1+1d Adjoint QCD and non-invertible topological lines

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based on WIP with

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Introduction and summary

- 1+1d Adj. QCD was studied extensively in '90s:
  [Kutasov '93][Boorstein, Kutasov '94],[Kutasov, Schwimmer '95],
  [Gross, Klebanov, Matytsin, Smilga ’95], [Gross, Klebanov, Hashimoto ’98]...
- When massless, claimed to be in **deconfined** phase, although fermion cannot screen a probe in fundamental representation.
- [Cherman, Jacobson, Tanizaki, Unsal ’19] revisited the problem.
- They analyzed symmetry (incl. one-form) and its anomaly. Concluded it is in confined (or partially deconfined) phase when $N \geq 3$.
- Symmetry is not enough. **Non-invertible topological line** accounts for deconfinement.
- First (non-topological) **gauge theory** example of non-invertible top. op.

1+1d massless Adjoint QCD

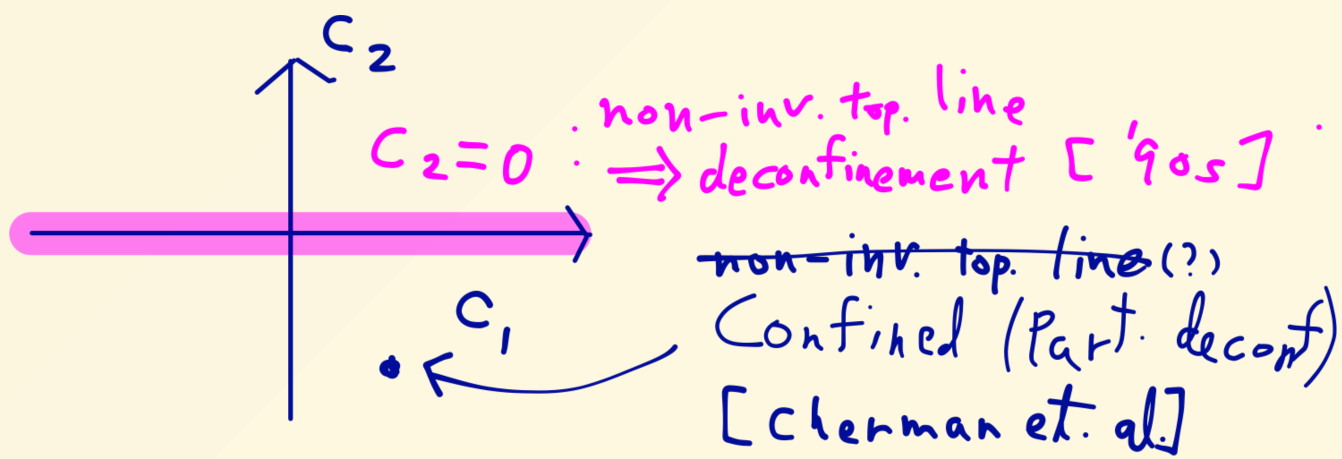
- 1+1d gauge theory with $G = \mathrm{SU}(N)$ with massless Majorana fermions $(\psi_L^{i\bar{j}}, \psi_R^{i\bar{j}})$ $(\sum_i \psi_{L,R}^{i\bar{i}} = 0)$
- $\mathcal{L} = \mathrm{Tr}\left(-\frac{1}{4g^2}F^2 + \mathrm{i}\psi_L \partial \psi_L + \mathrm{i}\psi_R \bar{\partial} \psi_R + j_L A_z + j_R A_{\bar{z}}\right)$
- $j_{L,R}^{i\bar{j}} = \sum_k \psi_{L,R}^{i\bar{k}} \psi_{L,R}^{k,\bar{j}}$
- Symmetry: $\mathbb{Z}_2^C \times \mathbb{Z}_2^\chi \times \mathbb{Z}_2^F$ $(\times \mathbb{Z}_N^{(1)}$: one-form (a.k.a. center) symmetry)
- $c = 0$: gapped

Quartic couplings

- Two independent classically marginal couplings preserving all the symmetry
- $\mathcal{L}_q = c_1\mathcal{O}_1 + c_2\mathcal{O}_2$
  $\mathcal{O}_1 = \mathrm{Tr}(\psi_+\psi_+\psi_-\psi_-) = \mathrm{Tr} j_L j_R,$
  $\mathcal{O}_2 = \left((\mathrm{Tr}(\psi_+\psi_-))^2 - \frac{2}{N}\mathrm{Tr}(\psi_+\psi_+\psi_-\psi_-)\right)$
- In the N^2-1 free fermion theory, $\mathcal{O}_2$ is a sum of $SU(N)_N$ primaries
- **Fusion rule** : $\langle \mathcal{O}_2(0)\, j_L(z_1) j_L(z_2)\cdots j_R(w_1) j_R(w_2)\cdots\rangle = 0$
- **No Feynman diagram** that can generate $\mathcal{O}_2$ with $j_L A_z + j_R A_{\bar{z}}$ and $\mathcal{O}_1$ coupling in adj QCD!

Protection by non-invertible line

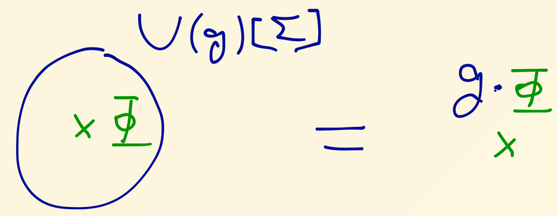
- What protects $\mathcal{O}_2$ from radiative generation?
- There is **no symmetry** that $\mathcal{O}_2$ violates.
- We claim that **non-invertible top. lines** protects it.
- The same set of lines also explains **deconfinement**.
- Parameter space:



- We expect that $\mathcal{O}_2$ def. breaks all the non-invertible lines and thus leads us to the picture of [Cherman, Jacobson, Tanizaki, Unsal '19] but have not succeeded to proof.

Symmetry and top. op.s

- Symmetry $G \implies$ Topological codim.-1 op $U(g)[\Sigma]$ for $g \in G$
  For $e^{\mathrm{i}\alpha} \in \mathrm{U}(1)$, $U(e^{\mathrm{i}\alpha})[\Sigma] = e^{\mathrm{i}\alpha \int_\Sigma J_\mu \mathrm{d}S^\mu}$

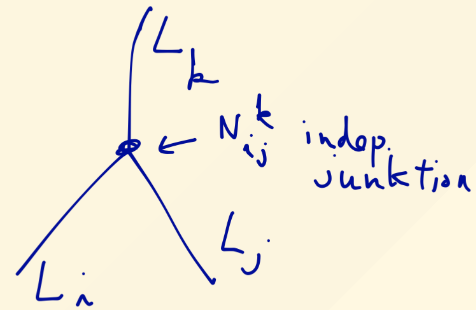


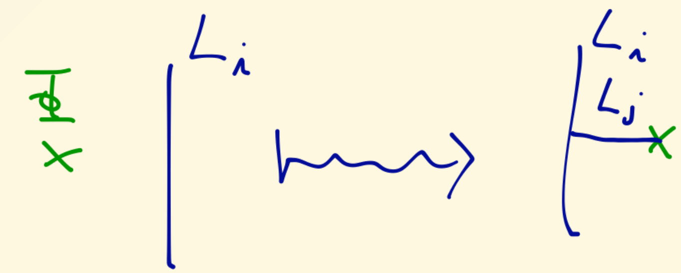
- $U(g)[\Sigma]$ is **invertible**: $U(g)[\Sigma]U(g^{-1})[\Sigma] = \mathbf{1}$
- "Higher-form" symmetry $\iff$ invertible top. op. with **higher codimension**.
  [Gaiotto,Kapustin,Seiberg,Willett '14]
- Not all topological operators have its inverse: **non-invertible** top. op.s.

Non-invertible topological lines

- Top. lines have **fusion rule**:

$$L_i \,\Big|\; \Big|\, L_j = \sum_k N_{ij}^k \,\Big|\, L_k$$





- Data of lines and topological junctions = **Fusion category** (e.g. Verlinde lines)

- Should be regarded as **generalization of symmetry**, as they shares key features with symmetry (+anomaly): gauging, **RG flow invariance**.

  [Brunner, Carqueville, Plencner '14],[Bhardwaj, Tachikawa, '17],[Chang, Lin, Shao, Wang, Yin, '18]

- E.g. Tricritical ($c = \frac{7}{10}$) Ising + $\sigma'_{\frac{7}{16},\frac{7}{16}}$ relevant perturbation preserves W line with fusion $W^2 = 1 + W \implies$ asymmetric 2 vacua

  [Chang, Lin, Shao, Wang, Yin, '18]

- Massless Adj. QCD is another example.

Outline

- Charge q massless Schwinger model
- Non-abelian bosonization
- Non-invertible lines and confinement in 1+1d massless adj. QCD

Charge q massless Schwinger model

- 1+1d $\mathrm{U}(1)$ gauge theory with charge q massless Dirac fermion Ψ_q, $\Psi_q \to e^{\mathrm{i}q\alpha}\Psi_q$
- (Ordinary) Symmetry: $\mathbb{Z}_2^C \times \mathbb{Z}_q^\chi$
- $\mathbb{Z}_q \subset \mathrm{U}(1)$ acts trivially on Ψ_q: $\mathbb{Z}_q^{(1)}$ one-form (a.k.a. center) symmetry
- Wilson line $W_p = e^{2\pi \mathrm{i} p \oint A}$: worldline of heavy probe with charge p
- W_q is screened by Ψ_q and deconfined.
- How about W_p when $p \neq 0 \mod q$?

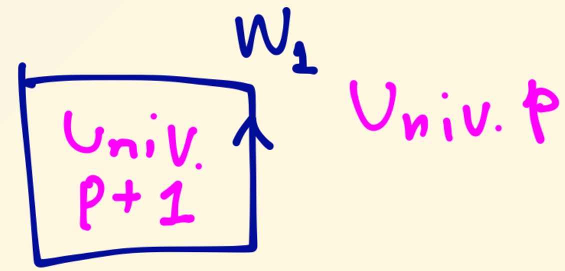
One-form symmetry in 1+1d and "Universe"

- The electric field $\frac{1}{e^2}F_{01}$ (classically in $\mathbb{Z}$) fluctuates because of Ψ_q, but jumps only by q.
- $U_k = e^{\frac{2\pi i k}{qe^2}F_{01}}$ is $\mathbb{Z}_q \subset \mathrm{U}(1)$ valued **topological** local (codim-2) operator
- Interpreted as the **symmetry operator** for $\mathbb{Z}_q^{(1)}$
- Clustering energy eigenstates (on $\mathbb{R}$) diagonalizes U_k: $U_k|p\rangle = e^{\frac{2\pi i k p}{q}}|p\rangle$
- Even on S^1, $|p_1\rangle$ and $|p_2\rangle$ does not mix if $p_1 \neq p_2 \mod q$:
  $\langle p_1|U_1 U(t)|p_2\rangle_{S^1} = e^{\frac{2\pi i p_1}{q}}\langle p_1|U(t)|p_2\rangle_{S^1} = e^{\frac{2\pi i p_2}{q}}\langle p_1|U(t)|p_2\rangle_{S^1}$
- No domain wall between $|p_1\rangle$ and $|p_2\rangle$ with **finite tension**
- Separated sectors even on **compact** space: **"universe"**

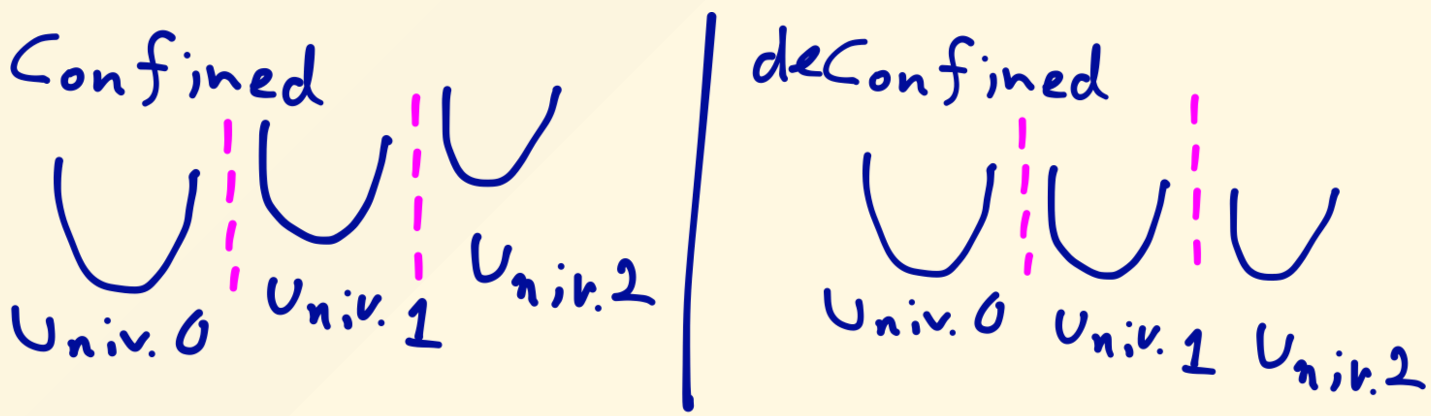
"Universe" and (de)confinement

- Wilson line (worldline of infinitely heave partible) separates "universes":
  $U_k W_p = e^{\frac{2\pi i k p}{q}} W_p U_k$

- Wilson loop contains another "universe" in it:



- $E_p \neq E_{p+1} \implies$ area law, confinement
  $E_p = E_{p+1} \implies$ perimeter law, deconfinement

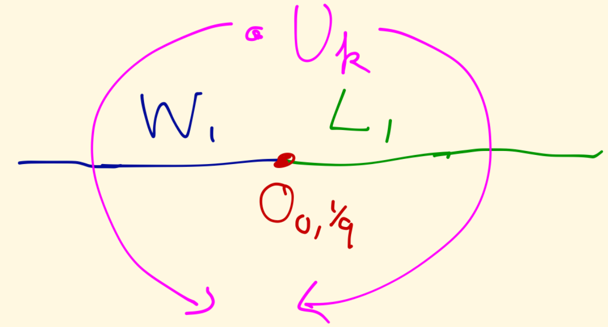


Abelian bosonization

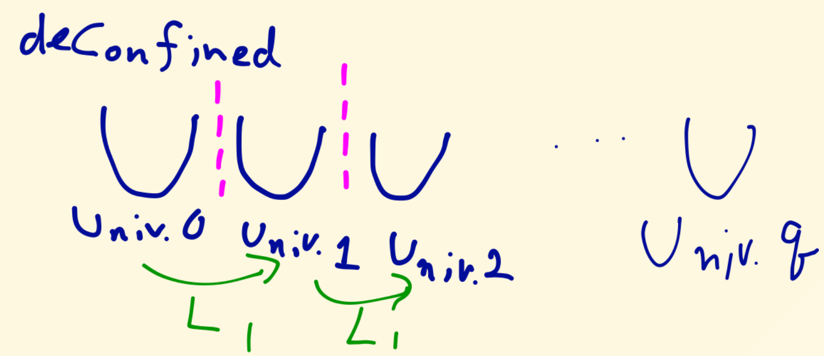
- A way to study the charge q Schwinger model is the bosonization: Dirac fermion $\Psi \Longleftrightarrow \phi$, where ϕ: **periodic scalar** (set to be 2π)
- $\mathcal{O}_{n,w} = e^{in\phi + iw\tilde{\phi}}$ $\Delta = n^2 + \frac{1}{4}w^2, S = nw, Q = wq, \Psi_q = \mathcal{O}_{\frac{1}{2},1}$
- To be precise, the duality is valid only after the spin-structure is summed in the fermion side.
- In the Schwinger model the spin-structure sum is a part of $U(1)$ gauge group
- The dual description is: $\frac{1}{8\pi}(\partial\phi)^2 - \frac{1}{4e^2}F^2 + \frac{q}{2\pi}\phi F$
- $\mathbb{Z}_q^{\chi} : \phi \to \phi + \frac{2\pi k}{q}$ for $k \in \mathbb{Z}_q^{\chi}$.
- Naively, IR limit seems equivalent to $e \to \infty$. If true, theory is BF theory (G/G TQFT with $G = U(1)_q$) describing q vacua $\Longrightarrow$ **deconfined**.
- **UV reason?**

$\mathbb{Z}_q^{\chi} \times \mathbb{Z}_q^{(1)}$ anomaly and deconfinement

- $\mathcal{O}_{0,\frac{1}{q}}$: **defect operator** at the edge of $\mathbb{Z}_q^{\chi}$ line L_1 in free boson, $Q = 1$.
  $\mathcal{O}_{n,w}(z)\mathcal{O}(0)_{0,\frac{1}{q}} = e^{\frac{2\pi i n}{q}}\mathcal{O}_{n,w}(e^{2\pi i}z)\mathcal{O}_{0,\frac{1}{q}}(0)$
- After gauging $\mathrm{U}(1)$, $\mathcal{O}_{0,\frac{1}{q}}$ connects W_1 and L_1:



- $U_k W_p = e^{\frac{2\pi i k p}{q}} W_p U_k \implies U_k L_p = e^{\frac{2\pi i k p}{q}} L_p U_k$: $\mathbb{Z}_q^{\chi} \times \mathbb{Z}_q^{(1)}$ **anomaly**
- L_1 is **topological**:
  $L_1|\psi\rangle$ and $|\psi\rangle$ have degenerate energy:



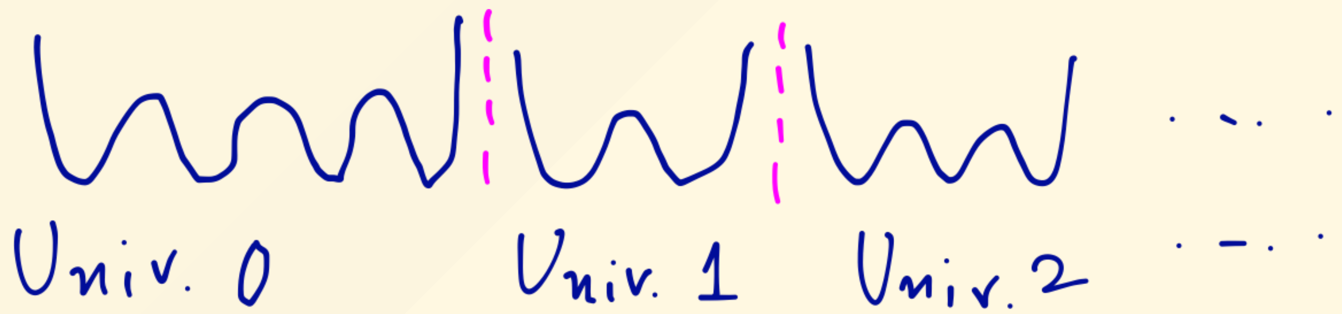
- Adj QCD has a smiliar story but requires to consider **non-invertible** top. lines.

Nonabelian bosonization

- We would like to repeat a similar analysis for massless adjoint QCD with $\mathrm{SU}(N)$ gauge group.
- Dualize $N^2 - 1$ Maj. fermions while keeping the $\mathrm{SU}(N)$ symmetry manifest.
  $\Longrightarrow$ **Nonabelian bosonization** [Witten '84]
- $n\,\psi$ (Maj.) $/(-1)^F \Longleftrightarrow \mathrm{Spin}(n)_1$ WZW model [Ji, Shao, Wen '19]
- $\mathrm{PSU}(N) \subset \mathrm{Spin}(N^2-1)$, $\widehat{\mathfrak{su}}(N)_N \subset \widehat{\mathfrak{spin}}(N^2-1)_1$:
  conformal embedding ($c(\widehat{\mathfrak{su}}(N)_N) = c(\widehat{\mathfrak{spin}}(N^2-1)_1)$)
- (Adj. QCD with $g_{\mathrm{YM}} \to \infty$)$/(-1)^F \Longleftrightarrow \mathrm{Spin}(N^2-1)_1/\mathrm{SU}(N)_N$ coset TQFT
- "Gauge back" $(-1)^F$ by gauging $\mathbb{Z}_2^{\mathrm{spinor}}$ with Arf twist.
  [Thorngren '18],[Karch, Tong, Turner '19]
- Adj. QCD with $g_{\mathrm{YM}} \to \infty \Longleftrightarrow \mathrm{Spin}(N^2-1)_1/\mathrm{SU}(N)_N/_{\mathrm{Arf}}\mathbb{Z}_2^{\mathrm{spinor}}$
  Precise version of bosonization prediction by [Kutasov '93],[Boorstein, Kutasov '94], [Kutasov, Schwimmer '95]

$\mathrm{Spin}(N^2-1)_1/\mathrm{SU}(N)_N/_{\mathrm{Arf}}\mathbb{Z}_2^{\mathrm{spinor}}$

- Spin-TQFT due to the Arf twist.
- Coset counting $\implies$ 2^{N-1} **vacua**. :[Kutasov '93]
  Most of them are not because of SSB
- All the N universes (due to $\mathbb{Z}_N^{(1)}$) are degenerate = **deconfined**.

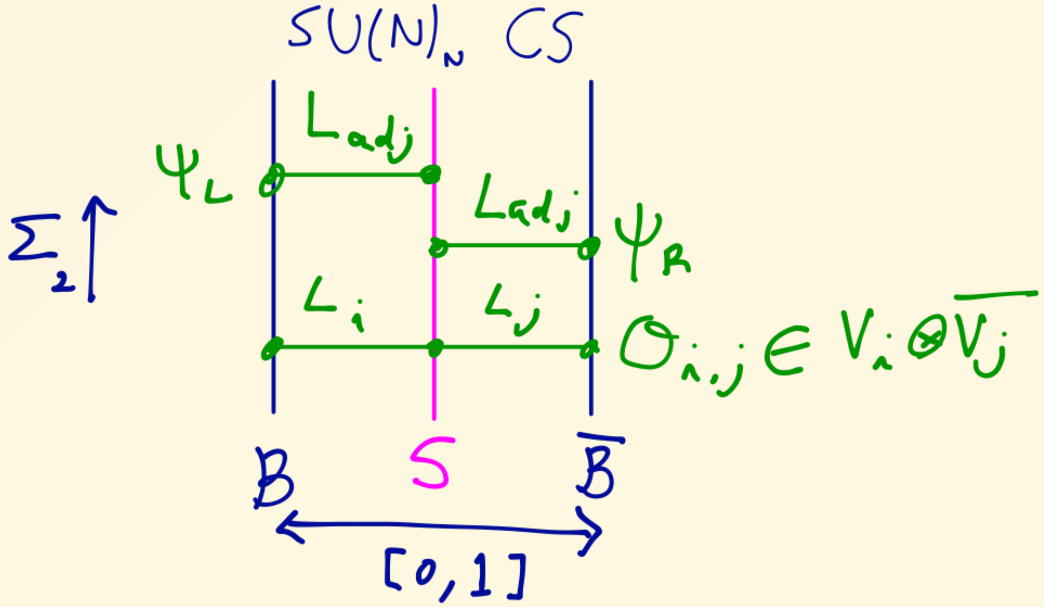


- Naively IR limit = $g \to \infty$, as g is super-renormalizable. However it is not very clear whether the flow generate other terms in the strongly coupled regime.
- **UV reason** of deconfinement and exponentially many vacua? : **Topological lines**
- Constrain possible IR TQFTs

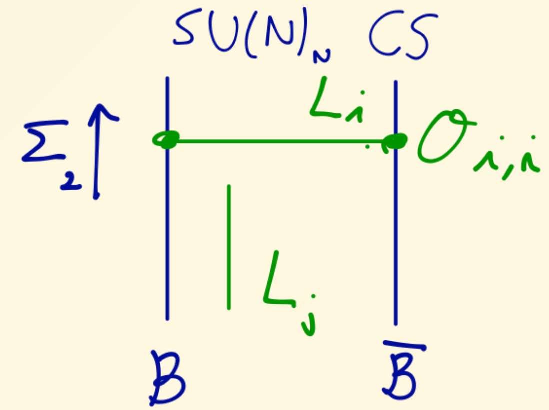
Fermions as $\mathfrak{su}(N)_N$ RCFT

- $N^2 - 1$ Majorana fermions $\supset \widehat{\mathfrak{spin}}(N^2-1)_1 \supset \widehat{\mathfrak{su}}(N)_N$
- Topological lines in adj QCD = $\mathfrak{su}(N)$ **preserving top. lines** in fermions
- $\mathfrak{su}(N)_N$ **non-diagonal (spin-)RCFT**
- $\psi_L^{i\bar{j}} \in V_{\mathbf{adj}} \otimes \overline{V}_0, \;\; \psi_R^{i\bar{j}} \in V_0 \otimes \overline{V}_{\mathbf{adj}}, \quad \mathcal{H}_{\mathrm{NSNS}} = \bigoplus_{k,l} Z_{k,l} V_k \otimes \overline{V}_l$
- Non-diagonal RCFT = CS theory on a interval with surface op. insertion:

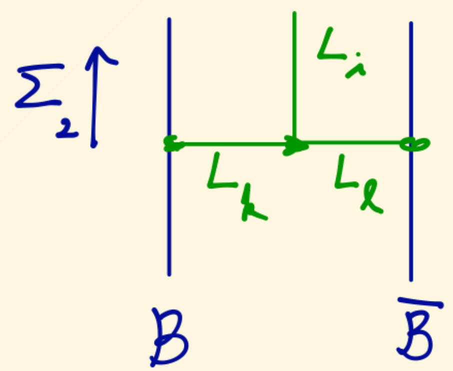
  [Kapustin Saulina '10], [Fuchs, Schweigert, Valentino '12], [Carqueville, Runkel, Schaumann '17]

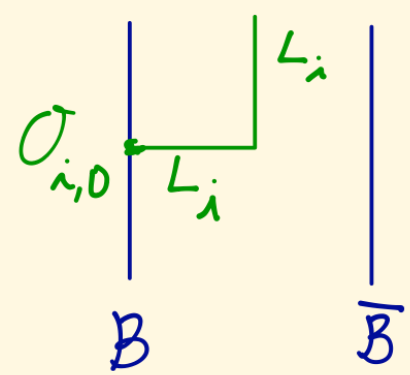


Verlinde lines in diagonal RCFT



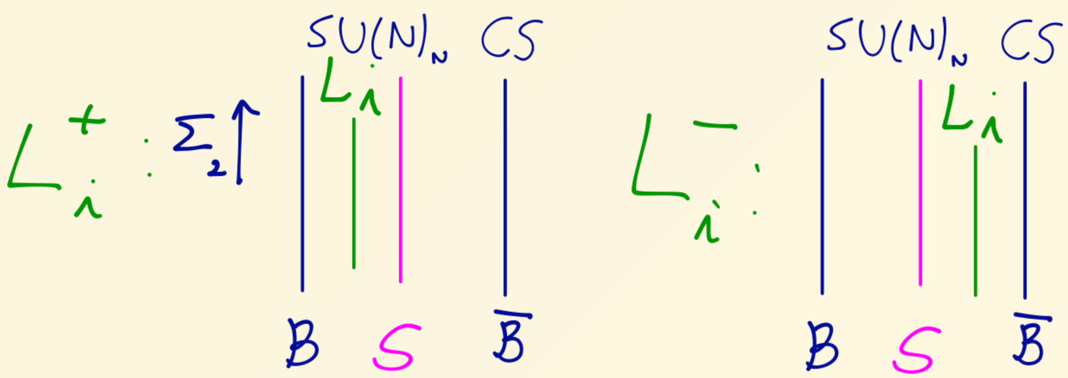
- Diagonal RCFT = CS theory on a interval (S is trivial).
- $\mathcal{O}_{i,i}$: Line L_i bridging boundaries
- Chiral alg. pres. topological line in RCFT = topological line in CS along Σ_2: **Verlinde line** ($O(2^N)$ of them)
  (L_i is the topological Wilson line of the auxiliary gauge field in 3d bulk. Not to be confused with the Wilson line W_i of the physical gauge field in adj QCD.)
- $L_i \otimes L_j = \bigoplus_k N_{i,j}^k L_k$
- **Defect operator** at the edge of L_i: $\bigoplus_{k,l} N_{i,k}^l V_k \otimes \overline{V}_l$:



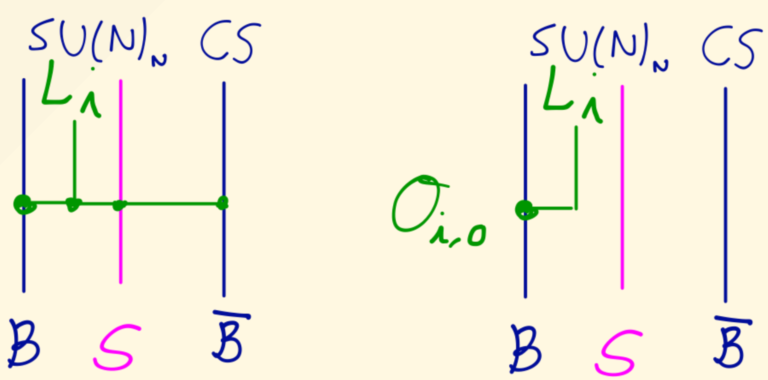


$SU(N)_N$ preserving topological lines in $\psi^{i\bar{j}}$

- Subset of topological lines : $L_i^{\pm}$ defined by



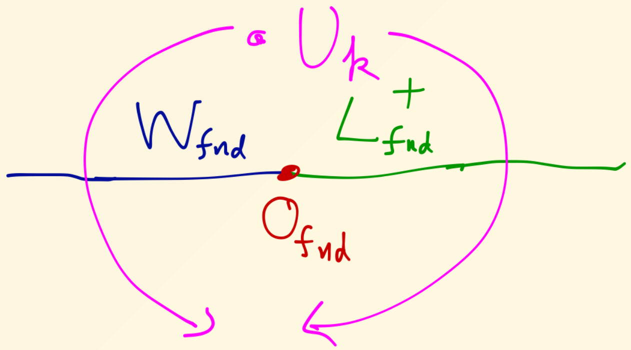
- Defect operator at the edge of L_i^+: $\bigoplus_{k,l,m} N_{l,i}^{k} Z_{k,m} V_l \otimes \overline{V}_m$



- In particular, $\mathcal{O}_i \in V_i \otimes \overline{V}_0$ always exists.

Topological line - $\mathbb{Z}_N^{(1)}$ mixed anomaly

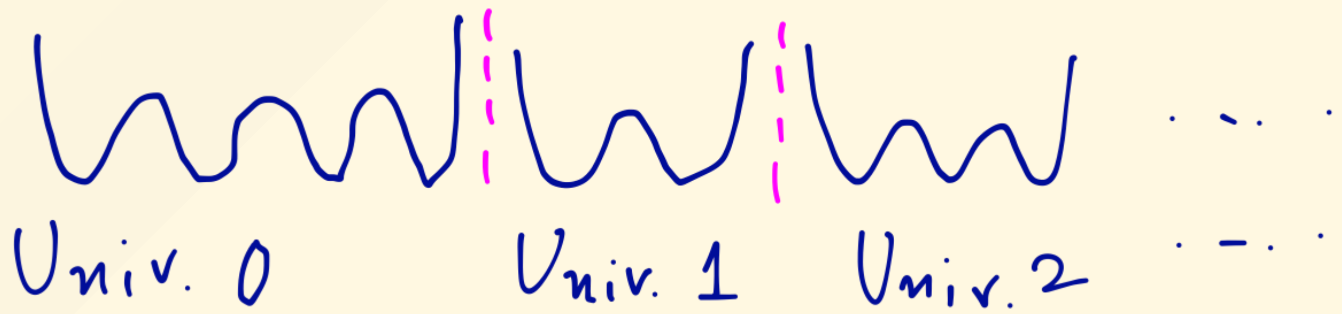
- L^+_{fnd} in free $\psi^{i\bar{j}}$ theory have the defect op. $\mathcal{O}_{\mathrm{fnd},0}$, which is in fnd of $\mathrm{SU}(N)$.
- When gauging $\mathrm{SU}(N)$, $\mathcal{O}_{\mathrm{fnd},0}$ becomes a **line changing operator** between W_{fnd} and L^+_{fnd}:



- $\mathbb{Z}_N^{(1)}$ one-form sym. acts on Wilson line: W_{fnd} by $U_k W_{\mathrm{fnd}} = e^{\frac{2\pi ik}{N}} W_{\mathrm{fnd}} U_k$
- $U_k L^+_{\mathrm{fnd}} = e^{\frac{2\pi ik}{N}} L^+_{\mathrm{fnd}} U_k$: **"(non-invertible) top. line - $\mathbb{Z}_N^{(1)}$ mixed anomaly"**
- $|0\rangle$ and $L_{\mathrm{fnd}}|0\rangle$ are degenerate and in different universes: **Deconfinement**

IR TQFT?

- The IR TQFT fixed point should admit the whole set of $\mathrm{SU}(N)$ preserving top. lines in $\psi^{i\bar{j}}$ theory.
- A candidate is $\mathrm{Spin}(N^2-1)/SU(N)/_{\mathrm{Arf}}\mathbb{Z}_2$ (= CS theory on S^1 with S insertion). **Other candidates**?
- The full structure of the lines (fusion category) is complicated.
- Classifying TQFTs that admit given a set of lines is not easy. ($\cong$ classifying modular invariants of the chiral algebra ($\mathfrak{su}(N)_N$))
- Analysing small N ($\sim 4, 5$).



Summary and prospect

- 1+1d massless adj. QCD has many ($\mathcal{O}(2^N)$) **topological line operators**, most of which are non-invertible.
- Topological line is an interface between different "universes" due to **"top. line - $\mathbb{Z}_N^{(1)}$ mixed anomaly"** $\Longrightarrow$ **deconfinement**
- We expect non-invertible lines will be broken by the **double trace quartic** $\mathcal{O}_2$ $\Longrightarrow$ confinement (of probe in fundamental rep)
- **Higher dimensions?**
  - Math? ("Fusion n-category?")
    [Douglas, Reutter '18]
  - **Concrete examples** of non-invertible topological operators in higher dimensional non-topological QFT? **Free theory**? (Even in 1+1d, the full list of topological operators in a general free theory is lacking)

$$\begin{tikzcd}
\begin{array}{c}\text{Sym.}\\ = \text{inv'ble Codim 1}\\ \text{top. surface}\end{array} \arrow[r, rightsquigarrow, "\text{gen.}"] \arrow[d, rightsquigarrow] & \begin{array}{c}\text{p-form Sym.}\\ \text{p-grp}\end{array} \arrow[d, rightsquigarrow] \\
\begin{array}{c}\text{Non-inv'ble Codim 1}\\ \text{top. surface}\\ \text{(fusion Cat.)}\end{array} \arrow[r, rightsquigarrow] & \begin{array}{c}\text{All top. ops.}\\ \text{(??)}\end{array}
\end{tikzcd}$$