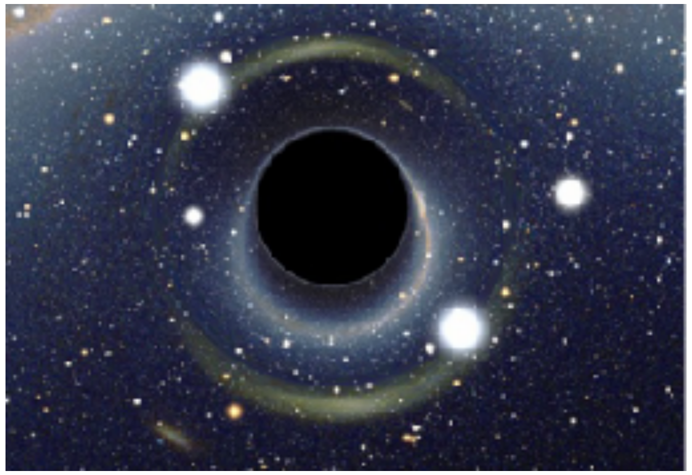
What QCD teaches us about Quantum Gravity, and vise versa

Masanori Hanada
University of Southampton



28 June 2019 @ Qui Nhon

QCD “=” Quantum Gravity

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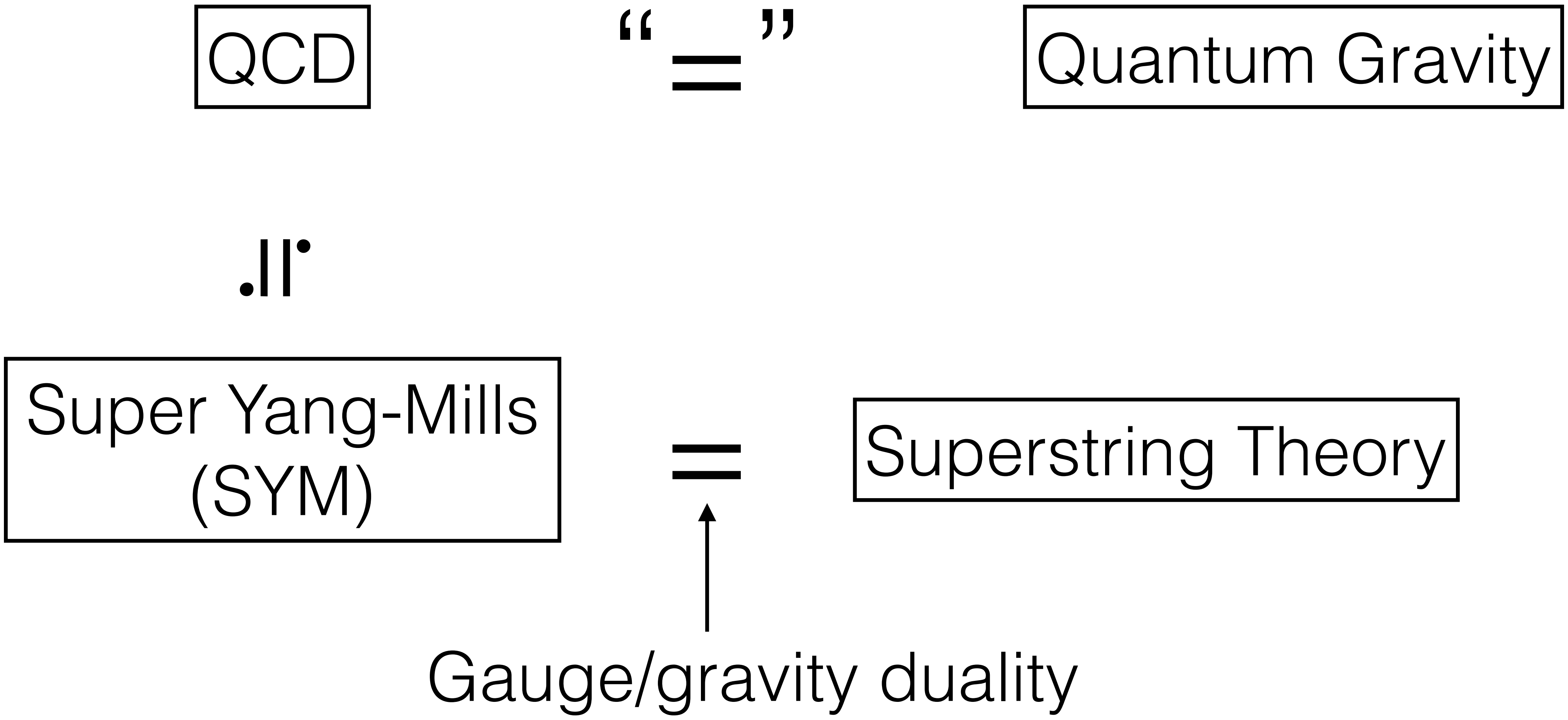
“=”

Super Yang-Mills
(SYM)

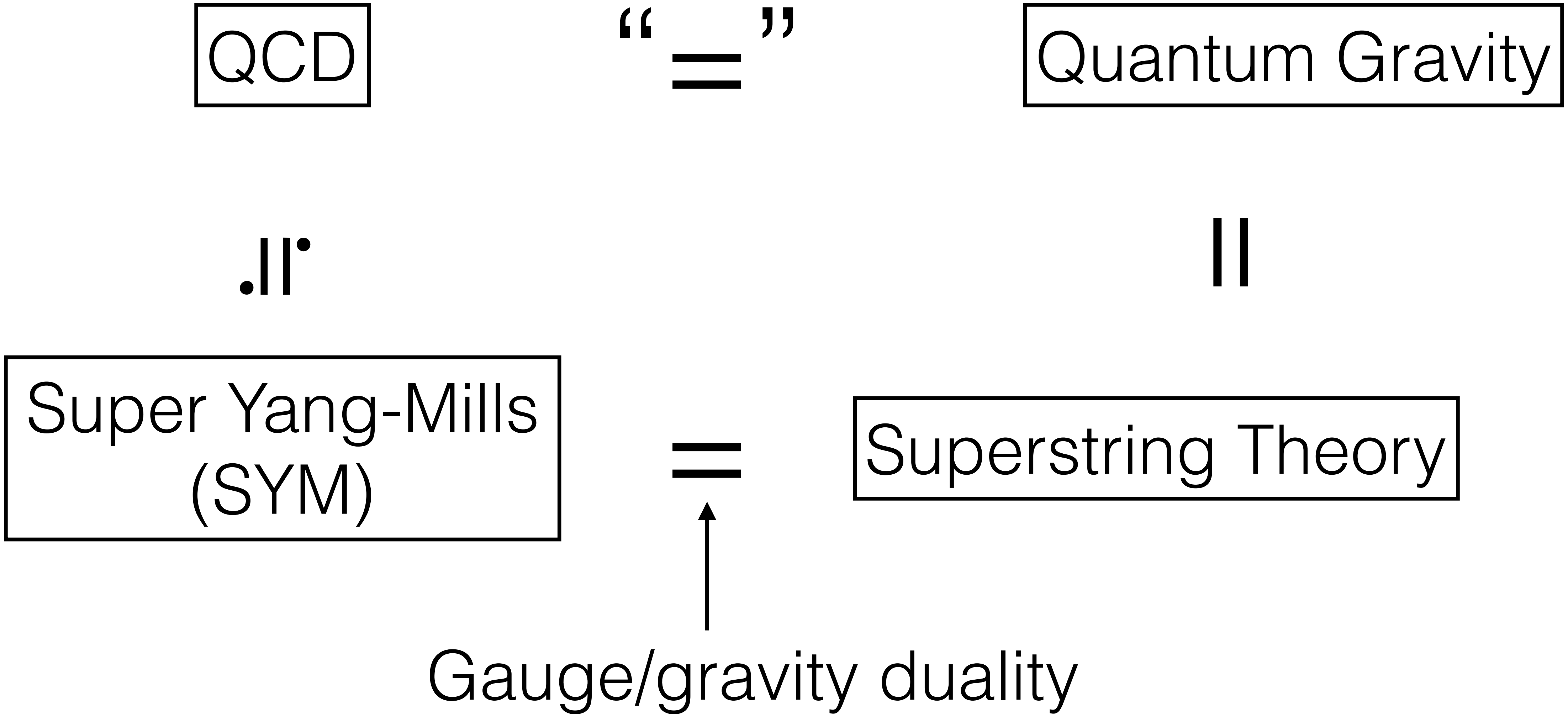


QCD “=” Quantum Gravity

≒

Super Yang-Mills (SYM) = Superstring Theory

Gauge/gravity duality



QCD “=” Quantum Gravity

Super Yang-Mills (SYM) = Superstring Theory

Gauge/gravity duality

- QCD to String

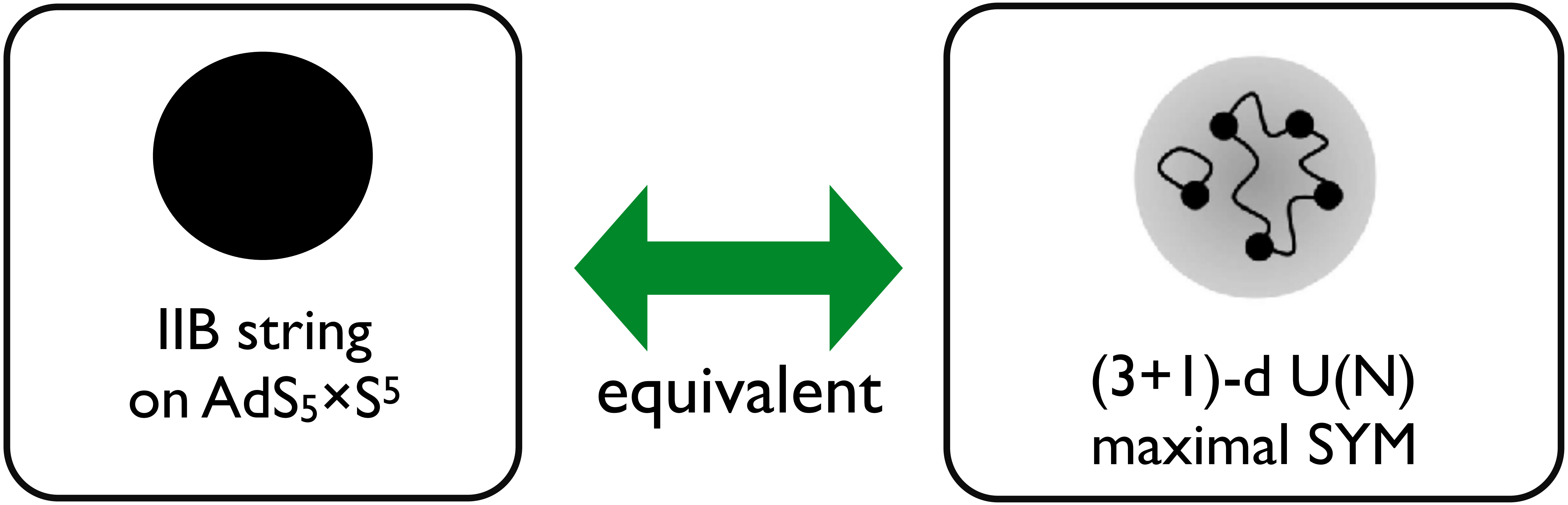
(Lattice Simulation)

- String to QCD

(New symmetry breaking mechanism)

AdS/CFT Duality

(Maldacena 1997)



IIB string on $AdS_5 \times S^5$

equivalent

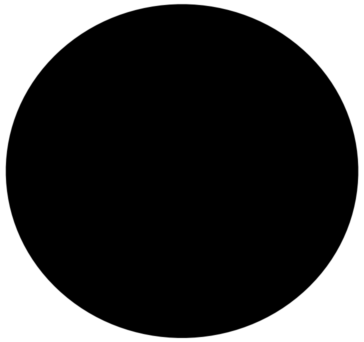
(3+1)-d U(N) maximal SYM

.II•

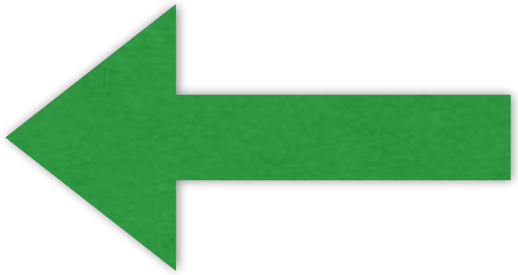
QCD

AdS/CFT Duality

(Maldacena1997)



IIB string
on $AdS_5 \times S^5$



definition

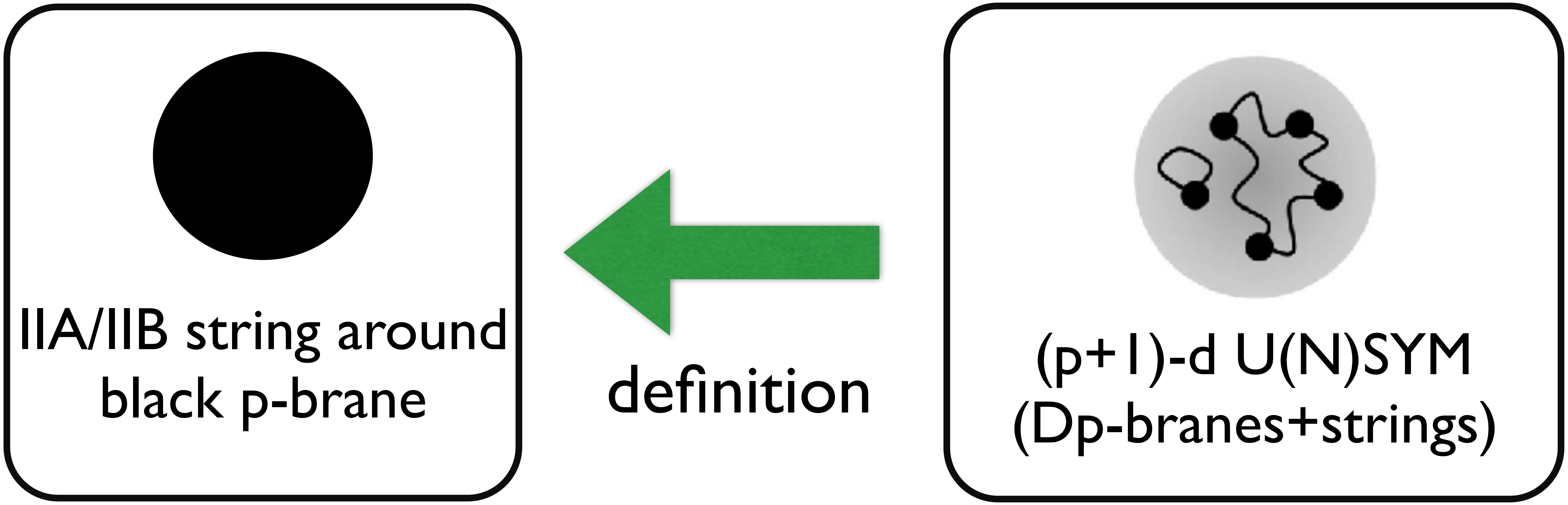
(3+1)-d U(N)
maximal SYM

$\rotatebox{90}{$\fallingdotseq$}$

QCD

Gauge/Gravity Duality

(Maldacena1997, Itzhaki-Maldacena-Sonnenschein-Yankielowicz 1998, …)



IIA/IIB string around black p-brane

definition

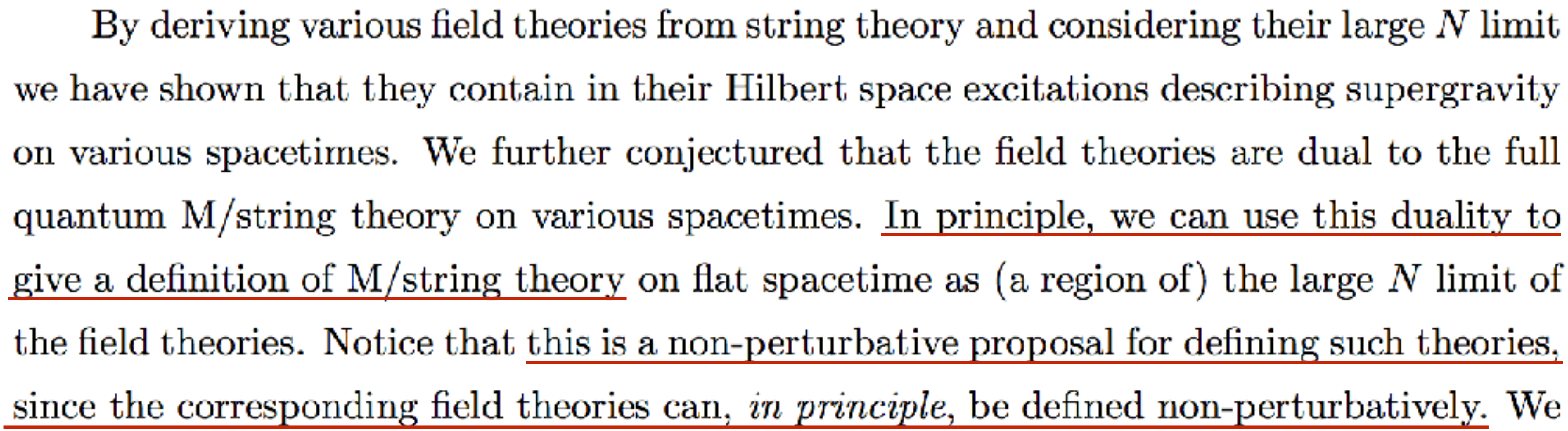
(p+1)-d U(N)SYM
(Dp-branes+strings)

p=3 → $AdS_5 \times S^5$

p=0,1,2,3

$\rotatebox{90}{$\fallingdotseq$}$

QCD



By deriving various field theories from string theory and considering their large N limit we have shown that they contain in their Hilbert space excitations describing supergravity on various spacetimes. We further conjectured that the field theories are dual to the full quantum M/string theory on various spacetimes. In principle, we can use this duality to give a definition of M/string theory on flat spacetime as (a region of) the large N limit of the field theories. Notice that this is a non-perturbative proposal for defining such theories, since the corresponding field theories can, *in principle*, be defined non-perturbatively. We

Maldacena,
“The Large N Limit of Superconformal Field Theories and Supergravity”
(1997)

- QCD to String

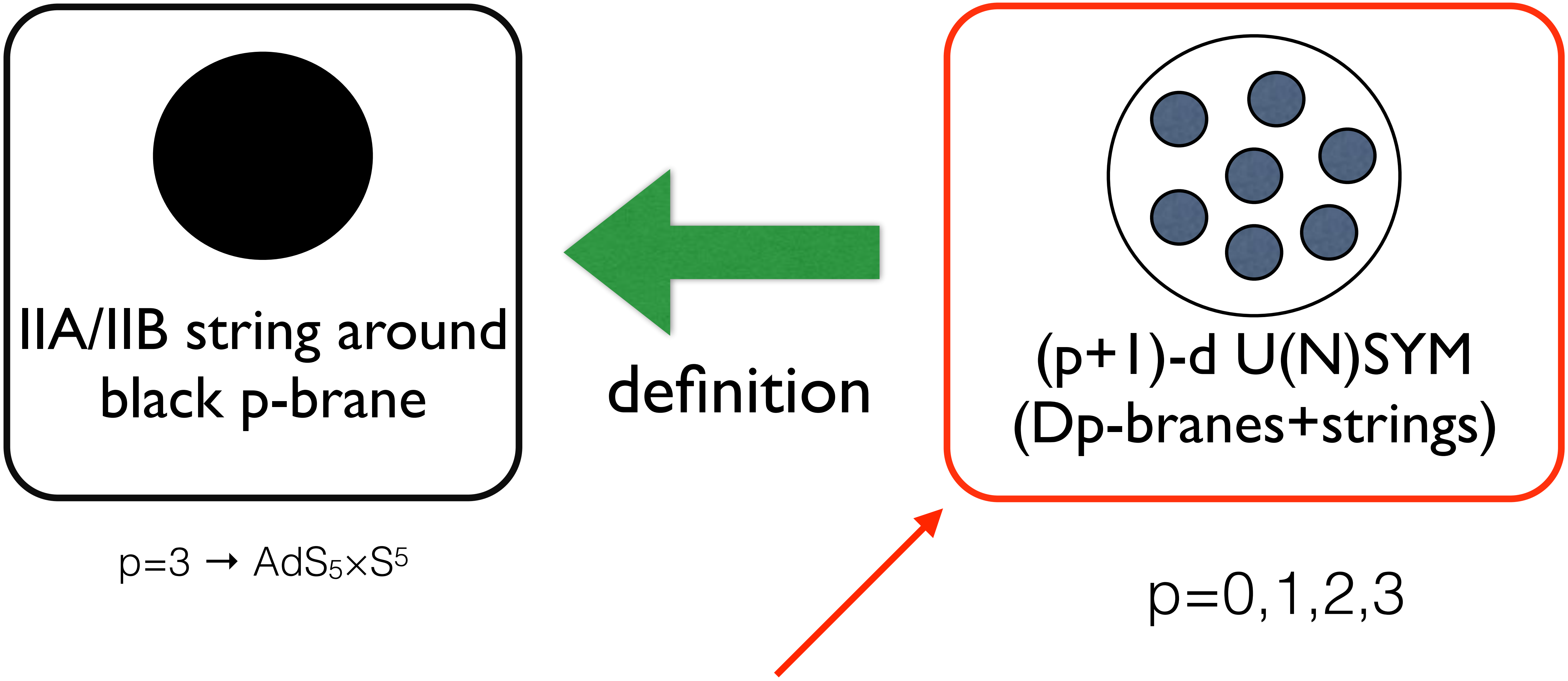
  (Lattice Simulation)

- String to QCD

  (New symmetry breaking mechanism)

Gauge/Gravity Duality

(Maldacena1997, Itzhaki-Maldacena-Sonnenschein-Yankielowicz 1998)



IIA/IIB string around black p-brane

definition

(p+1)-d U(N)SYM
(Dp-branes+strings)

p=3 → $AdS_5 \times S^5$

p=0,1,2,3

Solve it by using lattice methods.

And learn about quantum gravity.

SYM$_{\text{difficult}}$	STRING
large-N, strong coupling	SUGRA easier
large-N, finite coupling	tree-level string (SUGRA+α') more difficult
finite-N, finite coupling	Quantum string $(g_s > 0)$ very difficult

SYM difficult

large-N,
strong coupling

large-N,
finite coupling

finite-N,
finite coupling

STRING

SUGRA
easier

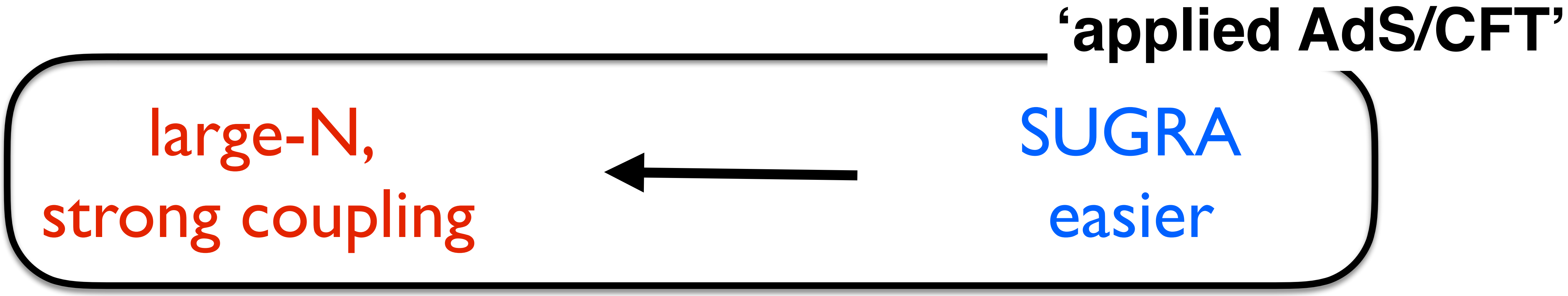
tree-level string
(SUGRA+α’)
more difficult

Quantum string
(g_s >0)
very difficult

have to solve it

SYM difficult	STRING
large-N, strong coupling	SUGRA easier **But this is much easier**
large-N, finite coupling	tree-level string (SUGRA+α') more difficult
finite-N, finite coupling	Quantum string (g_s >0) very difficult

SYM difficult STRING



‘applied AdS/CFT’

SYM	STRING
large-N, strong coupling	SUGRA easier
large-N, finite coupling	tree-level string (SUGRA+α') more difficult
finite-N, finite coupling	Quantum string ($g_s > 0$) very difficult

Various cool applications.

SYM$_{\text{difficult}}$		STRING
large-N, strong coupling		SUGRA easier
large-N, finite coupling	→	tree-level string (SUGRA+α’) more difficult
finite-N, finite coupling		Quantum string (g_s >0) very difficult

that’s cool, but we want to learn about quantum gravity

SYM difficult STRING

large-N,
strong coupling
→
SUGRA
easier

+ integrability, supersymmetric nonrenormalization, …

large-N,
finite coupling

tree-level string
(SUGRA+α’)
more difficult

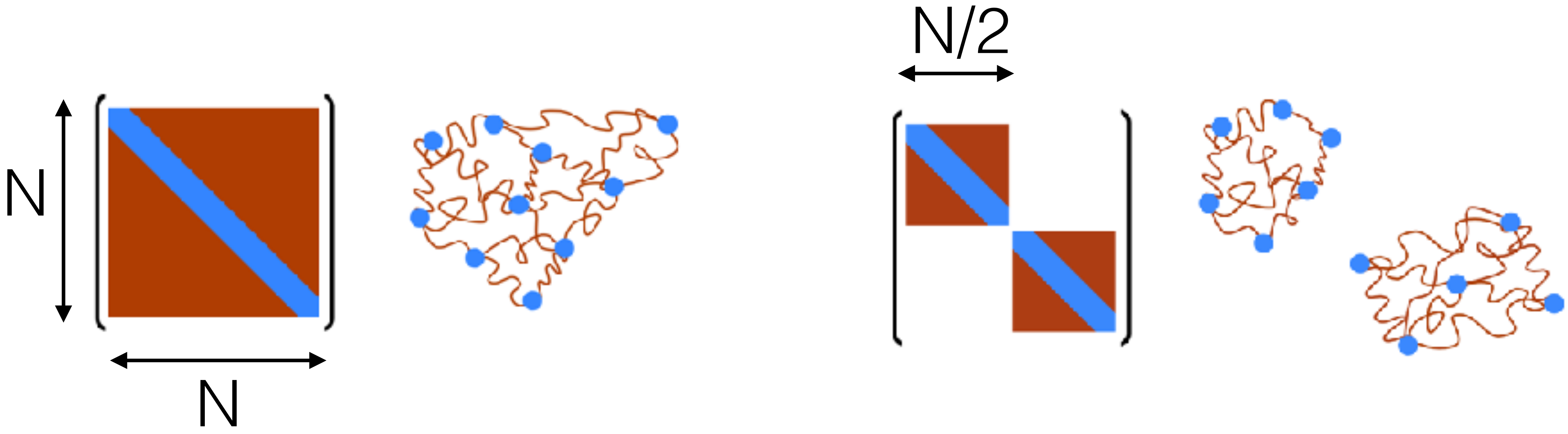
finite-N,
finite coupling

Quantum string
($g_s > 0$)
very difficult

SYM difficult	STRING
large-N, strong coupling	SUGRA easier
large-N, finite coupling	tree-level string (SUGRA+α') more difficult
finite-N, finite coupling	Quantum string ($g_s > 0$) very difficult

But this part is more important…

<u>Lattice Gauge Theory Simulation</u>



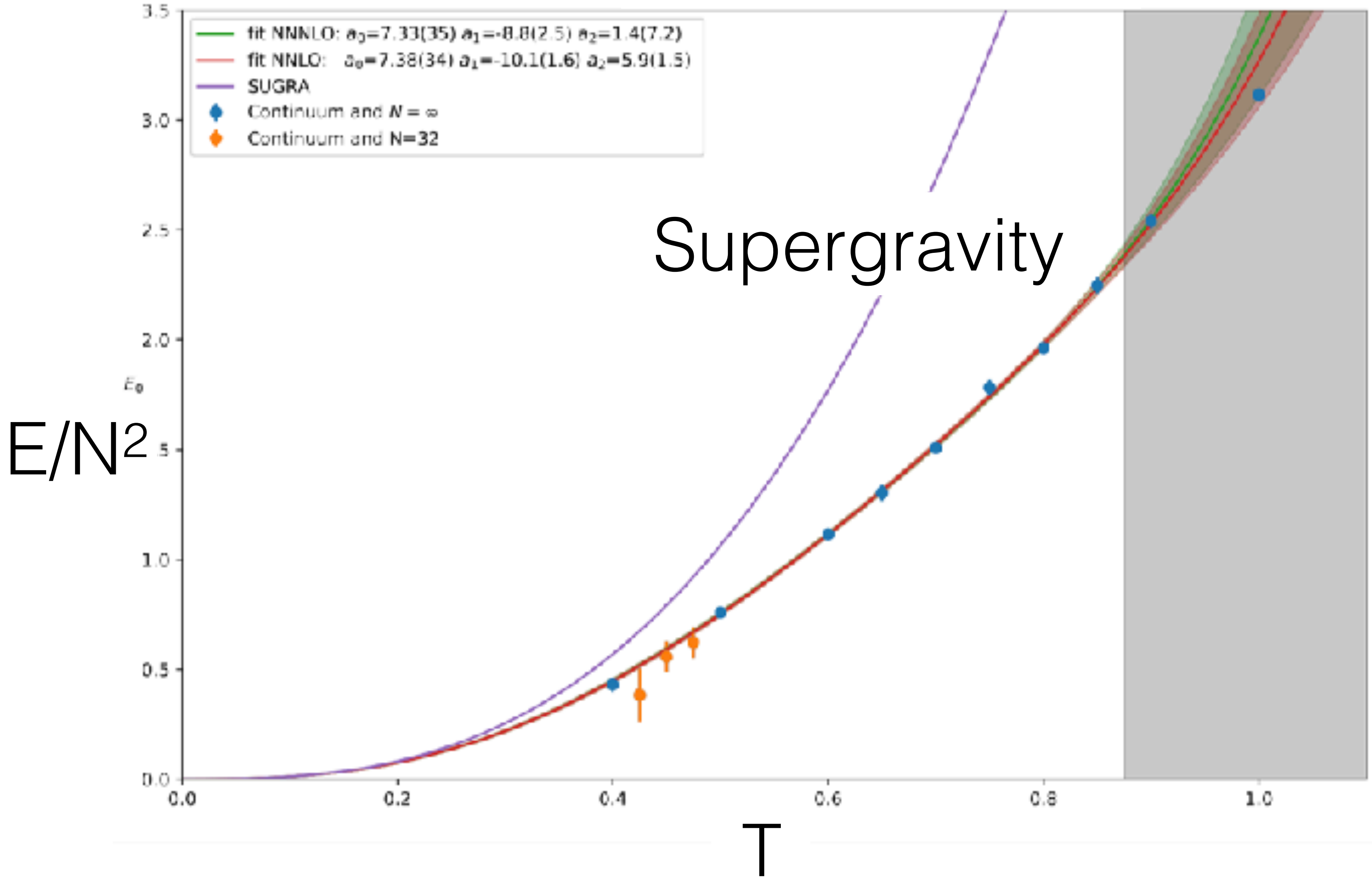
diagonal elements = particles (D-branes)
off-diagonal elements = open strings

(Witten, 1994)

black hole = bound state of D-branes and strings
= deconfined phase

N=∞ obtained from N=16, 24, 32

Continuum limit from 8,12,16, …, 64 lattice points



E. Rinaldi

E. Berkowitz

Monte Carlo String/M-theory Collaboration

Gravity = SYM @ finite-T

$$E/N^2 = aT^{14/5} + b\,T^{23/5} + c\,T^{29/5}$$

3-parameter fit
(4-parameter is too much)

$$\boxed{a = 7.33 \pm 0.35}$$

1606.04951 [hep-lat] + recent data

$\updownarrow$ 👍

$$E/N^2 = 7.41T^{14/5} + b\,T^{23/5} + c\,T^{29/5} + \ldots + O(1/N^2)$$

STRING = SYM @ finite-T

$$E/N^2 = 7.41T^{14/5} + b\,T^{p} + c\,T^{p+6/5}$$

3-parameter fit
(4-parameter is too much)

$$\boxed{p = 4.6 +/- 0.3}$$

1606.04951 [hep-lat]

$$E/N^2 = 7.41T^{14/5} + b\,T^{23/5} + c\,T^{29/5} + \ldots + O(1/N^2)$$

※ We are adding more data points to make the fit even more reliable; especially studying the parameter region where higher order terms become smaller.

- Higher dimensions can also be studied by lattice simulation. (Serious attempts by several groups.)

- 1/N correction vs quantum correction tested as well.

(MH-Hyakutake-Ishiki-Nishimura, Science 2014)

- QCD to String

(Lattice Simulation)

- String to QCD

(New symmetry breaking mechanism)

J. Maltz

G. Ishiki

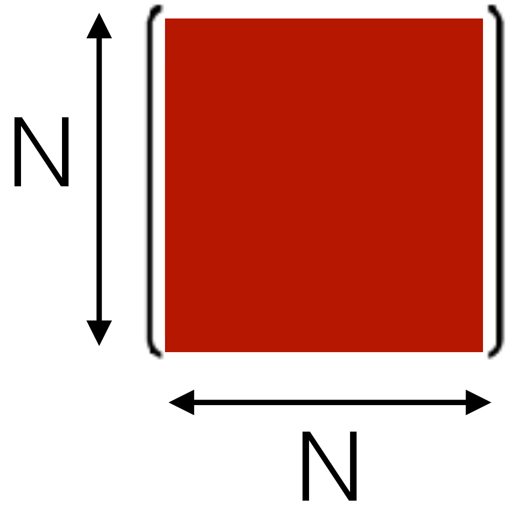
H. Watanabe

C. Peng

A. Jevicki

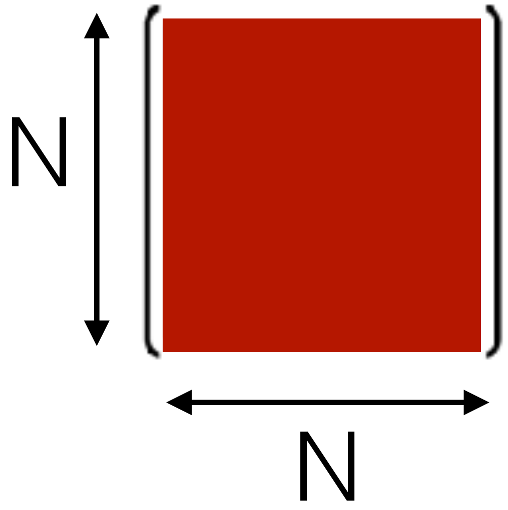
N. Wintergerst

- Confinement phase: E ~ N^0
- Deconfinement phase: E ~ N^2



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

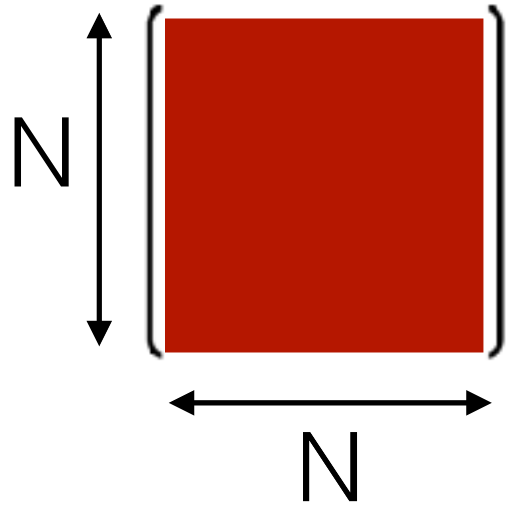
- Deconfinement phase: $E \sim N^2$



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

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

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



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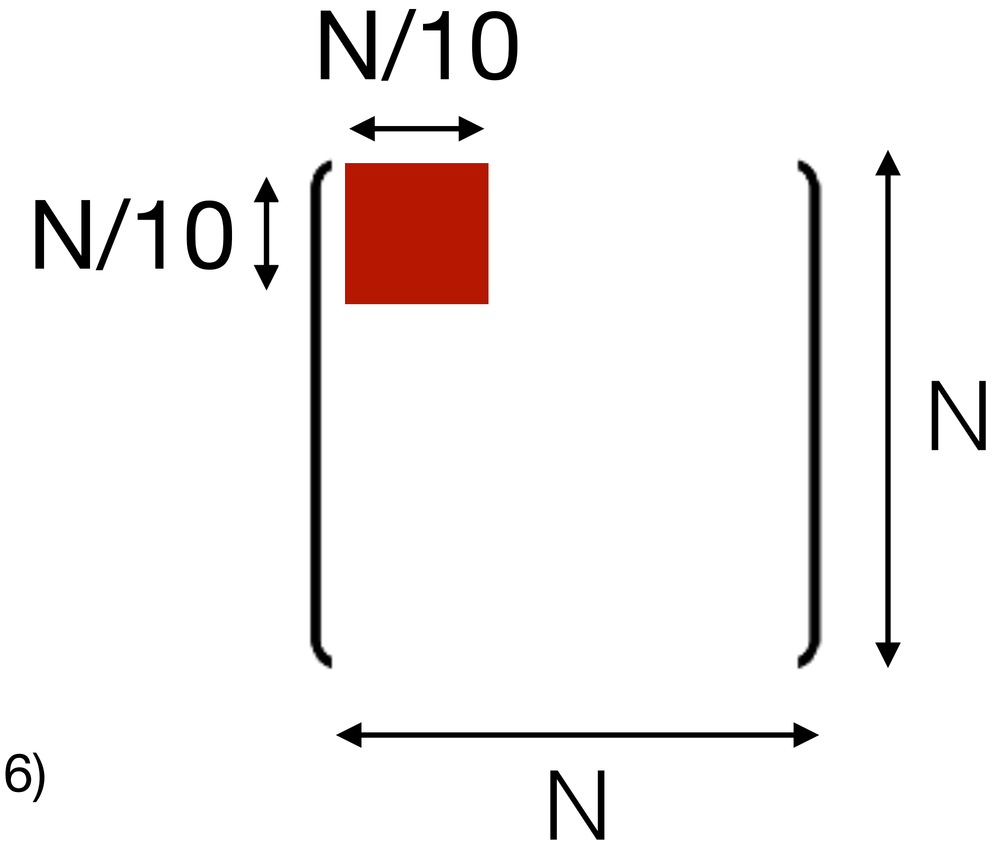


<u>'partially' deconfine</u>

(MH-Maltz, 2016)

Why is it interesting?

- We have studied black hole with *positive specific heat*

T ↗ E ↗

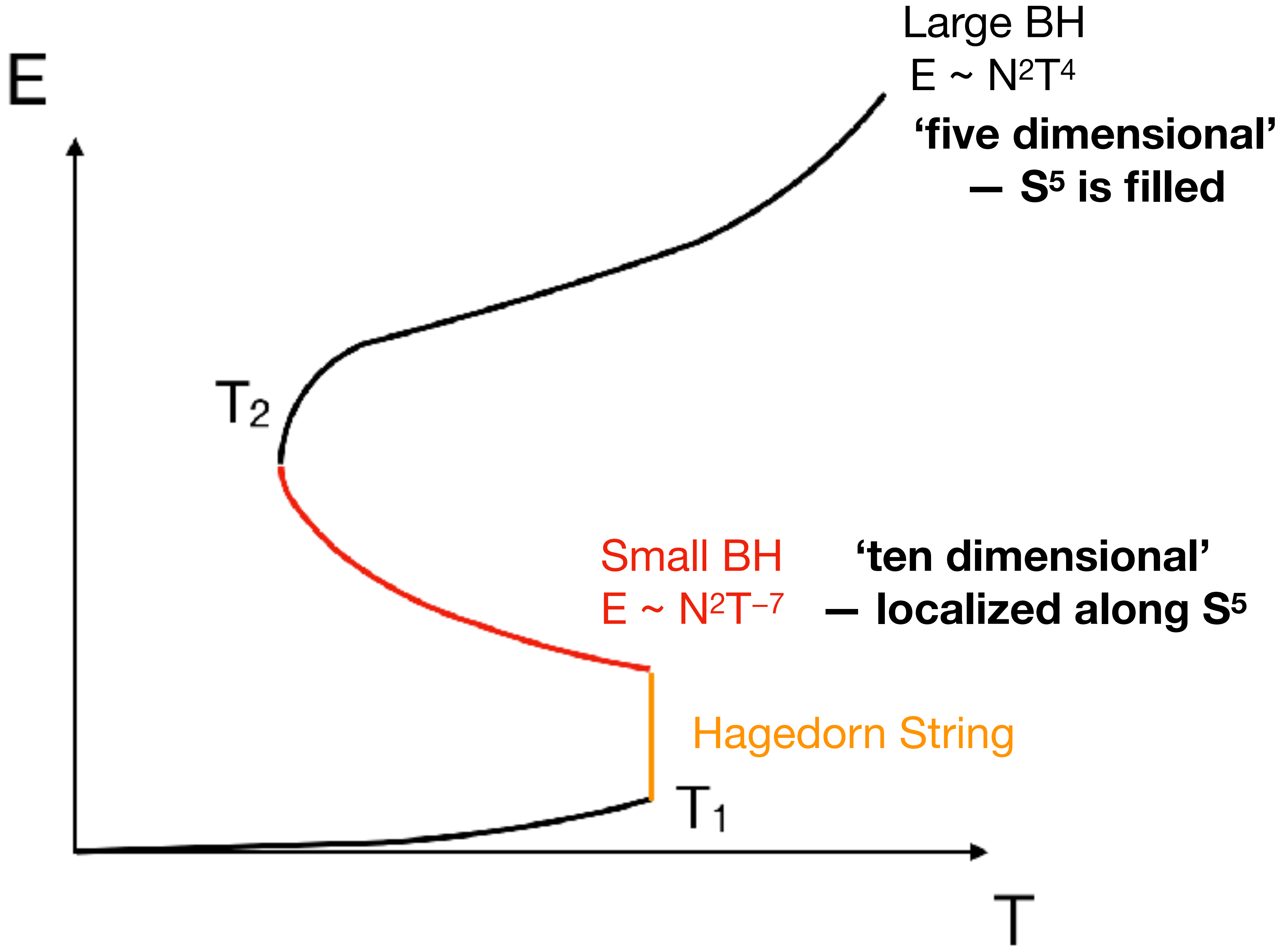
- Schwarzschild black hole has *negative specific heat*

T ↗ E ↘

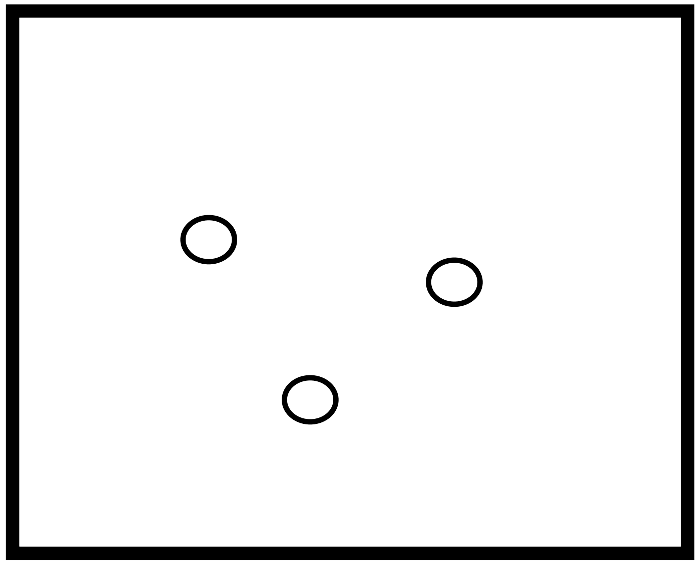
Partial deconfinement
~ Schwarzschild black hole

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

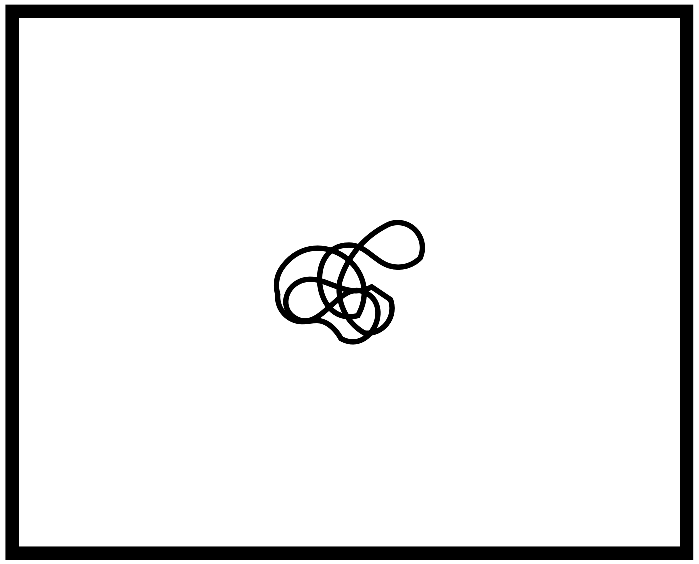
microcanonical ensemble (E fix)

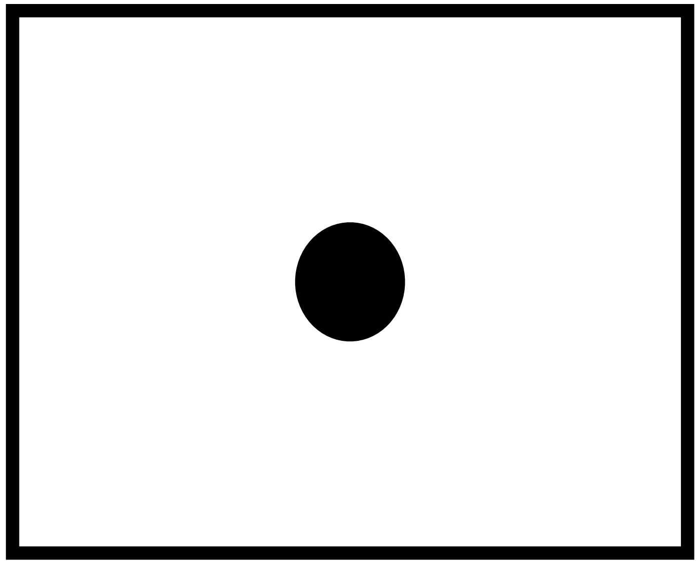


Graviton gas

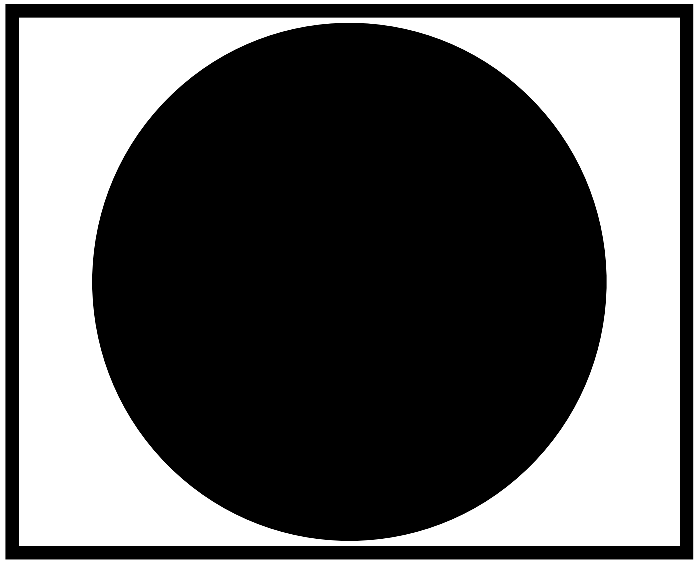


Hagedorn String





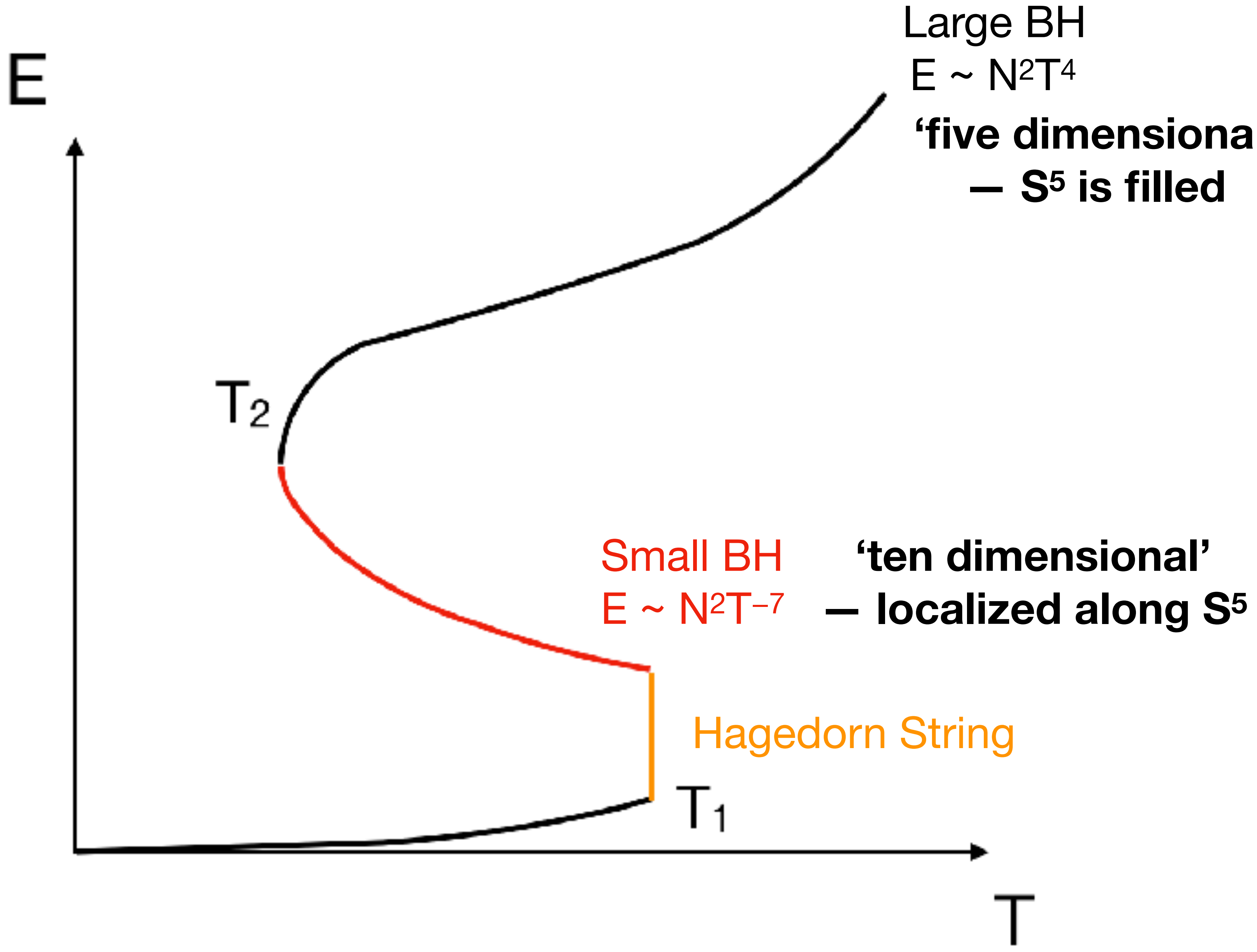
Small BH
$E \sim N^2T^{-7}$



Large BH
$E \sim N^2T^4$

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

microcanonical
ensemble
(E fix)



Large BH
$E \sim N^2 T^4$

‘five dimensional’
— S^5 is filled

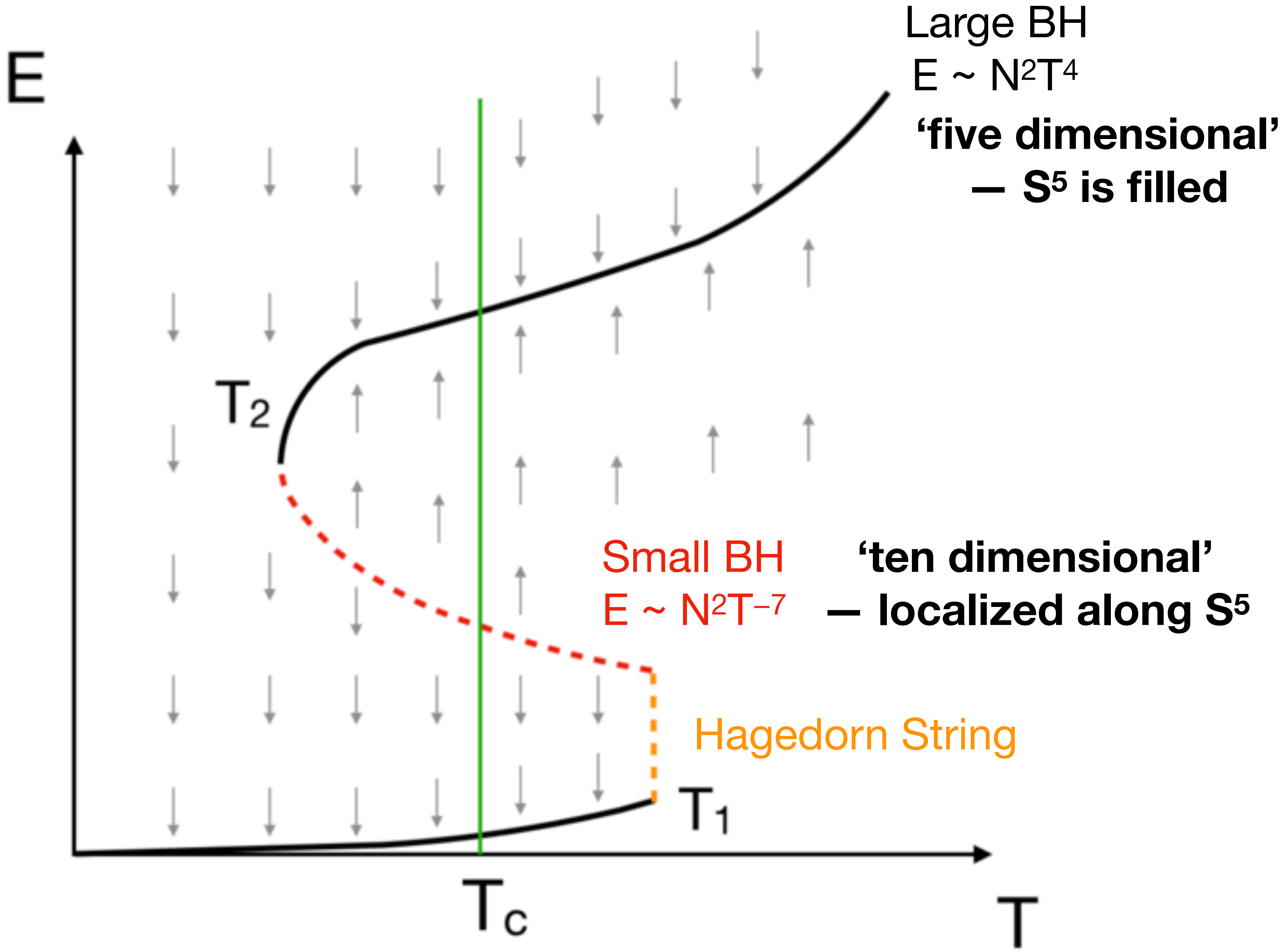
Small BH
$E \sim N^2 T^{-7}$

‘ten dimensional’
— localized along S^5

Hagedorn String

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

canonical ensemble
(T fix)



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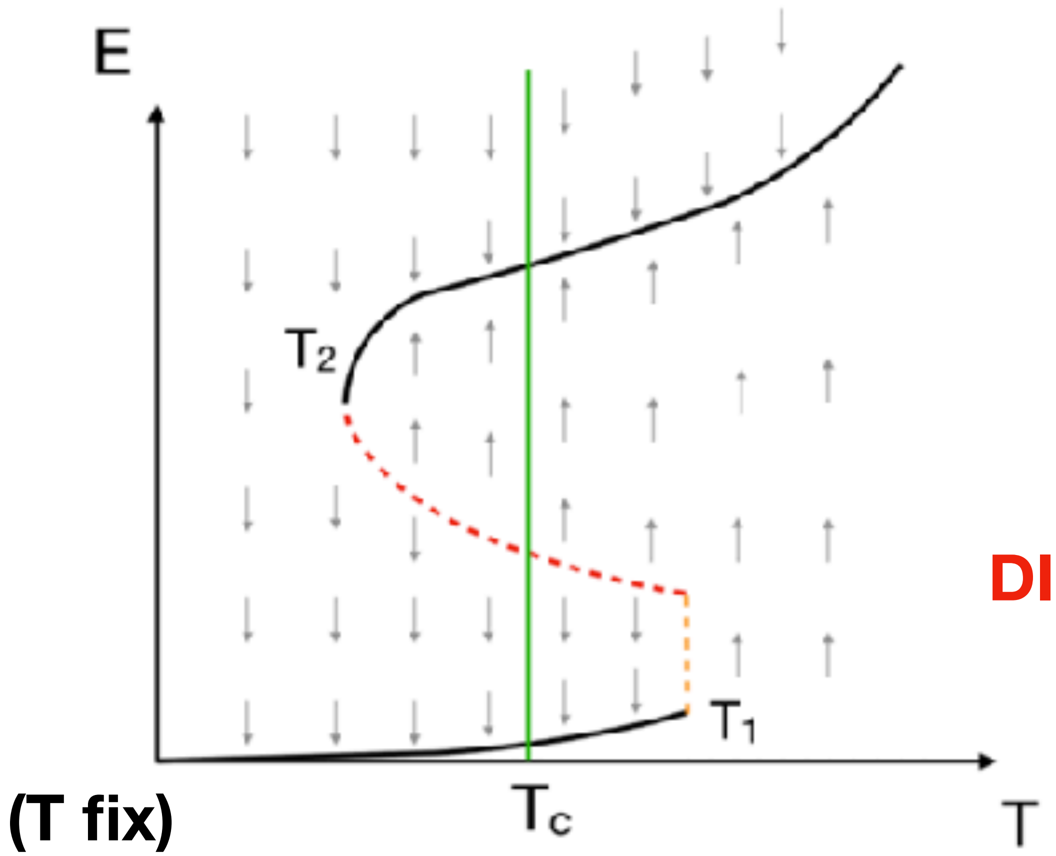
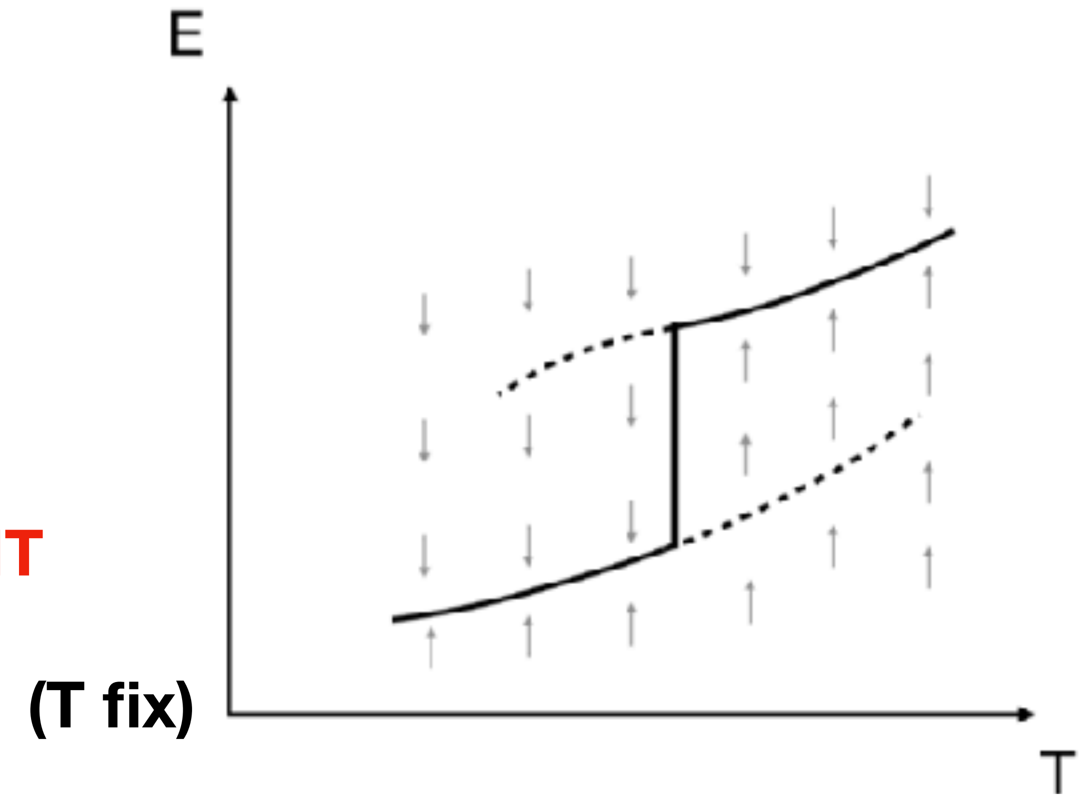
Hagedorn String

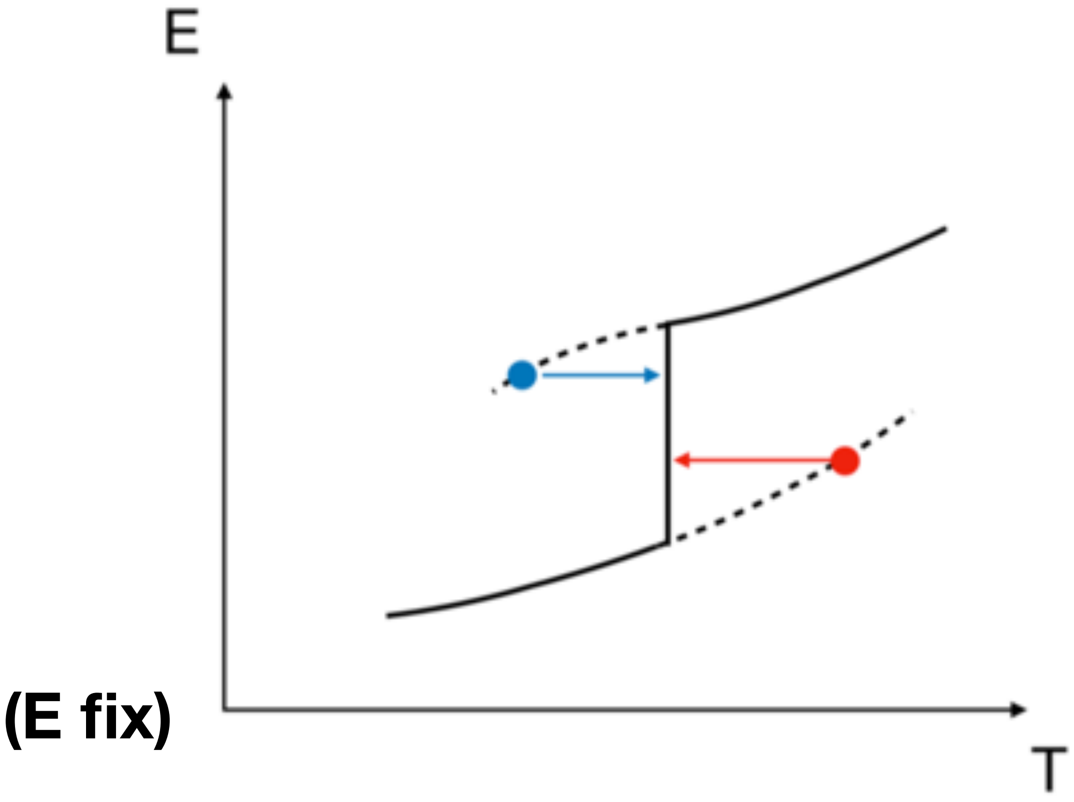
strongly coupled
4d SYM



water/ice

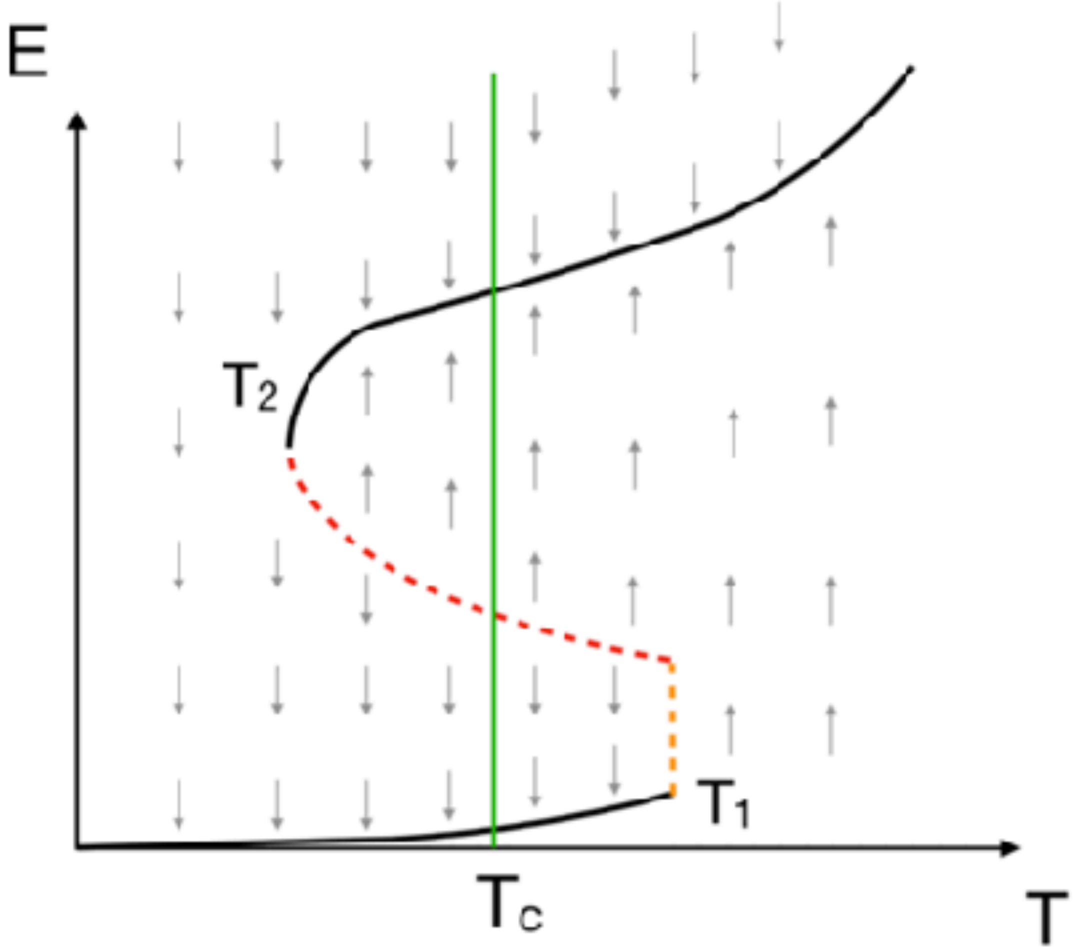


VERY DIFFERENT



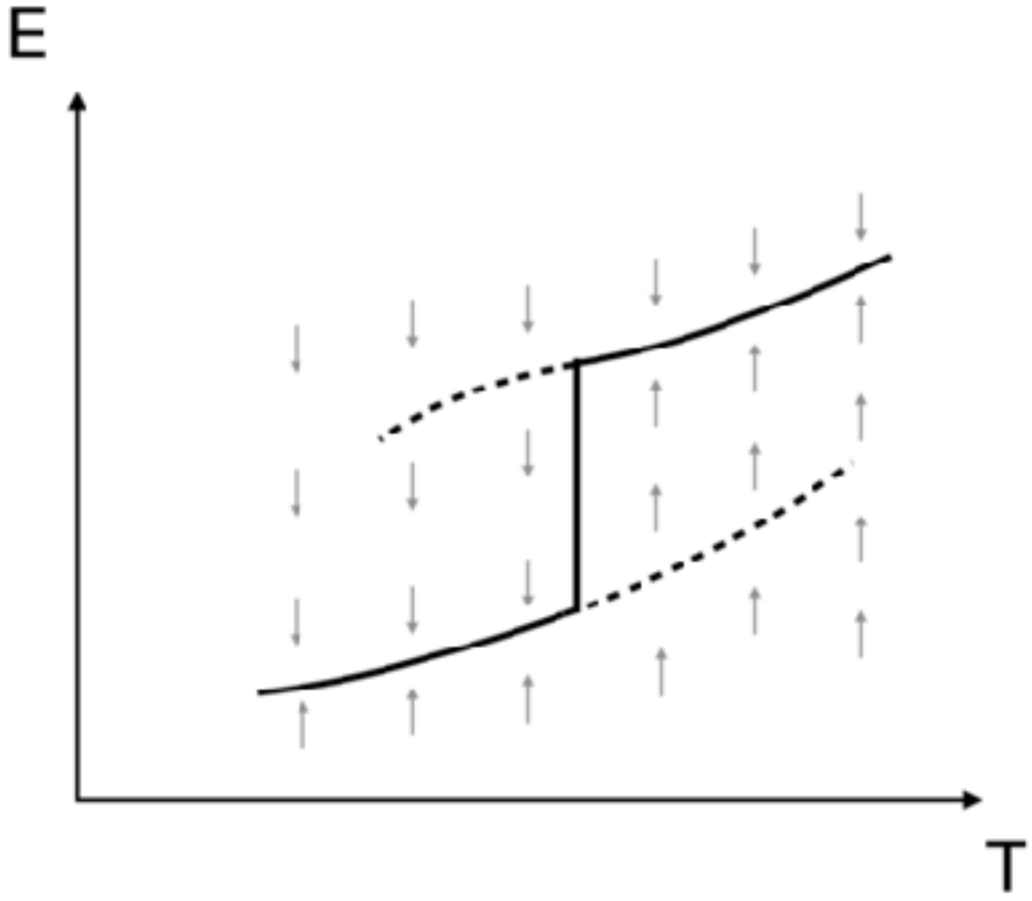
How can we explain such difference?

strongly coupled
4d SYM

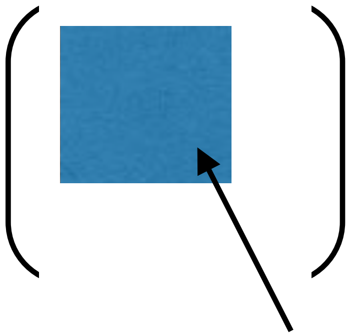


VERY DIFFERENT

water/ice



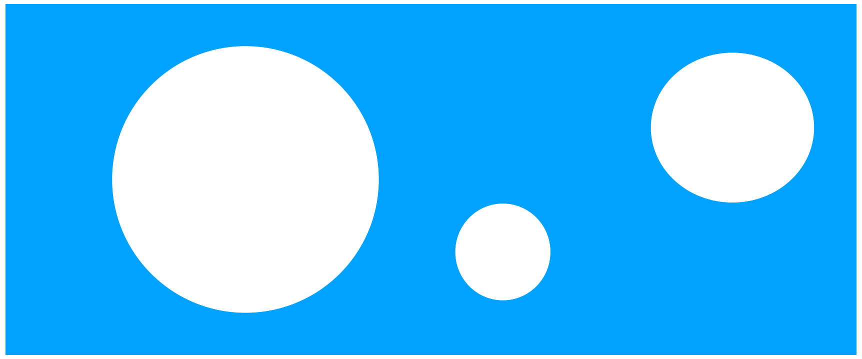
separation in color d.o.f

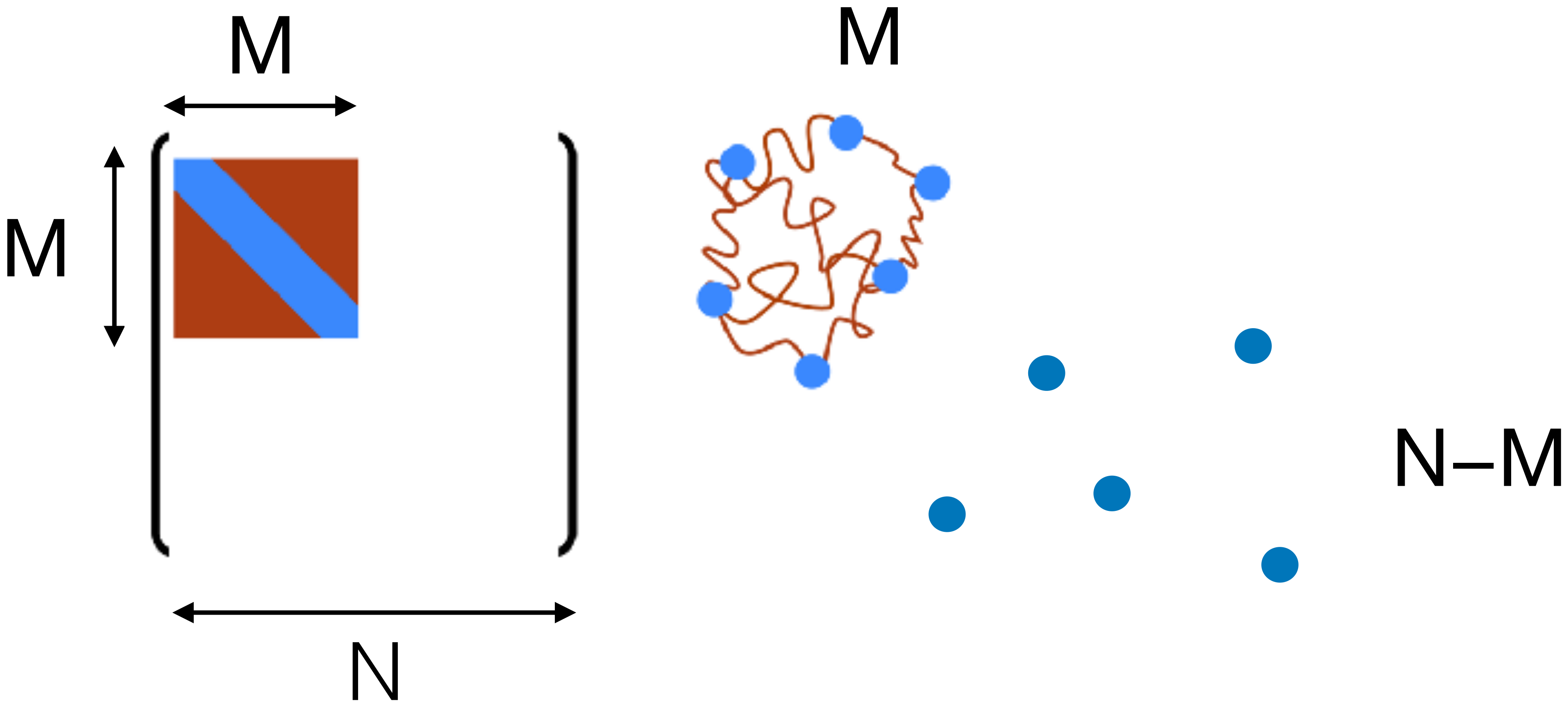


partially deconfined

(MH-Maltz, 2016)

separation in space





M D-branes form the bound state

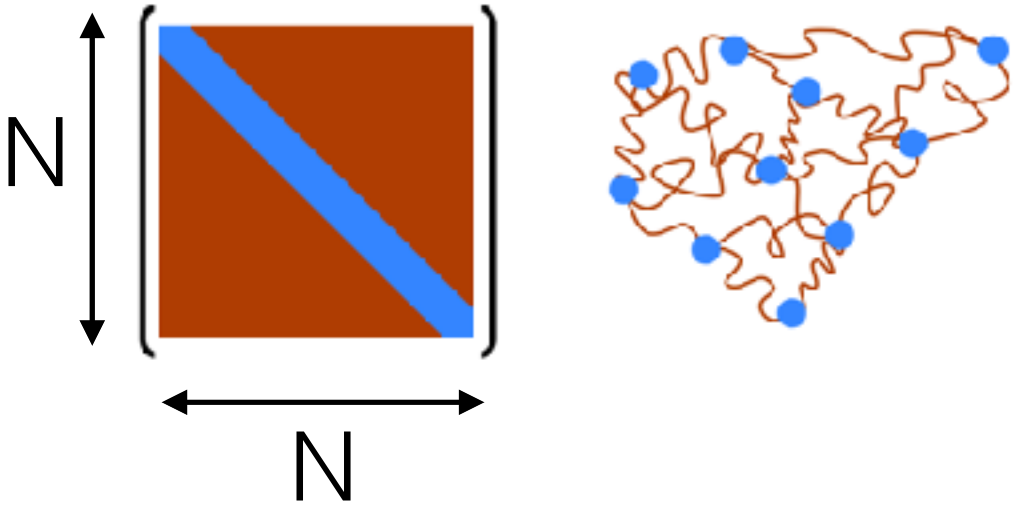
SU(M) is deconfined — ‘partial deconfinement’

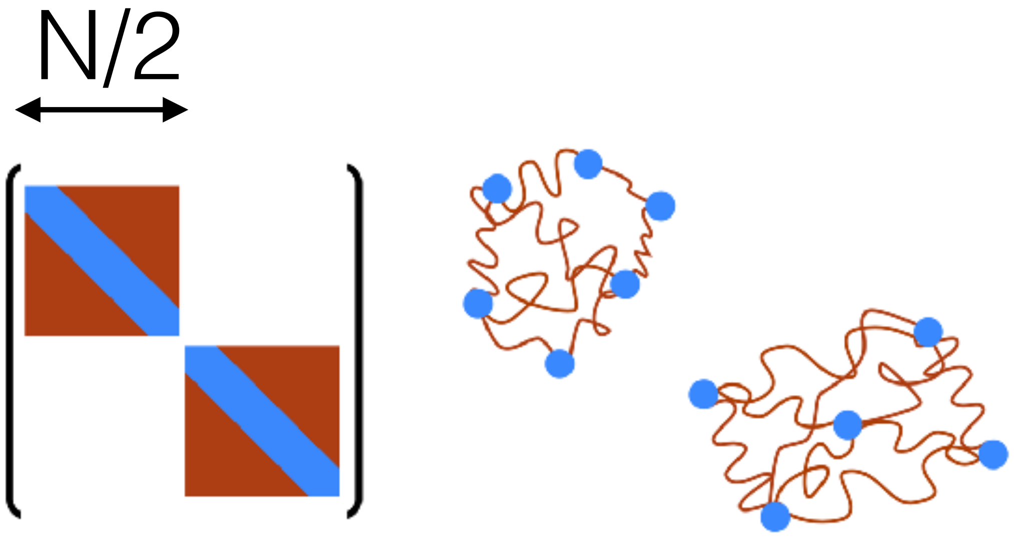
Can explain $E \sim N^{2}T^{-7}$ for 4d SYM, $N^{3/2}T^{-8}$ for ABJM

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

(MH-Maltz, 2016)

Why can negative specific heat appear?



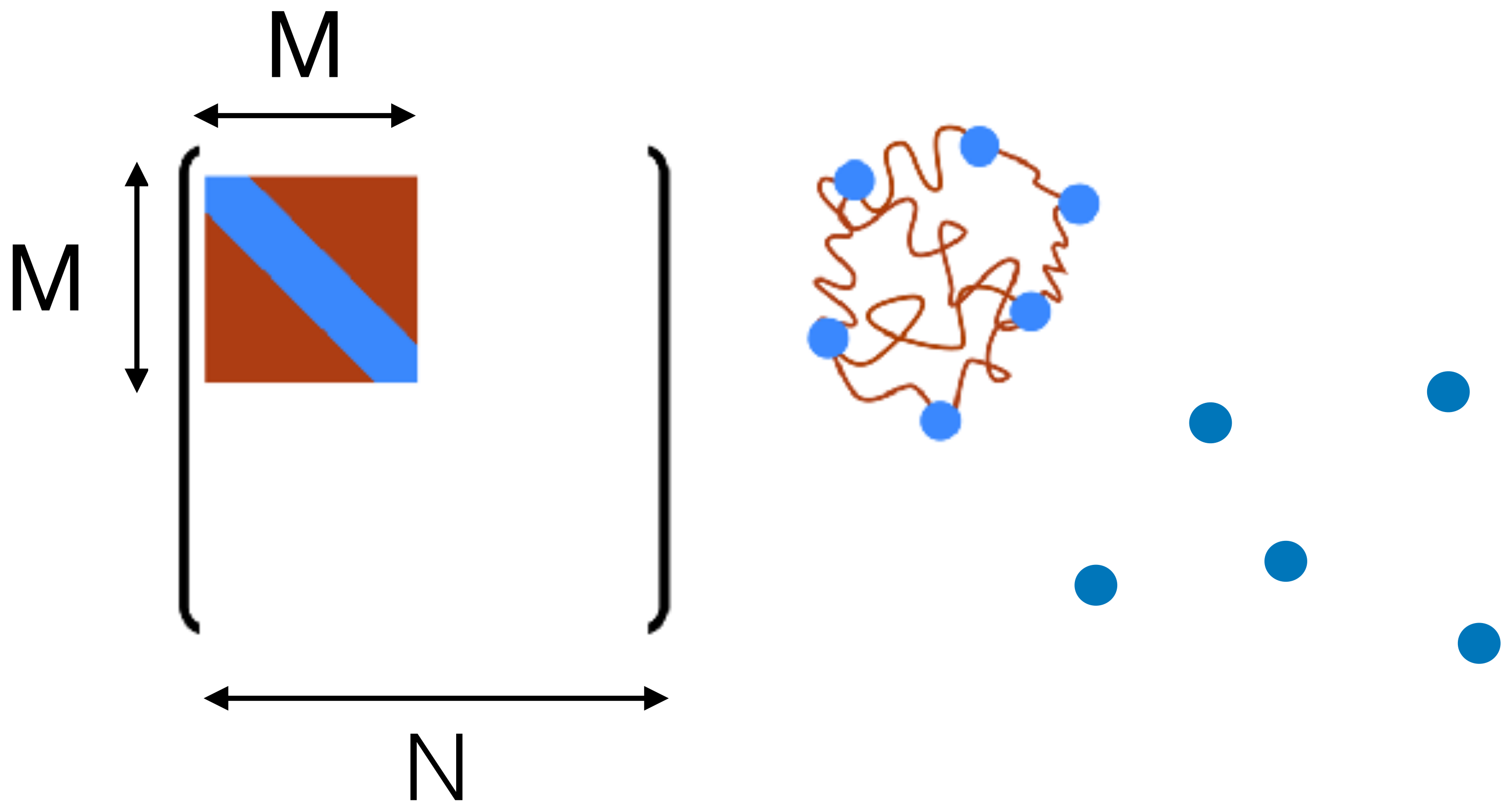


$T \sim E/N^2$

$T' \sim E'/[2 \times (N/2)^2]$

$\boxed{T' > T \text{ if } E' > E/2}$

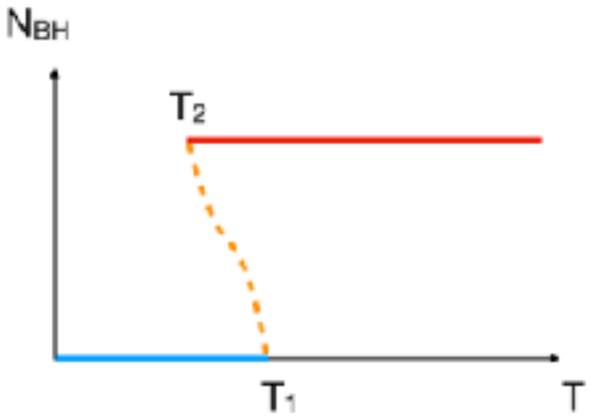
Why can negative specific heat appear?

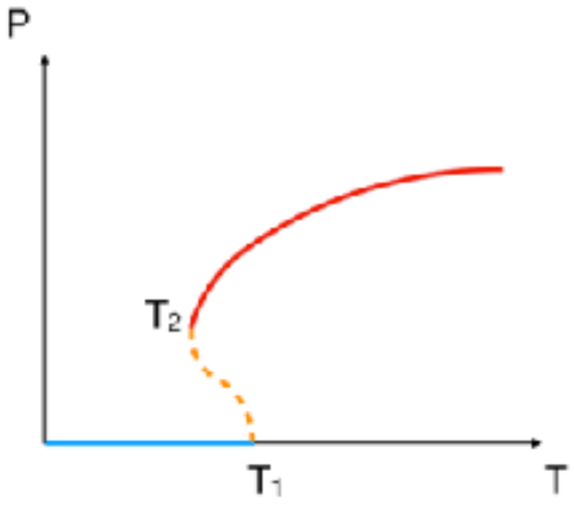


$$T \sim E/M^2$$

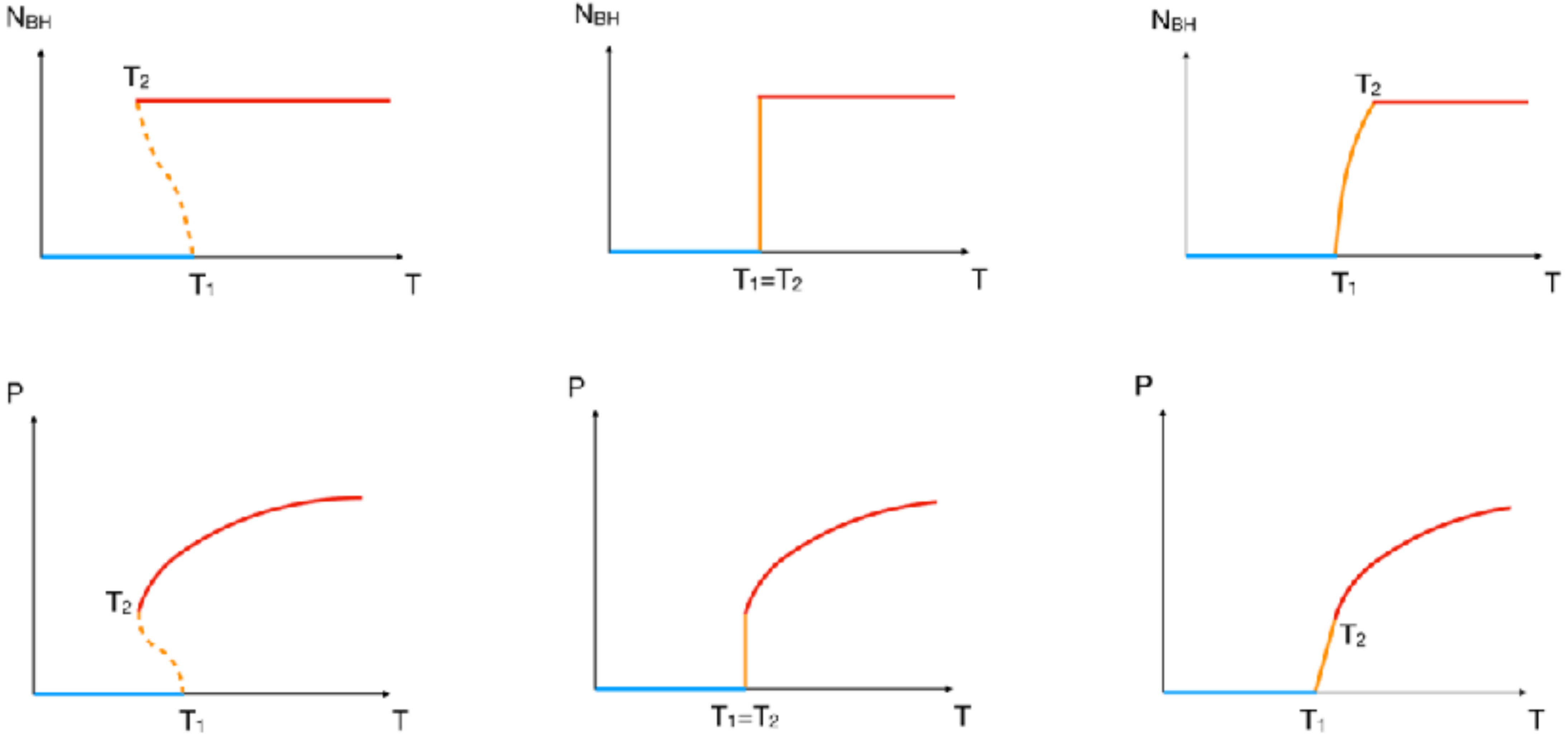
M is a function of E

strongly coupled
4d SYM

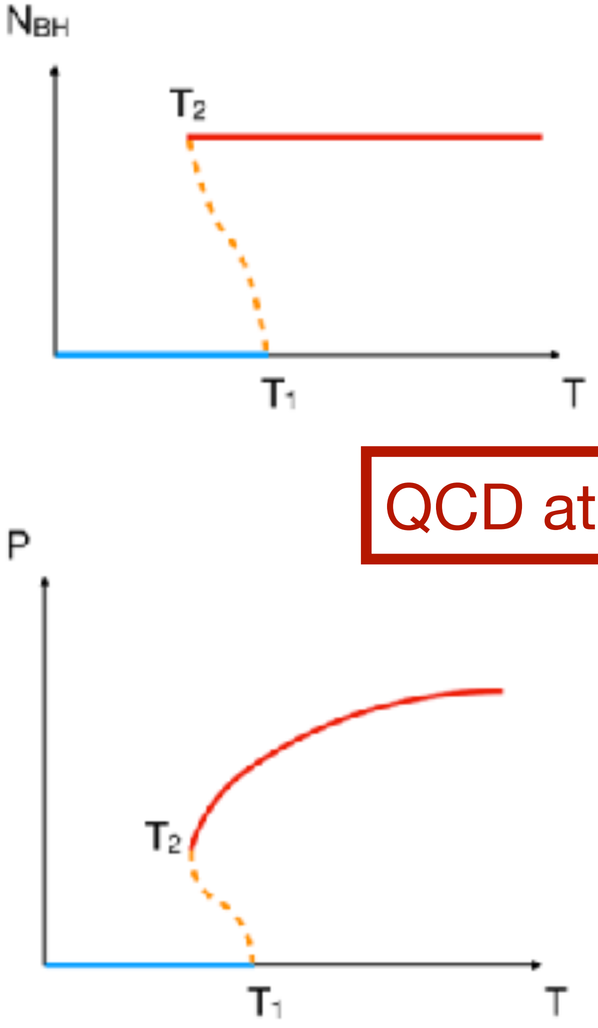




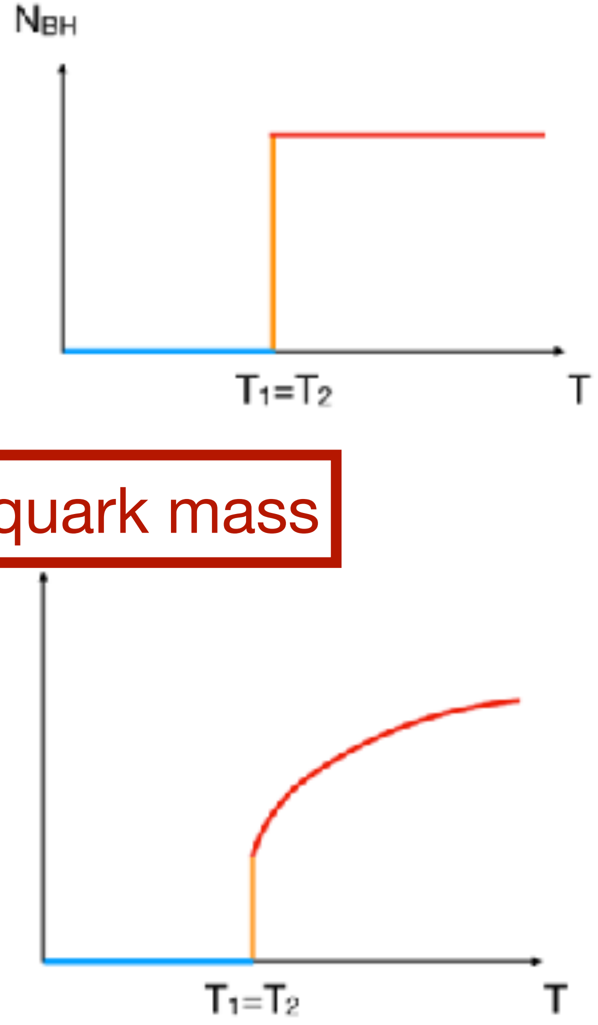
strongly coupled
4d SYM

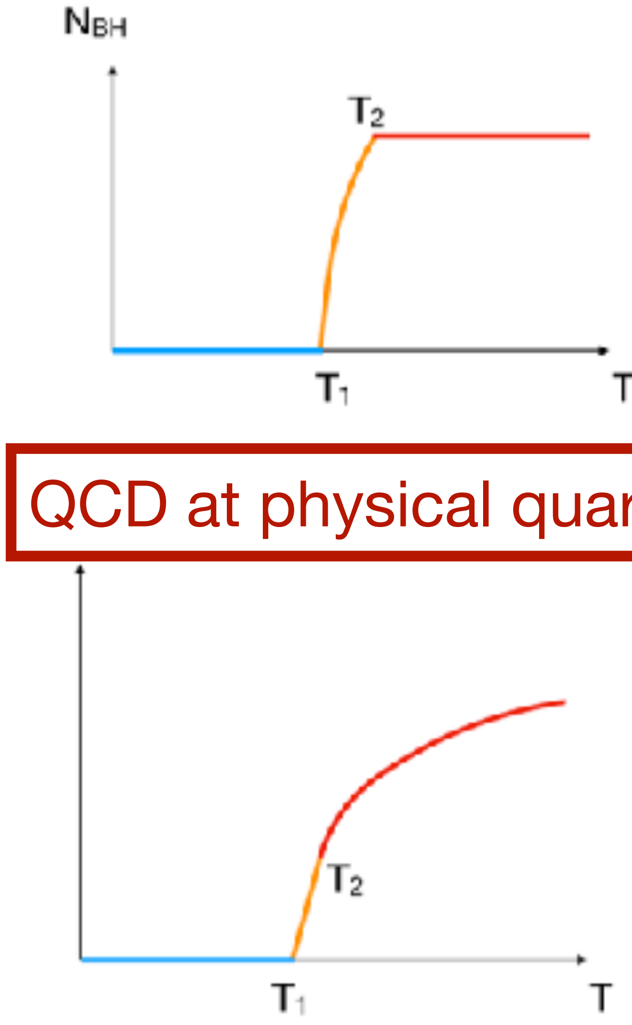


strongly coupled
4d SYM



weakly coupled
4d SYM





QCD at large quark mass

QCD at physical quark mass

- Can explain $E \sim N^2 T^{-7}$ for 4d SYM.

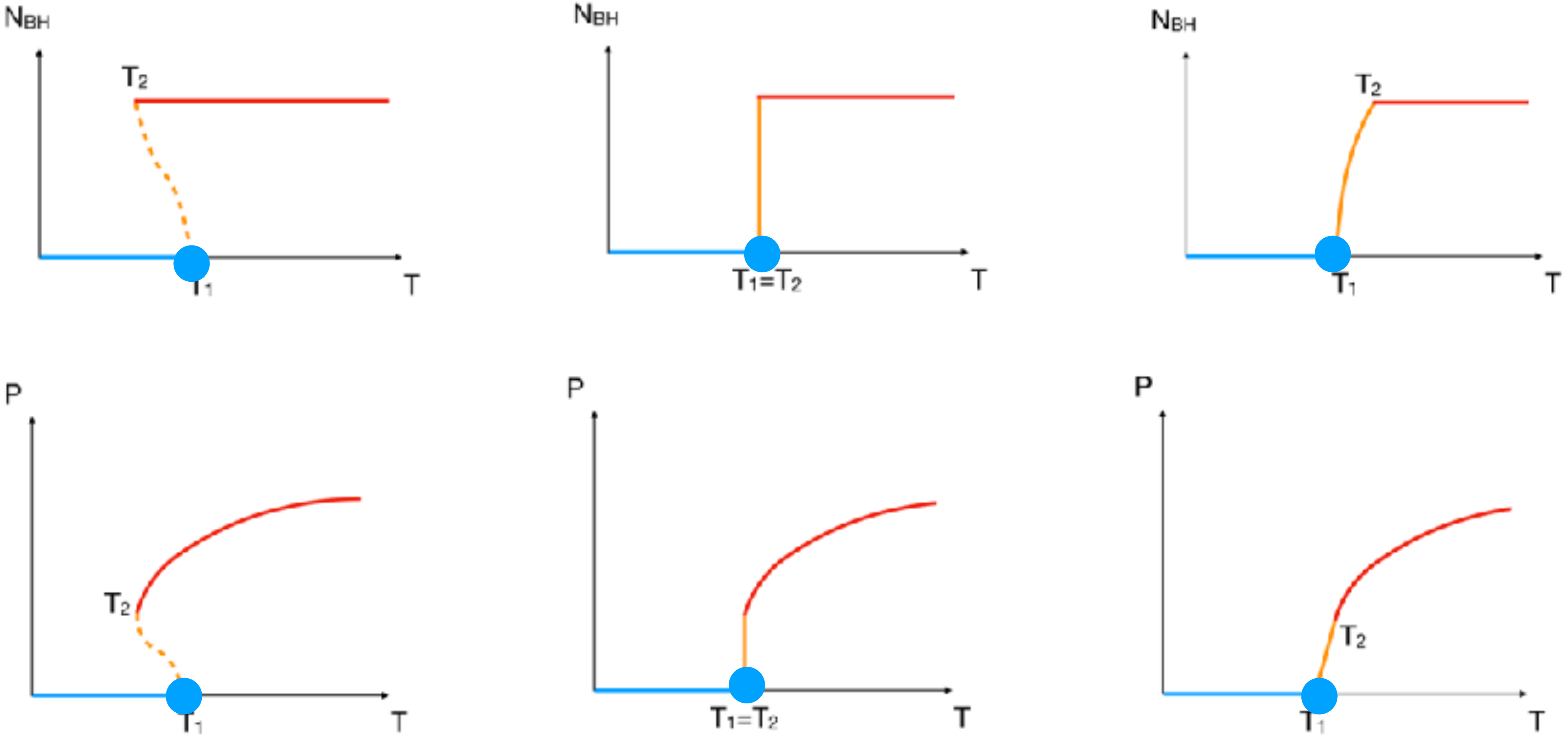
- Various consistency checks, with and without assuming holographic dual.
- Can be proven for some weakly-coupled theories.
- Gauge symmetry gets broken, then restored.

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

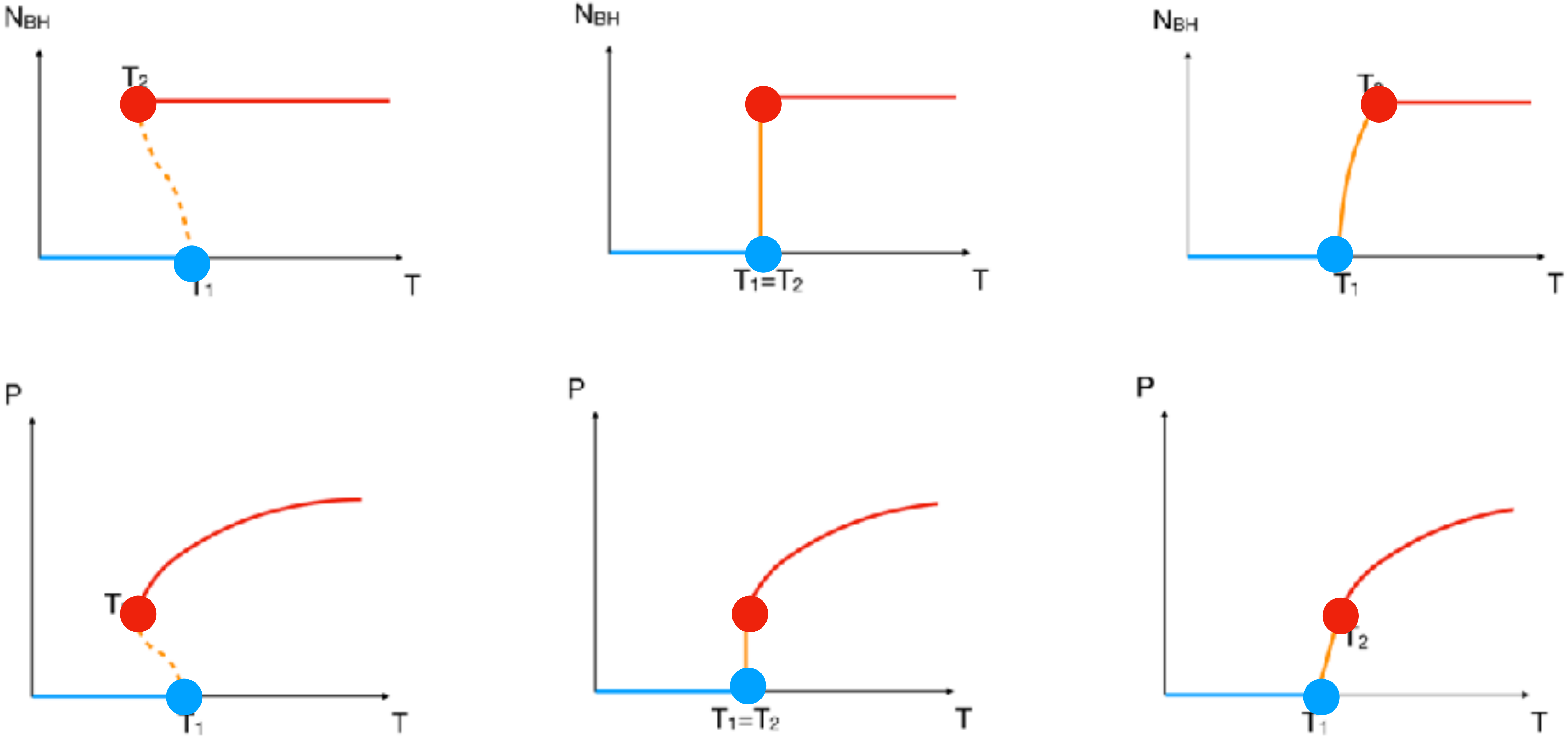
- No need for center symmetry, in order to define 'deconfinement'.
- U(1) deconfinement, SU(2) confinement phase in QCD?

M.H.-Maltz, 2016, JHEP
M.H.-Ishiki-Watanabe, 2018, JHEP
M.H.-Jevicki-Peng-Wintergerst, to appear, hep-th
Evans-M.H.-O'Bannon-Robinson, in progress

(For details and precise meanings, please ask me questions anytime after the talk!)

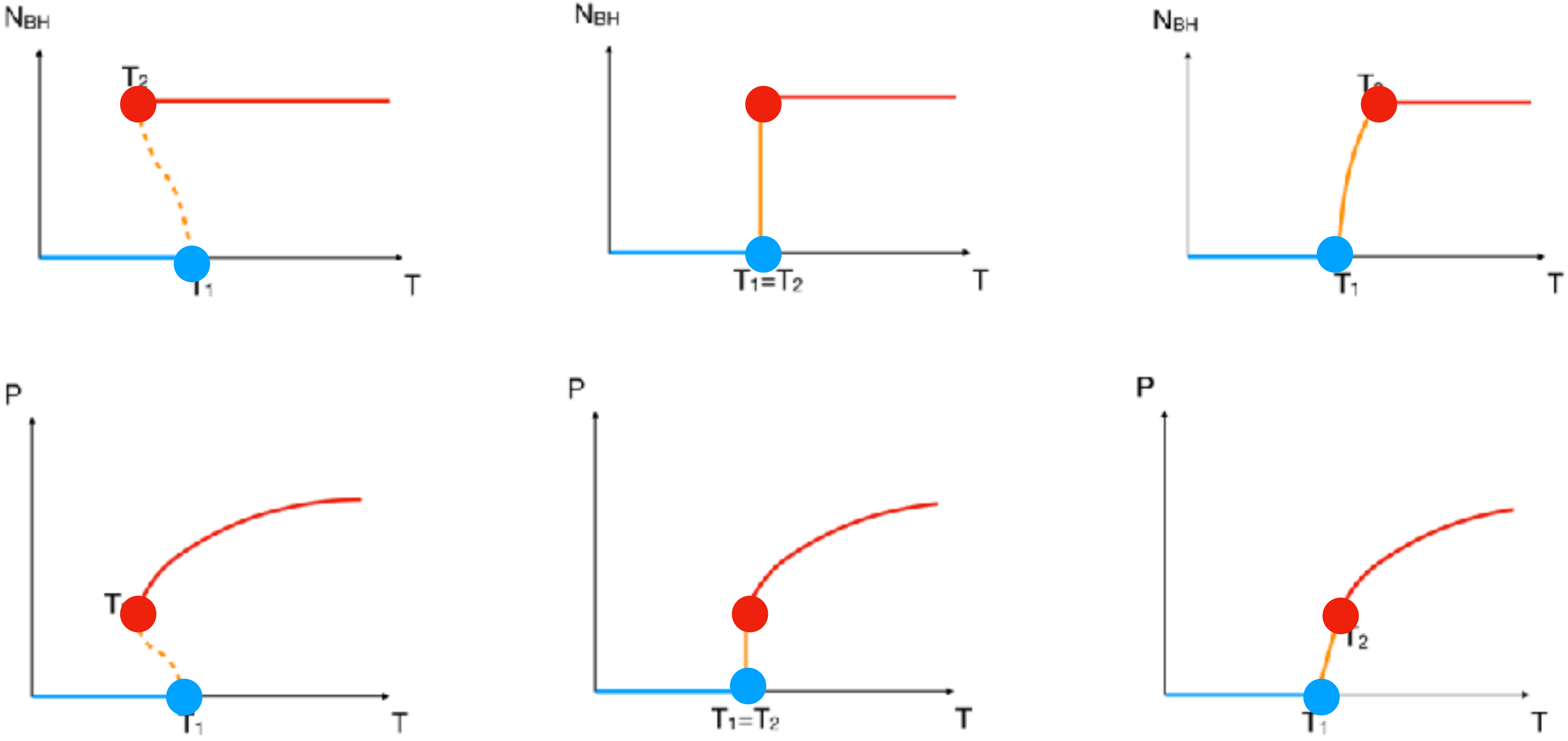


transition 1: confinement to partial deconfinement
(black hole formation begins)



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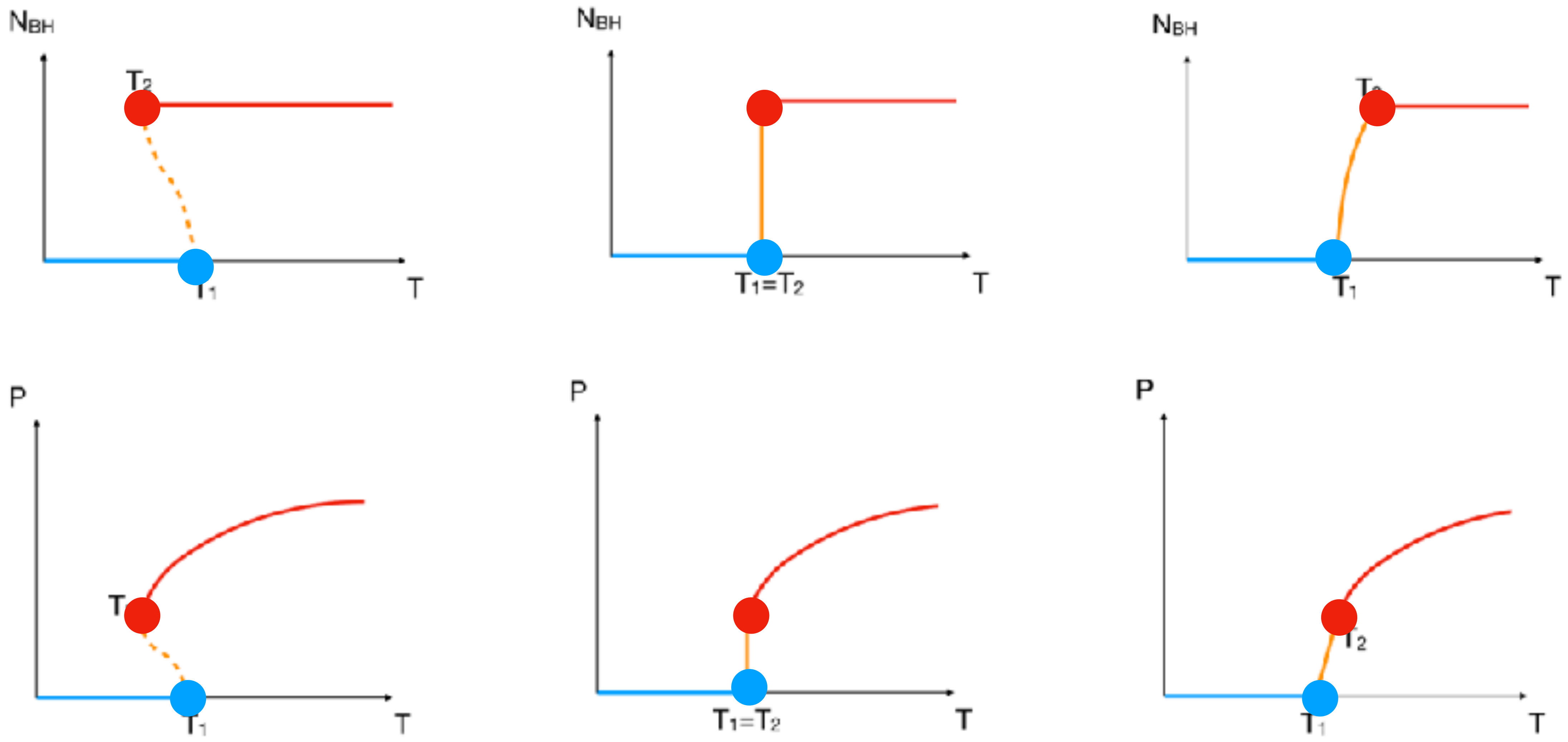
$$\boxed{SU(N) \to SU(M)\times SU(N-M)\times U(1) \to SU(N)}$$



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

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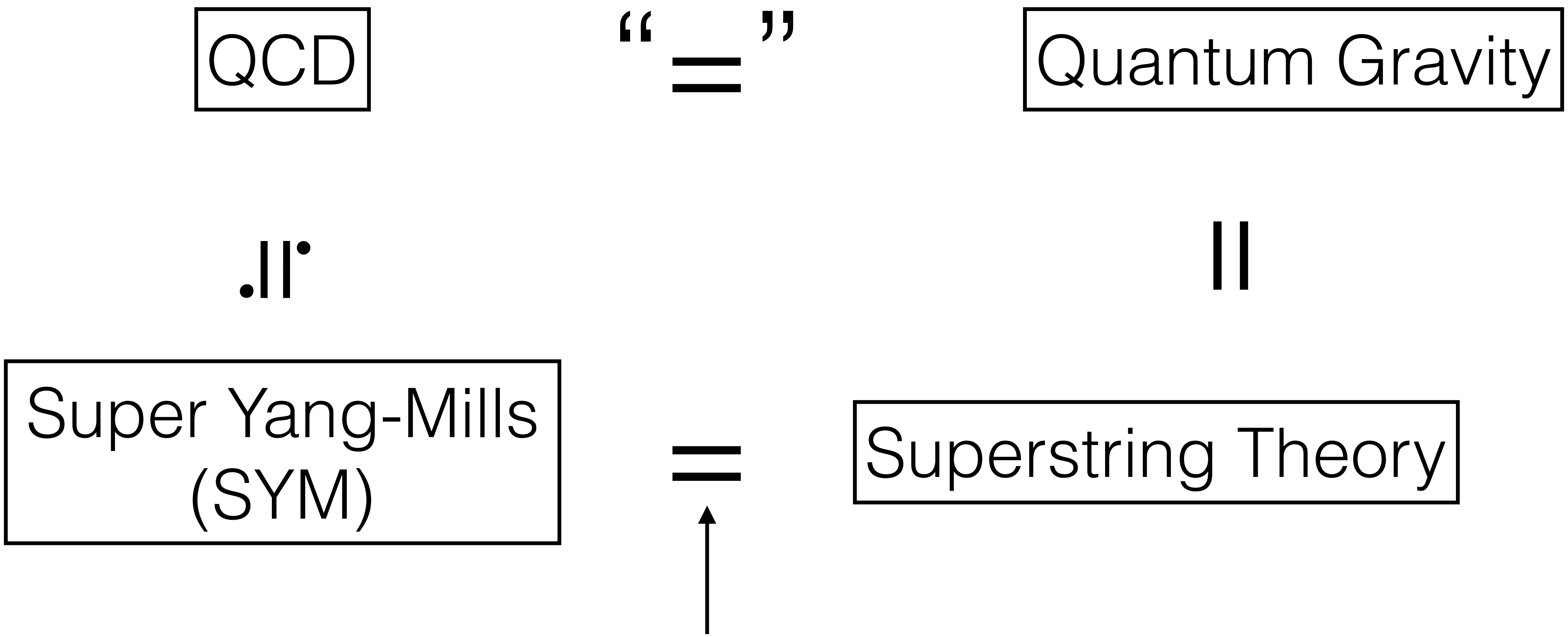
(black hole formation ends)

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

SU(2) confines in QCD → enhanced chiral symmetry → new ‘pion’?

Conclusion



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≒ =

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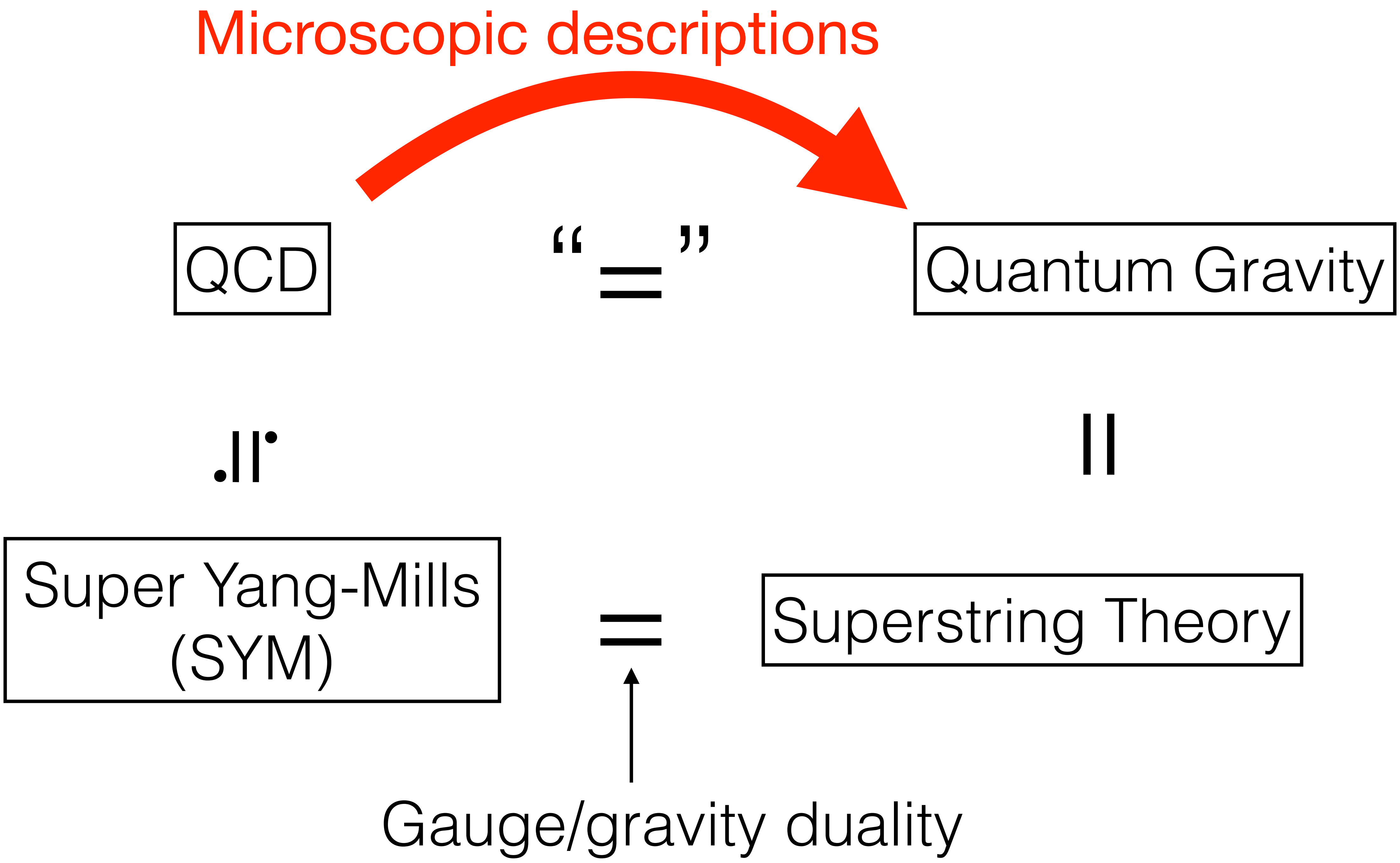


Microscopic descriptions

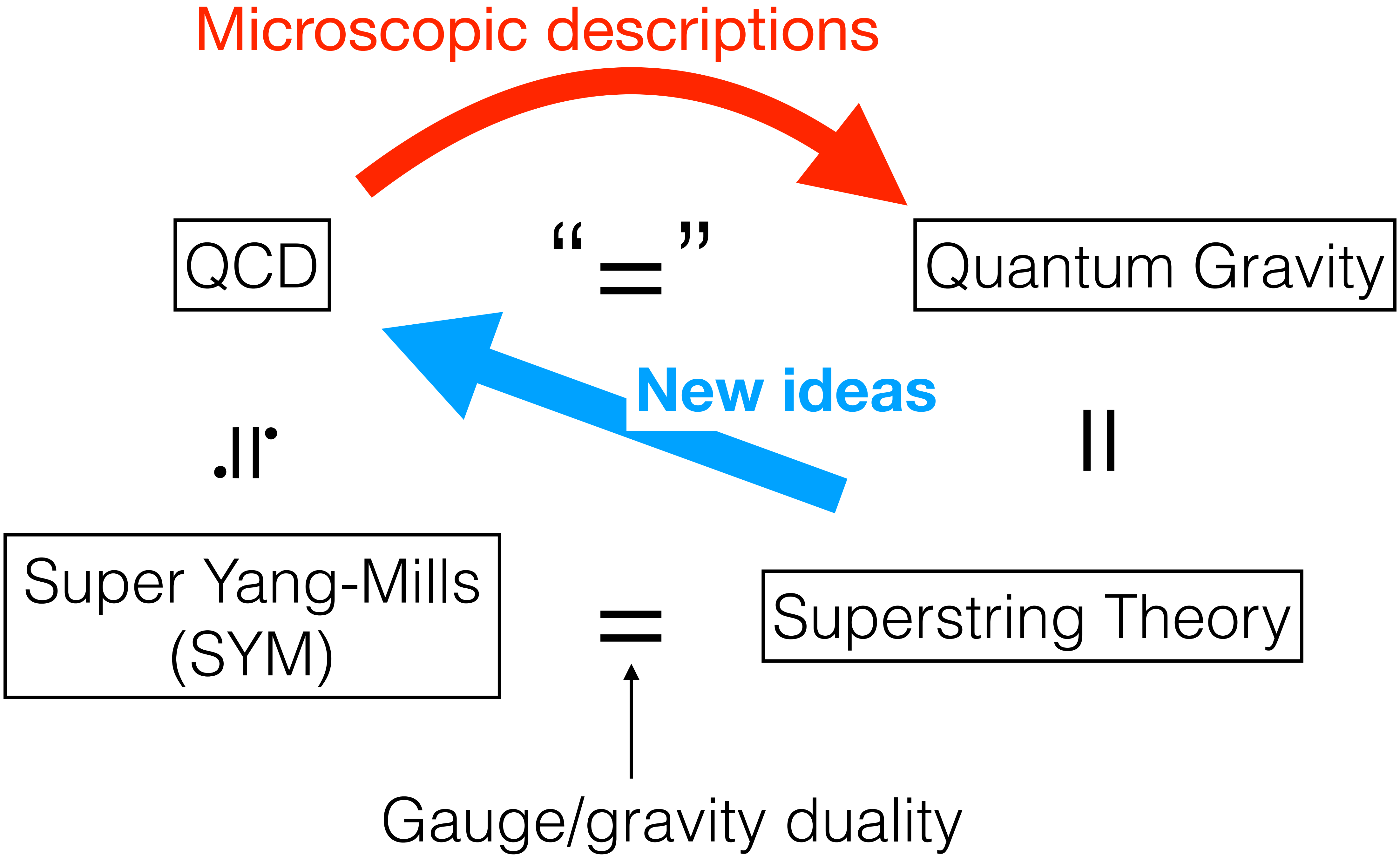
QCD “=” Quantum Gravity

≐ ||

Super Yang-Mills (SYM) = Superstring Theory

Gauge/gravity duality

Conclusion



Microscopic descriptions

QCD “=” Quantum Gravity

New ideas

Super Yang-Mills (SYM) = Superstring Theory

Gauge/gravity duality