EAJWS 2019 @ NCTS (Oct 28 – Nov 1)   2019 Oct 31

Hierarchy problem: "Implication from Superstring"

Hierarchy problem is a key idea to go beyond SM in particle physics, cosmology, string theory

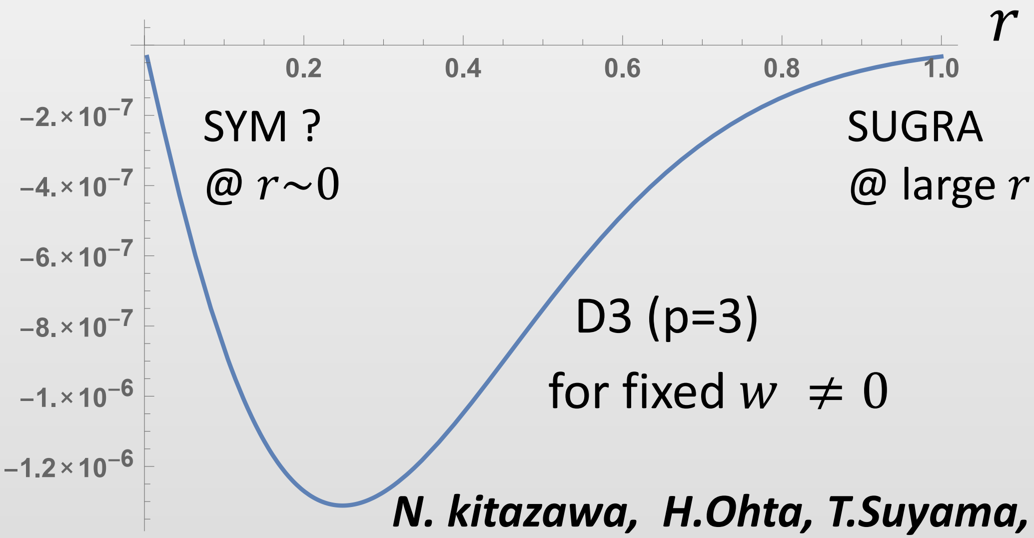
Satoshi Iso (KEK & Sokendai)

based on collaborations with

Phenomenology:	Yuta Orikasa, Nobu Okada, Michio Hashimoto	2009, 10, 12, 13 ....
Cosmology:	Kengo Shimada, Pasquale Serpico, Kazu Kohri	2010, 11.... 17, ...
String:	Nori Kitazawa, Hikaru Ohta, Takao Suyama	2015, 18, 19 ...
Hierarchy problem:	Hajime Aoki, Kiyoharu Kawana	2011, 18, ...

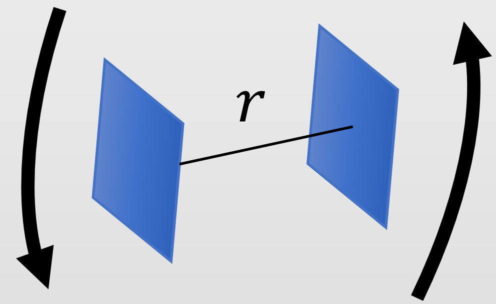
"A main result of this talk"

the effective potential $V(r)$ between revolving D3s is given by



N. kitazawa, H.Ohta, T.Suyama, SI
hep-th/1909.10717

Angular frequency ω



BPS at $\omega = 0$

[1] Bottom-up Motivation for this calculation   Hierarchy problem
[2] Implication from Superstring   string threshold corrections @ $r<l_s$
[3] Method to calculate $V(r)$ "partial modular transformation"

[1] Bottom-up Motivation: *Hierarchy Problem*

Hierarchy problem:

$$\delta m_H^2 = \frac{g^2}{16\pi^2}\left(\Lambda^2 + M^2\log(\Lambda/M)\right)$$

Radiative correction to the Higgs mass has quadratic dependence on M ($\gg m_H$) due to the logarithmic corrections with large coefficient M.

Decoupling Theorem by Appelquist Carazzone = existence of EFT

IR EFT is described by light particles after integrating heavy particles.

The effects of heavy particles are renormalization of parameters in EFT.

But Higgs mass in EFT may receive large threshold corrections by UV physics.

TeV SUSY is used to be a promising solution, but the situation has changed after the discovery of Higgs at 125 GeV.

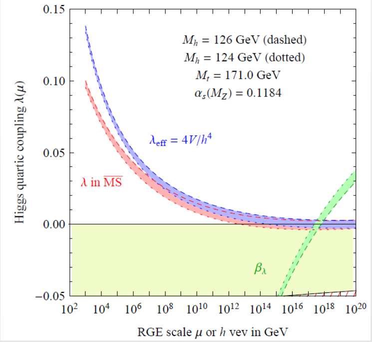
2 important lessons from LHC for the Higgs potential

$$V = -\mu^2 |H|^2 + \lambda (|H|^2)^2$$

(1) mass = 125 GeV

"EW" physics may be directly related to Planck scale physics
without intermediate scales in between.

Froggatt Nielsen (96)
M.Shaposhnikov (07)



(2) No deviations from SM / no TeV SUSY?

→ An alternative to the Naturalness (=hierarchy) problem

Before Higgs

SM — MSSM — RHN, SUSY GUT — CY — Superstring

After Higgs

SM + *something* ---------------------------- Superstring

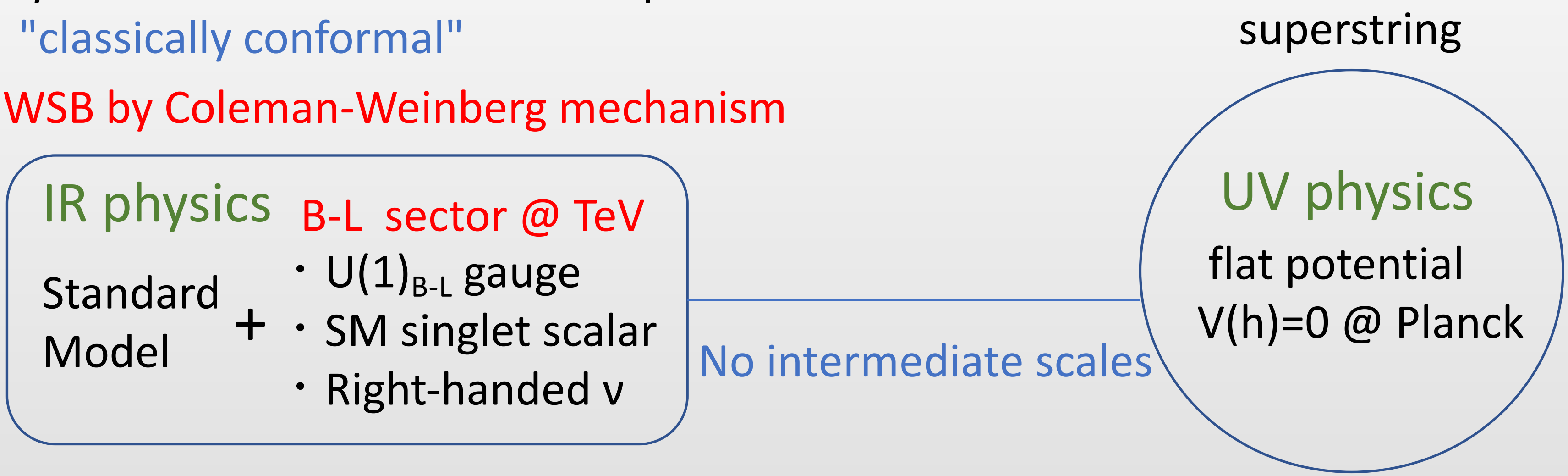
IR physics UV physics

My approach to the hierarchy problem:

SI, Okada, Orikasa (2009)

IR physics contains no dimensionful parameter.
= "classically conformal"

EWSB by Coleman-Weinberg mechanism



In order to embed this model in superstring w/o hierarchy problem, what conditions are necessary ?

(1) EFT must contain scalar field with flat potential

(2) No intermediate scales exist
Susy is broken at Planck scale

(3) Threshold corrections of UV physics must be suppressed

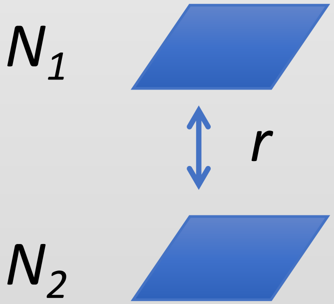
N.kitazawa, H.Ohta, T.Suyama, SI
hep-th/1909.10717

[2] Implication from Superstrings:

embedding in superstring

calculation of *stringy threshold corrections*

Brane-world scenario



D-branes

$U(N_1 + N_2) \rightarrow U(N_1) \times U(N_2)$

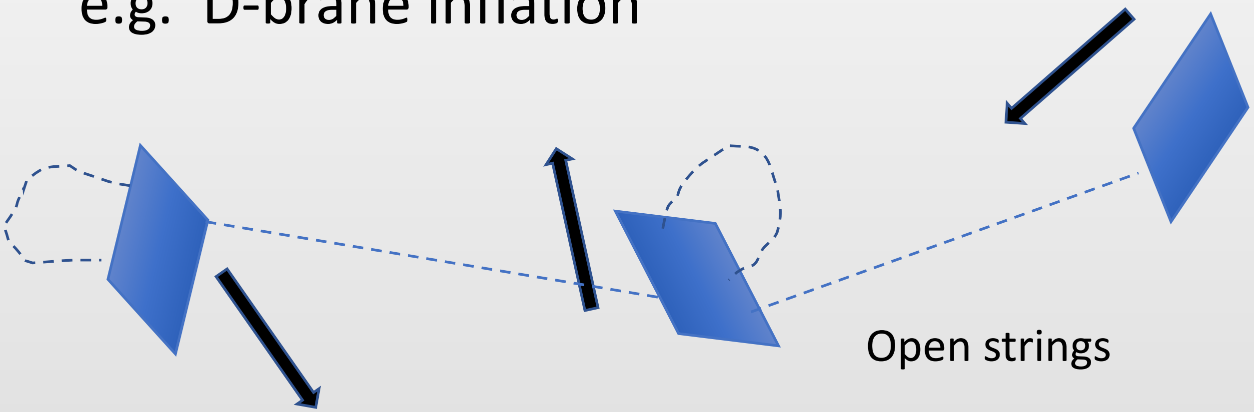
How can we obtain a small value of $r \ll l_{string}$?

= Hierarchy problem in string theory

D-brane universe

Suppose that many D-branes are moving randomly.

e.g. D-brane inflation



Masses of the open strings stretched between them vary according to their distances.

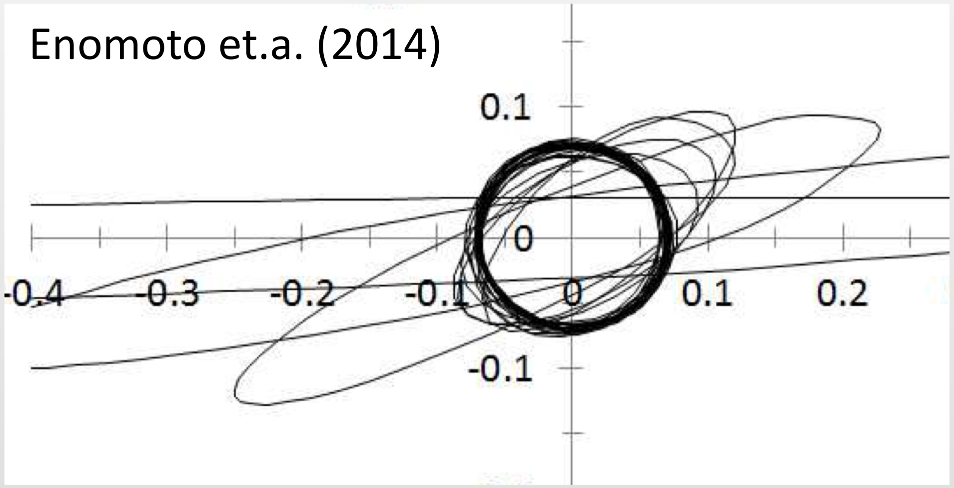
→ If the mass varies nonadiabatically,

D-branes lose their energy by emitting a pair of open strings.

(similar to preheating mechanism) "Beauty is attractive"

Kofman et.a. (04)

What is the fate of D-branes ?



In the bosonic string, they form a bound state
(if closed string emission is neglected.)

In superstring theory $\quad Dp$ in $d = 10$

No interaction
(BPS)

Bachas (96)

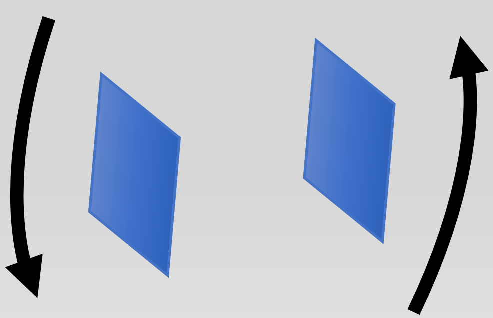
velocity v

distance r

$$\frac{v^4}{r^{7-p}}$$

Attractive potential is generated by one-loop string amplitude

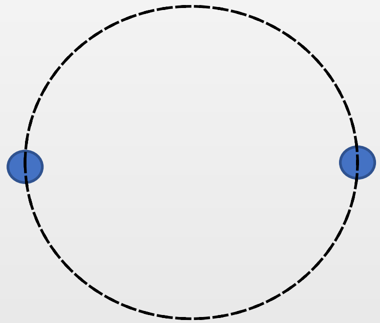
Angular frequency ω



Can they form a bound state ?
(cf. $D0s$: threshold bound state)

Rotational motion breaks SUSY
→ SUSY breaking scale = ω

Interaction potential between revolving D3-branes



Suppose that two parallel D3s
are rotating in a transverse plane

Calculation of the potential in string theory
= one-loop open string amplitude with rotating boundary condition

$$V(r) \;=\; -\int_0^\infty \frac{dt}{t}\, e^{-\frac{r^2}{2\pi\alpha'}t} Z(t)$$

Z(t): partition function of open string
(η(t), $\theta_{ab}(t)$) in a simple case, but generally difficult to obtain
because the open string is not exactly quantized.

In field theory, the stringy calculation is interpreted as

a sum of one-loop amplitudes of infinitely many fields

massless (SYM) + massive fields

$$
\begin{aligned}
V \quad &\sim \quad \frac{1}{2}\sum_{N=0}^{\infty}(-1)^F d_N \mathrm{tr}\log(p^2+m_N^2) \\
&= \sum_{N=0}^{\infty} d_N \frac{(-1)^F}{64\pi^2}\left(\Lambda^2 m_N^2 + m_N^4 \log m_N^2/\Lambda^2\right)
\end{aligned}
$$

$$m_N^2 = f(m_{\mathrm{str}}, r^2, \omega^2) \sim (N m_{str})^2 + \mathcal{O}(r^2, \omega^2)$$

Supersymmetry at ω= 0 → V(r) ~ $\omega^2 r^2$

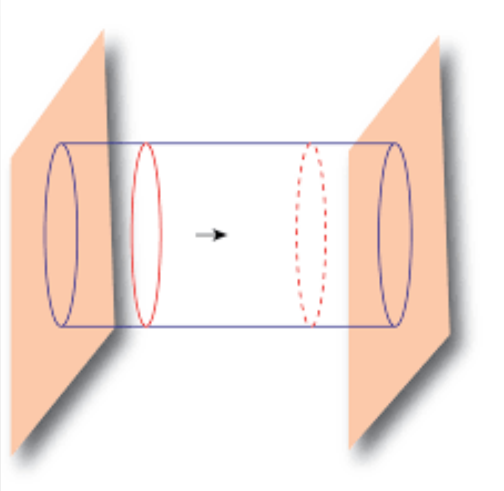
- Massless states (SYM) may dominantly contribute to V(r).
- Infinitely many massive states can also contribute to V(r) = $\sum \omega^2 r^2$

How to calculate the stringy threshold corrections ?

= hierarchy problem

[3] A new method to calculate the effective potential in D-brane models

N.Kitazawa, H. Ohta, T. Suyama, SI (19)



one-loop open string amplitude
= closed string exchange

In the revolving boundary conditions, we can not exactly calculate it.

"Partial Modular Transformation"

Partial sum of open strings (SYM) and closed strings (SUGRA)

- But no double counting.
- And numerically, with less than a few % accuracy

"Partial Modular Transformation"

Schwinger parameter of open string amplitude

$$t = [0, \infty] \Rightarrow \underbrace{t = [0,1]}_{\text{open UV}} + \underbrace{[1, \infty]}_{\text{open IR}} \Rightarrow \underbrace{s = [1, \infty]}_{\text{closed IR}} + \underbrace{t = [1, \infty]}_{\text{open IR}}$$

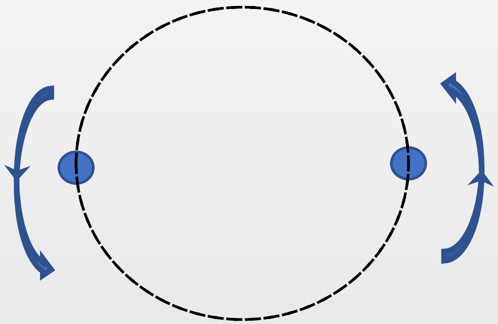
approximation
with 3% accuracy

SUGRA + SYM

Potential $V(R)$ ≒ sum of SYM and SUGRA with UV cutoff

Free from double counting due to the appropriate UV cut-off at t=s=1.

Interaction potential between revolving $D3$-branes



Two parallel $D3s$ are revolving around each other in a transverse plane

SYM with cutoff at $t = 1$ + SUGRA with cutoff at $s = 1$

$$\tilde{V}_o(R) = -\int_1^\infty \frac{dt}{t} \int \frac{d^D k}{(2\pi)^D} \sum_{\text{light open}} e^{-2\pi t E_o(k) - \frac{R^2}{2\pi\alpha'} t},$$

$$\tilde{V}_c(R) = -\int_1^\infty ds \sum_{\substack{\text{massless} \\ \text{closed}}} \int \frac{d^{D'} k}{(2\pi)^{D'}} \langle B|c\rangle\langle c|B'\rangle e^{-2\pi s E_c(k) - \frac{R^2}{2\pi\alpha'} s^{-1}}.$$

(a) SU(N) SYM calculations in background field gauge

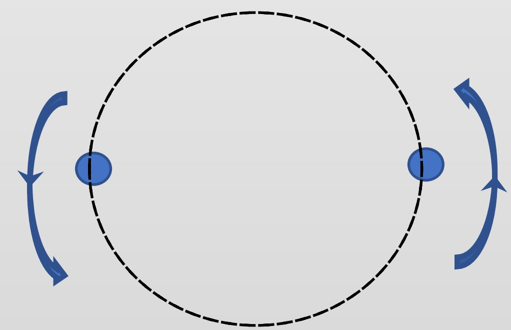
$$S = \frac{1}{g^2}\int d^{p+1}x \,\mathrm{Tr}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}D_\mu\Phi_I D^\mu\Phi^I + \frac{1}{4}([\Phi_I,\Phi_J])^2 + \frac{i}{2}\bar{\Psi}\Gamma^\mu D_\mu\Psi + \frac{1}{2}\bar{\Psi}\Gamma^I[\Phi_I,\Psi]\right]$$

N=2

background field gauge $\partial^\mu A_\mu - i[B_I,\Phi^I] = 0.$ such that $\Phi_I = B_I + \phi_I,$

$$B_I = b_I(t)\sigma_3, \qquad b_8 = r\cos\omega\tau, \qquad b_9 = r\sin\omega\tau,$$

$t = -i\tau,$ (Euclidean time τ)



$$\Rightarrow \quad \log\left[\det(-\partial^2+r^2)^{-6}\det(E_{B+}(-i\partial))^{-1}\det(E_{B-}(-i\partial))^{-1} \times \det(E_{F+}(-i\partial))^4\det(E_{F-}(-i\partial))^4\right]$$

(b) SUGRA calculations

$$X^\mu = X^\mu(\zeta)$$

Interactions between Dp-brane and SUGRA fields are obtained from DBI +CS

$$S_{\mathrm{DBI+CS}} = T_p \int d^{p+1}\zeta \left[e^{\frac{1}{4}(p-3)\Phi} \sqrt{-\hat{g}} + \hat{C}_{p+1} \right]$$

$$\hat{g}_{\alpha\beta} = \partial_\alpha X^\mu \partial_\beta X^\nu g_{\mu\nu},$$

$$\hat{C}^{(p+1)}_{\alpha_1 \cdots \alpha_{p+1}} = \partial_{\alpha_1} X^{\mu_1} \cdots \partial_{\alpha_{p+1}} X^{\mu_{p+1}} C^{(p+1)}_{\mu_1 \cdots \mu_{p+1}}$$

Propagators

$$\begin{aligned}
&\text{dilaton:} && \Delta(x) := 2\kappa_{10}^2 \int \frac{d^{10}k}{(2\pi)^{10}} \frac{e^{ik\cdot x}}{k^2}, \\
&\text{graviton:} && \Delta_{\mu\nu;\rho\sigma}(x) := \left(\eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \frac{1}{4}\eta_{\mu\nu}\eta_{\rho\sigma} \right) \Delta(x), \\
&\text{R-R field:} && \Delta_{\mu_0\cdots\mu_p;\nu_0\cdots\nu_p}(x) := \sum_{\sigma\in\mathcal{S}_{p+1}} \mathrm{sgn}(\sigma)\, \eta_{\mu_0\nu_{\sigma(0)}} \cdots \eta_{\mu_p\nu_{\sigma(p)}} \Delta(x),
\end{aligned}$$

Potential is given by

$$\tilde{V}_c = -2\kappa_{10}^2 \int d^{p+1}\zeta \int d^{p+1}\tilde{\zeta}\, \Delta(X - \tilde{X}) \left(F_\Phi(X,\tilde{X}) + F_g(X,\tilde{X}) + F_C(X,\tilde{X}) \right)$$

$$F_\Phi(X,\tilde{X}) = \left(\frac{p-3}{4}\right)^2 T_p^2 \sqrt{-\det \hat{\eta}_{\alpha\beta}(X)} \sqrt{-\det \hat{\eta}_{\gamma\delta}(\tilde{X})},$$

$$F_C(X,\tilde{X}) = T_p^2 \det(\partial_\alpha X \cdot \partial_\beta \tilde{X}).$$

$$F_g(X,\tilde{X}) = T_p^2 \sqrt{-\det \hat{\eta}_{\alpha\beta}(X)} \sqrt{-\det \hat{\eta}_{\gamma\delta}(\tilde{X})} \left(-\frac{(p+1)^2}{16} + \frac{1}{2} \hat{\eta}^{\alpha\beta}(X)(\partial_\beta X \cdot \partial_\delta \tilde{X}) \hat{\eta}^{\delta\gamma}(\tilde{X})(\partial_\gamma \tilde{X} \cdot \partial_\alpha X) \right)$$

Potential between Revolving D-branes: result

SYM part = effective potential from massless modes

$$\boxed{\Lambda = m_s}$$

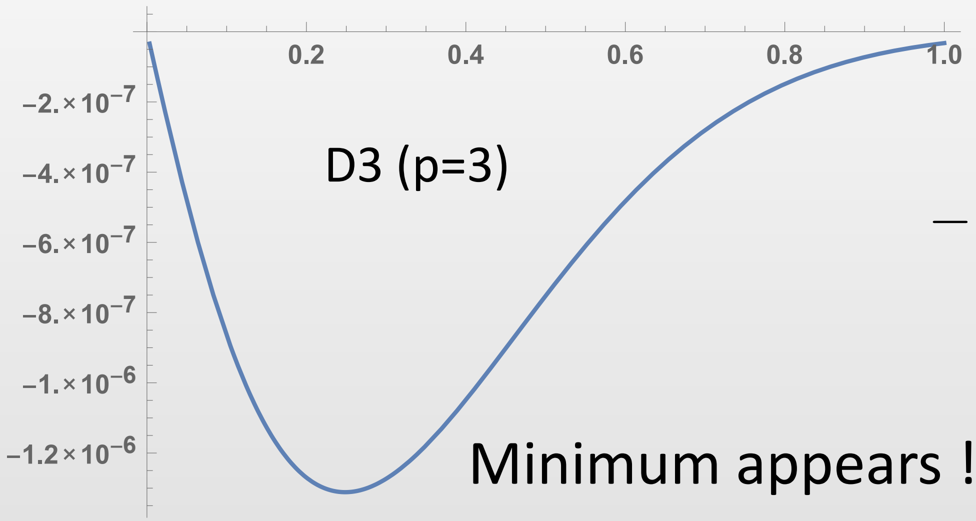
$$\begin{aligned}\tilde{V}_{o,B} &= -\int_{\Lambda^{-2}}^{\infty}\frac{dt}{t}\int\frac{d^{p+1}k}{(2\pi)^{p+1}}e^{-t(k^2+4r^2)} \\ &\times\left[6+2e^{-t\omega^2+t\frac{8(r\omega)^2}{k^2+4r^2}}\cosh\left(t\sqrt{4\omega^2k_0^2+\left(\frac{8(r\omega)^2}{k^2+4r^2}\right)^2}\right)\right] \\ \tilde{V}_{o,F} &= 4\int_{\Lambda^{-2}}^{\infty}\frac{dt}{t}\int\frac{d^{p+1}k}{(2\pi)^{p+1}}e^{-t(k^2+4r^2)}e^{-t\cdot\frac{\omega^2}{4}}\cdot 2\cosh\left(t\sqrt{\omega^2k_0^2+4(r\omega)^2}\right)\end{aligned}$$

SUGRA part = threshold corrections from stringy massive modes

$$\boxed{\tilde{\Lambda} = 2m_s}$$

$$\begin{aligned}\tilde{V}_c(r) &= -\kappa_{10}^2T_p^2V_{p+1}(4\pi)^{-\frac{10-p}{2}}\frac{v^4}{1-v^2}\int_{\tilde{\Lambda}^{-2}}^{\infty}ds\ s^{-\frac{10-p}{2}} \\ &\times\int d\zeta\exp\left[-\frac{1}{4s}\left(\zeta^2+2r^2(1+\cos\omega\zeta)\right)\right](1+\cos\omega\zeta)^2\end{aligned}$$

Effective potential $V(r)$ at fixed ω



Minimum appears !

Large r behavior is simple:

$$-(4\pi^2\alpha')^{3-p}(4\pi)^{-\frac{7-p}{2}}\Gamma(\tfrac{7-p}{2})\frac{v^4}{r^{7-p}}$$

Newton potential

The dominant contribution to V(r) at $r \sim 0$ comes from SYM.

$$\tilde{V}_o = \frac{\beta^2\omega^4}{\pi^2}\left(-\frac{m_s^2}{\omega^2}\left(1-E_2(\omega^2/m_s^2)\right)+\int_{\omega^2/m_s^2}^{\infty}\frac{dt}{t}e^{-t/4}F(\tfrac{1}{2},\tfrac{3}{2};\tfrac{t}{4})\right)+\mathcal{O}(\beta^4)$$

$$\sim -\frac{\omega^2 r^2}{\pi^2}$$

ω sets the susy breaking scale.

Stringy threshold corrections to Higgs potential

$\sum_{infinite\ modes\ in\ open\ string} \omega^2 r^2$ $\Rightarrow$ SUGRA calculation

$$V(r) = \sum_{N=0}^{\infty} d_N \frac{(-1)^F}{64\pi^2}\left(\Lambda^2 m_N^2 + m_N^4 \log m_N^2/\Lambda^2\right) \qquad m_N(m_{str}, r, \omega)$$

Naive expectation: V(r) ~ (large coefficient) × $\omega^2 r^2$

ω : SUSY breaking scale in SUGRA

But the result is different!

$$\tilde{V}_c(2r) = -\frac{\omega^4}{16\pi^2}\left[1-\left(1+4r^2/m_s^2\right)e^{-4r^2/m_s^2}\right] + \mathcal{O}(\omega^6) \sim -\frac{\omega^4 r^4}{2\pi^2 m_s^4}$$ at small r

The coefficient of $\omega^2 r^2$ is cancelled among infinite modes.

Stringy threshold corrections to Higgs mass are highly suppressed.

Comment 1. A possibility of a bound state

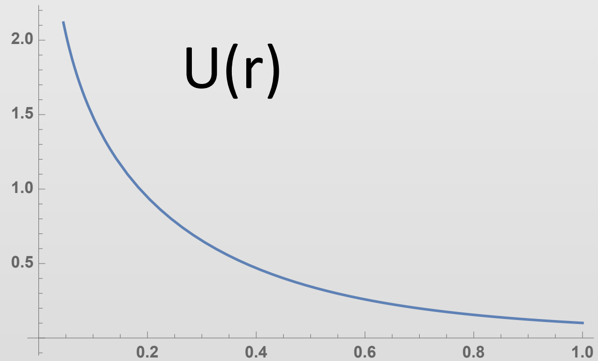
$$U(r) := \frac{L^2}{4T_3 r^2} + \tilde{V}(r)$$

Centrifugal potential

L: angular momentum for unit volume of D3-brane

$$\omega = \frac{L}{T_3 r^2}$$

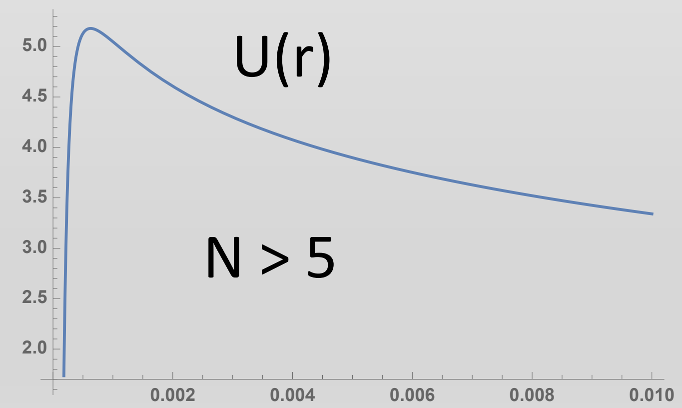
Potential = induced potential + centrifugal potential



no bound states exist.

If N-stack of D3-branes are revolving together,

$$U_N(r) := \frac{NL^2}{4T_3 r^2} + N^2\tilde{V}(r)$$



Bound states may exist.

Comment 2. Lorentz violation in the Higgs sector
Experimental test of the geometric scenario

Lorentz violation occurs only in the Higgs sector
(Coriolis force for Higgs field since it is geometrical.)

$$\omega^2 = M^2 + (1 + \frac{4\omega_0^2}{M^2})p^2 + 16\frac{\omega_0^4}{M^6}p^4 + \cdots$$

N. Kitazawa, SI ('18)

$\omega_0 < 0.1$ GeV

Summary

QCD-induced EW PT

Higgs physics
@ LHC + ILC + ...

early universe

String theory
space-time physics

Lorentz violation in Higgs

naturalness
stability
Yukawa couplings

Dark matter
Baryogenesis
Inflation, PBH, ...

moduli = geometry
SUSY breaking
Dark energy

Hierarchy problem is a key idea to go beyond SM
in particle physics, cosmology, string theory

From string theory, there are two important issues related to hierarchy problem.

1. embedding of EFT in superstring
2. calculation of stringy threshold corrections

→ "partial modular transformation"

Mass terms of Higgs may not be generated

Thank you for your attention

continued to the next talk by Takao Suyama