# Lattice gauge theory meets quantum gravity

-- the holographic principle at quantum gravity level and the fate of evaporating black hole --


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Anagnostopoulos-M.H.-Nishimura-Takeuchi, PRL2008
M.H.-Hyakutake-Nishimura-Takeuchi, PRL 2009
M.H.-Hyakutake-Ishiki-Nishimura, 1311.5607 [hep-th]

The standard model might be valid
all the way up to Planck scale…

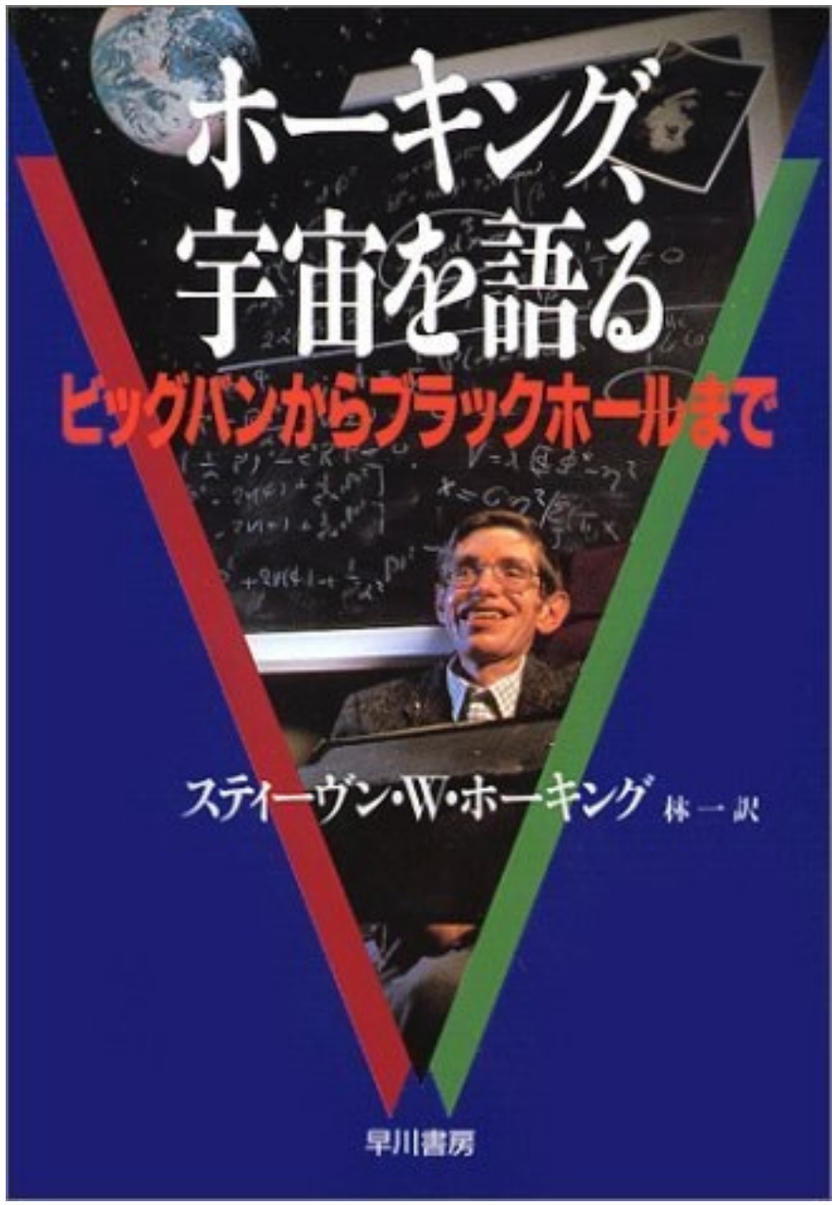
what can lattice do
for learning about physics
at Planck scale?

or, more ambitiously:
is there anything *only* lattice can do?

Lattice can solve important problems in superstring theory, which lead us to the understanding of the quantum nature of gravity.

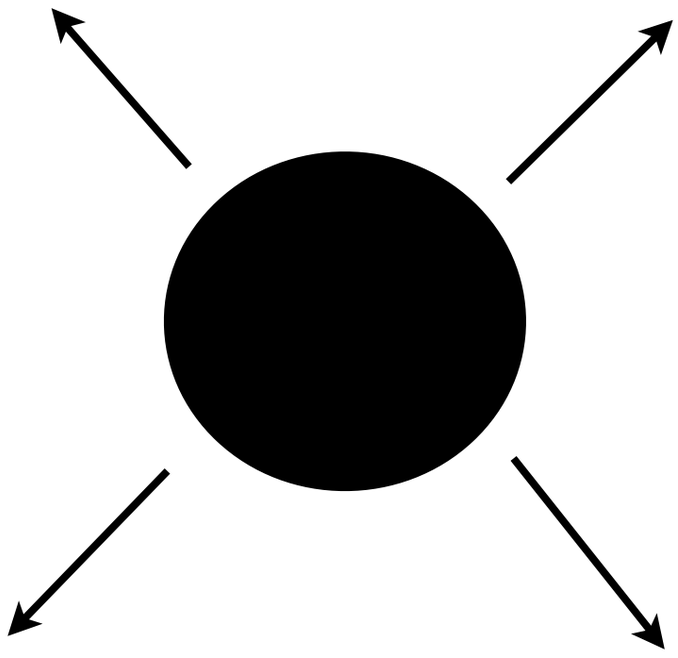
As an example, we consider the quantum nature of the black hole.

*Only lattice can do it!*




# S. Hawking, "A Brief History of Time"

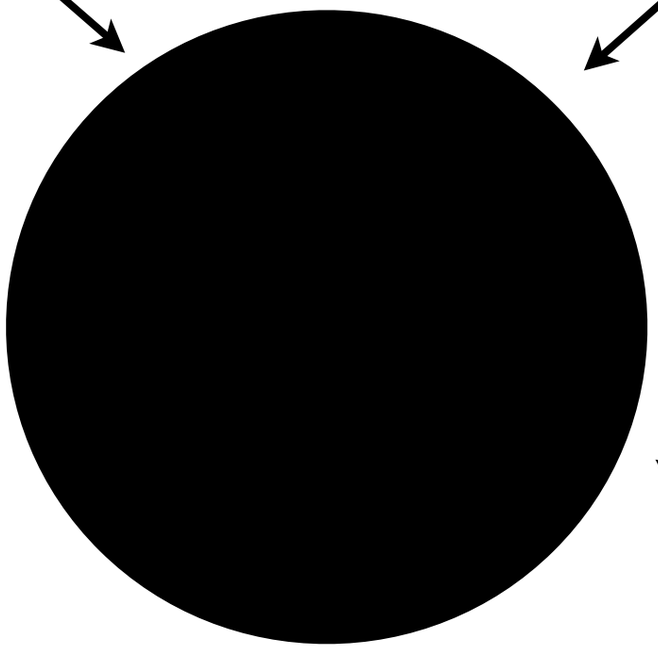
Ch. 1. Our Picture of the Universe
Ch. 2. Space and Time
Ch. 3. The Expanding Universe
Ch. 4. The Uncertainty Principle
Ch. 5. Elementary Particles and the Forces of Nature
Ch. 6. Black Holes
**Ch. 7. Black Holes Ain't So Black**
Ch. 8. The Origin and Fate of the Universe
Ch. 9. The Arrow of Time
Ch. 10. Wormholes and Time Travel
Ch. 11. The Unification of Physics
Ch. 12. Conclusion

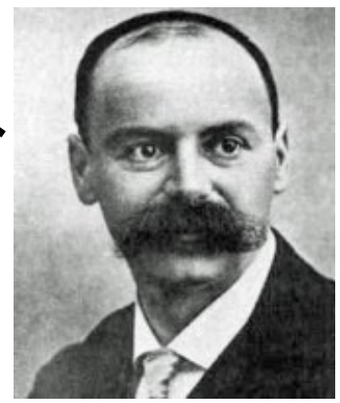


Due to quantum effect, black hole emits particles and evaporates.  (Hawking radiation)

"Black Holes Ain't So Black"

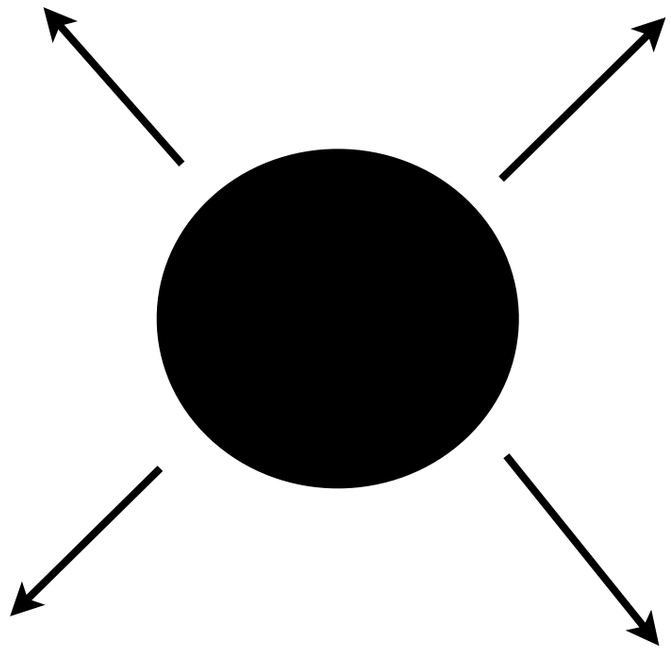
(Hawking, 1974)





Black hole should know who is swallowed.

# Hawking's Information loss paradox



Due to quantum effect, black hole emits particles and evaporates. (Hawking radiation)

"Black Holes Ain't So Black"

But the radiation does not care what is thrown into the black hole; it is always the same black body radiation.

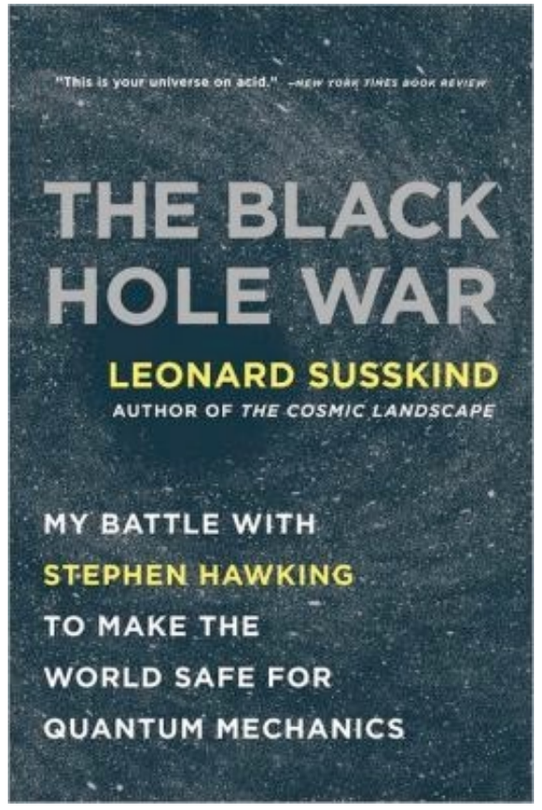
Information is lost!!!

Quantum mechanics must be modified???

(Hawking, 1974)

# The Black Hole War

- Information should be lost when it falls into BH. The Hawking radiation does not carry information.




- Information should not be lost. The Hawking radiation carries information.


v.s.

Maldacena's gauge/gravity duality conjecture, if correct, gives a counter-example.

**string theory on BH background** = *super Yang-Mills*

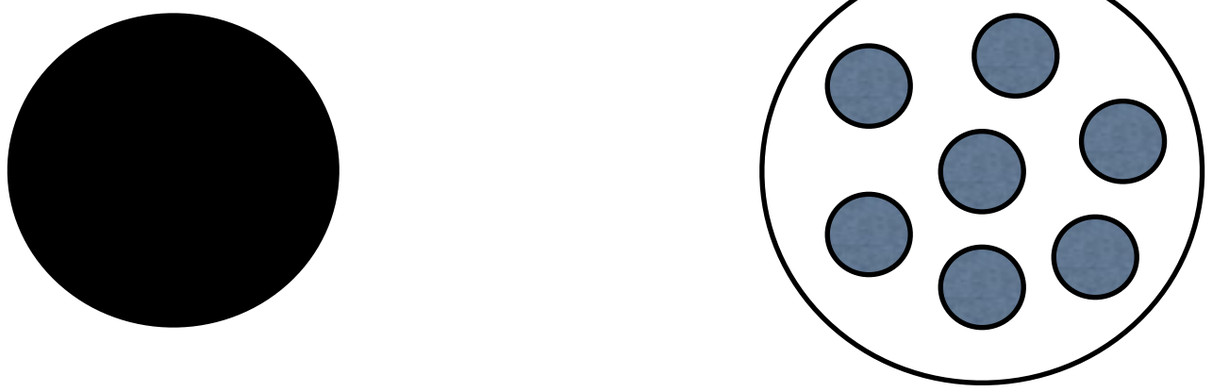
**no information loss**

In this talk I provide you with the first quantitative evidence for the Maldacena conjecture at quantum gravity level, which shows evaporating black hole can really described by gauge theory.

# Gauge theory description of quantum black hole based on the gauge/gravity duality conjecture

Black hole = bunch of D0-branes (D-particles)

( + strings between them)

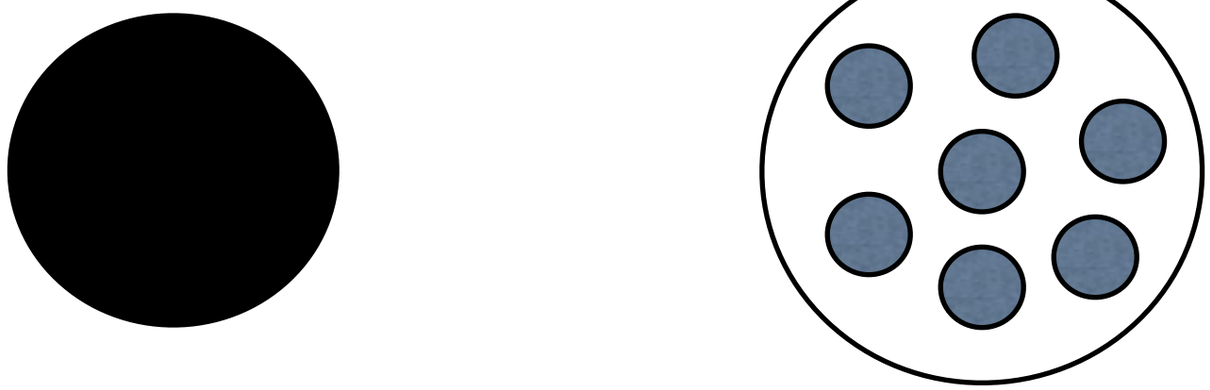


D0-brane : point-like object on which
open string can be attached

low-energy effective theory of D0-branes
= (0+1)-d SYM

Black p-brane = bunch of Dp-branes

( + strings between them)



Dp-brane : (p+1)-d object on which open string can be attached

low-energy effective theory of Dp-branes
= (p+1)-d SYM

# Gauge/gravity duality *conjecture*
(Maldacena 1997)

- SYM is not just an effective theory. It describes full string dynamics near horizon.
- (p+1)-d SYM = type II string around black p-brane

SYM = superstring

# Maldacena, hep-th/9711200

"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."

# 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

Today's goal: show the evidence for the correspondence at stringy level.

# D0-brane quantum mechanics

$$S = \frac{N}{\lambda}\int dt\ Tr\Big\{\frac{1}{2}(D_t X_i)^2 - \frac{1}{4}[X_i, X_j]^2 + \frac{1}{2}\bar{\psi} D_t \psi - \frac{1}{2}\bar{\psi}\gamma^i [X_i, \psi]\Big\}$$

- Dimensional reduction of 4d N=4 (or 10d N=1)
- D0-brane effective action
- Matrix model of M-theory (Banks-Fishler-Shenker-Susskind, 1996 de Wit-Hoppe-Nicolai, 1988)
- gauge/gravity duality →dual to black 0-brane

Simple but can be even more interesting than $AdS_5/CFT_4$ from string theory point of view!

# Confirmation at *classical* string level

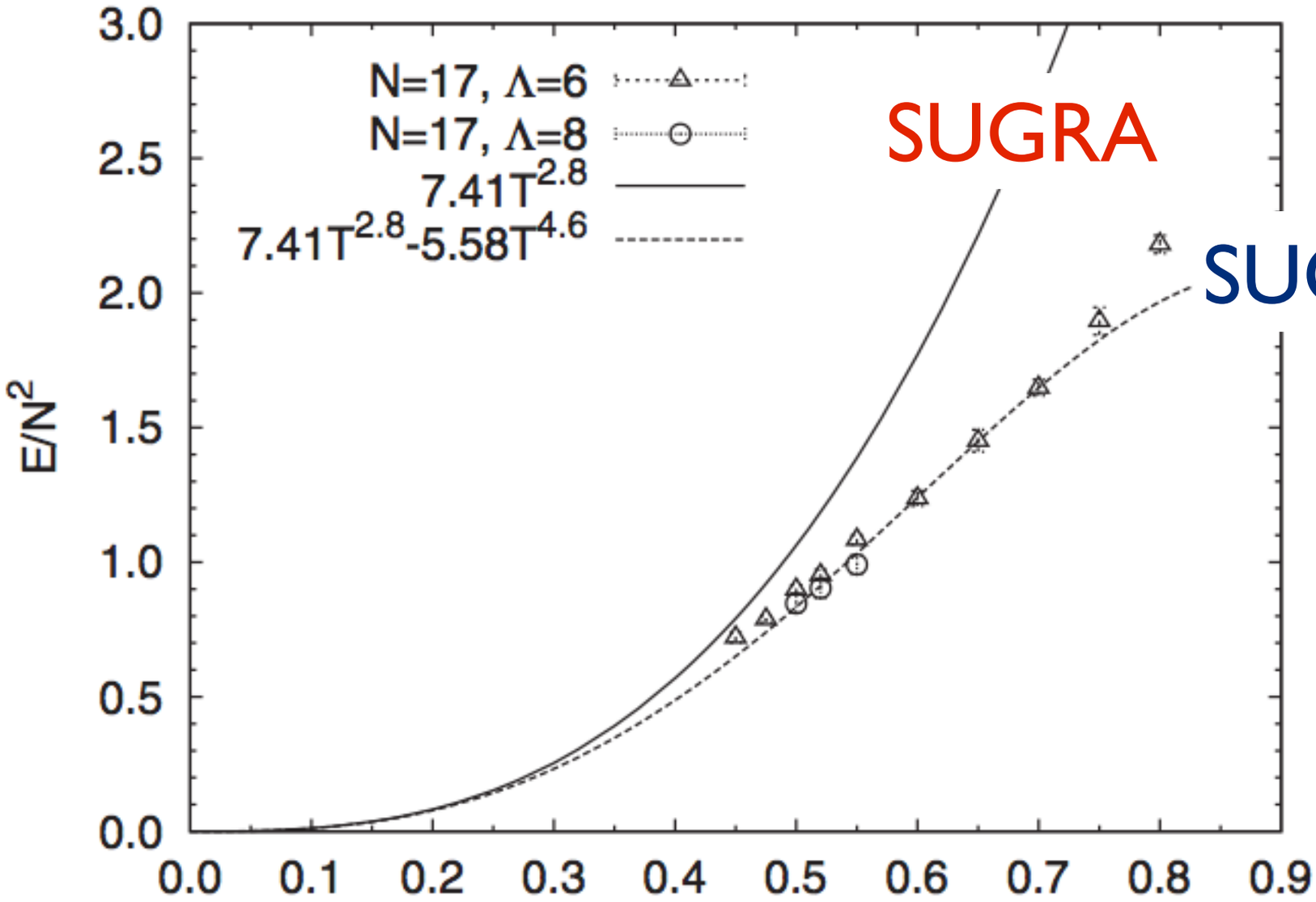
# BH mass vs energy density

$$E_{D0} = \frac{9}{2^{11}\pi^{\frac{13}{2}}\Gamma(\frac{9}{2})\lambda^2} N^2 U_0^7$$

$$\frac{1}{N^2} E_{D0} \sim 7.4\, T^{2.8} \quad (\lambda = 1)$$

at large-N & low temperature (strong coupling)

($\lambda^{-1/3}T$ : dimensionless effective temperature)




SUGRA

SUGRA+α'

low temp = strong coupling

high temp = weak coupling

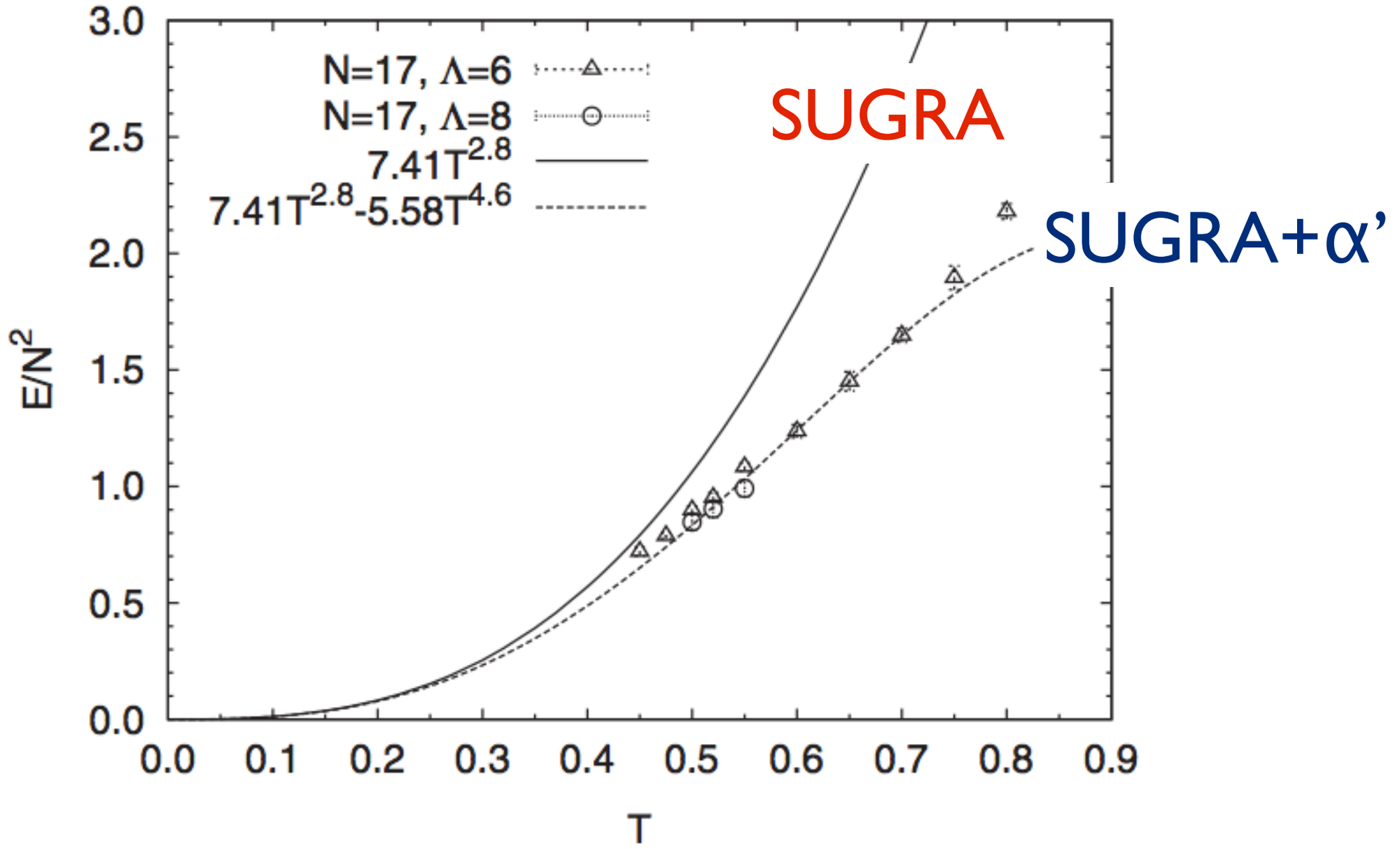
Anagnostopoulos-M.H.-Nishimura-Takeuchi, PRL 2008
M.H.-Hyakutake-Nishimura-Takeuchi, PRL 2009

# α' correction

- deviation from the strong coupling (low temperature) corresponds to the α' correction (classical stringy effect).
- The α' correction to SUGRA starts from $(\alpha')^3$ order
- Correction to the BH mass : $(\alpha'/R^2)^3 \sim T^{1.8}$
- $E/N^2=7.41T^{2.8} - 5.58T^{4.6}$

(4.6 = 2.8 + 1.8)
prediction by string

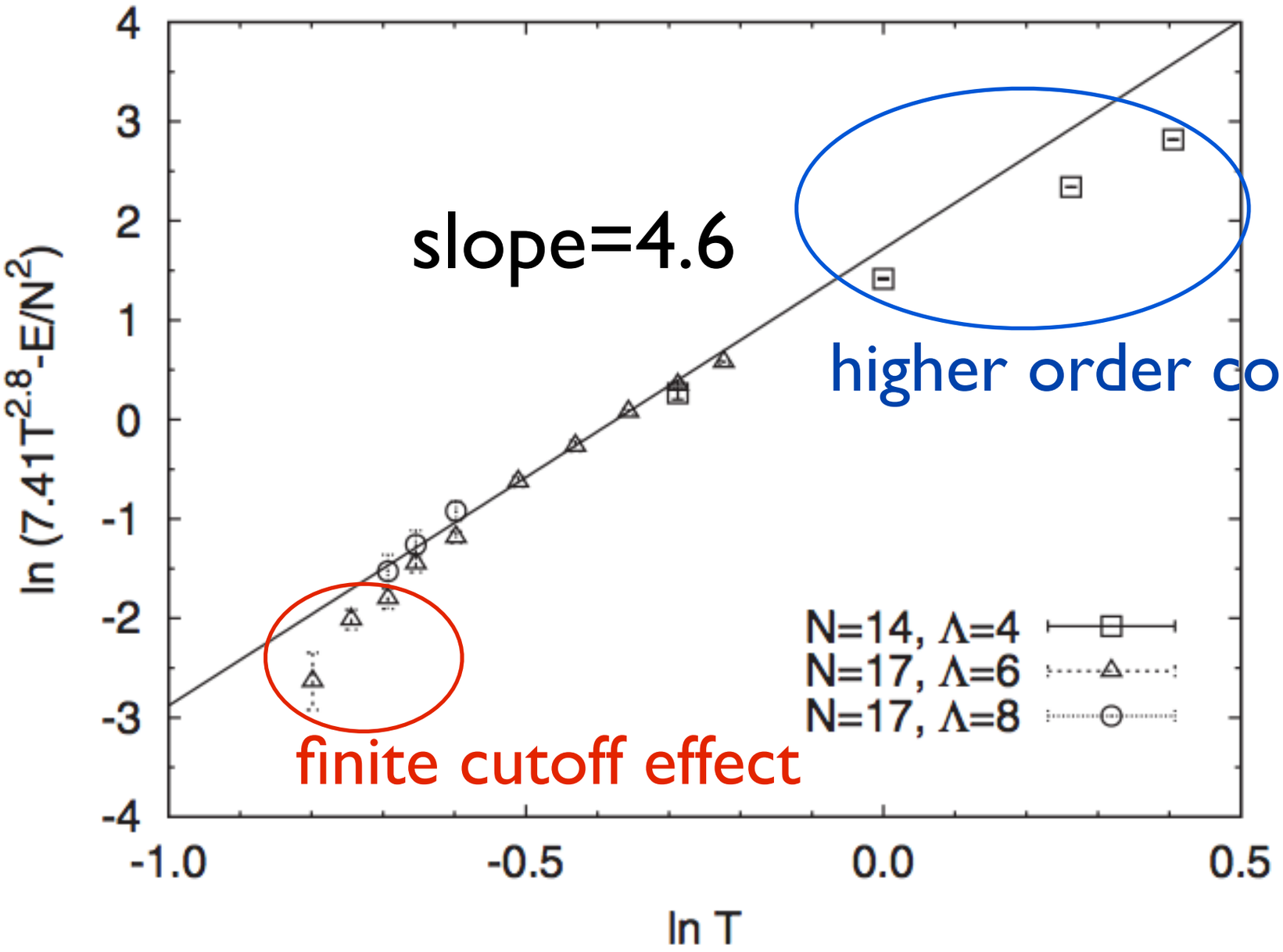
'prediction' by SYM simulation




SUGRA

SUGRA+α'

M.H.-Hyakutake-Nishimura-Takeuchi, PRL 2009




M.H.-Hyakutake-Nishimura-Takeuchi, PRL 2009

# Confirmation at *quantum* string level

# $g_s$ correction

$$E/N^2 = 7.41T^{2.8} - 5.58T^{4.6}+....$$

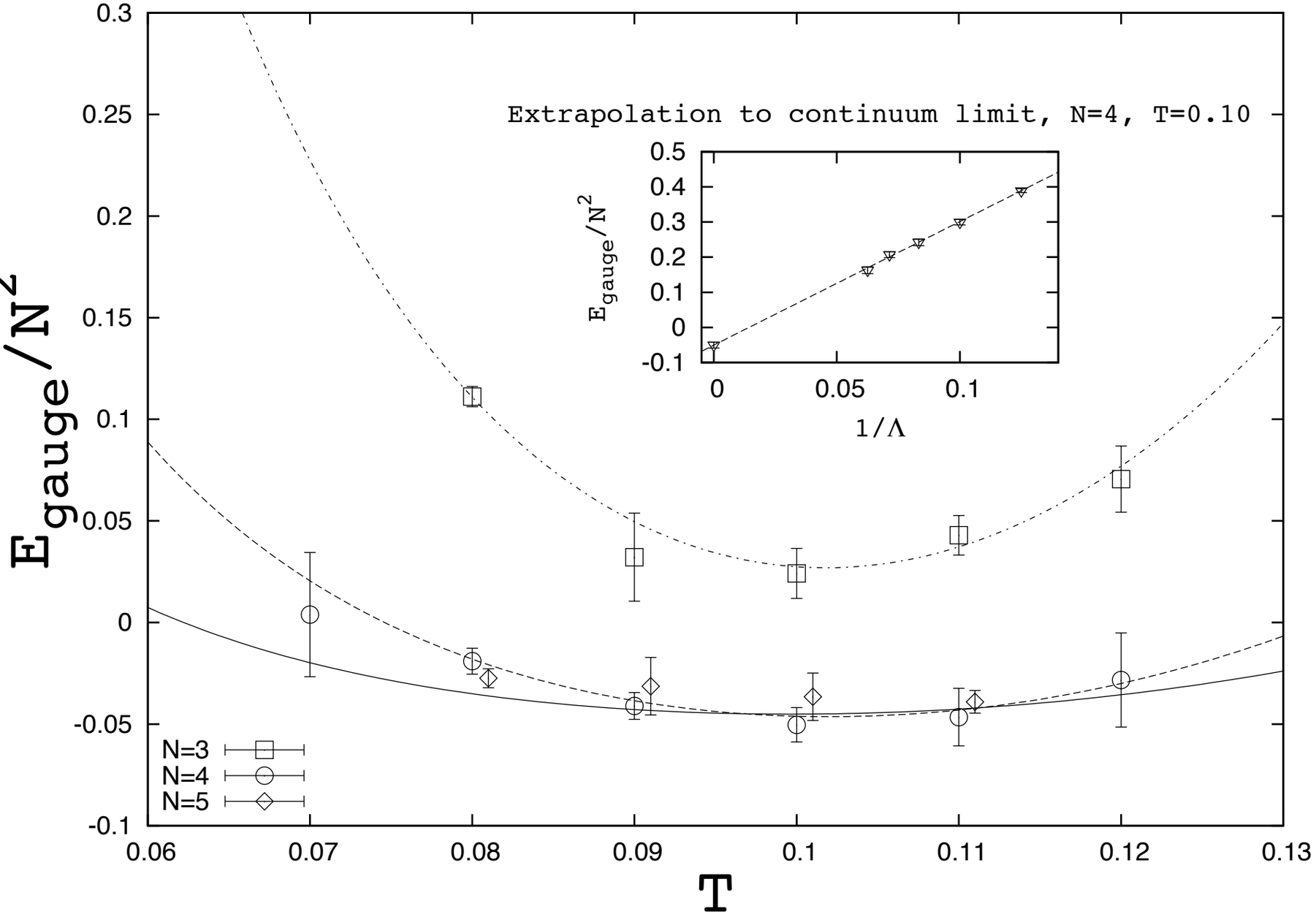
$$+(1/N^2)(-5.77T^{0.4}+aT^{2.2}+...)$$

$$+(1/N^4)(bT^{-2.6}+cT^{-2.0}+...)$$

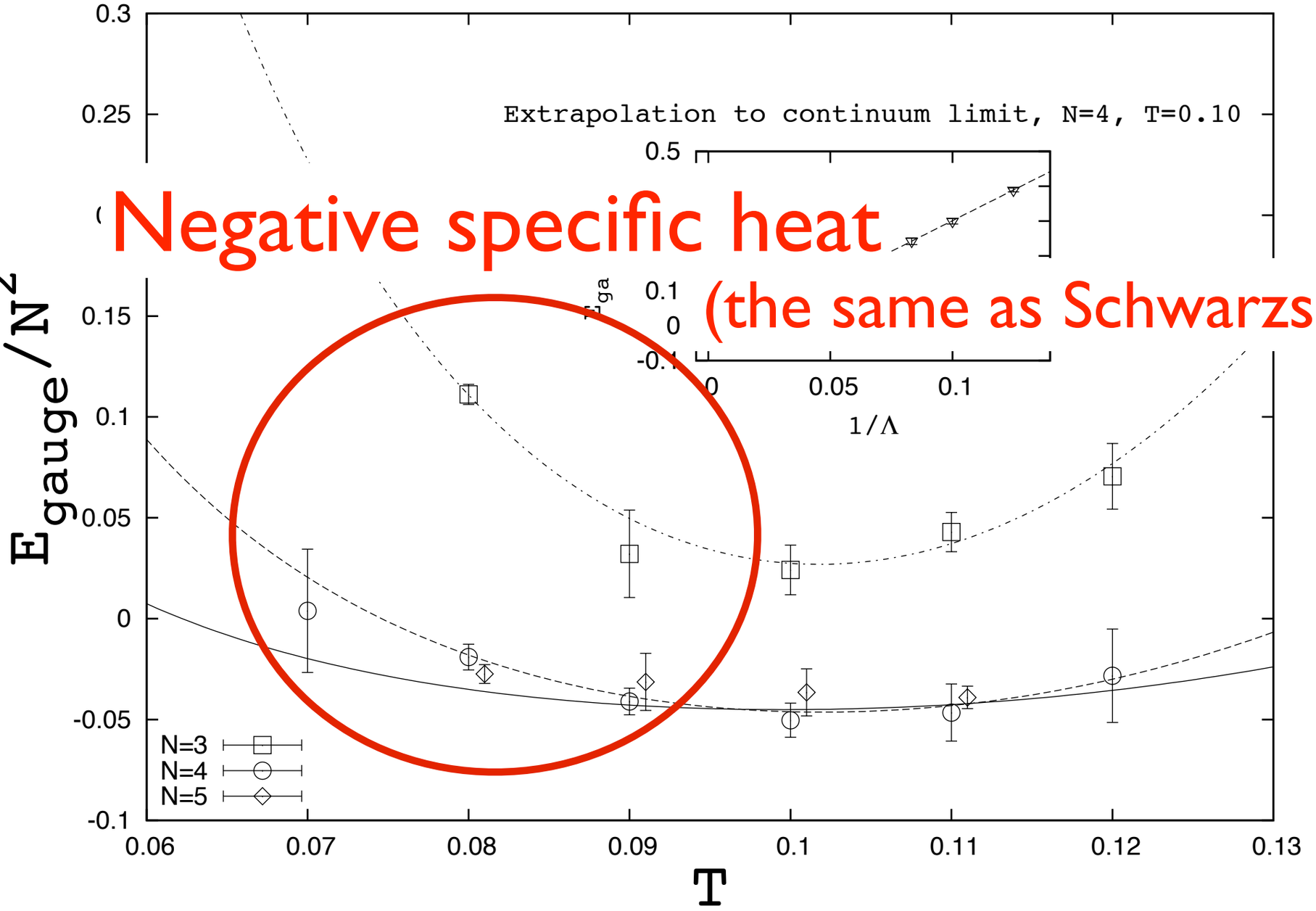
$$+.....$$

(Y. Hyakutake 2013)

Can we observe it in SYM ?




M.H.-Hyakutake-Ishiki-Nishimura, 2013.

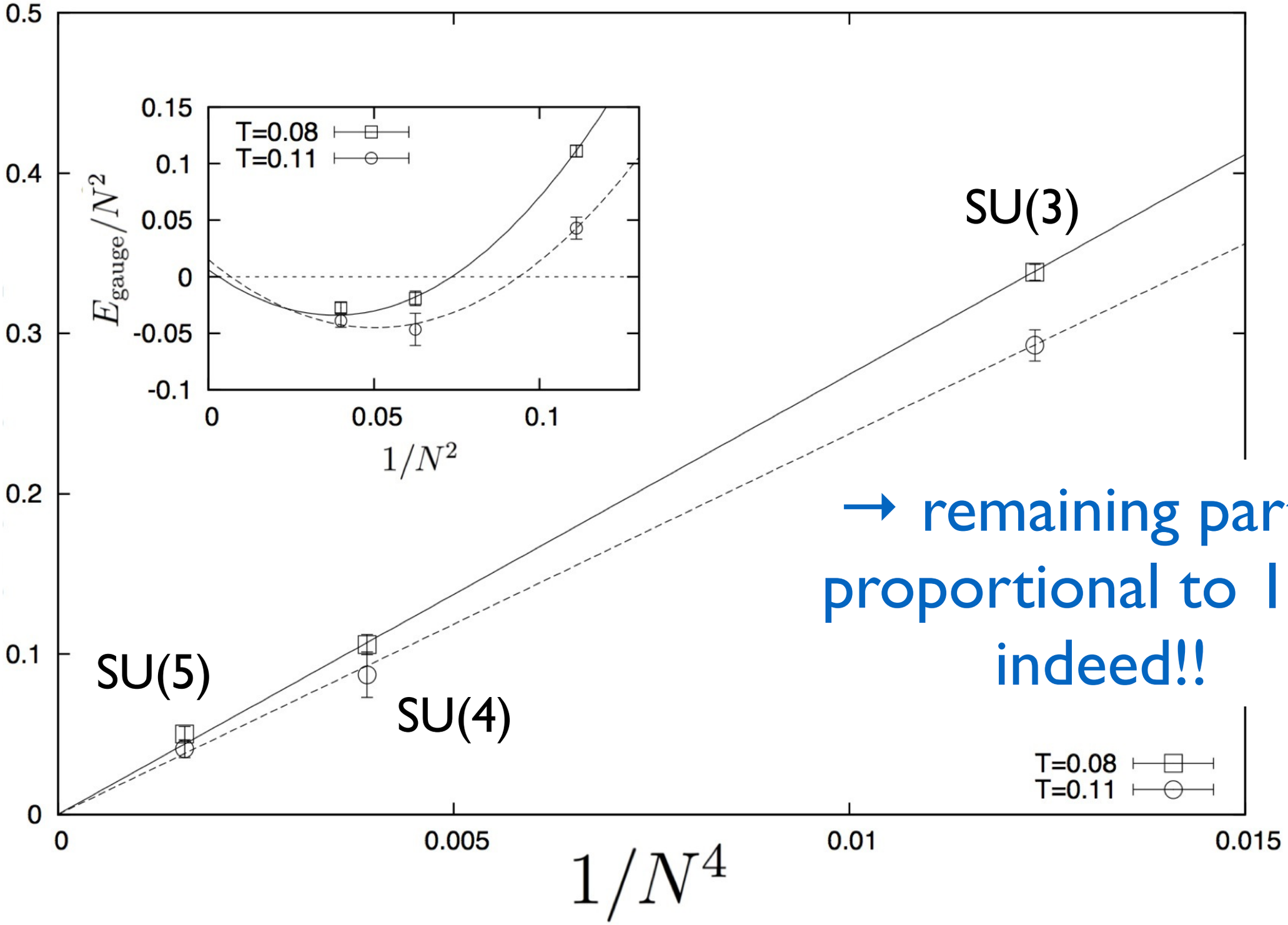



# Negative specific heat

# (the same as Schwarzschild BH)

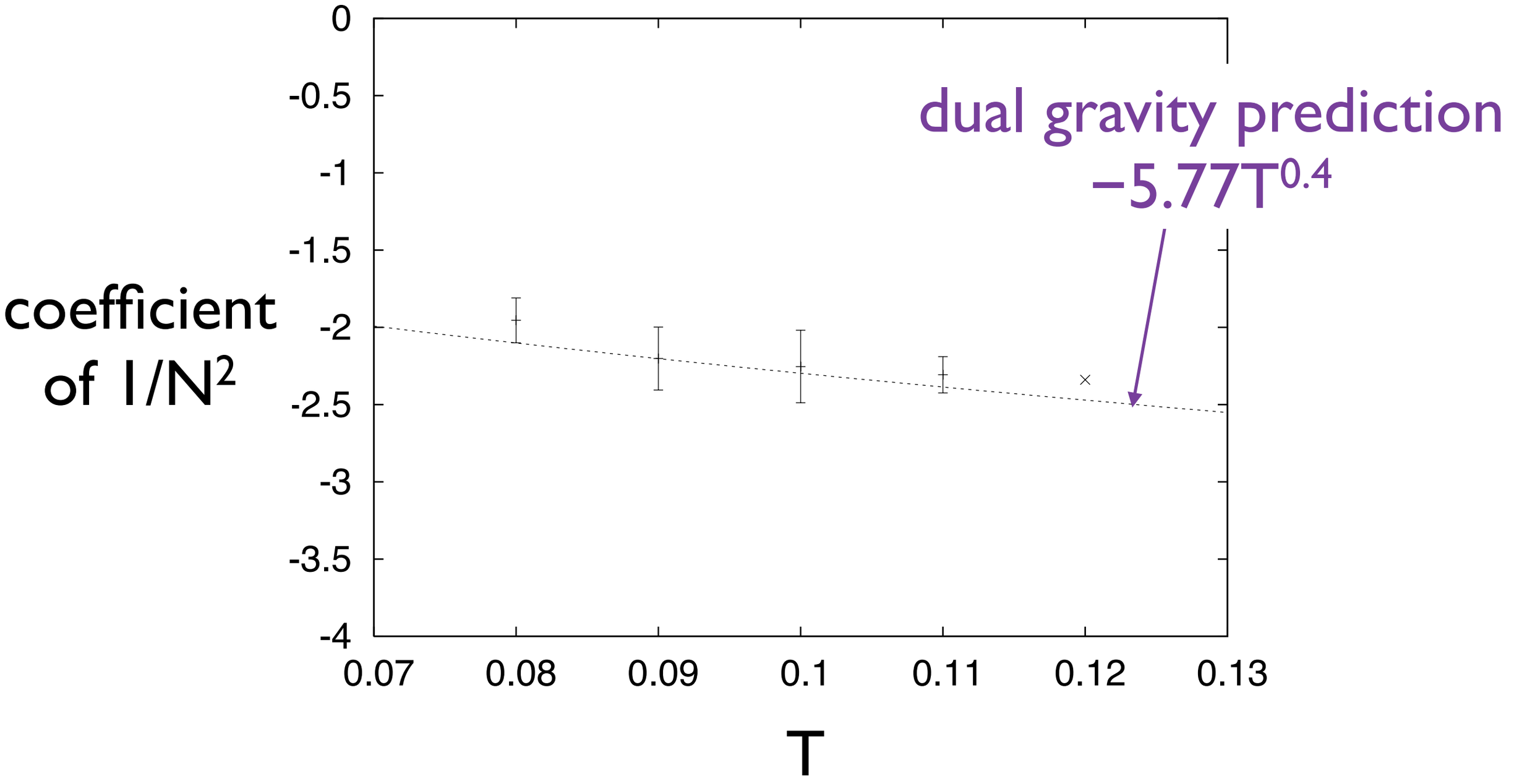
M.H.-Hyakutake-Ishiki-Nishimura, 2013.

# $E/N^2 - (7.41T^{2.8} - 5.76T^{0.4}/N^2)$ vs. $1/N^4$




→ remaining part is proportional to $1/N^4$ indeed!!

M.H.-Hyakutake-Ishiki-Nishimura, 2013.




M.H.-Hyakutake-Ishiki-Nishimura, 2013 ( + more data )

# Conclusion

String Theory
Quantum
Gravity

Lattice
Gauge
Theory

(Super)
Yang-Mills


Quantum
Gravity

- Monte Carlo is a useful tool to study SYM.

*computer simulation of quantum gravity.*

- Sign problem? No problem. (not explained today)
- 1d : detailed studies which support the correctness of the gauge/gravity duality at finite-N vs quantum string level. Should be useful to understand how information comes back.

- 2d : Catterall-Joseph-Wiseman(2008), Buchoff-M.H.-Matsuura (in progress)
- 4d N=4 : Catterall-DeGrand-Damgaard-Mehta (2012), Honda-Ishiki-Kim-Nishimura-Tsuchiya (2013), …
- For SUSY QCD, new ideas are needed.

(not explained today)