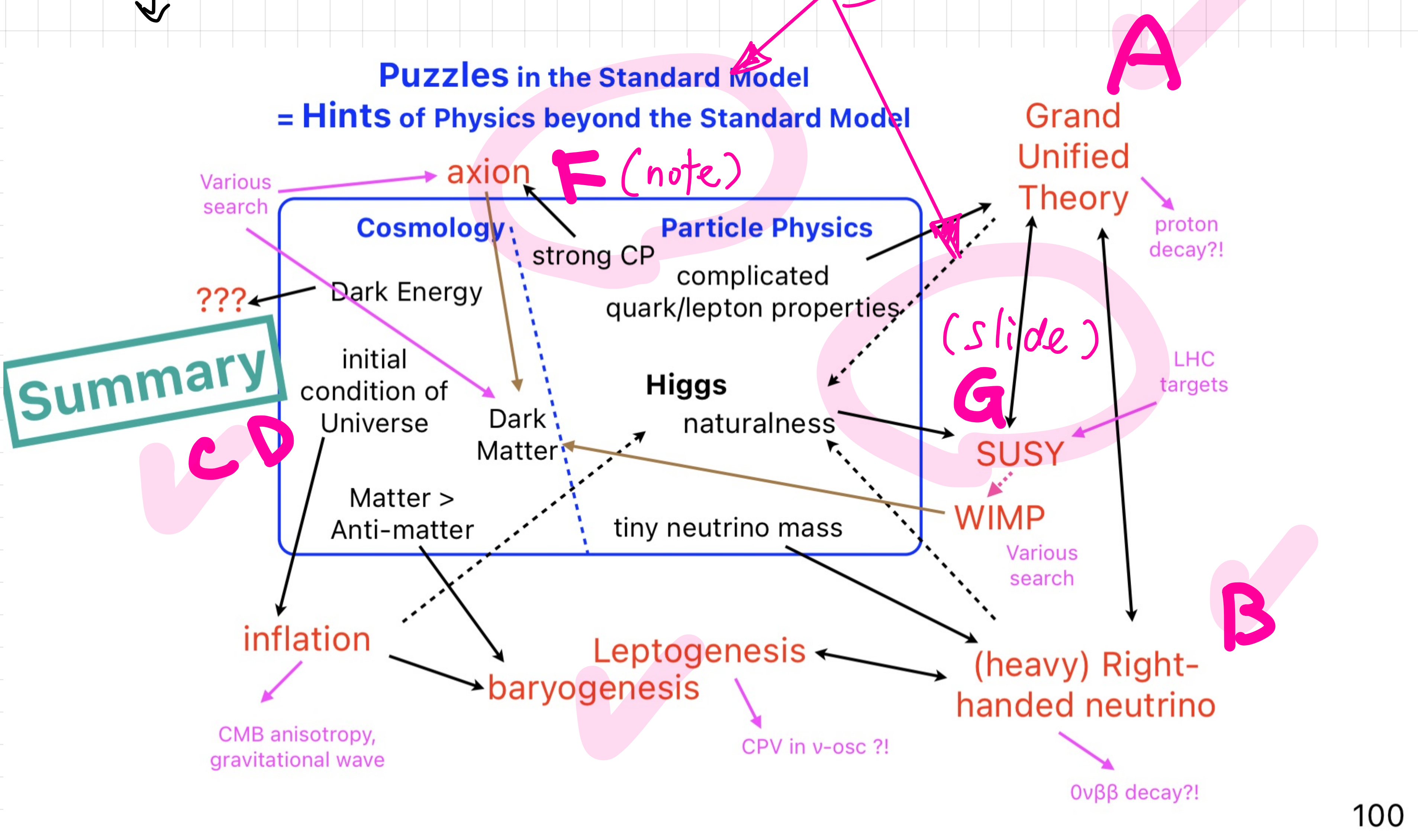
Informal lectures on BSM physics (day 5)

2021.9.28

Summary of Part I.

today



F. axion

§ F-1 strong CP problem

QCD

dim.-less para.

$$\mathcal{L} = \bar{\psi}_q (i\not{D} - m_q)\psi_q - \frac{1}{4} F^{a\mu\nu} F_{a\mu\nu} - \frac{g^2}{32\pi^2} \theta \tilde{F}^{a\mu\nu} F^a_{\mu\nu}$$

$$m_q = y_q \langle H \rangle$$

$$\left(\tilde{F}^{a\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} \qquad \epsilon^{0123} = 1 \right)$$

In general

$$\sum_{q=u,d} \sum_{i,j=1}^{3} \bar{\psi}_{qi} \underbrace{(m_q)_{ij}}_{3\times 3 \text{ matrix}} \psi_{qj} \xRightarrow[\text{redef}]{\text{fld}} \sum_{q=u,d} \sum_{i=1}^{3} \bar{\psi}_{qi} \underbrace{m_{qi}}_{\text{diagonal mass}} \psi_{qi}$$

through anomaly

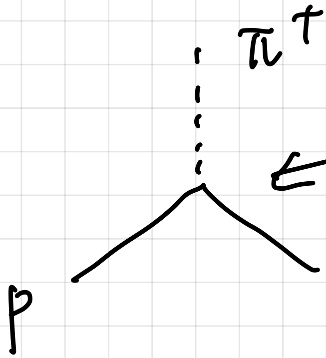
$$\theta \longrightarrow \underbrace{\theta + \arg(\det . m_q)}_{\text{observable}}$$

$\longrightarrow$ just θ. in the following

$\mathcal{L}_{QCD}$ depends on θ.

$\downarrow$ effective theory for hadrons

$\underline{\mathcal{L}_{chiral}}$ also depends on θ.
$(\pi \ p \ n)$



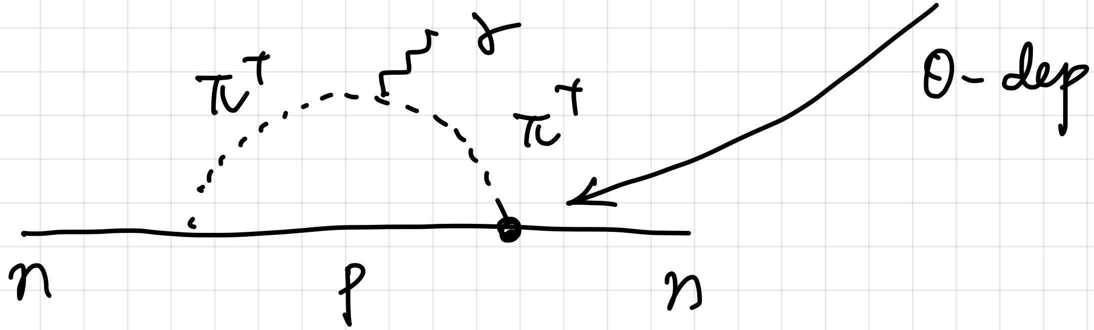
$\leftarrow$ θ-dependence

$$\tilde{m} = \frac{m_u m_d}{m_u + m_d}$$

(Srednicki Sec. 94)

$O(1)$

$$\mathcal{L}_{\pi \bar{N} N} = -i\sqrt{2}\, \pi^+ \bar{p} \left(\frac{g_A m_N}{f_\pi} \gamma_5 - i \frac{c\, \theta\, \tilde{m}}{f_\pi} \right) n$$



$\longrightarrow$ neutron electric dipole moment (EDM)

$$\underline{d_n = 3.2\times 10^{-16}\,\theta \cdot e\,\mathrm{cm}}$$

experiment $\quad \underline{|d_n| < 3\times 10^{-26}\ e\,\mathrm{cm}}$

$$\Rightarrow \boxed{|\theta| \lesssim 10^{-10}}$$

$$\theta = \theta_{(\text{org})} + \arg(\underbrace{\det M}_{\text{weak CP phase}})$$

Two terms cancel

Why so small?

Strong CP problem

fine-tuning

§ f-2 axion

strong CP problem can be solved by Peccei-Quinn mechanism

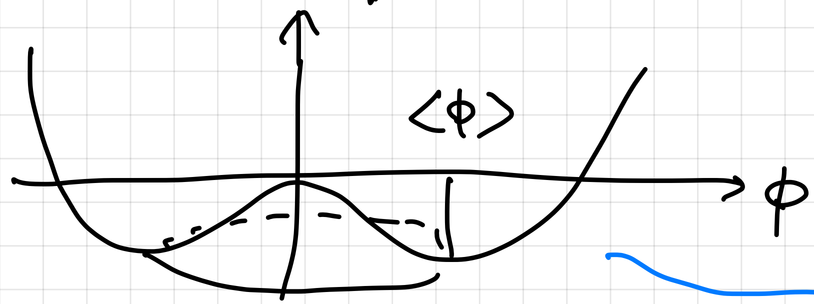
↳ predicts light scalar "axion"

KSVZ-axion example

$$\mathcal{L} = |\partial_\mu \phi|^2 - V(|\phi|) - (y \phi Q_1 Q_2 + h.c.)$$

complex scalar

new quarks having color charges (Weyl rep)



NG-boson

$$\phi = \langle \phi \rangle e^{ia/f}$$

▶ U(1) sym. $U(1)_{PQ}$ $\begin{cases} Q_1 \to e^{i\alpha} Q_1 \\ Q_2 \to e^{i\alpha} Q_2 \\ \phi \to e^{-2i\alpha} \phi \end{cases}$

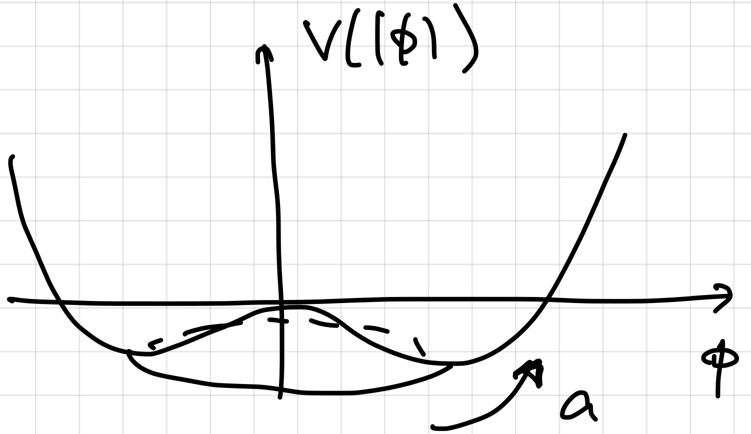
$\longrightarrow$ spontaneous sym. breaking

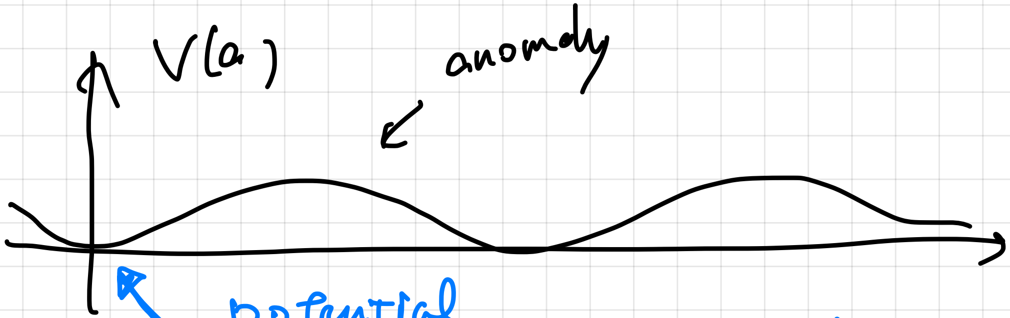
$\longrightarrow$ massless NG-boson

▶ But $U(1)_{PQ}$ is anomalous

QCD anomaly breaks $U(1)_{PQ}$

$\longrightarrow$ NG-boson has a potential.
(axion)





potential minimum corresponds to $\theta = 0$

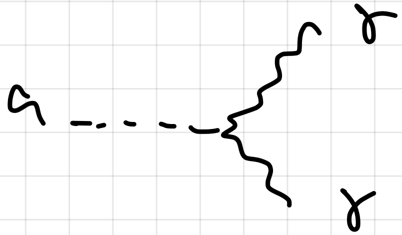
$\theta F\tilde{F}$

$\Downarrow$

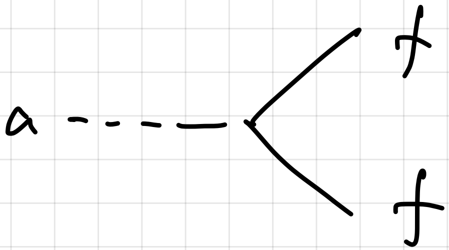
$\frac{a}{f_a} F\tilde{F}$

$\boxed{\text{Strong CP problem is solved}}$

▶ axion – SM particle couplings: $f_a = \sqrt{2}\langle\phi\rangle$



$\sim \overset{O(1)}{c} \frac{e^2}{32\pi^2} \frac{a}{f_a} F_{\mu\nu}F^{\mu\nu}$ photon



$\sim c \frac{m_f}{f_\pi} a \bar{\psi} \gamma_5 \psi$

$\underline{\mathcal{O}(10^8\,\mathrm{GeV})} \lesssim f_a \lesssim \underline{\mathcal{O}(10^{12}\,\mathrm{GeV})}$

- SN 1987A
- NS cooling

axion DM abundance

axion is VERY weekly interacting

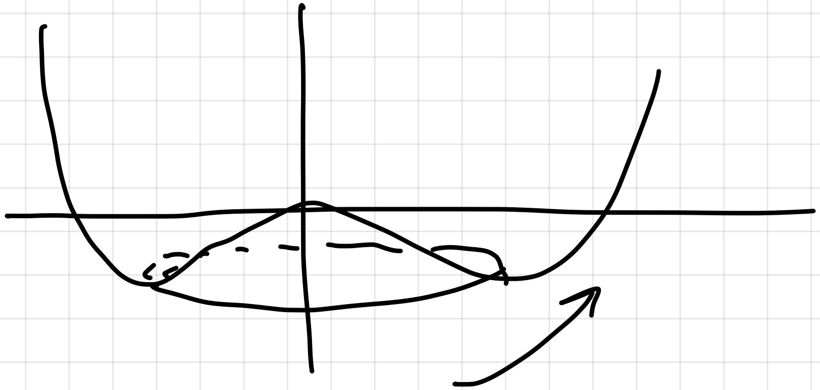
▶ axion mass

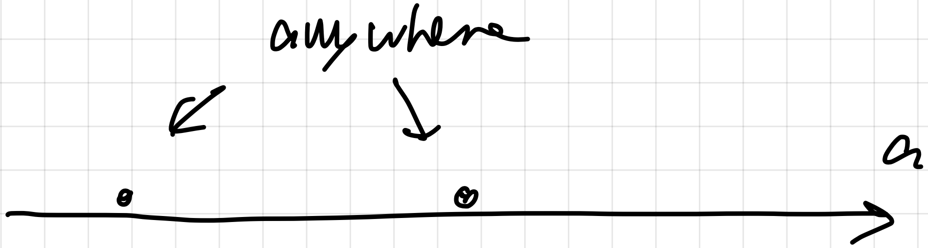
$$\underline{m_a \simeq 6 \times 10^{-4}\,\mathrm{eV} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)}$$

VERY light

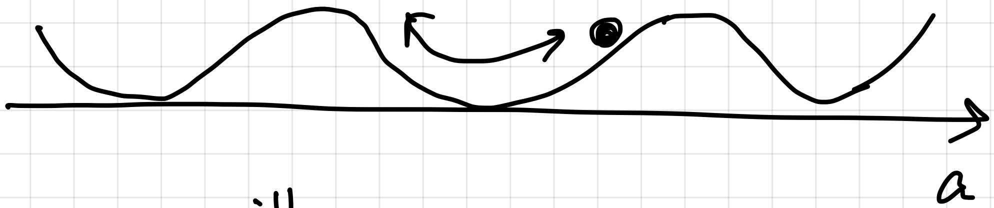
§ F-3 axion DM

▶ before QCD phase transition ($T \gg \mathrm{GeV}$)





▷ after QCD PT



coherent oscillation

$$a(t, \vec{x}) \simeq a(t) \simeq a_0 \cos(m_a t)$$

$$\left[\begin{array}{l} \text{amplitude} \\ a_0 \propto \underset{\text{factor}}{a_{\text{scale}}}(t)^{-3/2} \end{array} \right]$$

energy density

$$\rho_a \propto \underset{\text{factor}}{a_{\text{scale}}}(t)^{-3}$$ like DM.

[remark other contributions to DM exist.

axion e.g axion ← U(1)pq string]

BREAK

13:55 ~

SUSY