PARTICLE PHYSICS
IN THE
EARLY UNIVERSE

2021 / 2022

Lecture notes by Miha Nemevšek

- FIRST PART (COSMOLOGY) by Prof. Sašo Grozdanov
- [GUEST LECTURES by Dr. Lorenzo Ubaldi
  ↓
  not this year]

References and books

Of course, Weinberg's COSMOLOGY is one of the best books to dive into the topic. However, for the most part we will follow other references.

The newly updated

S. DODELSON, F. SCHMIDT : MODERN COSMOLOGY (2021)

provides a concise introduction to the relevant concepts in stat. mech.

When the experimental input is needed, we will use the freely available PDG reviews, in particular : PDG constants, astro - constants, cosmology (broad reading), Neutrinos, Dark matter, Big bang Nucleosynthesis, CMB. (DE is optional...)

For some topics, we draw from other recent lectures and courses, which I will cite as we go along, but they will include:

F. KAHLHOEFER's lectures on DM

J. CLINE, MORRISSEY on Baryogenesis

and papers on BBN:

BERNSTEIN, BROWN, FEINBERG '89

ESMAILDEH, STARKMAN, DIMOPOULOS '91.

PROGRAM / TOPICS

1) REVIEW OF THE SM / PARTICLE SIDE

2) REMINDER / NOTATION OF ΛCDM

3) EXPANDING UNIVERSE

4) STATISTICAL MECHANICS IN AN EXPANDING UNIVERSE (THERMODYNAMICAL QUANTITIES)

5) THE ENERGY BUDGET / CONTENT

6) EINSTEIN AND BOLTZMANN EQUATIONS

7) NEUTRINO DECOUPLING

8) RECOMBINATION

9) DARK MATTER
   - evidence, candidates, constraints
   - production (F-O, F-I, entropy dilution)
     freeze-out freeze-in
   - detection (indirect vs. direct)

10) BARYOGENESIS

⌜11) Big Bang Nucleosynthesis⌝ (time permitting)

$\boxed{\text{12) Axion DM}}$ in 9)

1) REVIEW OF THE STANDARD MODEL

1.1) INTERACTIONS AND PARTICLES

- gauge interactions : $\underset{\swarrow \atop \text{color, strong int.}}{SU(3)_c} \times \underset{\downarrow \atop \text{weak, chiral}}{SU(2)_L} \times \underset{\downarrow \atop \text{hypercharge, chiral}}{U(1)_Y}$

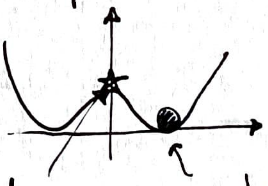
Each group has a coupling : g_3, g_2, g_1 and an associated gauge bosons : G_μ^a, A_μ^a, B_μ

$SU(3)_c$: G_μ^a ... gluons , $a = 1, \dots, n^2-1$ for $SU(n)$

$\rightarrow$ $a = 1, \dots, 8 = 8$ gluons

- $SU(3)_c$ is unbroken $m_g = 0$ but confining, so no free gluons, only mesons and baryons.

- $SU(2)_L \times U(1)_Y$ is spontaneously broken by the Higgs vacuum :



and not there where the symmetry remains intact.

we are here, in ● $\langle \varphi \rangle = v \neq 0$ the symmetry is broken.

- After breaking, we have: $\underbrace{W^{\pm}_{\mu},\ Z_{\mu}}_{\text{massive}},\ \underbrace{A_{\mu}}_{\text{massless}}$

- G^{a}_{μ} and A_{μ} (8 gluons and a photon) are massless $m_g = 0$, $m_A = 0$. They have two polarization (L, R or ↻, ↺) and therefore two degrees of freedom (d.o.f.s).

- Relativistic d.o.f. will be important to characterize the energy and entropy content of the plasma in the early universe: $n_g = 2\times 8 = 16$, $n_A = 2$.

- Massive gauge bosons have 3 d.o.f; $\underset{\overset{\uparrow}{\text{spin}}}{s} = 1$, $2s+1 = 3$

$$W^{\pm}, \quad n_W = \underset{\overset{\nearrow}{\text{charge}}}{2}\cdot\underset{\overset{\uparrow}{\text{spin}}}{3} = 6, \quad M_W = \frac{1}{2}g_2 v \simeq 80\ \text{GeV}$$

$$Z, \quad n_Z = 3, \quad M_Z = \frac{1}{c_W}M_W \simeq 90\ \text{GeV}$$

- Strength of interaction is set by $\alpha_i = \frac{g_i^2}{4\pi}$:

STRONG	WEAK	ELECTROMAGNETIC
$\alpha_s\Big\|_{\mu=M_Z} = \frac{g_3^2}{4\pi} = 0.118$,	$\alpha_W\Big\|_{\mu=M_Z} = \frac{g_2^2}{4\pi} = 0.033$,	$\alpha\Big\|_{\mu=0} = \frac{1}{137}$ ~

FERMIONS $s = \frac{1}{2}$, $2s+1 = 2$ d.o.f. / particle

$\psi = \psi_L + \psi_R$, contains particles and anti-particles

$\uparrow$ Dirac spinor

$\Downarrow$

$n_\psi = 4$ d.o.f.

LEPTONS : no $SU(3)_c$ charges , 3 generations

- $$L_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R$$

$Q(e,\mu,\tau) = 0$, $Q(\nu) = 0$, no ν_R in SM $\Rightarrow m_\nu \overset{SM}{=} 0$.

$m_e \simeq 0.5$ MeV , $m_\mu = 105$ MeV , $m_\tau \sim 1.8$ GeV

- Neutrinos : $m_{\nu_{1,2,3}}$ from : - oscillations $\begin{cases} \Delta m^2_{12} \sim 10^{-3} eV^2 \\ \Delta m^2_{23} \sim 10^{-5} eV^2 \end{cases}$
  - KATRIN $\searrow$ $m_{\nu_e} < 0.8$ eV ('21)
  - cosmology $\searrow$ $\sum_{i=1}^{3} m_{\nu_i} < 0.44$ eV

baryons & mesons
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HADRONS / QUARKS & GLUONS

- below GeV : $p, n, \pi^+, \pi^0, K, \eta, \rho, \dots$ while above $\Lambda_{QCD} \sim$ GeV
- above GeV : Q_L, q_R, g $\leftarrow$ gluons

QUARKS

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L ,$$

$$u_R \quad c_R \quad t_R ,$$

$$d_R \quad s_R \quad b_R ,$$

CHARGES

$$Q(u,c,t) = \frac{2}{3} , \quad Q(d,s,b) = -\frac{1}{3} .$$

$$m_u = 2\,\mathrm{MeV} , \quad m_c = 1.3\,\mathrm{GeV} , \quad m_t = 174\,\mathrm{GeV} ,$$

$$m_d = 5\,\mathrm{MeV} , \quad m_s = 93\,\mathrm{MeV} , \quad m_b = 4.2\,\mathrm{GeV} .$$

MASSES

- each quark carries three colors e.g. $u_{R,G,B}$

$$\Rightarrow \quad n_u = \underset{\text{color}}{3} \cdot \underset{\text{spin}}{2} \cdot \underset{\text{particle/antiparticle}}{2} = 12 .$$

- This counting makes sense at $T \gg \mathrm{GeV}$, when the universe is so hot that $q, \bar{q}$ & g exist.

- Below Λ_{QCD}, we get BARYONS : $p, n, \Lambda, \dots$ (qqq)

  and MESONS : $\pi, K, \eta, \rho, \dots$ $(q\bar{q})$

SCALARS In the SM, the only scalar particle is the complex $SU(2)_L$ doublet

$$\phi = \begin{pmatrix} G^+ \xrightarrow{} \text{charged would-b Goldston} \\ \frac{1}{\sqrt{2}}\left(\underset{\substack{\nearrow \\ \text{constant} \\ \text{vev}}}{v} + \underset{\substack{\uparrow \\ \text{Higgs}}}{h} + i\,\underset{\substack{\uparrow \\ \text{neutral} \\ \text{would-be-Goldst}}}{G^0}\right) \end{pmatrix}$$

$S = 0$

- $v = 246$ GeV is the constant vacuum expectation value
- $G^\pm$ and G^0 are longitudinal d.of.s already counted in $W^\pm$ and Z, their masses are unphysical, gauge dependent.
- h is the Higgs, the only physical, propagating state, $2S+1 = 2\cdot 0+1 = 1$,

  $Q(h) = 0$, $m_h = 125$ GeV.

- Chirality of $SU(2)_L$: weak interactions couple only to ν_L, or to the ψ_L part of the Dirac spinor. Thus only $n_\nu = 2$ per generation will interact with W and Z and thermalize.