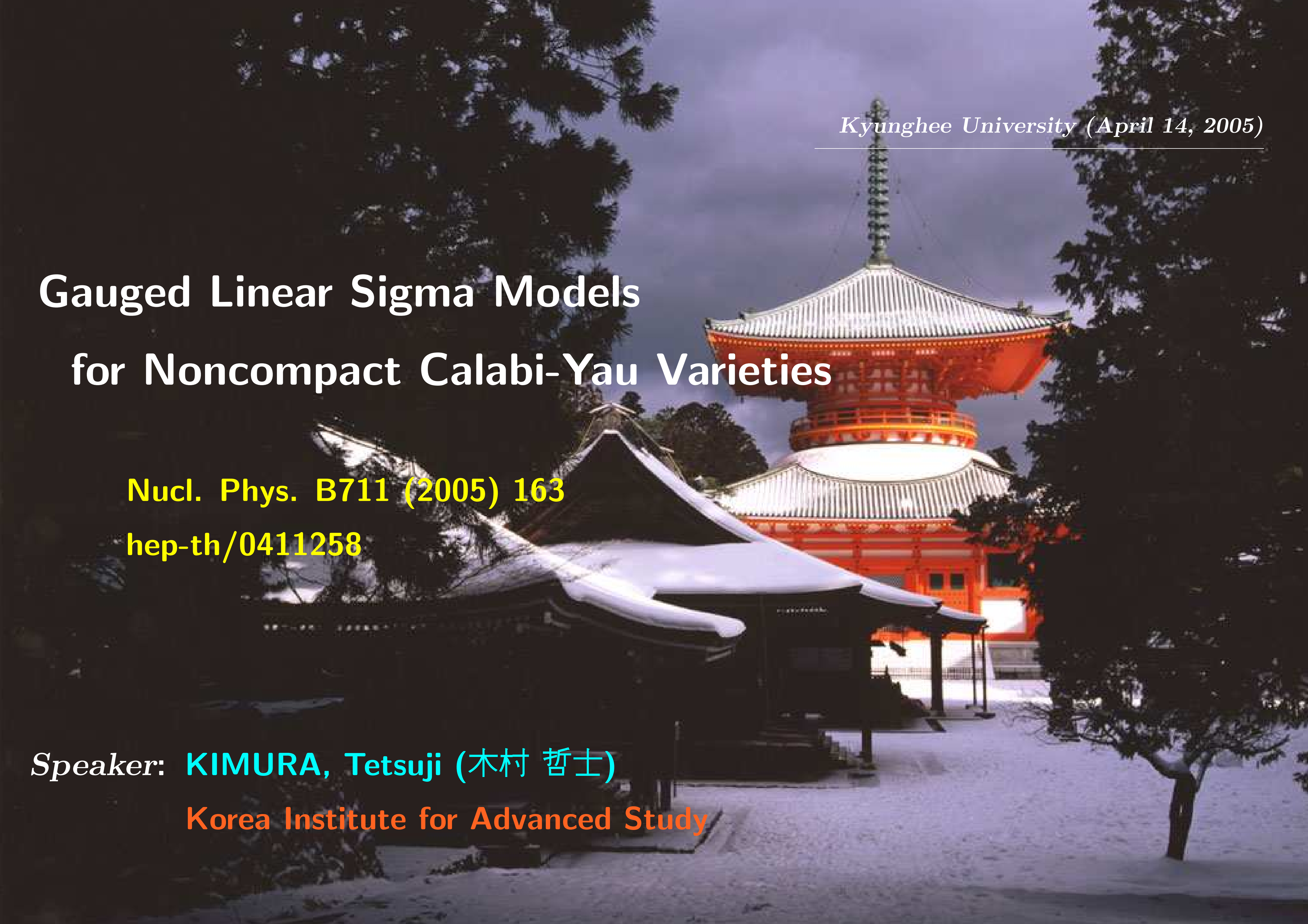

Kyunghee University (April 14, 2005)

Gauged Linear Sigma Models for Noncompact Calabi-Yau Varieties

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hep-th/0411258

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Self Introduction

I have mainly studied the following two topics:

- Two-dimensional SUSY (gauge) theories — Today's Talk
- Higher-dimensional supergravity — My Ph.D Thesis (hep-th/0402054)

My purpose: **to understand physics on curved spacetime**

from the worldsheet and spacetime points of view

Useful models and tools:

(Non)linear sigma model:	Maurer-Cartan one-form, differential geometry
	toric geometry, chiral rings, etc.
(gauged) gravity with matter:	Maurer-Cartan, Einstein-Hilbert, etc.

Two-dimensional field theory is a powerful framework

We have studied 2-dim. SUSY nonlinear sigma models...

– 1999: Supersymmetric nonlinear sigma models on hermitian symmetric spaces

introducing an auxiliary gauge field

by Higashijima and Nitta

2000: $1/N$ expansion of SUSY NLSM on $Q^{N-2} = \dfrac{SO(N)}{SO(N-2) \times U(1)}$

two non-trivial vacua, asymptotically free

by Higashijima, Nitta, Tsuzuki and TK: hep-th/0010272

2001 – 2002: Ricci-flat metrics on noncompact Kähler manifolds ($\equiv$ noncompact Calabi-Yau's)

by Higashijima, Nitta and TK:

hep-th/0104184, 0107100, 0108084, 0110216, 0202064

Metrics on Noncompact Calabi-Yau

(K.Higashijima, M.Nitta and TK, 2001, 2002)

$$\frac{\mathrm{d}}{\mathrm{d}X}\mathcal{K}_{\text{noncompact}}(\rho,\varphi) \;=\; \left(\mathrm{e}^{CX}+b\right)^{1/D}$$

$$X \;=\; \log|\rho^{1/\ell}|^2 + K_{\text{compact}}(\varphi)\;, \qquad K_{\mathbb{C}P^{N-1}}(\varphi) = r\log\left(1+\sum_{i=1}^{N-1}|\varphi_i|^2\right)$$

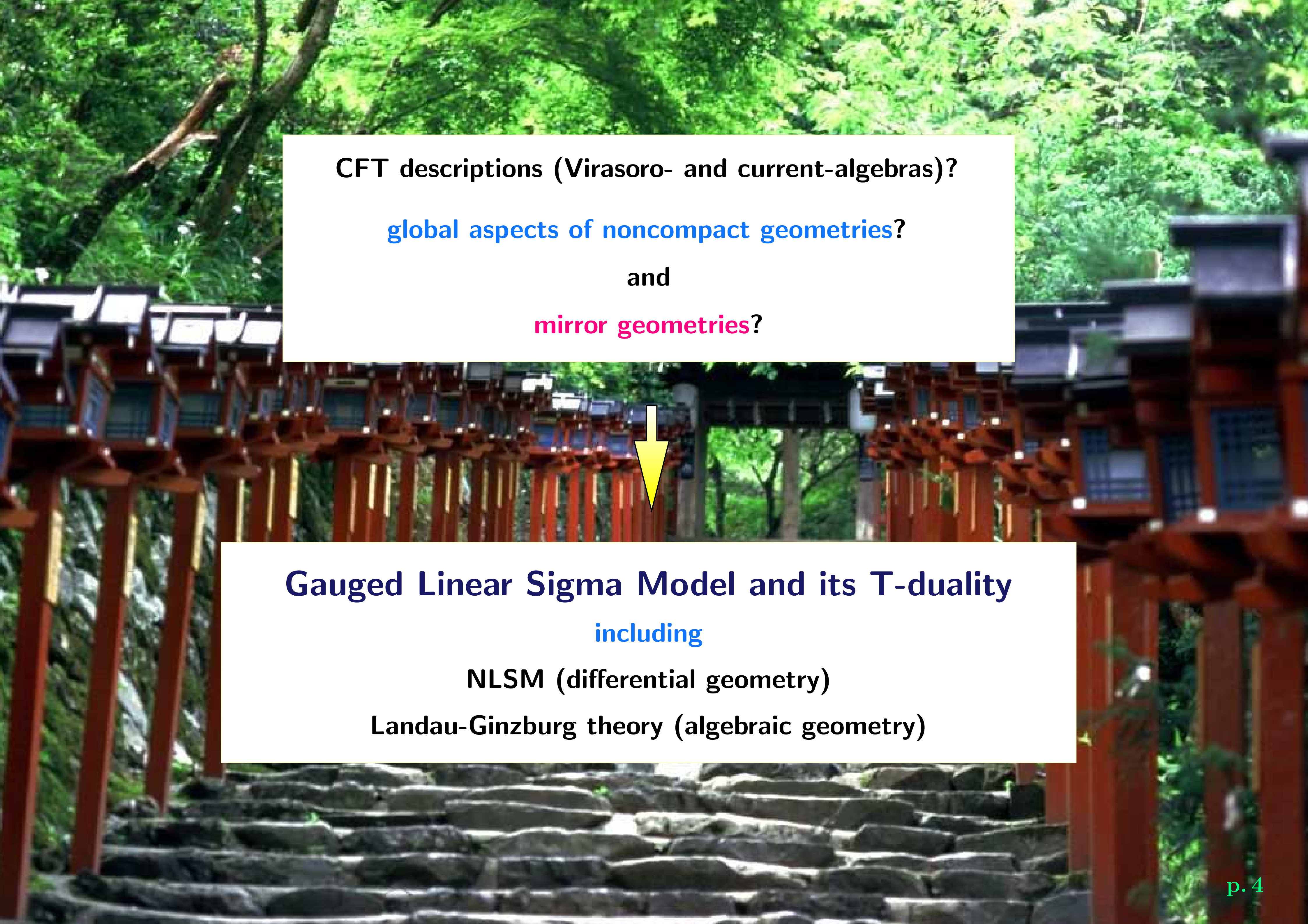
line bundles	total dim. D	dual Coxeter C	“orbifolding” ℓ
$\mathbb{C} \ltimes \left(\mathbb{C}P^{N-1} = \frac{SU(N)}{SU(N-1)\times U(1)}\right)$	$1+(N-1)$	N	N
$\mathbb{C} \ltimes \left(Q^{N-2} = \frac{SO(N)}{SO(N-2)\times U(1)}\right)$	$1+(N-2)$	$N-2$	$N-2$
$\mathbb{C} \ltimes E_6/[SO(10)\times U(1)]$	$1+16$	12	12
$\mathbb{C} \ltimes E_7/[E_6\times U(1)]$	$1+27$	18	18
$\mathbb{C} \ltimes \left(\mathrm{G}_{N,M} = \frac{U(N)}{U(N-M)\times U(M)}\right)$	$1+M(N-M)$	N	MN
$\mathbb{C} \ltimes SO(2N)/U(N)$	$1+\frac{1}{2}N(N-1)$	$N-1$	$N(N-1)$
$\mathbb{C} \ltimes Sp(N)/U(N)$	$1+\frac{1}{2}N(N+1)$	$N+1$	$N(N+1)$

CFT descriptions (Virasoro- and current-algebras)?

global aspects of noncompact geometries?

and

mirror geometries?



CFT descriptions (Virasoro- and current-algebras)?

global aspects of noncompact geometries?

and

mirror geometries?

Gauged Linear Sigma Model and its T-duality

including

NLSM (differential geometry)

Landau-Ginzburg theory (algebraic geometry)

GLSM, NLSM, LG CFT

Gaugeded linear sigma model E. Witten (1993), K. Hori and C. Vafa (2000)

$\mathcal{N} = (2,2)$ SUSY gauge theory with matters $(\mathrm{FI}: \ t \equiv r - i\theta)$

$$\begin{aligned}\mathscr{L} \ &= \int \mathrm{d}^4\theta \Big\{ -\frac{1}{e^2}\overline{\Sigma}\Sigma + \sum_a \overline{\Phi}_a \, \mathrm{e}^{2Q_a V} \Phi_a \Big\} \\ &\quad + \Big(\frac{1}{\sqrt{2}} \int \mathrm{d}^2\widetilde{\theta} \, (-\Sigma \, t) + c.c. \Big) + \Big(\int \mathrm{d}^2\theta \, W_{\mathrm{GLSM}}(\Phi_a) + c.c. \Big)\end{aligned}$$

- $\left[\begin{array}{ll} \Phi_a : & \text{charged chiral superfield, } \ \overline{D}_{\pm}\Phi_a = 0 \\ \Sigma : & \text{twisted chiral superfield, } \ \overline{D}_{+}\Sigma = D_{-}\Sigma = 0 \ , \ \Sigma = \frac{1}{\sqrt{2}}\overline{D}_{+}D_{-}V \end{array}\right.$
- There exist at least two phases:

$\mathrm{FI} \gg 0 :$ differential-geometric phase $\rightarrow$ SUSY NLSM

$\mathrm{FI} \ll 0 :$ algebro-gemetric phase $\rightarrow$ LG, orbifold, SCFT

- Calabi-Yau/Landau-Ginzburg correspondence

harmonic forms $\leftrightarrow$ NS-NS chiral primary states

- "Mirror geometry" appears in the T-dual theory in terms of twisted chiral superfields Y_a

$$Y_a + \overline{Y}_a \ \equiv \ 2 \, \overline{\Phi}_a \, \mathrm{e}^{2Q_a V} \Phi_a$$

Effective theories

The potential energy density is given by

$$\mathcal{U}(\phi,\sigma) \;=\; \frac{e^2}{2}\mathcal{D}^2 + \sum_a |F_a|^2 + \mathcal{U}_\sigma(\phi,\sigma)$$

$$\mathcal{D} \;=\; \frac{1}{e^2}D \;=\; r - \sum_a Q_a|\phi_a|^2 \;, \quad \overline{F}_a \;=\; -\frac{\partial}{\partial\phi_a}W_{\mathrm{GLSM}}(\phi) \;, \quad \mathcal{U}_\sigma(\phi,\sigma) \;=\; 2|\sigma|^2\sum_a Q_a^2|\phi_a|^2$$

The supersymmetric vacuum manifold $\mathcal{M}$ is defined by

$$\boxed{\mathcal{M} \;=\; \Big\{(\phi_a,\sigma)\in\mathbb{C}^n \,\Big|\, \mathcal{D}=F_a=\mathcal{U}_\sigma=0\Big\}\Big/U(1)}$$

Renormalization of the FI parameter is $r_0 \;=\; r_R + s\cdot\log\Big(\dfrac{\Lambda_{\mathrm{UV}}}{\mu}\Big)$, $\quad s \;=\; \sum_a Q_a$

Thus we find that

$s>0$	$\longrightarrow$	the theory is asymptotic free
$s=0$	$\longrightarrow$	the theory is conformal
$s<0$	$\longrightarrow$	the theory is infrared free

In the IR limit $e\to\infty$, there appears the supersymmetric NLSM on $\mathcal{M}$ whose coupling is

$$r \;=\; \frac{1}{g^2}$$

Example: quintic hypersurface

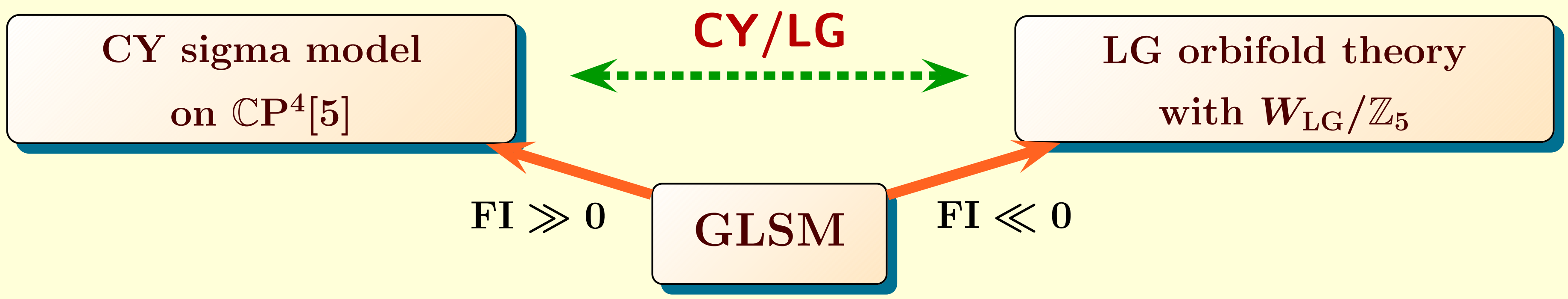
GLSM

— configuration —

chiral superfield Φ_a	S_1	S_2	$\cdots$	S_5	P
$U(1)$ charge Q_a	1	1	$\cdots$	1	-5

$$W_{\text{GLSM}} = P \cdot G_5(S) \;\longrightarrow\; P(S_1^5 + S_2^5 + \cdots + S_5^5)$$

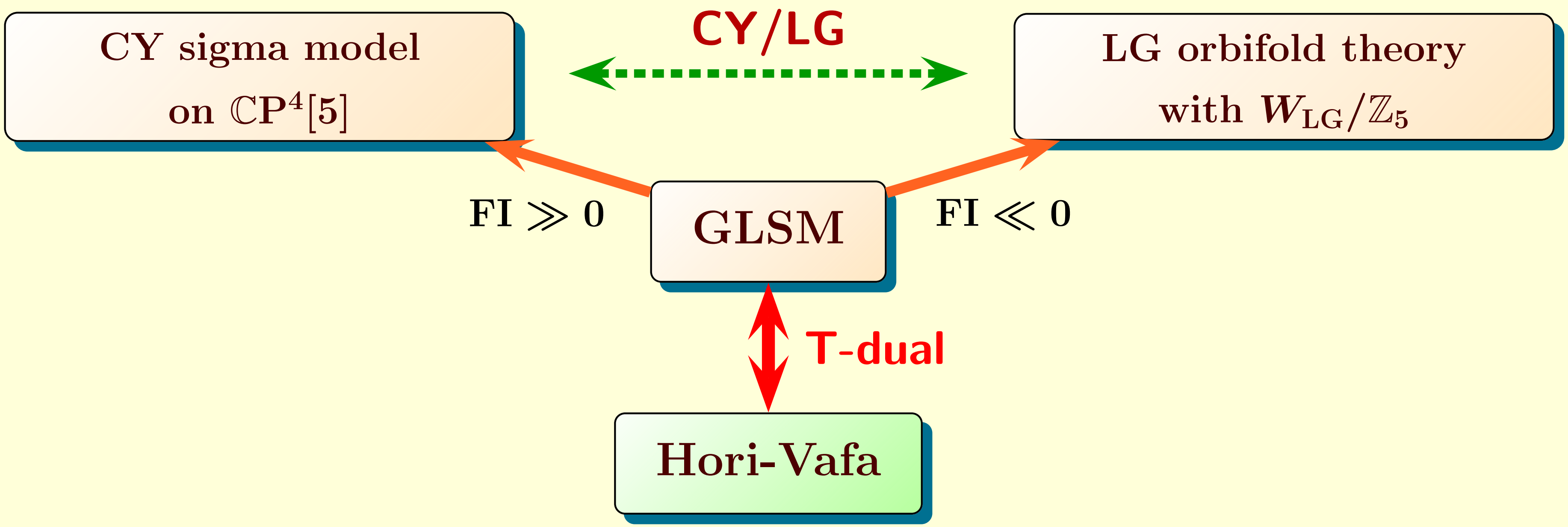
Example: quintic hypersurface



— configuration —

$$\mathbb{C}\mathbf{P}^4[5] = \Big\{ r = \sum_{i=1}^{5} |s_i|^2 > 0, \sum_i s_i^5 = 0 \Big\} \Big/ U(1) \qquad W_{\rm LG} \;=\; \sqrt{|r|/5}\langle p\rangle (S_1^5 + S_2^5 + \cdots + S_5^5)$$

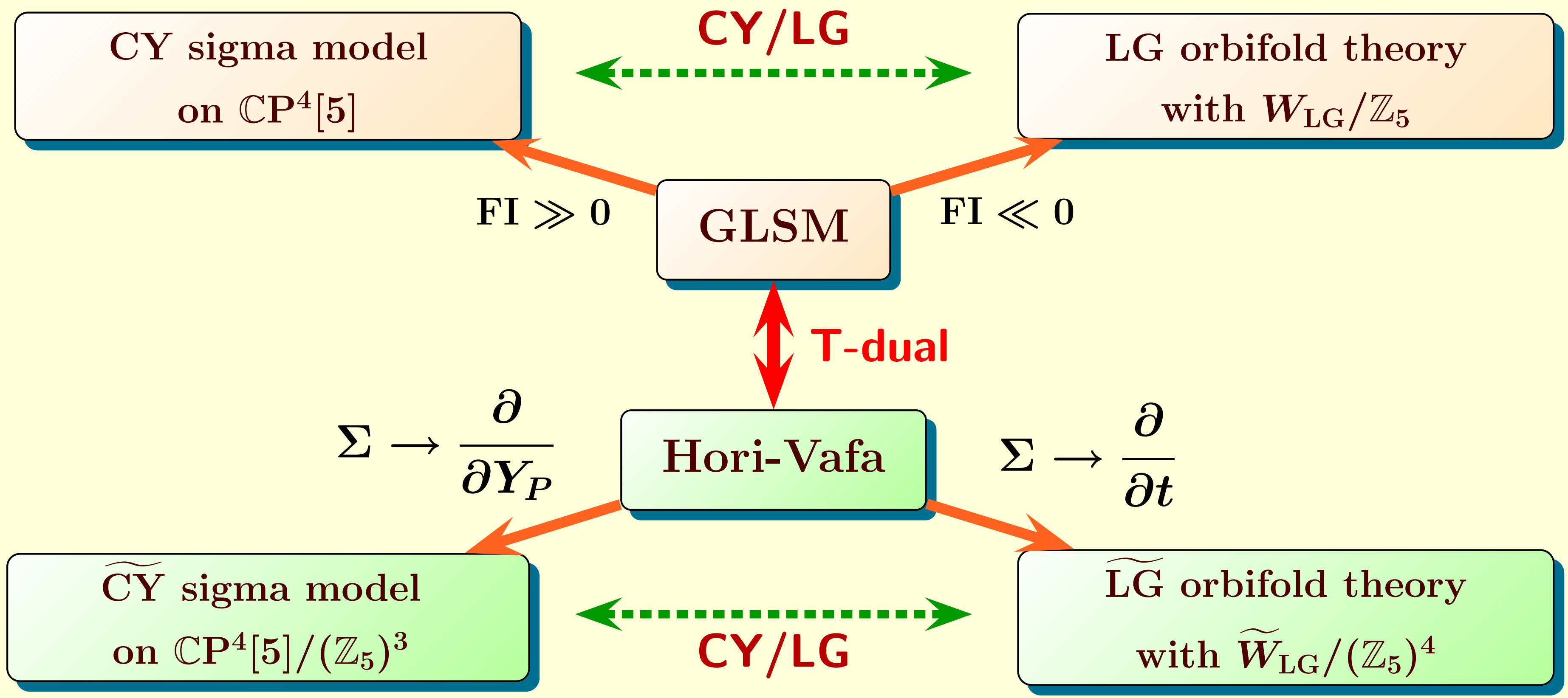
Example: quintic hypersurface



— configuration —

$$Y_a + \overline{Y}_a \;=\; 2\overline{\Phi}_a\, e^{2Q_a V}\, \Phi_a$$

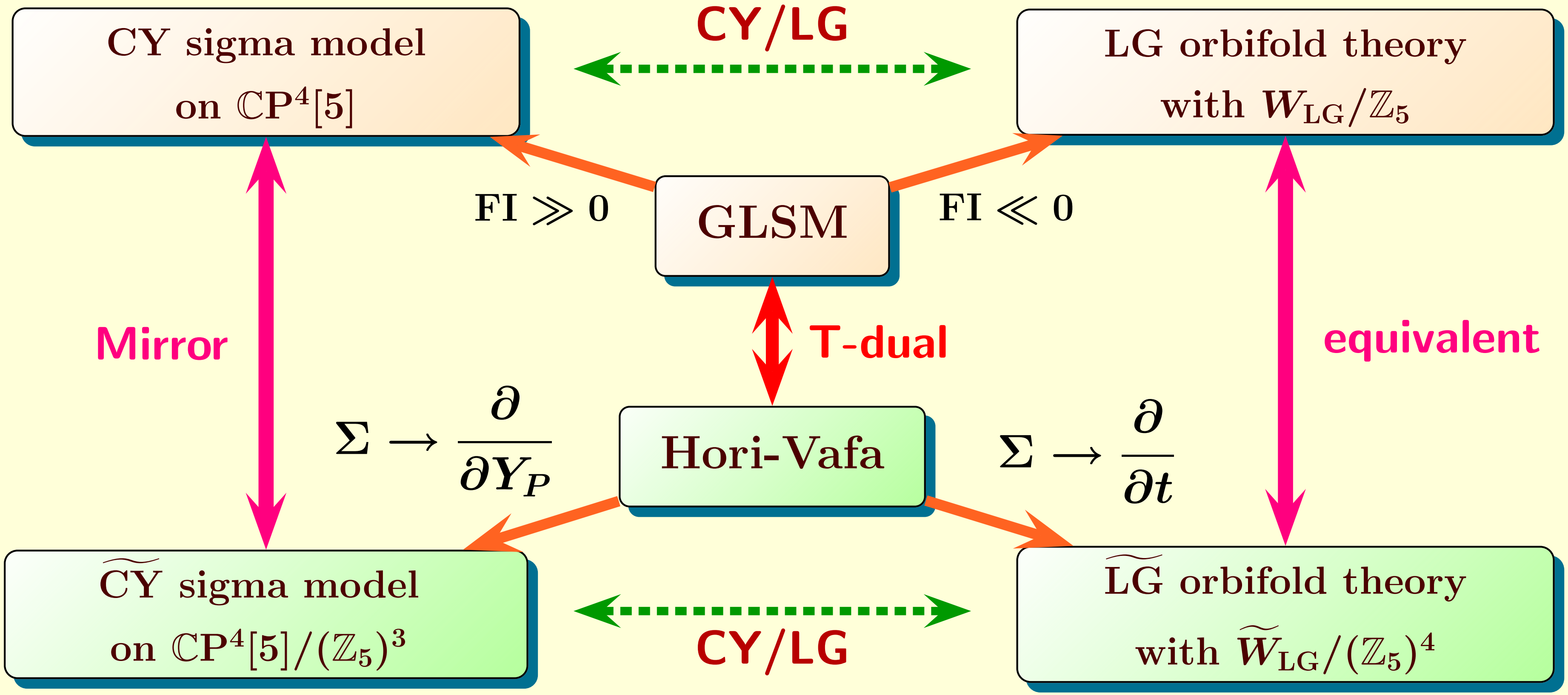
Example: quintic hypersurface



— configuration —

$$\widetilde{W}_{\mathrm{LG}} = X_1^5 + X_2^5 + X_3^5 + X_4^5 + X_5^5 + e^{t/5} X_1 X_2 X_3 X_4 X_5 \qquad X_i := \exp(-Y_i/5)$$

Example: quintic hypersurface



— configuration —

$h_{21}(\mathbb{C}\mathrm{P}^4[5]) = h_{11}(\mathbb{C}\mathrm{P}^4[5]/(\mathbb{Z}_5)^3) = 101$ $\qquad$ $h_{11}(\mathbb{C}\mathrm{P}^4[5]) = h_{21}(\mathbb{C}\mathrm{P}^4[5]/(\mathbb{Z}_5)^3) = 1$

Gauged Linear Sigma Model for $\mathcal{O}(-N+\ell)$ bundle on $\mathbb{CP}^{N-1}[\ell]$

chiral superfield	S_1	$\cdots$	S_N	P_1	P_2
$U(1)$ charge	1	$\cdots$	1	$-\ell$	$-N+\ell$

$$W_{\rm GLSM} = P_1 \cdot G_\ell(S_i)$$

$G_\ell(S_i)$: homogeneous polynomial of degree ℓ

"Homogeneous" means

$$\boxed{\text{if } G_\ell(s) = \partial_1 G_\ell(s) = \cdots = \partial_N G_\ell(s) = 0, \ \text{then } {}^\forall s_i = 0}$$

Potential energy density:

$$\mathcal{U} = \frac{e^2}{2}\mathcal{D}^2 + \big|G_\ell(s)\big|^2 + \sum_{i=1}^N \big|p_1 \partial_i G_\ell(s)\big|^2 + \mathcal{U}_\sigma$$

$$\mathcal{D} = r - \sum_{i=1}^N |s_i|^2 + \ell|p_1|^2 + (N-\ell)|p_2|^2 \,, \quad \mathcal{U}_\sigma = 2|\sigma|^2 \Big\{ \sum_{i=1}^N |s_i|^2 + \ell^2|p_1|^2 + (N-\ell)^2|p_2|^2 \Big\}$$

Let us analyze SUSY vacuum manifold $\mathcal{U}=0$ and massless effective theories

- $\ell = 1$ case: already well-known model

$$\text{GLSM reduces to } \begin{cases} r \gg 0: & \mathcal{O}(-N+1) \text{ bundle on } \mathbb{CP}^{N-2} \\ r \ll 0: & \mathbb{C}^{N-1}/\mathbb{Z}_{N-1} \text{ orbifold theory} \end{cases}$$

- $\ell = N$ case: already well-known model

$$\text{GLSM reduces to } \begin{cases} r \gg 0: & \mathbb{C}^1 \text{ free theory} \otimes \text{CY sigma model on } \mathbb{CP}^{N-1}[N] \\ r \ll 0: & \mathbb{C}^1 \text{ free theory} \otimes \text{LG theory with } \{W_{\mathrm{LG}} = G_N(S)\}/\mathbb{Z}_N \end{cases}$$

$\boxed{2 \le \ell \le N-1 \text{ cases are nontrivial}}$

▼ $r \gg 0$ **region: CY phase appears**

$$\mathcal{M}_{\rm CY} = \Big\{ (s_i; p_2) \in \mathbb{C}^{N+1} \,\Big|\, r = \sum_{i=1}^{N} |s_i|^2 - (N-\ell)|p_2|^2, \;\; G_\ell(s_i) = 0 \Big\} \Big/ U(1)$$

➡ $\mathcal{O}(-N+\ell)$ **bundle on** $\mathbb{C}\mathrm{P}^{N-1}[\ell]$

- **Fluctuation modes tangent to** $\mathcal{M}_{\rm CY}$ **remain massless**
- **Modes non-tangent to** $\mathcal{M}_{\rm CY}$ **and gauge fields**

  obtain masses of order $\mathcal{O}(e^2 r)$ **via Higgs mechanism**

taking the IR limit ($e \to \infty$)

$\longrightarrow$ **all the massive modes are decoupled from the theory**

$\boxed{\mathcal{N} = (2,2) \text{ SUSY nonlinear sigma model on } \mathcal{M}_{\rm CY}}$

▼ $r \ll 0$ region: orbifold phase and "new" phase appear

$$\begin{aligned}
\mathcal{M}_{\mathrm{orbifold}} &= \Big\{ (p_1, p_2; s_i) \in \mathbb{C}^{N+2} \,\Big|\, \mathcal{D} = G_\ell(S_i) = p_1 \partial_i G_\ell = 0,\ r < 0 \Big\} \Big/ U(1) \\
&= \mathcal{M}^1_{r<0} \cup \mathcal{M}^2_{r<0} \\
\mathcal{M}^1_{r<0} &:= \Big\{ (p_1, p_2) \in \mathbb{C}^2 \,\Big|\, \mathcal{D} = 0\,,\ r < 0 \Big\} \Big/ U(1) \ = \ \mathrm{W}\mathbb{C}\mathrm{P}^1_{\ell, N-\ell} \\
\mathcal{M}^2_{r<0} &:= \Big\{ (p_2; s_i) \in \mathbb{C}^{N+1} \,\Big|\, \mathcal{D} = G_\ell = 0\,,\ r < 0 \Big\} \Big/ U(1)
\end{aligned}$$

Homogeneity of $G_\ell(s)$ and $p_1 \partial_i G_\ell(s) = 0$ decompose $\mathcal{M}_{\mathrm{orbifold}}$ into two parts!!

For simplicity, we only consider the case of $3 \leq \ell \leq N-1$.

▼ Massless effective theory on $\mathcal{M}^1_{r<0}$:

$$\mathcal{N} = (2,2) \text{ supersymmetric NLSM on } \mathrm{W}\mathbb{C}\mathrm{P}^1_{\ell,N-\ell}$$

$$\text{coupled to “LG” theory with } \Big\{ W_{\mathrm{LG}} = (\langle p_1 \rangle + P_1) G_\ell(S) \Big\} \Big/ \mathbb{Z}_\alpha$$

$$(\alpha = \mathrm{GCM}\{\ell, N-\ell\})$$

Especially on the point $(p_1, p_2) = (*, 0) \in \mathcal{M}^1_{r<0}$, the theory looks like

$$\boxed{\Big\{ \text{CFT on } \mathbb{C}^1 \otimes \text{ LG theory with } W_{\mathrm{LG}} = \langle p_1 \rangle G_\ell(S) \Big\} \Big/ \mathbb{Z}_\ell} \quad \text{(?)}$$

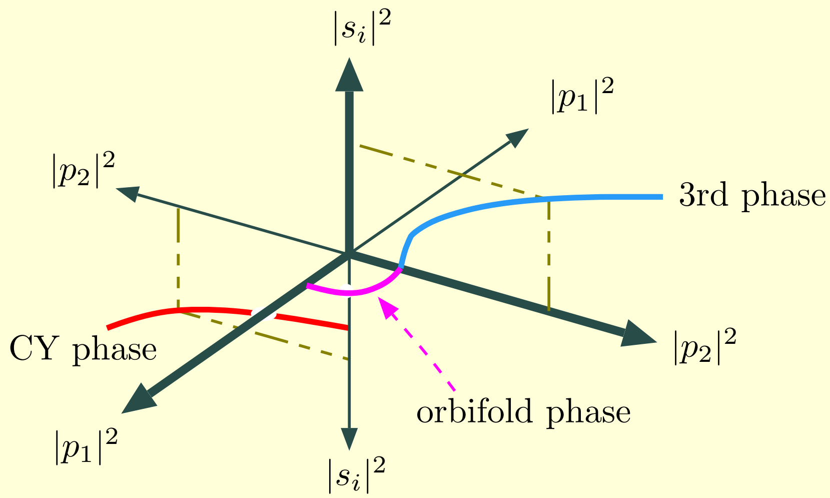
and on the point $(p_1, p_2) = (0, *) \in \mathcal{M}^1_{r<0}$, the theory looks like

$$\boxed{\Big\{ \text{LG theory with } W_{\mathrm{LG}} = P_1 \cdot G_\ell(S) \text{ on } \mathbb{C}^{N+1} \Big\} \Big/ \mathbb{Z}_{N-\ell}} \quad \text{(?)}$$

▼ Massless effective theory on $\mathcal{M}^2_{r<0}$:

$$\boxed{\text{Conformal NLSM on } \mathcal{M}^2_{r<0}} \quad \textbf{NEW phase!}$$

Supersymmetric vacua



- **CY phase on $\mathcal{M}_{\mathrm{CY}}$**
  conformal sigma model on $\mathcal{M}_{\mathrm{CY}}$
- **orbifold phase on $\mathcal{M}^1_{r<0}$ (two "LG"s appear)**
  $\big\{$**CFT on** $\mathbb{C}^1 \otimes$ **LG with** $W_{\mathrm{LG}} = \langle p_1 \rangle G_\ell(S)\big\}/\mathbb{Z}_\ell$
  $\big\{$**"LG" with** $W_{\mathrm{LG}} = P_1 \cdot G_\ell(S)\big\}/\mathbb{Z}_{N-\ell}$
- **3rd phase on $\mathcal{M}^2_{r<0}$ NEW!**
  conformal sigma model on $\mathcal{M}^2_{r<0}$

$$\mathcal{M}_{\mathrm{CY}} = \Big\{(s_i; p_2) \in \mathbb{C}^{N+2}\,\Big|\,\mathcal{D} = G_\ell = 0,\ r > 0\Big\}\Big/U(1) \equiv \mathcal{O}(-N+\ell) \text{ bundle on } \mathbb{CP}^{N-1}[\ell]$$

$$\mathcal{M}^1_{r<0} = \Big\{(p_1, p_2) \in \mathbb{C}^2\,\Big|\,\mathcal{D} = 0, r < 0\Big\}\Big/U(1) \equiv \mathrm{W}\mathbb{CP}^1_{\ell,N-\ell}$$

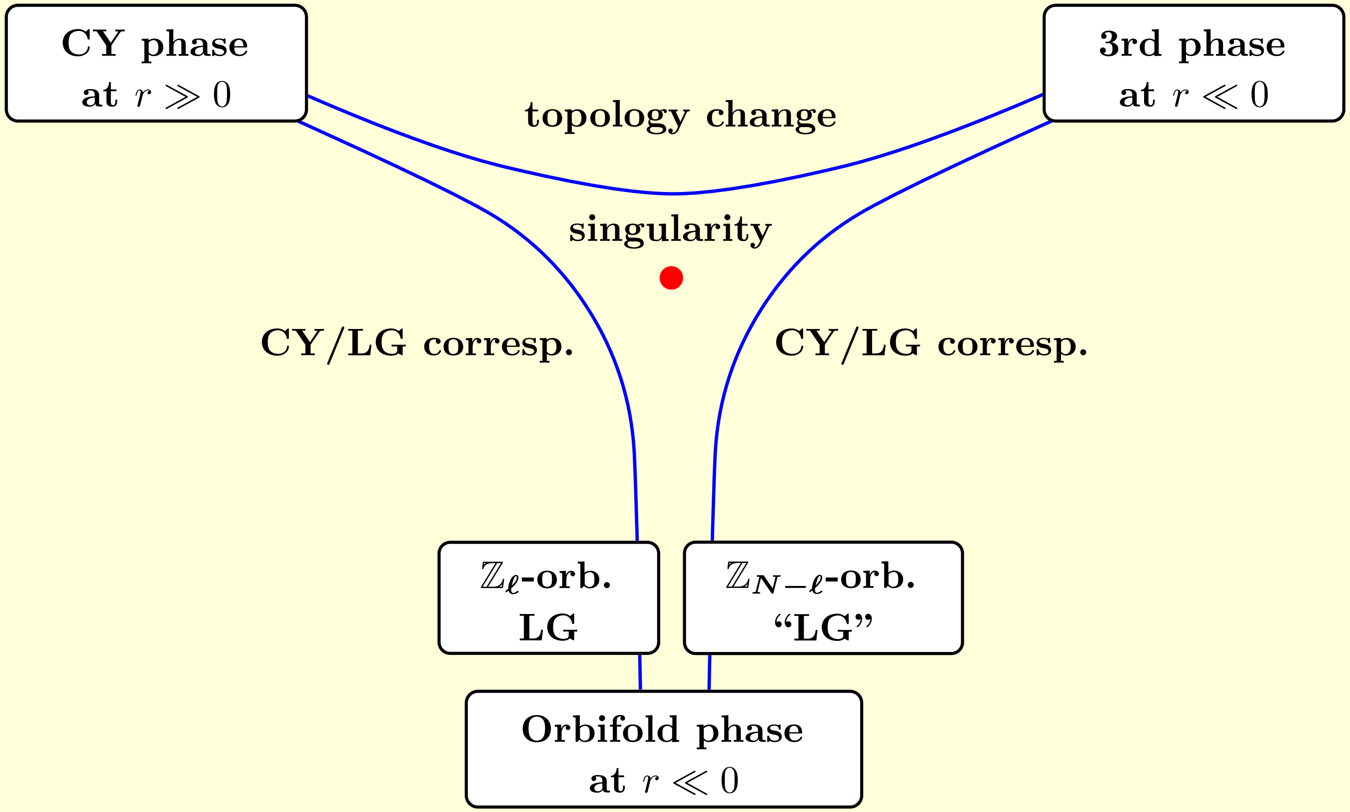
$$\mathcal{M}^2_{r<0} = \Big\{(s_i; p_2) \in \mathbb{C}^{N+2}\,\Big|\,\mathcal{D} = G_\ell = 0,\ r < 0\Big\}\Big/U(1)$$

Caution!: These effective theories are just approximately described

because we do not integrate out but ignore all massive mode.

CY/LG correspondence and topology change

The four theories are related to each other via CY/LG correspondence and topology change:



as a Conjecture

We also notice that we have obtained various massless effective theories by decomposing (not by integrating out) all massive modes. Thus they are just approximate descriptions.

T-dual description of the GLSM is also powerful

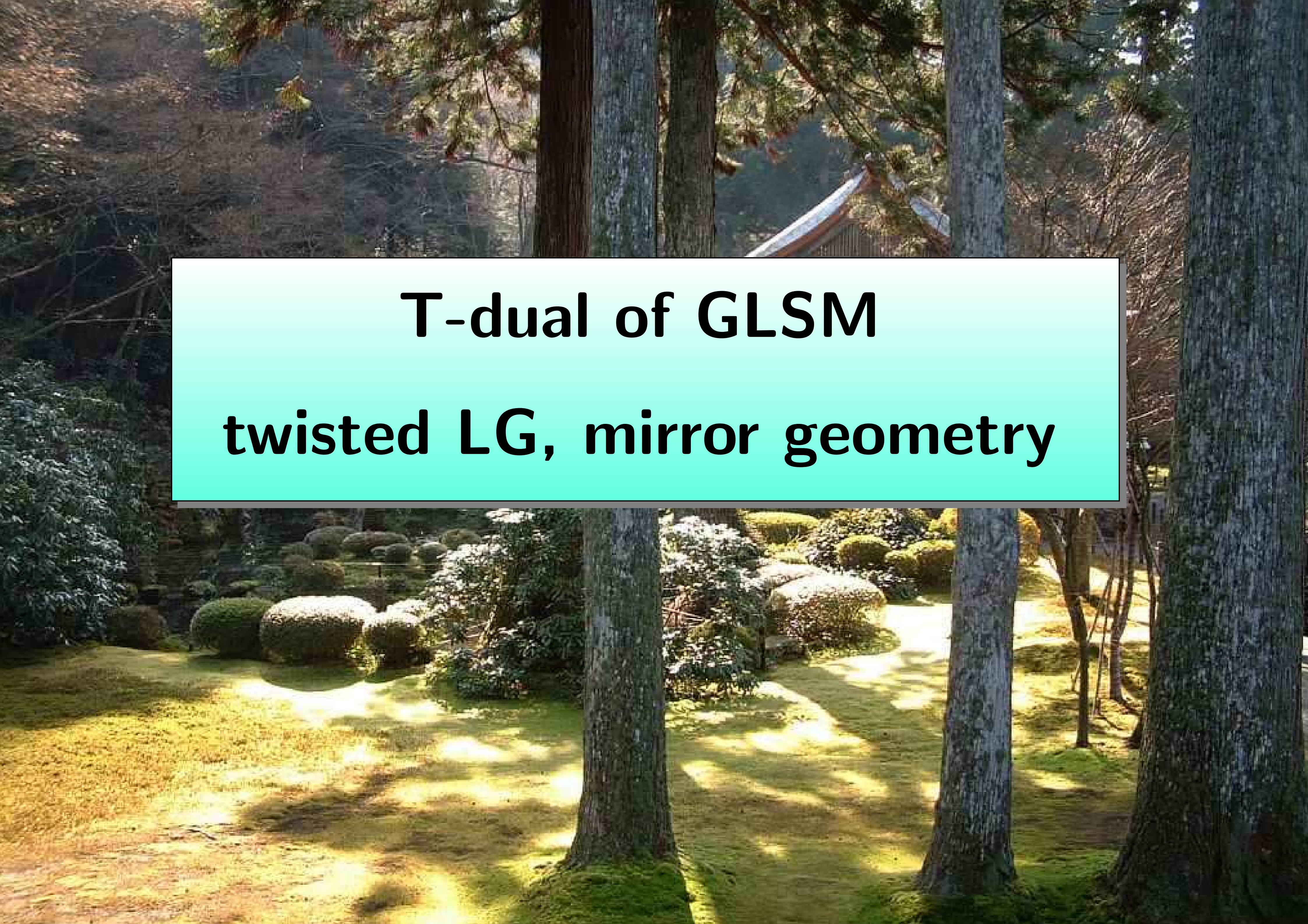
to investigate low energy theories.

Analyzing them

we will re-investigate the massless effective theories in the original GLSM.

T-dual of GLSM

twisted LG, mirror geometry



T-dual Theory

$$\mathscr{L} = \int d^4\theta \Big\{ -\frac{1}{e^2}\overline{\Sigma}\Sigma - \sum_a \Big(\frac{1}{2}(Y_a + \overline{Y}_a)\log(Y_a + \overline{Y}_a)\Big)\Big\} + \Big(\frac{1}{\sqrt{2}}\int d^2\widetilde{\theta}\,\widetilde{W} + c.c.\Big)$$

$$\widetilde{W} = \Sigma\Big(\sum_{i=1}^{N} Y_i - \ell Y_{P_1} - (N-\ell)Y_{P_2} - t\Big) + \sum_{i=1}^{N} e^{-Y_i} + e^{-Y_{P_1}} + e^{-Y_{P_2}}$$

We often use the following functional integral:

Period integral : $\widehat{\Pi} \equiv \int d\Sigma \prod_{i=1}^{N} dY_i\, dY_{P_1}\, dY_{P_2}\, (\ell\Sigma)\, \exp\big(-\widetilde{W}\big)$

roughly, this functional is a "partition function of topological theory"

chiral superfield	S_1	S_2	$\cdots$	S_N	P_1	P_2
$U(1)$ charge	1	1	$\cdots$	1	$-\ell$	$-N+\ell$
twisted chiral	Y_1	Y_2	$\cdots$	Y_N	Y_{P_1}	Y_{P_2}

where, $2\,\overline{\Phi}_a\, e^{2Q_aV}\,\Phi_a = Y_a + \overline{Y}_a$

$U(1)$ phase rotation symmetry on Φ_a ⇨ shift symmetry on Y_a: $Y_a \equiv Y_a + 2\pi i$

In the IR limit $e \to \infty$, the gauge field Σ is no longer dynamical and integrated out!

In order to perform this, we replace Σ to $\Sigma \to \dfrac{\partial}{\partial t}$ or $\Sigma \to \dfrac{\partial}{\partial Y_P}$

(via partial integration)

There are two ways to solve: $Y_P \equiv Y_{P_1}$ or $Y_P \equiv Y_{P_2}$.

We will obtain $(\mathbb{Z}_\ell)^*$- or $(\mathbb{Z}_{N-\ell})^*$-orbifolded theories, respectively.

$$\left\{ \begin{array}{rl} (\mathbb{Z}_\ell)^*\text{-orbifolded theory}: & \text{related to } W_{\rm LG}/\mathbb{Z}_\ell \\ (\mathbb{Z}_{N-\ell})^*\text{-orbifolded theory}: & \text{related to } W_{\rm LG}/\mathbb{Z}_{N-\ell} \end{array} \right. \quad \text{in the original GLSM side}$$

In order to avoid some confusions, we consider only $(\mathbb{Z}_\ell)^*$-orbifolded cases.

Twisted Landau-Ginzburg theory:

$$\widehat{\Pi} = \ell \frac{\partial}{\partial t} \int \prod_{i=1}^{N} \mathrm{d}Y_i \mathrm{d}Y_{P_1} \mathrm{d}Y_{P_2}\, \delta\Big(\sum_i Y_i - \ell Y_{P_1} - (N-\ell) Y_{P_2} - t \Big) \exp\Big(- \sum_i \mathrm{e}^{-Y_i} - \mathrm{e}^{-Y_{P_1}} - \mathrm{e}^{-Y_{P_2}} \Big)$$

Solve the δ-functional in terms of Y_{P_1}:

$$Y_{P_1} = \frac{1}{\ell} \Big\{ t - \sum_{i=1}^{N} Y_i + (N-\ell) Y_{P_2} \Big\}$$

Field re-definition preserving canonical measure in $\widehat{\Pi}$ (to avoid anomaly):

$$X_i \equiv \mathrm{e}^{-\frac{1}{\ell} Y_i}, \quad X_{P_2} \equiv \mathrm{e}^{\frac{N-\ell}{\ell} Y_{P_2}}, \quad X_i \rightarrow \omega_i X_i, \quad X_{P_2} \rightarrow \omega_{P_2} X_{P_2}, \quad (\mathbb{Z}_\ell)^N \text{ symmetry}$$

Thus we obtain the twisted LG superpotential:

$$\boxed{\Big\{ \widetilde{W}_\ell = X_1^\ell + \cdots + X_N^\ell + X_{P_2}^{-\frac{\ell}{N-\ell}} + \mathrm{e}^{t/\ell} X_1 \cdots X_N X_{P_2} \Big\} \Big/ (\mathbb{Z}_\ell)^N}$$

The negative power term describes $\mathcal{N}=2$ Kazama-Suzuki model on $SL(2,\mathbb{R})_k/U(1)$:

$$\frac{\ell}{N-\ell} = k = \frac{2}{Q^2}$$

Thus we argue that

this effective theory is the LG minimal model coupled to the KS model with $(\mathbb{Z}_\ell)^N$ orbifold symmetry

Twisted mirror geometry:

We replace $\ell\Sigma$ to $\dfrac{\partial}{\partial Y_{P_1}}$ and obtain

$$\widehat{\Pi} = \int \prod_{i=1}^{N} \mathrm{d}Y_i \, (\mathrm{e}^{-Y_{P_1}} \mathrm{d}Y_{P_1}) \, \mathrm{d}Y_{P_2} \, \delta\Big(\sum_i Y_i - \ell Y_{P_1} - (N-\ell) Y_{P_2} - t \Big) \exp\Big(- \sum_i \mathrm{e}^{-Y_i} - \mathrm{e}^{-Y_{P_1}} - \mathrm{e}^{-Y_{P_2}} \Big)$$

Re-defining the variables in order to obtain the canonical measure (to avoid anomaly):

$$\mathrm{e}^{-Y_{P_1}} = \widetilde{P}_1 \, , \quad \mathrm{e}^{-Y_a} = \mathrm{e}^{-t/\ell} \frac{\widetilde{P}_1 Z_a^{\ell}}{Z_1 \cdots Z_N} \, , \qquad \mathrm{e}^{-Y_{P_2}} = - \widetilde{P}_2 \, , \quad \mathrm{e}^{-Y_b} = \widetilde{P}_2 Z_b^{\ell}$$

We obtain

$$\boxed{\begin{aligned} \widetilde{\mathcal{M}}_{\ell} &= \Big\{ \{ \mathcal{F}(Z_i) = 0 \} / \mathbb{C}^* \, , \, \mathcal{G}(Z_b; u, v) = 0 \Big\} \Big/ (\mathbb{Z}_{\ell})^{N-2} \\ \mathcal{F}(Z_i) &= Z_1^{\ell} + \cdots + Z_{\ell}^{\ell} + \psi Z_1 \cdots Z_{\ell} \, , \quad \psi = \mathrm{e}^{t/\ell} Z_{\ell+1} \cdots Z_N \\ \mathcal{G}(Z_b; u, v) &= Z_{\ell+1}^{\ell} + \cdots + Z_N^{\ell} + 1 - uv \end{aligned}}$$

$Z_a \mapsto \lambda \, \omega_a \, Z_a$ for $a = 1, \cdots, \ell$ (homogeneous coordinates of $\mathbb{C}\mathrm{P}^{\ell-1}[\ell]$)

$Z_b \mapsto \omega_b \, Z_b$ for $b = \ell+1, \cdots, N$ (homogeneous coordinates of $\mathbb{C}^{N-\ell}$)

$$\omega_a^{\ell} = \omega_b^{\ell} = \omega_1 \cdots \omega_N = 1 \, , \qquad \lambda : \mathbb{C}^*\text{-value}$$

Return to the original GLSM

Recall the following two arguments:

- $\mathcal{N}=2$ SCFT on $SL(2,\mathbb{R})_k/U(1)$ is equivalent to $\mathcal{N}=2$ Liouville theory via T-duality
- If a CFT $\mathcal{C}$ has an abelian discrete symmetry group Γ, the orbifold CFT $\mathcal{C}'=\mathcal{C}/\Gamma$ has a symmetry group Γ' which is isomorphic to Γ. Furthermore a new orbifold CFT $\mathcal{C}'/\Gamma'$ is identical to the original CFT $\mathcal{C}$.

Thus we insist that

"{CFT on $\mathbb{C}^1$ $\otimes$ LG with $W_{\mathrm{LG}}=\langle p_1\rangle G_\ell(S)\}/\mathbb{Z}_\ell$" in the original GLSM

is described by

$\{\mathcal{N}=2$ Liouville theory coupled to the LG minimal model with $W_{\mathrm{LG}}\}/\mathbb{Z}_\ell$

as an exact effective theory

Summary and Discussions

Summary

- We found three non-trivial phases and four effective theories in the GLSM

  two CY sigma models

  two orbifolded LG theories coulped to 1-dim. SCFT

- We constructed four exact effective theories in the T-dual theory

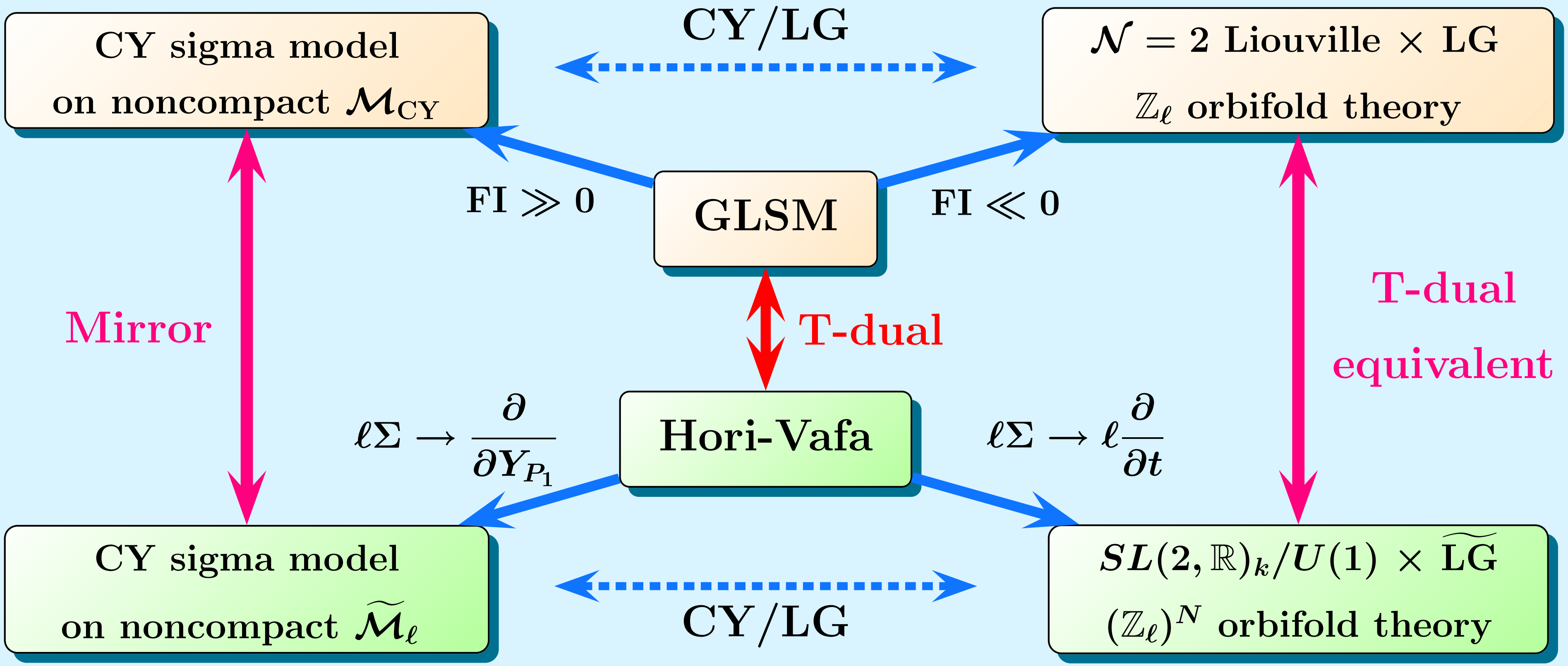
  two NLSMs on mirror CY geometries

  two orbifolded LG theories including a term with negative power $-k$

  This term represents a gauged WZW model

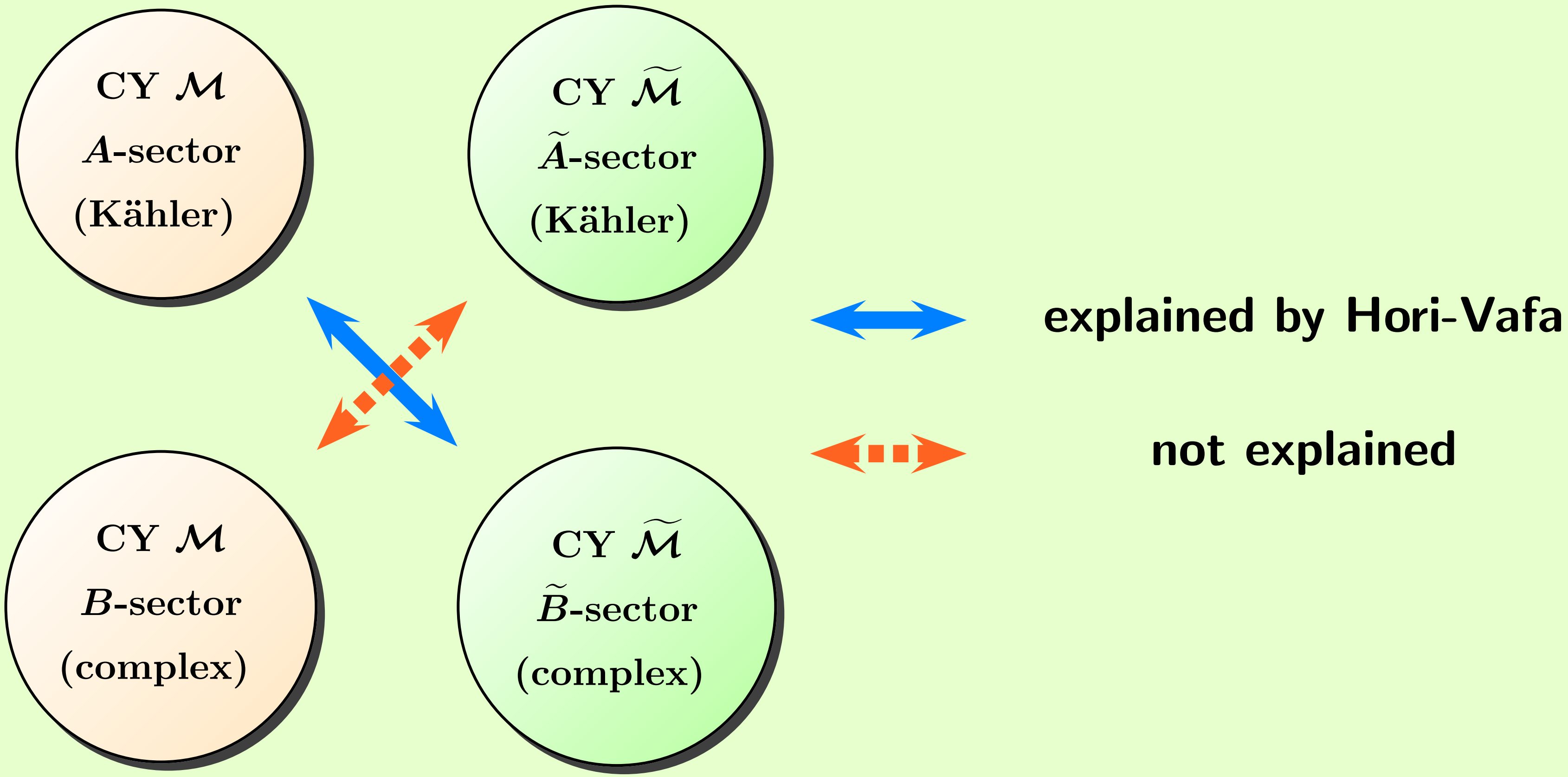
  on $SL(2,\mathbb{R})_k/U(1)$ at level k

- We argue that the LG theories in the orignal GLSM can be interpreted as $\mathcal{N}=2$ Liouville theories coupled to LG minimal models



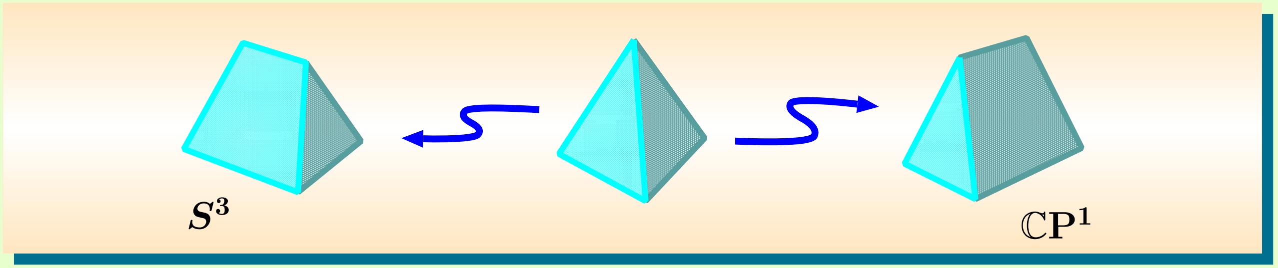
CY sigma model
on noncompact $\mathcal{M}_{\rm CY}$
CY/LG
$\mathcal{N} = 2$ Liouville $\times$ LG
$\mathbb{Z}_\ell$ orbifold theory
FI $\gg 0$
GLSM
FI $\ll 0$
Mirror
T-dual
T-dual
equivalent
$\ell\Sigma \to \frac{\partial}{\partial Y_{P_1}}$
Hori-Vafa
$\ell\Sigma \to \ell\frac{\partial}{\partial t}$
CY sigma model
on noncompact $\widetilde{\mathcal{M}}_\ell$
CY/LG
$SL(2,\mathbb{R})_k/U(1) \times \widetilde{\rm LG}$
$(\mathbb{Z}_\ell)^N$ orbifold theory

Discussions

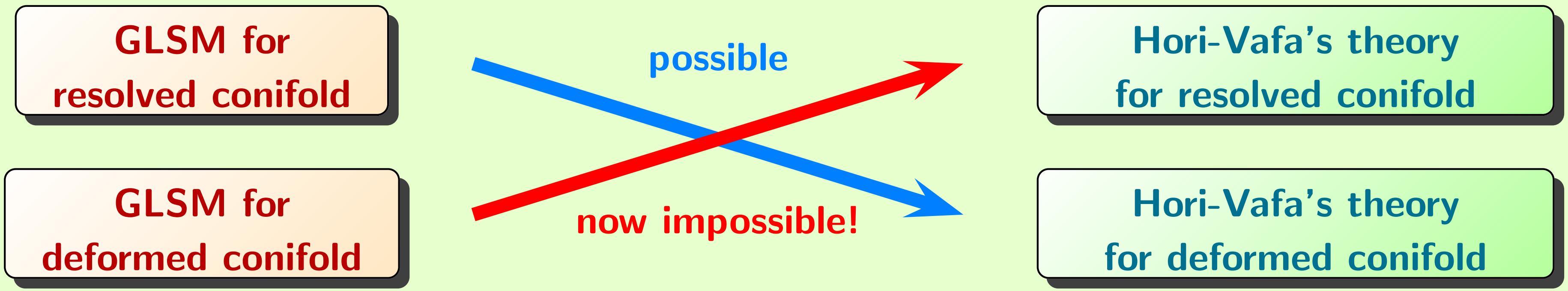


- Hori-Vafa's T-dual theory is only valid when we consider the GLSM without a superpotential or with a superpotential given simply by a homogeneous polynomial such as $W_{\rm GLSM} = P \cdot G_\ell(S)$. Even though the polynomial $G_\ell(S)$ has an additional symmetry, the period integral $\widehat{\Pi}$ cannot recognize the existence of this additional symmetry. Thus the T-dual theory does not map all structures of the CY $\mathcal{M}$ to the mirror geometry completely.

Example: resolved/deformed conifold

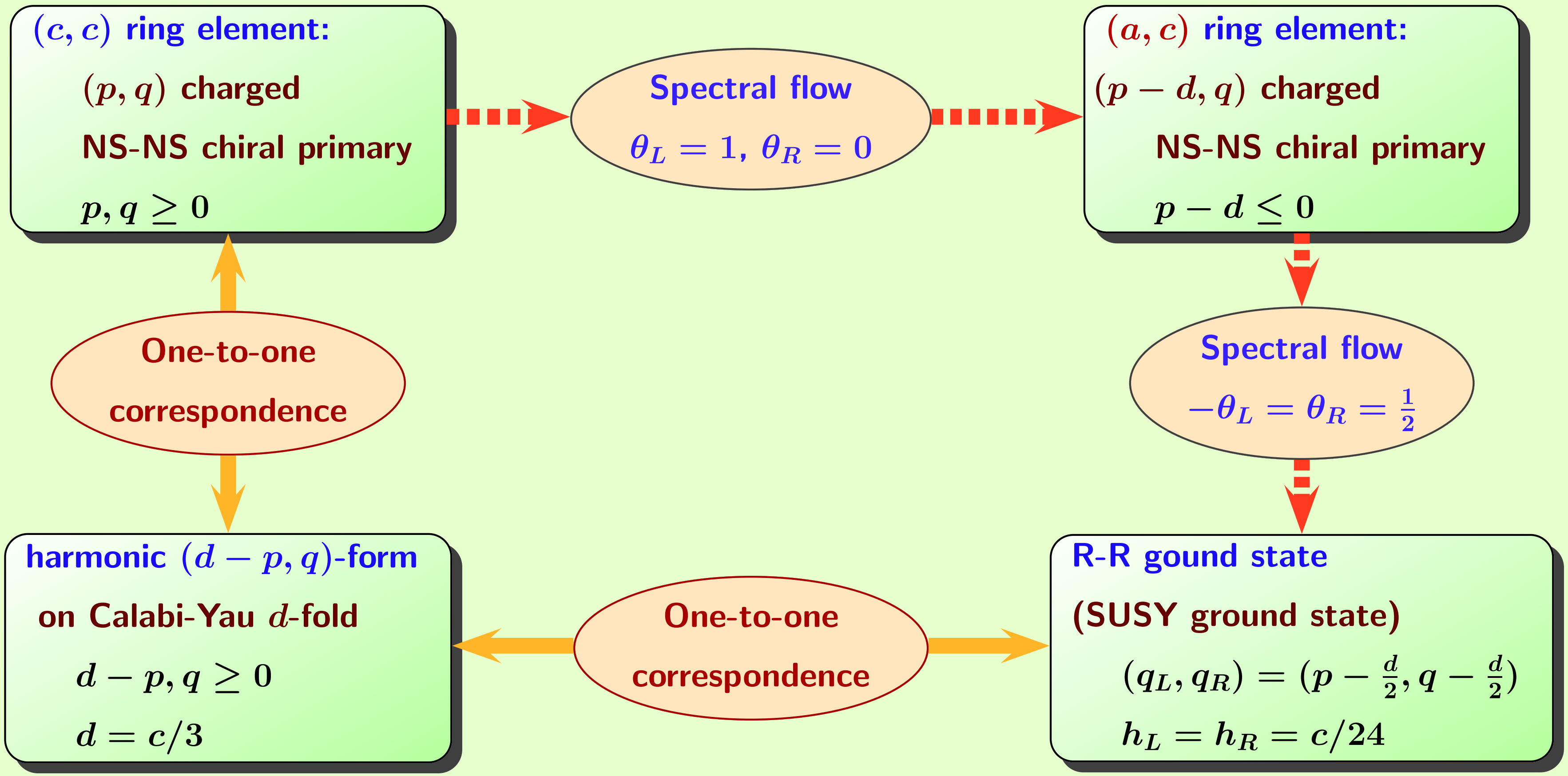


- **deformed conifold: deformation of complex moduli**
  resolved conifold: deformation of Kähler moduli




APPENDIX

$\mathcal{N}=(2,2)$ "LG" SCFT and (compact) Calabi-Yau geometry



I would like to apply the above strategy to "noncompact" CY varieties

Now we ignore precise definitions of "topological charges" (normalizability etc.)

Derivation of the T-dual Lagrangian

Here we briefly review the T-duality of a generic GLSM without any superpotentials. We start from

$$\mathscr{L}' = \int \mathrm{d}^4\theta \Big\{ -\frac{1}{e^2}\overline{\Sigma}\Sigma + \sum_a \Big(\mathrm{e}^{2Q_aV+B_a} - \frac{1}{2}(Y_a + \overline{Y}_a)B_a \Big) \Big\} + \Big(\frac{1}{\sqrt{2}} \int \mathrm{d}^2\widetilde{\theta}\,(-\Sigma\,t) + (c.c.) \Big) \,, \tag{1}$$

where Y_a and B_a are twisted chiral superfields and a real superfields B_a.

Integrating out twisted chiral superfields Y_a, we obtain $\overline{D}_+ D_- B_a = D_+ \overline{D}_- B_a = 0$, whose solutions are written in terms of chiral superfields Ψ_a and $\overline{\Psi}_a$ such as $B_a = \Psi_a + \overline{\Psi}_a$. When we substitute them into (1), $\mathscr{L}_{\mathrm{GLSM}}$ appears:

$$\mathscr{L}'\Big|_{B_a = \Psi_a + \overline{\Psi}_a} = \int \mathrm{d}^4\theta \Big\{ -\frac{1}{e^2}\overline{\Sigma}\Sigma + \sum_a \overline{\Phi}_a\, \mathrm{e}^{2Q_aV}\, \Phi_a \Big\} + \Big(\frac{1}{\sqrt{2}} \int \mathrm{d}^2\widetilde{\theta}\,(-\Sigma\,t) + (c.c.) \Big) \equiv \mathscr{L}_{\mathrm{GLSM}} \,, \tag{2}$$

where we re-wrote $\Phi_a = \mathrm{e}^{\Psi_a}$.

On the other hand, when we first integrate out B_a in $\mathscr{L}'$, we obtain $B_a = -2Q_aV + \log\Big(\dfrac{Y_a + \overline{Y}_a}{2}\Big)$. Let us insert these solutions into (1). By using a deformation $\int \mathrm{d}^4\theta\, Q_a V Y_a = -\dfrac{Q_a}{2} \int \mathrm{d}^2\widetilde{\theta}\, \overline{D}_+ D_- V Y_a = -\dfrac{Q_a}{\sqrt{2}} \int \mathrm{d}^2\widetilde{\theta}\, \Sigma Y_a$, we find that a Lagrangian of twisted chiral superfields appears:

$$\mathscr{L}_{\mathrm{T}} = \int d^4\theta \Big\{ -\frac{1}{e^2}\overline{\Sigma}\Sigma - \sum_a \Big(\frac{1}{2}(Y_a + \overline{Y}_a) \log(Y_a + \overline{Y}_a) \Big) \Big\} + \Big(\frac{1}{\sqrt{2}} \int \mathrm{d}^2\widetilde{\theta}\, \widetilde{W} + (c.c.) \Big) \,,$$

$$\widetilde{W} = \Sigma\Big(\sum_a Q_a Y_a - t \Big) + \mu \sum_a \mathrm{e}^{-Y_a} \,.$$

Notice that the twisted superpotential $\widetilde{W}$ is corrected by instanton effects where the instantons are the vortices of the gauge theory. In attempt to analyze a model satisfying $\sum_a Q_a = 0$, the scale parameter μ is omitted by field re-definitions.

Derivation of the twisted geometry

Let us study how to obtain the geometry with $\mathbb{Z}_\ell$-type orbifold symmetry. Replacing $\ell\Sigma$ in $\widehat{\Pi}$ to

$$\ell\Sigma \ \to \ \frac{\partial}{\partial Y_{P_1}} \, ,$$

we can perform the integration of Σ and obtain

$$\widehat{\Pi} \ = \ \int \prod_{i=1}^{N} \mathrm{d}Y_i \, (\mathrm{e}^{-Y_{P_1}} \mathrm{d}Y_{P_1}) \, \mathrm{d}Y_{P_2} \, \delta\Big(\sum_i Y_i - \ell Y_{P_1} - (N-\ell) Y_{P_2} - t \Big) \exp\Big(- \sum_i \mathrm{e}^{-Y_i} - \mathrm{e}^{-Y_{P_1}} - \mathrm{e}^{-Y_{P_2}} \Big) \, . \tag{3}$$

We perform the re-definitions of the variables Y_i, Y_{P_1} and Y_{P_2}:

$$\mathrm{e}^{-Y_{P_1}} \ = \ \widetilde{P}_1 \, , \quad \mathrm{e}^{-Y_a} \ = \ \widetilde{P}_1 \, U_a \quad \text{for } a = 1, \ldots, \ell \, , \qquad \mathrm{e}^{-Y_{P_2}} \ = \ \widetilde{P}_2 \, , \quad \mathrm{e}^{-Y_b} \ = \ \widetilde{P}_2 \, U_b \quad \text{for } b = \ell+1, \ldots, N \, .$$

Substituting these re-defined variables into (3), we continue the calculation:

$$\begin{aligned}
\widehat{\Pi} \ &= \ \int \prod_{i=1}^{N} \Big(\frac{\mathrm{d}U_i}{U_i} \Big) \, \mathrm{d}\widetilde{P}_1 \, \Big(\frac{\mathrm{d}\widetilde{P}_2}{\widetilde{P}_2} \Big) \, \delta\Big(\log \Big(\prod_i U_i \Big) + t \Big) \, \exp \Big\{ - \widetilde{P}_1 \Big(\sum_{a=1}^{\ell} U_a + 1 \Big) - \widetilde{P}_2 \Big(\sum_{b=\ell+1}^{N} U_b + 1 \Big) \Big\} \\
&= \ \int \prod_i \Big(\frac{\mathrm{d}U_i}{U_i} \Big) \, \mathrm{d}\widetilde{P}_2 \, \mathrm{d}u \, \mathrm{d}v \, \delta\Big(\log \Big(\prod_i U_i \Big) + t \Big) \, \delta\Big(\sum_a U_a + 1 \Big) \, \exp \Big\{ - \widetilde{P}_2 \Big(\sum_b U_b + 1 - uv \Big) \Big\} \\
&= \ \int \prod_i \Big(\frac{\mathrm{d}U_i}{U_i} \Big) \, \mathrm{d}u \, \mathrm{d}v \, \delta\Big(\log \Big(\prod_i U_i \Big) + t \Big) \, \delta\Big(\sum_a U_a + 1 \Big) \, \delta\Big(\sum_b U_b + 1 - uv \Big) \, ,
\end{aligned} \tag{4}$$

where we introduced new variables u and v taking values in $\mathbb{C}$ and used a following equation

$$\frac{1}{\widetilde{P}_2} \ = \ \int \mathrm{d}u \, \mathrm{d}v \, \exp \big(\widetilde{P}_2 \, uv \big) \, .$$

It is obvious that (4) still includes a non-canonical integral measure. Thus we perform further re-definitions such as

$$U_a \;=\; \mathrm{e}^{-t/\ell}\frac{Z_a^{\ell}}{Z_1 \cdots Z_N}\,, \qquad U_b \;=\; Z_b^{\ell}\,.$$

Note that the period integral (4) is invariant under the following transformations acting on the new variables Z_i:

$$Z_a \;\mapsto\; \lambda\,\omega_a\,Z_a\,, \quad Z_b \;\mapsto\; \omega_b\,Z_b\,, \qquad \omega_a^{\ell} \;=\; \omega_b^{\ell} \;=\; \omega_1 \cdots \omega_N \;=\; 1\,,$$

where λ is an arbitrary number taking in $\mathbb{C}^*$. The ω_i come from the shift symmetry of the original variables $Y_i \equiv Y_i + 2\pi i$. Combining these transformations we find that $\widehat{\Pi}$ has $\mathbb{C}^* \times (\mathbb{Z}_{\ell})^{N-2}$ symmetries. Substituting Z_i into (4), we obtain

$$\widehat{\Pi} \;=\; \int \frac{1}{\mathrm{vol.}(\mathbb{C}^*)} \prod_{i=1}^{N} \mathrm{d}Z_i\,\mathrm{d}u\,\mathrm{d}v\,\delta\Big(\sum_{a=1}^{\ell} Z_a^{\ell} + \mathrm{e}^{t/\ell} Z_1 \cdots Z_N\Big)\,\delta\Big(\sum_{b=\ell+1}^{N} Z_b^{\ell} + 1 - uv\Big)\,,$$

which indicates that the resulting mirror geometry is described by

$$\widetilde{\mathcal{M}}_{\ell} \;=\; \Big\{(Z_i;u,v) \in \mathbb{C}^{N+2} \,\Big|\, \{\mathcal{F}(Z_i) \;=\; 0\}/\mathbb{C}^*\,,\;\; \mathcal{G}(Z_b;u,v) \;=\; 0\Big\}\Big/(\mathbb{Z}_{\ell})^{N-2}\,,$$

$$\mathcal{F}(Z_i) \;=\; \sum_{a=1}^{\ell} Z_a^{\ell} + \psi Z_1 \cdots Z_{\ell}\,, \qquad \mathcal{G}(Z_b;u,v) \;=\; \sum_{b=\ell+1}^{N} Z_b^{\ell} + 1 - uv\,, \qquad \psi \;=\; \mathrm{e}^{t/\ell} Z_{\ell+1} \cdots Z_N\,.$$

This is an $(N-1)$-dimensional complex manifold.

The equation $\mathcal{F}(Z_i) = 0$ denotes that the complex variables Z_a consist of the degree ℓ hypersurface in the projective space: $\mathbb{CP}^{\ell-1}[\ell]$. This subspace itself is a compact CY manifold, which is parametrized by a parameter ψ which is subject to the equation $\mathcal{G}(Z_b;u,v) = 0$. Moreover we can also interpret that the total space is a noncompact CY manifold whose compact directions are described by Z_i, while the variables u and v run in the noncompact directions under the equations.

$(\mathbb{Z}_{N-\ell})^*$-orbifolded LG theory

Solve Y_{P_2} by using the constraint derived from integrating out Σ:

$$Y_{P_2} \;=\; \frac{1}{N-\ell}\Big\{ t - \sum_{i=1}^{N} Y_i + \ell Y_{P_1} \Big\}$$

Field re-definition preserving canonical measure in $\widehat{\Pi}$:

$$X_i \;\equiv\; \mathrm{e}^{-\frac{1}{N-\ell} Y_i} \,, \quad X_{P_1} \;\equiv\; \mathrm{e}^{\frac{\ell}{N-\ell} Y_{P_1}} \,, \quad X_i \;\to\; \omega_i X_i \,, \qquad X_{P_1} \;\to\; \omega_{P_1} X_{P_1} \,, \quad (\mathbb{Z}_{N-\ell})^N \text{ symmetry}$$

Thus we obtain the twisted LG superpotential:

$$\Big\{ \widetilde{W}_{N-\ell} \;=\; X_1^{N-\ell} + \cdots + X_N^{N-\ell} + X_{P_1}^{-\frac{N-\ell}{\ell}} + \mathrm{e}^{t/\ell} X_1 \cdots X_N X_{P_1} \Big\} \Big/ (\mathbb{Z}_{N-\ell})^N$$

negative power term = interpreted as $\mathcal{N}=2$ Kazama-Suzuki model on $SL(2,\mathbb{R})_k/U(1)$:

$$\frac{N-\ell}{\ell} \;=\; k \;=\; \frac{2}{Q^2}$$

Thus we argue that

this effective theory is the LG minimal model coupled to the KS model with $(\mathbb{Z}_{N-\ell})^N$ orbifold symmetry

$(\mathbb{Z}_{N-\ell})^*$-orbifolded algebraic geometry

We replace $\ell\Sigma$ to $\dfrac{\partial}{\partial Y_{P_2}}$ and obtain

$$\widehat{\Pi} \;=\; \int \prod_{i=1}^{N} \mathrm{d}Y_i \, \mathrm{d}Y_{P_1} \, (\mathrm{e}^{-Y_{P_2}} \mathrm{d}Y_{P_2}) \, \delta\Big(\sum_i Y_i - \ell Y_{P_1} - (N-\ell) Y_{P_2} - t \Big) \exp\Big(- \sum_i \mathrm{e}^{-Y_i} - \mathrm{e}^{-Y_{P_1}} - \mathrm{e}^{-Y_{P_2}} \Big)$$

Re-defining the variables in order to obtain the canonical measure, we obtain

$$\begin{aligned}
\widetilde{\mathcal{M}}_{N-\ell} \;&=\; \Big\{ F(Z_a; u, v) \;=\; 0 \,,\; \{ G(Z_i) \;=\; 0 \} / \mathbb{C}^* \Big\} \Big/ (\mathbb{Z}_{N-\ell})^{N-2} \\
F(Z_a; u, v) \;&=\; Z_1^{N-\ell} + \cdots + Z_{\ell}^{N-\ell} + 1 - uv \\
G(Z_i) \;&=\; Z_{\ell+1}^{N-\ell} + \cdots + Z_N^{N-\ell} + \psi Z_{\ell+1} \cdots Z_N \,, \quad \psi = \mathrm{e}^{t/(N-\ell)} Z_1 \cdots Z_{\ell}
\end{aligned}$$

$$\begin{aligned}
Z_a \;&\mapsto\; \omega_a \, Z_a \qquad \text{for} \quad a \;=\; 1, \cdots, \ell \qquad &&\text{(homogeneous coordinates of } \mathbb{C}^{\ell}\text{)} \\
Z_b \;&\mapsto\; \lambda \, \omega_b \, Z_b \qquad \text{for} \quad b \;=\; \ell+1, \cdots, N \qquad &&\text{(homogeneous coordinates of } \mathbb{CP}^{N-\ell-1}[N-\ell]\text{)}
\end{aligned}$$

$$\omega_a^{N-\ell} \;=\; \omega_b^{N-\ell} \;=\; \omega_1 \cdots \omega_N \;=\; 1 \,, \qquad \lambda \;:\; \mathbb{C}^*\text{-value}$$

linear dilaton CFT and Liouville theory

$$\mathbb{R}^{9,1} = \underbrace{\mathbb{R}^{d-1,1}}_{\text{free SCFT}} \times \underbrace{X^{2n}}_{\text{singular CY}} \sim \mathbb{R}^{d-1,1} \times \underbrace{\mathbb{R}_\phi \times S^1}_{\text{linear dilaton SCFT}} \times \underbrace{\mathcal{M}/U(1)}_{\mathcal{N}=2\ \text{Landau-Ginzburg}}$$

linear dilaton: $\Phi = -\frac{Q}{2}\phi$

Landau-Ginzburg: $W_{\text{LG}} = F(Z_a), \;\; F(\lambda^{r_a} Z_a) = \lambda F(Z_a)$

$$c_{\text{total}} = c_d + c_{\text{dilaton}} + c_{\text{LG}} \quad \to \quad 15 = \frac{3}{2}d + \left(\frac{3}{2} + 3Q^2\right) + 3\sum_{a=1}^{n+1}(1 - 2r_a)$$

$$\boxed{\begin{array}{c} \mathcal{N}=2\ \text{“LG” on } \mathbb{R}_\phi \times S^1 \times \mathcal{M}/U(1):\ W = -\mu Z_0^{-k} + F(Z_a) \\ k = \dfrac{1}{r_\Omega} = \dfrac{2}{Q^2}, \qquad r_\Omega \equiv \sum_a r_a - 1 \end{array}}$$

linear dilaton SCFT on $\mathbb{R}_\phi \times S^1$ $\equiv$ “LG” with 「$W = -\mu Z_0^{-k}$」

$\equiv$ Kazama-Suzuki model on $SL(2,\mathbb{R})_k/U(1)$

$\overset{\text{T-dual}}{\equiv}$ Liouville theory of charge Q

Strictly, we consider the Euclidean black hole: $SL(2,\mathbb{R})_k/U(1) \to [SL(2,\mathbb{C})_k/SU(2)]/U(1)$