Title: Nonstandard Tensor Modes from Inflation

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Abstract: Several mechanisms can lead to production of particles during inflation. I discuss how this phenomenon can induce a contribution to the primordial spectrum of gravitational waves with unusual properties: the tensors produced this way can violate parity; can have a large three-point function; can have a relatively large tensor-to-scalar ratio even if inflation occurs at low energies; finally, their spectrum can display a feature that can be directly detected by second-generation gravitational interferometers such as advanced LIGO.

Strongly coupled QFT is hard, but

- There are theories that have weak coupling descriptions in terms of dual variables
  - Original `particles' remain strongly coupled and have short life time, yet they are organized into long-lived (weakly coupled) collective excitations
  - Duality provides new windows into strong coupling physics
  - Dual variable may carry new (sometimes fractional) quantum numbers : fractionalization
  - Dual variable may live in different space : holography

Slide-particle approach to fractionalized phases

$$\vec{S}_r = f^\dagger_{r\alpha}\vec{\sigma}_{\alpha\beta}f_{r\beta} \quad \text{Spinon : EM charge 0, spin 1/2}$$

$$\text{Gauge redundancy : } f_{r\alpha} \to f_{r\alpha}e^{i\theta_r}$$

- An exact change of variable; applicable to any system
- Phase redundancy : gauge theory
- Gauge field introduced as Lagrangian multiplier of constraint
- No bare kinetic term : bare gauge coupling is infinite

- Large 'N'
  - Deconfinement
  - Emergent gauge field
  - Quantum order
  - Emergent internal space
- Small `N'
  - Confinement
  - No emergent gauge field
  - No quantum order
  - No emergent internal space

Quantum order in fractionalized phase

[Wen]

- `Order' in the pattern of long range entanglement
- Provide `explanation' for why there exist gapless modes whose robustness is not from any microscopic symmetry
- Can be used to classify phases of matter beyond the symmetry breaking scheme
  - In particular, phases with different quantum order form different universality classes
- Associated with the suppression of topological defects

$$Z = \sum e^{-S} \quad \rightarrow \quad Z = \sum e^{-S}$$

Gauge-string duality

[Maldacena; Gubser, Klebanov, Polyakov; Witten]

$$Z[J(x)] = \int D\phi(x) e^{-S_{field\ theory}[\phi]}$$

D-dimensional gauge theory

$$= \int D \text{ ``}J(x,z)\text{''}\, e^{-S'[J(x,z)]}\Big|_{J(x,0)=J(x)}$$

(D+1)-dimension string theory

- Best understood in the maximally supersymmetric gauge theory in 4D
  - Weak coupling description for strongly coupled QFT
  - Non-perturbative definition of string theory (quantum gravity)
- Believed to be a general framework for a large class of QFT's

[Das, Jevicki; Gopakumar; Heemskerk, Penedones, Polchinski; Lee; Faulkner, Liu, Rangamani; Douglas, Mazzucato, Razamat,...]

Gauged matrix model

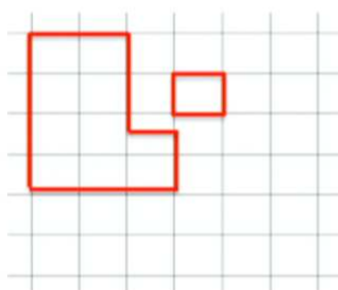
$$S[U] = NM^2 \sum_{<i,j>} \mathrm{tr}(U_{ij}^\dagger U_{ij}) + N^2 V[W_C/N]$$

$$V = -\sum_{n=1}^{\infty} N^{-n} \sum_{\{C_1,..,C_n\}} J_{\{C_1,..,C_n\}} \prod_{k=1}^{n} W_{C_k}$$

U_{ij} : N × N complex matrices

U(N) gauge symmetry : $U_{ij} \to V_i^\dagger U_{ij} V_j$

$W_C = \mathrm{tr} \prod_{<i,j>\in C} U_{ij}$: Wilson loop



D-dimensional Euclidean lattice

$\mathcal{J}_C$: Sources for single-trace operators

$\mathcal{J}_{C_1,C_2}$: Sources for double-trace operators

⋮

$\mathcal{J}_{\{C_1,..,C_n\}}$: Sources for general multi-trace operators

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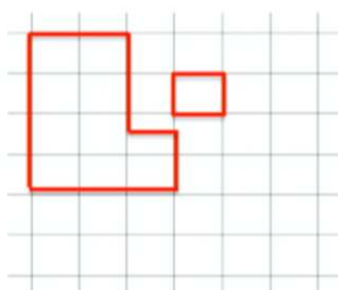

D-dimensional Euclidean lattice

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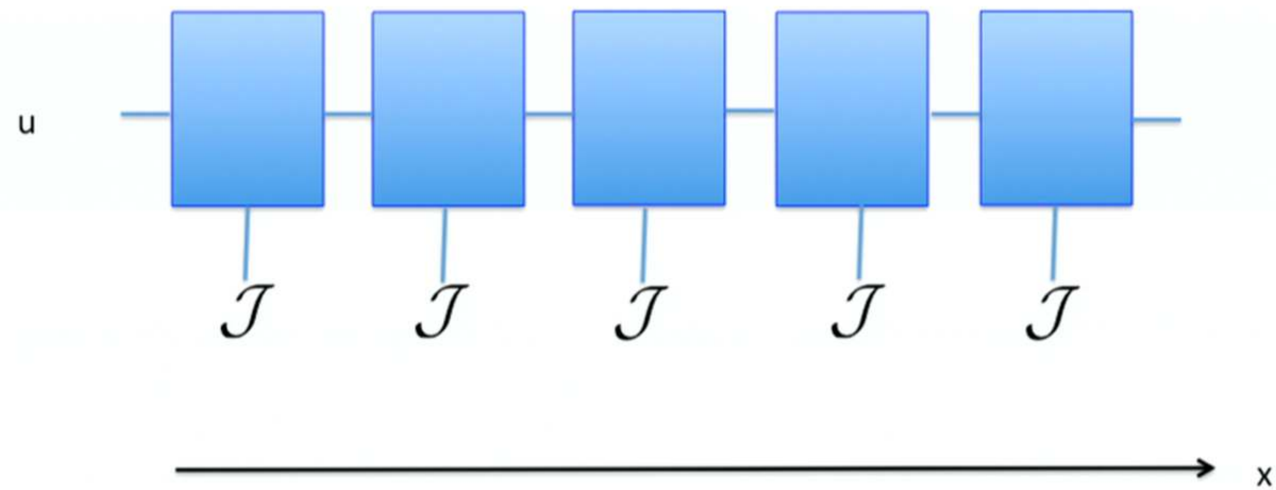
$\mathcal{J}_{\{C_1,...,C_n\}}$: Sources for general multi-trace operators

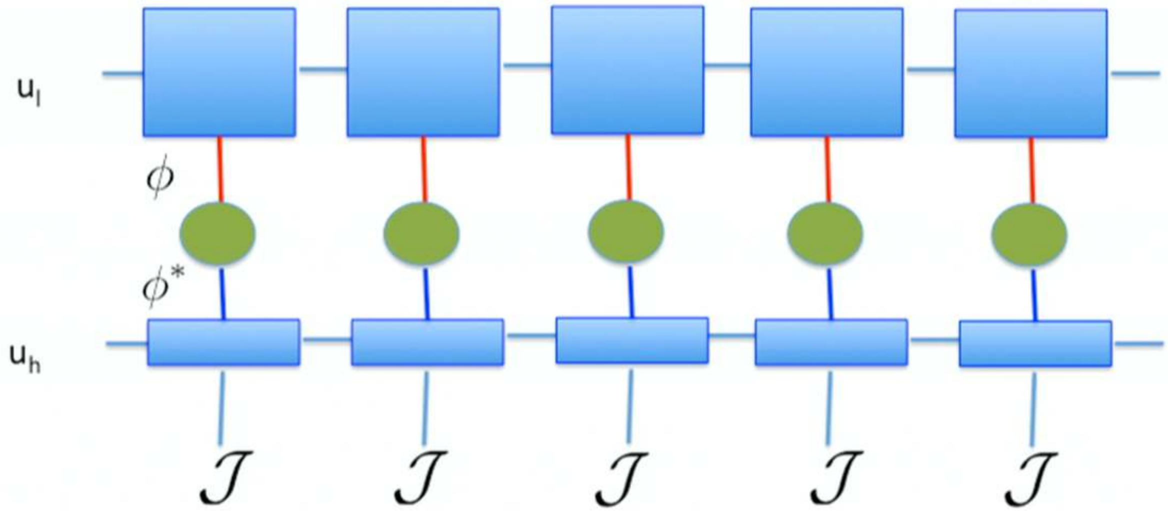
Construction of holographic theory

Partition function can be viewed as contractions of an D-dimensional array of tensors which depend on external sources



Construction of holographic theory

- High energy fields can be viewed as fluctuating sources for the low energy fields



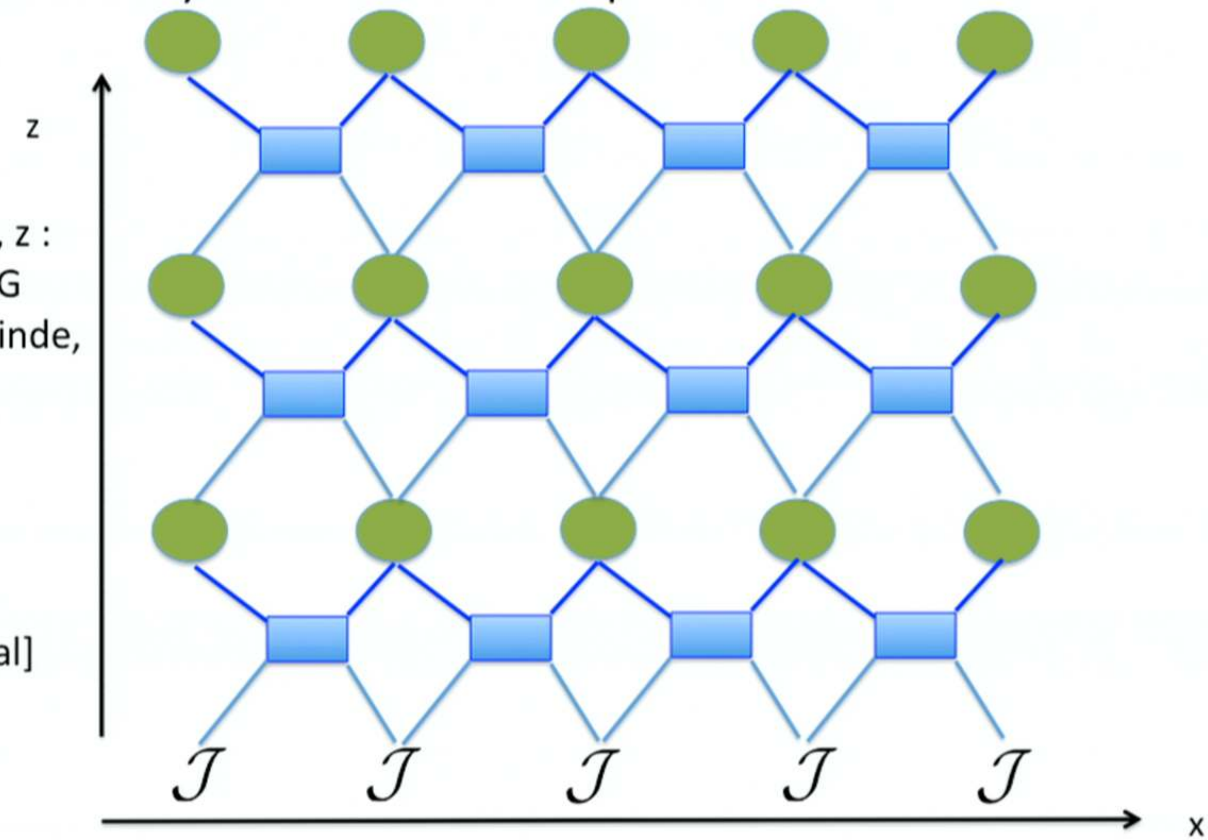
ϕ : an auxiliary field that plays the role of fluctuating source for low energy field
ϕ^* : a Lagrangian multiplier than impose the constraint between ϕ and J

Construction of holographic theory

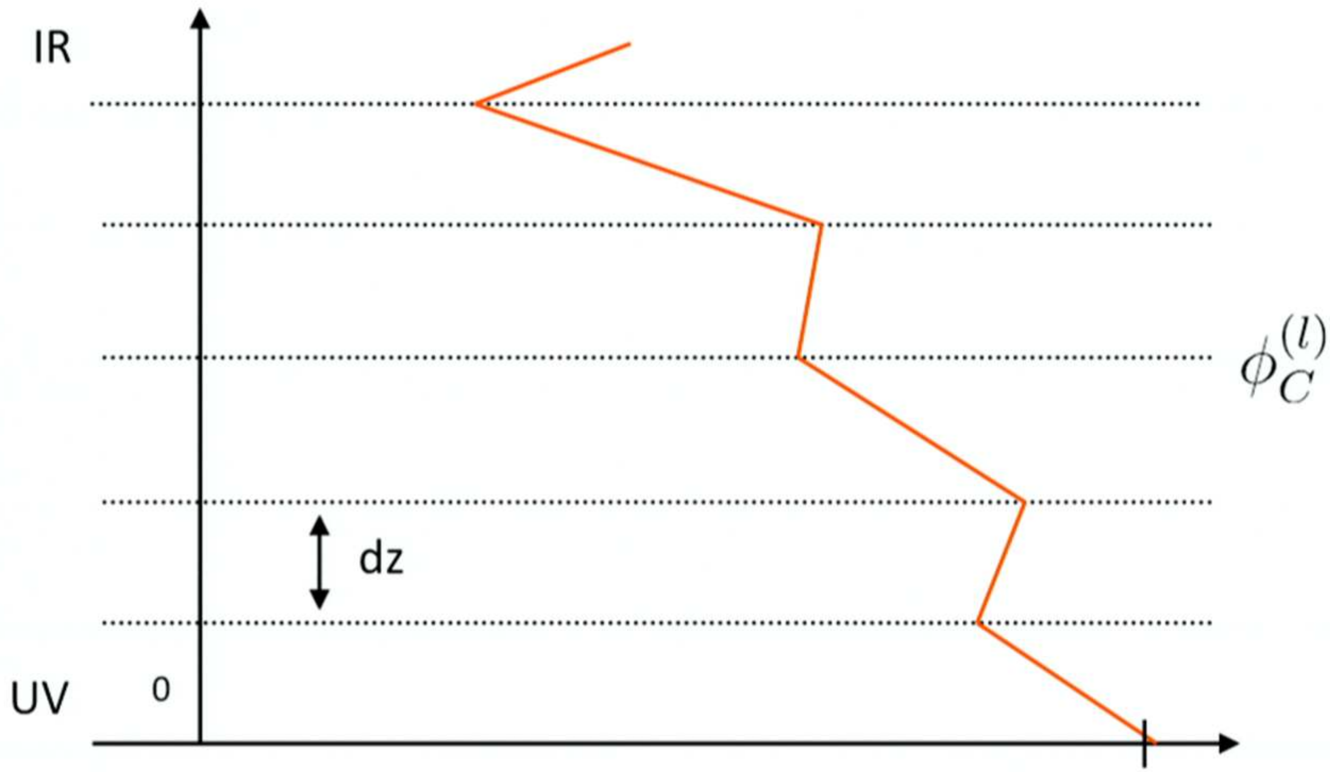
Repetition of these step leads to contractions of (D+1)-dimensional array of matrices for the partition function

Extra dimension, z : length scale in RG [J. de Boer, Verlinde, Verlinde]

Cf. MERA [Vidal]



Extra dimension as a length scale



(D+1)-dimensional field theory of closed loops

$$Z = \int D\phi_C D\phi_C^* \;\; e^{-\left(S_{bulk}[\phi_C^*(z),\phi_C(z)]+N^2\phi_C^*(0)\phi_C(0)+N^2V[\phi_C^*(0)]\right)}$$

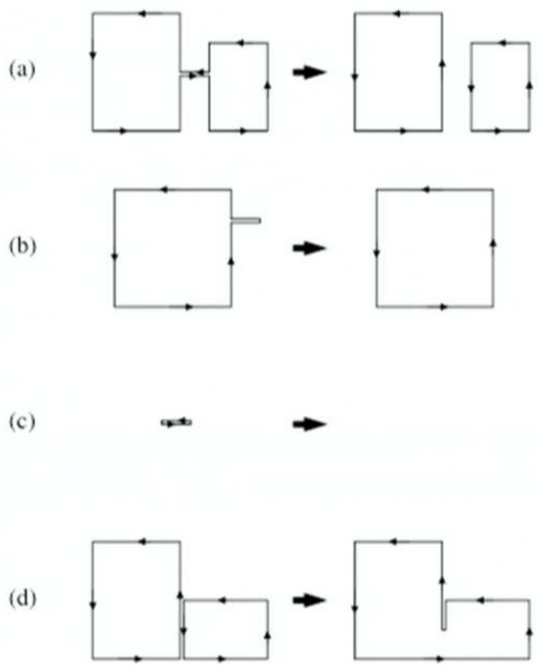
$$S_{bulk} = N^2 \int_0^\infty dz\Big[\phi_C^*\partial_z\phi_C + \alpha L_C \phi_C^*\phi_C - \frac{\alpha}{M^2}\Big(F_{ij}[C_1,C_2]\phi_{C_1}^*\phi_{C_2}^*\phi_{[C_1+C_2]_{ij}} + G_{ij}[C_1,C_2]\phi^*_{(C_1+C_2)_{ij}}\phi_{C_1}\phi_{C_2}\Big)\Big]$$

- $\phi_C(z), \phi_C^*(z)$: coherent fields for annihilation/creation operators of loop
- S_{bulk} : action for closed loop fields in (D+1)-dimensions
- V : J_C dependent action for the UV(z=0) boundary fields
  - Single trace potential : the standard Dirichlet B.C.
  - Multi-trace potential : mixed B.C.

Loop Hamiltonian in the bulk

$$Z = \lim_{\beta \to \infty} < \Psi_f | e^{-\beta H} | \Psi_i >$$

$$H = \alpha L_C a_C^\dagger a_C - \frac{\alpha}{NM^2} \Big(F_{ij}[C_1, C_2] a_{C_1}^\dagger a_{C_2}^\dagger a_{[C_1+C_2]_{ij}} + G_{ij}[C_1, C_2] a_{(C_1+C_2)_{ij}}^\dagger a_{C_1} a_{C_2} \Big)$$

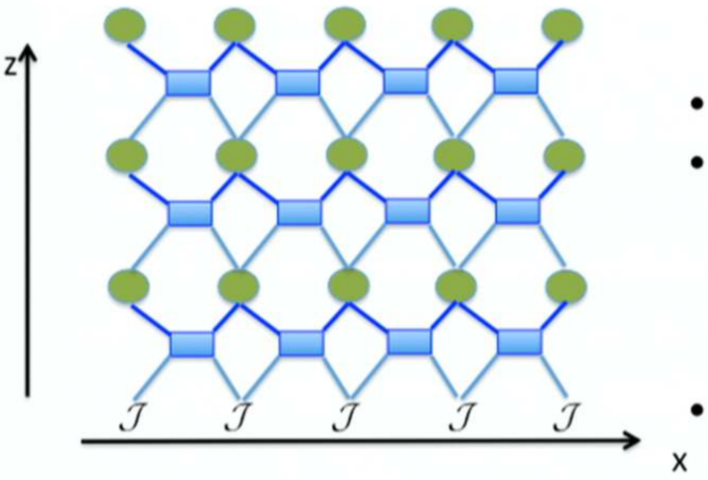


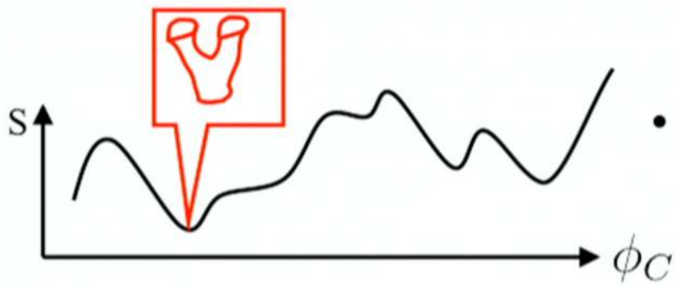
– Tension

– Joining/splitting

Similar to the loop Hamiltonian studied by Kawai & Ishibashi; Jevicki & Rodrigues, ...

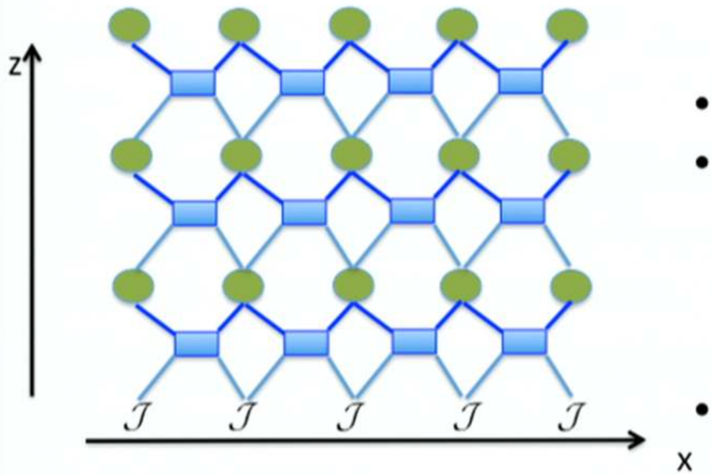
Saddle point and beyond

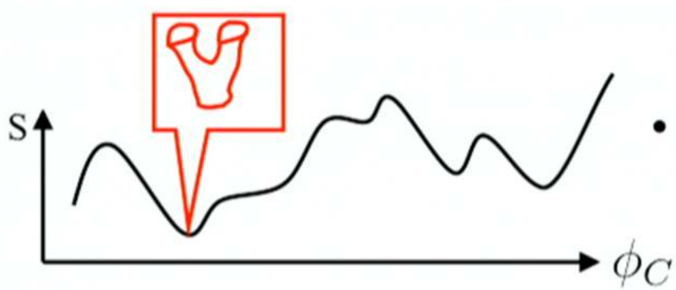




- S ~ N[2] (…)
- Fluctuations of loop fields around a saddle point describe weakly interacting closed strings in (D+1)-dimensional space for a large N
- The background (metric and the two-form gauge field) for closed strings are determined by the saddle point solution
- Key question : When is the saddle point solution stable ?

Saddle point and beyond





- $S \sim N^2$ (…)
- Fluctuations of loop fields around a saddle point describe weakly interacting closed strings in (D+1)-dimensional space for a large N
- The background (metric and the two-form gauge field) for closed strings are determined by the saddle point solution
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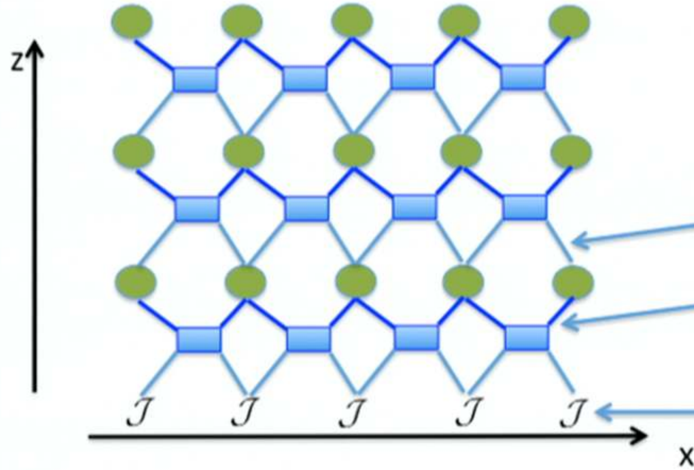
Gauge symmetry

- Relative phases between sources and operators are ill-defined $J_n \to e^{i\theta_n} J_n, \quad O_n \to e^{-i\theta_n} O_n$

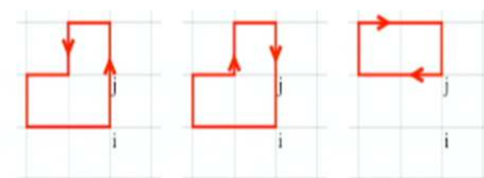


$$\phi_C(z) \to e^{i\theta_\mu(i,z)Q_{ii+\mu}[C]} \phi_C(z),$$

$$\phi^*_C(z) \to e^{-i\theta_\mu(i,z)Q_{ii+\mu}[C]} \phi^*_C(z),$$

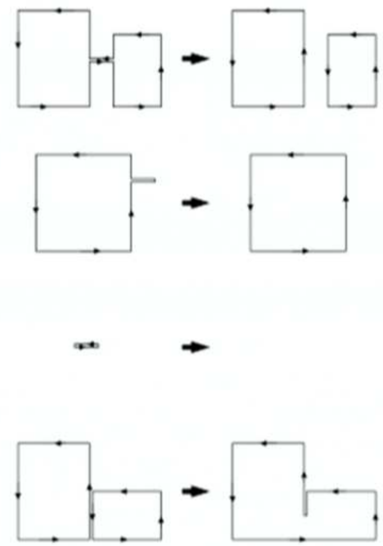
$$J_C \to e^{i\theta_\mu(i,0)Q_{ii+\mu}[C]} J_C$$

External sources J_C explicitly break the gauge symmetry at the UV boundary.



$Q_{ij}[C] =$ +1 -1 0

Consequences of gauge symmetry

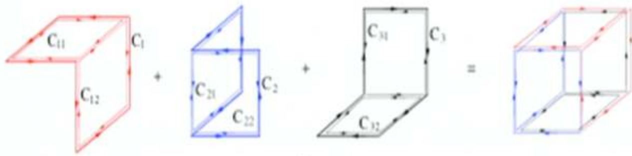


- No-quadratic hopping : flux conservation
- The cubic interactions between loops generate the kinetic term for strings

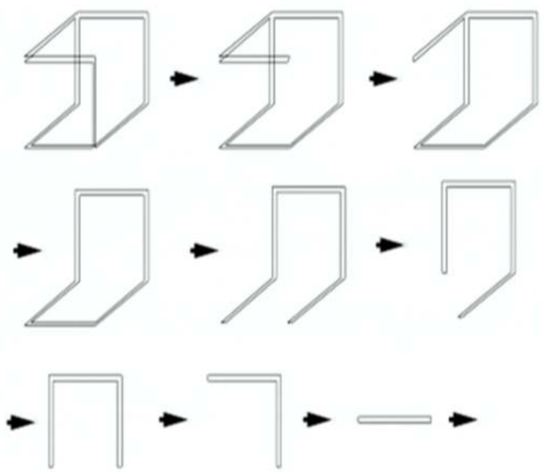
$$-\frac{\alpha < \phi_C >}{M^2} a^\dagger_{C+C'} a_{C'}$$

- The phase of the background loop field provides a Berry phase for strings that moves in space $\phi_C = |\phi_C| e^{ib_C}$
- $b_C = \int_{A_C} B$ ← compact two-form gauge field $b_C \sim b_C + 2\pi$

Quantum fluctuations generate kinetic energy for the two-form gauge field



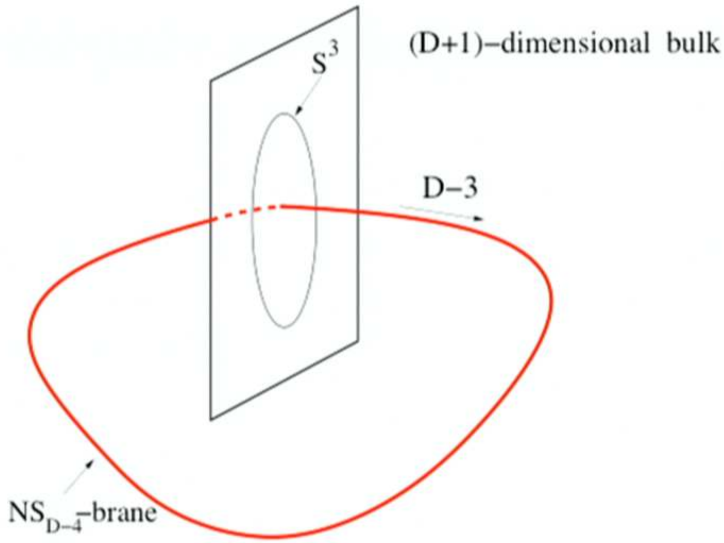
- Integrating out heavy (long) loops generate the kinetic energy for the two-form gauge field



$$S_{eff} = \frac{1}{g_{KR}^2}\int dz\Big(\sum_{\square}(\partial_z B_{\mu\nu})^2 - \sum_{\text{cubes}} \cos\left[a^3(\Delta_\mu B_{\nu\lambda} + \Delta_\nu B_{\lambda\mu} + \Delta_\lambda B_{\mu\nu})\right]\Big)$$

$$g_{KR}^2 \sim 1/(|\phi_\square|^6 N^2)$$

Topological defect for the compact two-form gauge field



$$H = dB$$

$$\int_{S^3} H = 2\pi$$

- Tension of the brane ~ N^2

NS-brane determines the fate of string

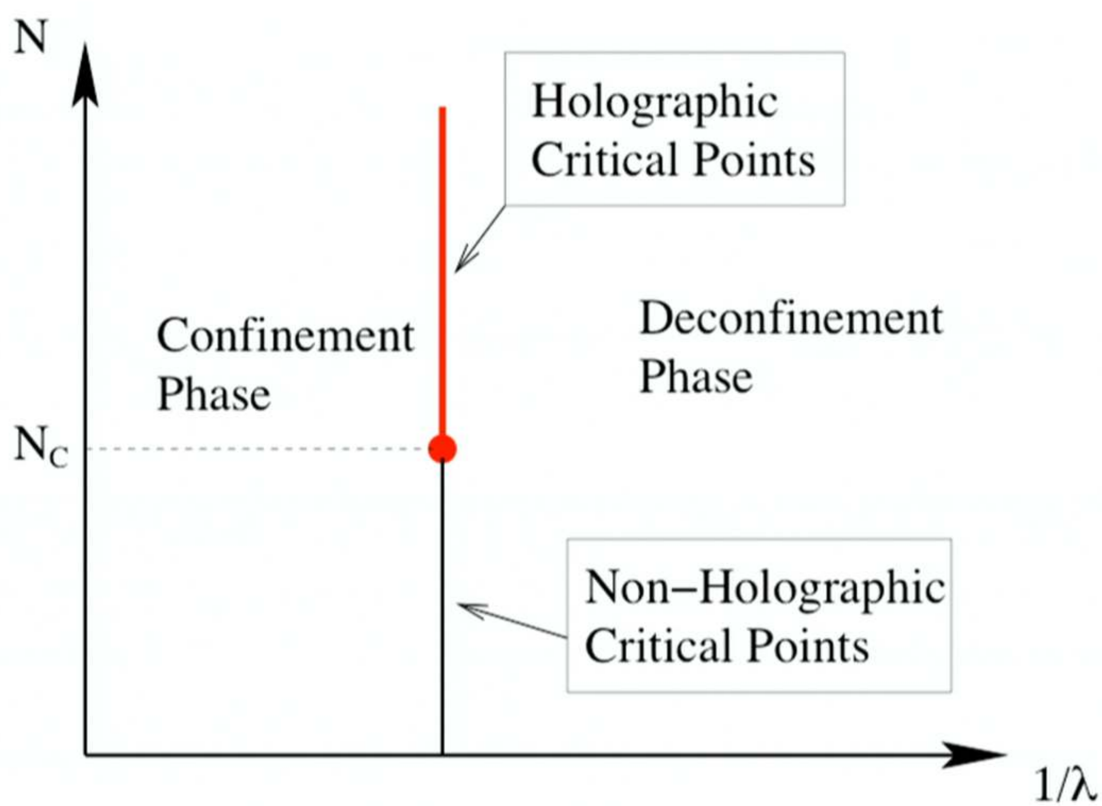
Gapped NS-brane

- Emergent Bianchi identity dH=0 at long distances
- Strings are deconfined
- Emergent space
- Two-form gauge field remains light even at strong coupling
- Non-trivial quantum order!

Condensed NS-brane

- Bianchi identity is violated at all distance scales
- Strings are confined
- No emergent space
- No light propagating mode deep inside the bulk
- No quantum order

A proposed phase diagram for a pure bosonic gauged matrix model in D>4



Summary

- General D-dimensional gauged matrix model can be mapped into (D+1)-dimensional string field theory which include compact two-form gauge field
- Those phases that admit holographic description have a distinct quantum order
  - Emergent space
  - Deconfined string
  - Protected scaling dimension