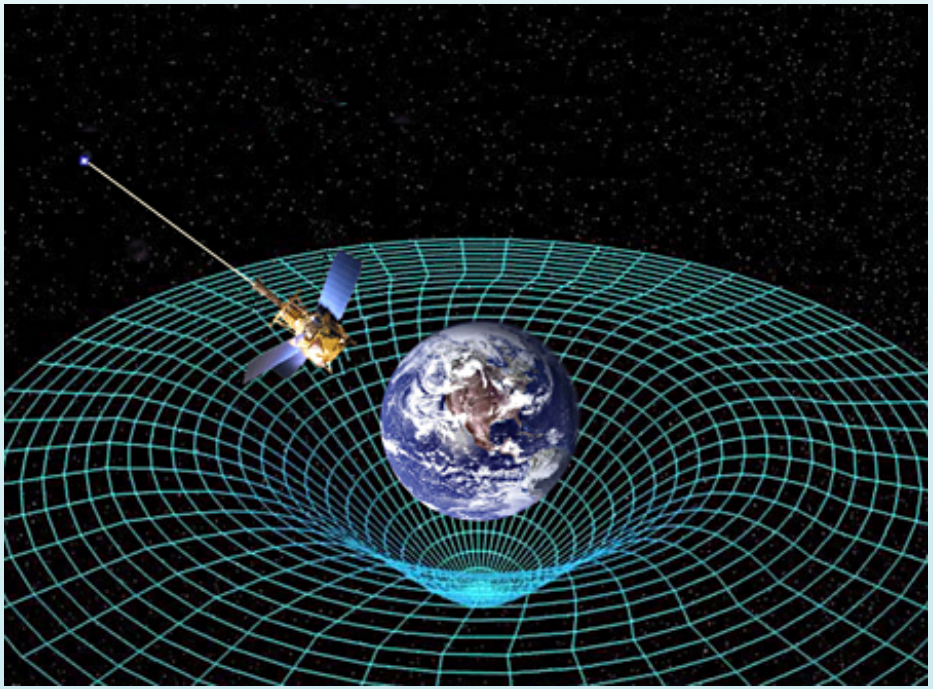
$$\Lambda_{\rm Pl} = (G_N)^{-1/2} \simeq 1.22 \times 10^{19}\ \text{GeV}$$

G_N Newton's gravitational constant

- SM works up to Planck scale, this mean that in makes sense to consider the SM as the Planck medium as seen from far away i.e. the SM is emergent at low energies.
- looking at shorter and shorter distances (higher energies) we can see the bare Planck system as it was evolving after the Big Bang!
- 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.

Gravitation and Cosmological Models

Gravitation $\Leftrightarrow$ all masses and even massless particle attract each other
Einstein's General Relativity Theory (GRT): masses (energy density) determine the geometry of space-time (Riemannian Geometry)



Mass tells space how to curve – curved space tells bodies how to move
$\Rightarrow$Einstein's equation!

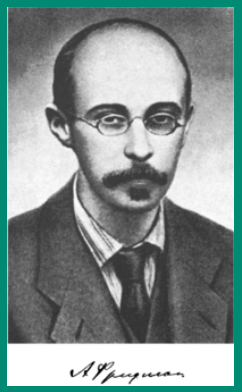
$$G_{\mu\nu} \equiv R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = \kappa \; T_{\mu\nu}$$

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,
- Hubble's law [galaxies: $velocity_{recession} = H\,Distance$], H Hubble constant
- temperature, energy density, pressure huge at begin, decreasing with time

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

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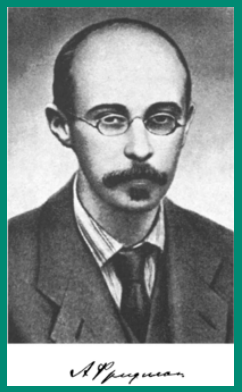


$$3\,\frac{\dot{a}^2+kc^2}{c^2a^2} = \kappa\,(\rho+\rho_\Lambda)$$

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

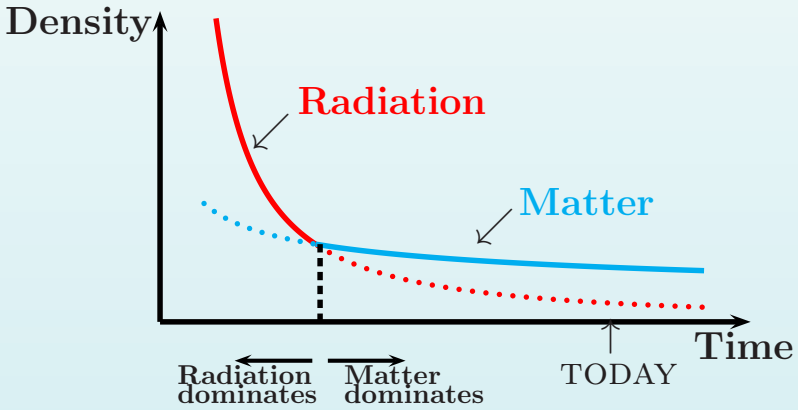
$a(t)$ Robertson-Walker radius of the universe

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

- universe must be expanding, Big Bang,
- Hubble's law [galaxies: $velocity_{recession} = H\,Distance$], H Hubble constant
- temperature, energy density, pressure huge at begin, decreasing with time

History of the Universe

The further we look back to the past, the universe appears to be compressed more and more. We therefore expect the young universe was very dense and hot:



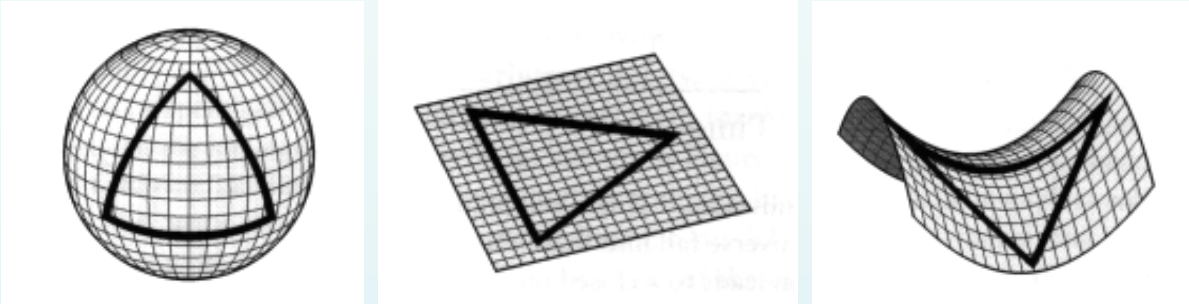
At Start a Light-Flash: ➽ **Big-Bang (fireball)**

Light quanta very energetic, all matter totally ionized, all nuclei disintegrated. Elementary particles only!: $\gamma, e^+, e^-, p, \bar{p}, \cdots$

Processes: $2\gamma \leftrightarrow e^+ + e^-$
$2\gamma \leftrightarrow \bar{p} \ + p$
$\vdots$

Particle–Antiparticle Symmetry!

☛ Digression into high energy physics: example LEP



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 instable

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

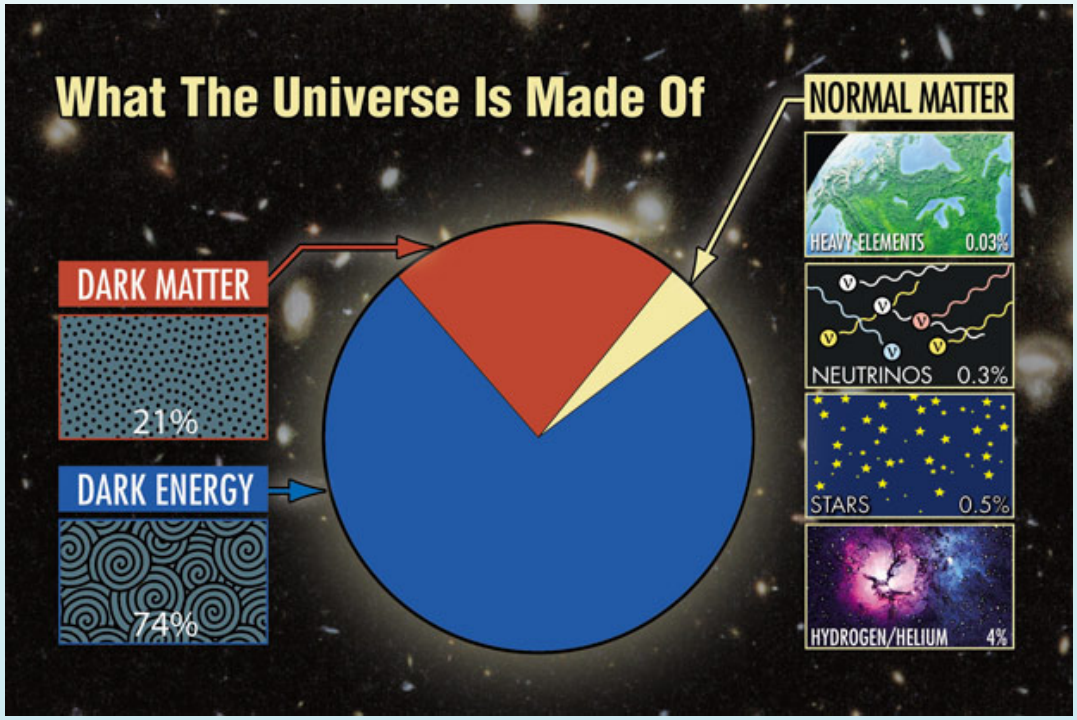
where H_0 is the present Hubble constant, and h its value in units of 100 km s^{-1} Mpc^{-1}. Ω expresses the energy density in units of $\rho_{0,\mathrm{crit}}$. Thus the present density ρ_0 is represented by

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

Forms of energy:

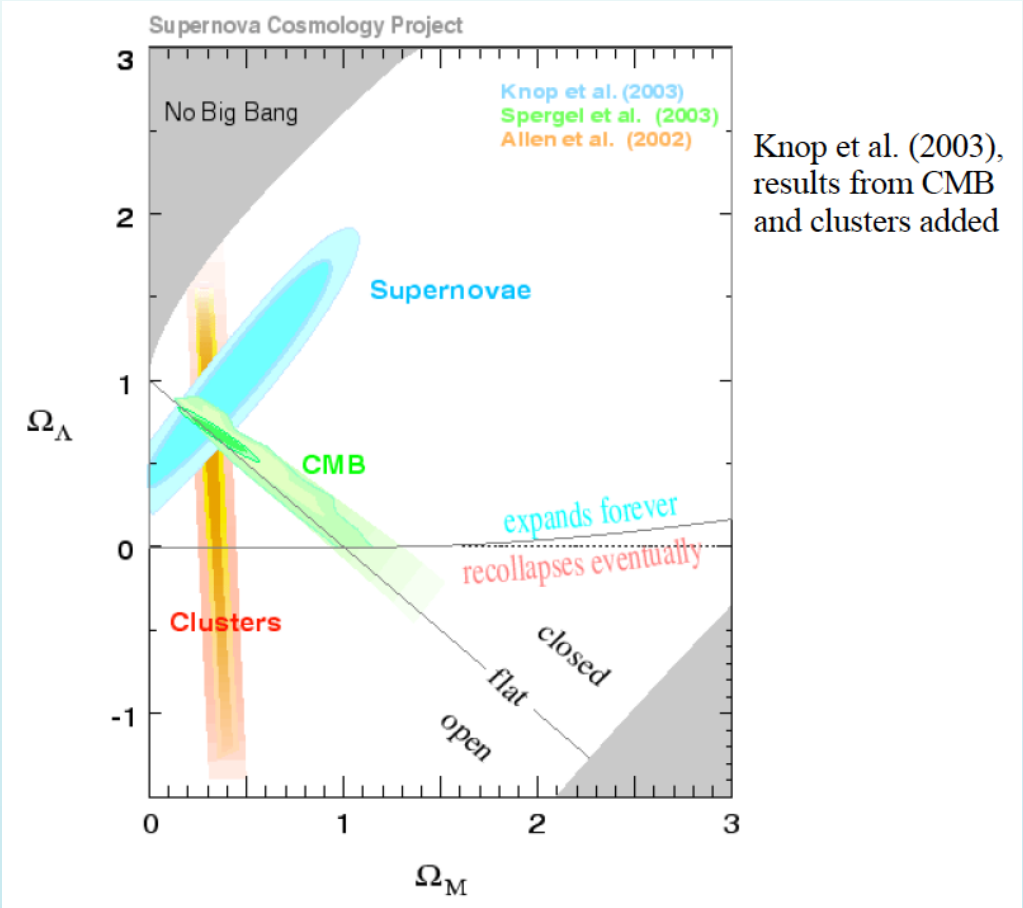
- radiation: photons, highly relativistic particles $p_{\mathrm{red}} = \rho_{\mathrm{rad}}/3$

- normal and dark matter (non-relativistic, dilute) $p_{\text{matter}} \simeq 0\,,\ \rho_{\text{matter}}$
- dark energy (cosmological constant) $p_{\text{vac}} = -\rho_{\text{vac}}$
- findings from Cosmic Microwave Background (COBE, WMAP, PLANCK)



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

- expansion is accelerated i.e. non-zero positive cosmological constant .
  (dark energy) Perlmutter NP 2011

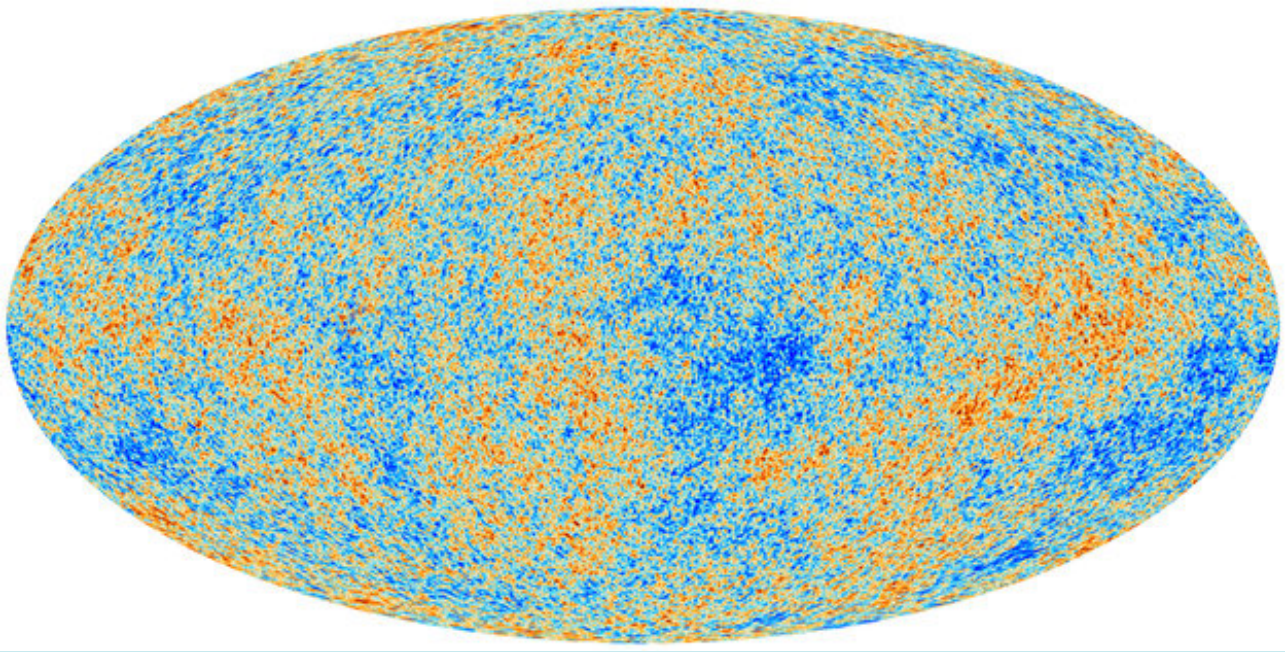


Knop et al. (2003), results from CMB and clusters added

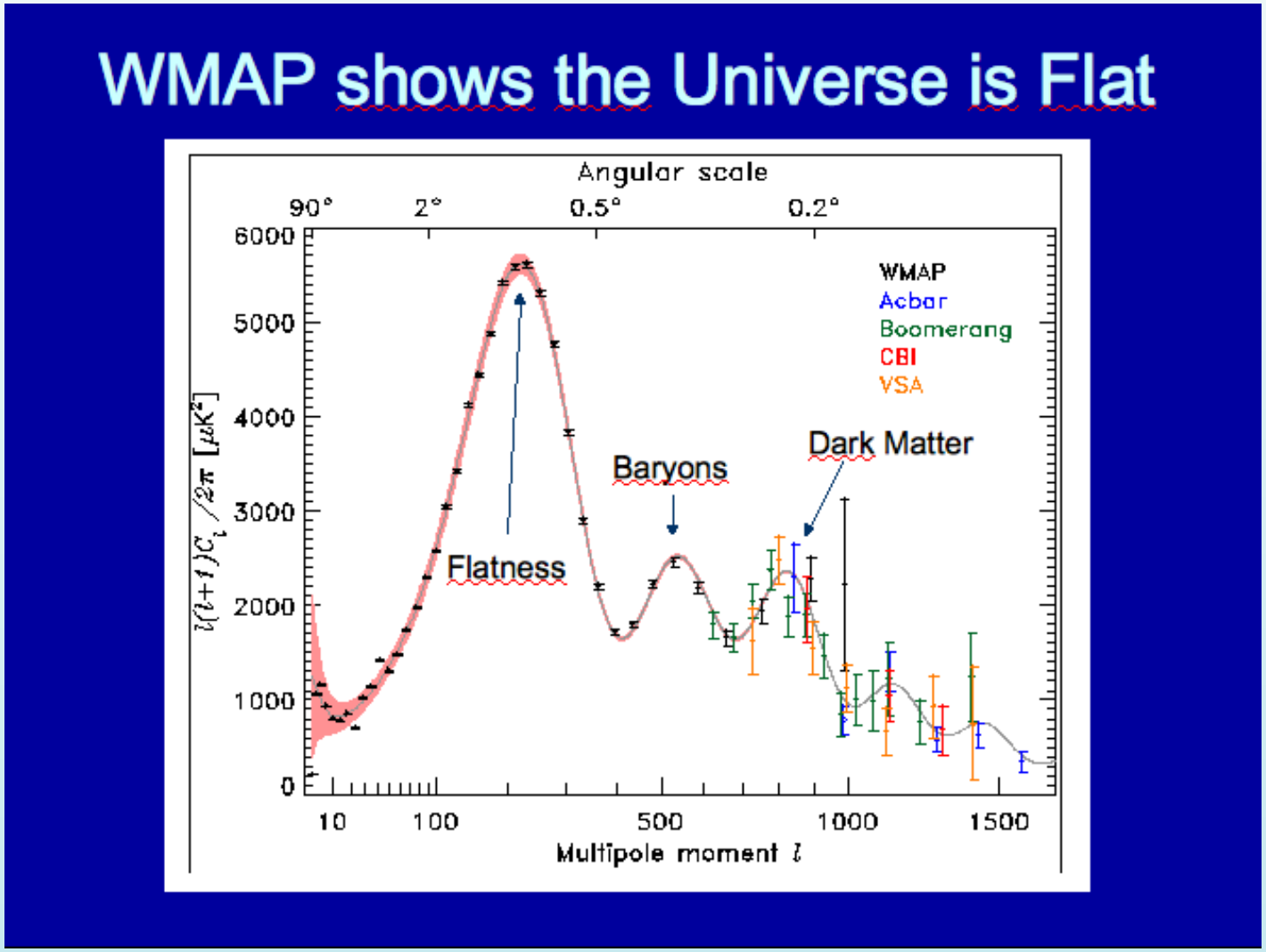
The Cosmic Microwave Background

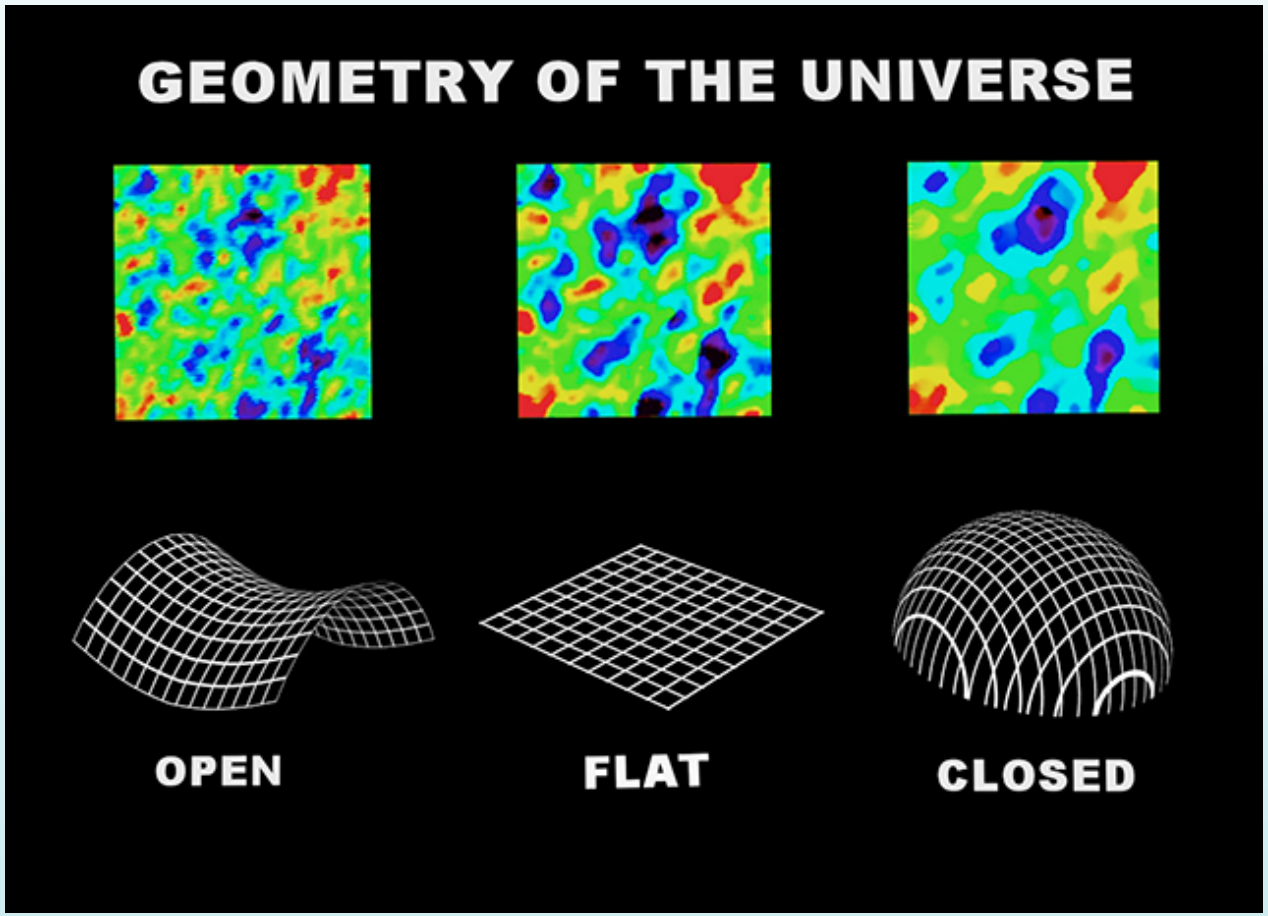
Cosmic black-body radiation of $3\ ^{\circ}\mathrm{K}$ Penzias, Wilson NP 1978

❒ The CMB fluctuation pattern: imprinted on the sky when the universe was just 380 000 years (after B.B.) old. Photons red-shifted by the expansion until the cannot ionize atoms (Hydrogen) any longer (snapshot of surface of last scattering). Smoot, Mather, NP 2006

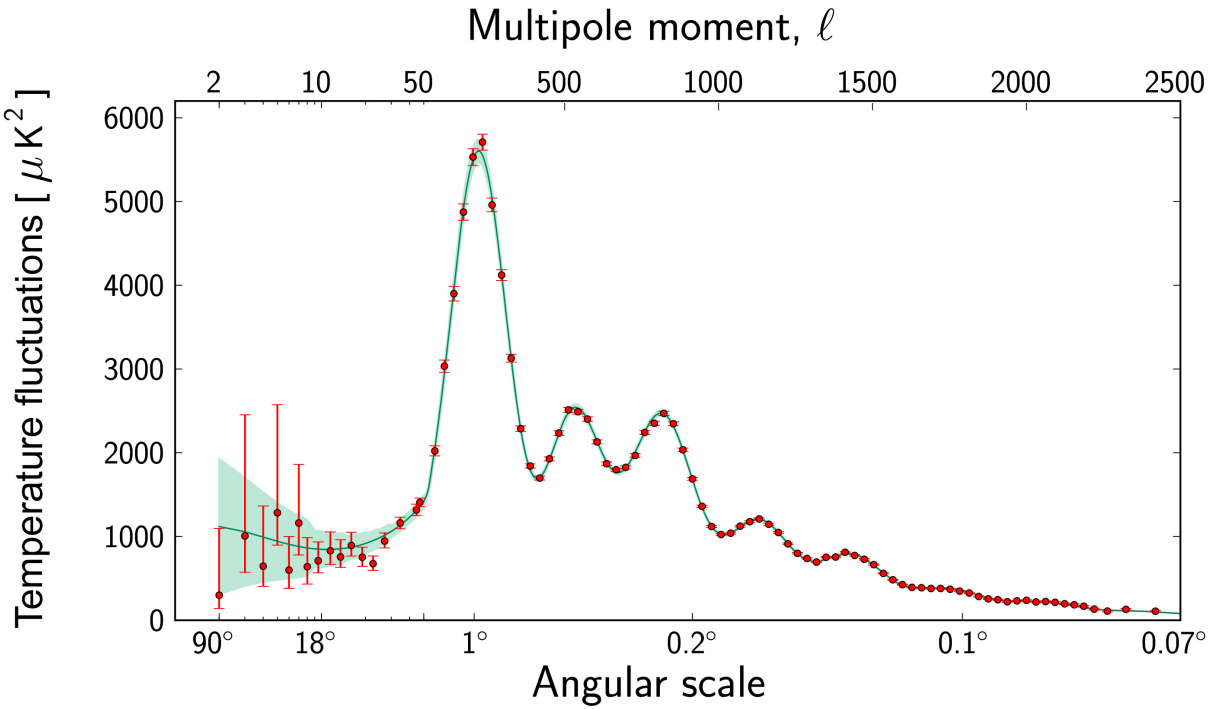


- The power spectrum: (the acoustic peaks)



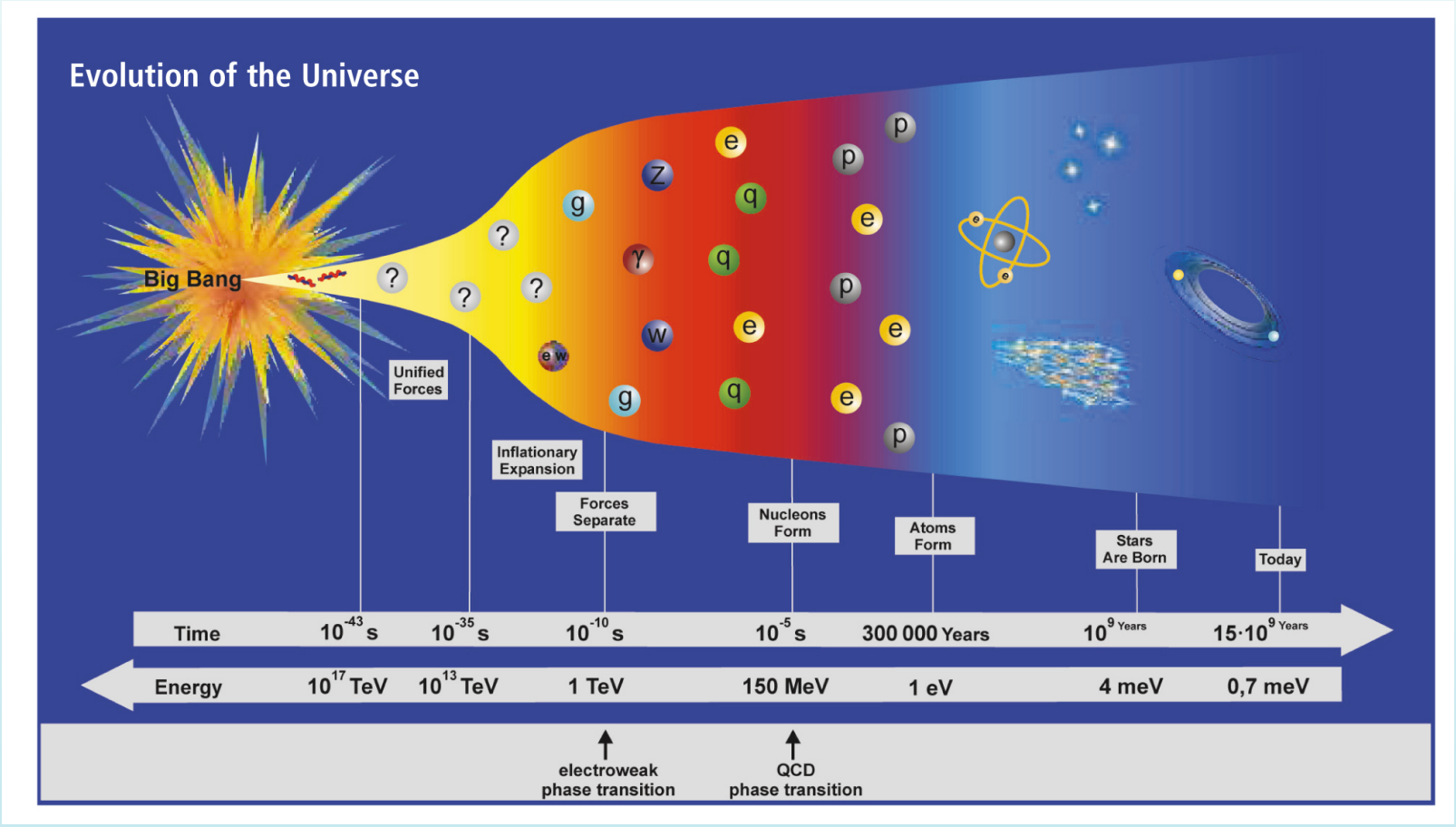


❒ The PLANCK mission power spectrum:


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μ K^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Inflation

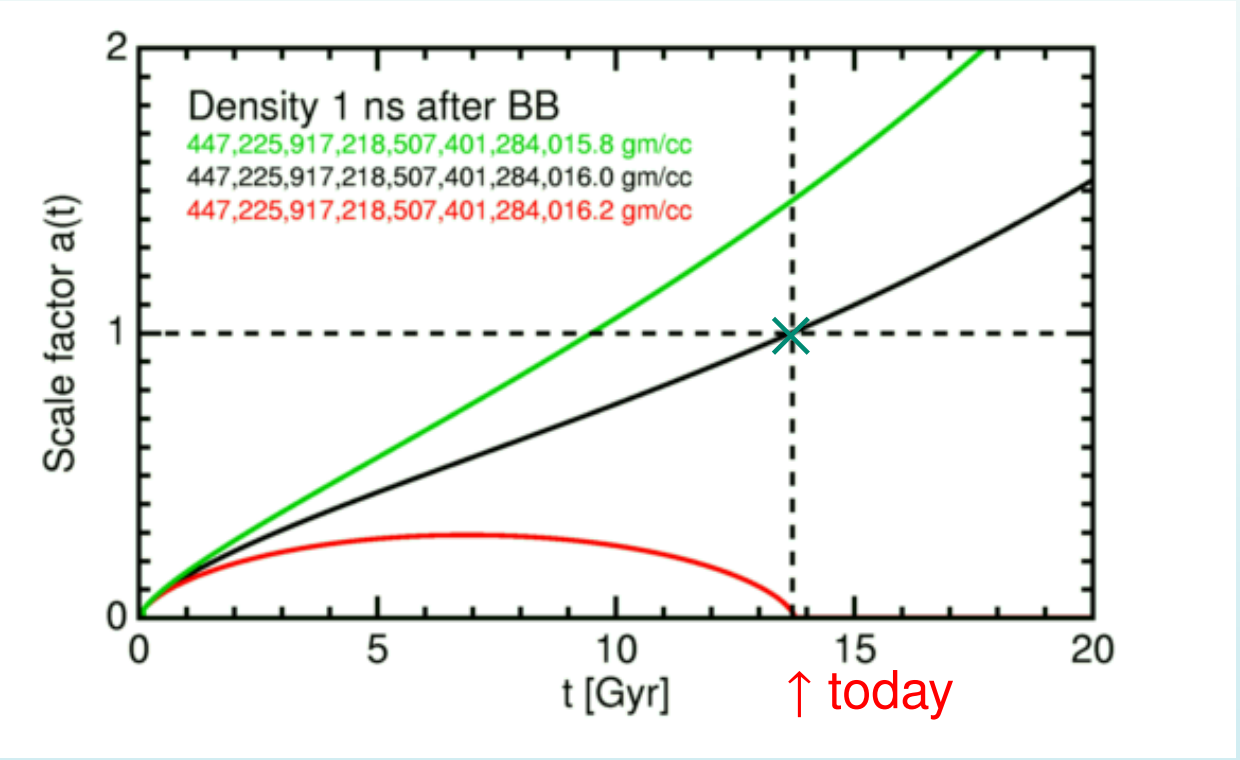
Need inflation! universe must blow up exponentially for a very short period, such that we see it to be flat!



Solves:

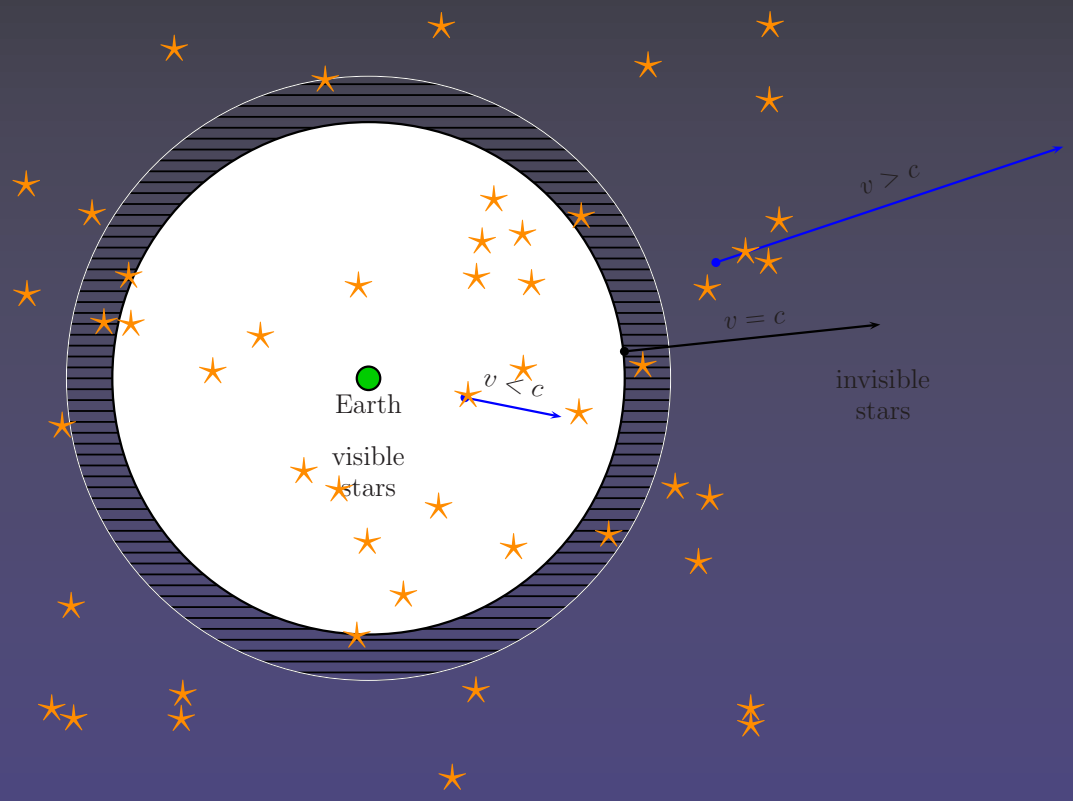
- Flatness problem
- Horizon problem: what does it mean homogeneous isotropic for causally disconnected parts of the universe? Initial value problem required initial data on space-like plane. Data on space-like plane are causally uncorrelated! Is initial value problem adequate at all to understand evolution of universe?
- Problem of fluctuations: magnitude, various components (dark matter, baryons, photons, neutrinos) related: same fractional perturbations.

Flatness problem: observed today: (COBE,WMAP) $\Omega_{\rm tot} = 1.02 \pm 0.02$



Flat space instable against perturbations: shown here initial data agree to 24 digits! CMB data say we life in flat space!

$$\frac{|\Omega_{\rm tot}(t)-1|_{\rm Pl}}{|\Omega_{\rm tot}(t)-1|_0} = \frac{a^2(t_{\rm Pl})}{a_0^2} \simeq \frac{T_0^2}{T_{\rm Pl}^2} \sim \mathcal{O}(10^{60})$$



The universe shows a horizon: recession velocity c ; $D_{\max} = c\,t_0 = \frac{c}{H_0} \simeq 4.23$ Gpc

Flatness, Causality, primordial Fluctuations $\Rightarrow$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" : $\Rightarrow$inflation term

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

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

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

$$\Rightarrow \quad \| \quad N\equiv \ln\frac{a_{\rm end}}{a_{\rm initial}} = H\,(t_e-t_i)$$

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

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 ➠ $w \to -1$

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

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

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

- 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 $\Rightarrow$first order phase transition
- ❖ vacuum jumps from $v = 0$ to $v \neq 0$

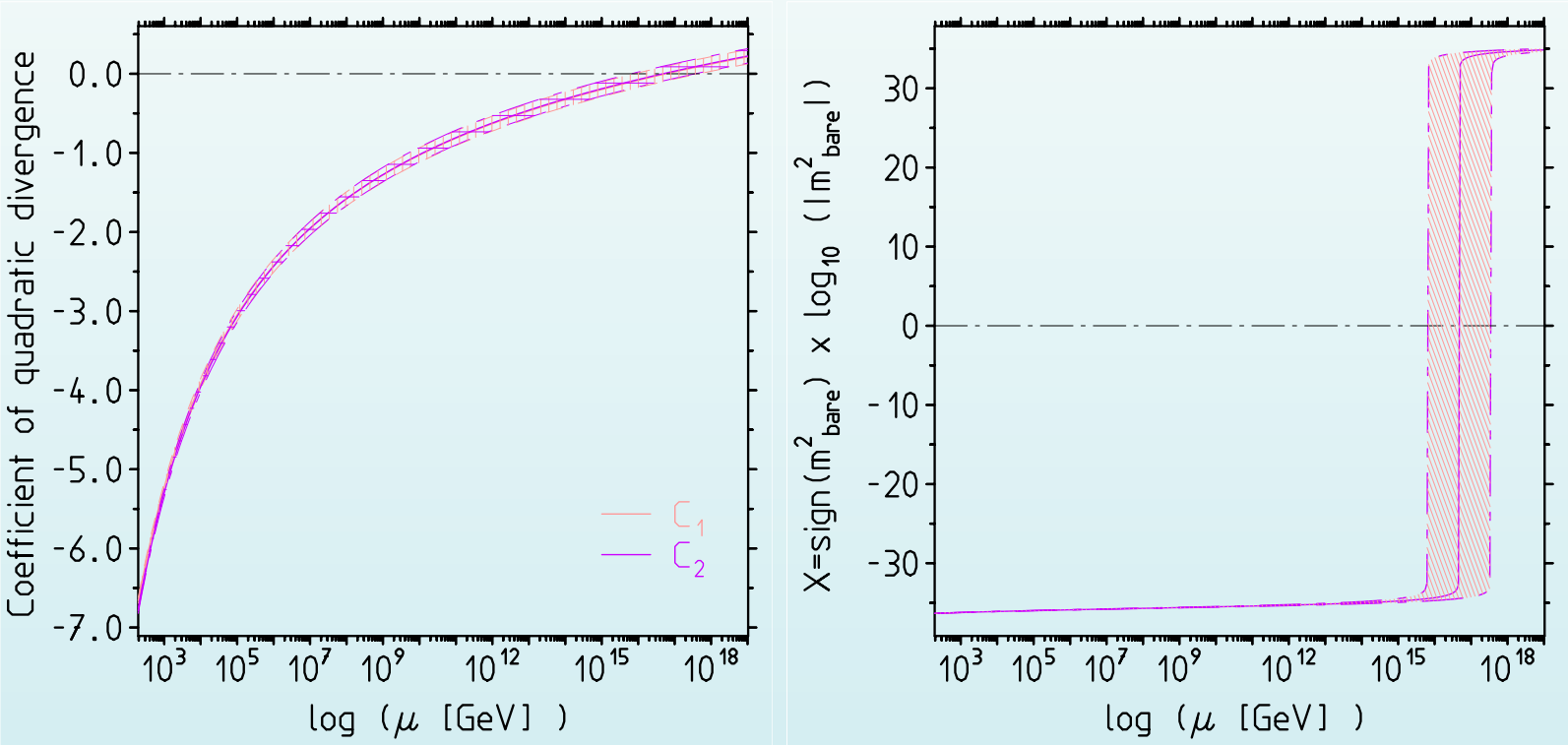
The issue of quadratic divergences in the SM

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

$$C_1 = \frac{6}{v^2}(M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\,\lambda + \frac{3}{2}\,g'^2 + \frac{9}{2}\,g^2 - 12\,y_t^2$$

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

- 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 $\mu_0 \sim 1.4 \times 10^{16}$, 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 $v_{\rm bare} = v(\mu_0^2)$,

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:

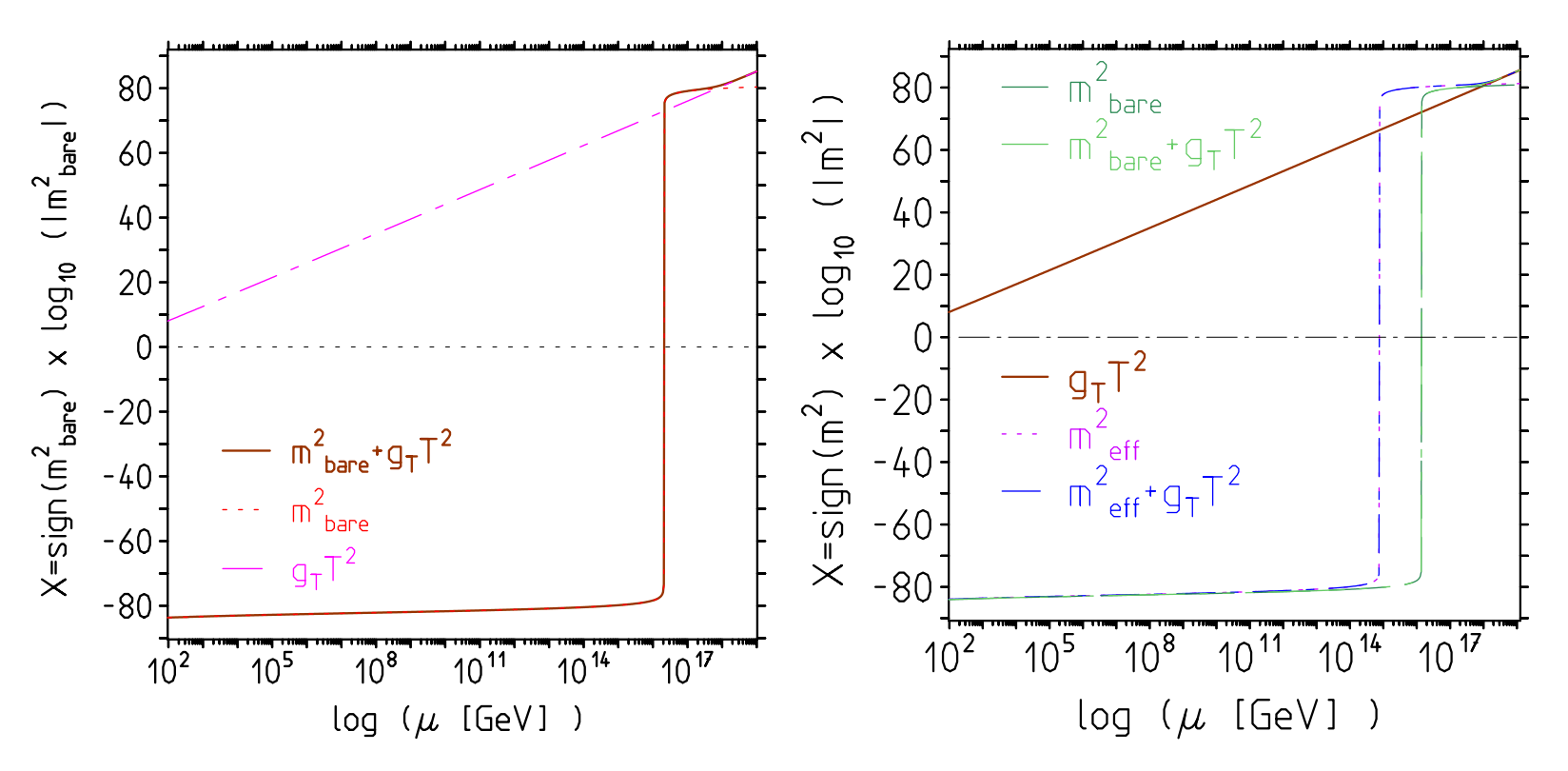
❒ finite temperature effective potential $V(\phi, T)$:

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

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

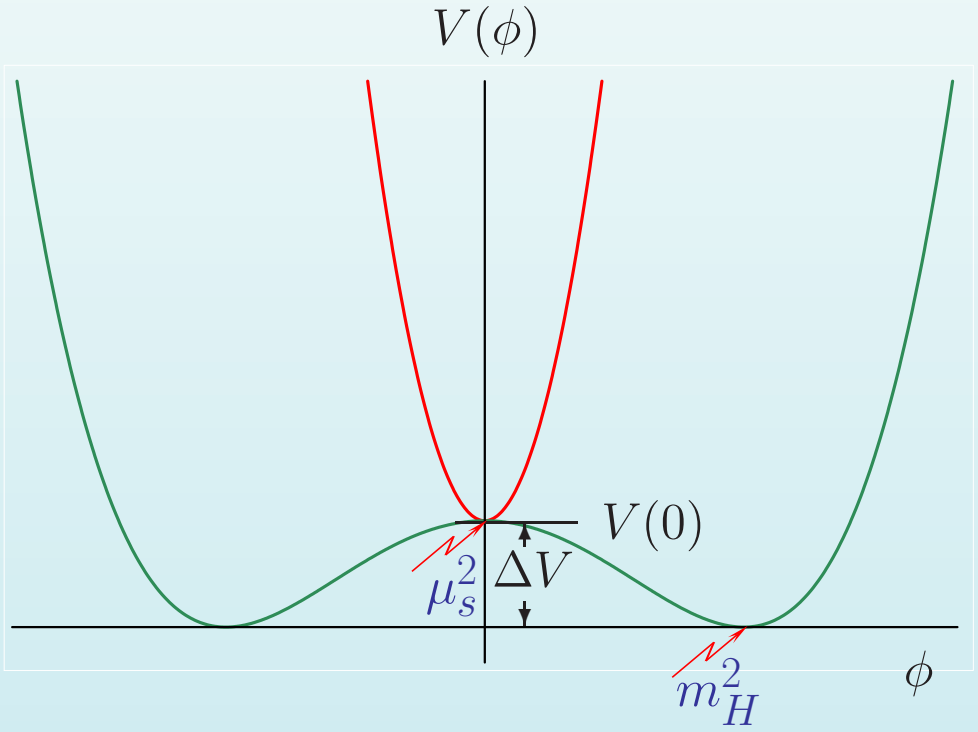
EW phase transition is taking place when the universe is cooling down below the critical temperature $T_c = \sqrt{\mu^2/g_T}$.

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



Effect of finite temperature on the phase transition: bare $[m^2, C_1]$ vs effective $[m'^2, C_1' = C_1 + \lambda]$

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



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

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

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

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

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

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

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

- fluctuation field eq. $3H\dot{\phi} \approx -(m'^2 + \frac{\lambda}{6}\phi^2)\,\phi$, ϕ decays exponentially, must have been very large in the early phase of inflation
- we adopt $\phi_0 \approx 4.51 M_{\rm Pl}$, big enough to provide sufficient inflation
- $V(0)$ very weakly scale dependent (running couplings): how to get ride of?
- intriguing structure again: the effective CC counterterm has a zero, which again is a point where renormalized and bare quantities are in agreement:

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

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

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

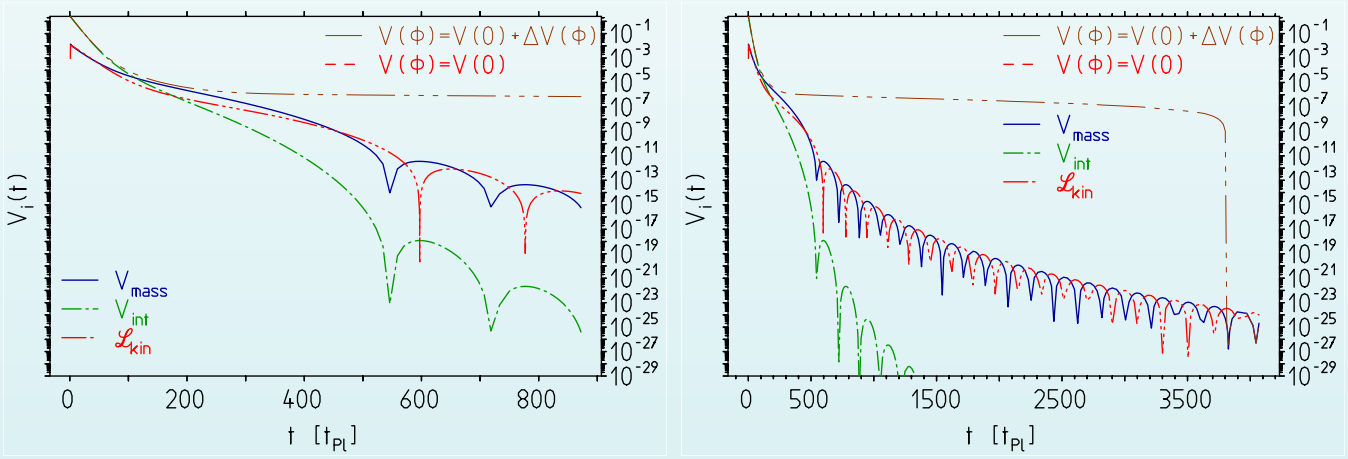
➠ Higgs potential provides huge dark energy in early universe which triggers inflation

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:



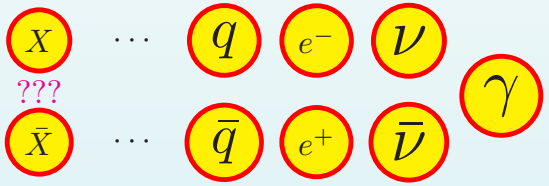
The mass-, interaction- and kinetic-term of the bare Lagrangian in units of $M_{\rm Pl}^4$ as a function of time. Left: the relative contributions when proper running of SM couplings is taken into account. The mass term is dominating in the range $t \simeq 100$ to $450\, t_{\rm Pl}$, where the slow-roll era ends and damped quasi-free field oscillations start. Right: After inflation the scene is characterized by a free damped harmonic oscillator behavior. Relevant scales are $\mu_0 \simeq 1.4 \times 10^{16} \Leftrightarrow t \simeq 870 M_{\rm Pl}^{-1}$ at the zero of $m^2_{\rm bare} - m^2_{\rm ren} = 0$, $\mu_{\rm CC} \simeq 3.1 \times 10^{15} \Leftrightarrow t \simeq 4000 M_{\rm Pl}^{-1}$ where $\rho_{\Lambda\,\rm bare} = \rho_{\Lambda\,\rm ren}$ and $\mu_0' \simeq 7.7 \times 10^{14} \Leftrightarrow t \simeq 15844 M_{\rm Pl}^{-1}$ the true Higgs transition point $m'^2 = 0$.

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"

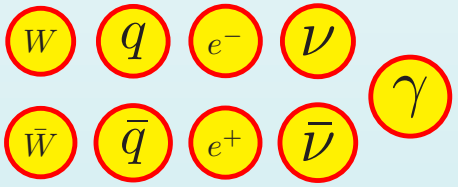
10^{-35} sec.



$X, \bar{X}$–Decay: $\Rightarrow$

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

10^{-30} sec.

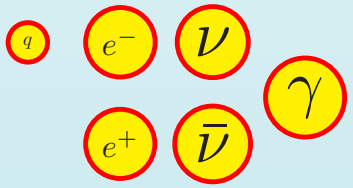


0.3×10^{-10} sec.

LEP events

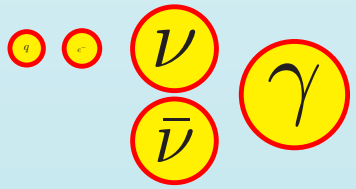
$q\bar{q} \to \gamma\gamma$:

10^{-4} sec.



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

1 sec.



$\Leftarrow$ 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

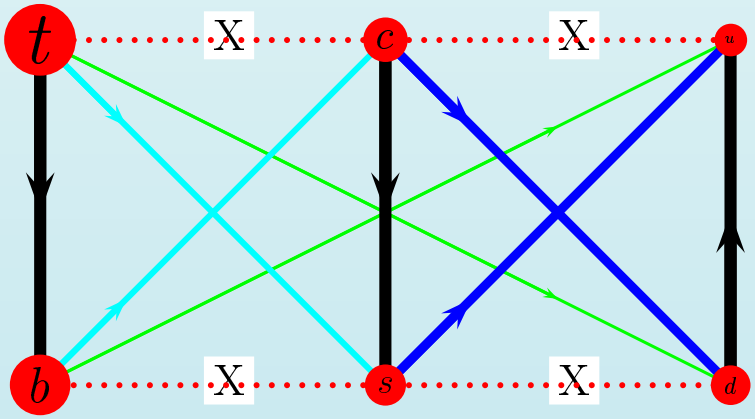
All relevant properties known: mass, width, branching fractions, CP violation properties!

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

❒ $H \approx \Gamma_X$ and $k_B T < m_X \Rightarrow$X-production suppressed, out of equilibrium

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

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



Higgses decay into heavy quarks afterwards decaying into light ones

Seems we are all descendants of four heavy Higgses!

Baryogenesis most likely a SM effect!

What about the hierarchy problem?

- In the Higgs phase:

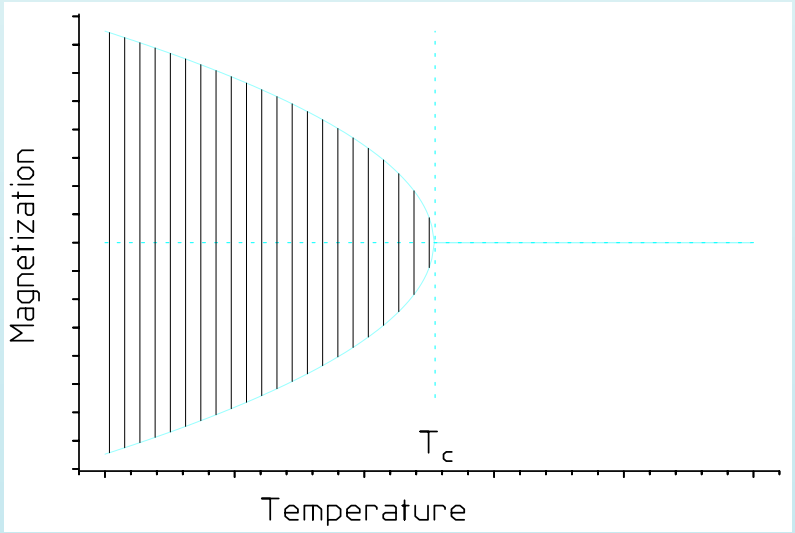
There is no hierarchy problem in the SM!

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

$$
\begin{aligned}
m_W^2(\mu) &= \frac{1}{4} g^2(\mu)\, v^2(\mu)\ ; \quad m_Z^2(\mu) = \frac{1}{4}\left(g^2(\mu) + g'^2(\mu)\right) v^2(\mu)\ ; \\
m_f^2(\mu) &= \frac{1}{2} y_f^2(\mu)\, v^2(\mu)\ ; \quad m_H^2(\mu) = \frac{1}{3} \lambda(\mu)\, v^2(\mu)\ .
\end{aligned}
$$

- 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.
- 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 $T \overset{\to}{<} T_c$

- $v/M_{\rm Pl} \ll 1$ 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

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

eliminates fine-tuning problem at all scales!

Many example in condensed matter systems.

Conclusion

- Higgs not just the Higgs: its mass $M_H = 125.9 \pm 0.4$ GeV has a very peculiar value!!

➠ 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

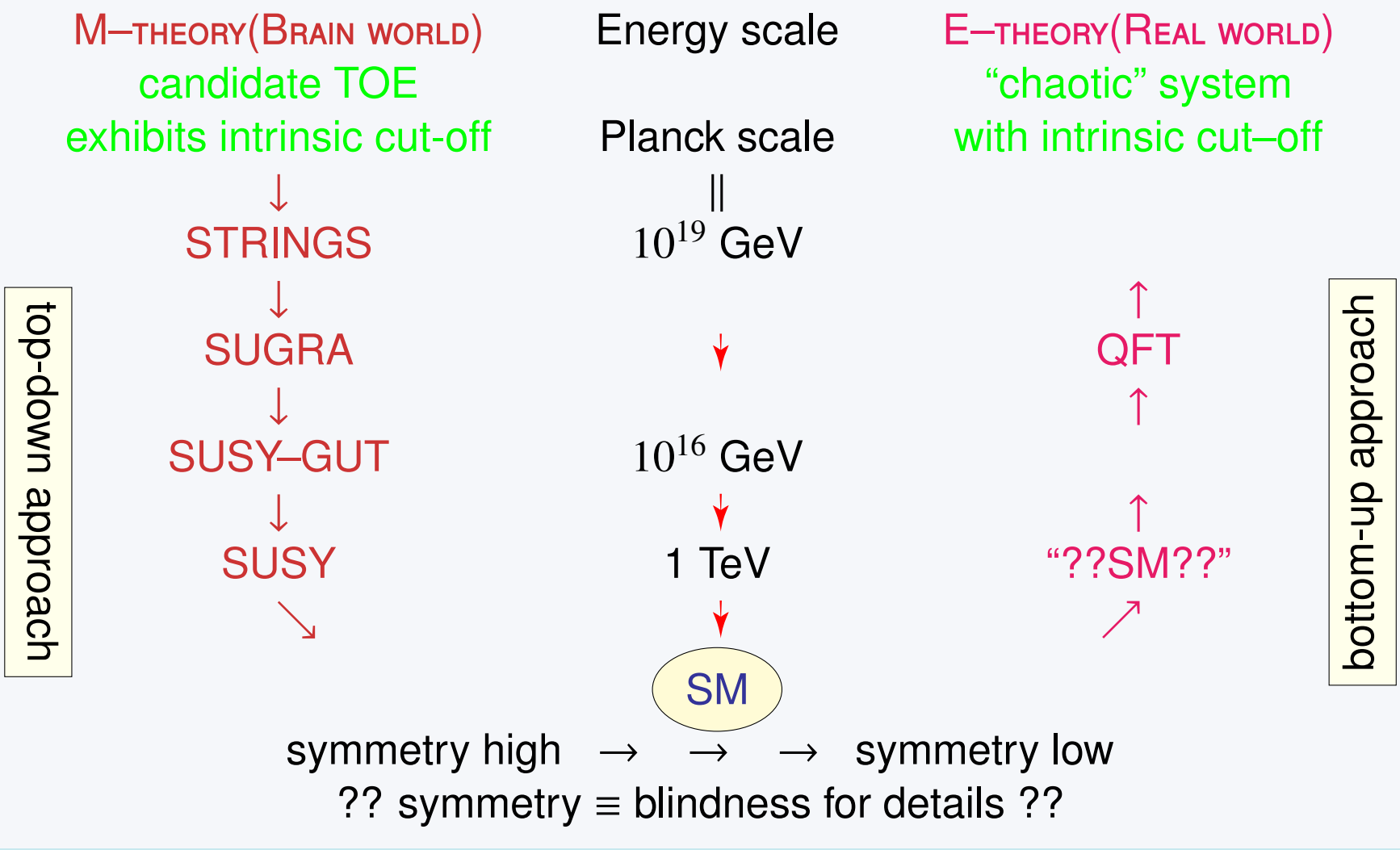
➠ SM as a low energy effective theory of some cutoff system at $M_{\rm Pl}$ consolidated; crucial point $M_{\rm Pl} >>>>$ ... from what we can see!

➠ change in paradigm:

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

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

Paths to Physics at the Planck Scale



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 the SM particles after the EW phase transition. For some time at and after the big bang the Higgs is the only particle which directly talks to gravity. It is the only SM particle which directly talks to the vacuum in the early universe (much later QCD phase transition also quark and gluon condensates). The Higgs is the one producing negative pressure and hence blowing continuously energy into the expanding universe. A lot yet to be understood!

- the big issue very delicate conspiracy between SM couplings:
  precision determination of parameters more important than ever $\Rightarrow$
  the challenge for LHC and ILC (λ, y_t and α_s),
  and for low energy hadron facilities for (hadronic effects in $\alpha(M_Z)$ and $\alpha_2(M_Z)$)

Thanks for your attention!