Domain walls

- $\boxed{RT = \text{const} = 10^{30}}$

$$ds^2 = R^2(t)\, d\vec{x}^2$$

$$H = \dot{R}/R = \frac{1}{t}$$

$\boxed{\pi = 4 = 1}$

$$\underbrace{R^3 T^3} = 10^{90}$$

$$n\,(\text{density}) = T^3 \quad (T \gg m)$$

$$V = R^3$$

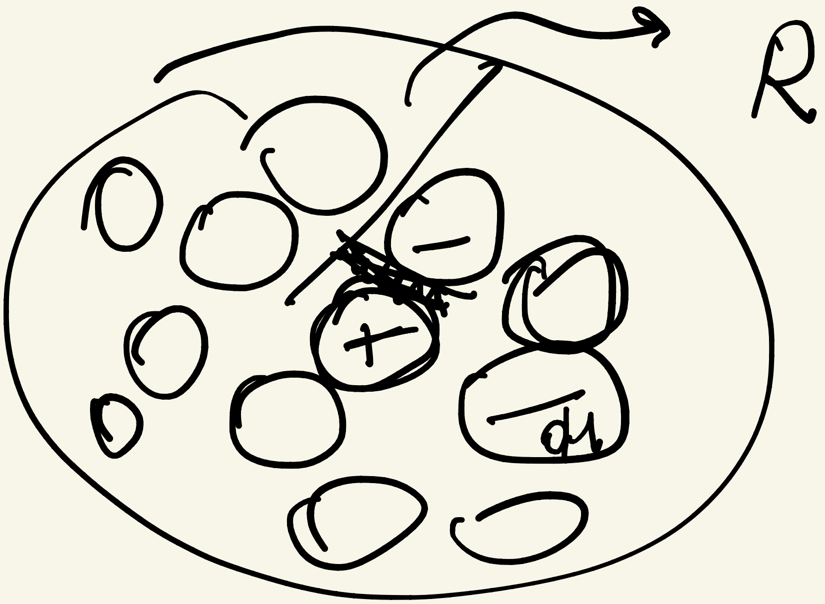
$$\boxed{R^3 T^3 = N} = \text{entropy}$$

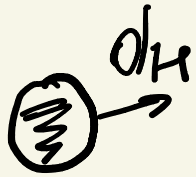
- $R = \frac{10^{30}}{T}$ = scale of universe

- $d_H = t = \frac{1}{T} \cdot \left(\frac{M_{pe}}{T} \right)$

$$\Downarrow$$

$$\boxed{R(T)/d_H(T) \gg 1 \quad T \gg m_e}$$





$\longrightarrow$ exponential growth (inflation)

Symmetries at high T

Dvali, G.S.

Is there a domain wall theorem?

Rochelle salt

Weinberg '74

High T

$$\boxed{\text{Gravity and domain wall}}$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G\, T_{\mu\nu}$$

$$\Downarrow$$

$$\boxed{R_{\mu\nu} = -8\pi G \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)}$$

$$\Downarrow$$

$\boxed{T \equiv T^{\mu}_{\mu}}$

$\eta_{\mu\nu}$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

field

Lorentz metric

$$\eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$$

$$h_{00} = 2\phi$$

$$\Box \phi \propto \left(T_{00} - \frac{1}{2} \eta_{00} T \right)$$

Newton : $T_{00} = \rho$

$$\boxed{\rho > 0 \iff \text{gravity} = \text{attractive}}$$

$$\boxed{T_{00} = \rho, \quad T_{ii} = p_i}$$

<u>earth</u> $\quad p_i = 0$

$\boxed{\text{domain wall (static)}}$

$$\boxed{T_{\mu\nu} = -\mathcal{L} g_{\mu\nu} + \partial_\mu \phi \frac{\partial \mathcal{L}}{\partial(\partial_\nu \phi)}}$$

translations

[conserved energy-momentum]

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$

$$\Downarrow$$

$$\boxed{T_{\mu\nu} = -\mathcal{L} \eta_{\mu\nu} + \partial_\mu \phi \partial_\nu \phi}$$

$\phi_{\text{wall}}(z)$

(x-y) plane

$$T_{00} = -\mathcal{L} + (\partial_0 \phi)^2 = -\mathcal{L}$$

$$T_{11} = +\mathcal{L} + (\partial_x \phi_w)^2 = +\mathcal{L}$$

$$T_{22} = +\mathcal{L} + (\partial_y \phi_w)^2 = +\mathcal{L}$$

$$\boxed{T_{33} = \mathcal{L} + (\partial_z \phi_w)^2 = \underbrace{\frac{1}{2}\left(\frac{d\phi_w}{dz}\right)^2 - V}_{\text{well solution}} = 0}$$

$$\boxed{\begin{aligned} T_{00} &= \frac{1}{2}\left(\frac{d\phi_W}{dt}\right)^2 + V = 2V \\ &\equiv \rho \\ T_{11} &= T_{22} = -\rho \end{aligned}}$$

$$\nabla^2 \phi \propto \left(T_{00} - \frac{1}{2} T\right)$$

$$T = T^0_0 + T^1_1 + T^2_2 + T^3_3$$

$$= \rho + \rho + \rho = 3\rho$$

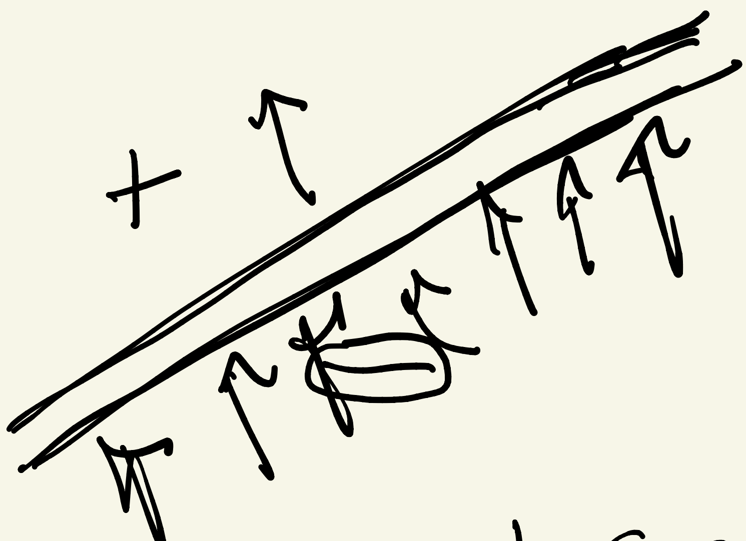
$$T^1_1 = -T_{11}$$

$$T^2_2 = -T_{22}$$

$$\Downarrow$$

$$\boxed{\nabla^2\phi \propto \left(\rho - \tfrac{1}{2}3p\right) = -\rho}$$

$$\boxed{\text{"anti-gravity"}}$$



$$\boxed{\text{Rai, G.S. '94}}$$

$$V = \frac{1}{4}\left(\phi^2 - v^2\right)^2 + \frac{\phi^5}{M_{pe}}$$

$\epsilon\, v^3 \phi$

$\phi \simeq v$

?

$\epsilon v^4 \longleftrightarrow v^5/M_{Pl}$

$\varepsilon \simeq v/M_{Pl}$ $\quad v = 1\,\text{TeV} = 10^3\,\text{GeV}$

10^{-15}

$\boxed{\begin{array}{l} G_N \to 0 \\ M \to \infty \end{array}}$

$\boxed{\text{Hawking}}$

$\boxed{R_s = G_N M = \text{finite}}$

$\|$

N (graviton) $\Longleftrightarrow N \to \infty$

$1/N$

$\varepsilon \simeq 10^{-30}$!

coupling

$$\boxed{\mathbb{Z}_2: \quad \phi \longrightarrow -\phi}$$

$$P: \quad \boxed{\begin{array}{c} \Delta_L \longleftrightarrow \Delta_R \\ \\ \Delta_L - \Delta_R \equiv \phi \end{array}}$$

$\boxed{CP:}$

$$\psi_L \xrightarrow{P} \psi_R$$

$$\psi_L \xrightarrow{C} C\,\overline{\psi_R}^T$$

$$\Rightarrow \boxed{\psi_L \longrightarrow C\,\overline{\psi_L}^T}$$

$$\Downarrow$$

SM: $\cancel{P, C}$ maximally broken

$W_\mu J^\mu_L$ (NO RH)

$\boxed{\cancel{CP} \text{ spont.?}}$

T.D. Lee '73

$x\, W^+_\mu \bar{u}_L \gamma^\mu d_L + x^* W^-_\mu \bar{d}_L \gamma^\mu u_L$

$CPL \longrightarrow x\, \bar{d}_L \gamma^\mu u_L\, W^-_\mu$

$$\boxed{\cancel{CP} \iff x = x^*}$$

$\boxed{x \in \mathbb{C} \text{ in SM?}}$

$M_q = U^+_{Lq}\, m_q\, U_{Rq}$

$$V_{CKM} = U_{Lu}^{\dagger} U_{Ld} \in \mathbb{C}$$

$$\Leftrightarrow \cancel{CP}$$

$$\boxed{\begin{array}{l} \Leftrightarrow M_q \in \mathbb{C} \\ \mu_e = y_e \langle \Phi \rangle \in \mathbb{C} \end{array}}$$

$\cancel{CP} \Rightarrow$ real before SM breaking

$\Rightarrow y_q \in \mathbb{R}$

$$\boxed{\text{Can I break CP spont. in SM?}}$$

$\Leftrightarrow \quad \langle\phi\rangle \in \mathbb{C}\ ??$

$\boxed{\text{Oto: } \langle\phi\rangle = \text{real ?}}$

$$\langle\Phi\rangle \equiv \Phi_0 = \begin{pmatrix} 0 \\ v e^{i\alpha} \end{pmatrix} \equiv \Phi_0^{\mathbb{C}}$$

$\boxed{\text{Oto: } \alpha = 0\ ?}$

Yes $\quad \Phi_0^{\mathbb{R}} = \underbrace{e^{-i\alpha}}_{U(1)} \Phi_0^{\mathbb{C}} = \begin{pmatrix} 0 \\ v \end{pmatrix}$

"Minimal" extension of SM.:

spont. $\cancel{CP}$

we like $\Phi =$ doublet(s)

$$\Rightarrow \rho = \frac{M_Z \cos\theta_W}{M_W} = 1$$

$\Phi_1, \Phi_2 \leftarrow$ T. D. Lee

$$\boxed{\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}} \qquad \langle \Phi_2 \rangle = \frac{v}{2} \begin{pmatrix} \cos\theta e^{i\alpha} \\ \sin\theta e^{i\beta} \end{pmatrix}$$

$$Q_{em} \langle \Phi_i \rangle = 0$$

$$\Downarrow$$

$$\langle \Phi_2 \rangle \overset{\downarrow}{=} v_2 \begin{pmatrix} 0 \\ e^{i\beta} \end{pmatrix}$$

$$\alpha (\Phi_1^{+} \Phi_2)(\Phi_2^{+} \Phi_1)$$

$$\ni \alpha v_1^2 v_2^2 \sin^2\theta$$

$\underline{\alpha < 0} \Rightarrow \boxed{\sin\theta = 1}$

$$\langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 e^{i\delta} \end{pmatrix}$$ ← CP phase

$\Downarrow$

$\phi_1^+ \phi_1 \underline{(\phi_1^+ \phi_2 + h.c.)}$

$\gamma (\phi_1^+ \phi_2)^2 + h.c.$

$\Downarrow$

$$\boxed{V = A\cos\delta + B\cos 2\delta + C}$$

$$\boxed{A, B \therefore \delta \neq 0}$$

$$\boxed{M_q = Y_q^1 \langle \phi_1 \rangle + Y_q^2 \langle \phi_2 \rangle}$$

a mess !

SM and phase transition

$$\boxed{T_c \simeq M_W \simeq 100 \text{ GeV}}$$

$$1 \text{ eV} \simeq 10^4 \,{}^\circ K$$

$$\boxed{T_c \simeq 10^{15} \,{}^\circ K}$$

$\boxed{\text{Generations}}$ Why question?

$\boxed{\text{muon: Who ordered that?}}$

$$m_i \neq m_j \quad (\leftrightarrow V_{ij})$$

high energy $\Longleftrightarrow$ mass irrelevant

Family = question

$\boxed{\text{Family symmetry?}}$

$$SO(3) \longrightarrow \boxed{SU(3) \xrightarrow{\text{spont.}} \mathbb{1}}$$

$$\Downarrow$$

$$\boxed{\text{derive } m_i/m_j \longleftrightarrow V_{ij}}$$

$$\begin{array}{c} d \\ s \end{array} \begin{pmatrix} 0 & b \\ b & a \end{pmatrix} \Longleftarrow \text{symmetry}$$

Weinberg '77

$$M_d = U_{Ld}^{\dagger}\, m_Q\, U_{RQ}$$

$$m_s \gg m_d \qquad (m_s \simeq 100 \text{ MeV}, \; m_d \simeq 5 \text{ MeV})$$

$$\Downarrow$$

$$\boxed{a \gg b}$$

$$\boxed{m_s \simeq a\,, \quad m_d \simeq b^2/a}$$

$$\boxed{\frac{1}{2}\tan 2\theta = \frac{b-c}{a}}$$

$$\begin{pmatrix} c & b \\ b & a \end{pmatrix} = O(\theta)\begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} O^T(\theta)$$

$$O(\theta) = \begin{pmatrix} c & s \\ -s & c \end{pmatrix}$$

$$\Rightarrow \boxed{\theta \simeq b/a}$$

$$\theta^2 = b^2/a^2 = m_d/m_s$$

$$\boxed{\theta_d^2 = m_d/m_s \qquad \theta_u^2 = \frac{m_u}{m_c}}$$

$d \longleftrightarrow u$

anology

$$V_{CKM} = U_{Lu}^{+} U_{Ld}$$

$$\theta_c = \theta_d - \theta_u = \sqrt{\frac{m_d}{m_s}} - \cancel{\sqrt{\frac{m_u}{m_c}}}$$

$$\Rightarrow \boxed{\theta_c^2 \simeq m_d/m_s}$$

$\boxed{\text{in practice}}$

$\boxed{\text{Nice symmetry} \Rightarrow \text{nice relations}}$

$$\boxed{\begin{array}{llll} m_u & m_c & m_t & V_{CKM} = \mathbb{1} \\ m_d & m_s & m_b & \end{array}}$$

$\Rightarrow \boxed{\text{BSM theory}}$

$$\boxed{\begin{array}{c} \text{W} \left(\theta_c = \theta_d - \theta_u\right) \\ \text{GUT: } \overline{X} \quad \theta_u \;\vdots\; \theta_d \end{array}}$$

$$\theta_q \simeq 0 \quad \left(\underset{(12)}{\theta_c} \simeq 13^\circ, \ \theta_{23} \simeq 10^{-2}, \ \theta_{13} \simeq 10^{-3} \right)$$

$$\theta_\ell \simeq (30^\circ, 45^\circ, 10^\circ)$$

why not unity int. + fermions?

$$\Downarrow$$

SO(10) : 1 family

SO(18) $\Leftarrow$ 3 family

G.S, Wilczek, Zee '84

Minimal SO(5) GG

$\Downarrow$

wrong!