Black Hole from Colors

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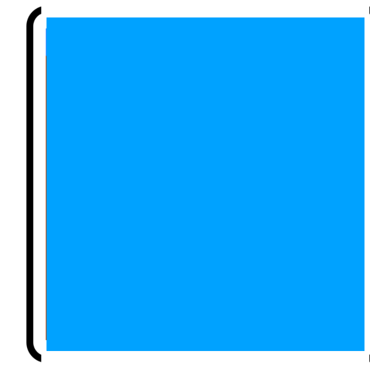
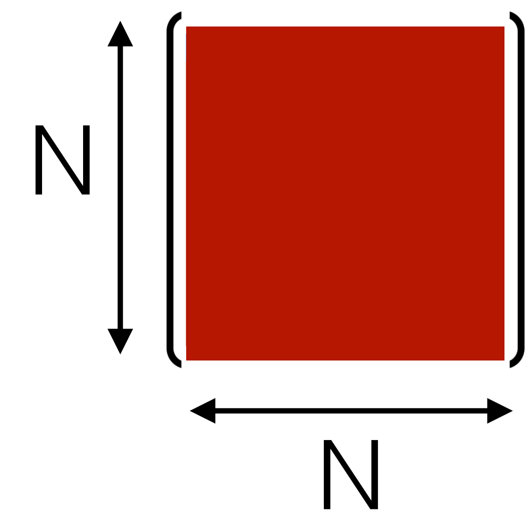
Sept 23, 2019 @ Corfu, Greece

M.H.-Maltz, 2016
M.H.-Ishiki-Watanabe, 2018
M.H.-Jevicki-Peng-Wintergert, 2019
M.H.-O'Bannon-Robinson, in preparation

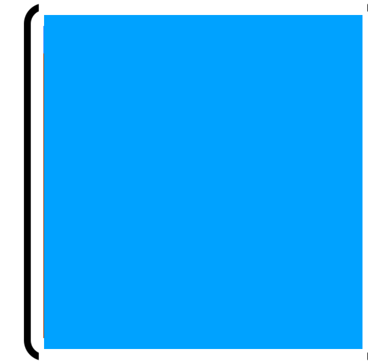


- Confinement phase: $E \sim N^0$



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

$\Longleftrightarrow$ Black Hole



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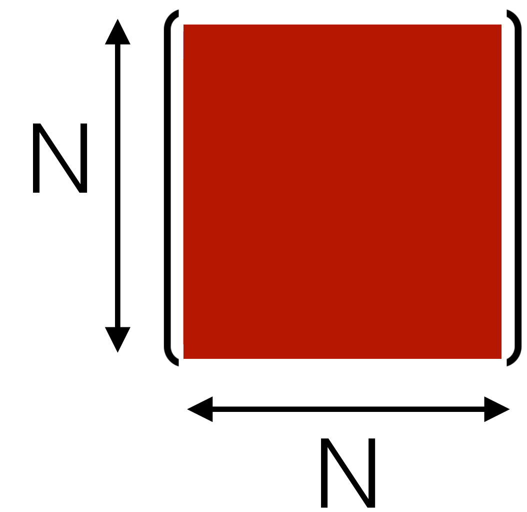

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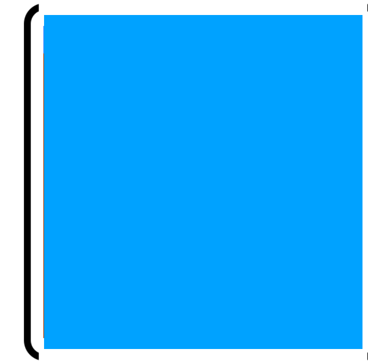
$\Longleftrightarrow$ Black Hole

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



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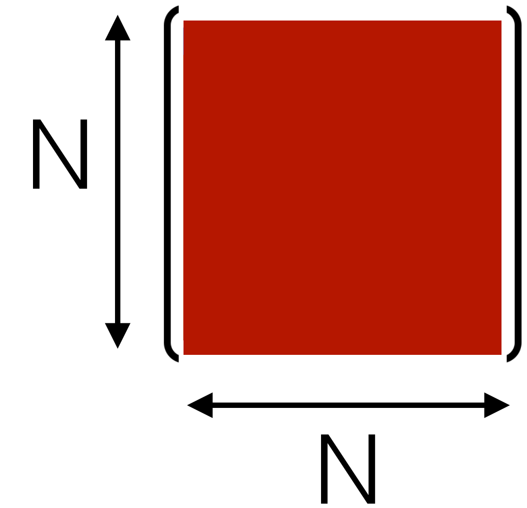
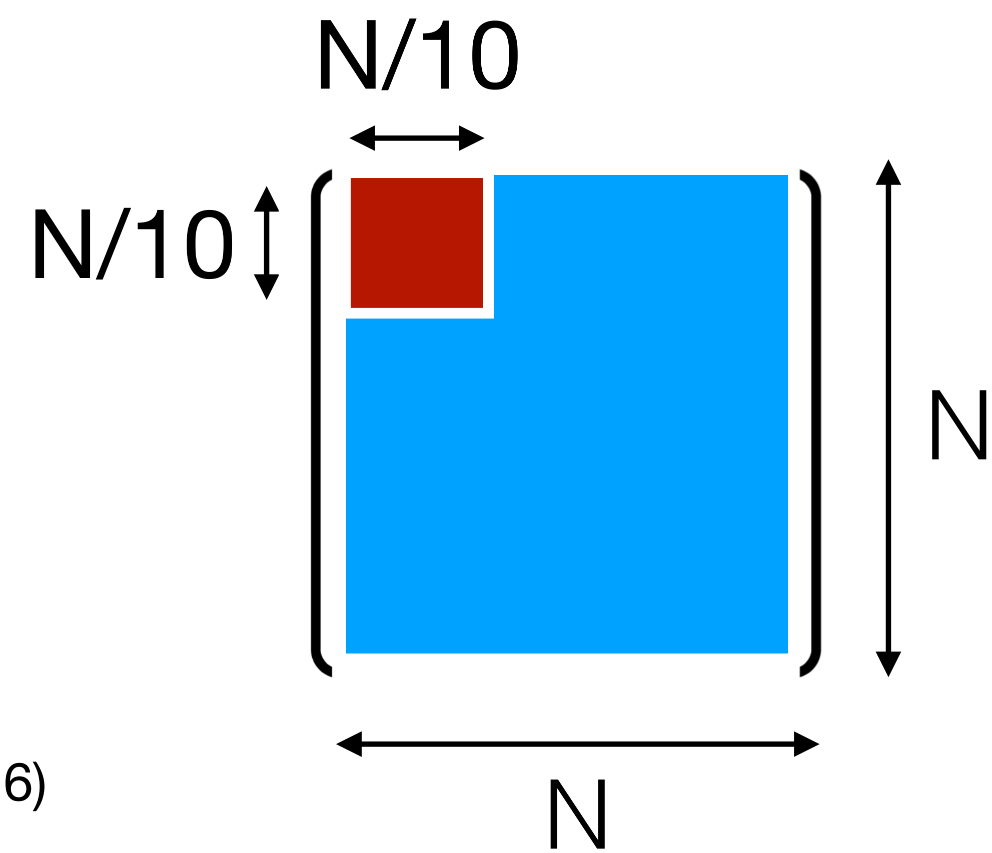


- Deconfinement phase: $E \sim N^2$

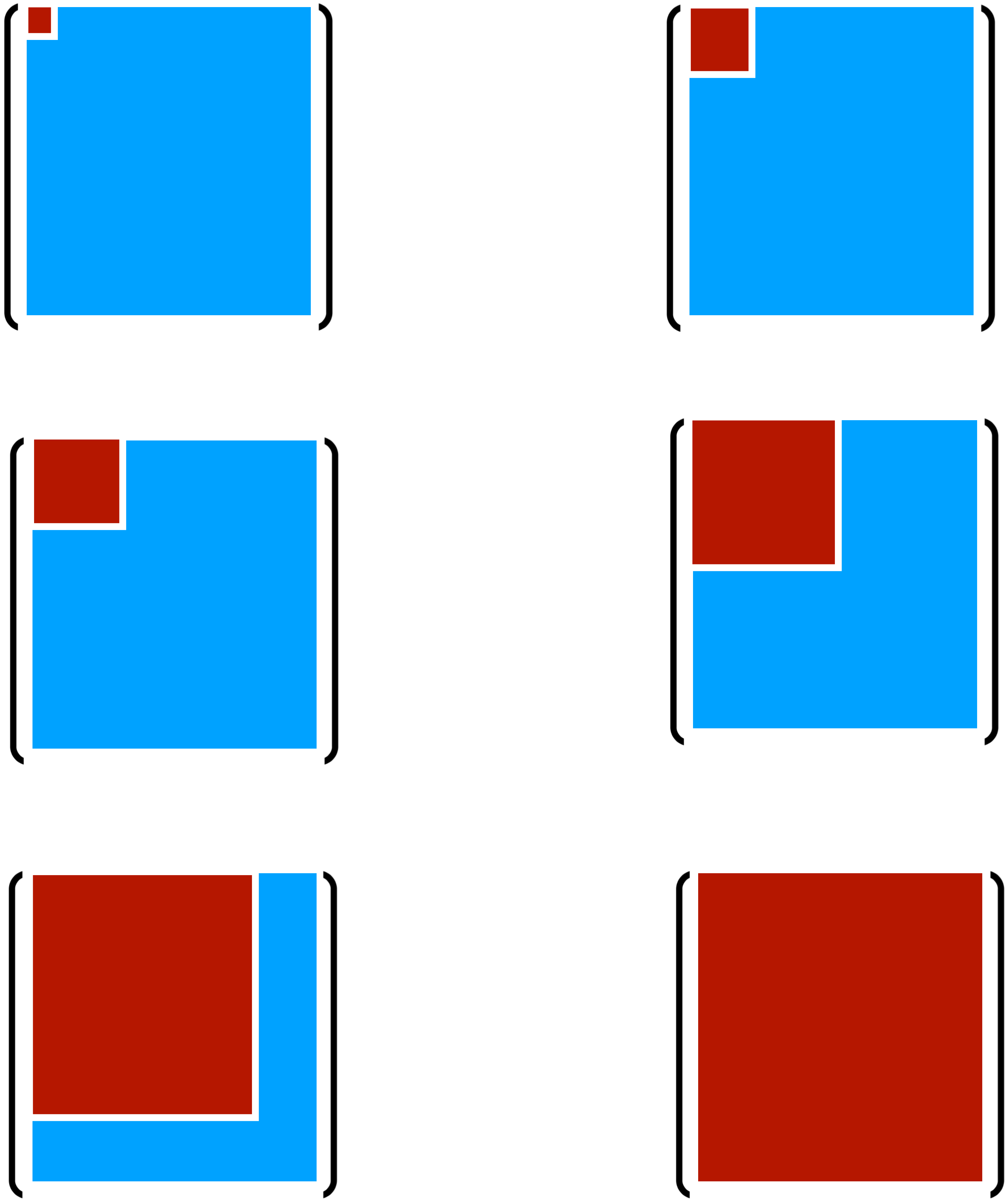
$\Longleftrightarrow$ Black Hole

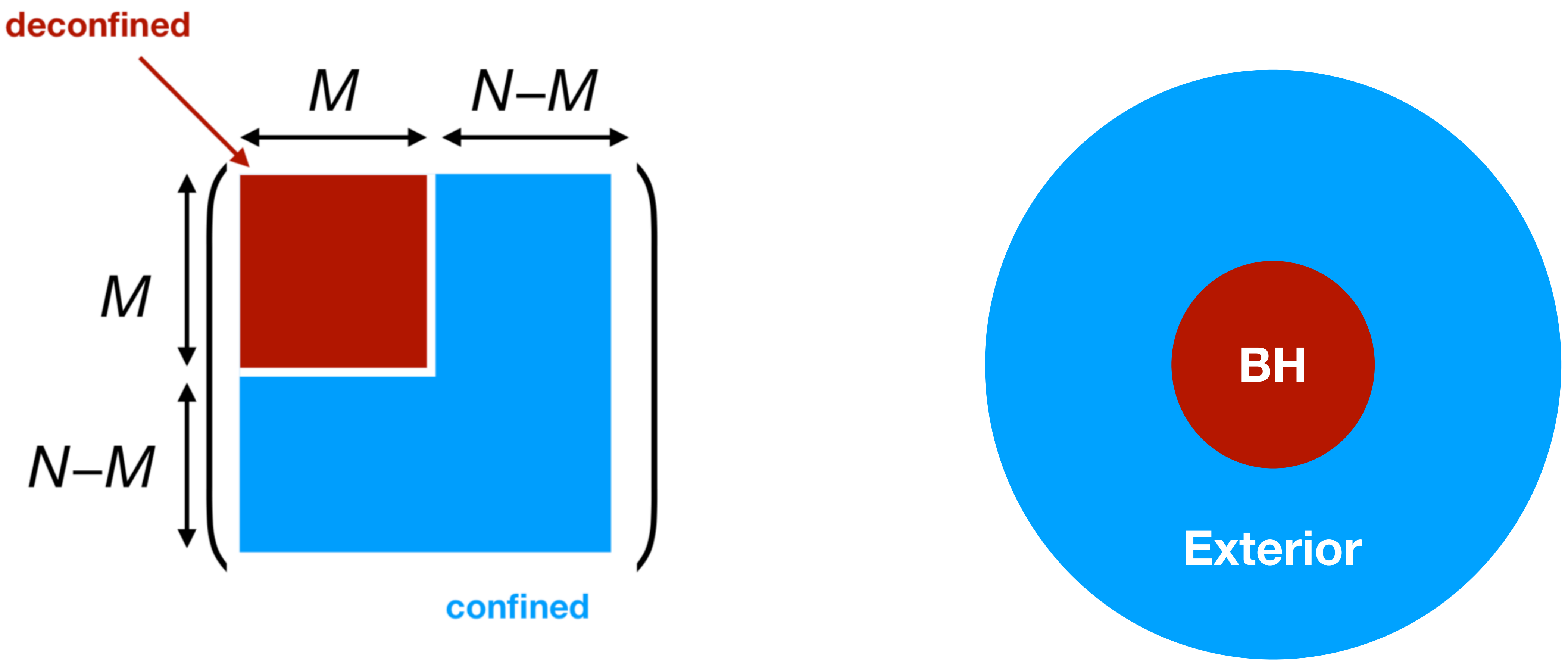
What if $E \sim N^2/100$?



<u>'partially' deconfine</u>

(MH-Maltz, 2016)

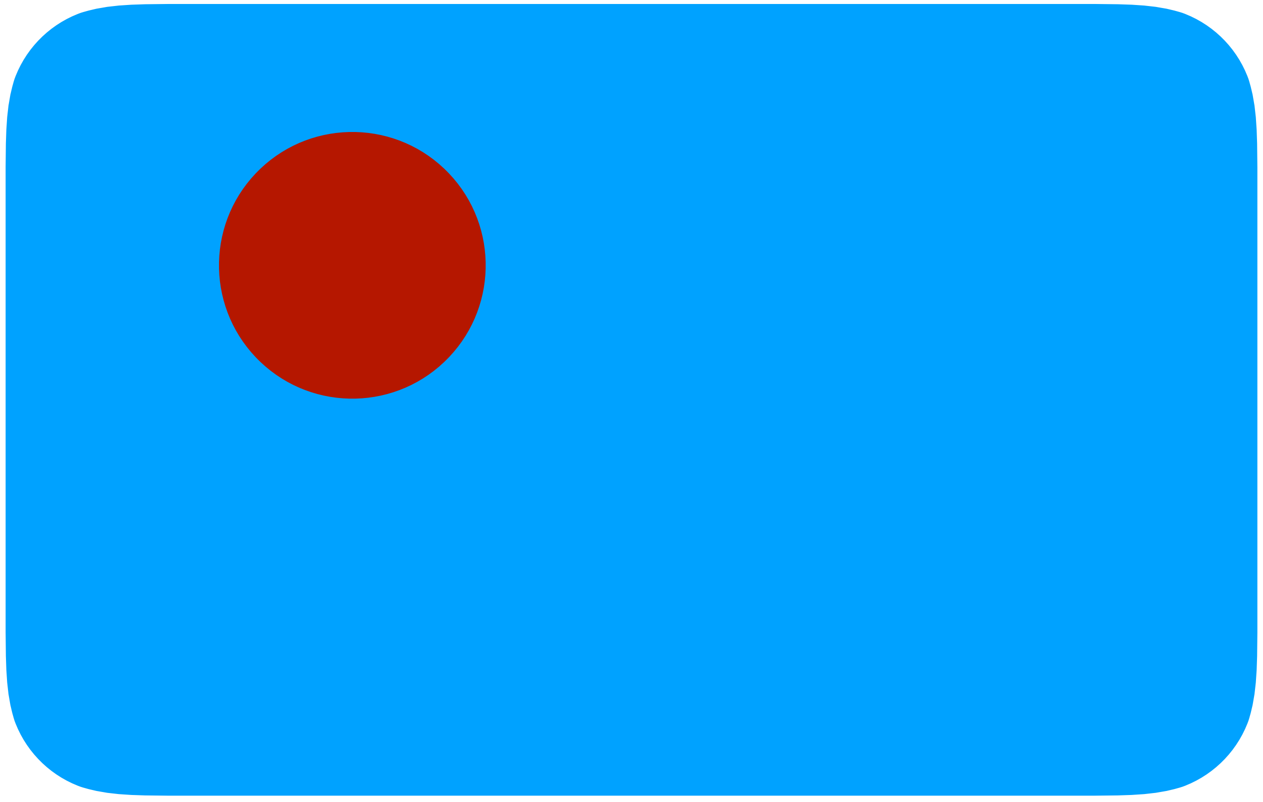



deconfined
M
N−M
M
N−M
confined
BH
Exterior

Heuristic justification

(more precise argument is given later)

Why doesn’t a part of the volume deconfine?



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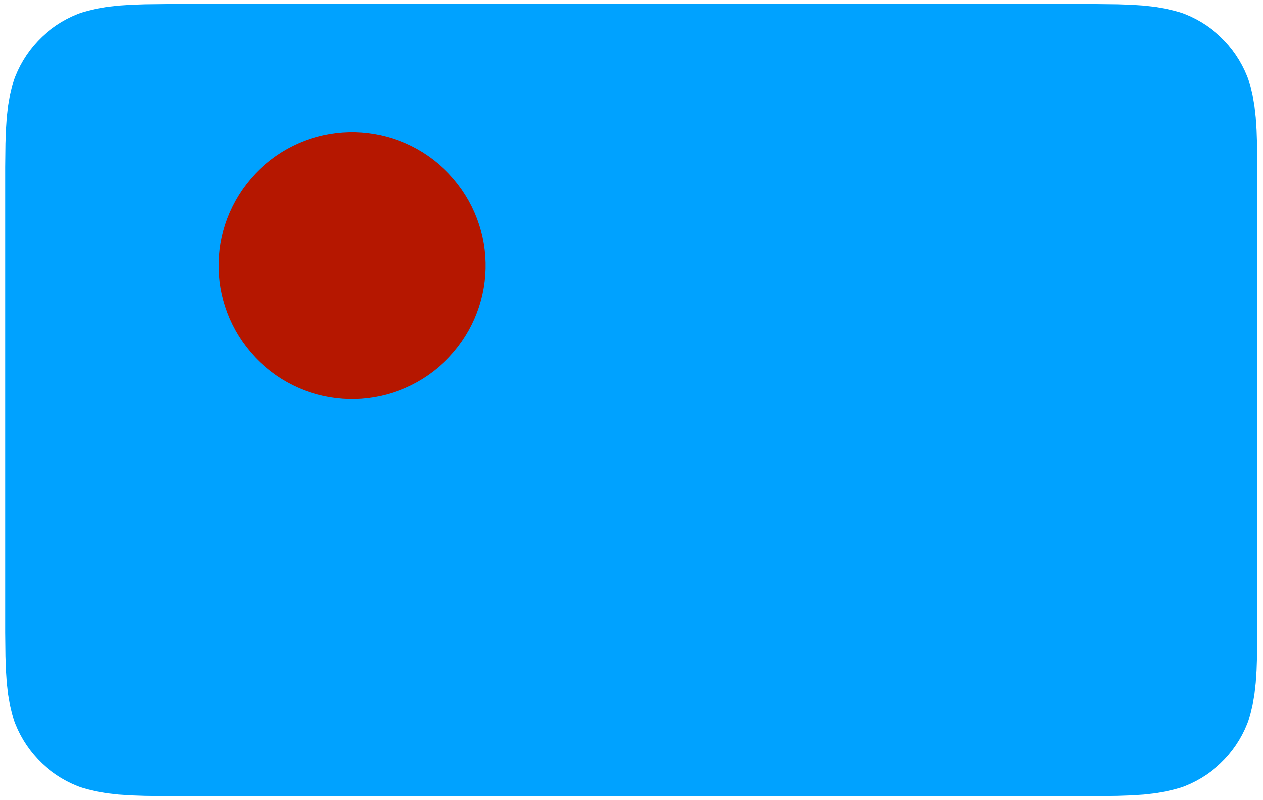
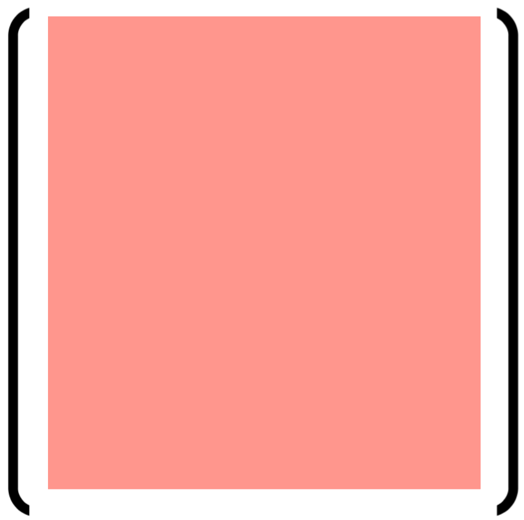
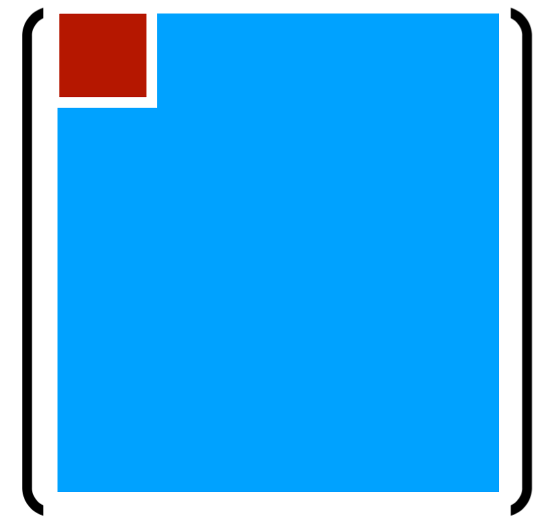


Deconfinement takes place even in matrix model, which has no spatial dimensions.

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

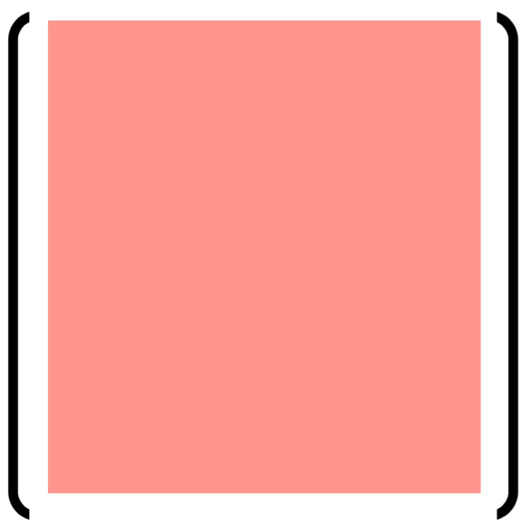
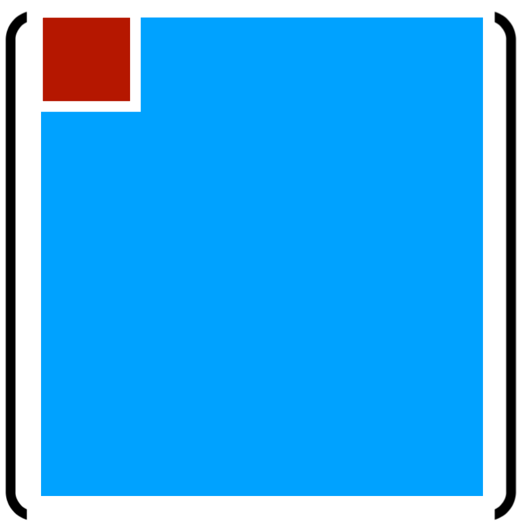


instead of



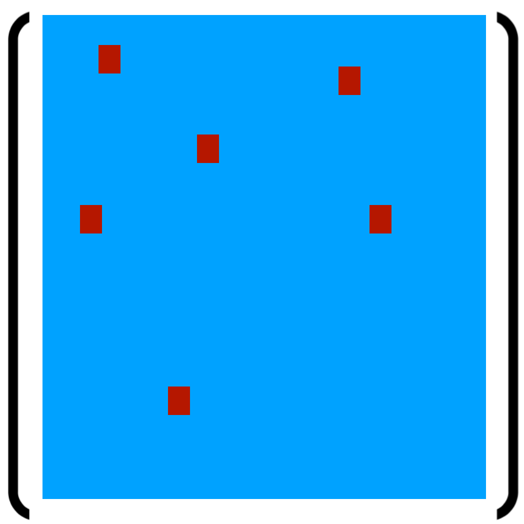
?

Why don’t all N^2 d.o.f. gently excited?

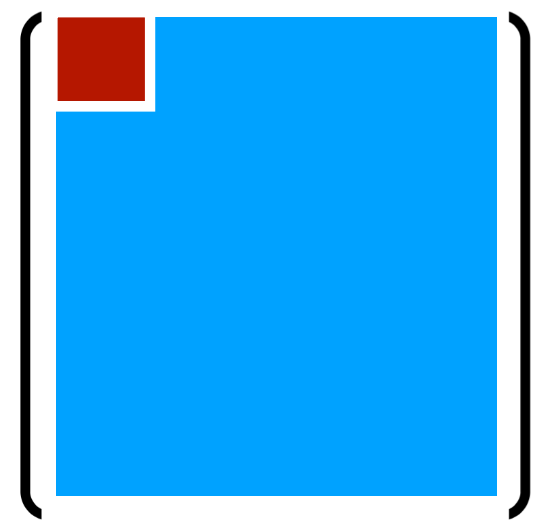
 instead of  ?

In quantum mechanics, parametrically small excitation is impossible.

Why should symmetry preserved partly?

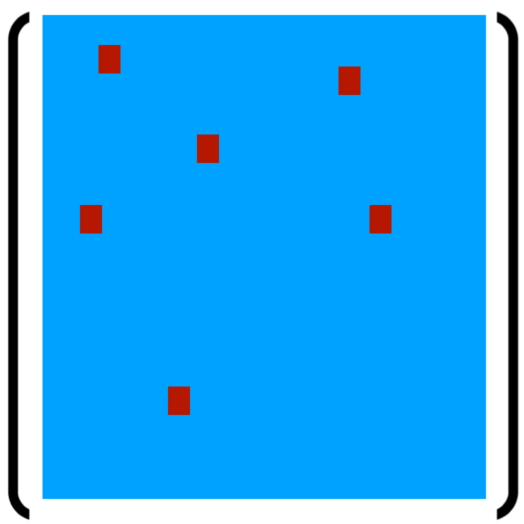


instead of



?

Why should symmetry preserved partly?



instead of

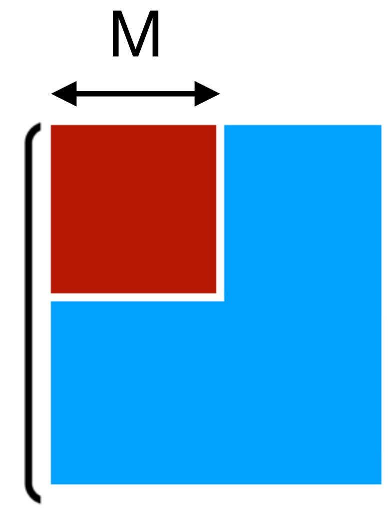
?

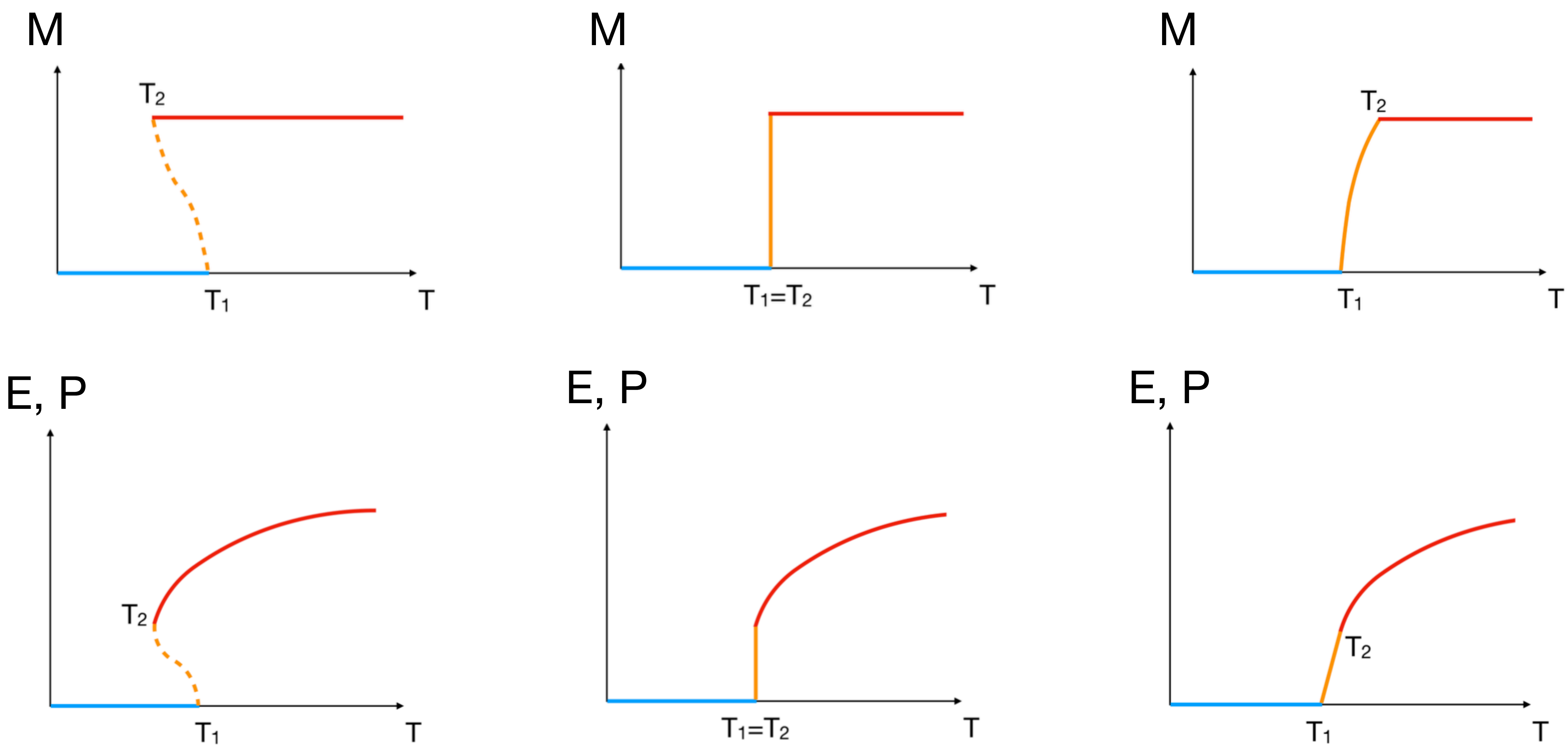
It is natural to expect a large symmetry at saddle point.

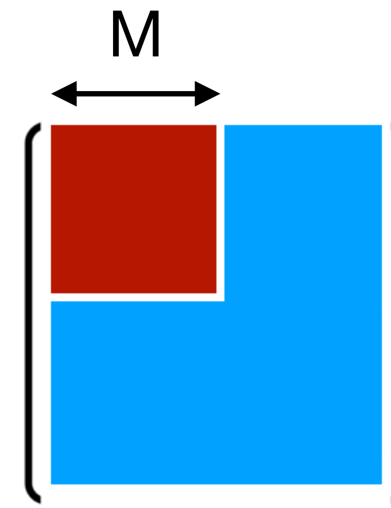
Phase Diagrams

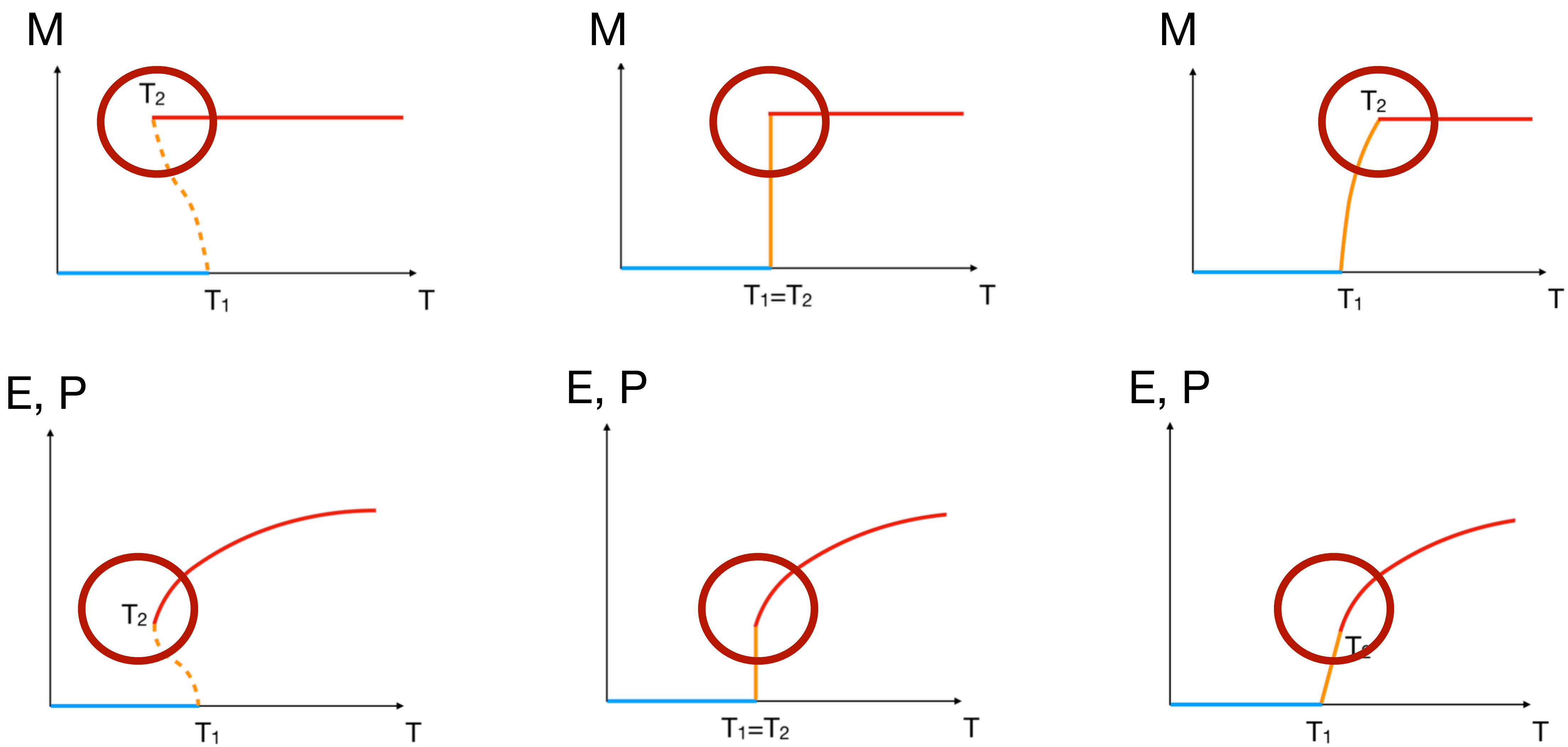
Hagedorn transition
Gross-Witten-Wadia transition
Gauge symmetry breaking

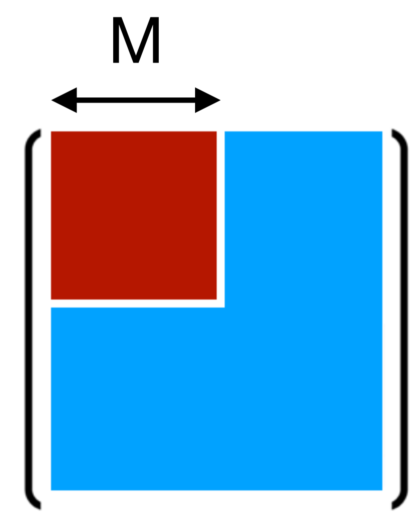
(more precise argument is given later)


M

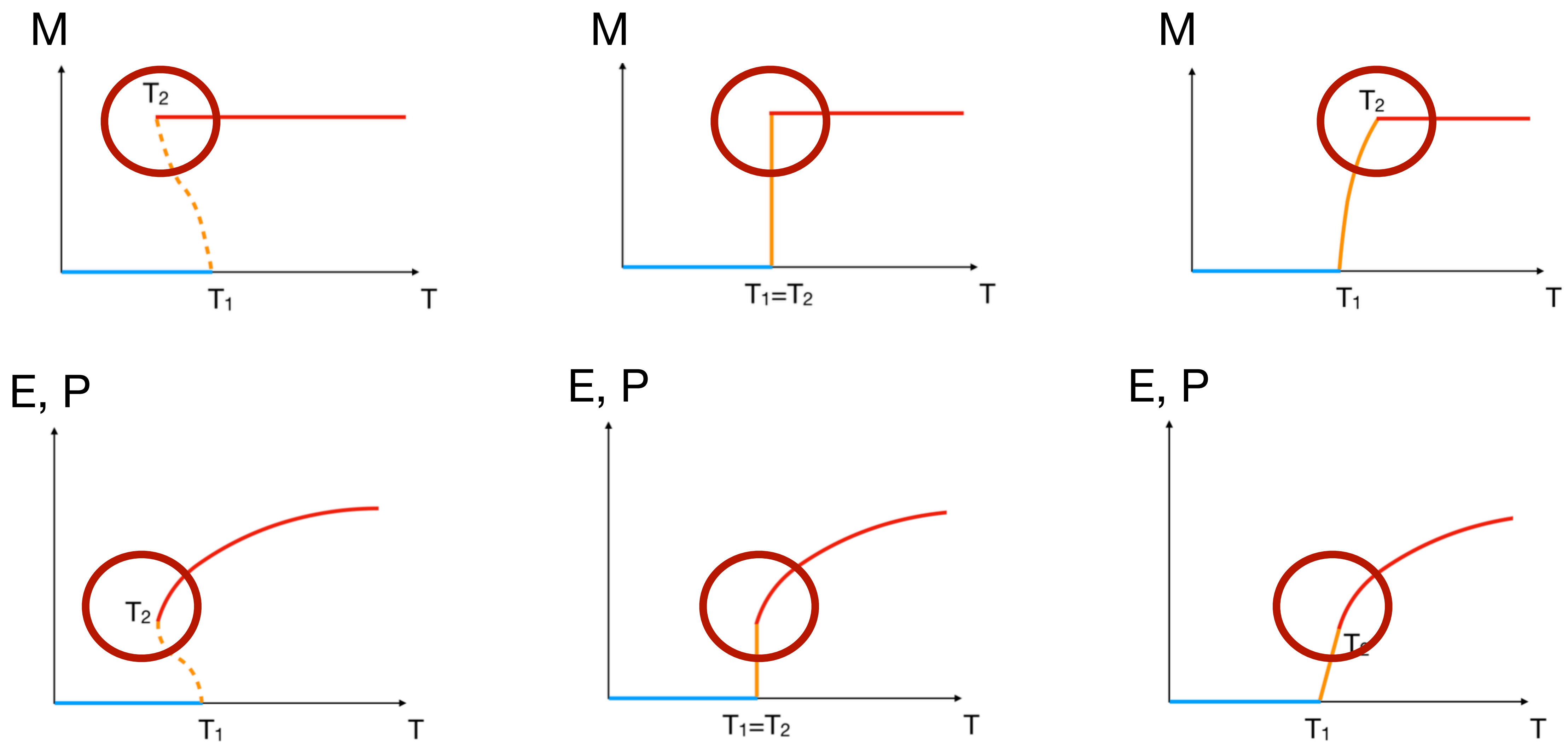

M
T2
T1
T
M
T1=T2
T
M
T2
T1
T
E, P
T2
T1
T
E, P
T1=T2
T
E, P
T2
T1
T


M


M
T2
T1
T
M
T1=T2
T
M
T2
T1
T
E, P
T2
T1
T
E, P
T1=T2
T
E, P
T1
T



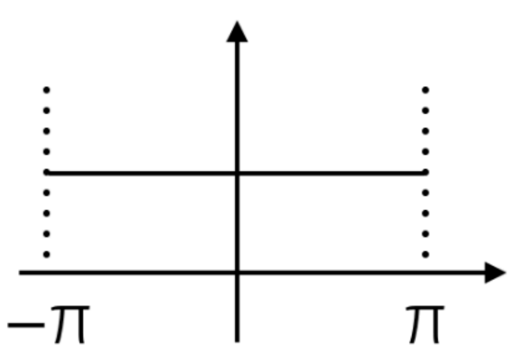
Gross-Witten-Wadia transition



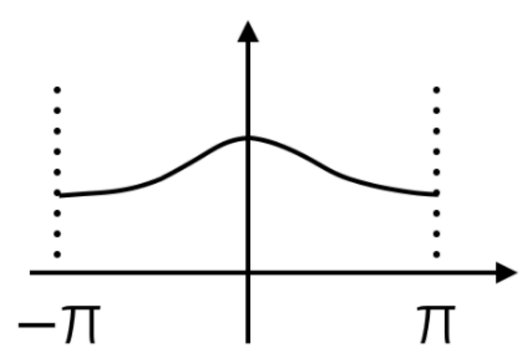
- Polyakov loop $$P = \frac{1}{N}\sum_{j=1}^{N} e^{i\theta_j}$$

- Phase distribution:

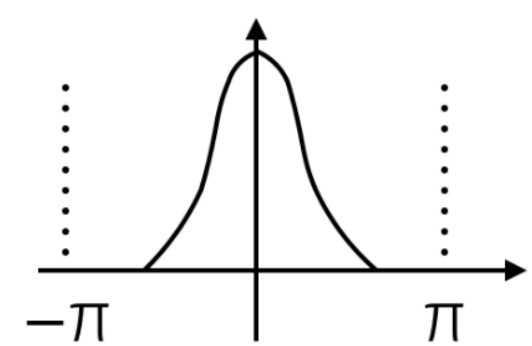
confined phase
P=0



deconfined phase
P ≠ 0



‘partially’ deconfined



‘completely’ deconfined

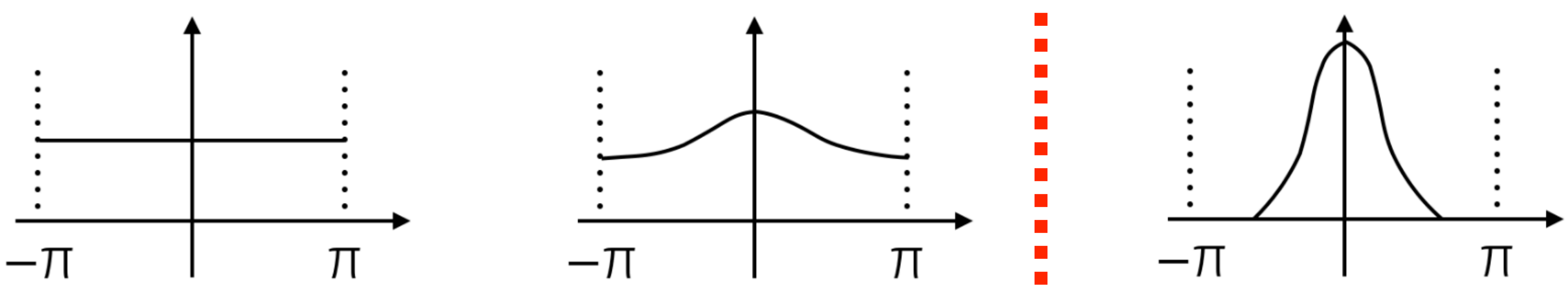
- Polyakov loop $$P = \frac{1}{N}\sum_{j=1}^{N} e^{i\theta_j}$$

- Phase distribution:

Gross-Witten-Wadia transition (GWW)

confined phase
P=0

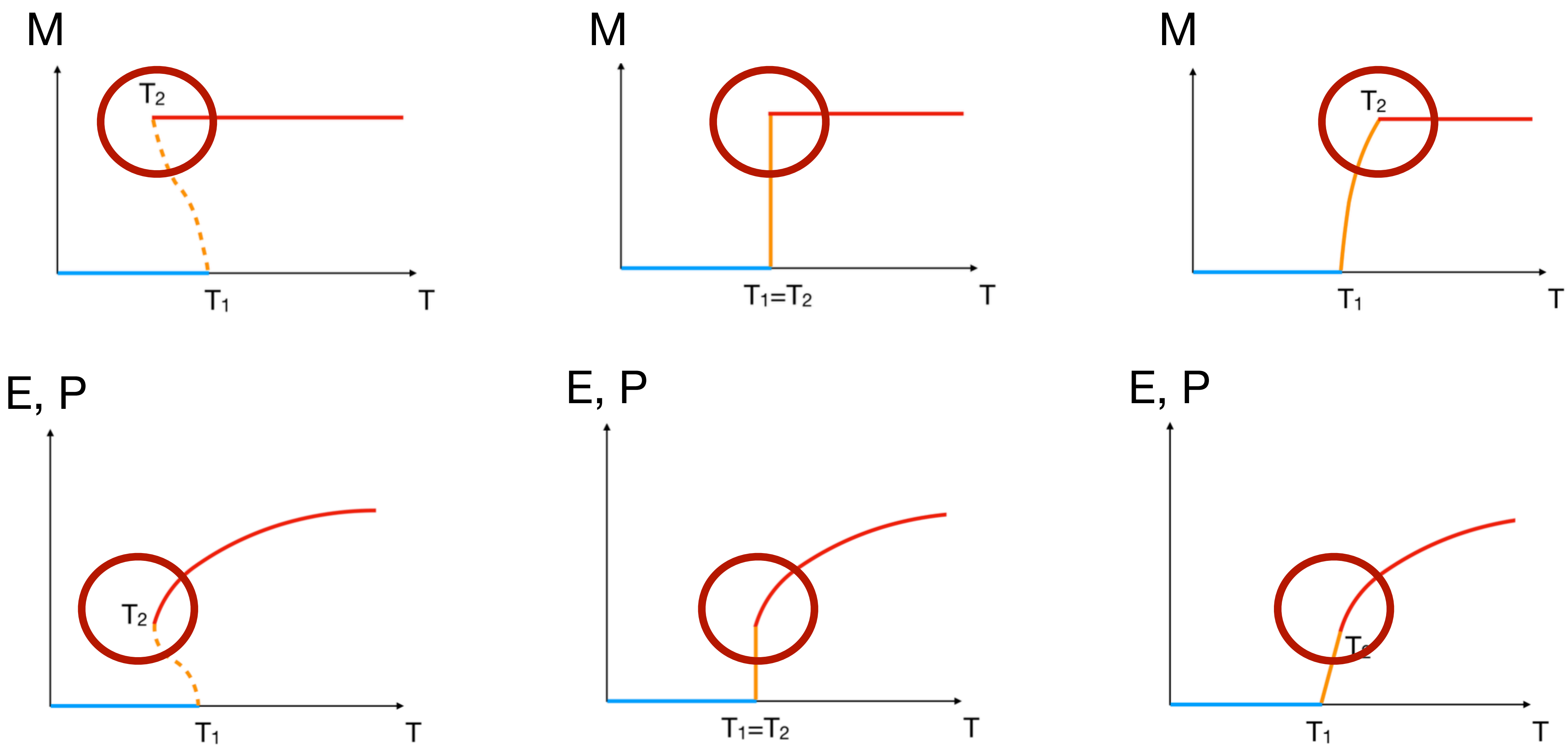
deconfined phase
P ≠ 0



‘partially’ deconfined

‘completely’ deconfined

Gross-Witten-Wadia transition = “partial deconfinement → complete deconfinement” transition



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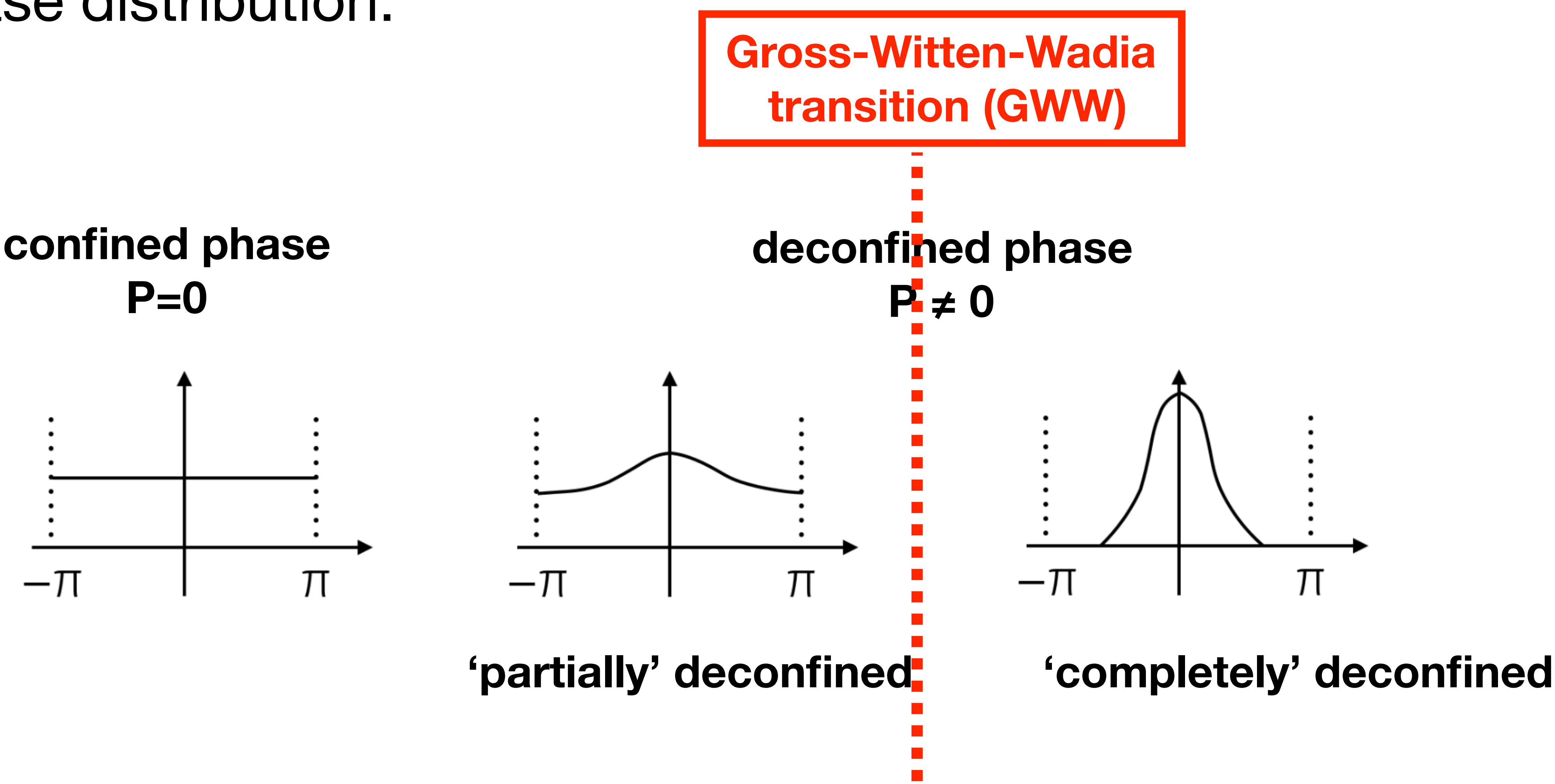

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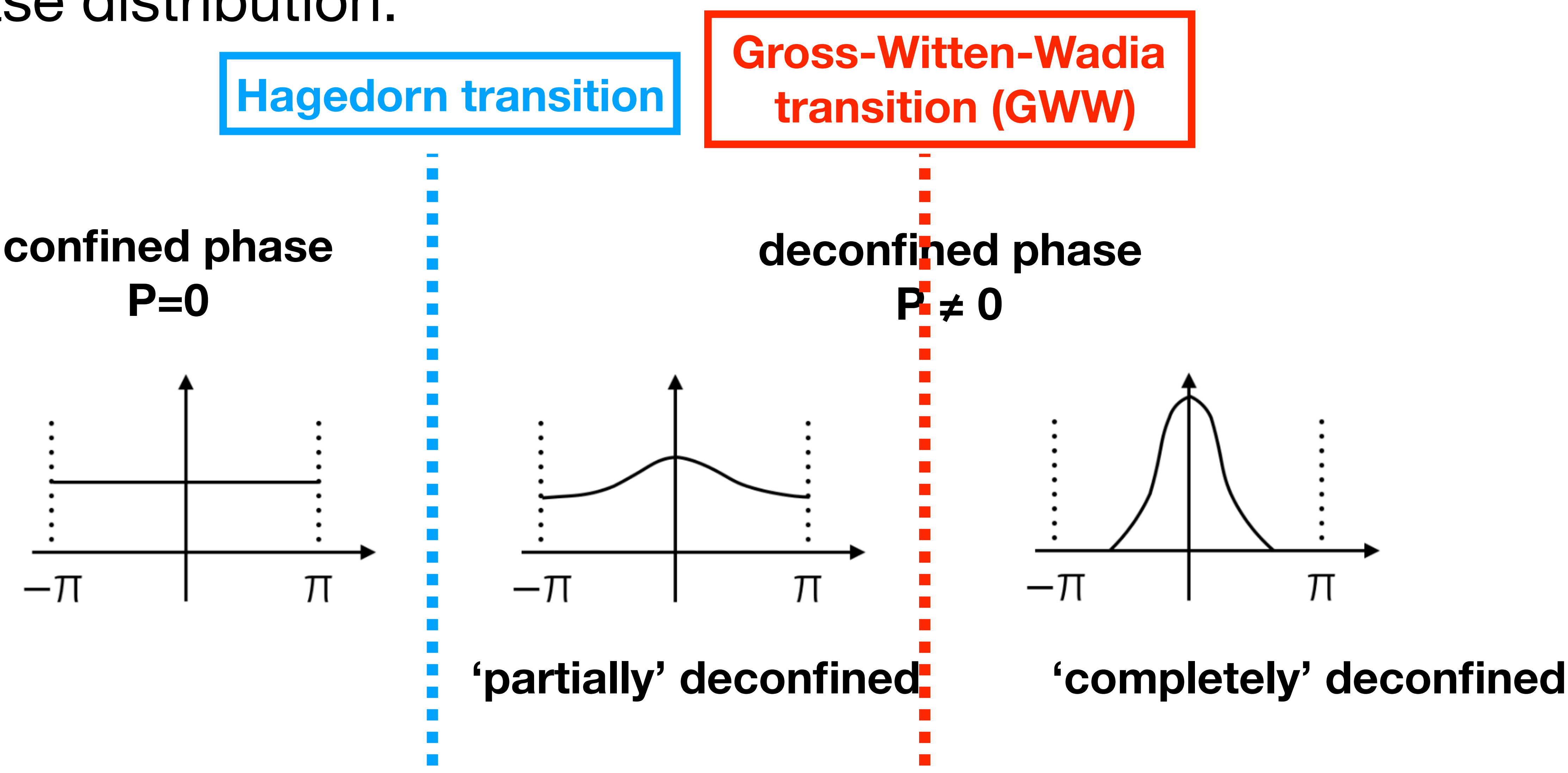
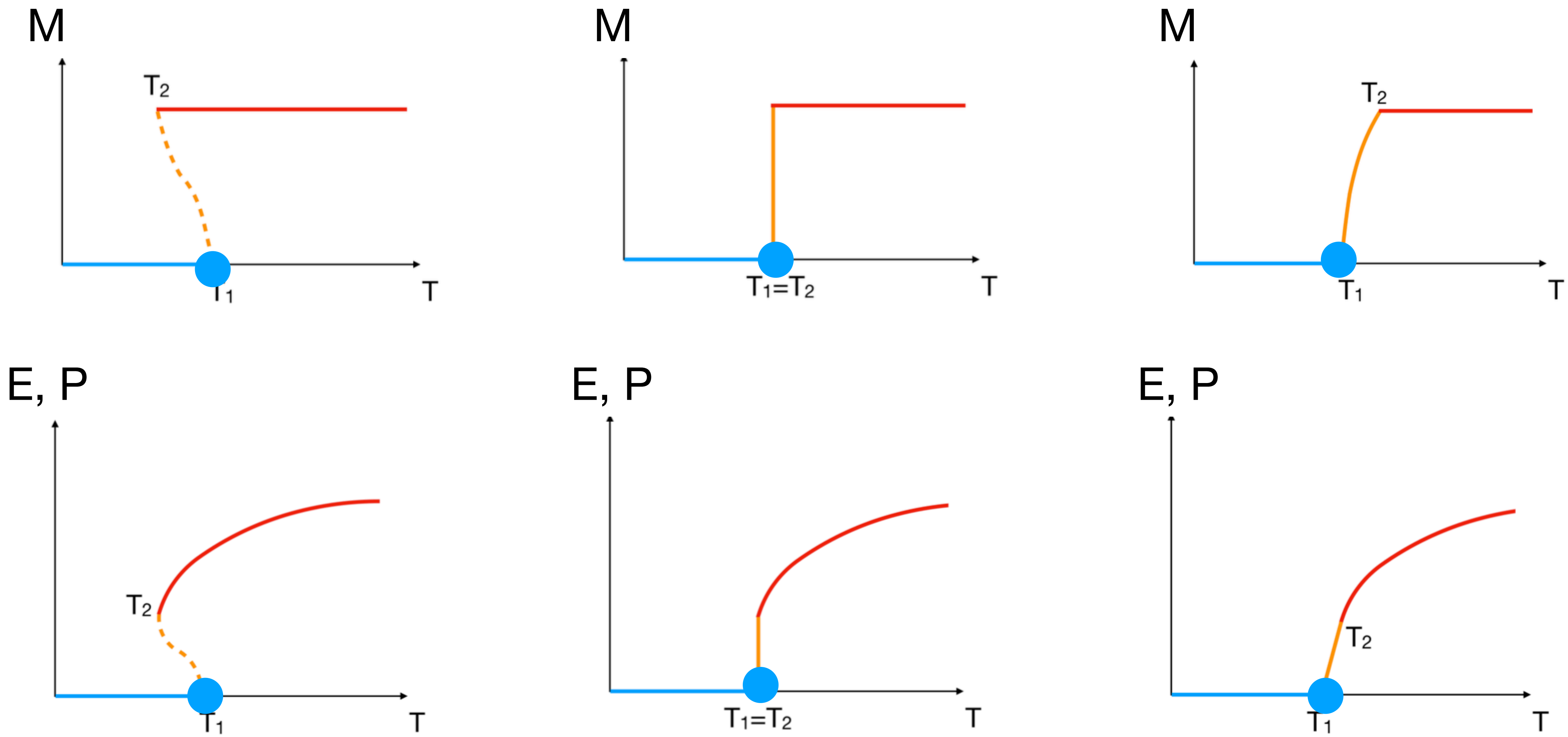
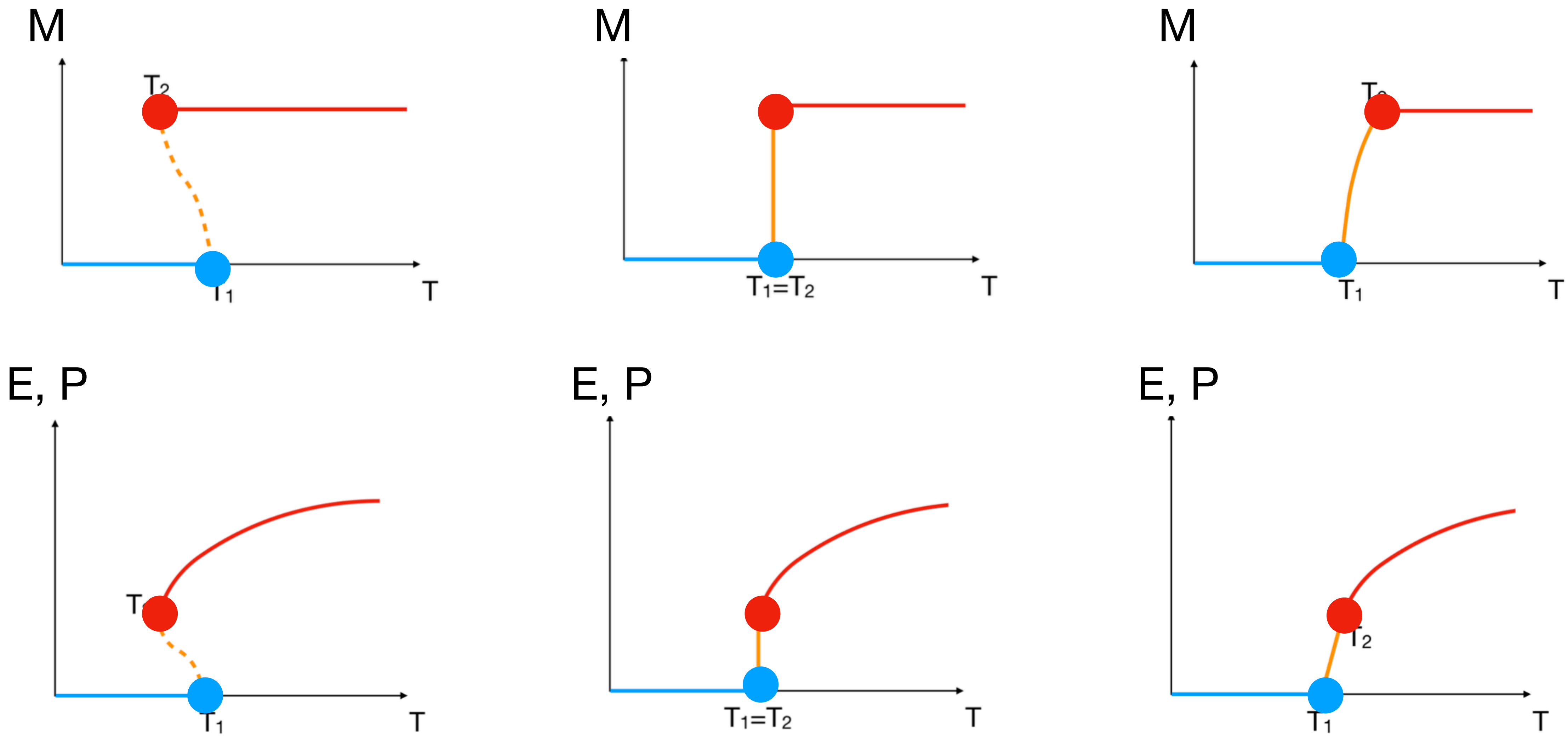


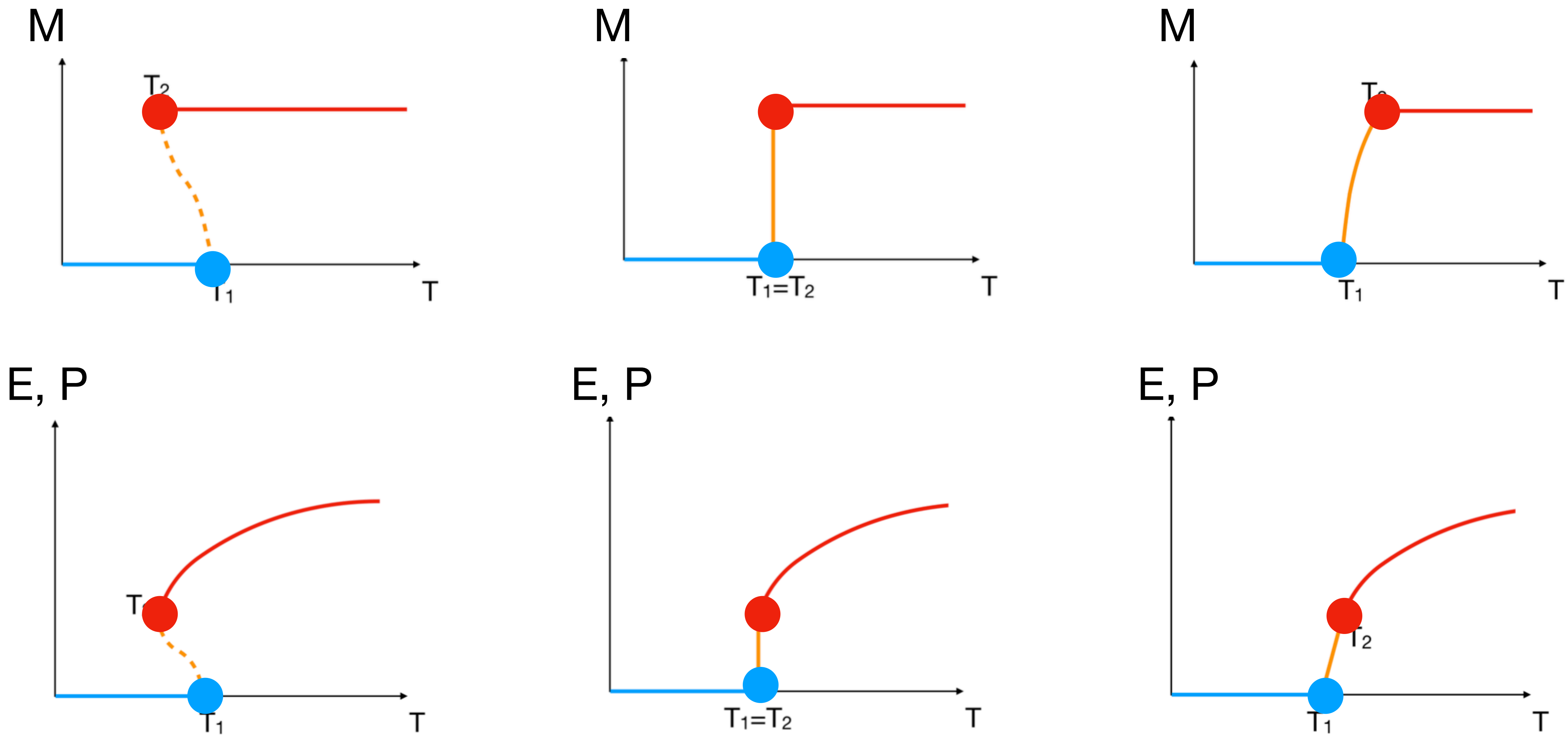


transition 1: confinement to partial deconfinement
(black hole formation begins)



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

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



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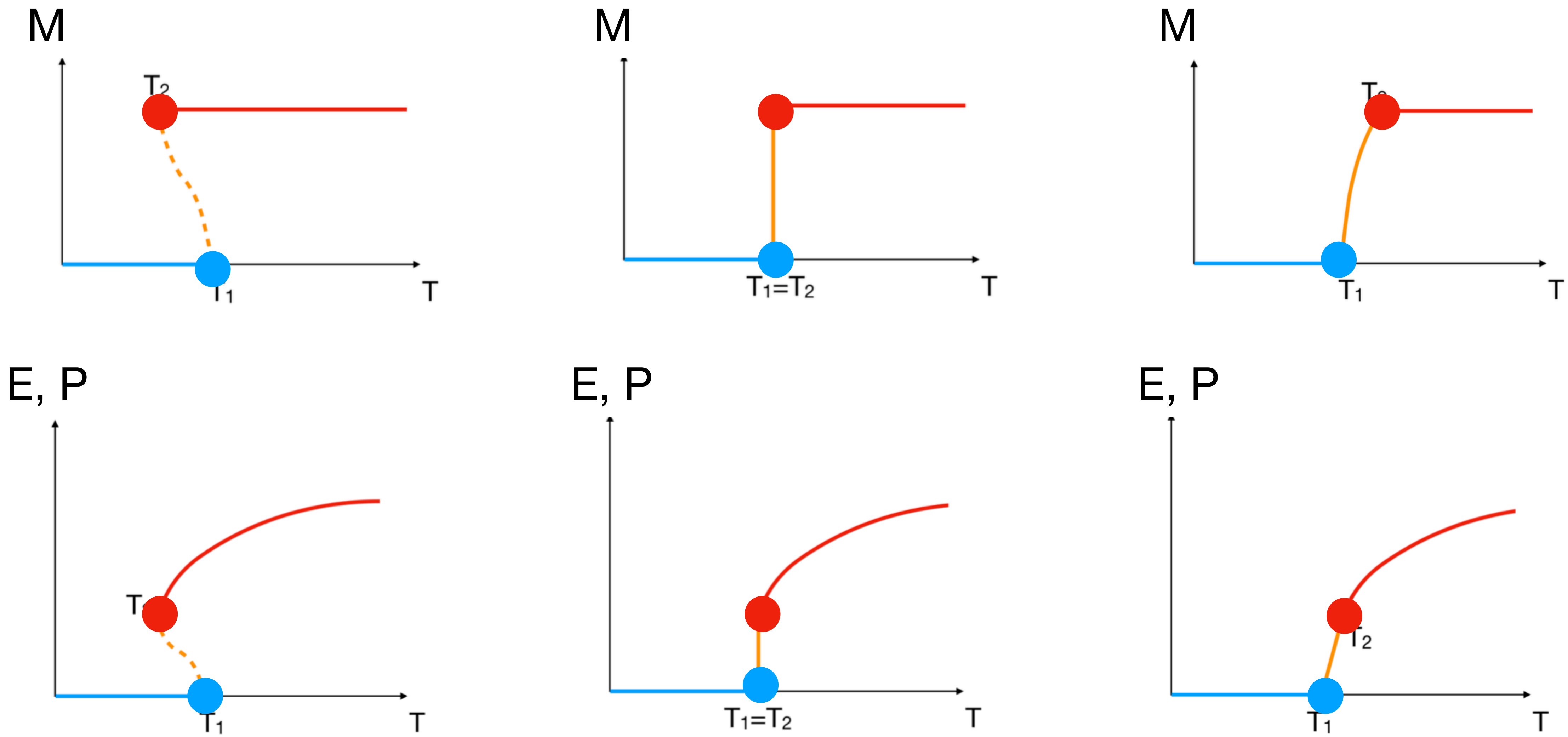
(black hole formation ends)

$$\boxed{SU(N) \to SU(M)\times SU(N-M)\times U(1) \to SU(N)}$$



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

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$$\boxed{SU(N) \to SU(M)\times SU(N-M)\times U(1) \to SU(N)}$$

No need for center symmetry. No need for chiral symmetry. Applies to QCD.

Where did it come from?

J. Maltz

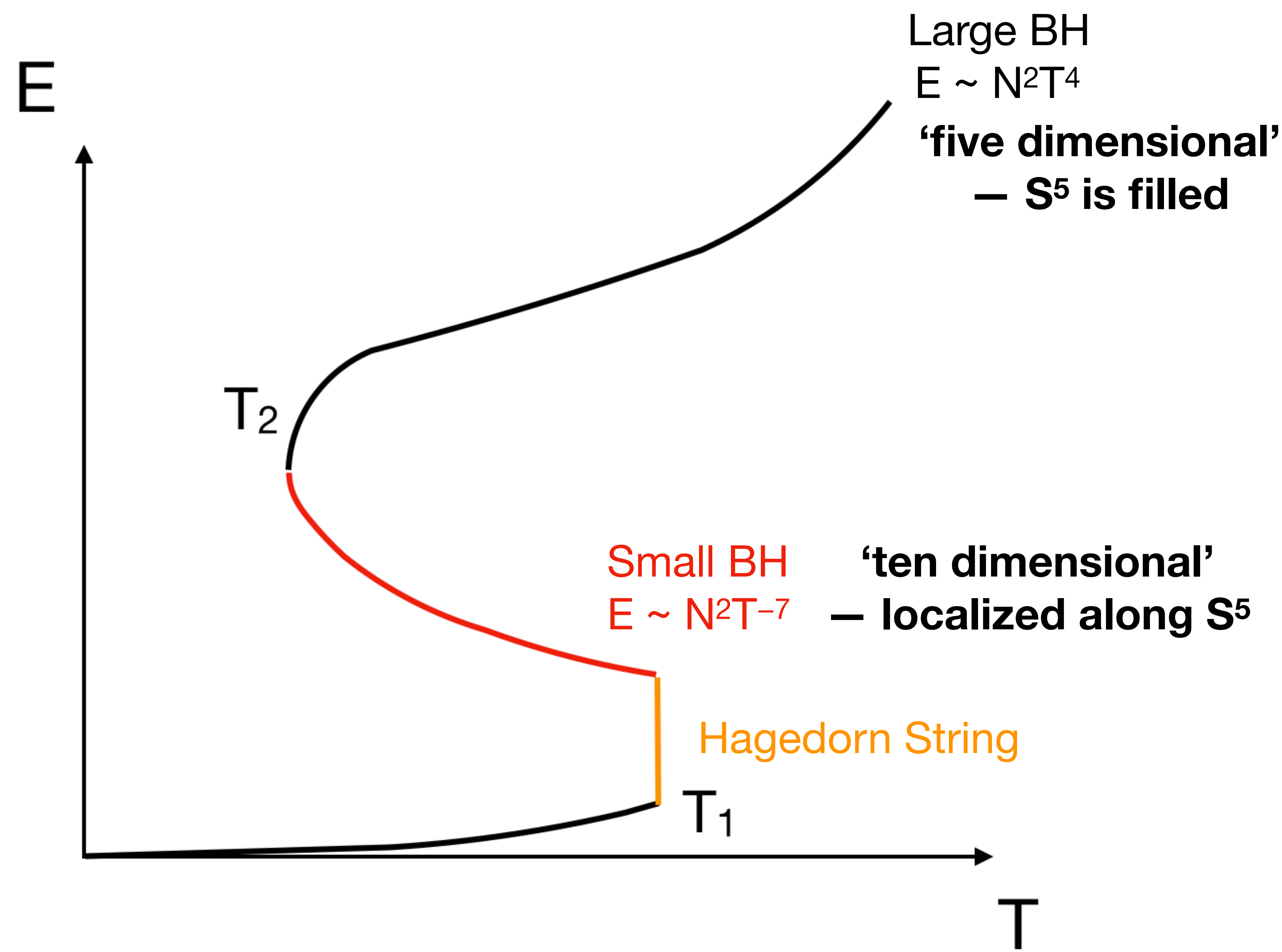
E. Berkowitz

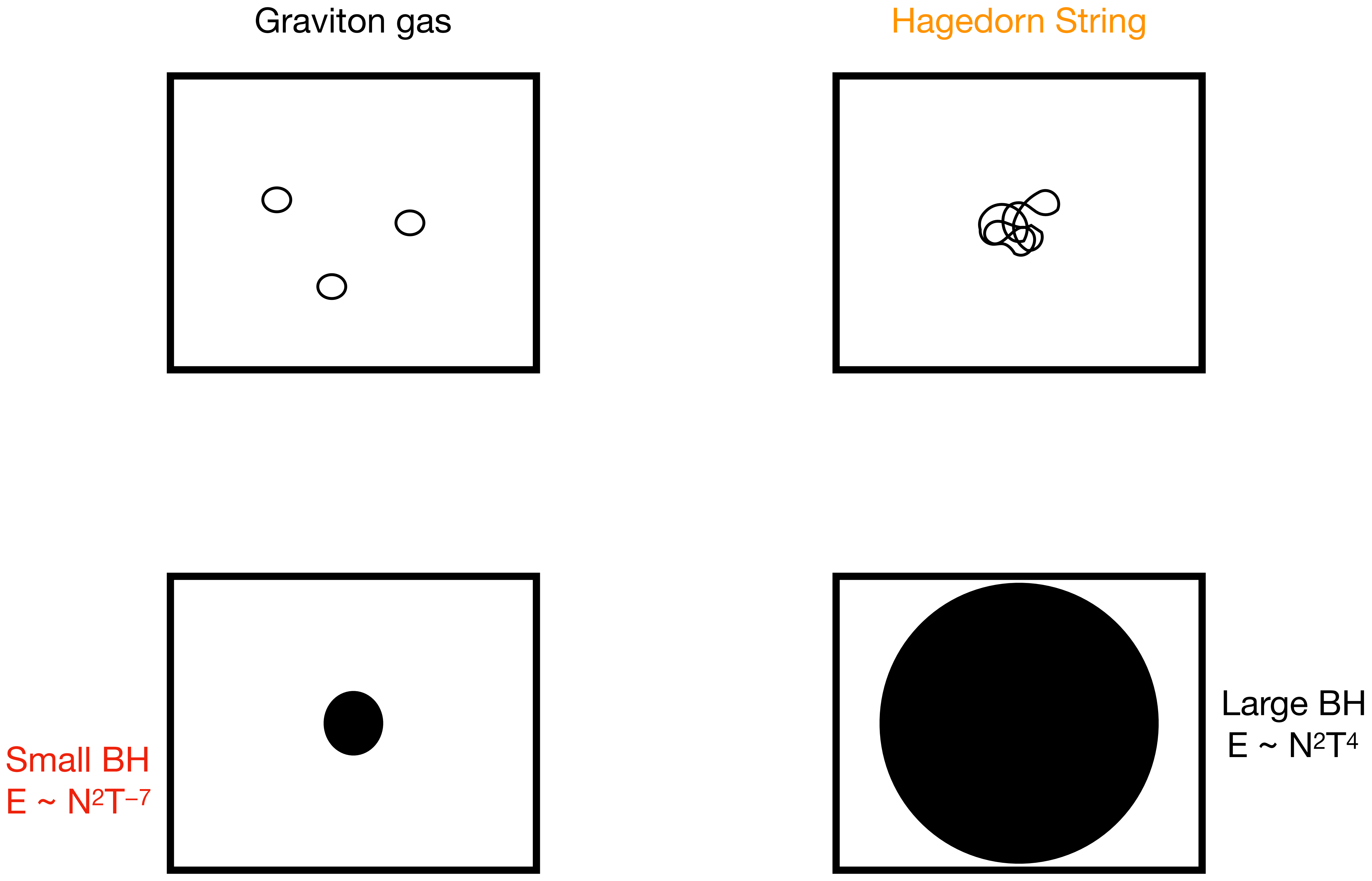
Berkowitz-M.H.-Maltz, 2016, PRD (Higgsing version)

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

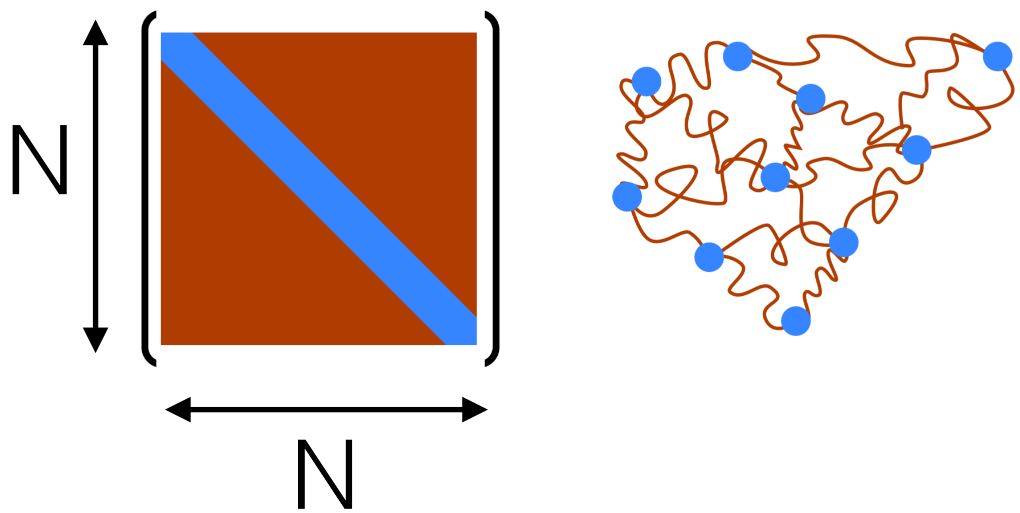
Black Hole in $AdS_5 \times S^5$ = 4d N=4 SYM on S^3

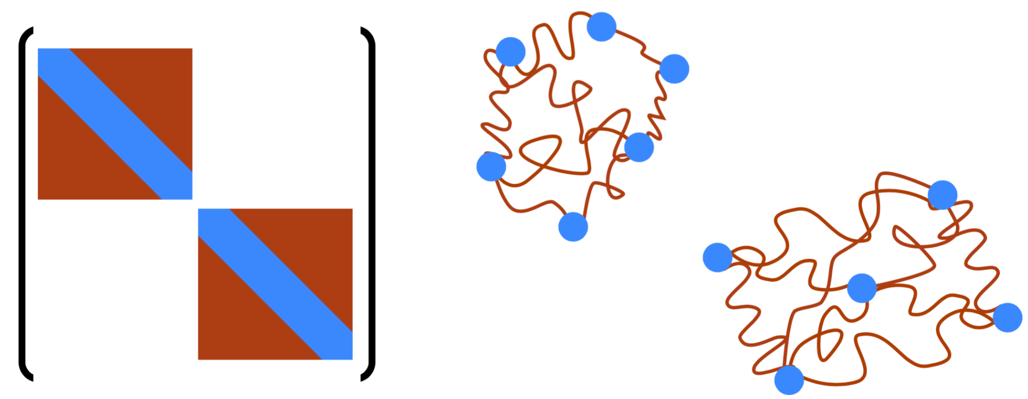
microcanonical ensemble (E fix)





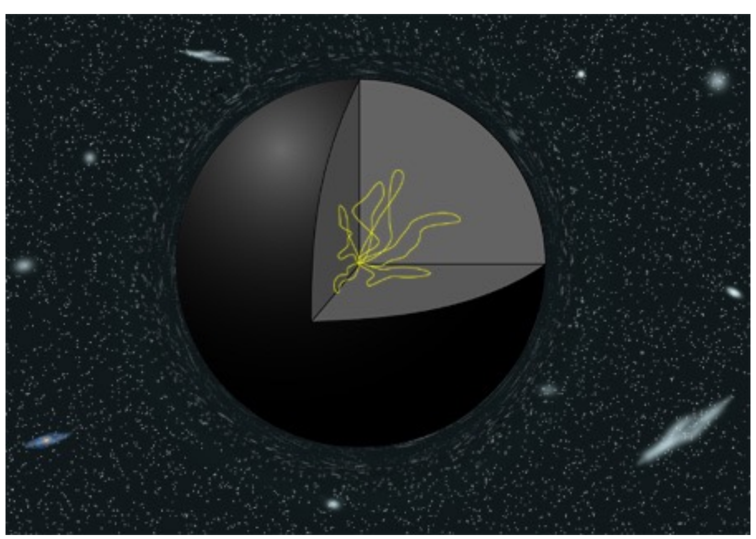
Graviton gas
Hagedorn String
Small BH
E ~ N²T⁻⁷
Large BH
E ~ N²T⁴



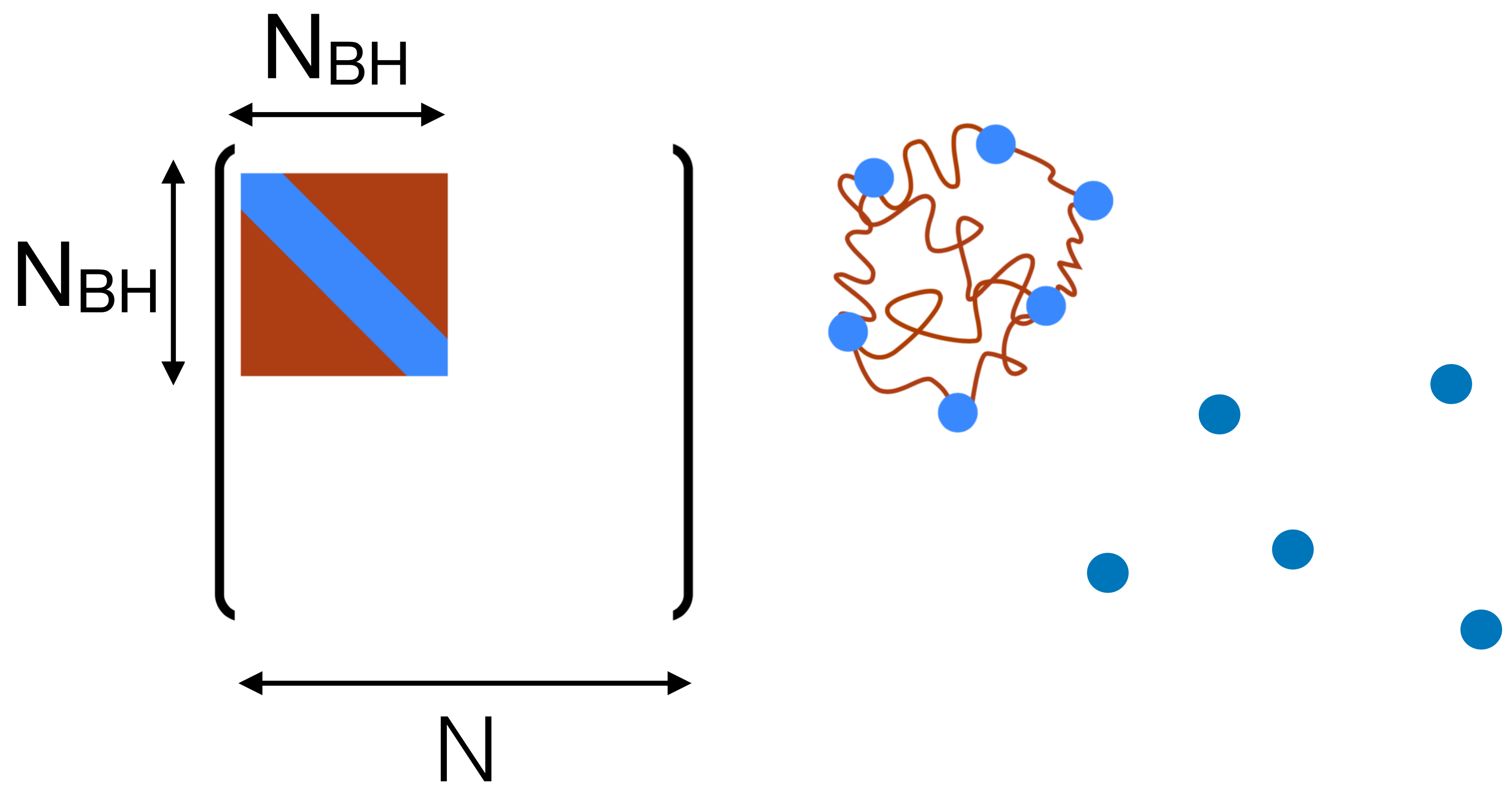


diagonal elements = particles (D-branes)
off-diagonal elements = open strings

(Witten, 1994)



$\boxed{\text{black hole = bound state of D-branes and strings}}$



N_{BH} D-branes form the bound state

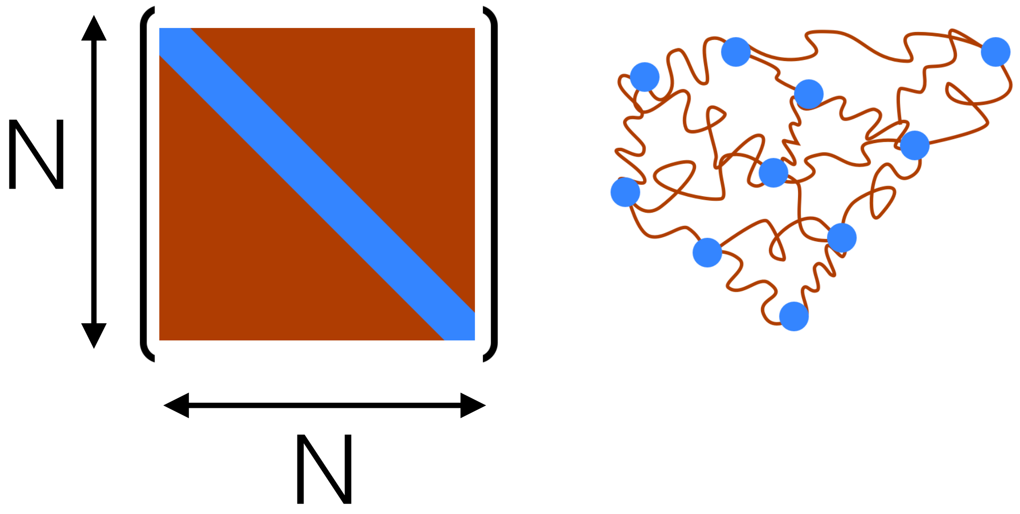
$U(N_{BH})$ is deconfined — 'partial deconfinement'

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

(String Theory → 10d) (M-Theory → 11d)

(MH-Maltz, 2016)

Why is positive specific heat natural?

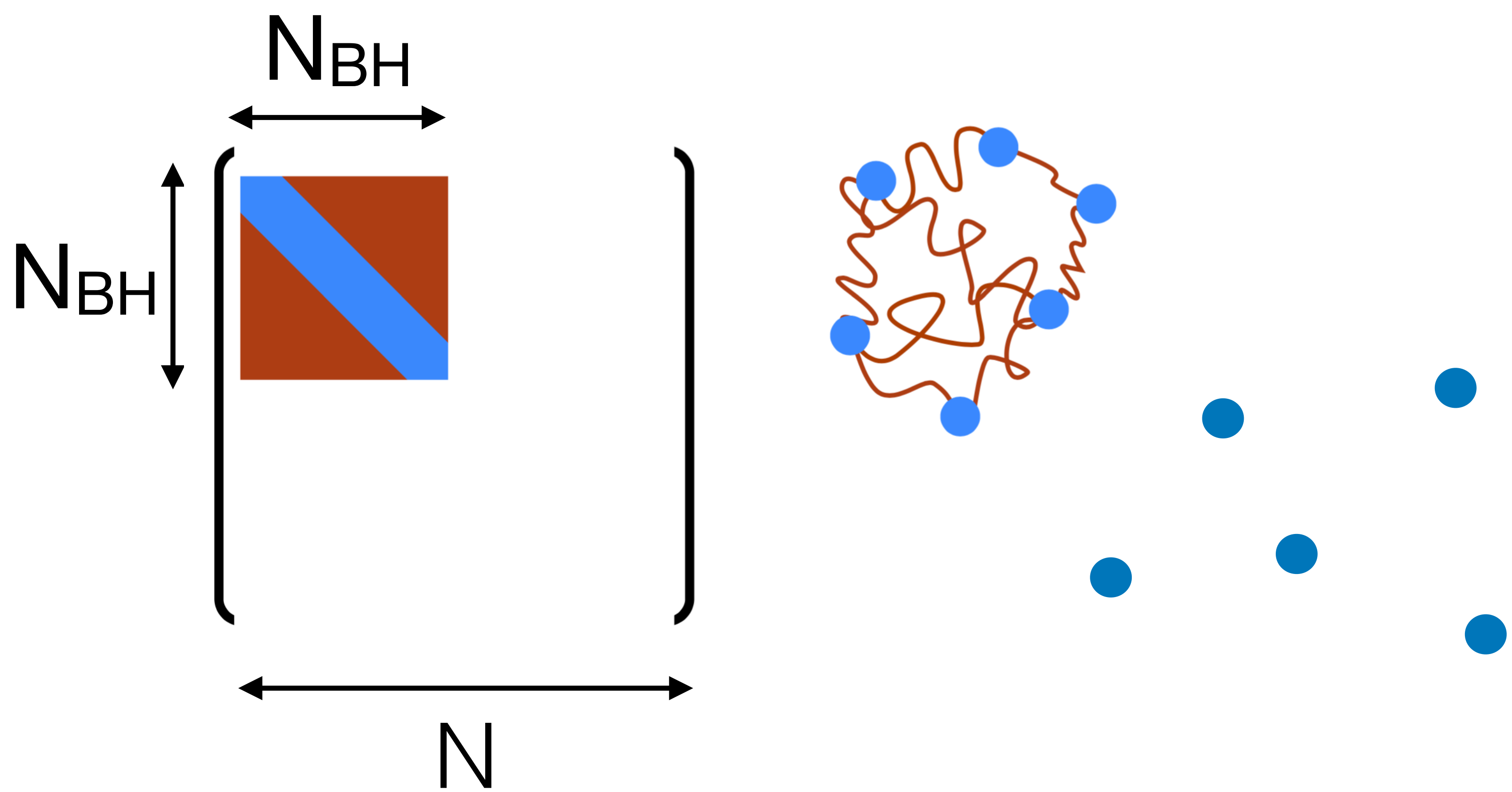


$T \sim E/N^2$

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

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

Why can negative specific heat appear?



$T \sim E_{BH}/(N_{BH})^2$

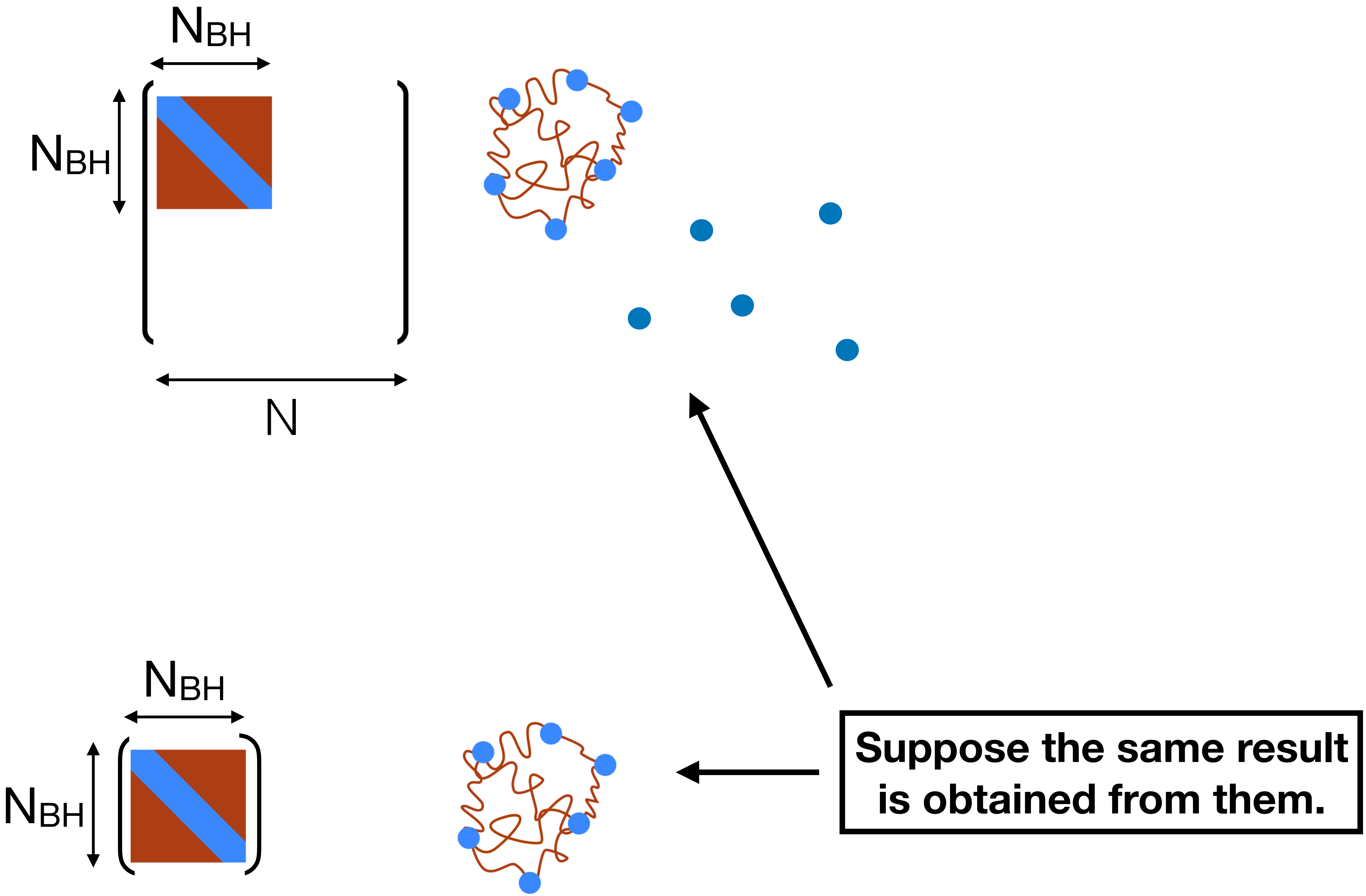
N_{BH} is a function of E_{BH}

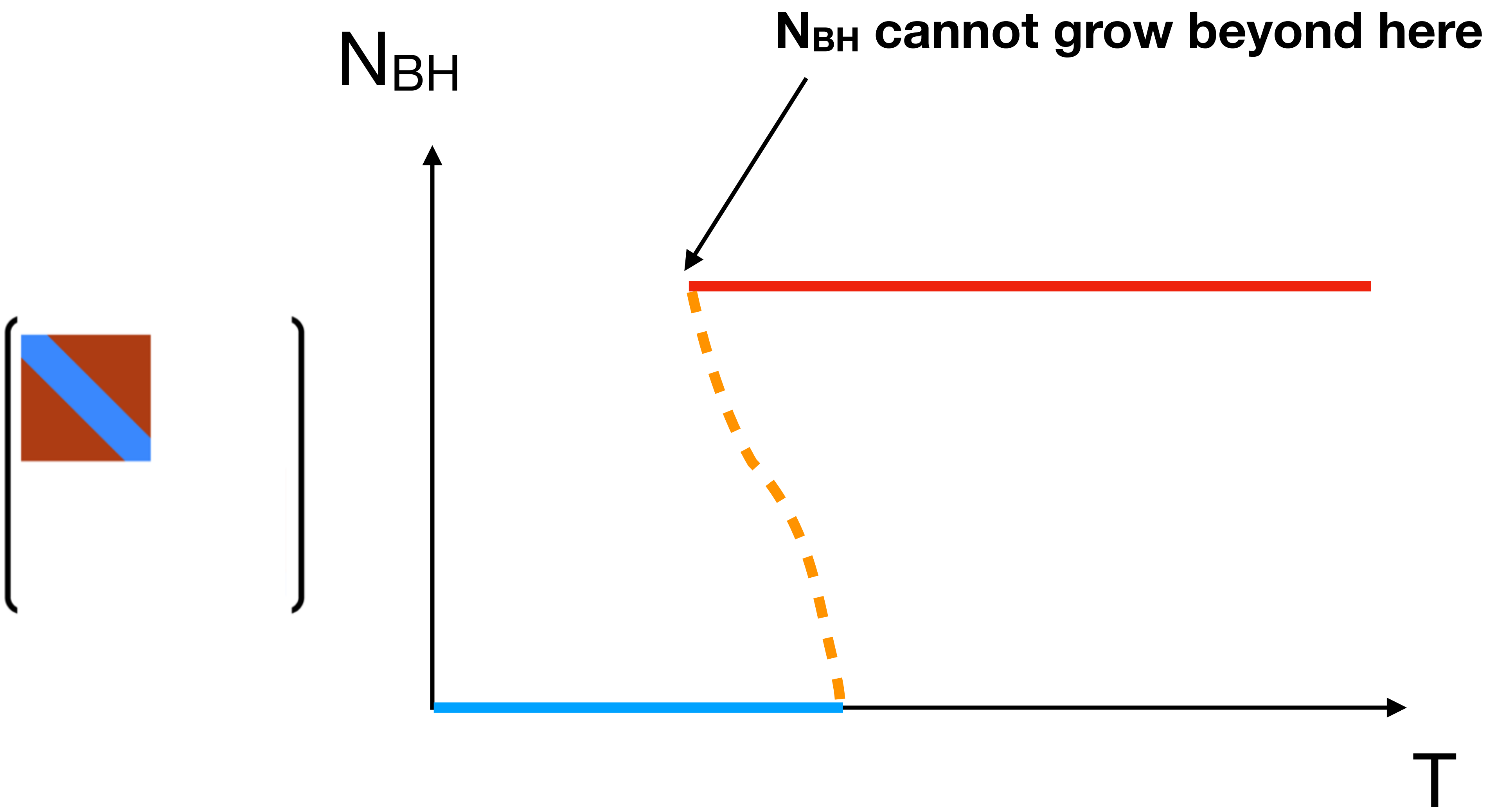
Berkowitz-M.H.-Maltz, 2016, PRD (Higgsing version)

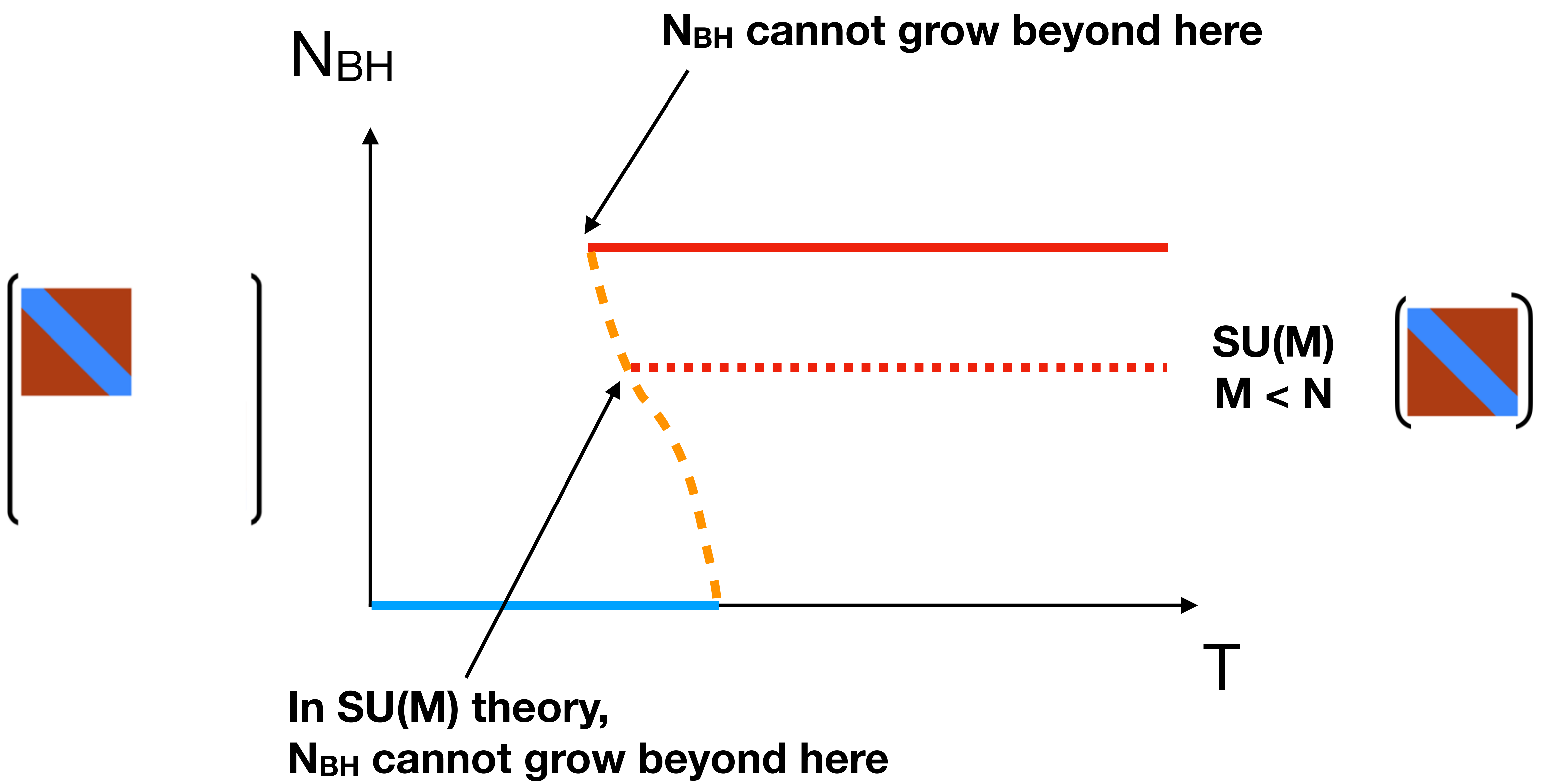
M.H.-Maltz, 2016, JHEP

Explicit demonstration in simple theories

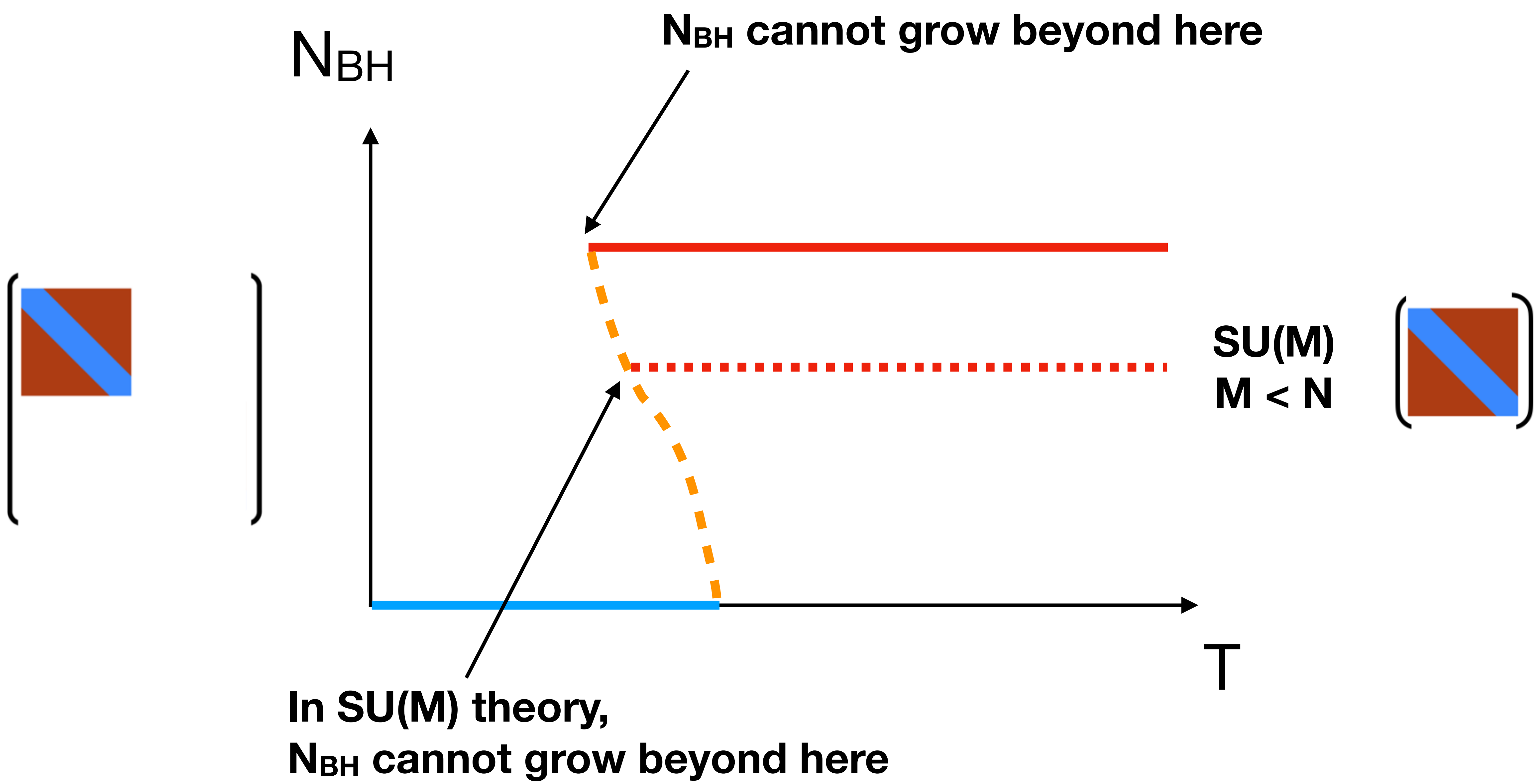
M.H., Jevicki, Peng, Wintergerst, 1909.09118 [hep-th]


N_{BH}
N_{BH}
N
N_{BH}
N_{BH}
Suppose the same result is obtained from them.


N_BH cannot grow beyond here
N_BH
T



N_BH cannot grow beyond here
N_BH
SU(M)
M < N
T
In SU(M) theory,
N_BH cannot grow beyond here

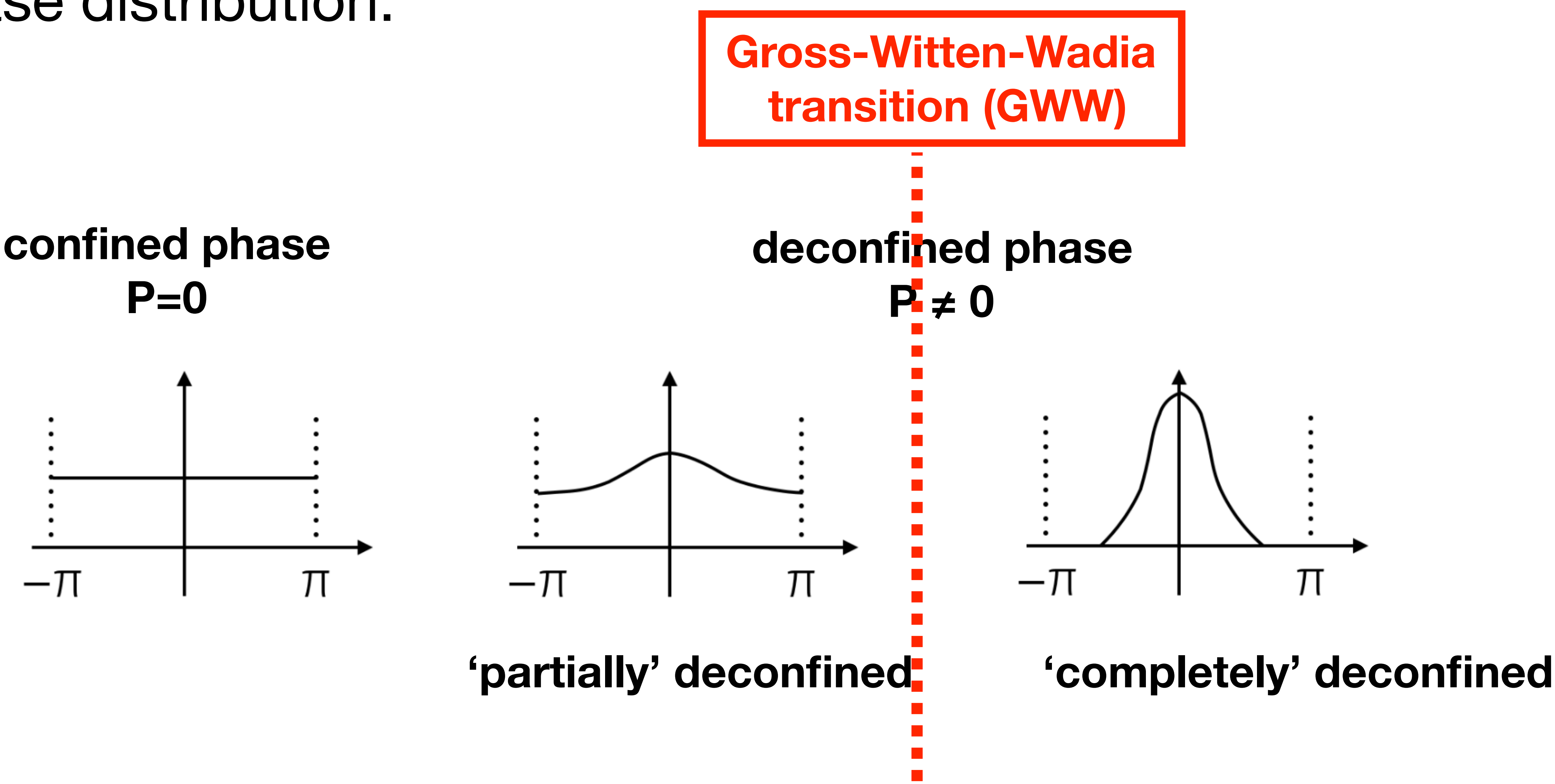


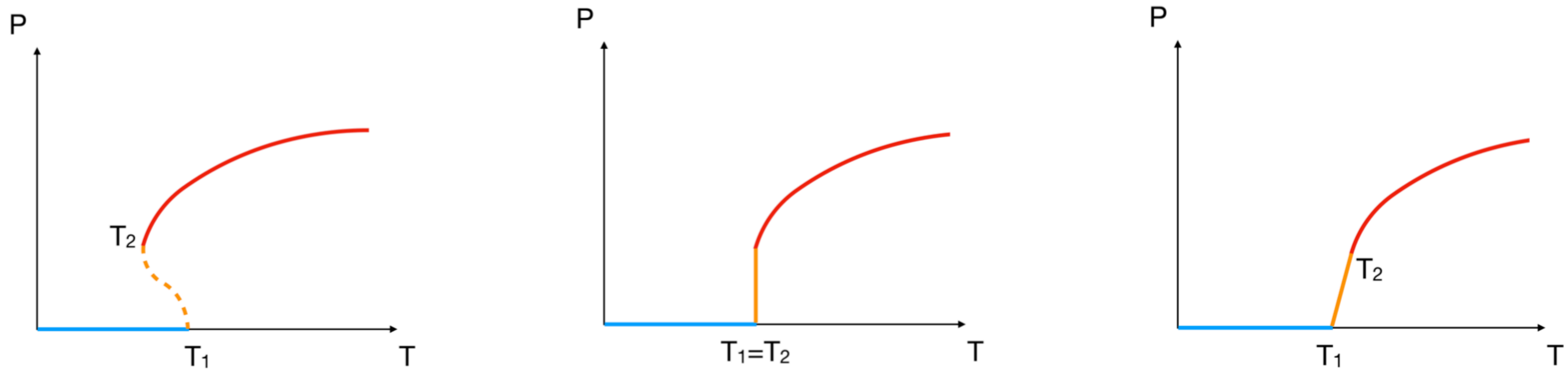
“Partial deconfinement → complete deconfinement” in SU(M) theory.

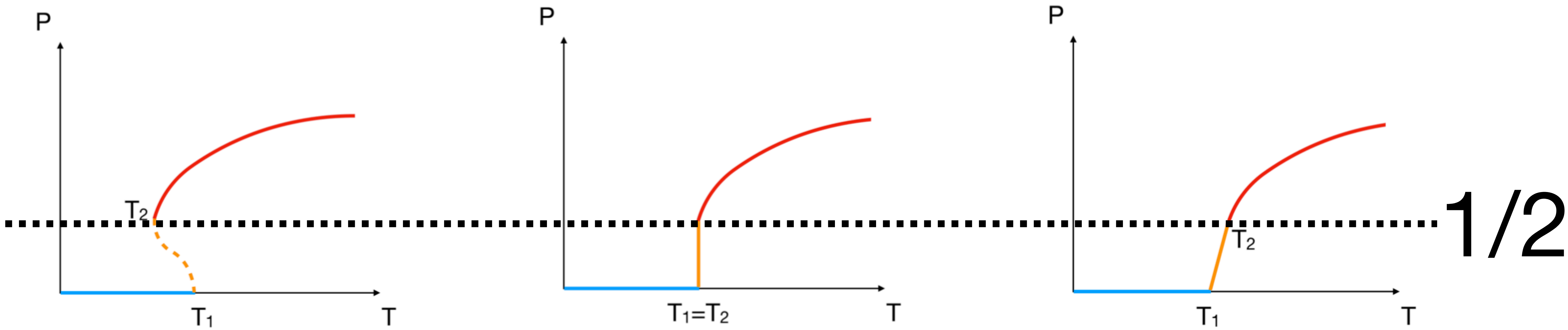
M.H., Maltz, 2016

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

- Phase distribution:



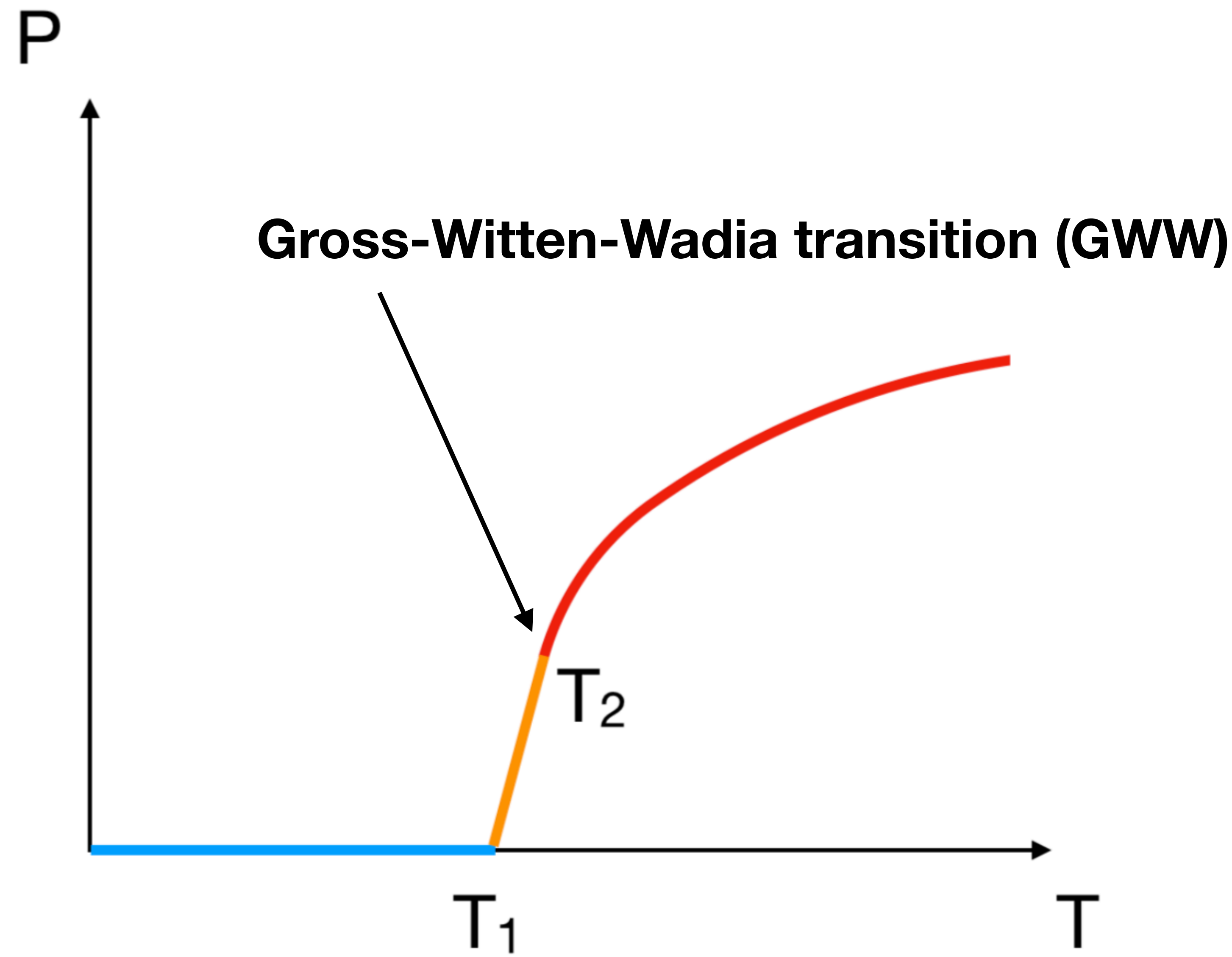

P
T2
T1
T
P
T1=T2
T
P
T2
T1
T

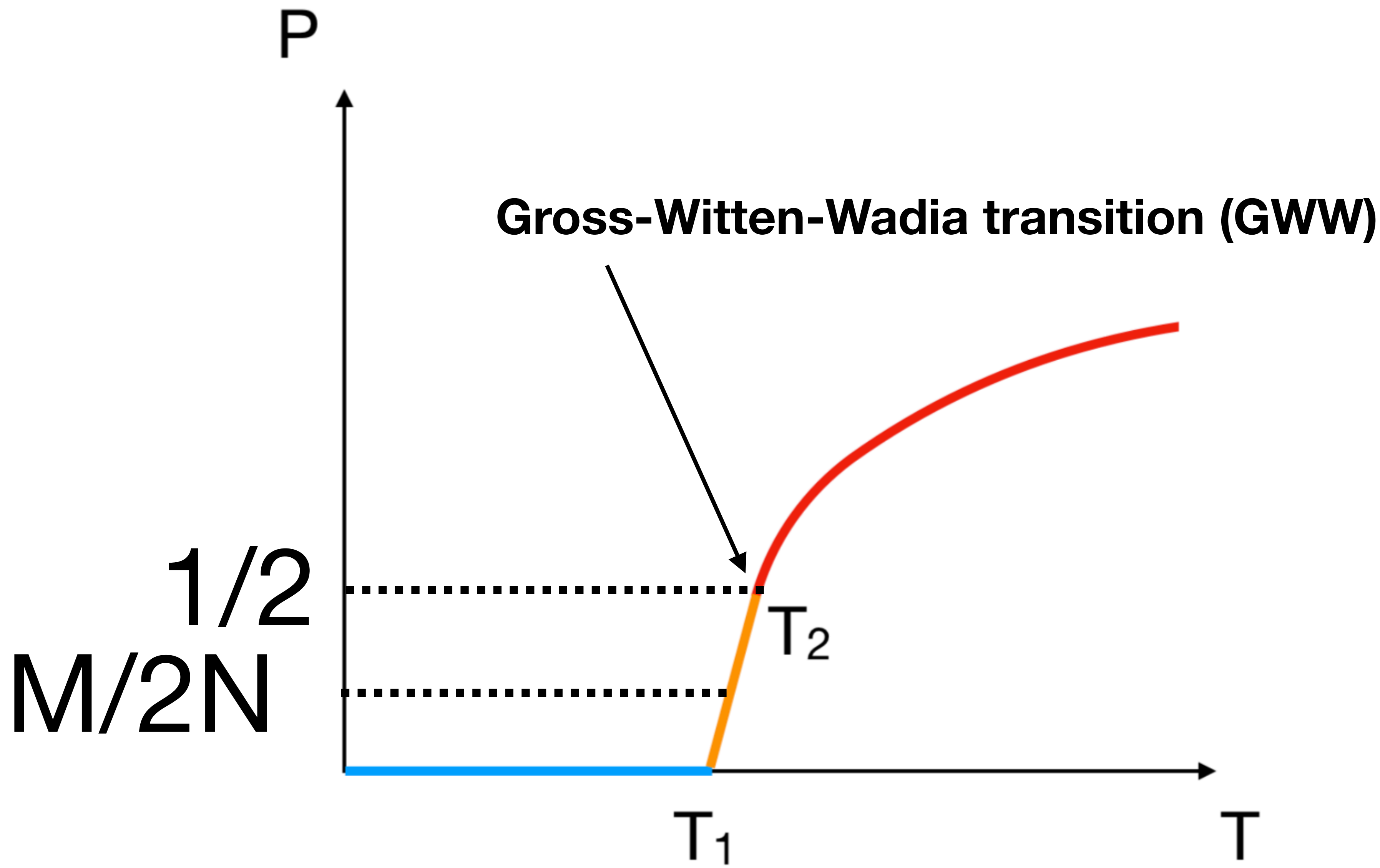


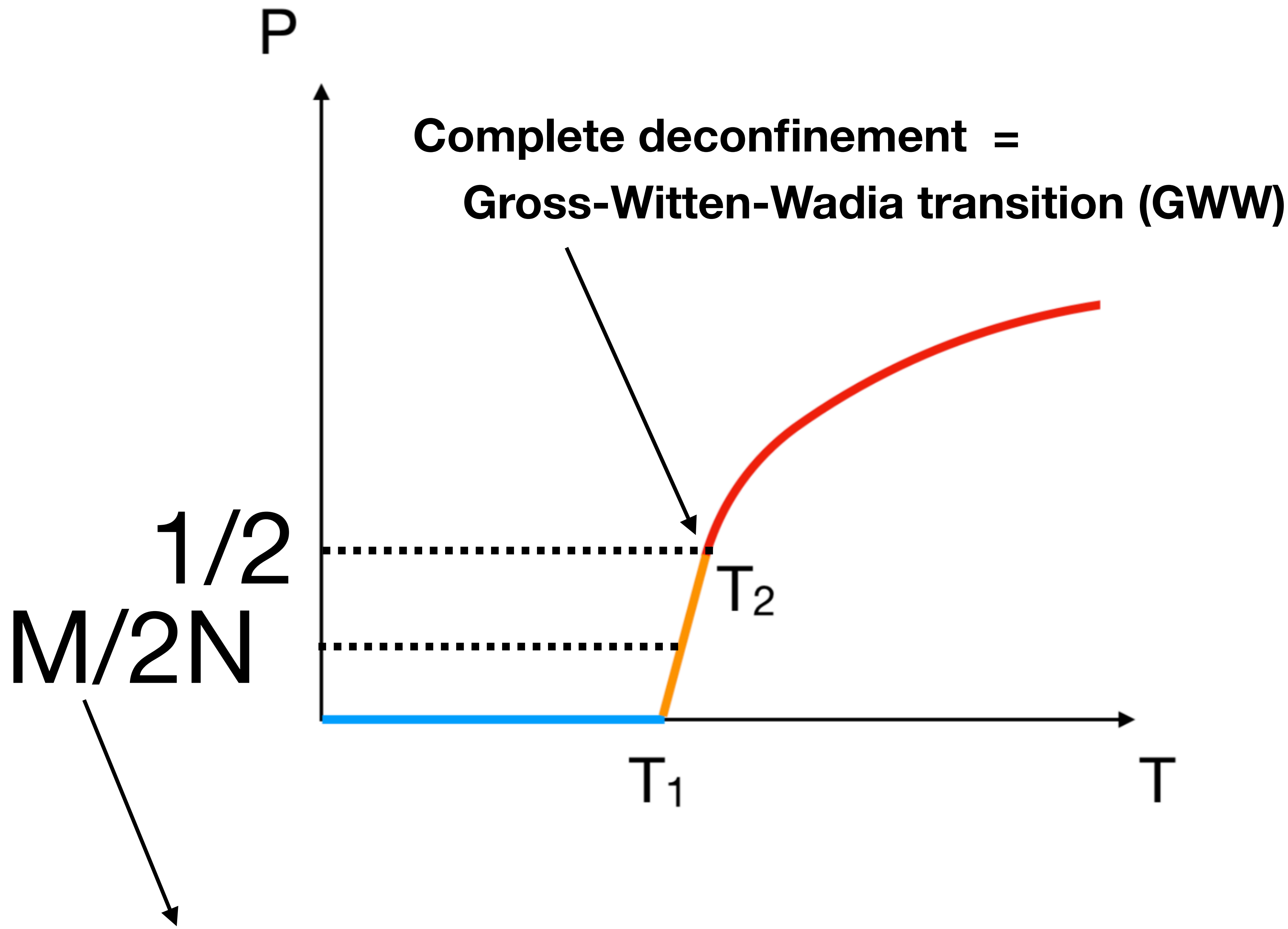
$$\begin{aligned}\rho(\theta) &= \left(1-\frac{M}{N}\right)\rho_{\text{confine}}(\theta)+\frac{M}{N}\cdot\rho_{\text{GWW}}(\theta;M)\\ &= \frac{1}{2\pi}\left(1-\frac{M}{N}\right)+\frac{M}{N}\cdot\rho_{\text{GWW}}(\theta;M).\end{aligned}$$

Holds in all examples we have studied.

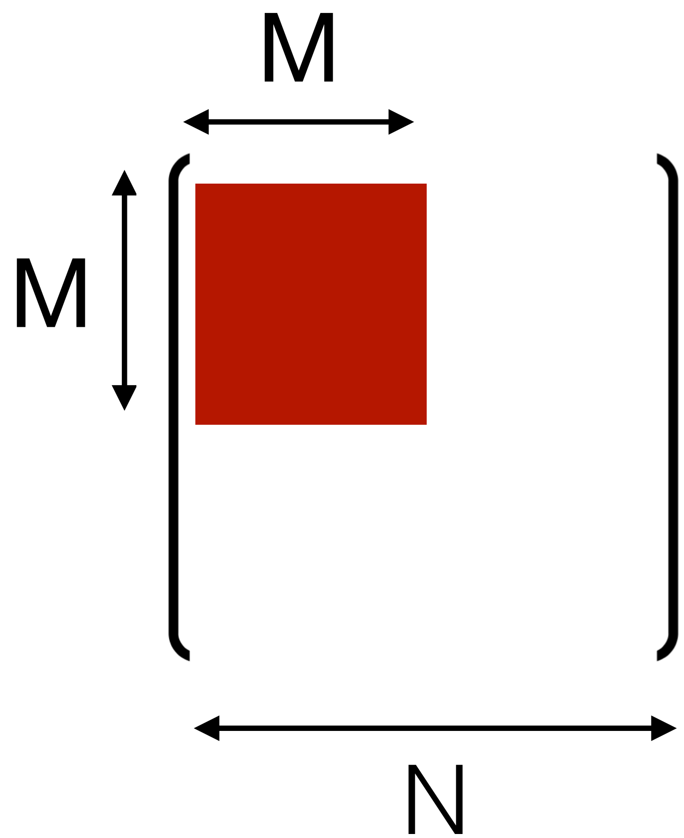
M.H.-Ishiki-Watanabe, 2018


P
Gross-Witten-Wadia transition (GWW)
T2
T1
T


P
Gross-Witten-Wadia transition (GWW)
1/2
M/2N
T2
T1
T



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

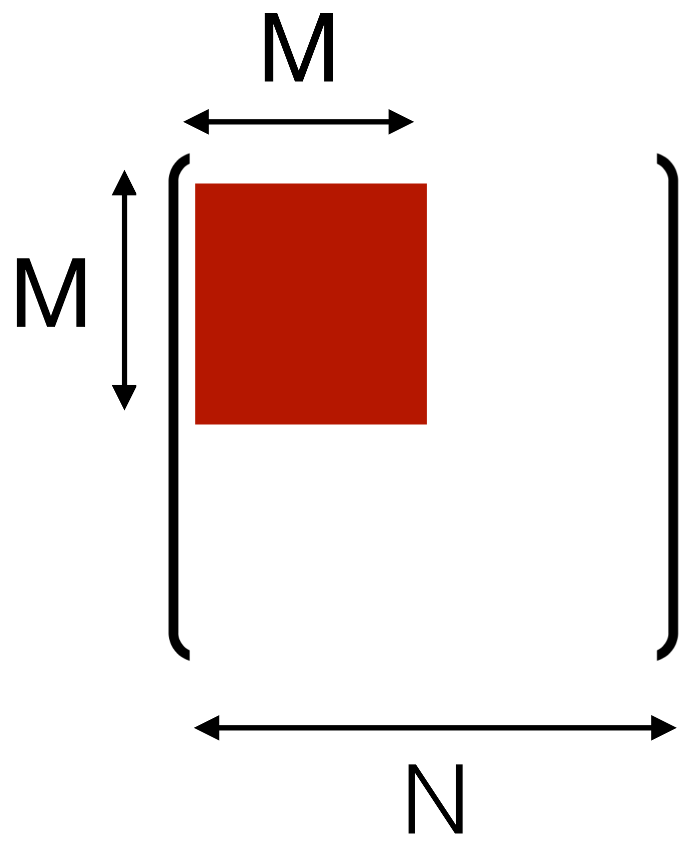


not SU(N)-invariant

$$|E; \mathrm{SU}(M)\rangle$$

At weak coupling, this is an energy eigenstate.

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



not SU(N)-invariant

$$|E;\mathrm{SU}(M)\rangle$$

At weak coupling, this is an energy eigenstate.

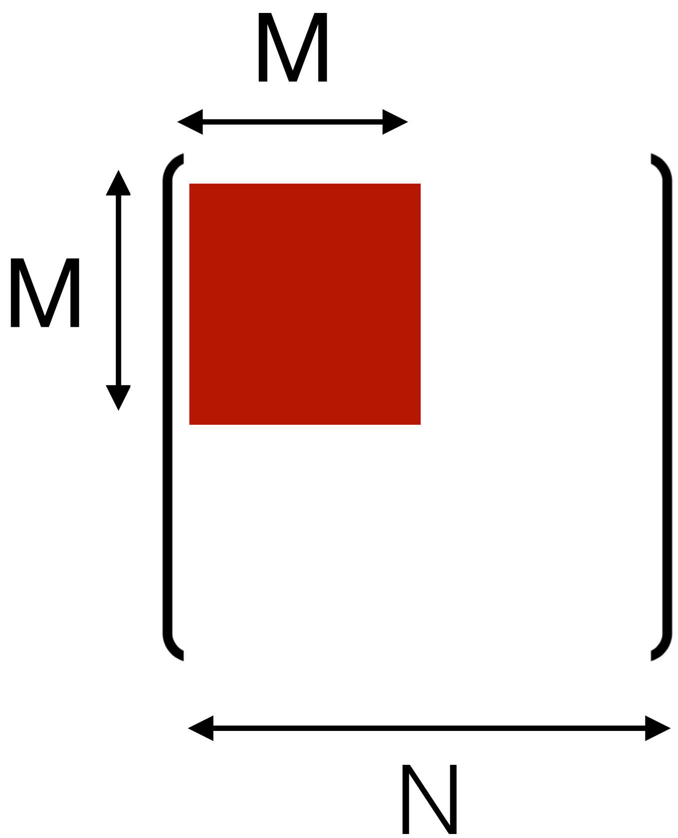
$$S = S_{\mathrm{GWW}}(M)$$

one-to-one correspondence

SU(N)-invariant

This is also an energy eigenstate.

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



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SU(N)-invariant

This is also an energy eigenstate.

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

<u>These states explain the entropy precisely.</u>

(Analytic calculation doable for weakly coupled QCD on S^3, O(N) vector model, matrix model)

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

‘Spontaneous gauge symmetry breaking’

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

SU(N)-invariant

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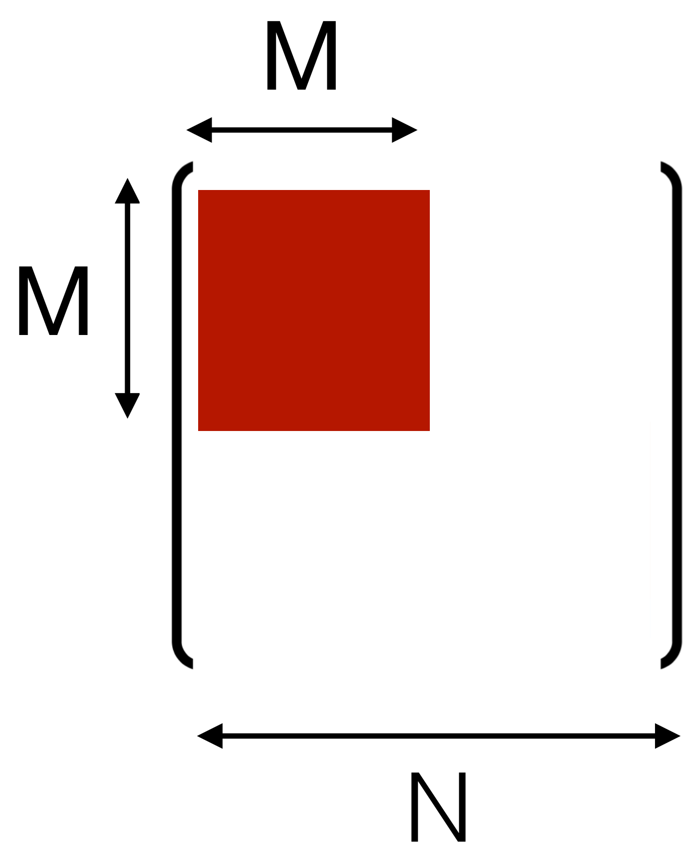
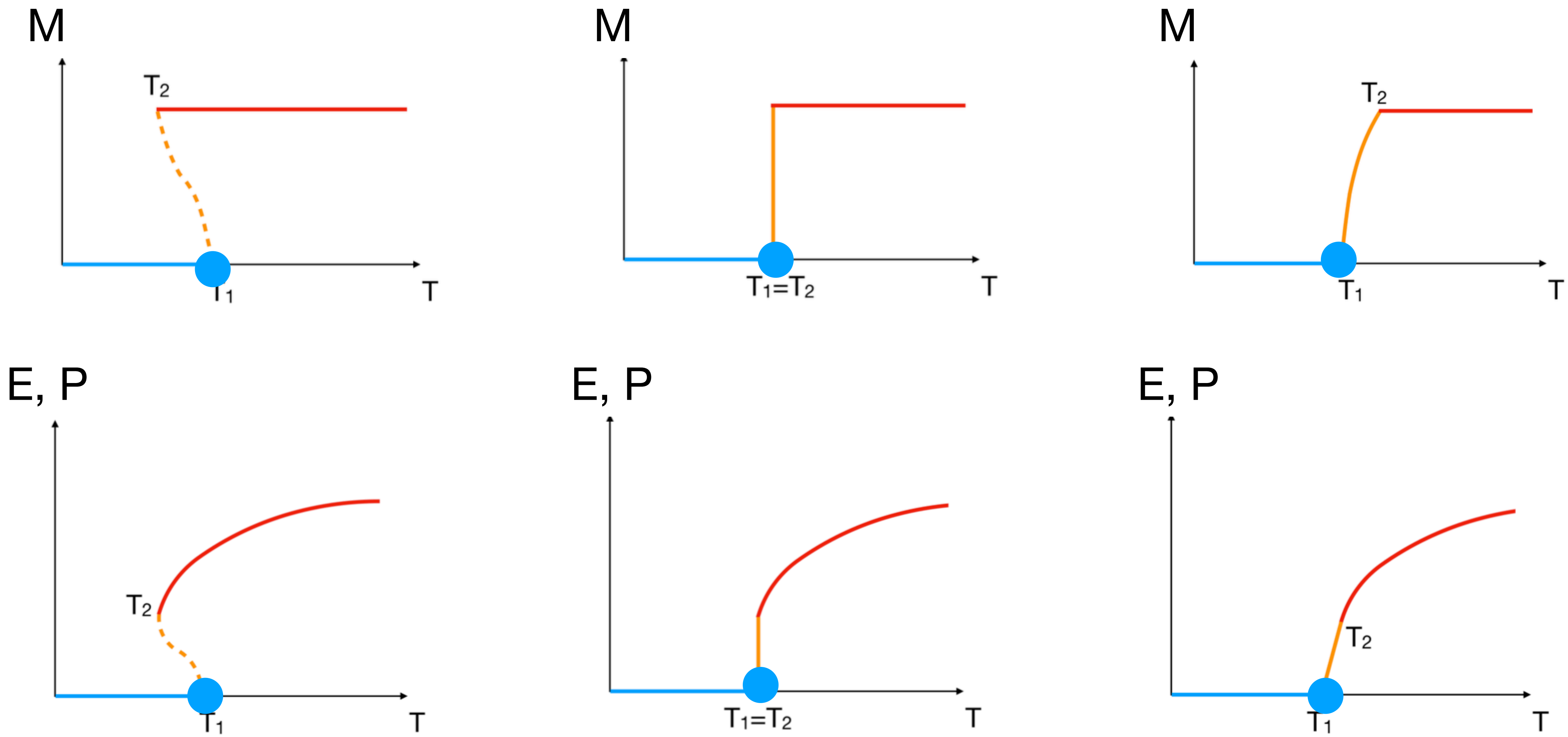


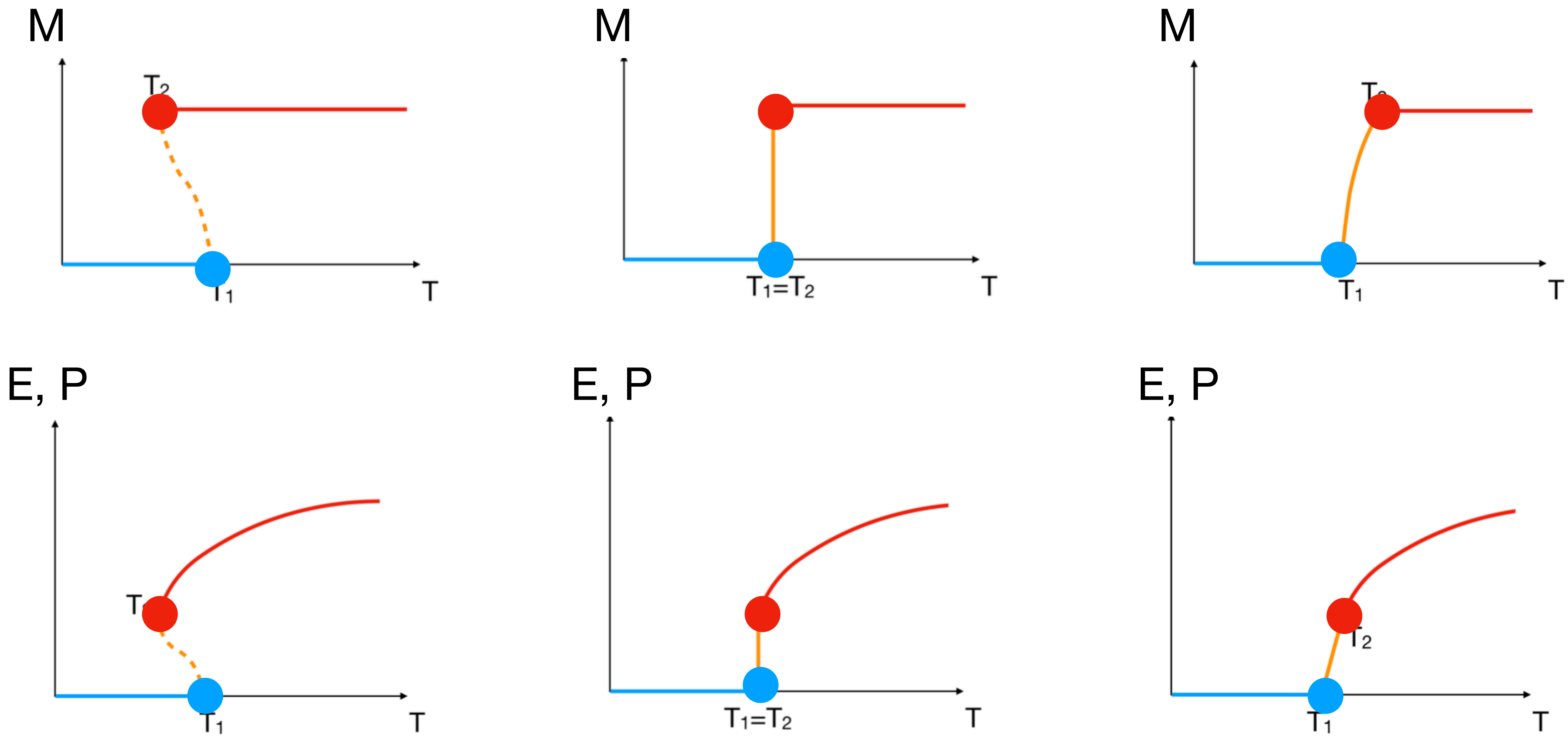
$\Big\downarrow$ gauge fixing

not SU(N)-invariant $\quad |E; \mathrm{SU}(M)\rangle$

- 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)



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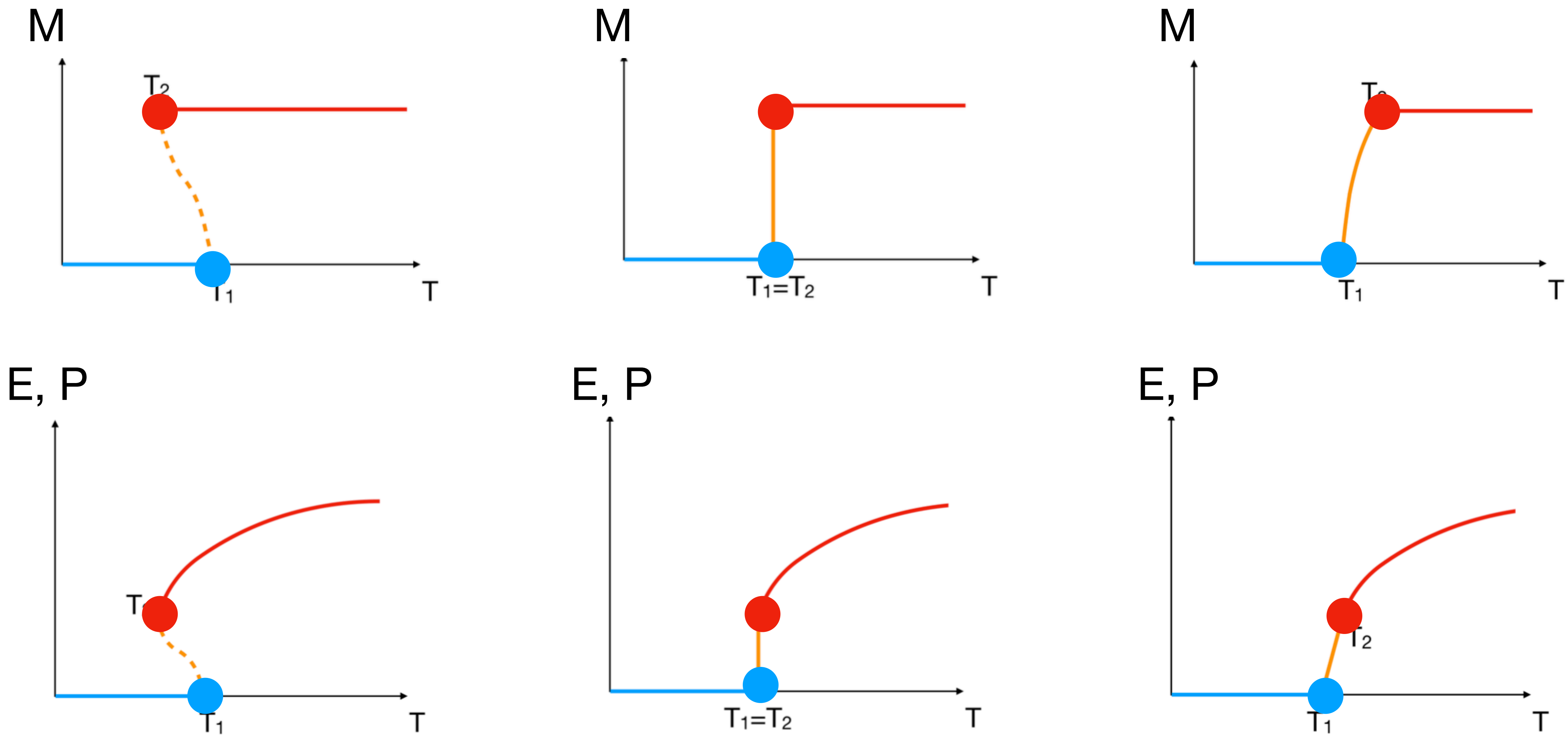

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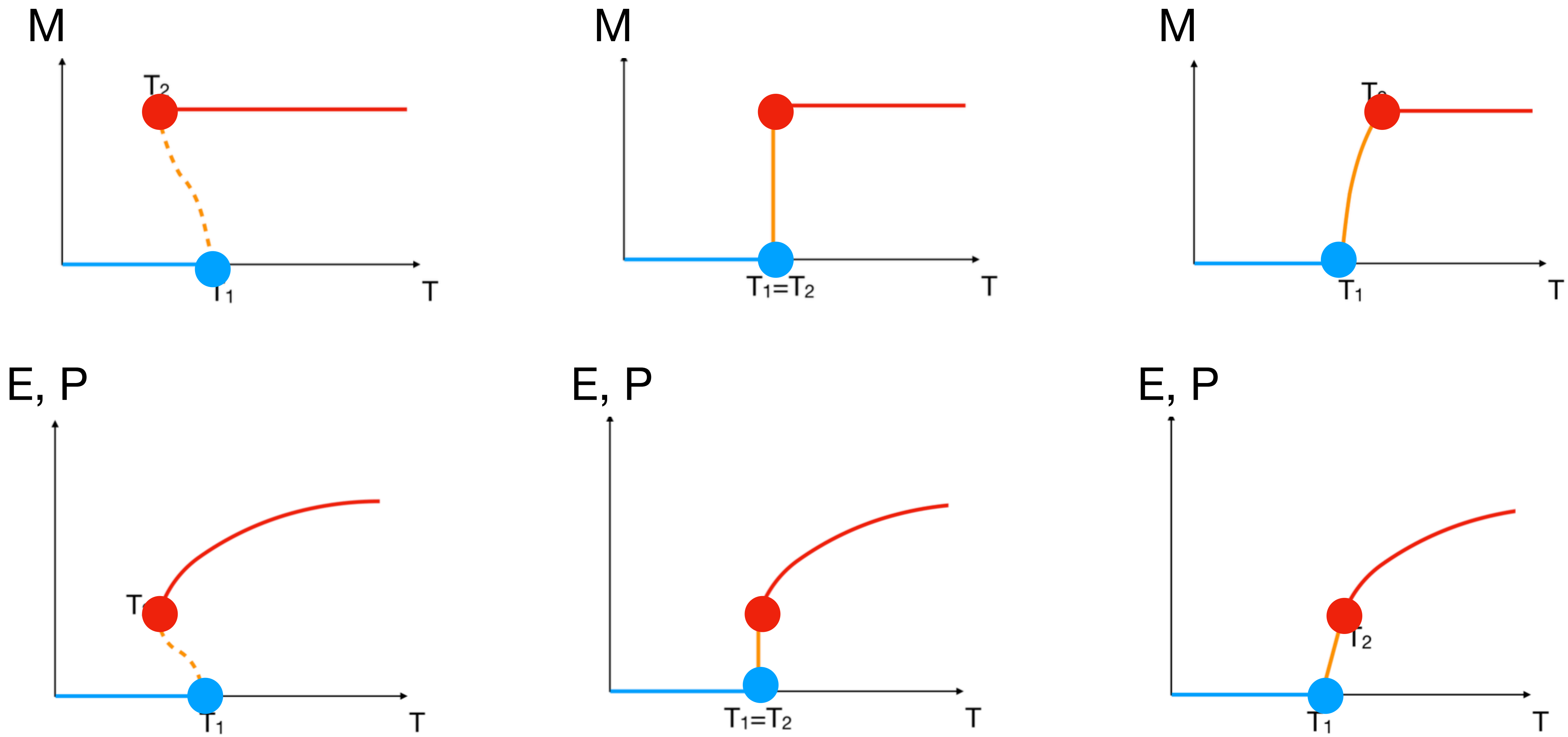
$$\boxed{SU(N) \to SU(M)\times SU(N-M)\times U(1) \to SU(N)}$$



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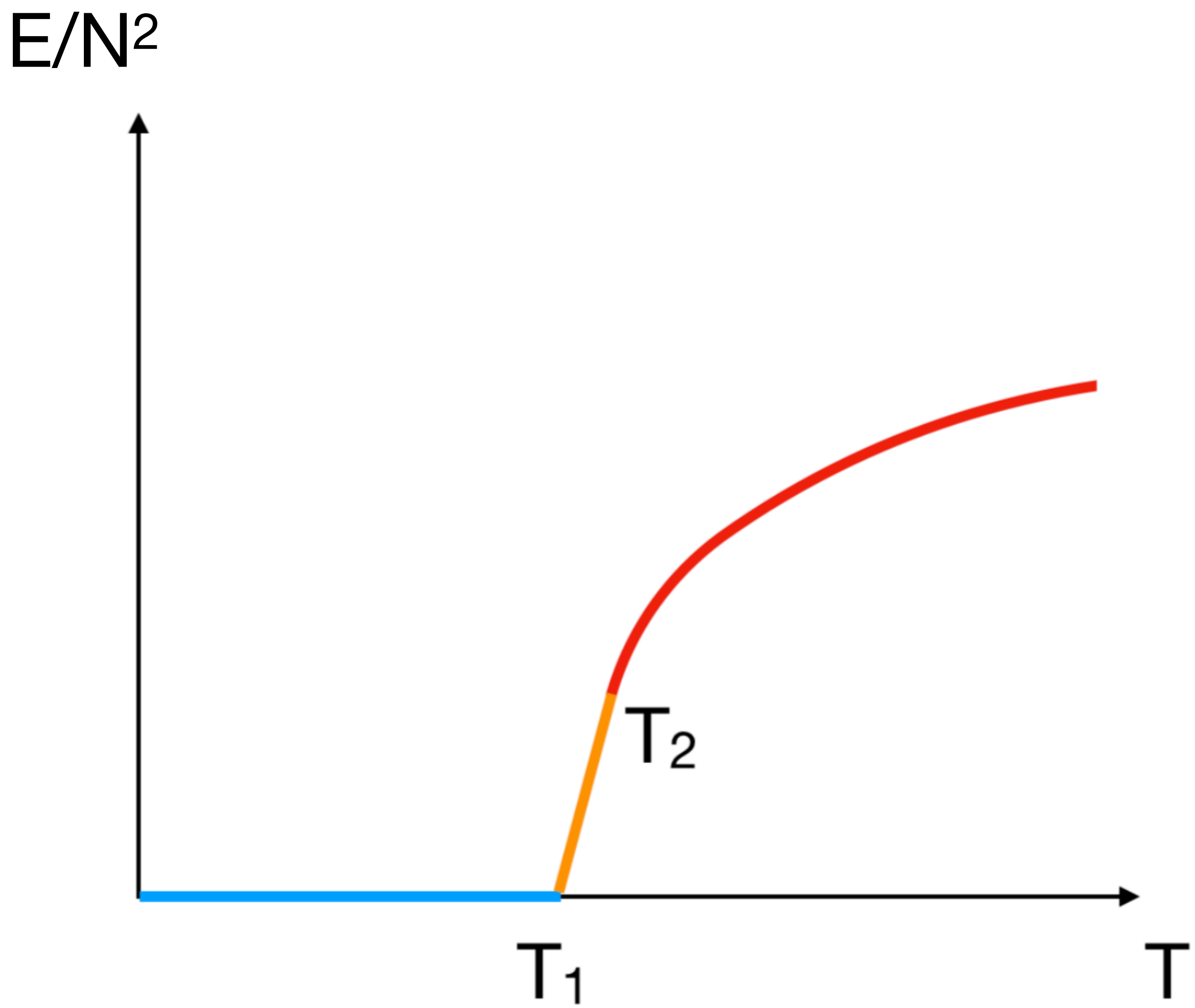
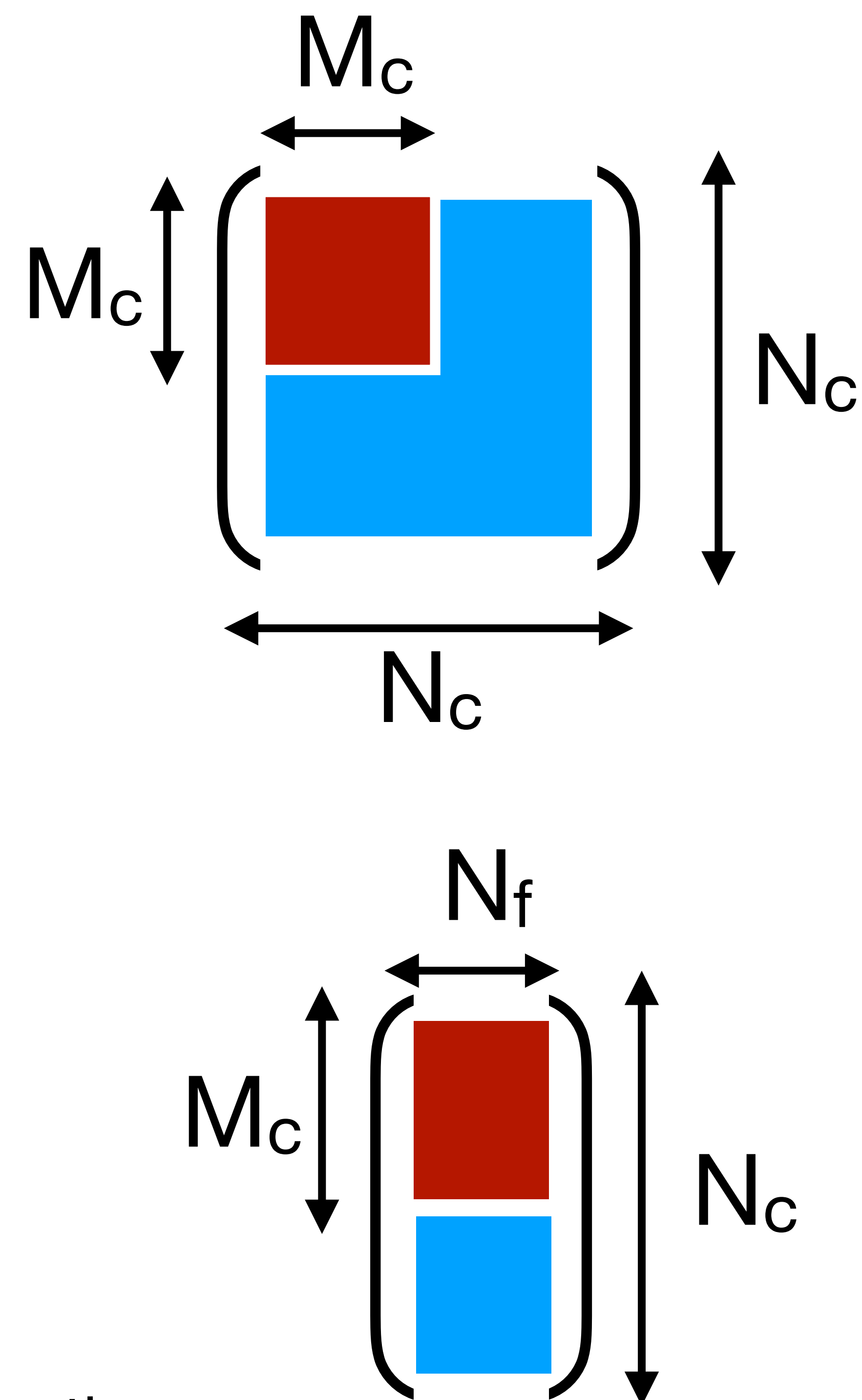
No need for center symmetry. No need for chiral symmetry. Applies to QCD.

QCD at zero chemical potential





M.H.-O'Bannon-Robinson, in preparation

Quantum Entanglement

between color d.o.f.

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

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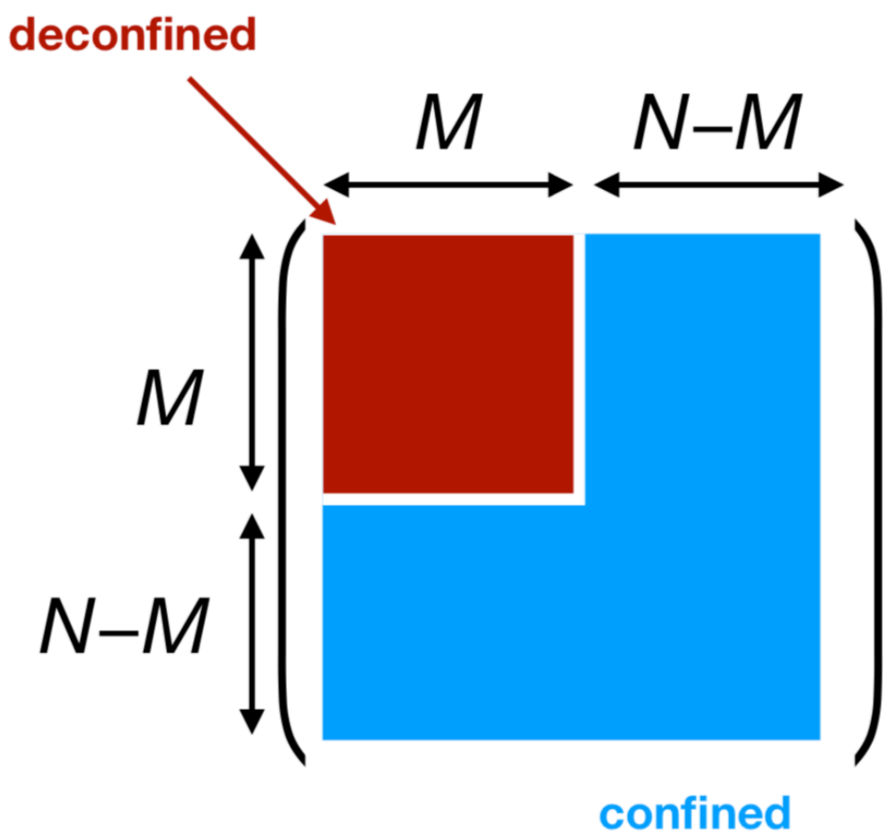

Confined → ground state up to 1/N corrections

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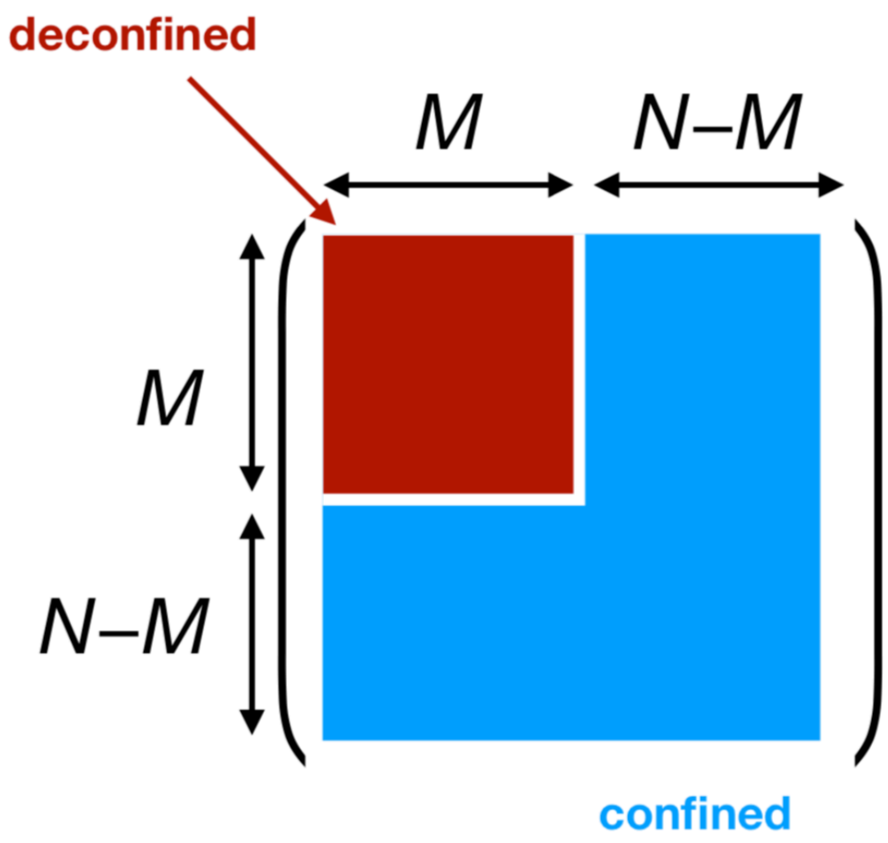
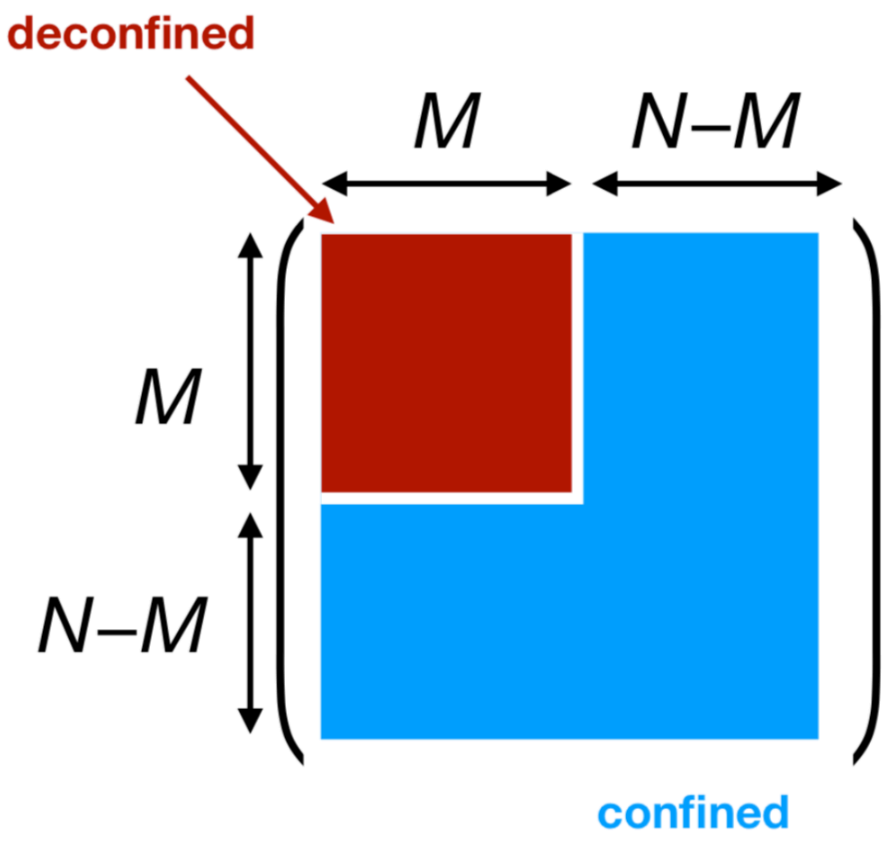
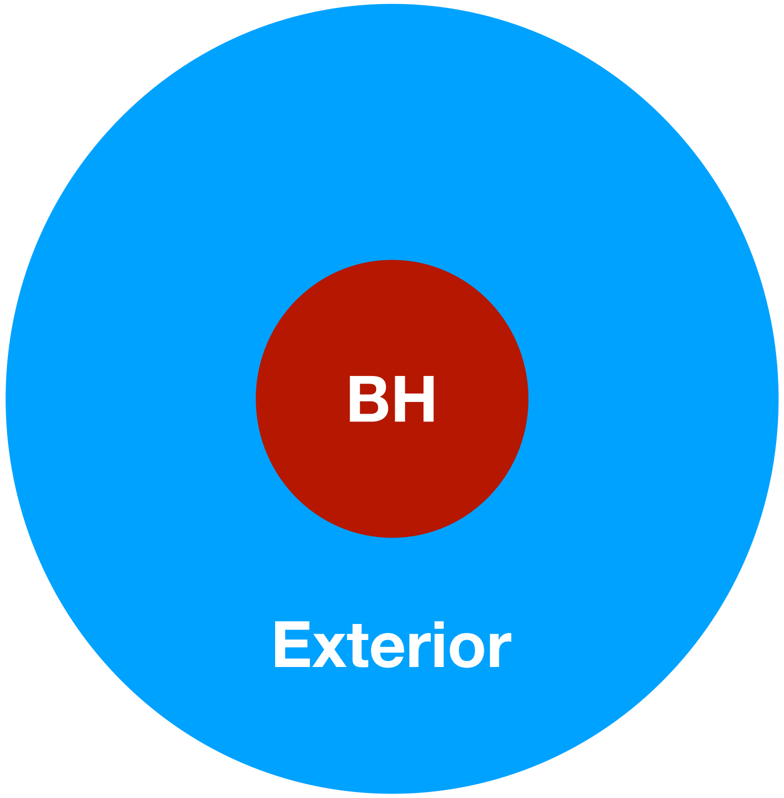


Confined → ground state up to 1/N corrections

Large entanglement can survive even at finite temperature.

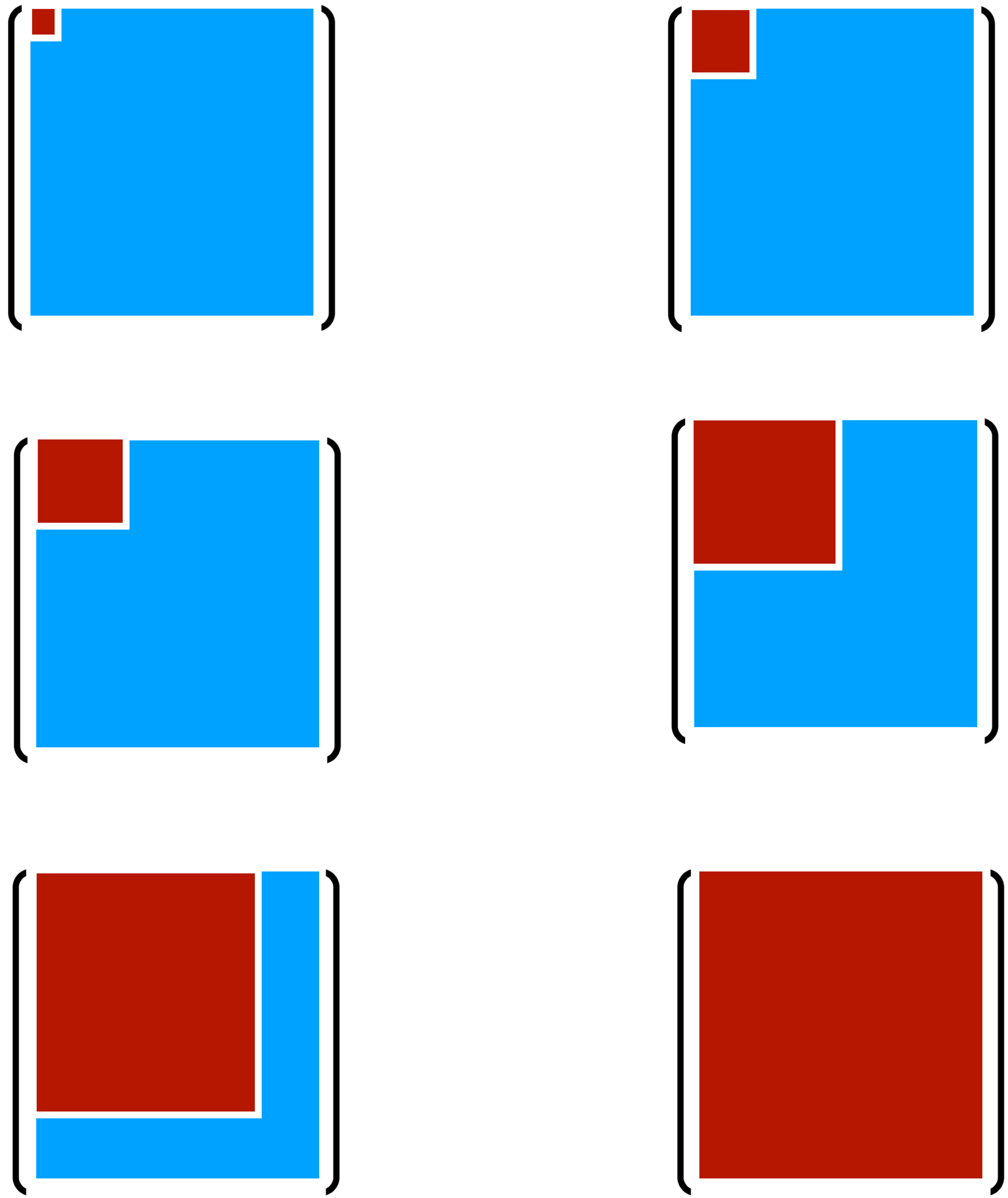
gauge/gravity duality

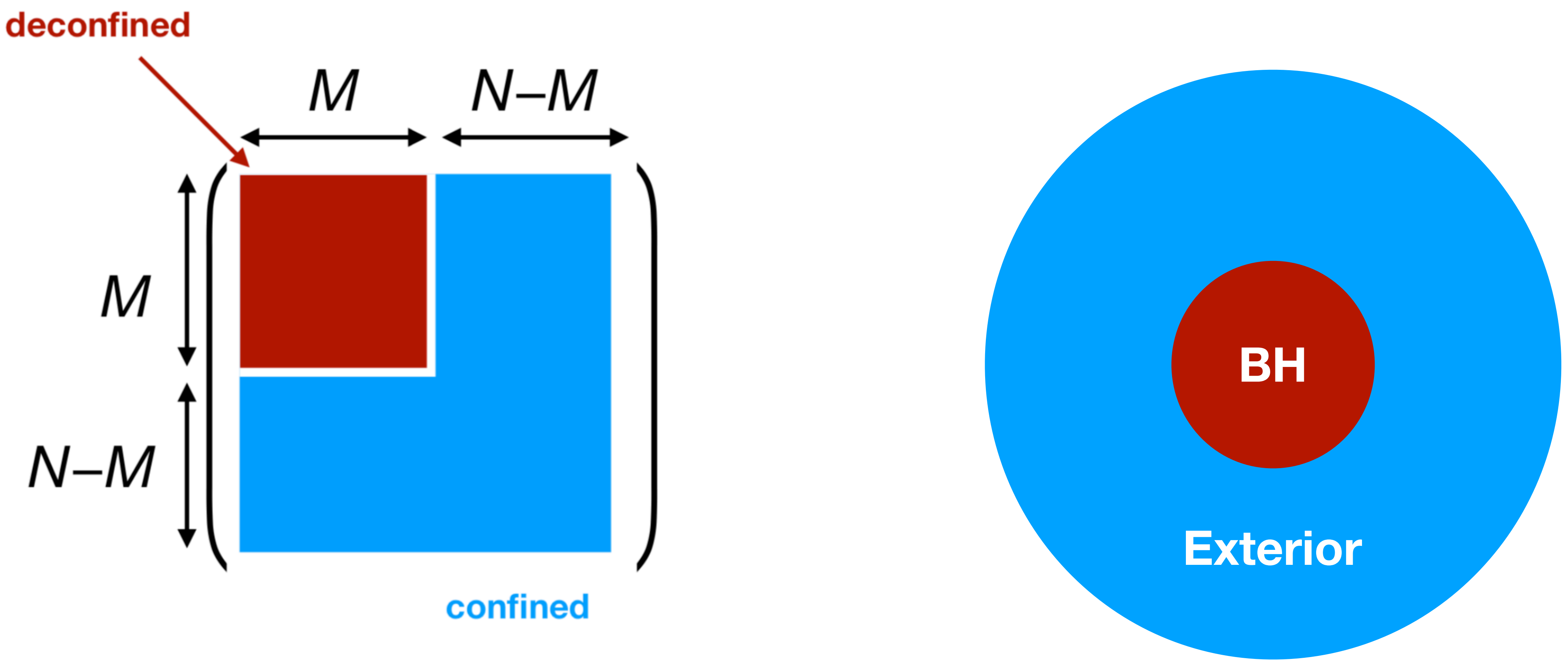


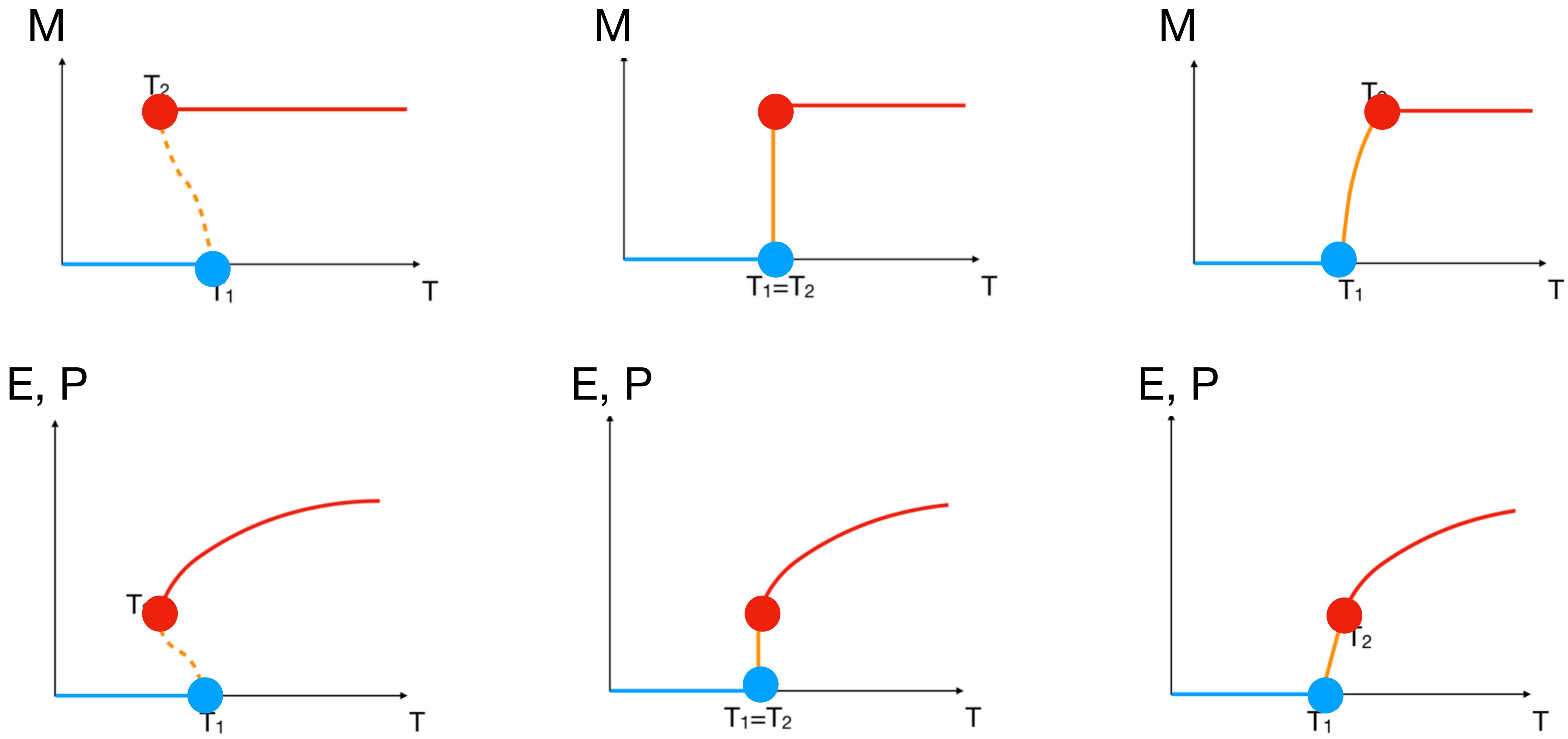


Entanglement between color d.o.f.
→ geometry outside the horizon?

Summary




deconfined
M
N−M
M
N−M
confined
BH
Exterior



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