Black Hole Evaporation and Emergent Geometry from Gauge Theory

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Berkowitz, M.H., Maltz (1603.03055[hep-th], 1602.01473[hep-th])
+ Monte Carlo String/M-theory collaboration, 1606.*****
+ work in progress + some old papers

Gauge difficult

(supersymmetric gauge theory)

Gravity

(superstring/M-theory)

Large-N,
strong coupling

←

Einstein Gravity
easier

Valuable tool to study strongly
coupled dynamics of gauge theory.

but this in only a half of the story…

Gauge$_{\text{difficult}}$ Gravity

(supersymmetric gauge theory) (superstring/M-theory)

Large-N, strong coupling ← Einstein Gravity easier

Large-N, finite coupling → Tree-level String (Finite string size) more difficult

Finite-N, finite coupling → Quantum String (Virtual string loops) very difficult

This direction is also important!

Gauge $_{\text{difficult}}$

(supersymmetric gauge theory)

Gravity

(superstring/M-theory)

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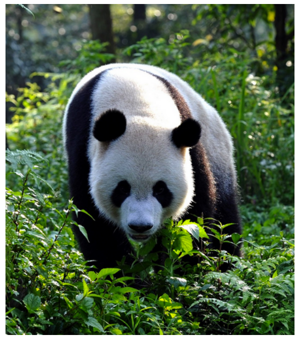

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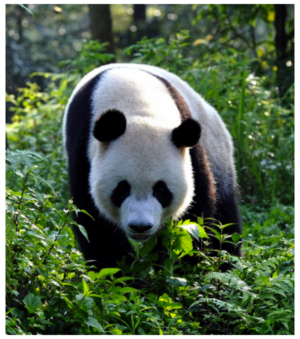

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嵯峨野竹林の道

This direction is also important!

Plan

- Updates on Monte Carlo study of SYM (imaginary time)

  (Monte Carlo String/M-theory Collaboration (MCSMC), 1606.*****)

  Give strong(est) evidence that gauge theory describes quantum gravity.

- Black hole evaporation *from gauge theory* (Berkowitz-M.H.-Maltz, 2016)

  A concrete counter-example to information loss.

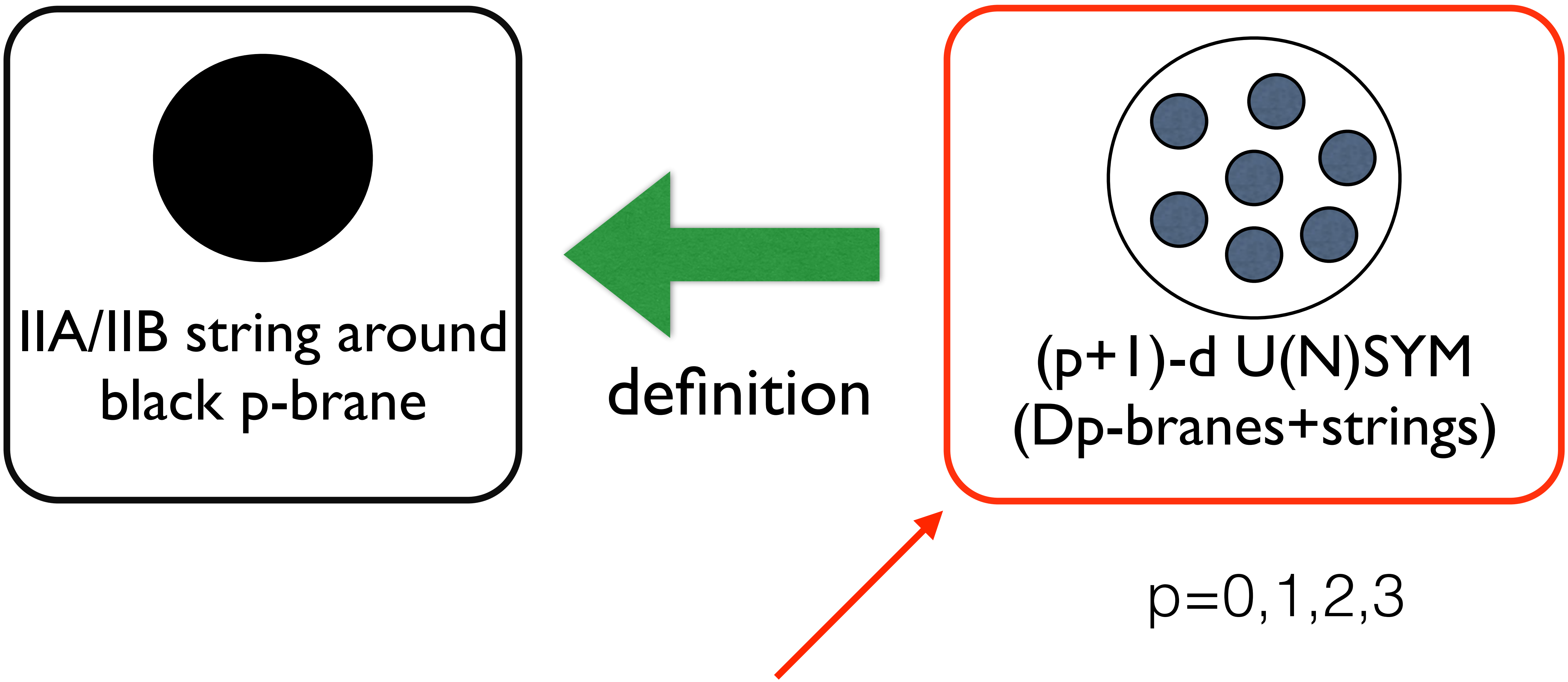
  (Precise meaning will be explained)

- Black hole geometry *from gauge theory* (Berkowitz-M.H.-Maltz, 2016)

  (Berkowitz, Gur-Ari, M.H., Maltz, Rinaldi, Vranas, 1607.*****)

  Explain how BH horizon can emerge *from gauge theory*.

Gauge/Gravity Duality



It is not very different from QCD.

Why don't we work with lattice QCD experts?

technical jargon: “fine tuning free formulation”

black hole ⟷ (0+1)-d SUSY gauge theory

Anagnostopoulos, M.H. ,Nishimura, Takeuchi, 2007
Catterall, Wiseman, 2008
Kadoh, Kamata 2015; Filev, O’cconer 2015

black string ⟷ (1+1)-d SUSY gauge theory

Cohen, Kaplan, Katz, Unsal; Sugino; Catterall 2002 — 2005

OK to all order in perturbation

Catterall, Giedt, 2005 — 2010 Fails at nonperturvative level?

M.H., Kanamori, 2010 OK at nonperturvative level

Further simulations: Kanamori, Sugino, Suzuki, 2010;
Catterall, Joseph, Wiseman, 2010; Kadoh, Kamata, 2015—; …

AdS_5 ⟷ (3+1)-d SUSY gauge theory

M.H., 2010; M.H., Matsuura, Sugino, 2011

O(a)-improved action: M.H., Kadoh, Matsuura, Sugino, in preparation.

(Simulation with fine tuning: Catterall, Damgaard, Degrand, Schaich, 2012 —)

- Coding is complicated but all you need is love for string theory. (Lennon-McCartney, 1967; Bonham-Dixon-Jones-Page-Plant, 1969)
- Even if you don’t have much love, you can still download a code from https://sites.google.com/site/hanadamasanori/home/mmmm

BFSS/BMN matrix models

N=2 ∼ 128 or 256 (maybe 512)

2 ∼ O(10^4) cores

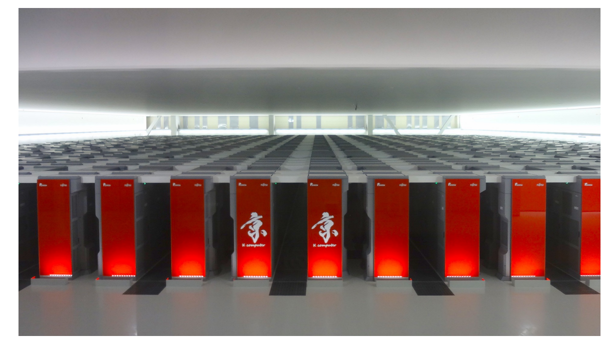
10d/11d BH, M2, M5….

Codes for 2d & 4d SYM will also be available soon.

Monte Carlo String/M-theory Collaboration (MCSMC)

Main target: quantum nature of black hole

Evan Berkowitz (LLNL)
M. H. (Kyoto U./Stanford U.)
Goro Ishiki (U. of Tsukuba)
So Matsuura (Keio U.)
Enrico Rinaldi (LLNL)
Shinji Shimasaki (Keio U.)
Pavlos Vranas (LLNL)



K-supercomputer
(RIKEN, Kobe, Japan)

4th
in TOP500
(1st in 2011)

Vulcan
(LLNL, Livermore, USA)

12th
in TOP500

Enrico Rinaldi

Evan Berkowitz

D0-brane quantum mechanics

$$S = \frac{N}{\lambda}\int_0^{\beta=1/T} dt\, Tr\Big\{\frac{1}{2}(D_t X_i)^2 - \frac{1}{4}[X_i, X_j]^2 + \frac{1}{2}\bar{\psi} D_t \psi - \frac{1}{2}\bar{\psi}\gamma^i [X_i, \psi]\Big\}$$

(dimensional reduction of 4d N=4 SYM)

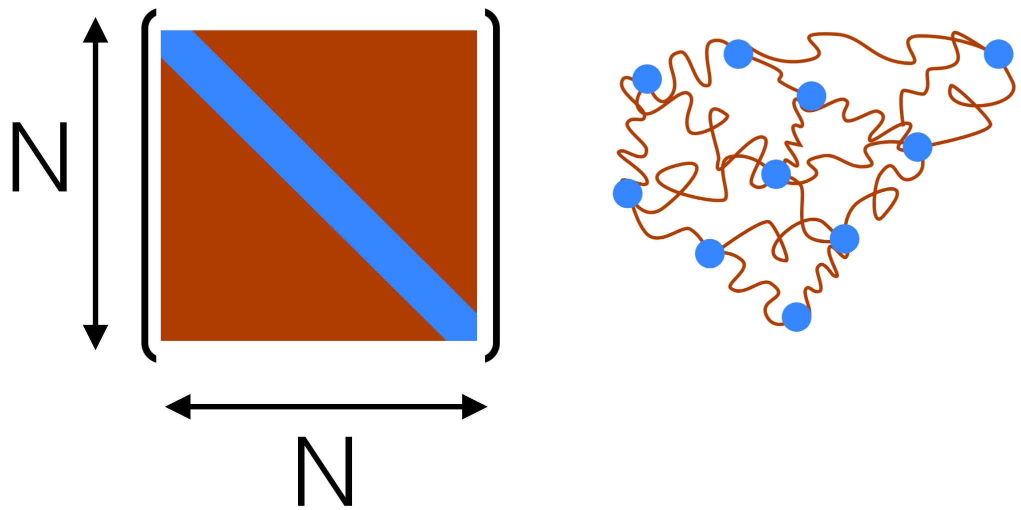
It should reproduce thermodynamics of black 0-brane.

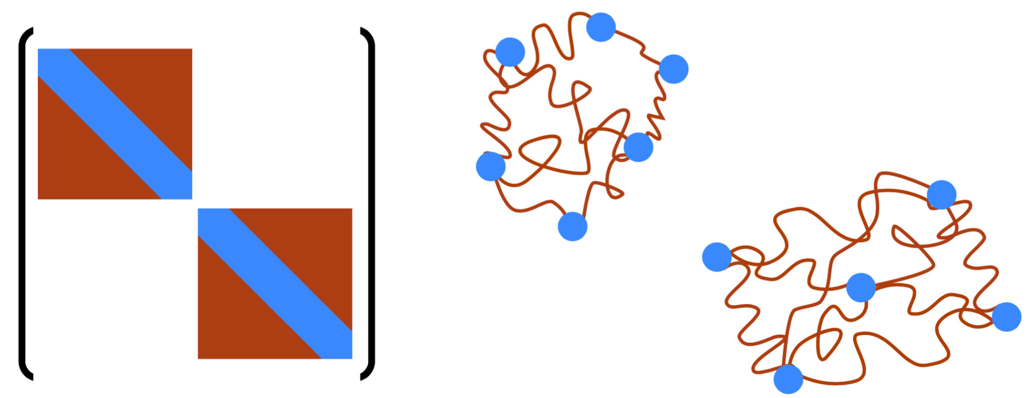
effective dimensionless temperature $T_{eff} = \lambda^{-1/3} T$

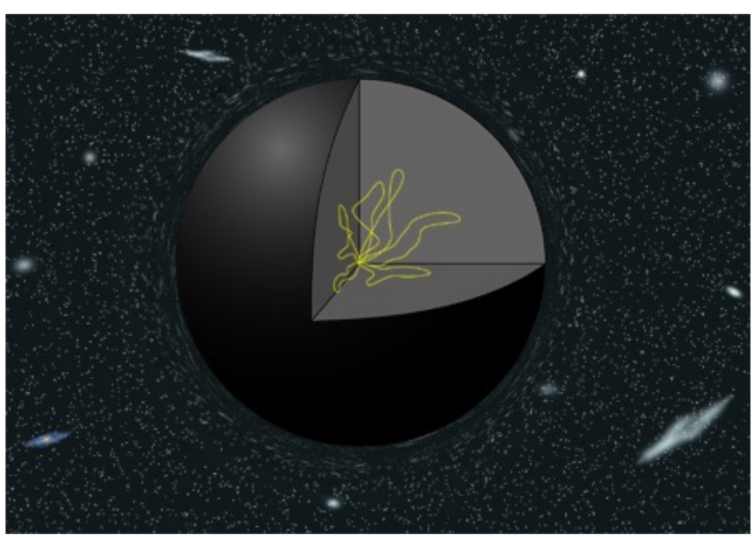
high-T = weak coupling = stringy (large α' correction)

Gauge theory description of a black hole (D0-brane quantum mechanics)

(Banks, Fischler, Shenker, Susskind 1996; Itzhaki, Maldacena, Sonnenschein, Yankielowicz1998)







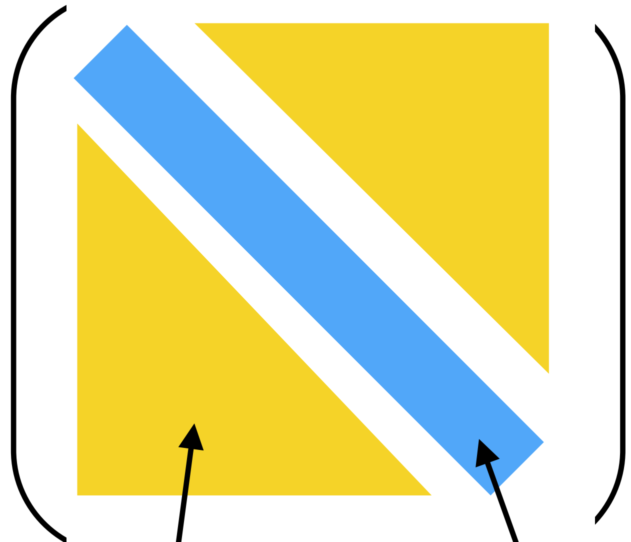
diagonal elements = particles (D0-branes)

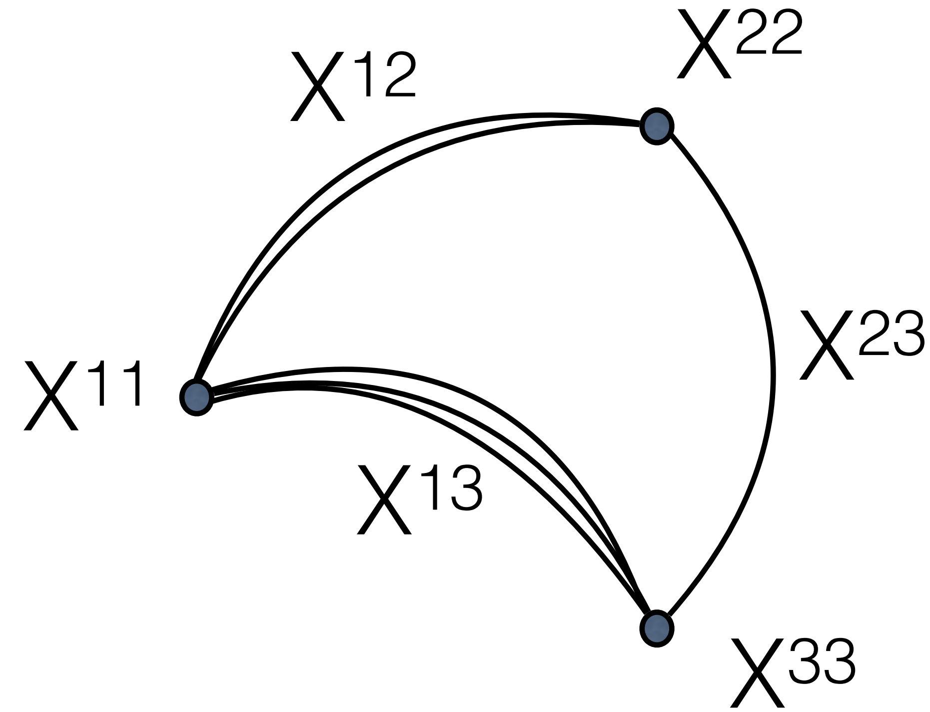
off-diagonal elements = open strings

(Witten, 1994)

black hole = soliton in gauge theory
(bound state of D-branes and strings)

$X_M =$





$(X_1^{ii}, X_2^{ii}, \ldots, X_9^{ii})$

position of i-th D0-brane in R^9

X_M^{ij} : open strings connecting i-th and j-th D0-branes.

large value → a lot of strings are excited

(Witten, 1994)

String theory prediction

$$\text{BH mass} = E = -\frac{\partial}{\partial\beta}\log Z$$

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

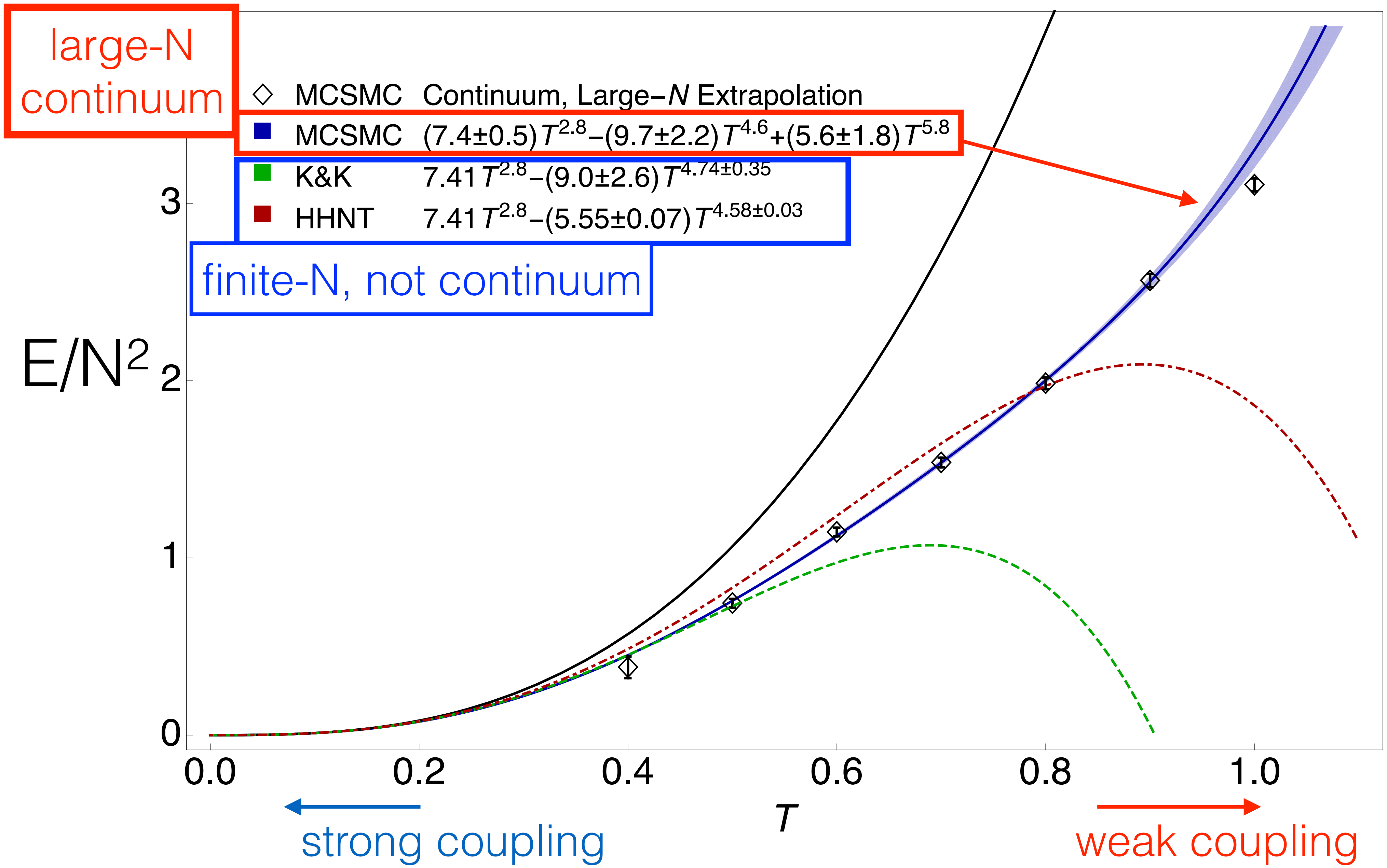
Took $N \to \infty$, and did 3-parameter fit by

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

N=∞ obtained from N=16, 24, 32

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

New!



MCSMC collaboration, 1606.*****

SUGRA = SYM @ finite-T

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

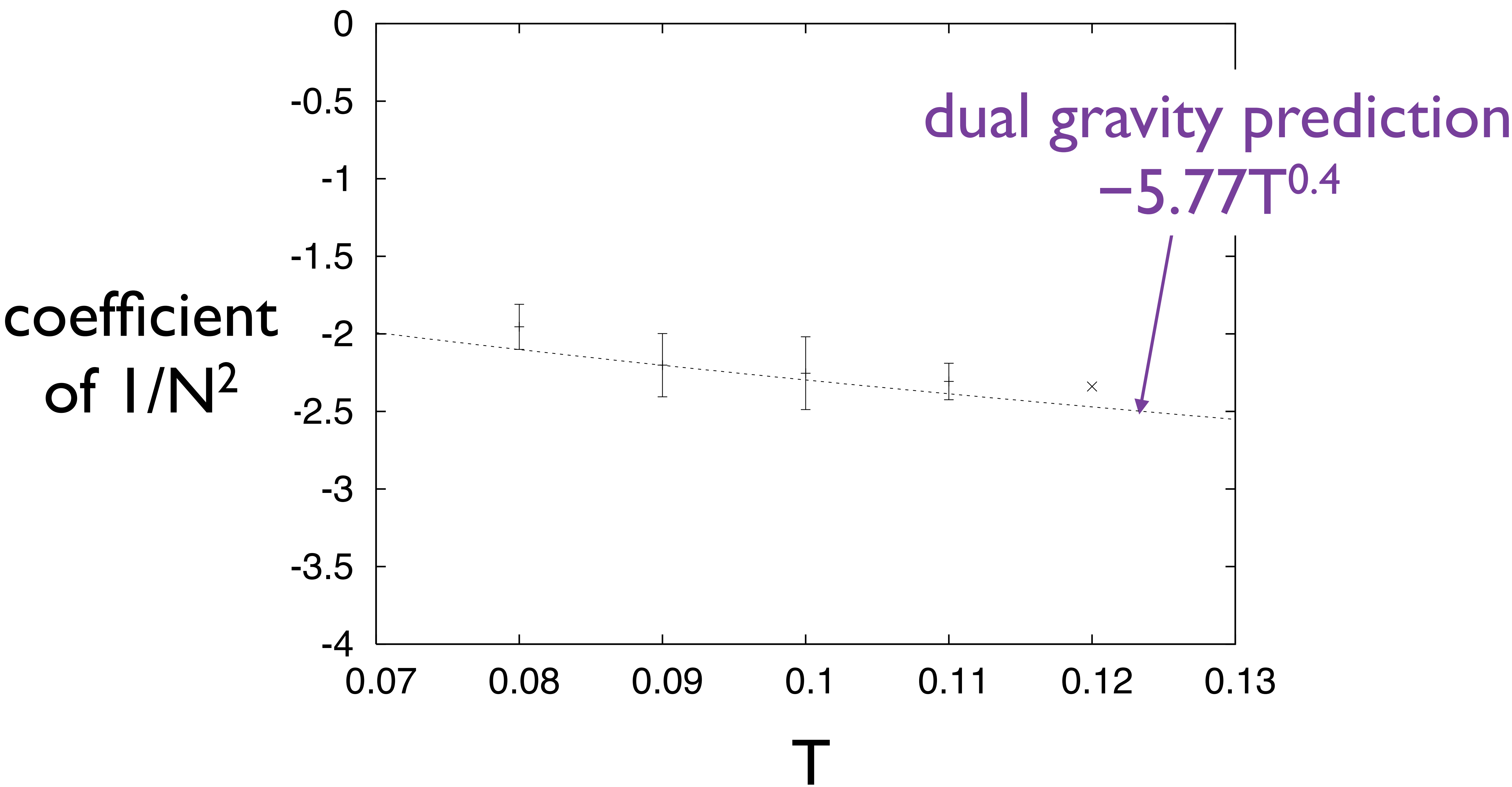
$a = 7.4 \pm 0.5$

MCSMC collaboration, 1606.***

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

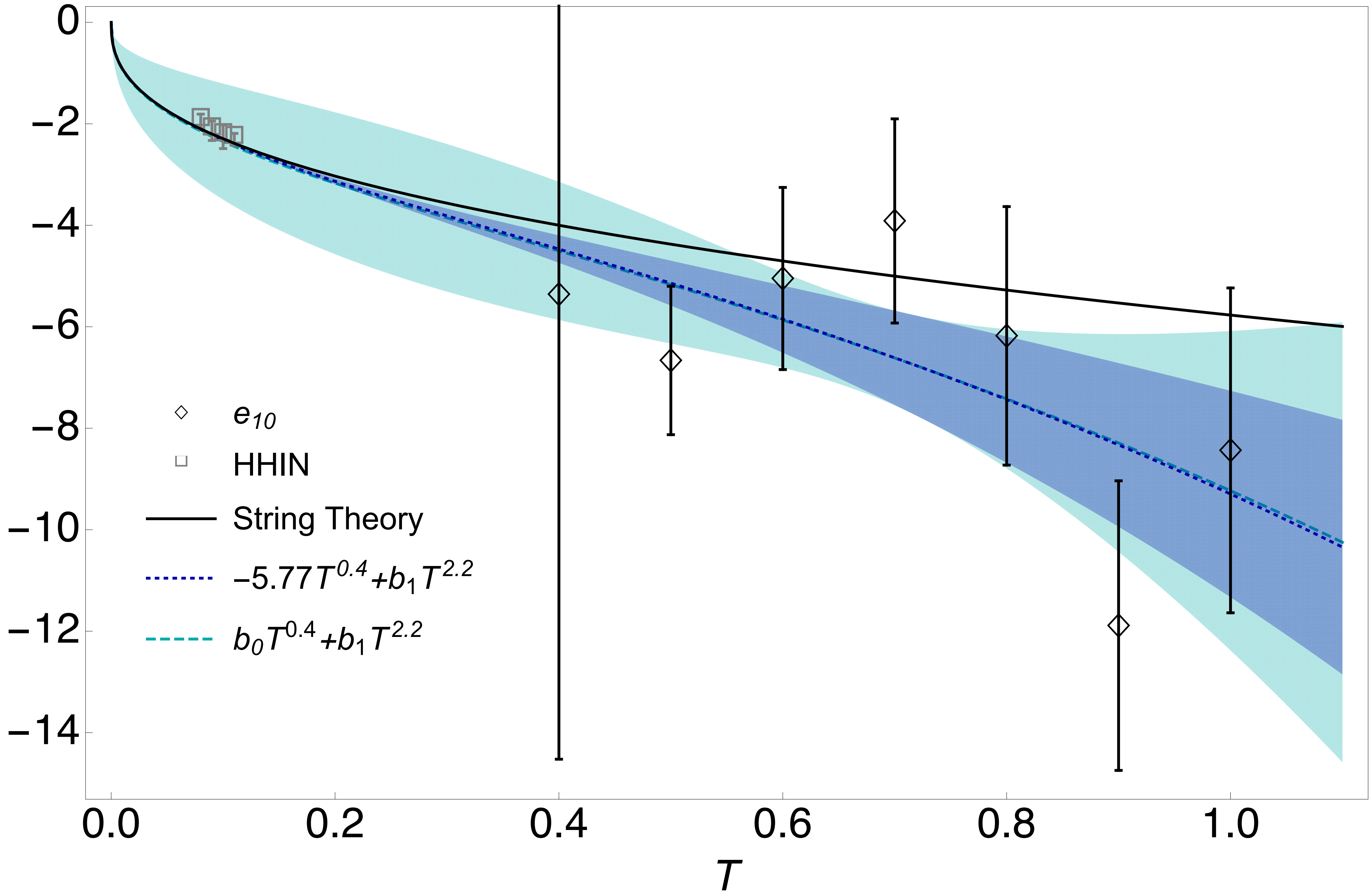
check this part as well.

$E/N^2 = 7.41T^{2.8} - 5.77T^{0.4}/N^2 + \ldots$



SU(3), SU(4) and SU(5), fit ansatz $7.4T^{2.8}+a/N^2+b/N^4$

M.H.-Hyakutake-Ishiki-Nishimura, Science 2014



MCSMC collaboration, 1606.*****

Did gauge/gravity duality solve Hawking's puzzle?

- Unitary evaporation process is not known.

— NO real-time study from gauge theory side.

— Radiation rate is zero when the gauge theory description is exact. (Nothing can bring the energy away from gauge theory itself.)

— Specific heat is positive.

※ Small AdS BH has negative specific heat, but has not been understood from gauge theory.

— There is a remnant — zero-T, SUSY BH

Let's fix these issues.

Rules of the game

- Use only gauge theory.
- Don’t assume anything from gravity.

(i.e. Don’t assume the answer.)

✗ “BH evaporation is described by SYM, if the duality between evaporating BH and SYM is correct.” ← Don’t assume the answer!

Before going to BH evaporation…

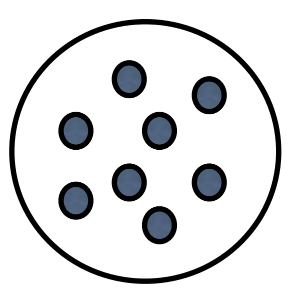
BH formation

※ We assume the ’t Hooft limit for simplicity.

Formation of BH

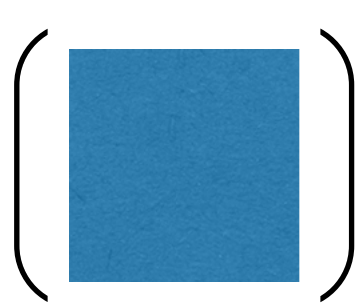
Because of the chaotic nature of the system, almost all initial conditions end up with ‘typical’ matrix configurations — BH.

BH

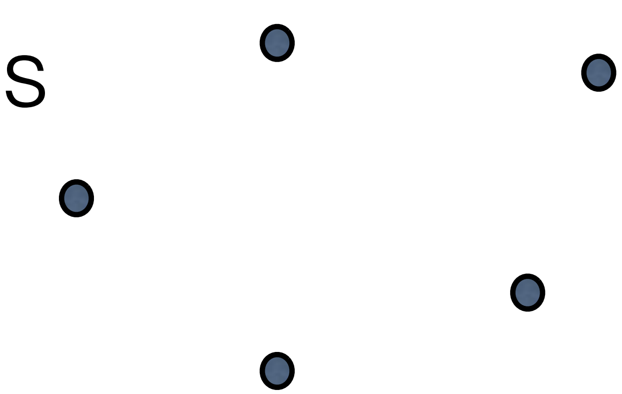


open strings
(off-diagonal components)
are excited

entropy $\sim N^2$

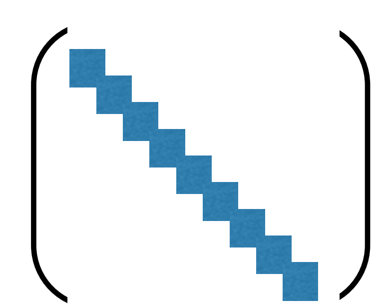


gas

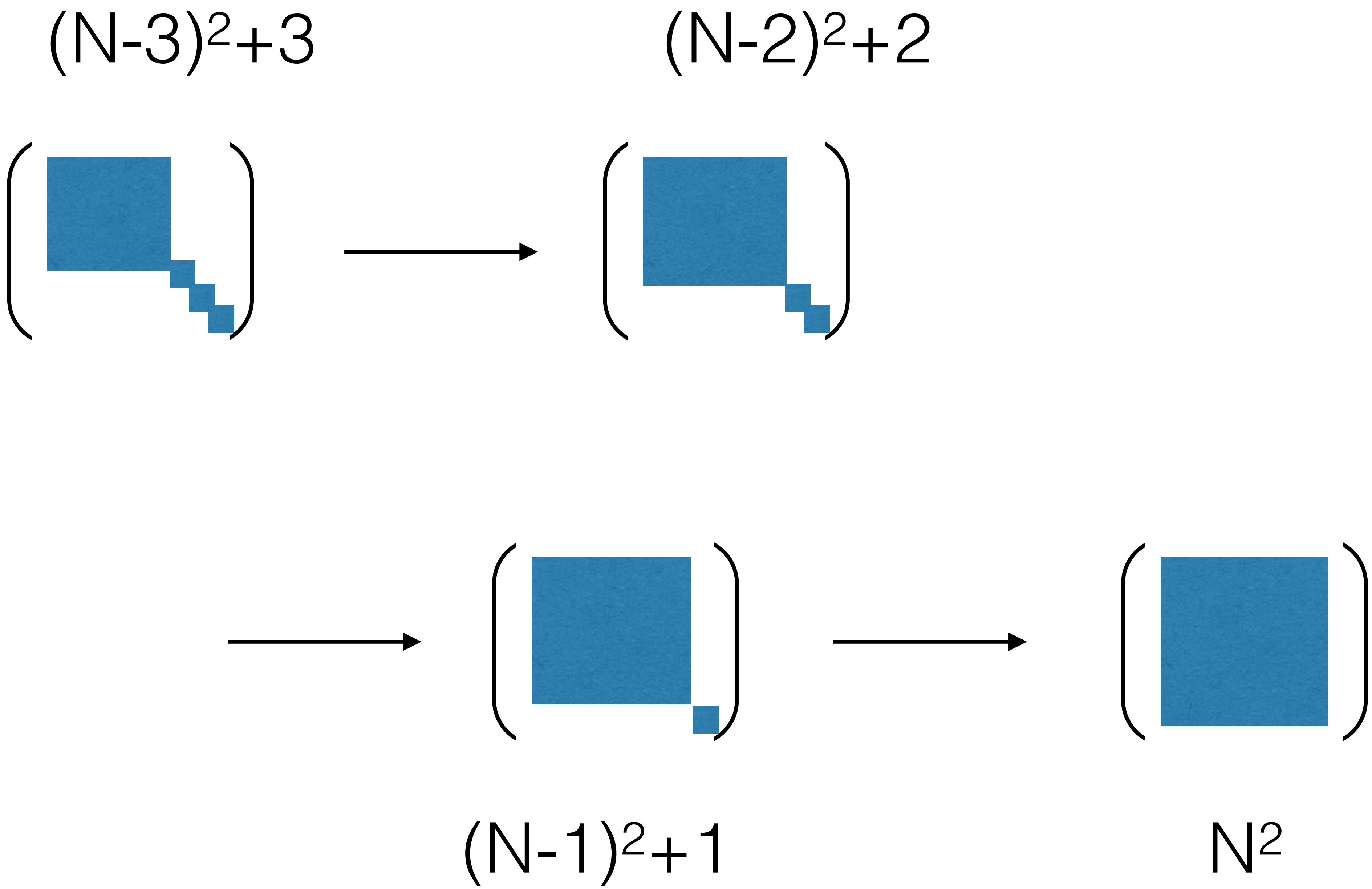


open strings are suppressed

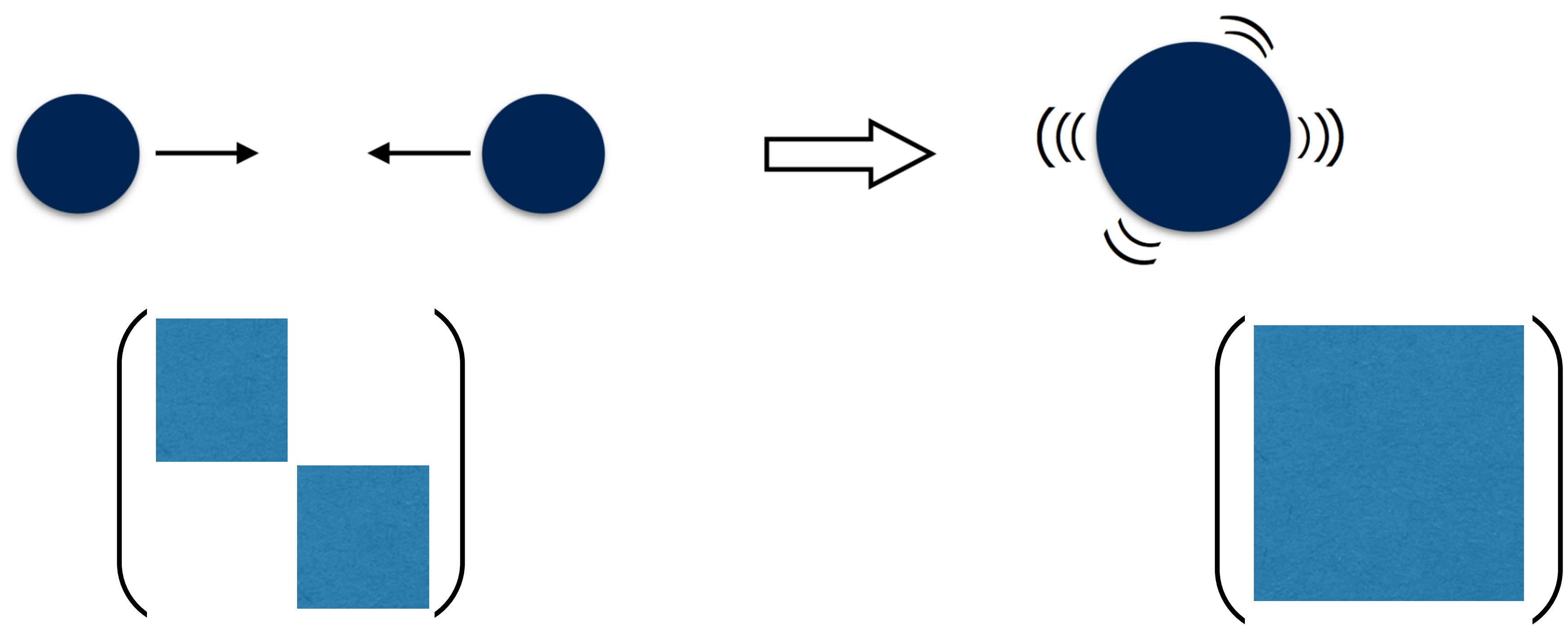
entropy $\sim N$



Formation of BH



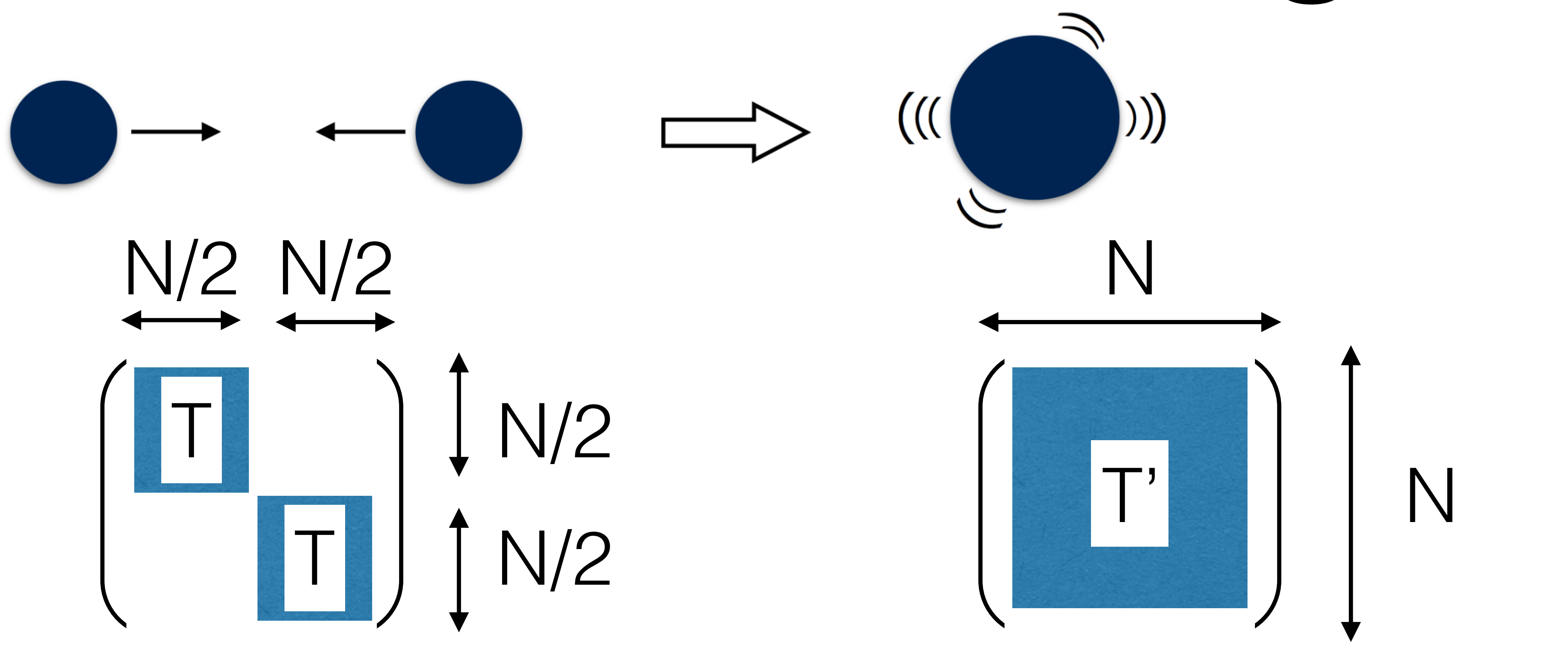
Merger of BH



$2 \times (N/2)^2 = N^2/2$

N^2

BH cools down as it grows



$T \sim$ (energy)/(# d.o.f)

- Energy does not change
- # d.o.f. increases

→ Black hole cools down

<u>high-T</u> $E = 2 \times 6T\,(N/2)^2 = 6T'N^2$ $T' = T/2$

low-T

$$(\lambda^{-1/3}E) = 7.4N^2(\lambda^{-1/3}T)^{14/5}$$

Gravity result?
(1) We tested it.
(2) Used only for determining the O(1) coeff. completely. Evaporation is not assumed.

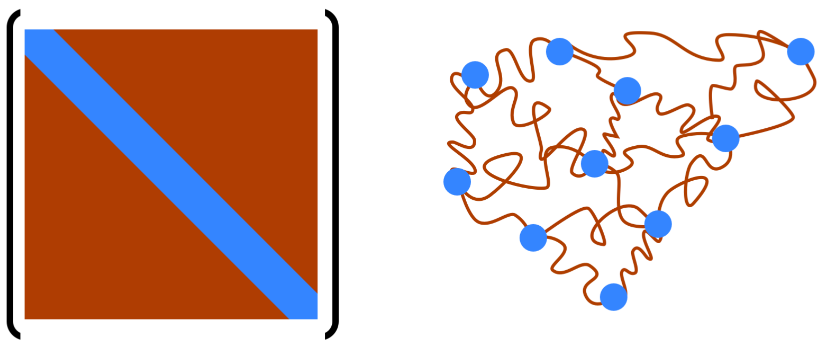
$$E = 7.4N^2T'^{14/5}(g_{YM}^2N)^{-3/5}$$
$$= 2\times 7.4\cdot (N/2)^2\cdot T^{14/5}(g_{YM}^2\cdot (N/2))^{-3/5}$$

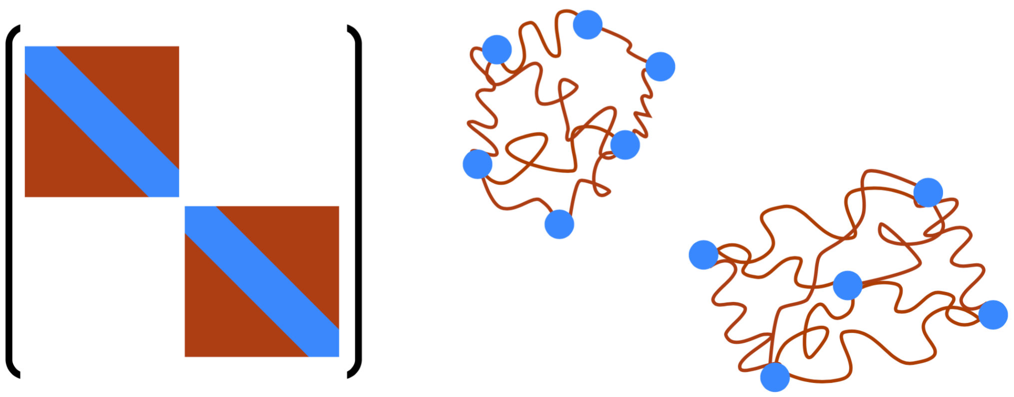
$$T' = T/2^{1/7}$$

Evaporation

Gauge theory description of a black hole

(Banks, Fischler, Shenker, Susskind 1996; Itzhaki, Maldacena, Sonnenschein, Yankielowicz1998)





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(Witten, 1994)

black hole = soliton in gauge theory
(bound state of D-branes and strings)

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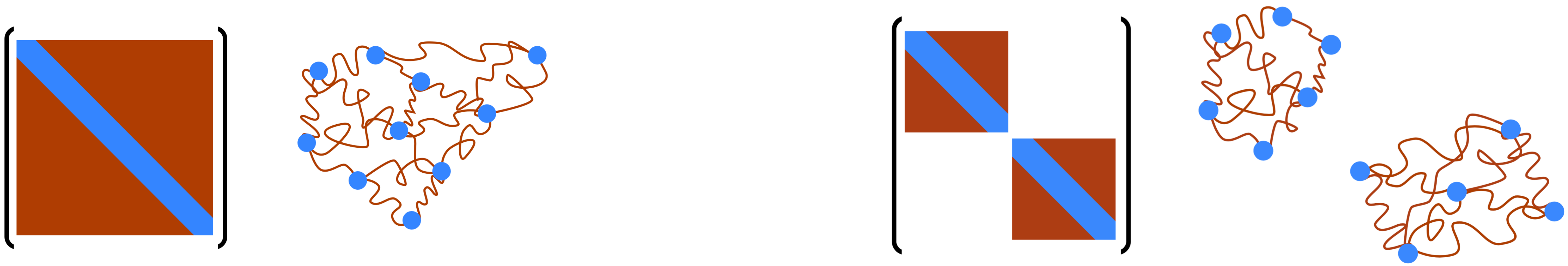


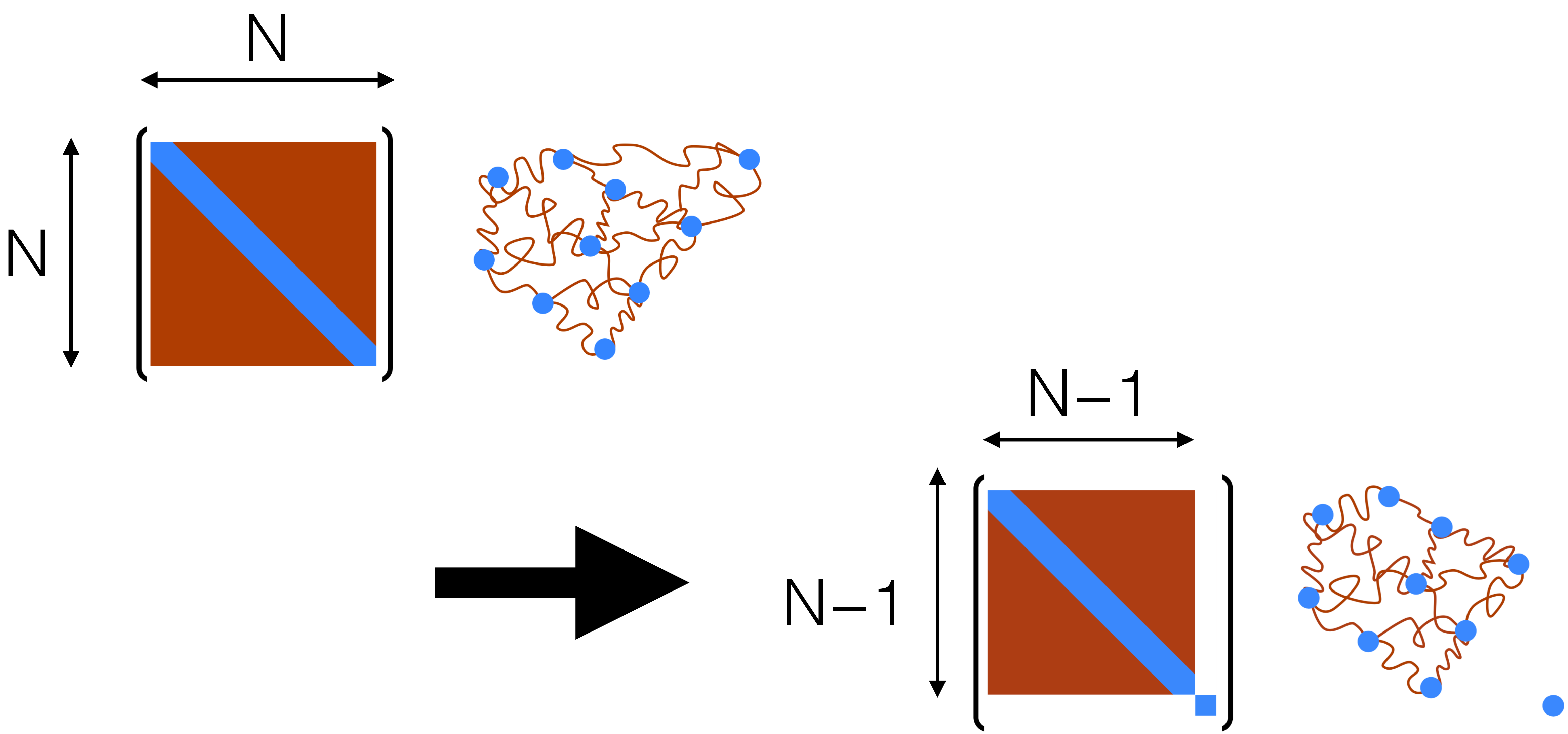
diagonal elements = particles (D0-branes)
off-diagonal elements = open strings

(Witten, 1994)

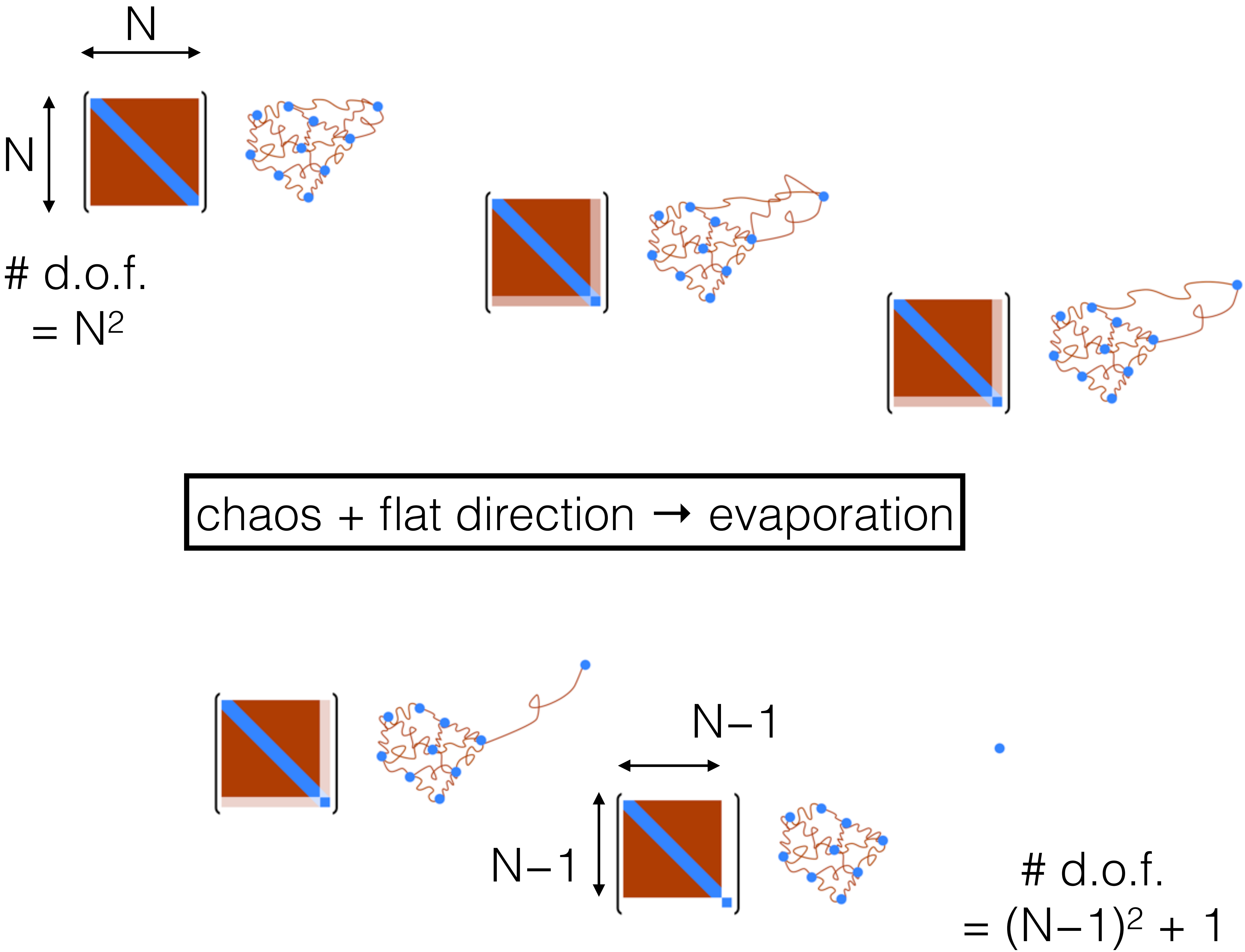
metastable state (resonance)

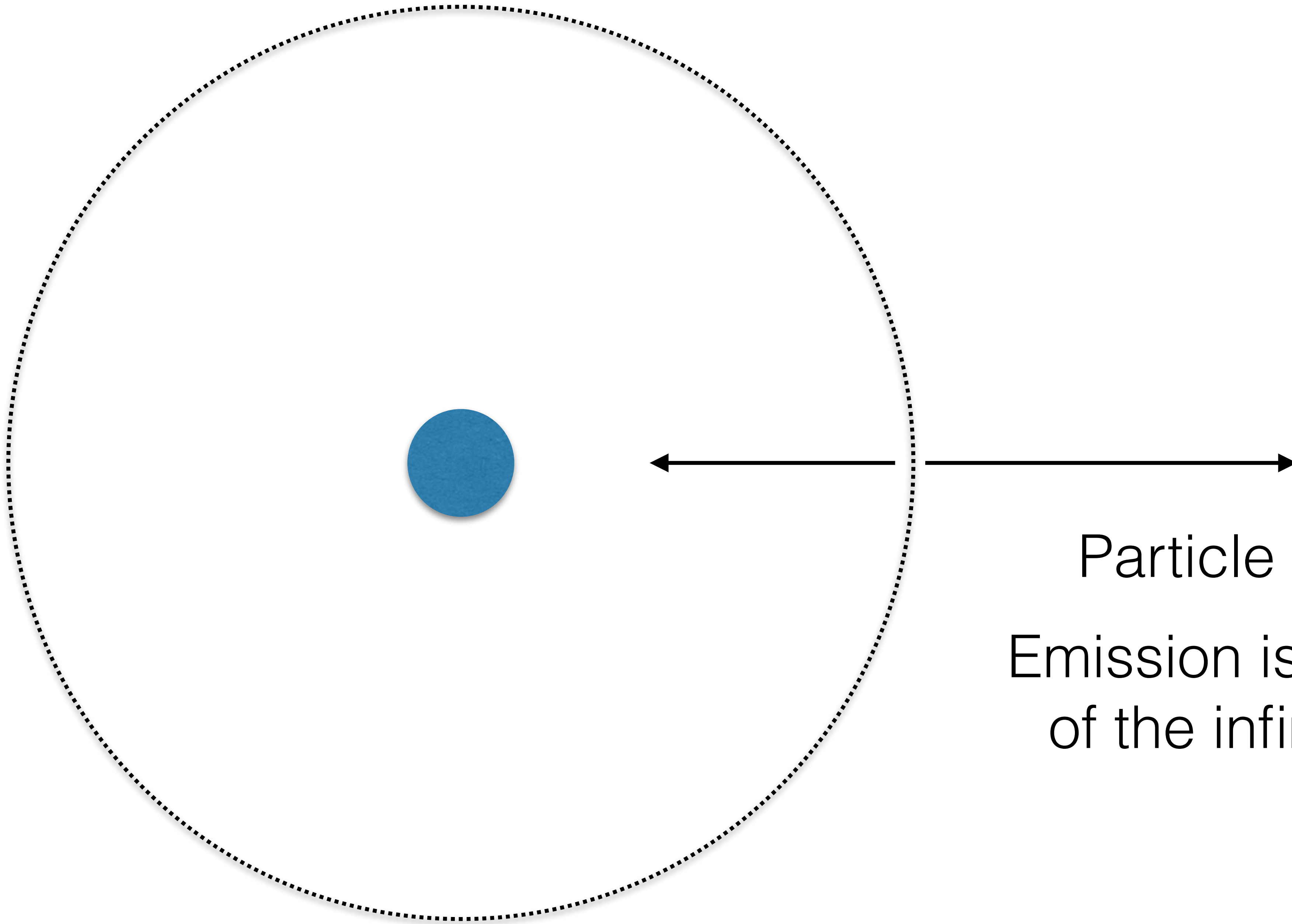
black hole = ~~soliton~~ in gauge theory
(bound state of D-branes and strings)

Particle emission from black hole



<u>Flat direction</u> due to supersymmetry


N
N
d.o.f.
= N2
chaos + flat direction → evaporation
N−1
N−1
d.o.f.
= (N−1)2 + 1

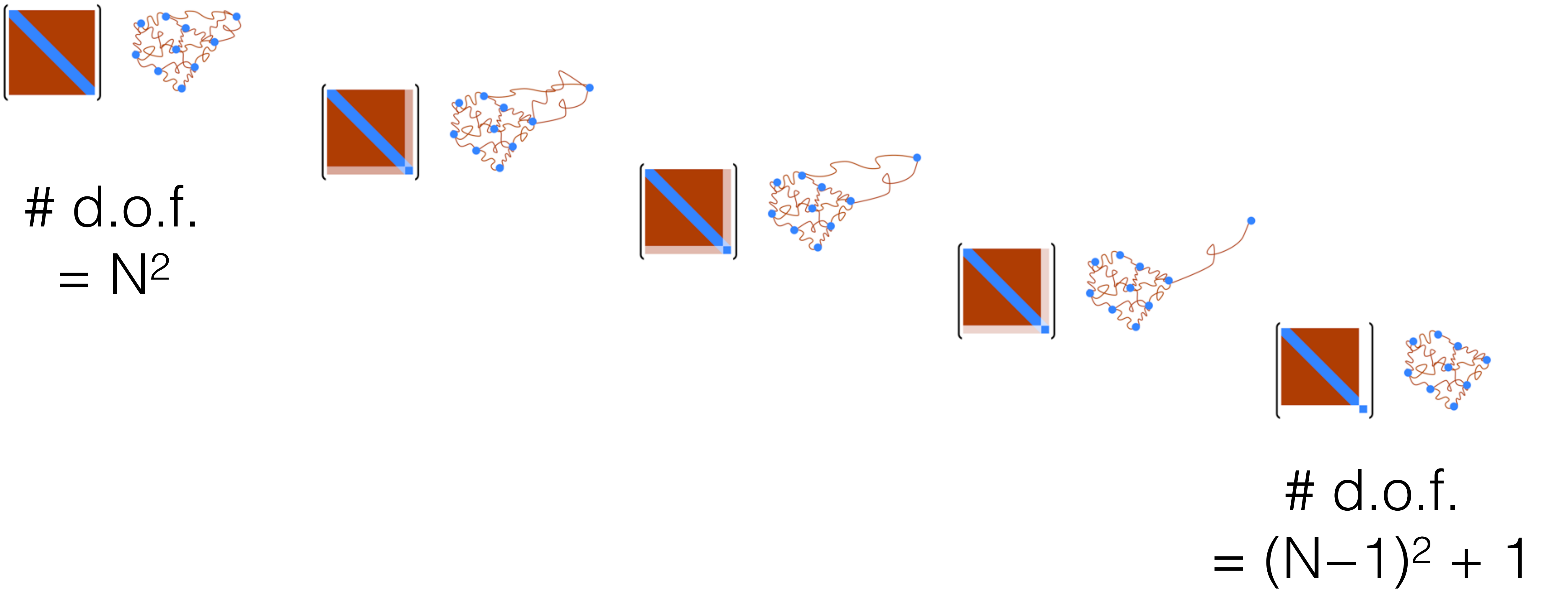


Particle travels almost freely.

Emission is preferred because of the infinite volume factor.

$$\# \text{ d.o.f.} = (N-1)^2 + 1 \times \log(\text{Volume})$$

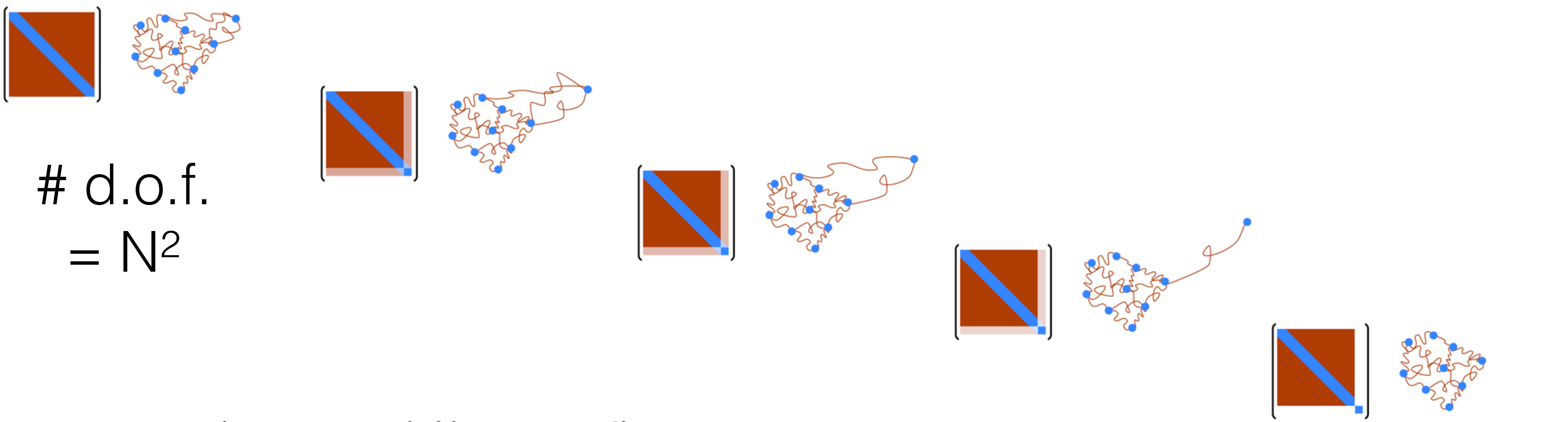
- Emission is entropically disfavored at short distance.
- Beyond some point, it is entropically favored.



- Finite probability of particle emission, suppressed at $N=\infty$
- Emission time $\sim \exp(N)$ note: recurrence time $\sim \exp(N^2)$
  scrambling time $\sim \log N$
- k-particle emission is suppressed; $\exp(kN)$
- Temperature goes up!

(Berkowitz, M.H., Maltz, 2016)

Microscopic derivation of negative specific heat



d.o.f. $= N^2$

$T \sim$ (energy)/(# d.o.f)

- Energy does not change
- # d.o.f. decreases

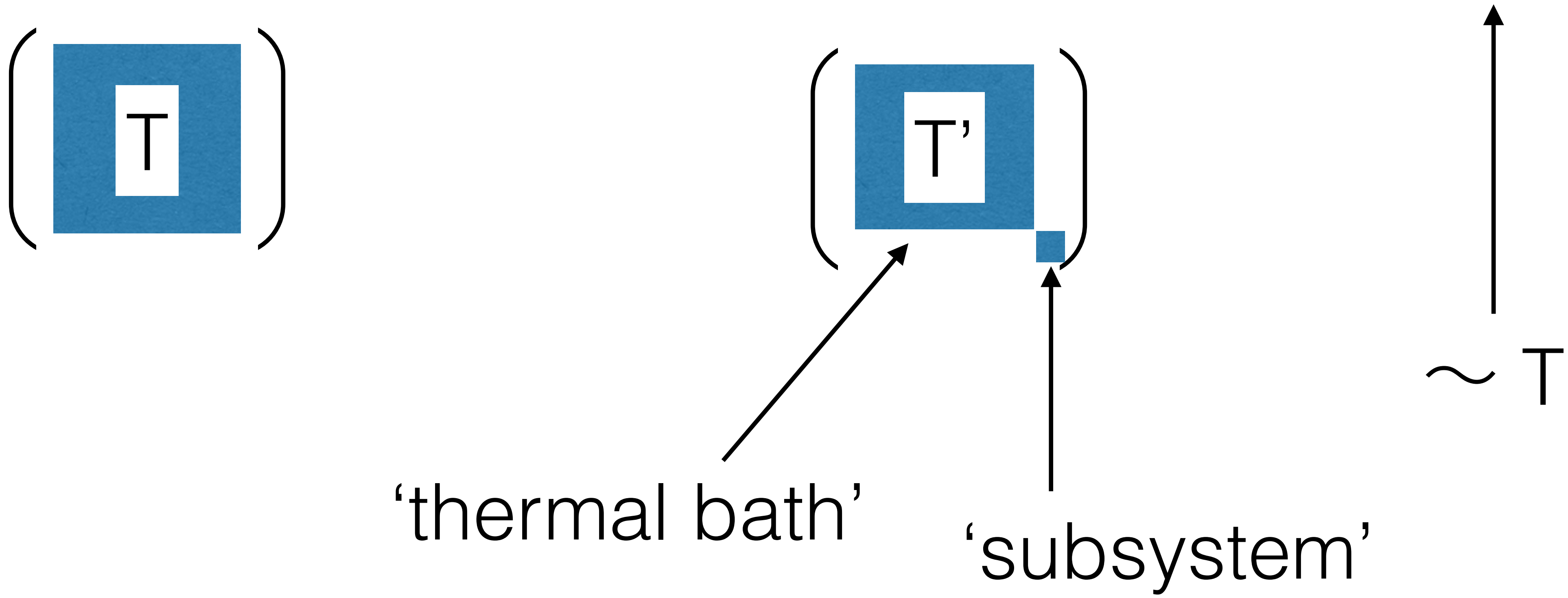
d.o.f. $= (N-1)^2 + 1$

→ Black hole heats up as it evaporates!

(Berkowitz, M.H., Maltz, 2016)

high-T

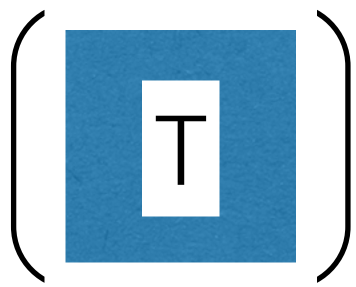
$$E = 6N^2T = 6(N-1)^2T' + E_{\mathrm{D0}}$$

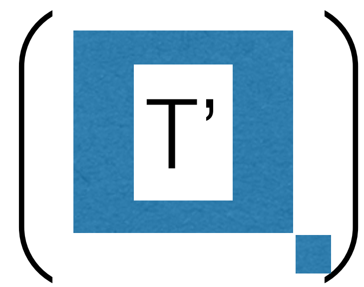


The spectrum is $\exp(-E_{D0}/T)$ when $N=\infty$.
1/N correction gives a deviation from thermal distribution.

high-T

$$E = 6N^2T = 6(N-1)^2T' + E_{\mathrm{D0}}$$





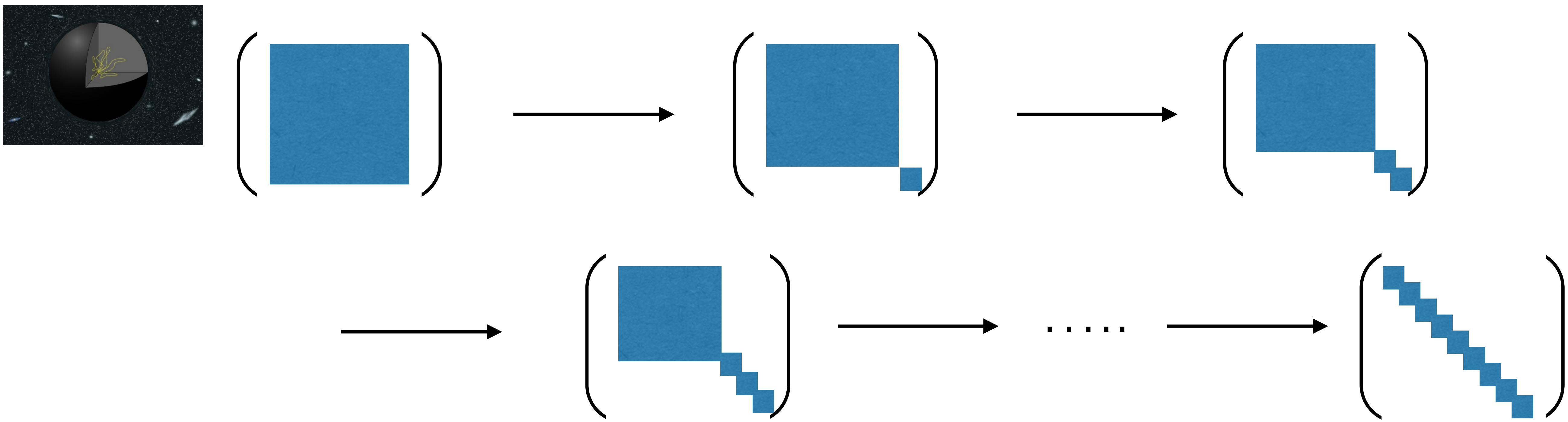
$\sim$ T

$$T = \left(1 - \frac{2}{N} + \frac{1}{N^2}\right) T' + \frac{E_{\mathrm{D0}}}{6N^2}$$

$$T < T' \simeq \left(1 + \frac{2}{N}\right) T$$

$T < T' \simeq \left(1 + \frac{1}{2N}\right) T$ at low-T

Black Hole Evaporation seen as Matrices



- ***Concrete counter-example to information loss!***

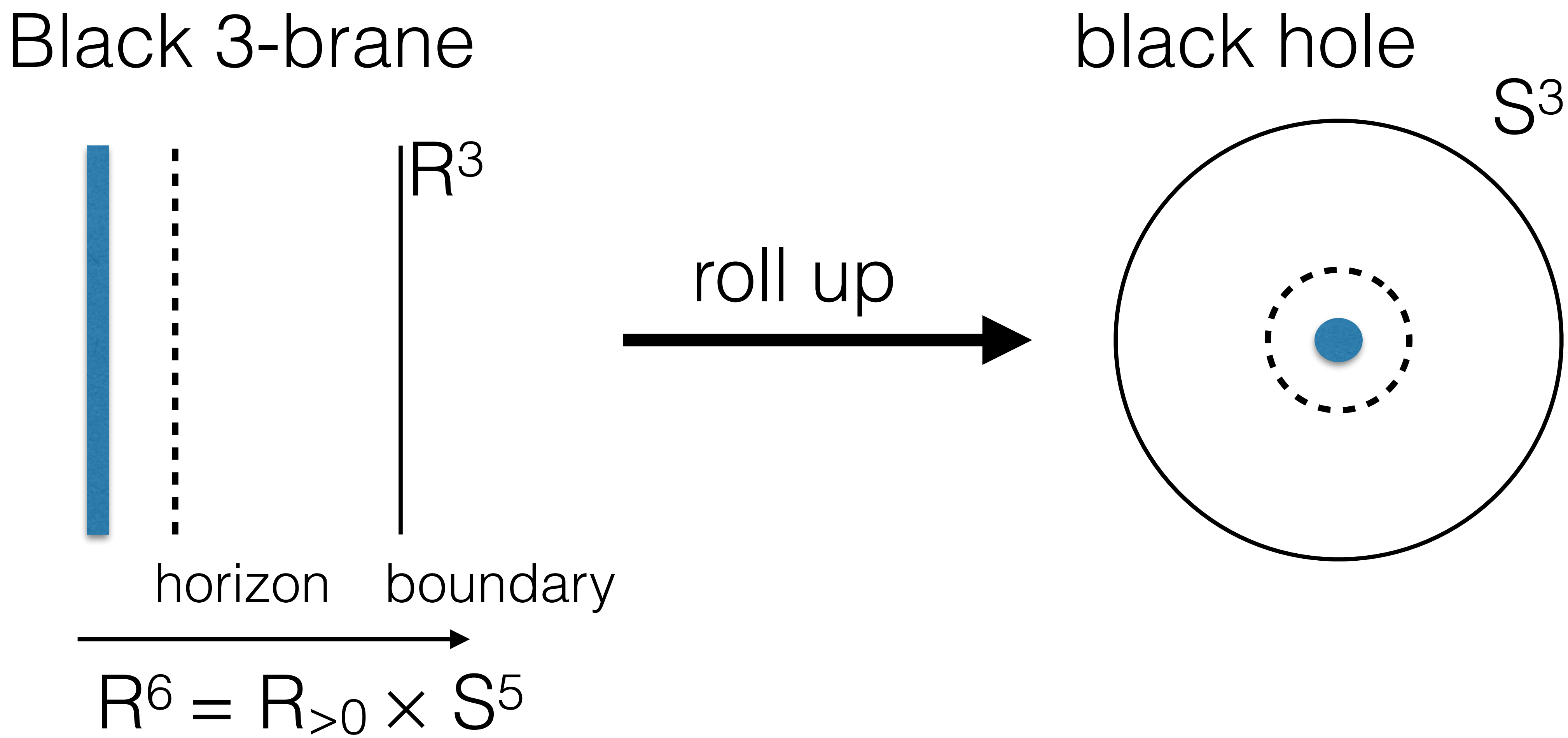
- Radiation spectrum is thermal, up to 1/N correction.
- Black hole heats up.
- Evaporation speeds up.
- No remnant.
- Detailed numerical analysis with nuclear theory methods.
- Bulk interpretation still not 100% clear.

M-theory region?

- So far we considered IIA string region, $g^2 \sim 1/N$. There are several differences from Schwarzschild BH.
- What about the M-theory region, $g^2 \sim N^0$?
- emission rate $\sim \exp(-1/g^2) \sim \exp(-N^0)$
- Massless objects can be described. (The philosophy of Matrix Theory conjecture!)
- Seen as the dynamics of eigenvalues, essentially the same. (Quantitative analysis is harder.)
- May be related to Banks-Fischler-Klebanov-Susskind?

4d N=4 on S^3

(Preliminary)



described by $X_1,\ldots,X_6$

black brane
= black hole
= bound state of
eigenvalues of $X_1,\ldots,X_6$

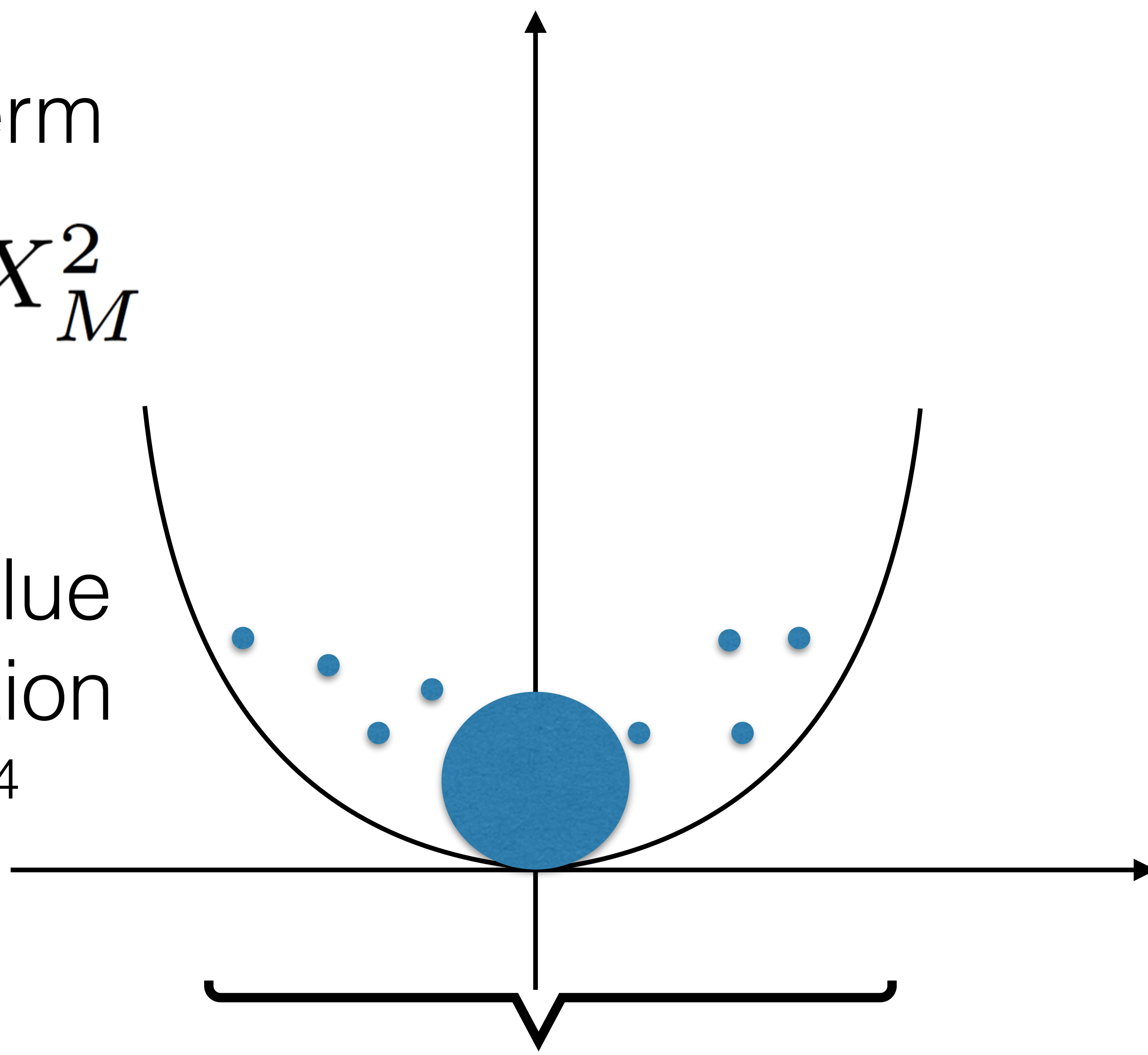
4d N=4 on S^3

(Preliminary)

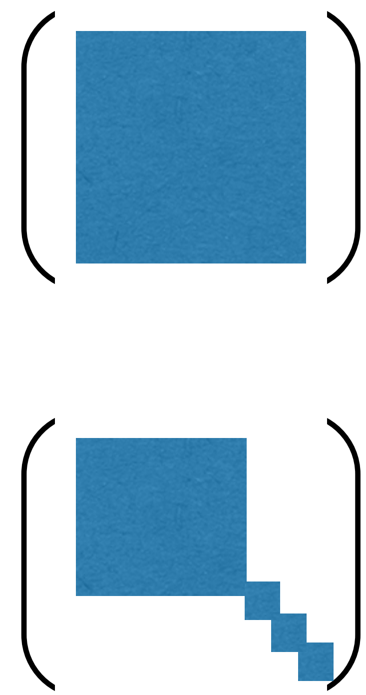
mass term

$\mathrm{Tr} X_M^2$

eigenvalue distribution $\sim \lambda^{1/4}$



$S^5 \times$ radial coord. of AdS

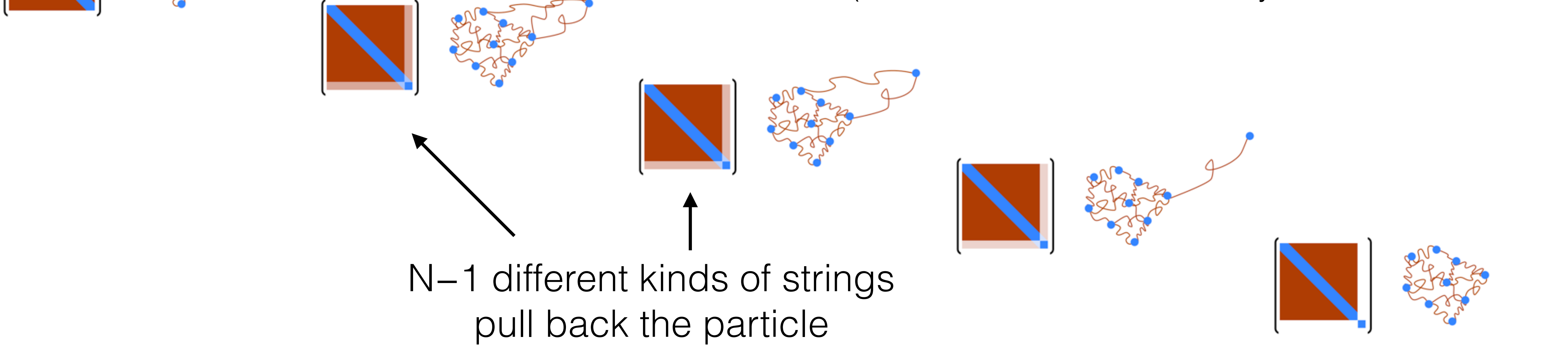


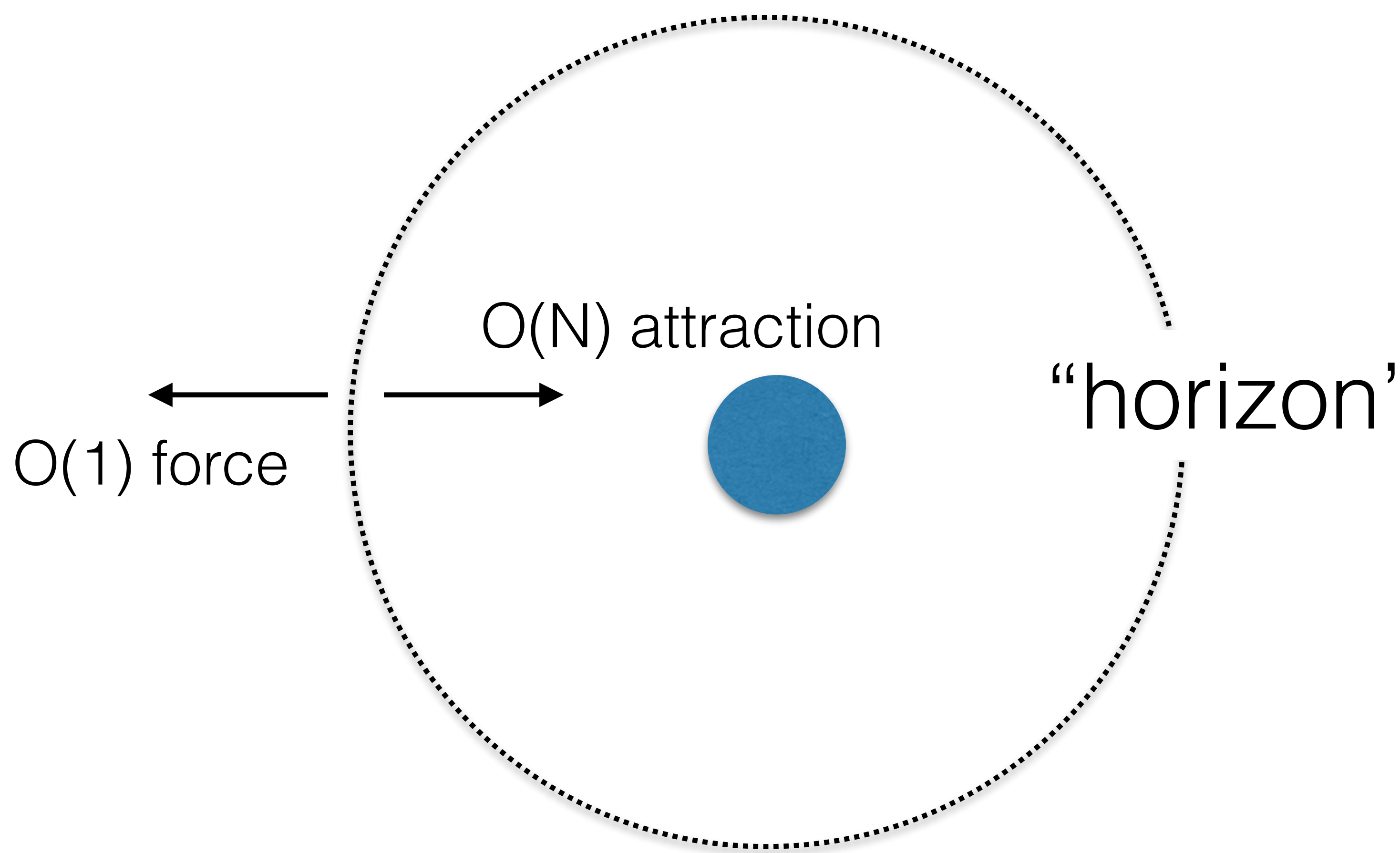
Emergent BH geometry

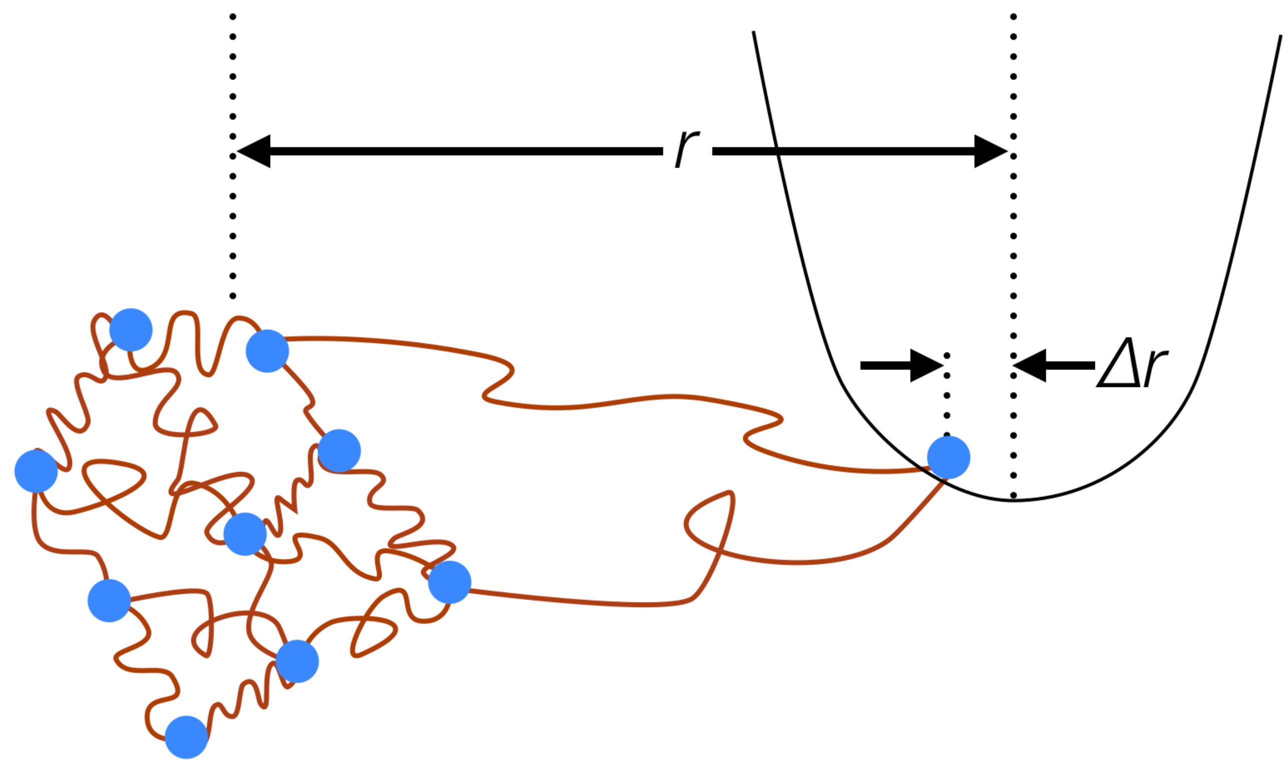
Emergent Geometry

(Berkowitz, Gur-Ari, M.H., Maltz, Rinaldi, Vranas, 1607.*****)

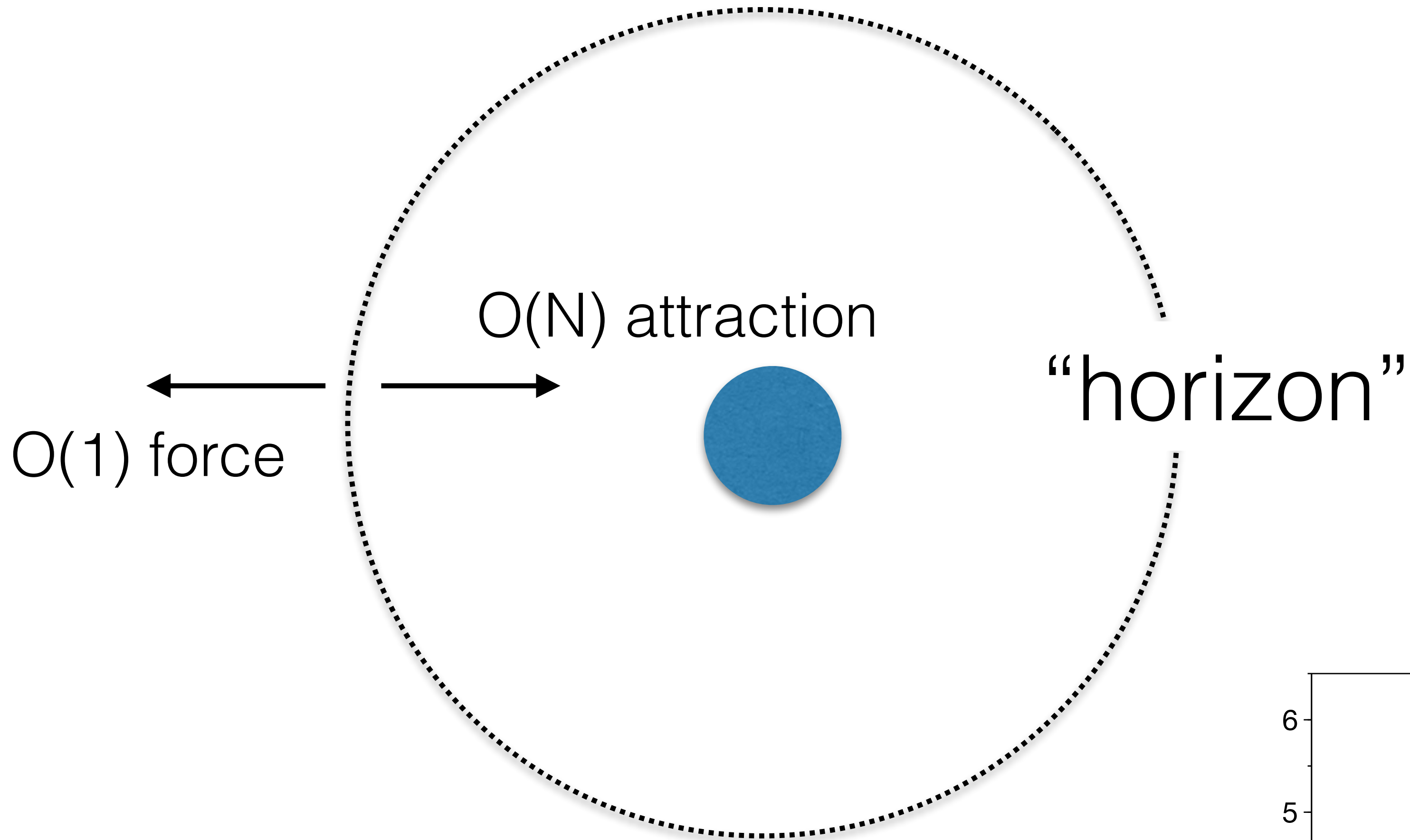
(Related ideas: Kabat, Lifschytz, 1999; Ferrari, 2011)

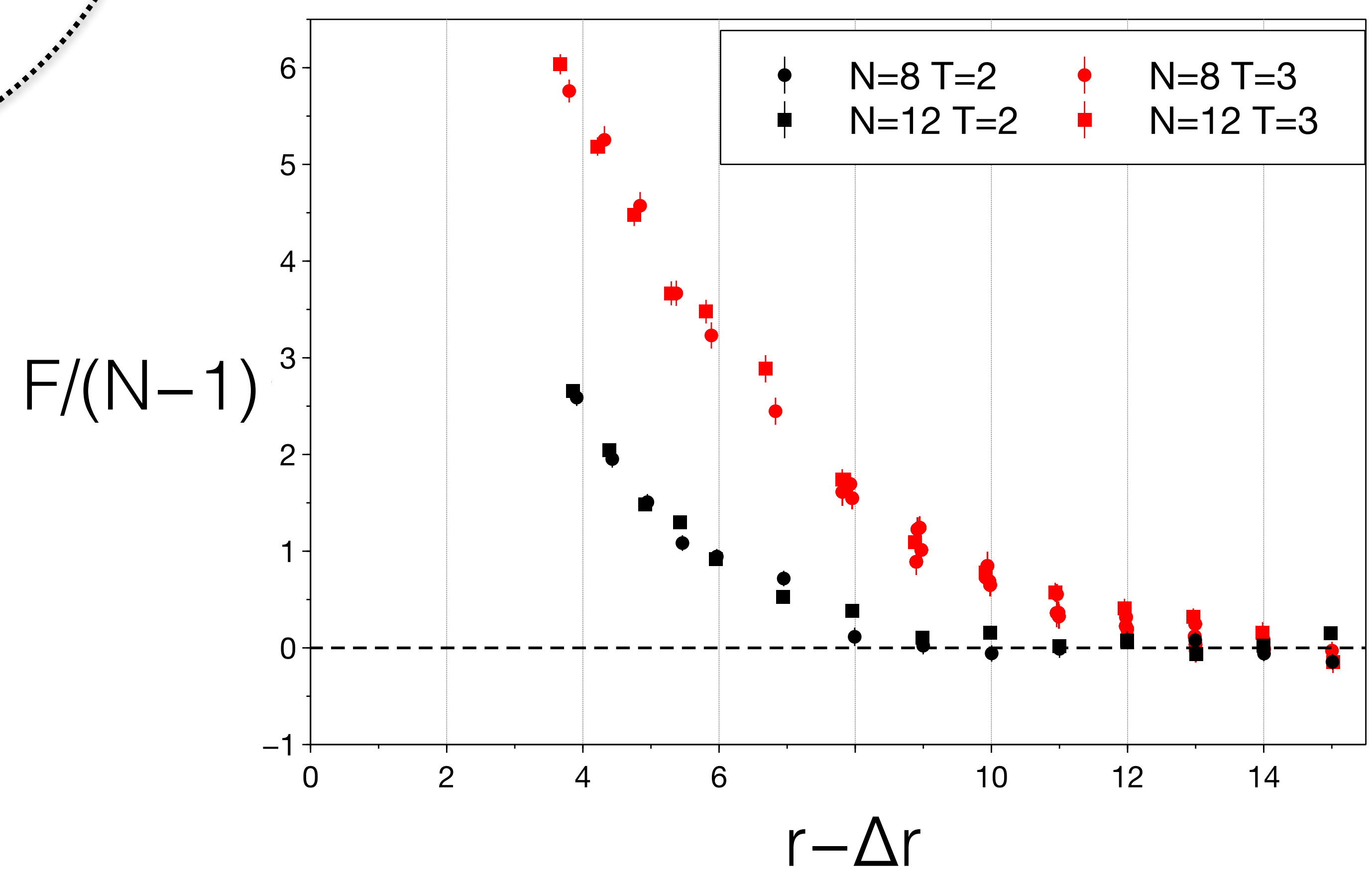






- Introduce a potential to fix the probe.
- The force can be read from the potential and the shift.





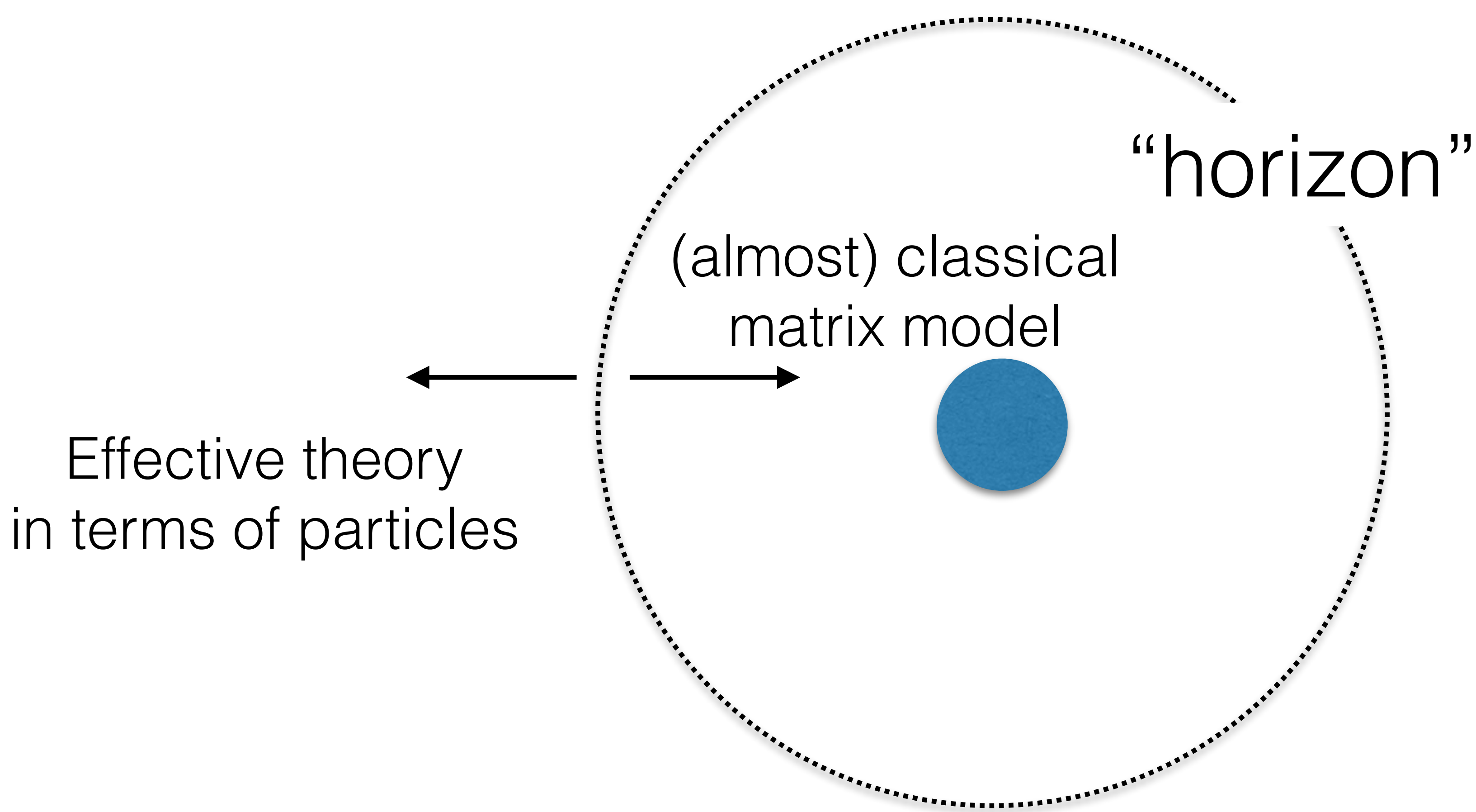
(Berkowitz, Gur-Ari, M.H., Maltz, Rinaldi, Vranas, 1607.*****)

The final stage of the evaporation

Black hole becomes hotter

→ Weak-coupling methods become better

→ Numerical real-time calculation can be done



Buividovich, M.H., Romatschke, Schafer, In progress

Summary

- Hot Black Hole can be studied. Mostly numerically, to some extent analytically.
- BH heats up as it evaporates. It is a generic property of string theory and gauge theory.
- Real-time simulation is possible for a very hot black hole.
- Black hole geometry is naturally encoded in gauge theory.
- Closed string picture of BH — ask me later, if you are interested.
- All these are just generic statements for any dual gauge theory description of quantum gravity.

Arashiyama Bamboo Forest
Yukawa Institute for Theoretical Physics
2 h 19 min
11.5 km
2 h 25 min
11.9 km
2 h 26 min
12.0 km
Kinkaku-ji
金閣寺
Ryōan-ji
龍安寺
Kita Ward Office
北区役所
Goryō Shrine
御靈神社
Takao Hospital
高雄病院
Buddhist Temple
直指庵
Daikaku-ji
大覚寺
Saga-Arashiyama
嵯峨嵐山
Utano
宇多野
Omuro-Ninnaji
御室仁和寺
Kitanohakubaicho
北野白梅町
Demachiyanagi
Chayama
茶山
Mototanaka
元田中
Uryuyama
瓜生山
Honen-in
法然院
Daimonjiyama
大文字山
Tokiwa
常盤
Hanazono
花園
Uzumasa
太秦
Katabiranotsuji
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Kyoto Gakuen University
京都学園大
Heian Shrine
平安神宮
Nanzen-ji
南禅寺
Keihan Oto Line
Higashi Oji Dori
Arashiyama
嵐山
Kasugadake
烏ケ岳
Matsuo-Taisha
松尾大社
Shijo Dori
Katsura River
Saiin
西院
Yasaka Shrine
八坂神社
Kōdai-ji
高台寺
Tambaguchi
丹波口
Kiyomizu-dera
清水寺
Suzumushi-dera Temple
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Kamikatsura
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山陰本線