

Title: Color Confinement, Bose-Einstein Condensation and Holographic Emergent Space

Speakers: Masanori Hanada

Series: Quantum Fields and Strings

Date: January 28, 2020 - 2:30 PM

URL: <http://pirsa.org/20010090>

Abstract: We propose a unified manner of understanding two important phenomena: color confinement in large-N gauge theory, and Bose-Einstein condensation (BEC).&nbsp;We do this by clarifying the relation between the standard criteria, based on the off-diagonal long range order (ODLRO) for the BEC and the Polyakov loop for gauge theory: the constant offset of the distribution of Polyakov line phase is ODLRO. Indistinguishability associated with the symmetry group --- SU(N) or O(N) in gauge theory,&nbsp;and S\_N permutation in the system of identical bosons --- plays the key role in both cases.&nbsp;This viewpoint may have implications to confinement at finite N, and to quantum gravity via gauge/gravity duality.&nbsp;

# Color Confinement, Bose-Einstein Condensation and Holographic Emergent Space

Masanori Hanada

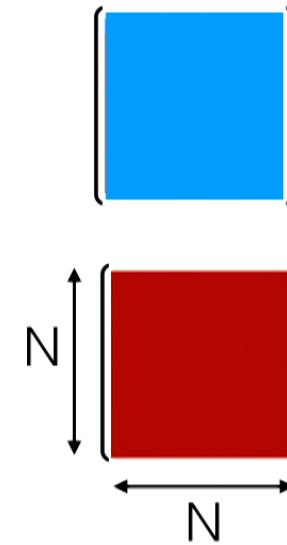
花田 政範  
Hana Da Masa Nori

**Jan. 28, 2020 @ Perimeter Institute**

M.H.-Shimada-Wintergerst, to appear (this evening!)  
+ M.H.-Maltz, 1608.03276 (JHEP)  
M.H.-Ishiki-Watanabe, 1812.05494 (JHEP)  
M.H.-Jevicki-Peng-Wintergerst, 1909.09118 (JHEP)  
M.H.-Robinson, 1911.06223  
Alet-M.H.-Jevicki-Peng, 2001.03158

- Partial deconfinement in  $SU(N)$  gauge theory
- Consequence to gravity: BH with negative specific heat, emergent geometry, ...
- Confinement = BEC  $\rightarrow$  generalization to strong coupling

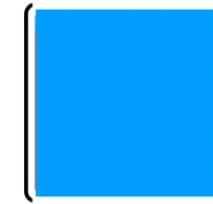
- Confinement phase:  $E, S \sim N^0$
  - Deconfinement phase:  $E, S \sim N^2$
- $\longleftrightarrow$  Black Hole



This ‘kinematical’ characterization works even at weak coupling and/or small volume.

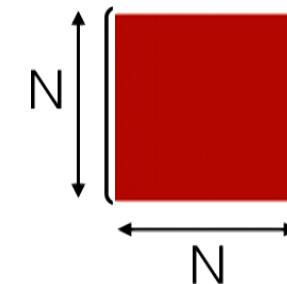
(Sundborg 1998; Aharony et al 2003)

- Confinement phase:  $E, S \sim N^0$



- Deconfinement phase:  $E, S \sim N^2$

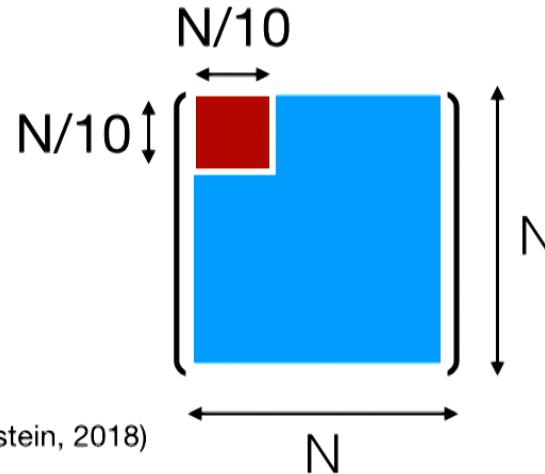
$\longleftrightarrow$  Black Hole

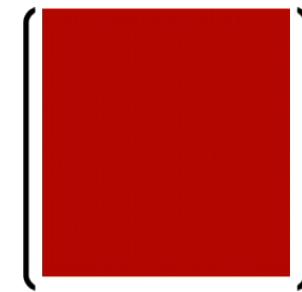
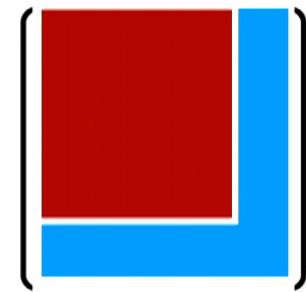
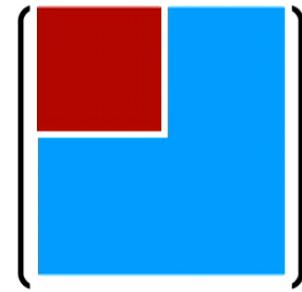
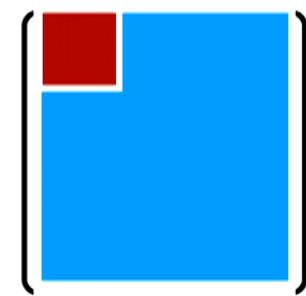
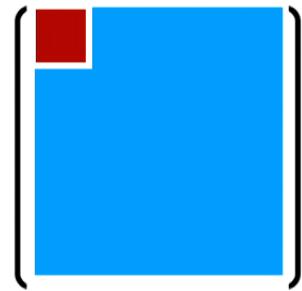
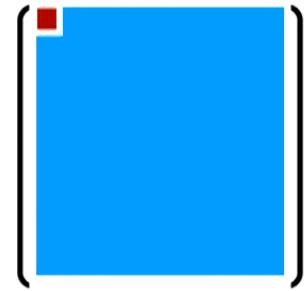


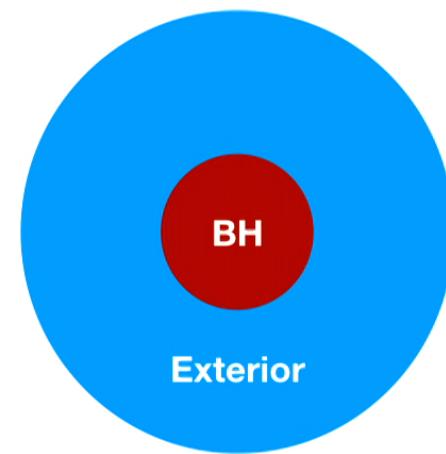
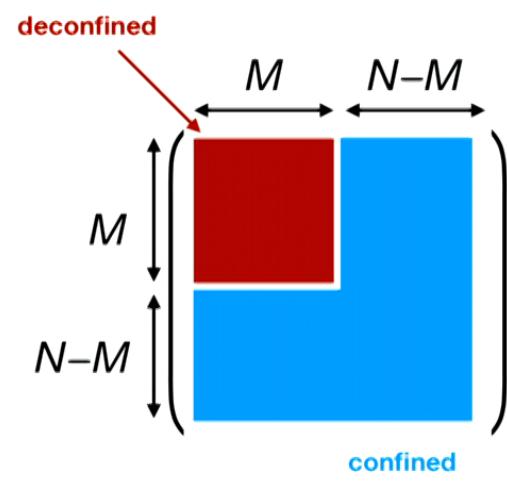
What if  $E \sim N^2/100$ ?

'partially' deconfine

(MH-Maltz, 2016; Berenstein, 2018)



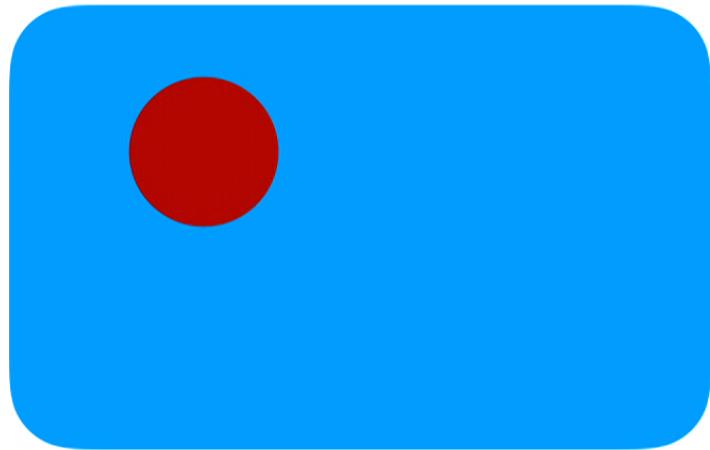




# Heuristic justification

(more precise argument is given later)

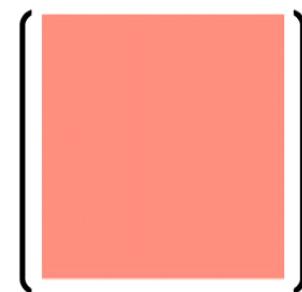
Why doesn't a part of the volume deconfine?



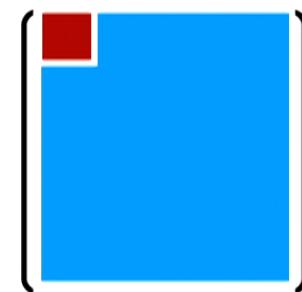
Deconfinement takes place even in matrix model,  
which has no spatial dimensions.

(Exception: first order transition, large volume)

Why don't all  $N^2$  d.o.f. gently deconfine?



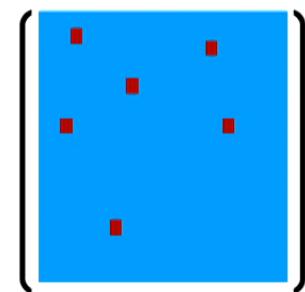
instead of



?

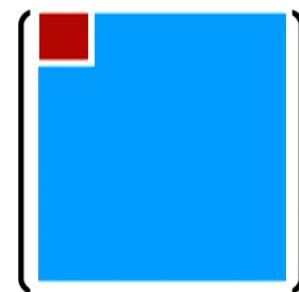
In quantum mechanics, parametrically  
small excitation is impossible.

Why should large symmetry be preserved?



no symmetry

instead of



$SU(M) \times SU(N-M)$

?

It is natural to expect a large symmetry  
at saddle point.

**“Confinement = BEC” will justify this expectation**

# Phase Diagrams

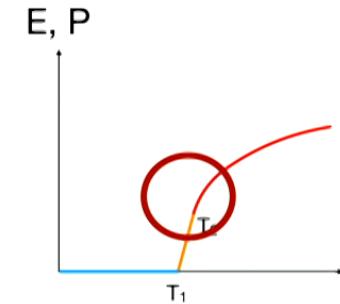
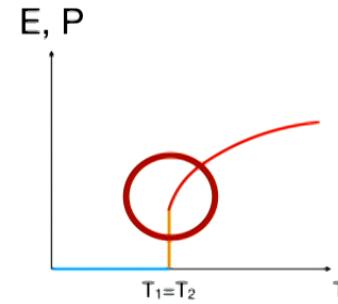
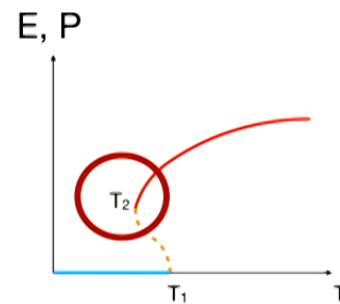
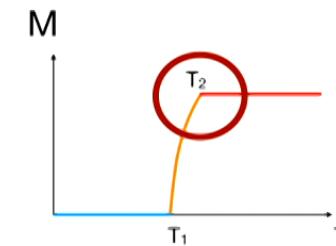
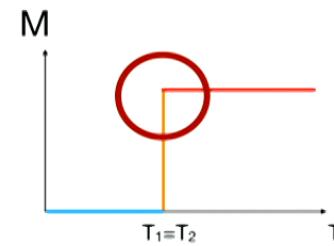
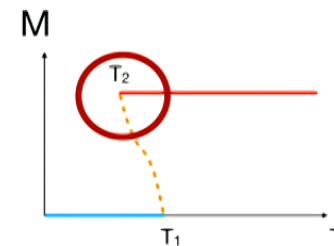
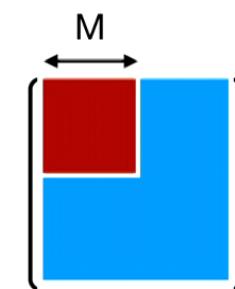
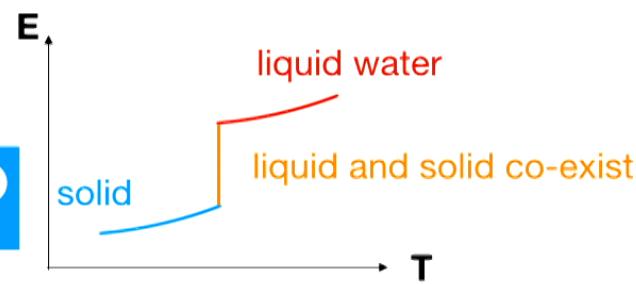
MH-Ishiki-Watanabe,  
arXiv:1812.05494 [hep-th]

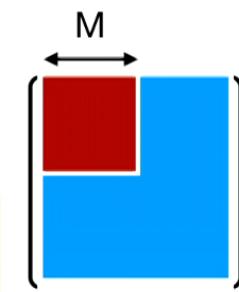
(JHEP)

- Hagedorn transition
- Gross-Witten-Wadia transition
- “Gauge symmetry breaking”

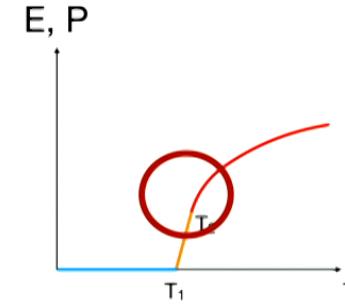
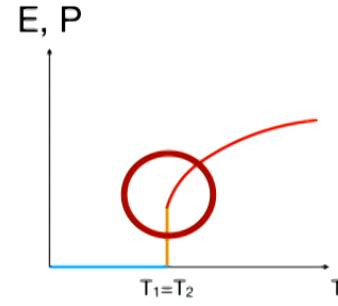
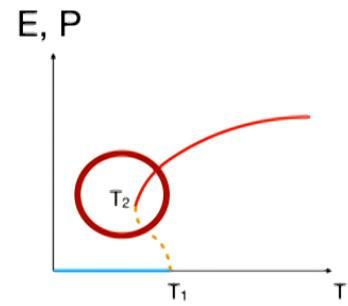
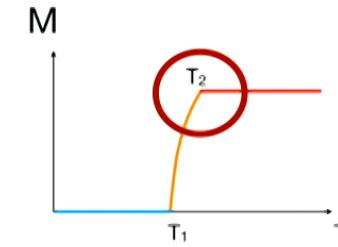
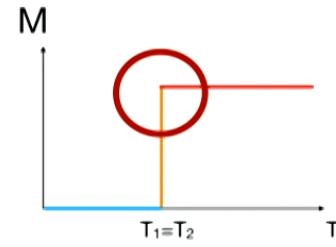
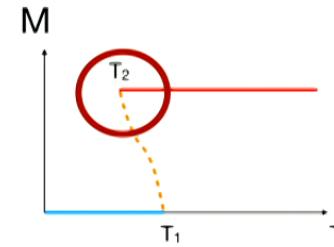
(more precise argument is given later)

cf) water/ice





## Gross-Witten-Wadia transition

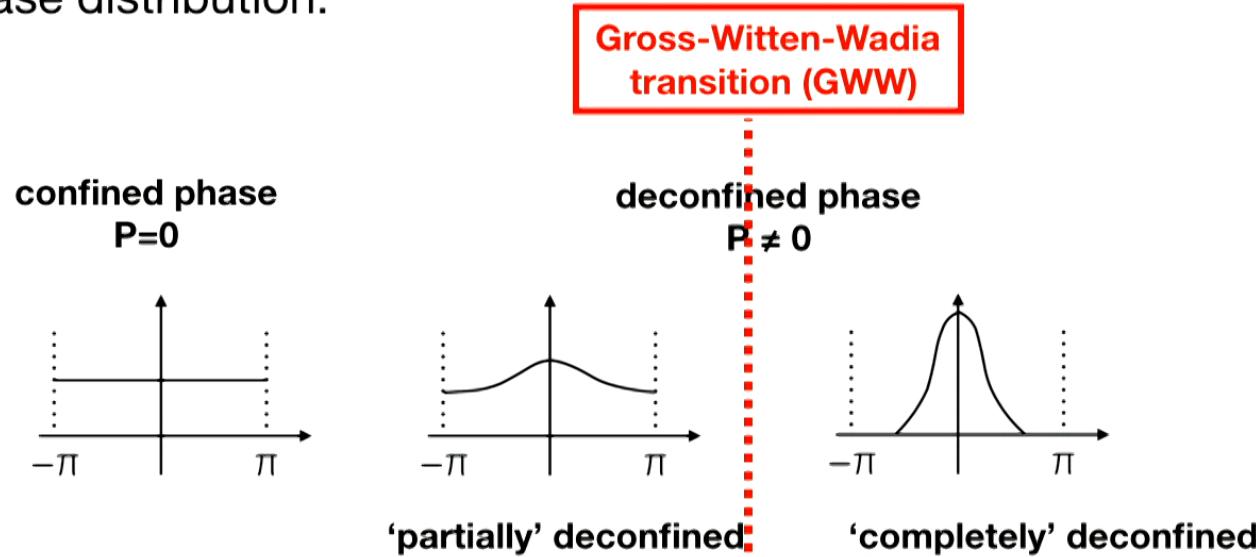


- Polyakov loop

(Wilson loop wrapped on  
the temporal circle)

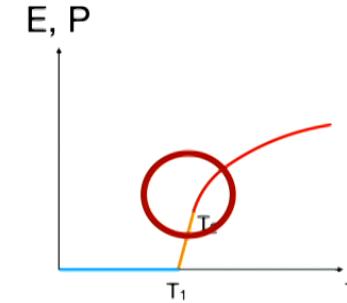
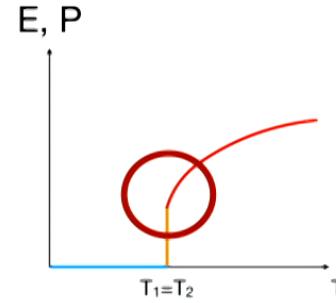
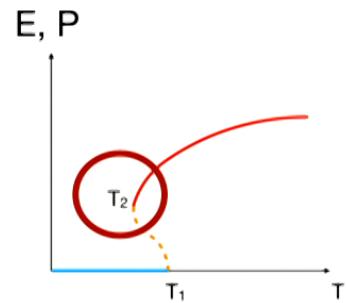
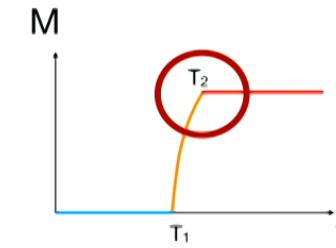
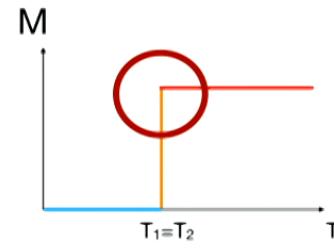
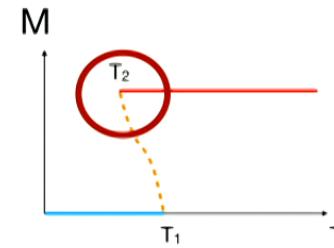
$$P = \frac{1}{N} \sum_{j=1}^N e^{i\theta_j}$$

- Phase distribution:



# Gross-Witten-Wadia transition

= “partial deconfinement → complete deconfinement” transition

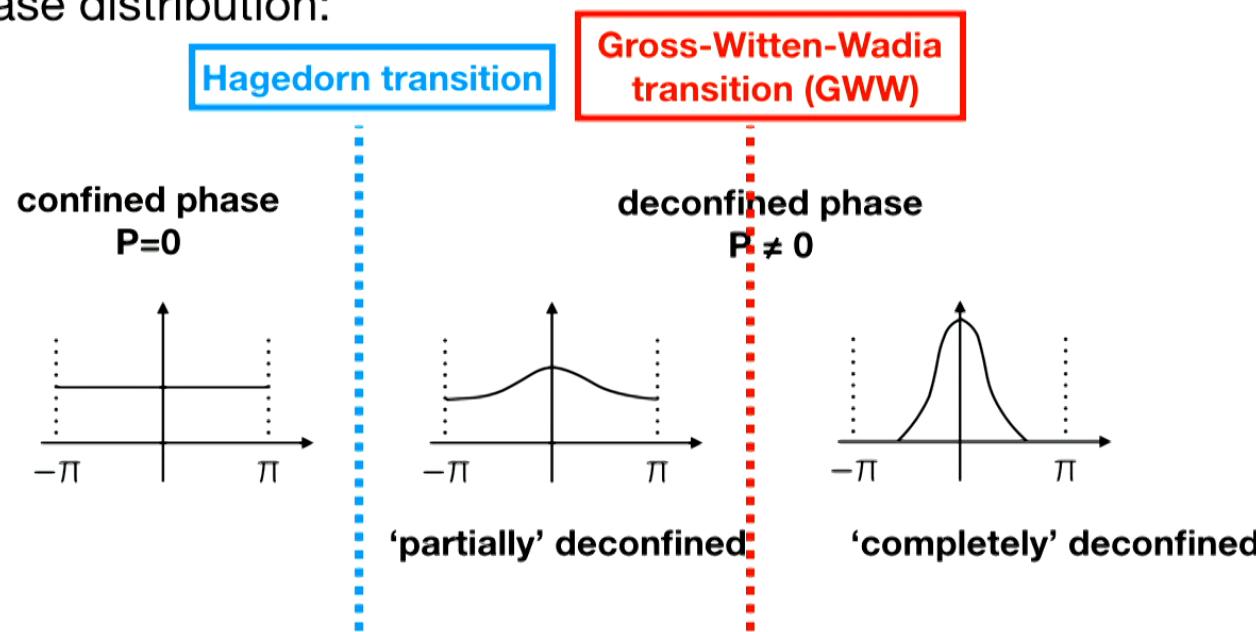


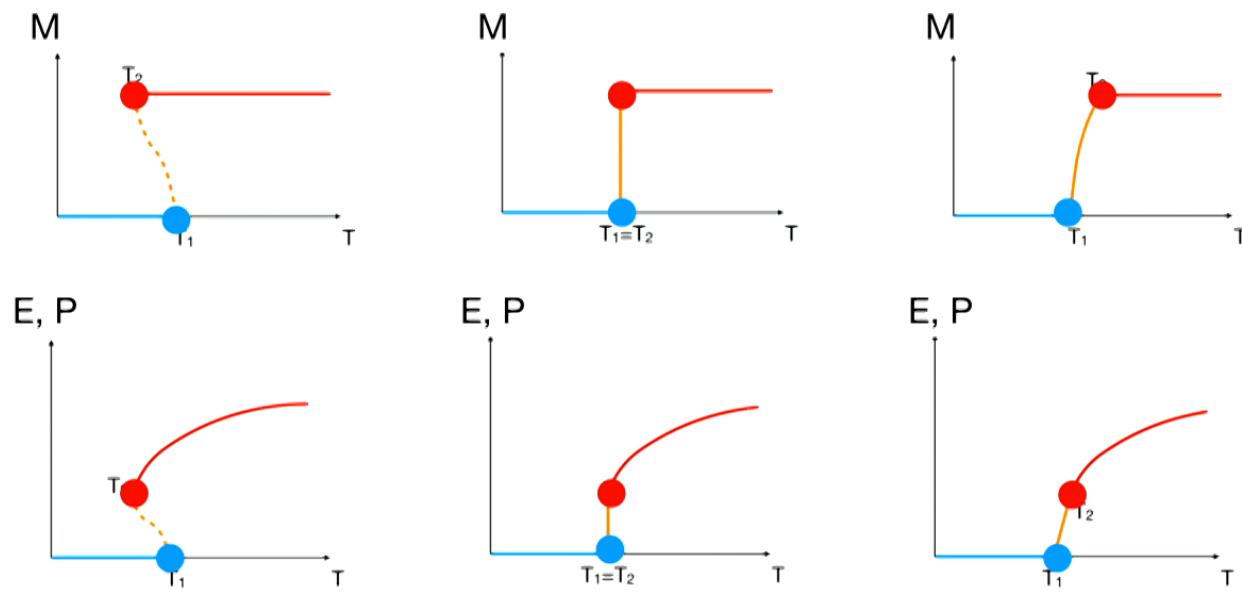
- Polyakov loop

(Wilson loop wrapped on  
the temporal circle)

$$P = \frac{1}{N} \sum_{j=1}^N e^{i\theta_j}$$

- Phase distribution:





transition 1: confinement to partial deconfinement  
(black hole formation begins)

transition 2: partial deconfinement to complete deconfinement  
(black hole formation ends)

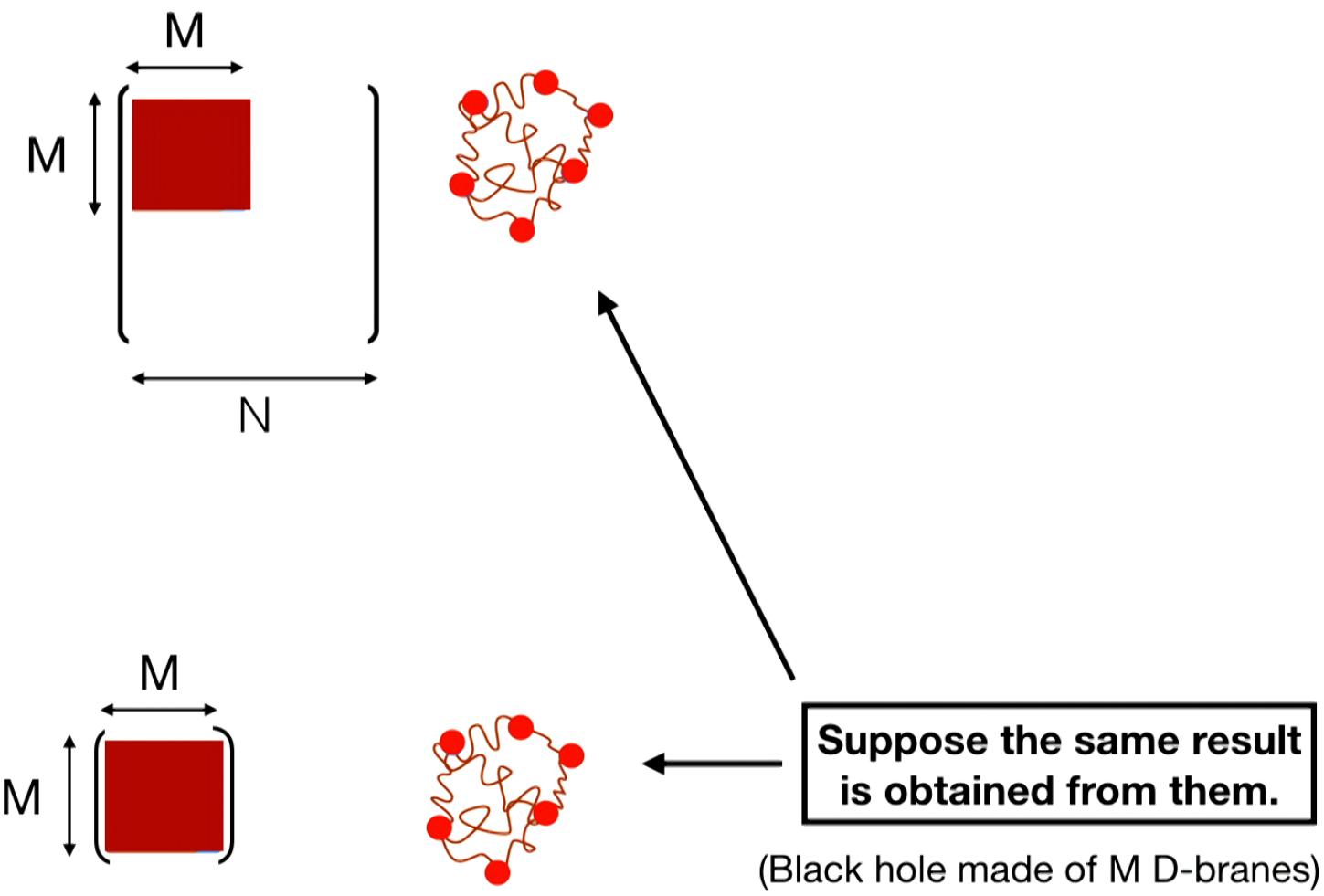
$$\text{SU}(N) \rightarrow \text{SU}(M) \times \text{SU}(N-M) \rightarrow \text{SU}(N)$$

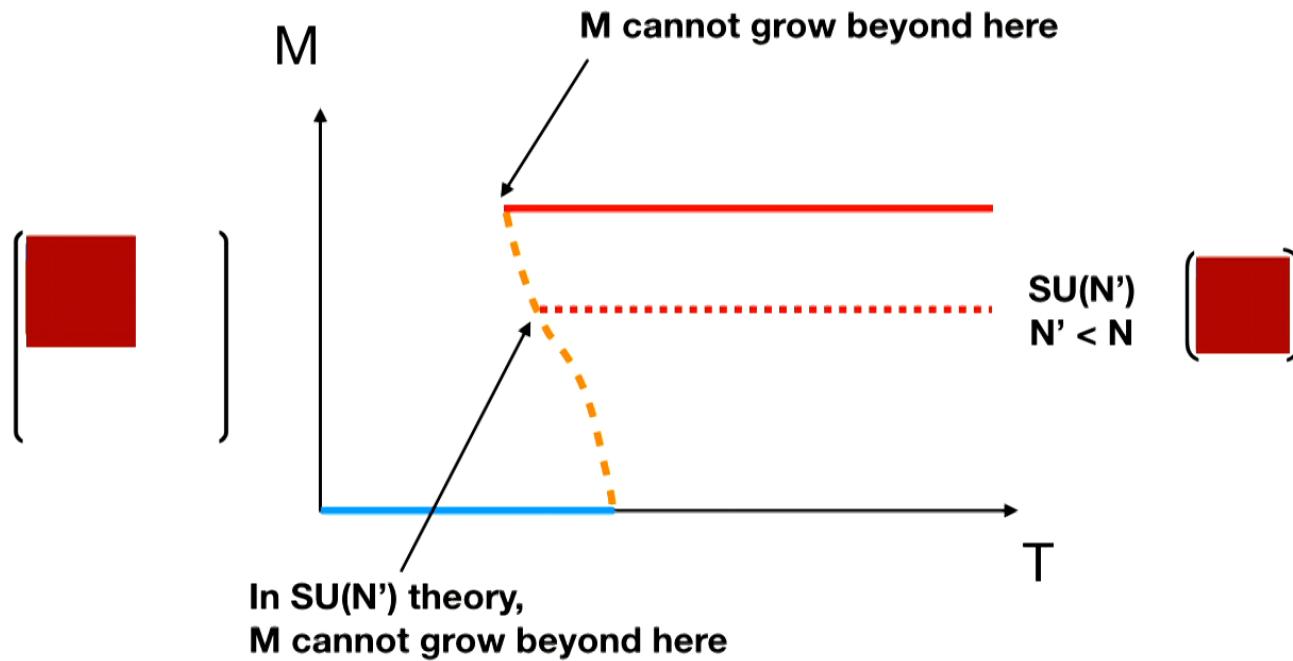
No need for center symmetry. Applies to QCD.

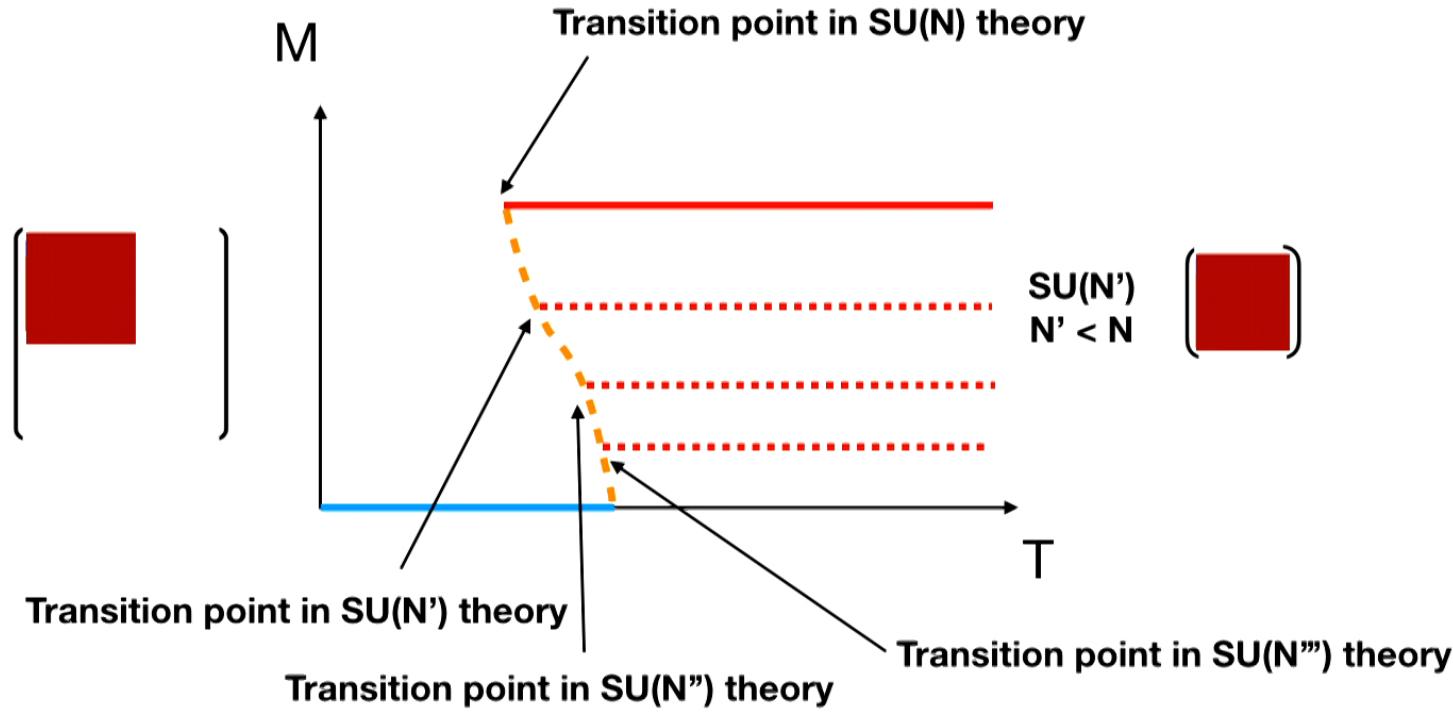
# Explicit demonstration in simple theories

M.H., Jevicki, Peng, Wintergerst, 1909.09118 [hep-th]

(JHEP)





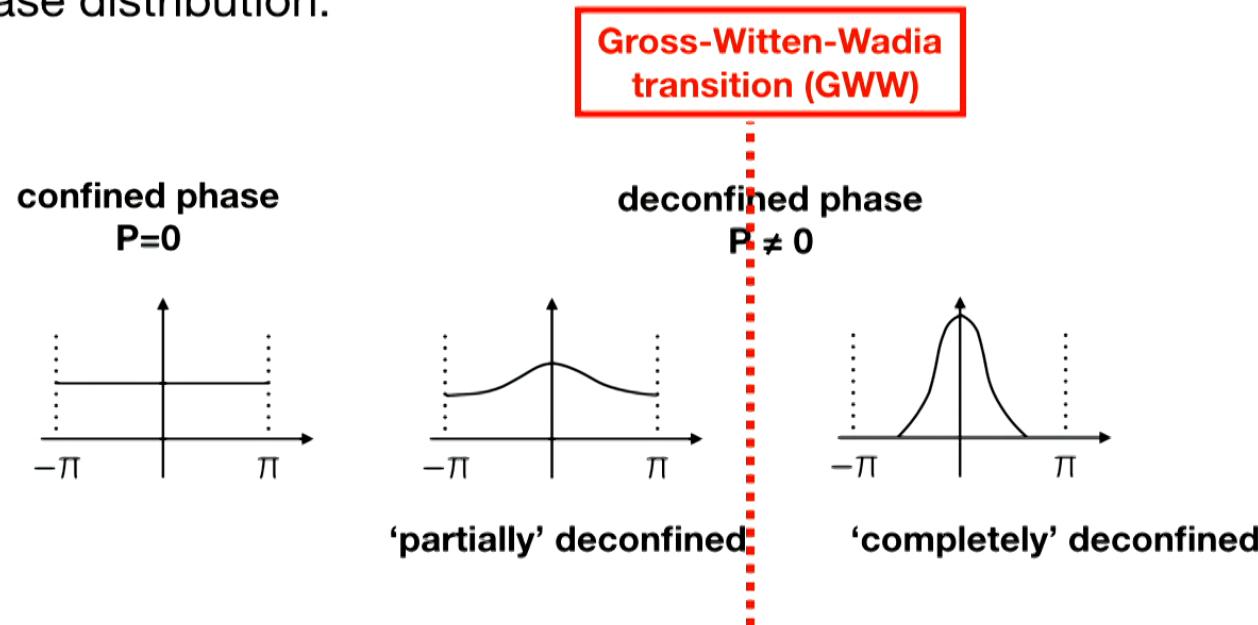


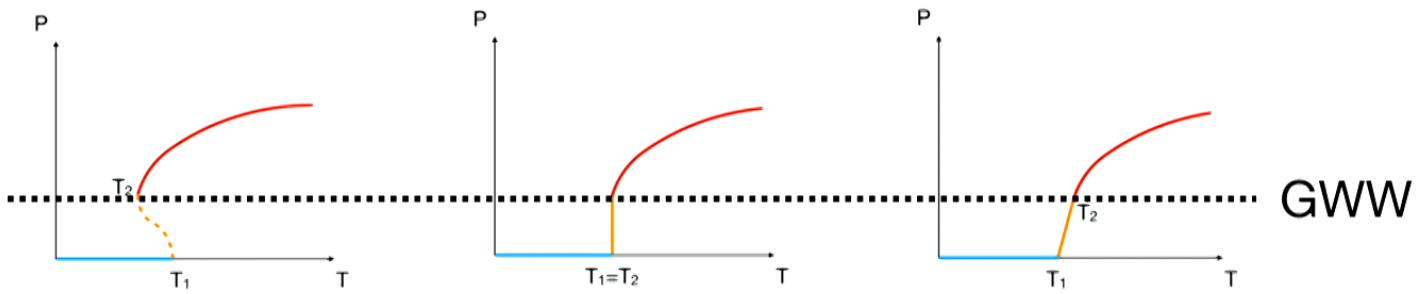
M.H., Maltz, 2016 (JHEP)

- Polyakov loop

$$P = \frac{1}{N} \sum_{j=1}^N e^{i\theta_j}$$

- Phase distribution:



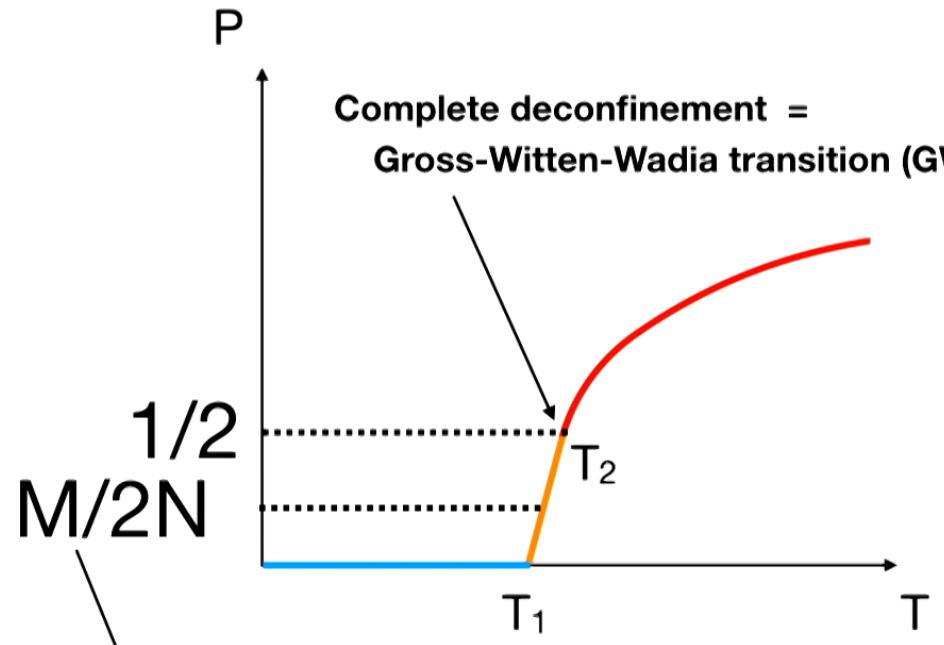


$$\begin{aligned}\rho(\theta) &= \left(1 - \frac{M}{N}\right) \rho_{\text{confine}}(\theta) + \frac{M}{N} \cdot \rho_{\text{GWW}}(\theta; M) \\ &= \frac{1}{2\pi} \left(1 - \frac{M}{N}\right) + \frac{M}{N} \cdot \rho_{\text{GWW}}(\theta; M).\end{aligned}$$

( $P = M/2N$  for many theories)

**Holds in various weakly-coupled theories.**

**M.H.-Ishiki-Watanabe, 2018; M.H.-Robinson, 2019**



$$E = E_{\text{GWW}}(M)$$

$$S = S_{\text{GWW}}(M)$$

# **Simplest Example:**

## **Gauged Gaussian Two Matrix Model**

$$\hat{H} = \frac{1}{2} \text{Tr} \left( \hat{P}_X^2 + \hat{X}^2 + \hat{P}_Y^2 + \hat{Y}^2 \right)$$

**(Other cases are very similar)**

$$\hat{H} = \frac{1}{2} \text{Tr} \left( \underbrace{\hat{P}_X^2 + \hat{X}^2}_{\hat{A}, \hat{A}^\dagger} + \underbrace{\hat{P}_Y^2 + \hat{Y}^2}_{\hat{B}, \hat{B}^\dagger} \right)$$

$$\underbrace{\text{Tr} \left( \hat{A}^\dagger \hat{A}^\dagger \hat{B}^\dagger \hat{A}^\dagger \dots \right)}_L |0\rangle$$

$E = L$  (up to zero-pt energy)

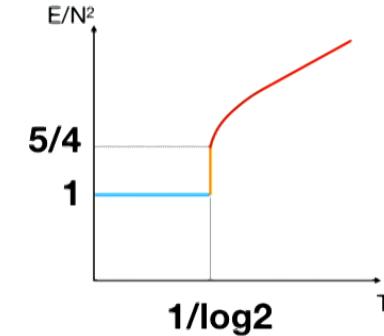
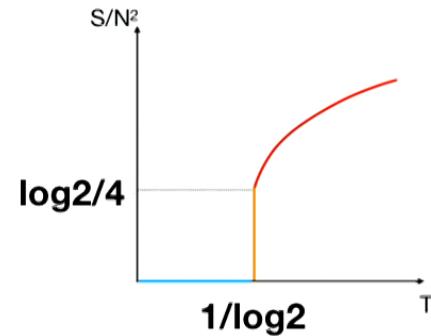
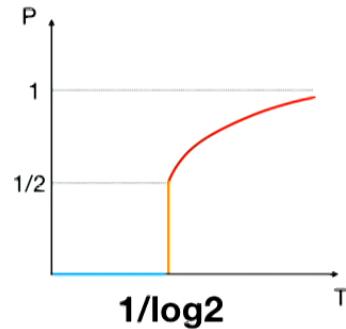
$S = L \log 2$  (# of states  $\sim 2^L$ )

(valid at  $L \ll N^2$ )

$$F = E - TS = L(1 - T \log 2)$$

(up to zero-pt energy; valid at  $L \ll N^2$ )

$$F = 0 \text{ @ } T = \frac{1}{\log 2}$$

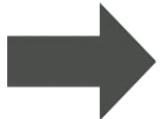


$$E(T = T_c, P, N) = N^2 + N^2 P^2 = N^2 + \frac{M^2}{4}$$

$$S(T = T_c, P, N) = \frac{M^2}{4} \log 2$$

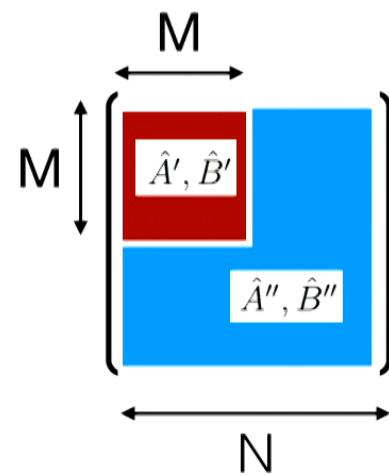
$$\begin{aligned}\rho(\theta) &= \frac{1}{2\pi} (1 + 2P \cos \theta) &= (1 - 2P) \cdot \frac{1}{2\pi} + 2P \cdot \frac{1}{2\pi} (1 + \cos \theta) \\ &= \left(1 - \frac{M}{N}\right) \cdot \frac{1}{2\pi} + \frac{M}{N} \cdot \frac{1}{2\pi} (1 + \cos \theta)\end{aligned}$$

$$P = \frac{M}{2N}$$



$$\boxed{\begin{aligned}E &= E_{\text{GWW}}(M) \\S &= S_{\text{GWW}}(M)\end{aligned}}$$

**Next & final step: Construct the states explicitly in Hilbert space.**



**not SU(N)-invariant**

$$|E; \text{SU}(M)\rangle = \text{Tr} \left( \hat{A}'^\dagger \hat{A}'^\dagger \hat{B}'^\dagger \hat{A}''^\dagger \dots \right) |0\rangle$$

**At weak coupling, this is an energy eigenstate.**

$$S = S_{\text{GWW}}(M)$$

**one-to-one correspondence**

**SU(N)-invariant**

**This is also an energy eigenstate.**

$$|E\rangle_{\text{inv}} \equiv \mathcal{N}^{-1/2} \int dU \mathcal{U}(|E; \text{SU}(M)\rangle)$$

These states explain the entropy precisely.

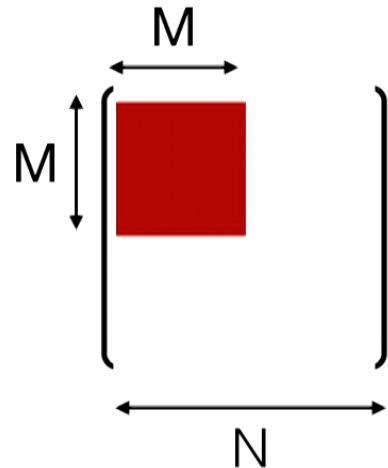
M.H.-Jevicki-Peng-Wintergerst, 2019

# ‘Spontaneous gauge symmetry breaking’

**M.H.-Jevicki-Peng-Wintergerst, 2019 (JHEP)**

**SU(N)-invariant**

$$|E\rangle_{\text{inv}} \equiv \mathcal{N}^{-1/2} \int dU \mathcal{U} (|E; \text{SU}(M)\rangle)$$

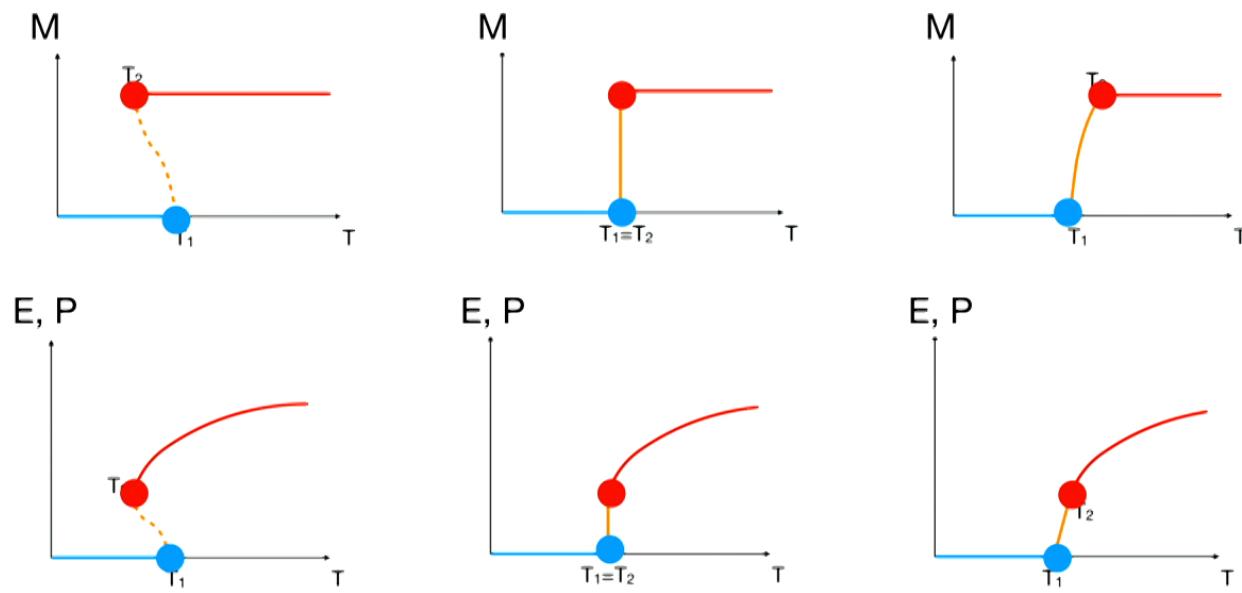


↓  
gauge fixing

**not SU(N)-invariant**

|E; SU(M)⟩

- Global part of gauge symmetry breaks spontaneously.
- It is convenient to fix the local part, like usual Higgsing.
- ‘Gauge symmetry breaking’ provides us with a ‘useful fiction’ which makes physics understandable.



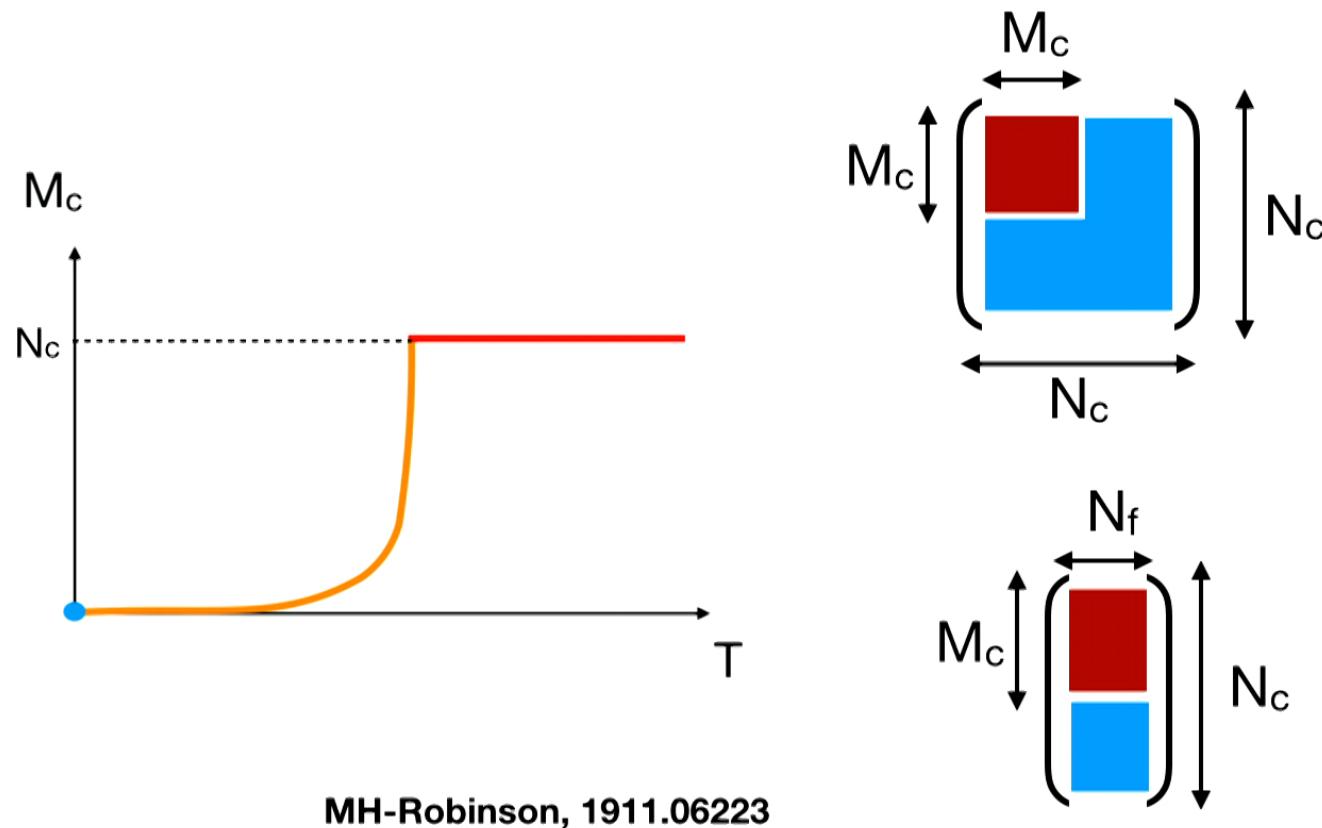
transition 1: confinement to partial deconfinement  
(black hole formation begins)

transition 2: partial deconfinement to complete deconfinement  
(black hole formation ends)

$$\text{SU}(N) \rightarrow \text{SU}(M) \times \text{SU}(N-M) \rightarrow \text{SU}(N)$$

No need for center symmetry. Applies to QCD.

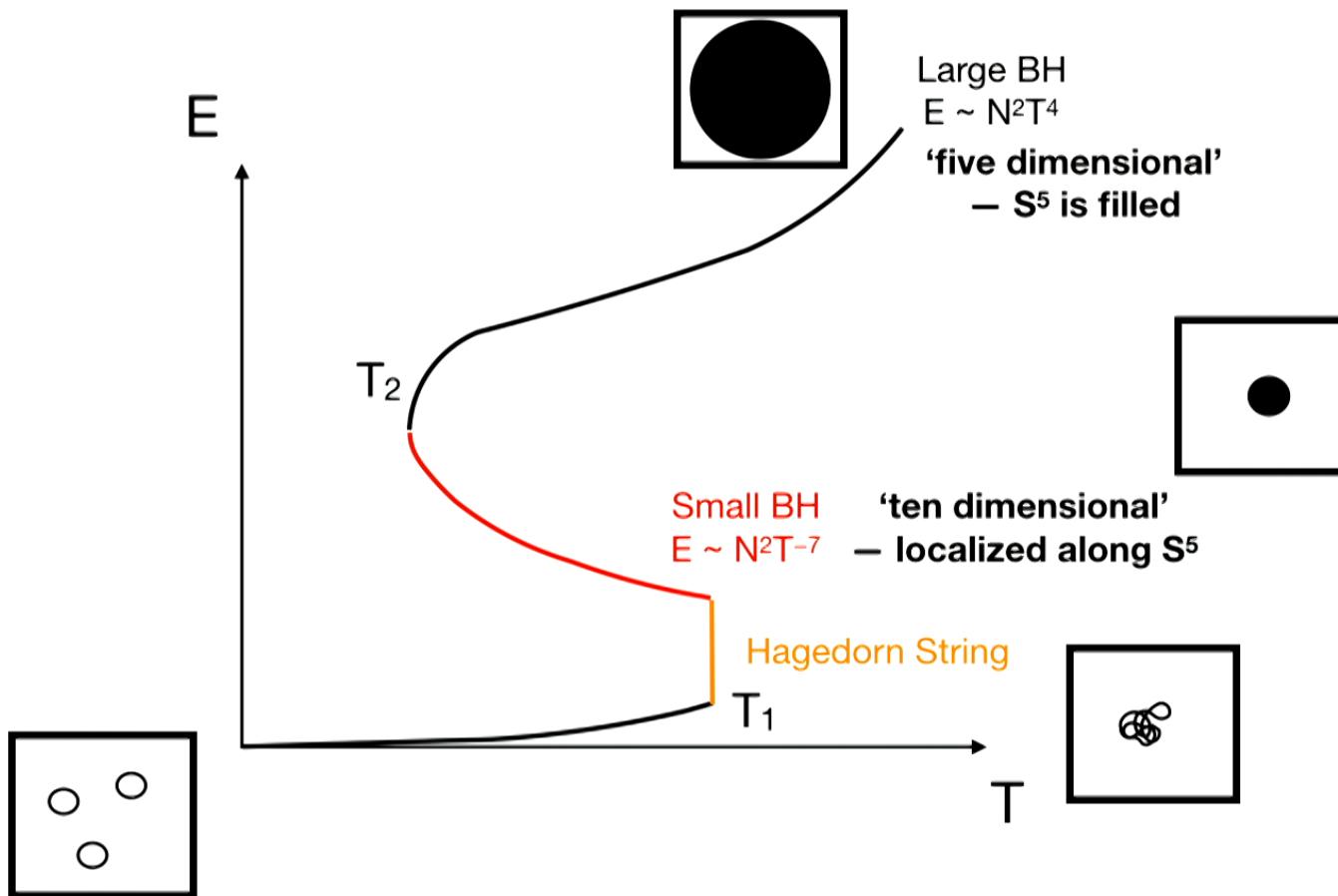
# Weakly-coupled QCD on $S^3$

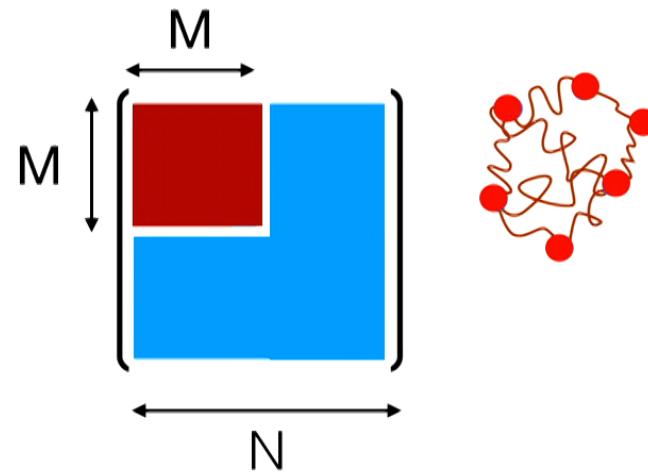


# **4d SYM on $S^3$ and Black Hole in $AdS_5 \times S^5$**

**M.H.-Maltz, 2016, JHEP; Susskind, unpublished**

## Black Hole in $\text{AdS}_5 \times S^5 = 4d$ N=4 SYM on $S^3$





Bound state of  $M$  D-branes

It can explain  $E \sim N^2 T^{-7}$  for 4d SYM,  $N^{3/2} T^{-8}$  for ABJM

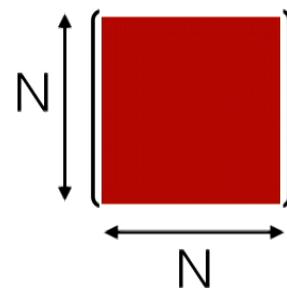
(String Theory  $\rightarrow$  10d)

(M-Theory  $\rightarrow$  11d)

(MH-Maltz, 2016)

M.H., Maltz, 2016 (JHEP)

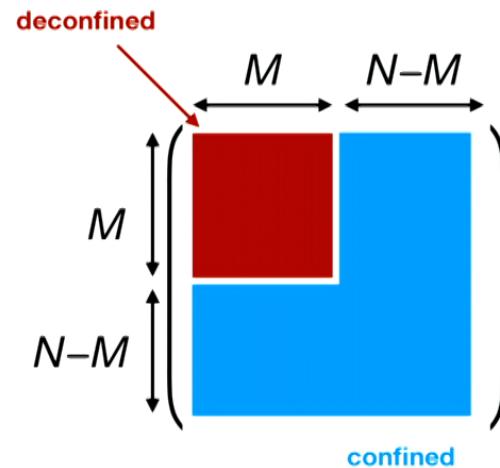
## Why is positive specific heat natural?



$$T \sim E/N^2 \quad T' \sim E'/N^2$$

$N^2$  is fixed  $\rightarrow T' > T$  if  $E' > E$

## Why can negative specific heat appear?



$$T \sim E/M^2$$

$M$  is a function of  $E$

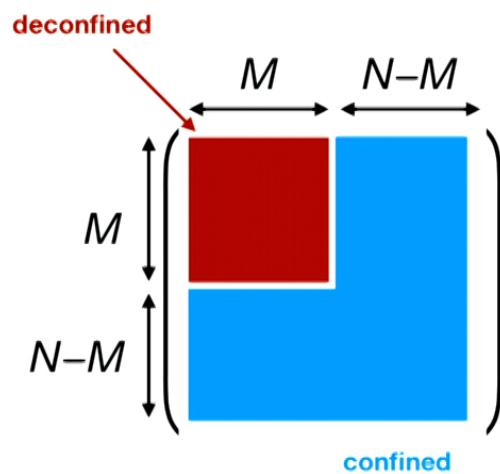
Berkowitz-M.H.-Maltz, 2016, PRD (Higgsing version)

M.H.-Maltz, 2016, JHEP

# Quantum Entanglement

## between color d.o.f.

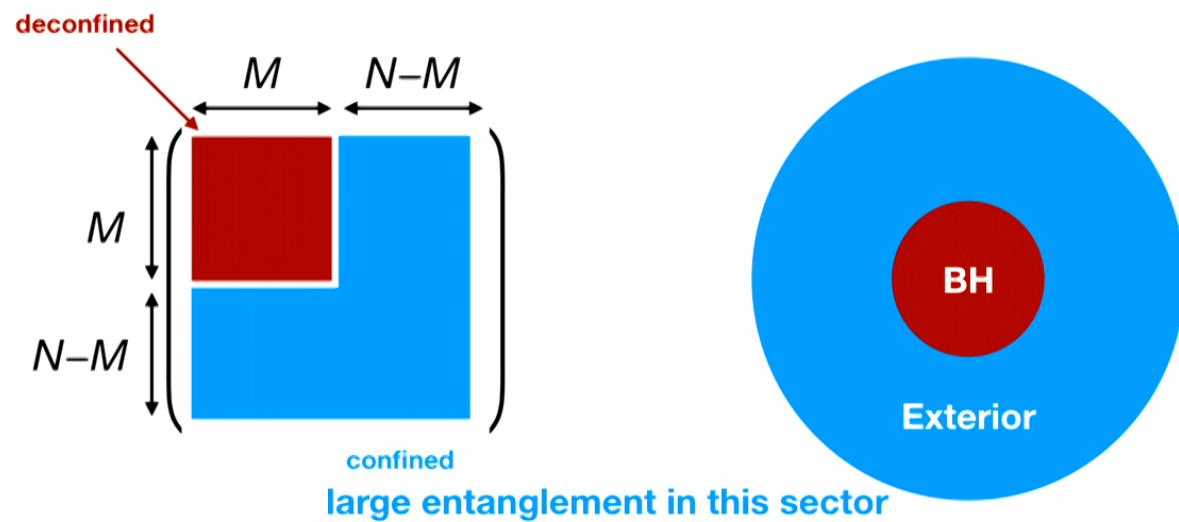
- Typically, ground state of interacting system is highly entangled.
- Thermal excitations can destroy the entanglement.



**Confined  $\rightarrow$  ground state up to  $1/N$  corrections**

**Large entanglement can survive even at finite temperature.**

# gauge/gravity duality



Entanglement between color d.o.f.  
→ geometry outside the horizon?

# Coupled SYK and wormhole

- Maldacena and Qi considered ‘coupled’ SYK

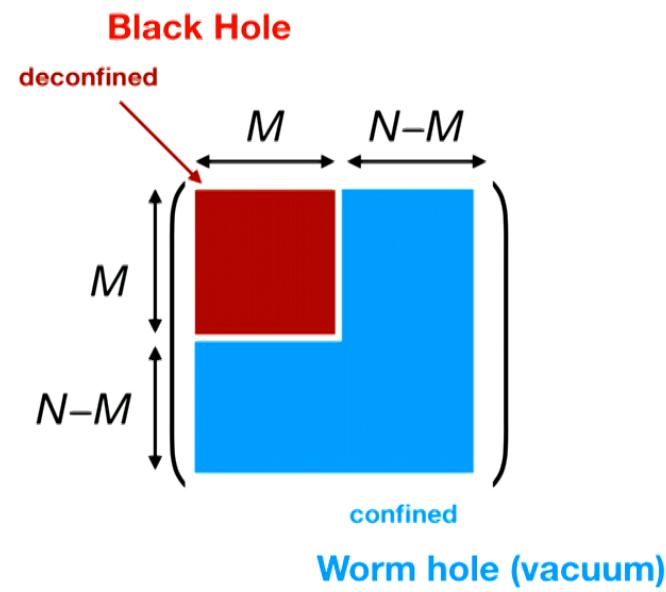
$$\hat{H}_{\text{coupled}} = \hat{H}_L \otimes \mathbf{1} + \mathbf{1} \otimes \hat{H}_R + \hat{H}_{\text{int}}$$
$$\hat{H}_{\text{int}} = i\mu \sum_{j=1}^{N/2} \hat{\chi}_L^j \hat{\chi}_R^j$$

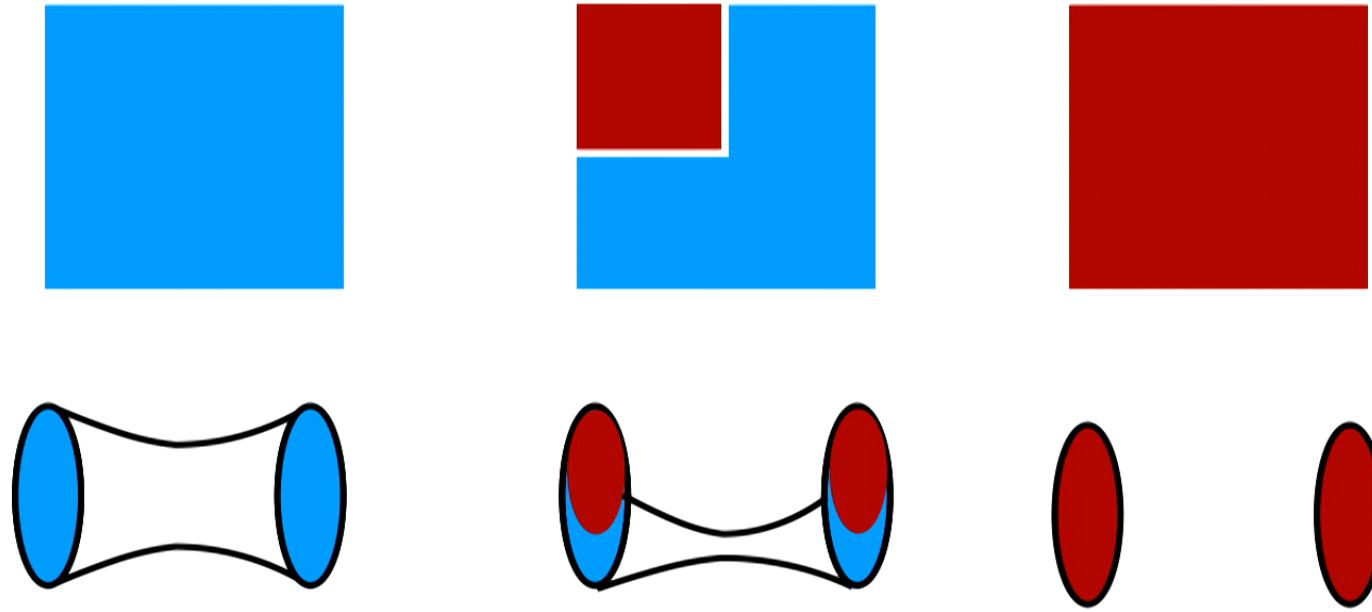
- $|\text{ground state}\rangle \sim |\text{TFD}\rangle$
- Gravity dual = ‘eternal traversable wormhole’
- Wormhole disappears when ‘deconfinement’ takes place

# Coupled Gauged Gaussian Matrix Model

- The simplest model of deconfinement+entanglement.
- ground state = product of TFD's

$$\begin{aligned} S = & N \int_0^\beta dt \text{Tr} \left( \frac{1}{2} (D_t X_I)^2 - \frac{1}{2} X_I^2 \right) + N \int_0^\beta dt \text{Tr} \left( \frac{1}{2} (D_t Y_I)^2 - \frac{1}{2} Y_I^2 \right) \\ & + \frac{NC_+}{2} \int_0^\beta dt \text{Tr} (X_I + Y_I)^2 - \frac{NC_-}{2} \int_0^\beta dt \text{Tr} (X_I - Y_I)^2. \end{aligned}$$



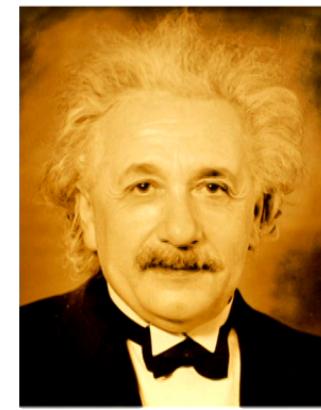


Entanglement between **colors** → connected space

# Confinement and BEC



Bose



Einstein

## Partial Deconfinement = Partial Confinement

- Many colors fall into ground state.
- Ground state and excited state can coexist.
- Happens even at zero-coupling limit.
- Gauge redundancy is crucial.

## Bose-Einstein Condensation

- Many particles fall into ground state.
- Ground state and excited state can coexist.
- Happens even at zero-coupling limit.
- Permutation redundancy is crucial.

## O(N) vector model on $S^d$

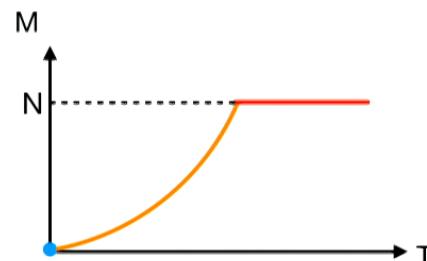
$\phi_1(x), \dots, \phi_N(x)$

$$\frac{M}{N} = \left(\frac{T}{T_c}\right)^d$$

$$T_c = \left(\frac{N}{4(1 - 2^{1-d})\zeta(d)}\right)^{1/d} \cdot \frac{1}{R}$$

$$E(T = T_c(M)) = E_c(M)$$

$$S(T = T_c(M)) = S_c(M)$$



## Non-interacting atoms in harmonic trap in $R^d$

$x_1, \dots, x_N; y_1, \dots, y_N; \dots$

' $S_N$  vector mechanics'

$$\frac{M}{N} = \left(\frac{T}{T_c}\right)^d$$

$$T_c = \left(\frac{N}{\zeta(d)}\right)^{1/d} \omega$$

$$E(T = T_c(M)) = E_c(M)$$

$$S(T = T_c(M)) = S_c(M)$$

# Positive interference of wave function

$$Z = \sum_{g \in G} \text{Tr} \left( \hat{g} e^{-\beta \hat{H}} \right)$$

- **Ground state** → all N particles are in the same state  
→ all g's returns the same value  
→ **factor  $N!$  enhancement**
- All N particles are in different states  
→ only  $g=1$  gives nonzero value

$$|\vec{n}_1, \vec{n}_2, \dots, \vec{n}_N\rangle \equiv \prod_{i=1}^d \frac{\hat{a}_{i1}^{\dagger n_{i1}}}{\sqrt{n_{i1}!}} \frac{\hat{a}_{i2}^{\dagger n_{i2}}}{\sqrt{n_{i2}!}} \cdots \frac{\hat{a}_{iN}^{\dagger n_{iN}}}{\sqrt{n_{iN}!}} |0\rangle$$

$$\begin{aligned}
Z &= \sum_{g \in S_N} \sum_{\vec{n}_1, \dots, \vec{n}_N} \langle \vec{n}_1, \dots, \vec{n}_N | \hat{g} e^{-\beta \hat{H}} | \vec{n}_1, \dots, \vec{n}_N \rangle \\
&= \sum_{\vec{n}_1, \dots, \vec{n}_N} e^{-\beta(E_{\vec{n}_1} + \dots + E_{\vec{n}_N})} \sum_{g \in S_N} \langle \vec{n}_1, \dots, \vec{n}_N | \hat{g} | \vec{n}_1, \dots, \vec{n}_N \rangle \\
&= \sum_{\vec{n}_1, \dots, \vec{n}_N} e^{-\beta(E_{\vec{n}_1} + \dots + E_{\vec{n}_N})} \sum_{g \in S_N} \langle \vec{n}_1, \dots, \vec{n}_N | \vec{n}_{g(1)}, \dots, \vec{n}_{g(N)} \rangle
\end{aligned}$$

$$|\vec{n}_1, \vec{n}_2, \dots, \vec{n}_N\rangle \equiv \prod_{i=1}^d \frac{\hat{a}_{i1}^{\dagger n_{i1}}}{\sqrt{n_{i1}!}} \frac{\hat{a}_{i2}^{\dagger n_{i2}}}{\sqrt{n_{i2}!}} \dots \frac{\hat{a}_{iN}^{\dagger n_{iN}}}{\sqrt{n_{iN}!}} |0\rangle$$

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# Positive interference of wave function

$$Z = \sum_{g \in G} \text{Tr} \left( \hat{g} e^{-\beta \hat{H}} \right)$$

- **Ground state** → all N <sup>colors</sup> particles are in the same state  
→ all g's returns the same value  
→ factor  $N!$  enhancement volume of  $O(N)$ ,  $SU(N)$
- All N <sup>colors</sup> particles are in different states  
→ only  $g=1$  gives nonzero value

The same mechanism holds for Yang-Mills as well

$$|\vec{n}_1, \vec{n}_2, \dots, \vec{n}_N\rangle \equiv \prod_{i=1} \frac{\omega_{i1}}{\sqrt{n_{i1}!}} \frac{\omega_{i2}}{\sqrt{n_{i2}!}} \dots \frac{\omega_{iN}}{\sqrt{n_{iN}!}} |0\rangle$$

Why should large symmetry be preserved?

$$\begin{pmatrix} & & & \\ & \textcolor{red}{\square} & & \\ & & \textcolor{red}{\square} & \\ & & & \textcolor{red}{\square} \\ & \textcolor{red}{\square} & & \\ & & & \\ & & & \end{pmatrix}$$

no symmetry

instead of

$$\begin{pmatrix} \textcolor{red}{\square} & & & \\ & & & \\ & & & \\ & & & \end{pmatrix}$$

$SU(M) \times SU(N-M)$

?



L. Onsager



O. Penrose



C. N. Yang

# Off-Diagonal Long Range Order (ODLRO) vs Polyakov Loop



A. Polyakov



L. Susskind

$$|\vec{n}_1, \vec{n}_2, \dots, \vec{n}_N\rangle \equiv \prod_{i=1}^d \frac{\hat{a}_{i1}^{\dagger n_{i1}}}{\sqrt{n_{i1}!}} \frac{\hat{a}_{i2}^{\dagger n_{i2}}}{\sqrt{n_{i2}!}} \cdots \frac{\hat{a}_{iN}^{\dagger n_{iN}}}{\sqrt{n_{iN}!}} |0\rangle$$

Reduced density matrix  $\hat{\rho}_1 = N \cdot \text{Tr}_{2,3,\dots,N} \hat{\rho}$

$$\hat{\rho}_1 = \underbrace{n_{\max} |\Psi\rangle\langle\Psi|}_{\text{O(N) term} \rightarrow \text{BEC}} + \sum_i n_i |\Psi_i\rangle\langle\Psi_i|$$

$\langle x | \hat{\rho}_1 | y \rangle$  non-vanishing at long distance

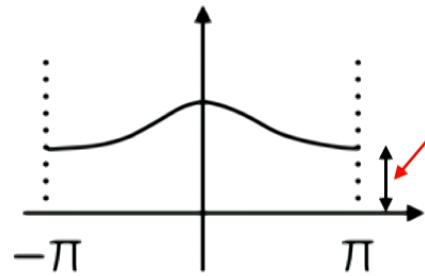
**Off-Diagonal Long Range Order**

## Off-Diagonal Long Range Order

$$\hat{\rho}_1 = n_{\max} |\Psi\rangle\langle\Psi| + \sum_i n_i |\Psi_i\rangle\langle\Psi_i|.$$

# of d.o.f. in BEC

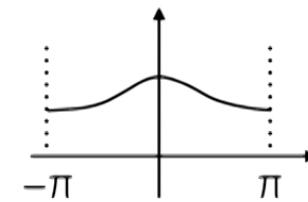
## Polyakov loop phases



$$Z = \sum_{g \in G} \text{Tr} \left( \hat{g} e^{-\beta \hat{H}} \right)$$



Polyakov loop



- Choose a ‘typical’ state.
- Permutations leaving this state invariant is dominant.

$$|\vec{n}_1, \vec{n}_2, \dots, \vec{n}_N\rangle \equiv \prod_{i=1}^d \frac{\hat{a}_{i1}^{\dagger n_{i1}}}{\sqrt{n_{i1}!}} \frac{\hat{a}_{i2}^{\dagger n_{i2}}}{\sqrt{n_{i2}!}} \cdots \frac{\hat{a}_{iN}^{\dagger n_{iN}}}{\sqrt{n_{iN}!}} |0\rangle$$

$$\{g = \{g_{\vec{n}}\} \in \prod_{\vec{n}} S_{M_{\vec{n}}}\} \quad M_{\vec{0}} \sim N \rightarrow \infty$$

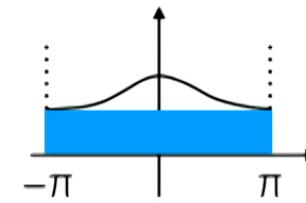
Long cyclic permutation becomes dominant;

length  $k \rightarrow$  eigenvalues  $e^{2\pi i l/k}$ ,  $l = 0, 1, \dots, k-1$

$$Z = \sum_{g \in G} \text{Tr} \left( \hat{g} e^{-\beta \hat{H}} \right)$$



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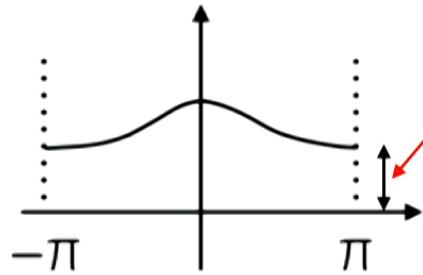
**→ constant offset**

## Off-Diagonal Long Range Order

$$\hat{\rho}_1 = n_{\max} |\Psi\rangle\langle\Psi| + \sum_i n_i |\Psi_i\rangle\langle\Psi_i|.$$

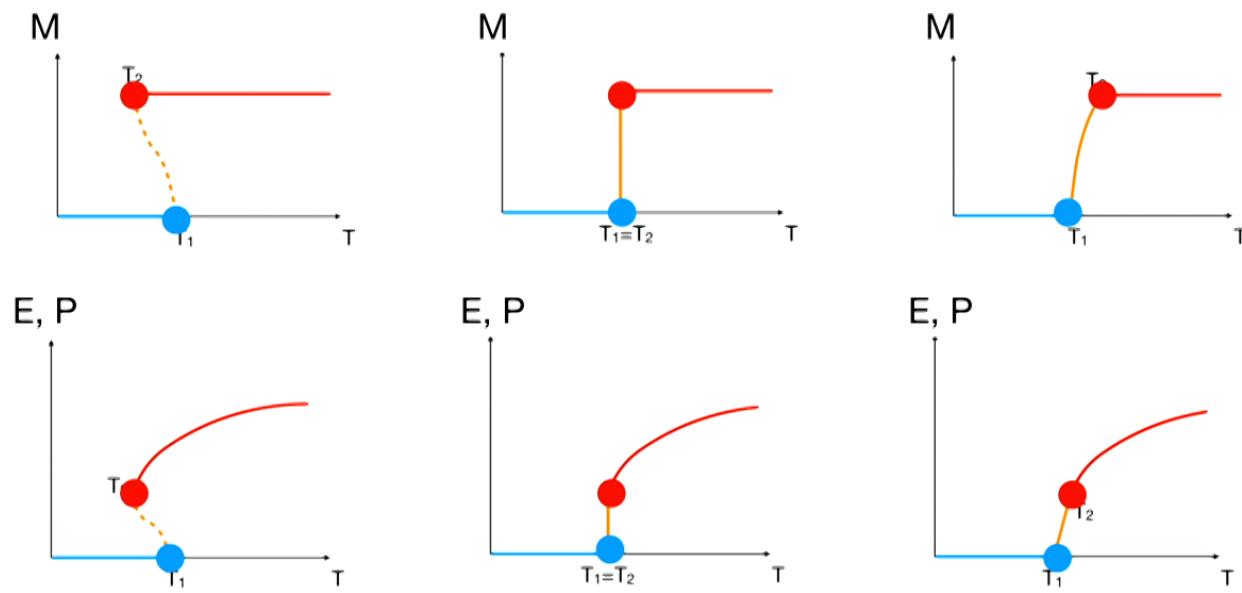
# of d.o.f. in BEC

## Polyakov loop phases



It works in any gauge theory,  
for any field representation,  
even at strong coupling.

# **Summary, Discussions & Speculations**

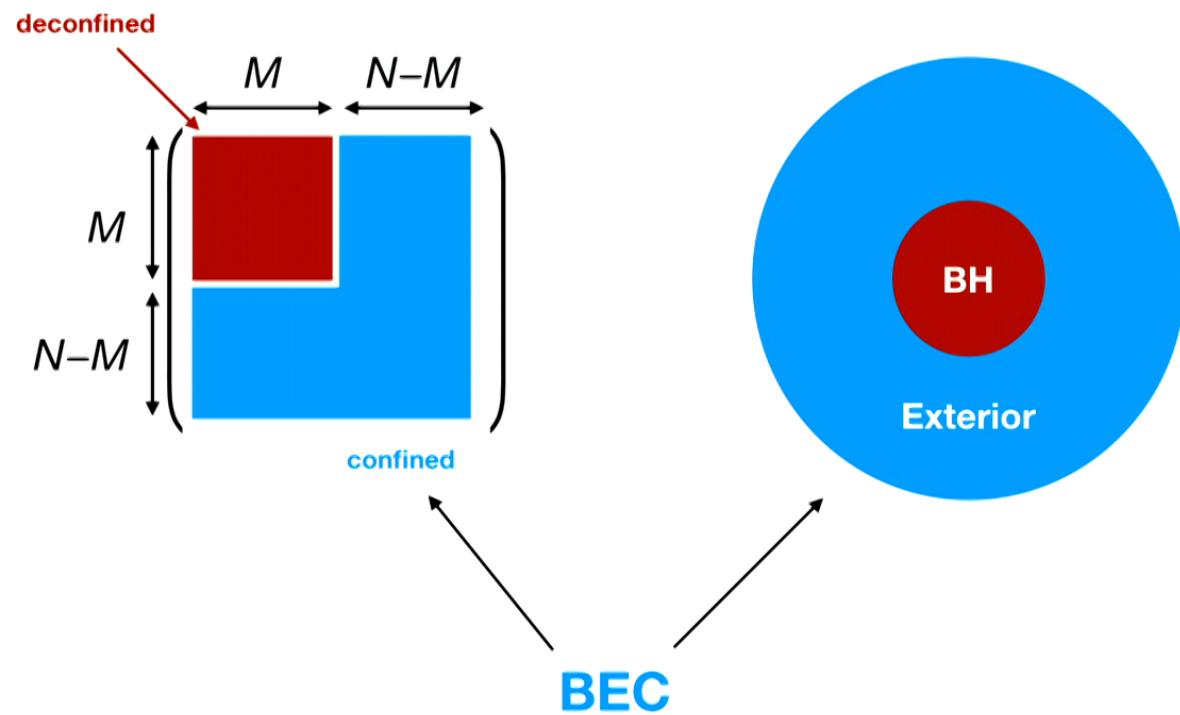


transition 1: confinement to partial deconfinement  
(black hole formation begins)

transition 2: partial deconfinement to complete deconfinement  
(black hole formation ends)

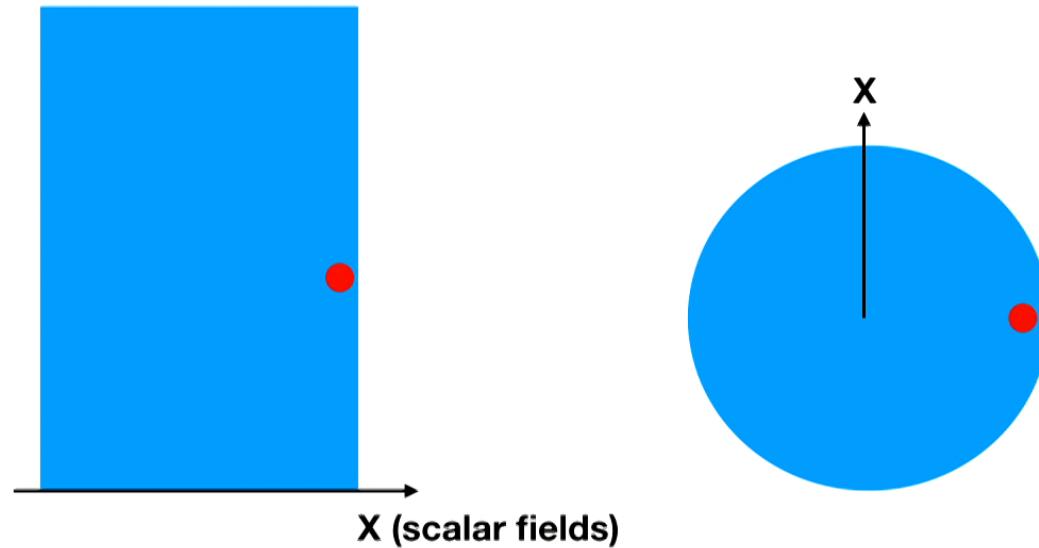
$$\text{SU}(N) \rightarrow \text{SU}(M) \times \text{SU}(N-M) \rightarrow \text{SU}(N)$$

No need for center symmetry. Applies to QCD.



Entanglement between colors  
→ holographic emergent space ?

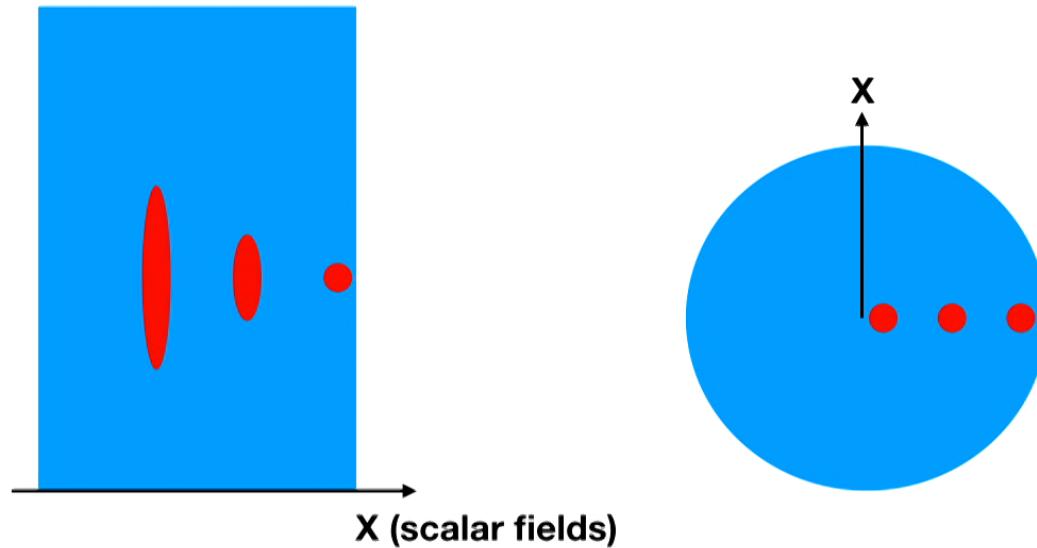
## BFSS meets Maldacena?



**Local operator adds energy to the state and creates a small deconfined block**

**'Boundary' = large  $X$  = high energy**

## BFSS meets Maldacena?



**Local operator adds energy to the state and creates a small deconfined block**

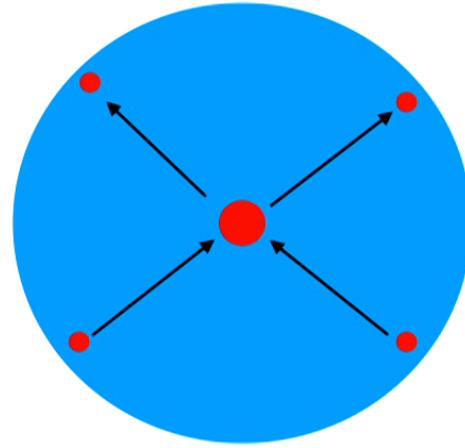
**'Boundary' = large X = high energy**

**'Bulk' = small X = low energy**

**Volume of the deconfined block increases (total energy fixed)**

**May lead to a better understanding about "space from colors"?**

## BFSS meets Maldacena?



Bulk dynamics looks like Banks-Fischler-Shekner-Susskind picture

Partial deconfinement, instead of Higgsing

Everything from matrices

← →  
**color = qubit**

It from qubit