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Topics in strongly coupled string cosmology

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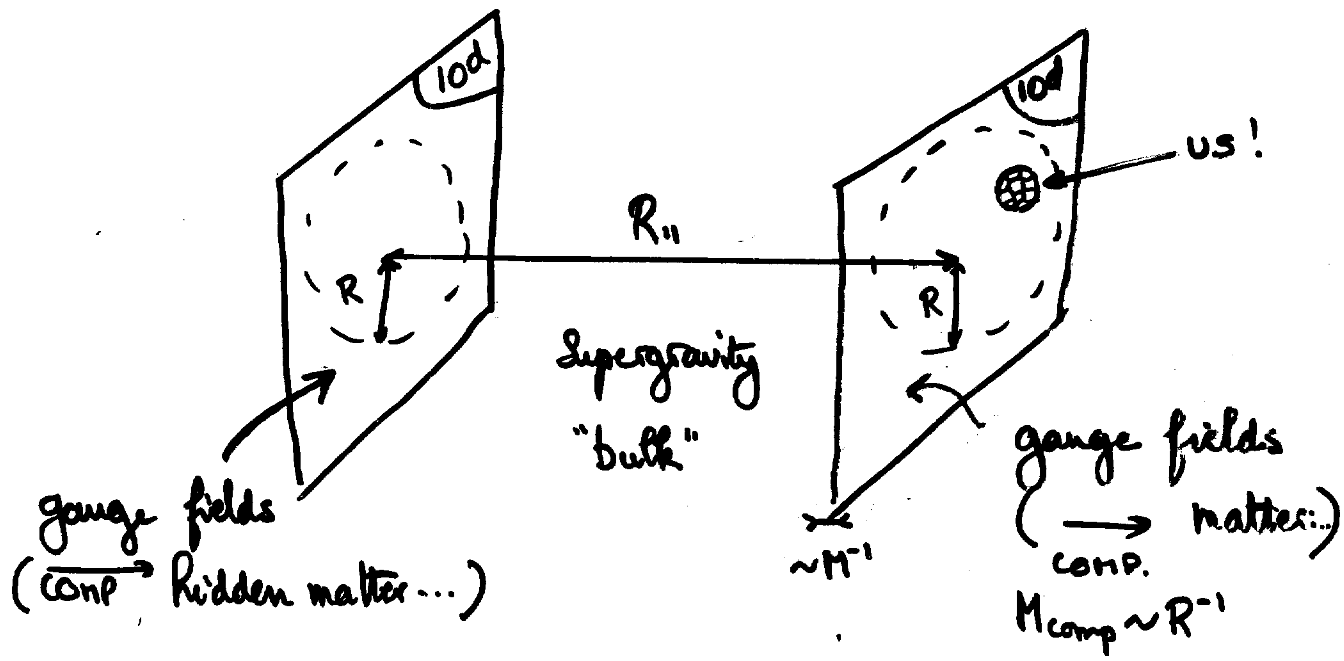
- The Horava-Witten picture
- Cosmological scenario
- Topological defects with trapped antisymmetric tensor fields.

STRONGLY COUPLED REGIME

Strongly coupled heterotic $E_8 \times E_8$ string theory adequately described by 11-dimensional M-theory

In the field theory limit,

Horava - Witten



Orbifold projection for the 11th dimension → $S_1/\mathbb{Z}_2$

11-dim. Sugra →

$$\mathcal{L} = M^9 \int d^{11}x \sqrt{g^{(11)}} \left[-\frac{1}{2} R^{(11)} - \frac{1}{48} G_{IJKL} G^{IJKL} - \frac{\sqrt{2}}{3456} \varepsilon^{I_1 \dots I_{11}} C_{I_1 I_2 I_3} G_{I_4 \dots I_7} G_{I_8 \dots I_{11}} + \dots \right]$$

10-dim YM →

$$- \frac{M^6}{8\pi(4\pi)^{2/3}} \int d^{10}x \sqrt{g^{(10)}} \; \mathrm{tr}\, F^{AB} F_{AB}$$

with $G = dC$

Dudas, Grojean
Antoniadis, Quiros
Nilles, Olechowski, Yamaguchi

Compactification down to 4 dimensions:

Frame (and units) in 4 dimensions depend on the Weyl rescaling of the 4-dimensional metric.

$\rightsquigarrow$ M (theory) - frame (mass unit M_{11})

$I,J \in \{5 \dots 10\}$ $\quad g^{(11)}_{IJ} = e^{\sigma(x)}\, g^{(0)}_{IJ}$ $\qquad \int d^6x \sqrt{g^{(0)}} = M_{11}^{-6}$

$g^{(11)}_{11,11} = e^{2\gamma(x)}\, \hat{g}^{(0)}$ $\qquad \int dx^{11} \sqrt{\hat{g}^{(0)}} = M_{11}^{-1}$

$\mu,\nu \in \{1 \dots 4\}$ $\quad g^{(11)}_{\mu\nu} = g_{\mu\nu}$ $\qquad$ ($\rightarrow$ no Weyl rescaling)

"dilaton" $\quad \underline{s = e^{3\sigma}}$ $\quad \longleftrightarrow$ radius of CY

"radius modulus" $\quad \underline{t = e^{\gamma} e^{\sigma}}$ $\quad \longleftrightarrow$ radius of 11^{th} dim.

$$\mathcal{L} = - M_{11}^2 \int d^4x \sqrt{g}\ \frac{1}{2} R\, e^{\gamma} e^{3\sigma}$$
$$- \frac{1}{8\pi (4\pi)^{2/3}} \int d^4x \sqrt{g}\ e^{3\sigma} F^{\mu\nu} F_{\mu\nu} + \dots$$

$$\frac{1}{g^2} = s$$
$$M_{Pl} \sim t^{1/2} s^{1/3} M_{11}$$
$$M_{comp} = (2\pi R_{CY})^{-1} \sim s^{-1/6} M_{11}$$
$$(R_{11})^{-1} \sim t^{-1} s^{1/3} M_{11}$$

→ E(instein)-frame (M_{Pl} units)

$$g^{(11)}_{IJ} = e^{\sigma(x)}\, g^{(0)}_{IJ}$$
$$g^{(11)}_{11,11} = e^{2\gamma(x)}\, \hat{g}^{(0)}$$
$$g^{(11)}_{\mu\nu} = e^{-2\sigma(x)}\, e^{-\gamma(x)}\, g_{\mu\nu}$$
$$s = e^{3\sigma}$$
$$t = e^{\gamma}$$

$$\int d^6x \sqrt{g^{(0)}} = M_{Pl}^{-6}$$
$$\int dx^{11} \sqrt{\hat{g}^{(0)}} = M_{Pl}^{-1}$$

$$M_{comp} \sim \frac{M_{Pl}}{\sqrt{ts}}$$
$$R_{11}^{-1} \sim \frac{M_{Pl}}{\sqrt{t^3}}$$

→ 5 dim.-frame (M_5 units) (S-frame P.B. '93)

$$g^{(11)}_{IJ} = e^{\sigma(x)}\, g^{(0)}_{IJ}$$
$$g^{(11)}_{11,11} = e^{2\gamma(x)}\, \hat{g}^{(0)}$$
$$g^{(11)}_{\mu\nu} = e^{-2\sigma(x)}\, g_{\mu\nu}$$

$$\int d^6x \sqrt{g^{(0)}} = M_5^{-6}$$
$$\int d^5x \sqrt{\hat{g}^{(0)}} = M_5^{-1}$$

$$s = e^{3\sigma}$$
$$t = e^{\gamma}$$
$$M_{Pl} \sim M_5 \sqrt{t}$$
$$M_{comp} \sim M_5/\sqrt{s}$$
$$(R_{11})^{-1} \sim \frac{M_5}{t}$$

Notes:

① Lowest order in an expansion in the dimensionful parameter M^{-3}

$\Rightarrow$ corrections of order M^6 to 11-dim. sugra lag.

② String coupling $\sim R_{11} \sim \frac{t}{M_S}$

$\rightarrow$ Weak coupling limit $\Leftrightarrow$ expansion around $R_{11} \sim 0$

$\downarrow$

10-dim. theory

$\rightarrow$ Strong coupling limit $\Leftrightarrow$ $t \gg 1$ in 5-dim. units

expansion in $1/t$

(also width of boundary $\ll R_{11}$ $\Rightarrow$ $t \gg 1$)

$\sim M_S^{-1}$

Putting numbers

E. Witten

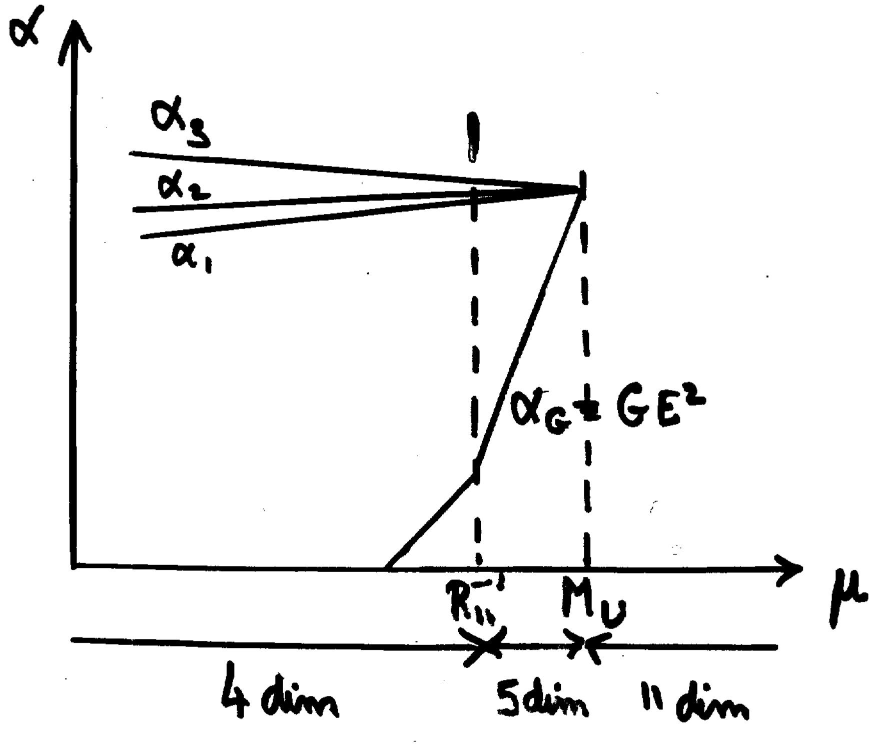
$$M_S \sim M_U (2\alpha_U)^{-1/2} \sim 3.4\, M_U$$

$M_U \simeq M_{comp}$ unification scale

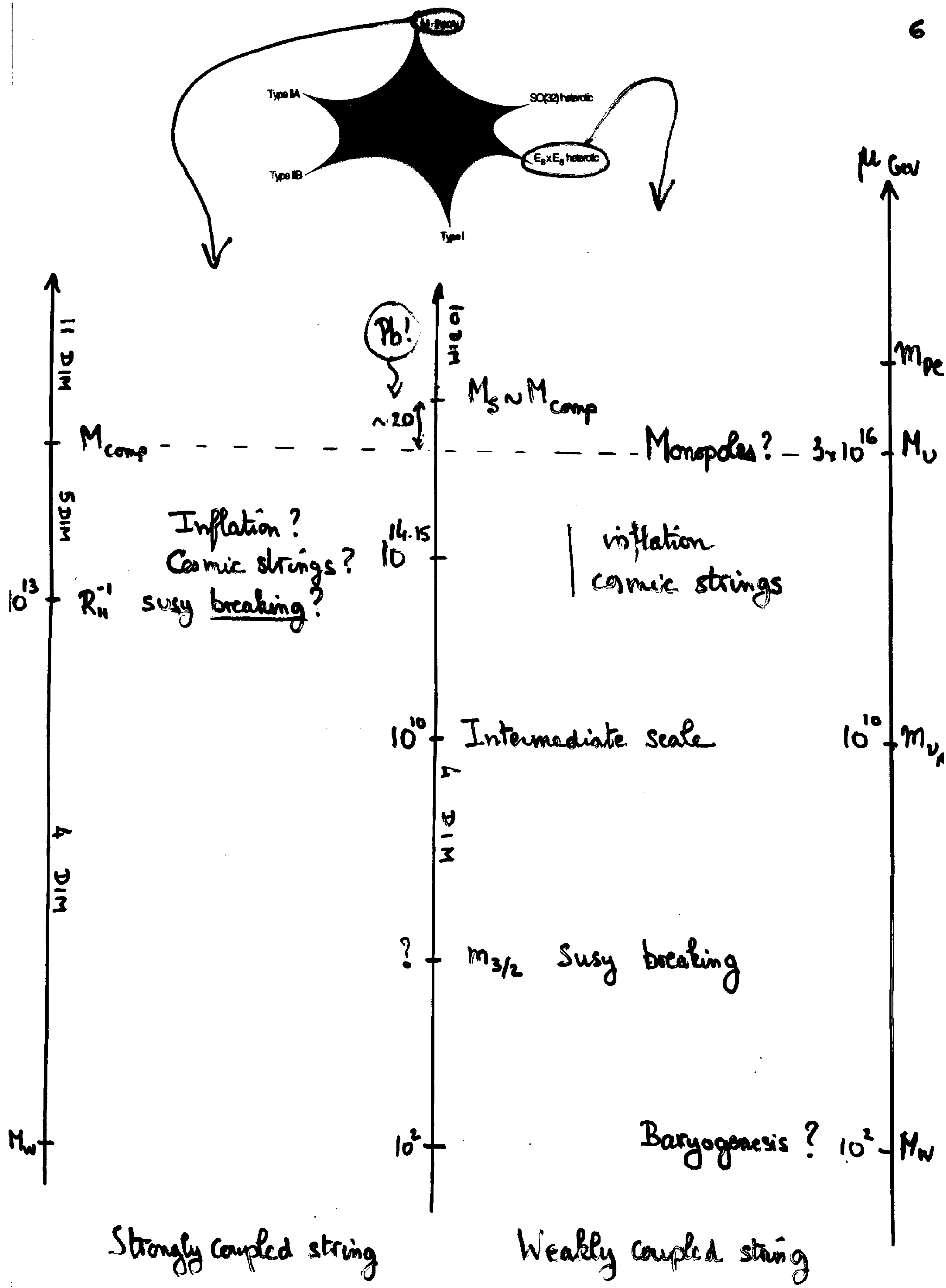
$$R_{11}^{-1} \sim \frac{1}{2\pi} \frac{M_U^3}{M_{Pl}^2} (2\alpha_U)^{-3/2} \sim 10^{-3} M_U$$

$$M_{11} \sim M_U (2\alpha_U)^{-1/6} \sim 1.5\, M_U$$

Hence rather large radius for the 11^{th} dimension which eases the grand unification of couplings.



Polchinski



M-theory
Type IIA
SO(32) heterotic
E8xE8 heterotic
Type IIB
Type I
μ GeV
11 DIM
Pb!
10 DIM
$M_s \sim M_{comp}$
~ 20
M_{pl}
M_{comp}
Monopoles? 3×10^{16} M_U
5 DIM
Inflation?
Cosmic strings?
$10^{14.15}$
inflation
cosmic strings
10^{13} R_{11}^{-1} susy breaking?
10^{10} Intermediate scale
10^{10} M_{ν_R}
4 DIM
4 DIM
? $m_{3/2}$ Susy breaking
M_W
10^2
Baryogenesis? 10^2 M_W
Strongly coupled string
Weakly coupled string

Inflation

If the compactification is dynamical, entropy is pumped into the effective 4-dimensional theory.

→ inflation?

E. Alvarez, B. Gavela '83

$$ds^2 = -dt^2 + a^2(t)\, g_{ij} \underbrace{dx^i dx^j}_{\text{space}} + b^2(t)\, g_{IJ} \underbrace{dx^I dx^J}_{\text{compact}}$$

Write Euler eqns in terms of $a(t)$ and $b(t)$.

Important role played by the charges associated with the 4-form $G = dC$

G_{0123} $G_{123,11}$

hep-th/9711027: Kaloper, Kogan, Olive
hep-th/9802041: Lukas, Ovrut, Waldram
hep-th/9806022

Maybe important for pre-big bang scenario.

For post-big bang scenarios, role of supersymmetry breaking?

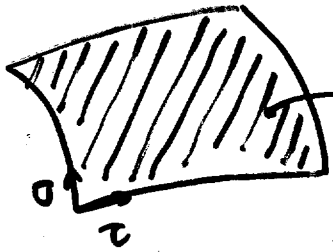
Cosmic strings.

Nielsen - Olesen model of superconducting string:

Nambu-Goto string in 5 dimensions

$$S \sim \int d\sigma\, d\tau \sqrt{(g_{AB}\partial_\tau X^A \partial_\sigma X^B)^2 - (g_{AB}\partial_\tau X^A \partial_\tau X^B)(g_{AB}\partial_\sigma X^A \partial_\sigma X^B)}$$

$A, B = 0, 1, 2, 3, 11$



surface

$$g_{AB} = \begin{pmatrix} g_{\mu\nu} & g_{\mu 11} \sim A_\mu \\ g_{11\nu} \sim A_\nu & e^{2\gamma} \end{pmatrix}$$

$A_\mu \to$ superconducting string

But in this case, $g_{\mu 11}$ is odd under the orbifold projection and vanishes on the boundaries

$$g_{\mu 11}(-x_{11}) = - g_{\mu 11}(x_{11})$$

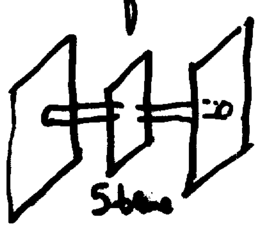
$$g_{\mu 11}(0) = 0$$

boundary.

But there are other objects of interest:

e.g. take a $U(1)_X$ symmetry which survives the orbifold projection and such that anomalies from (boundary) matter fields are not cancelled.

Ultimately, anomalies cancelled because of the presence of antisymmetric tensor fields B_{AB} ($\sim A_A$ in 5 dim)



Green-Schwarz mechanism

Seen from 4 dimensions $\underset{\text{antisym. tensor}}{B_{\mu\nu}} \sim \underset{\text{pseudoscalar}}{a}$ $\quad (\varepsilon^{\mu\nu\rho\sigma}\partial_\nu B_{\rho\sigma} \sim \partial^\mu a)$

$$\mathcal{L} = \frac{1}{4}\frac{a}{M_{pe}}\sum_a F^{a\,\mu\nu}F^a_{\mu\nu} + \dots$$

Under a $U(1)_X$ transformation, $A^{(X)}_\mu \to A^{(X)}_\mu + \partial_\mu\alpha$

$$\delta\mathcal{L} = -\frac{1}{2}\,\delta_{GS}\,\alpha\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

+ shift of the pseudoscalar $a \to a + 2M_{pe}\delta_{GS}\alpha$ $\Big] \to$ CANCELLATION

Green-Schwartz counterterm $B^{\mu\nu}F_{\mu\nu} \sim g^4\,\delta_{GS}M_p\,\partial^\mu a\,A_\mu$

SMALL $\quad g^4 \sim \frac{1}{t^2} \sim \left(\frac{M_s}{R_{11}}\right)^2$

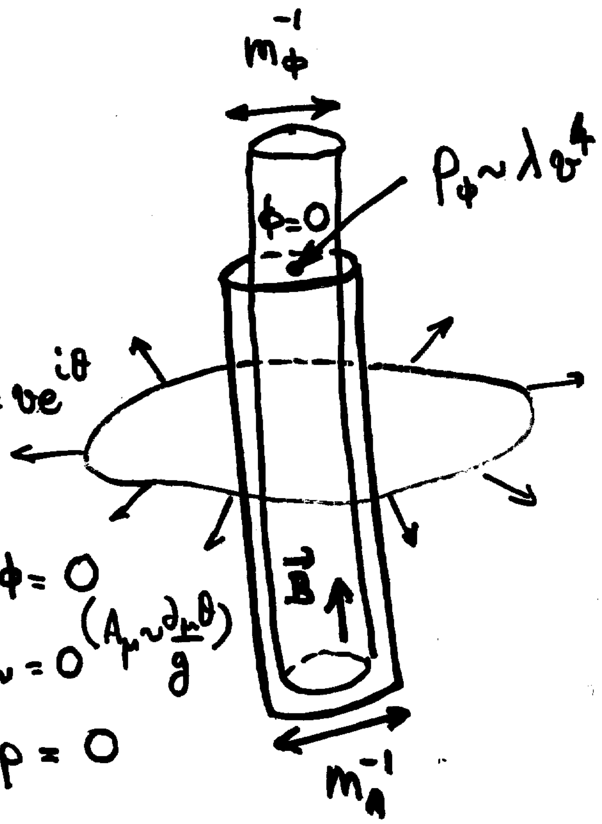
Cosmic strings associated with such pseudo-anomalous $U(1)$ have special properties.

Cosmic strings

local vs. **global**

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu}F_{\mu\nu} + D^\mu\phi^\dagger D_\mu\phi - \lambda(\phi^\dagger\phi - v^2)^2 \qquad \mathcal{L} = \partial^\mu\phi^\dagger\partial_\mu\phi - \lambda(\phi^\dagger\phi - v^2)^2$$

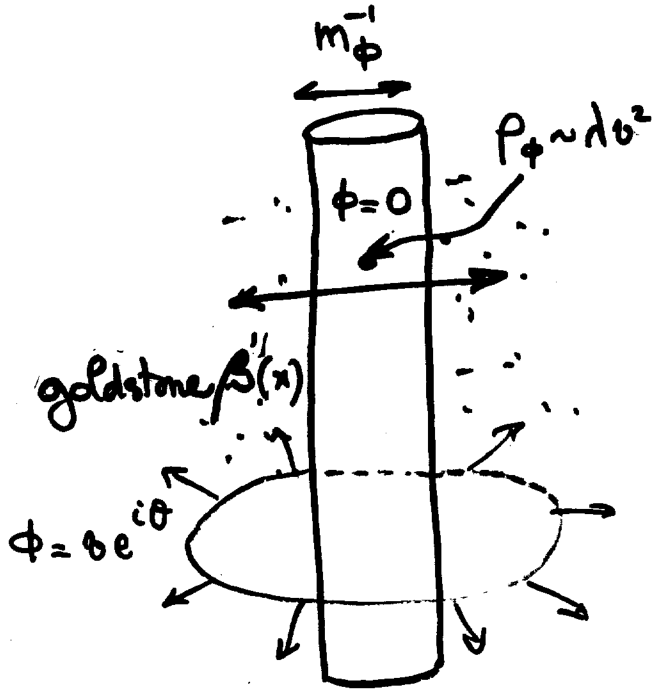
$$D_\mu\phi = \partial_\mu\phi - ieA_\mu\phi \qquad \phi \equiv \rho(x)\, e^{i\beta(x)}$$



$D_\mu\phi = 0$

$F_{\mu\nu} = 0 \; (A_\mu \sim \frac{\partial_\mu\theta}{g})$

$\Rightarrow \rho = 0$



Local:

$$m_\phi \sim \sqrt{\lambda}\, v$$

$\Rightarrow$ energy per unit length

$$\mu \sim \lambda v^4 (m_\phi^{-1})^2 \sim v^2$$

$$\left[m_A \sim gv, \; \int B\, dS \sim \frac{2n}{g} \Rightarrow B \sim gv^2 \right.$$

$$\left. \mu \sim (gv^2)^2 (m_A^{-1})^2 \sim v^2 \right]$$

Global:

$$m_\phi \sim \sqrt{\lambda}\, v$$

$\Rightarrow$ energy per unit length

$$\mu \sim \underbrace{\lambda v^4 (m_\phi^{-1})^2}_{\text{POTENTIAL}} + \underbrace{\int_{m_\phi^{-1}}^{R} \left(\frac{1}{r}\frac{\partial\phi}{\partial\theta}\right)^2 2\pi r\, dr}_{\text{KINETIC}}$$

$$\sim v^2 + v^2 \ln R m_\phi$$

LOG DIVERGENT

R cutoff: distance between strings, radius of loop, cosmic time ...

Cosmic string with pseudo-anomalous $U(1)_X$.

P.B., C. Deffayet, P. Peter

Introduce a field $\phi = \rho e^{i\eta}$ of charge $\underset{<0}{X}$ under $U(1)_X$

$$\mathcal{L} = D^\mu \phi^+ D_\mu \phi - \frac{g^2}{2}\left(X \phi^+\phi + g^2 \delta_{GS} M_P^2\right)^2$$

↳ FAYET-ILIOPOULOS D-TERM ξ^2

$$- \frac{1}{4g^2} F^{\mu\nu} F_{\mu\nu} + \frac{1}{4}\frac{a}{M_{pe}} F^{\mu\nu}\tilde{F}_{\mu\nu} - \frac{1}{4}\partial^\mu a\, \partial_\mu a$$

$$+ g^4 \delta_{GS} M_P A^\mu \partial_\mu a - g^4 \delta_{GS}^2 M_P^2 A^\mu A_\mu + \dots$$

GREEN-SCHWARZ

HIGGS MECHANISM

A_μ absorbs a combination of | the phase η / the string axion a

⇒ massive

Remains the other combination

$$\tilde{a} = \frac{2}{\delta_{GS}} a - \frac{M_P}{X}\eta$$

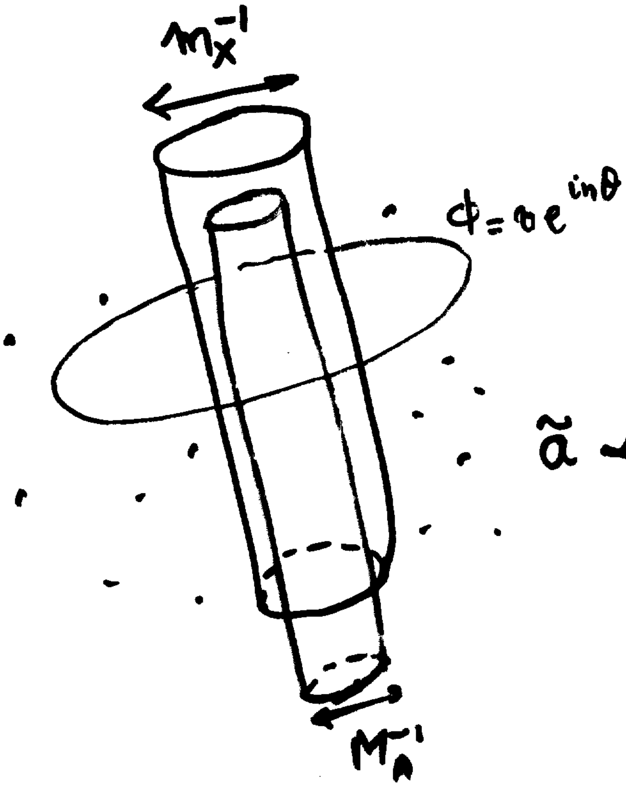
Mass scales:

$$\xi^2 = g^2 \delta_{GS} M_P^2 \;\rightarrow\; \sim \frac{1}{t} \ll 1$$

$$M_A^2 \sim g^2 \xi^2 \left(1 + \ell \frac{\xi^2}{M_{Pl}^2}\right)$$

$$m_X^2 \sim 4 g^2 \xi^2$$

$$F_a^2 \sim \frac{g}{16\pi} \sqrt{2}\, M_{Pl} \left(1 + 2\frac{\xi^2}{M_{Pl}^2}\right)$$



$\tilde{a}$

$\tilde{a} \neq 0$ axionic (global) string

$$\mu \sim F_a^2 \ln \underset{\downarrow}{R}\, m_X^{-1}$$

large distance cut-off

$\tilde{a} = 0$ asymptotically

Configuration minimizes the energy

$$\mu \propto \int_{r_0}^{M_A^{-1}} \frac{dr}{r} \left(\partial_\theta \eta - X A_\theta\right)^2$$

$r_0 \rightarrow$ short distance cut-off

$$\sim \frac{\delta_{GS}^2 M_P^2}{X^2} \ln \frac{M_A^{-1}}{r_0}$$

notes 1) μ depends on t

$\Rightarrow$ danger of oscillating strings releasing dilatons
moduli
Damour, Vilenkin

$\rightarrow$ associate with a scenario with heavy dilaton/moduli.

2) Superconducting string — Witten

Anomalous $U(1)_X$ often taken as a horizontal symmetry and used to generate fermion mass hierarchies: $m_f \propto \langle \Phi \rangle^n$

In the core of the string, $\langle \Phi \rangle = 0$

$\rightarrow$ fermion zero modes.

Circulation of currents $\Rightarrow$ superconducting strings

3) Anomalies in Spacetime

Witten
Harvey, Naculich

$\Rightarrow$ ANOMALIES IN THE (1+1) DIMENSIONAL THEORY

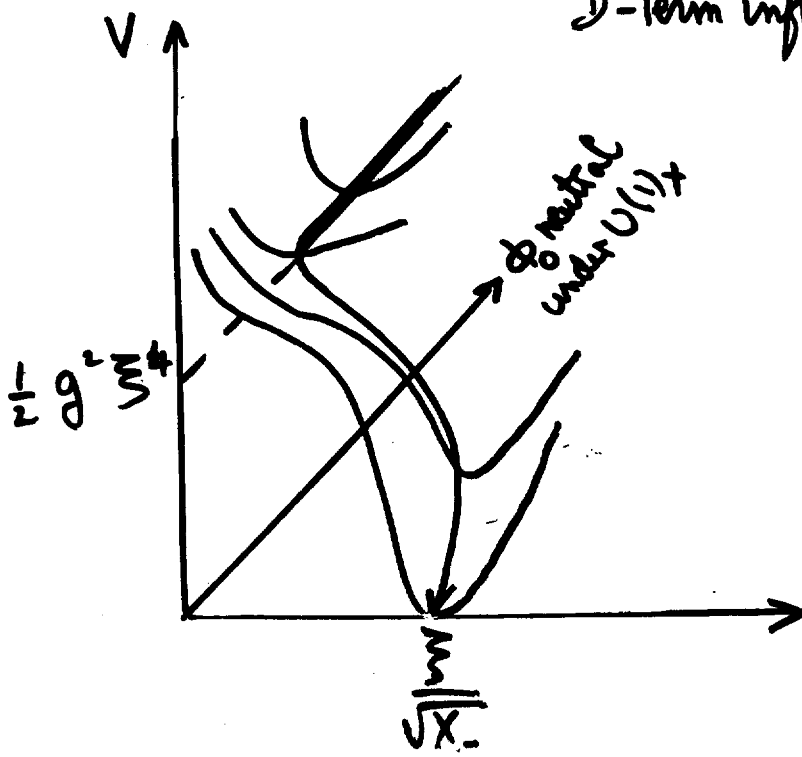
cancelled by charge inflows due to coupling of axion to gauge fields.

4) Possibility to have an inflation scenario using the D-term of the anomalous $U(1)$

$$V = \frac{1}{2} g^2 \Big(\sum_i X_i \, \phi_i^\dagger \phi_i + \xi^2 \Big)^2$$

D-term inflation

P.B., G. Dvali
C. Halyo
see also: Casas, Moreno, Muñoz, Quiros;
E.D. Stewart



cf. Hybrid Inflation
Linde Riotto

ϕ_- charged under $U(1)_X$
$(X_- < 0)$

CONCLUSIONS :

* RICH NEW POSSIBILITIES FOR COSMOLOGICAL SCENARIOS FROM STRONGLY COUPLED STRINGS

* COSMOLOGY MIGHT HELP TO PROBE A KEY REGION OF MASS SCALES

$(10^{13}$ to 10^{15} GeV$)$

* TOPOLOGICAL DEFECTS ARISING FROM SUCH THEORIES MOST PROBABLY HAVE SPECIFIC PROPERTIES (ANTISYMMETRIC TENSOR FIELDS TRAPPED).