Universität Regensburg

Studies of the D0-brane matrix models at low temperatures

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University of Regensburg, Germany

Workshop on Noncommutative and generalized geometry in string theory, gauge theory and related physical models

Kerkyra: 19/09/22

Based on: 2110.01312, 2205.06098 & work in progress

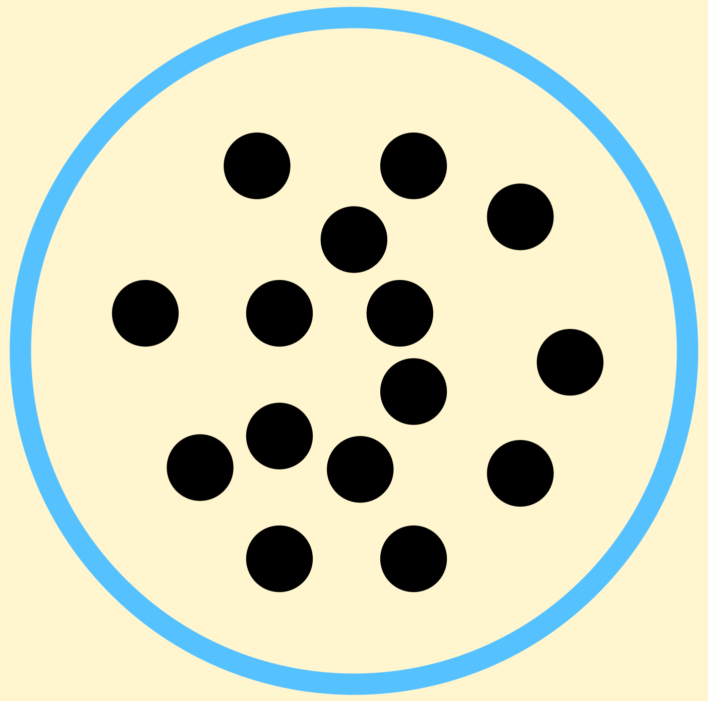
With: Bergner, Bodendorfer, Hanada, Rinaldi, Schäfer, Vranas, Watanabe (MCSMC)

Elitenetzwerk Bayern

Why low temperatures?

Plan of the talk

- Definition of the models
- Holography
- Relation with gravity
- Confinement in D0-matrix model
- Simulations, tests at low temperatures
- Comparison with eternal energy of the black zero brane
- Role of gauge constraint?



D0-matrix model (BFSS)

$$S = \frac{1}{2g_{YM}^2}\int dt Tr\left\{ (D_t X_M)^2 + [X_M, X_N]^2 + i\bar{\psi}^{\alpha} D_t \psi^{\beta} + \bar{\psi}^{\alpha}\gamma^M_{\alpha\beta}[X_M, \psi^{\beta}] \right\}$$

$X_{N\times N}$: $N\times N$ bosonic hermitian matrices with $M = 1,\cdots,9$

$\psi_{N\times N}$: $N\times N$ fermionic hermitian matrices with $\alpha = 1,\cdots,16$

D_t : $D_t\mathcal{O} = \partial_t\mathcal{O} - i[A_t, \mathcal{O}]$

$\lambda = g_{YM}^2 N = [\text{energy}]^3$

- Dimensional reduction of 4D $\mathcal{N} = 4$ / 10D $\mathcal{N} = 1$
- Matrix regularisation of 11D supermembrane De Wit-Hoppe-Nicolai, 1988
- Matrix model of M-theory (BFSS) Banks-Fischler-Shenker-Susskind, 1996
- Dual to type IIA black 0-brane near 't Hoof limit Itzhaki- Maldacena-Sonnenschein-Yankielowicz, 1998

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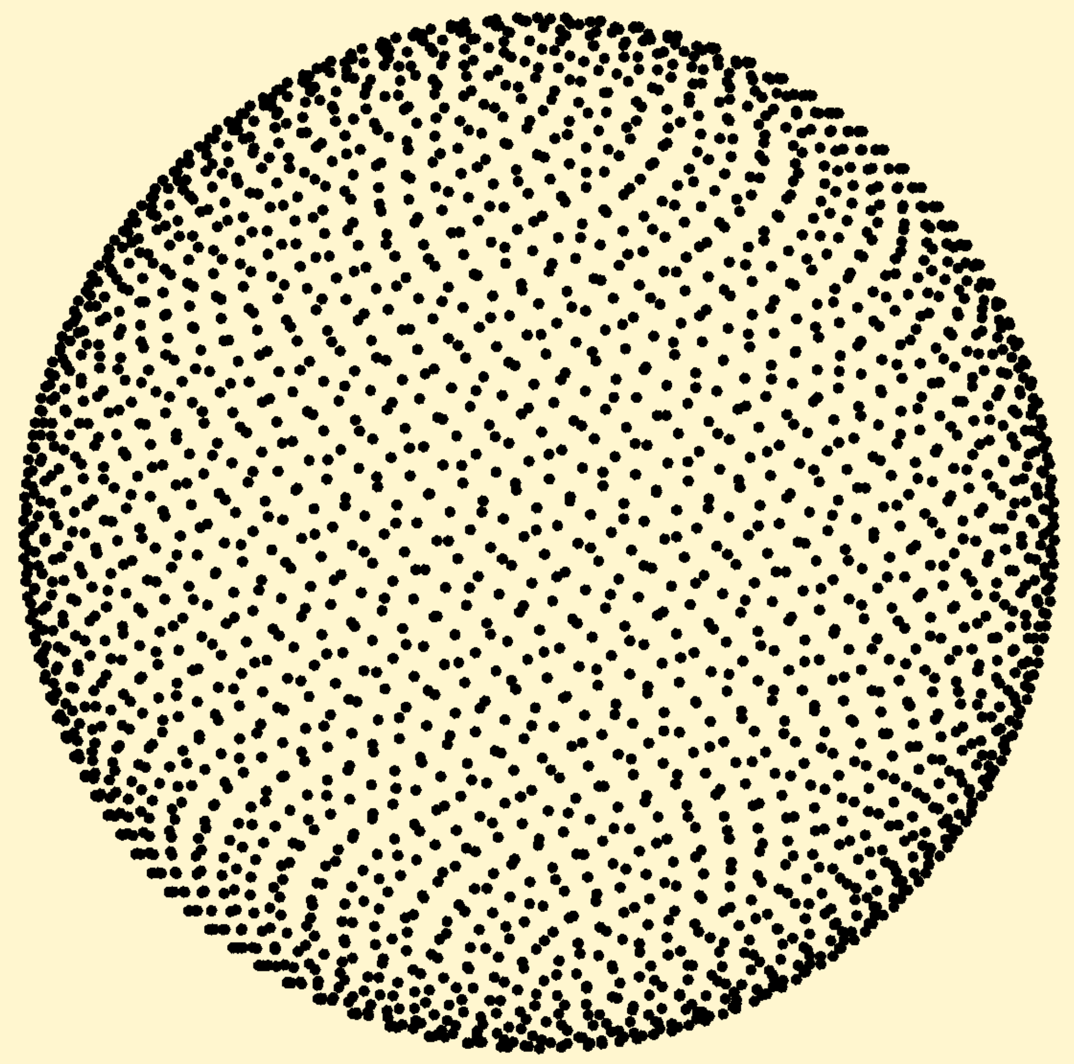

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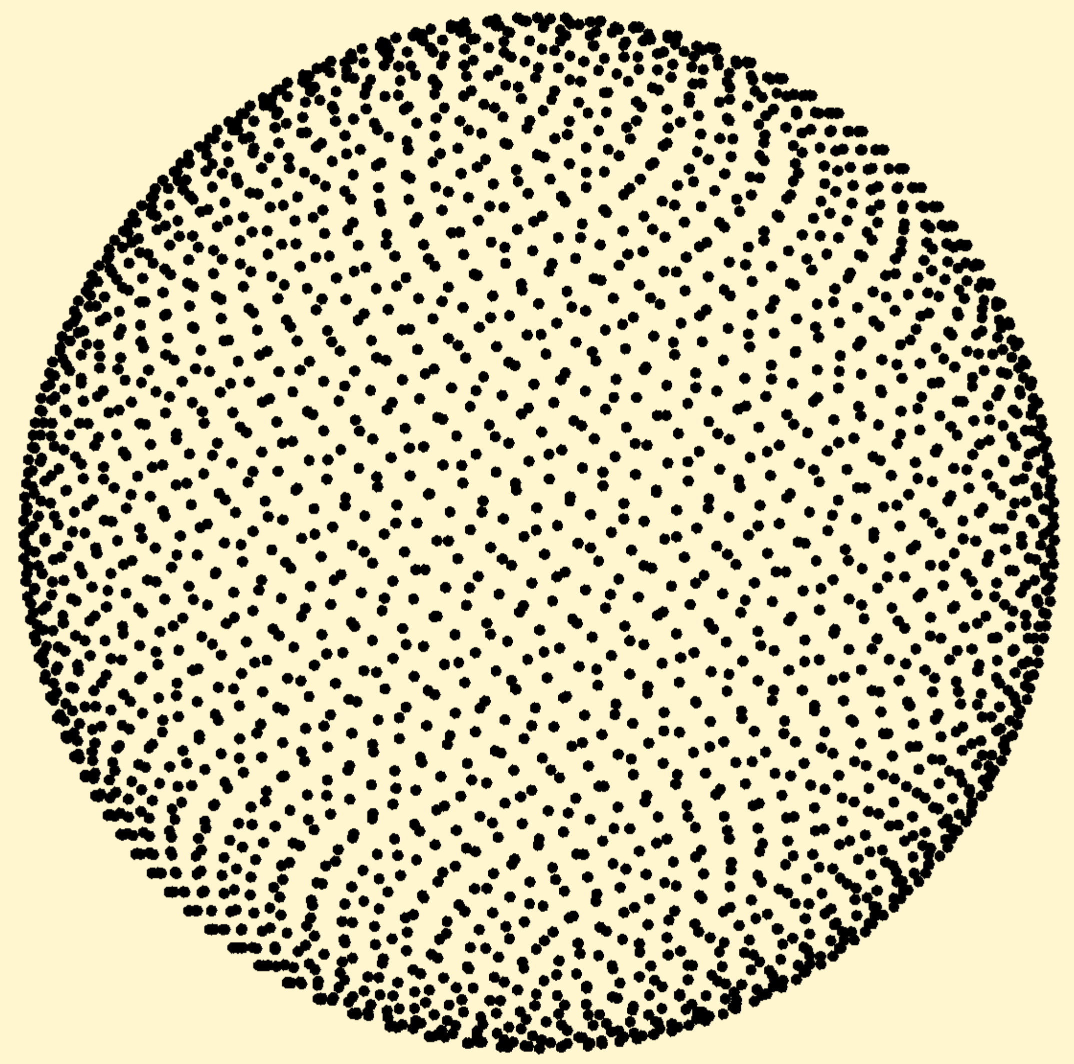
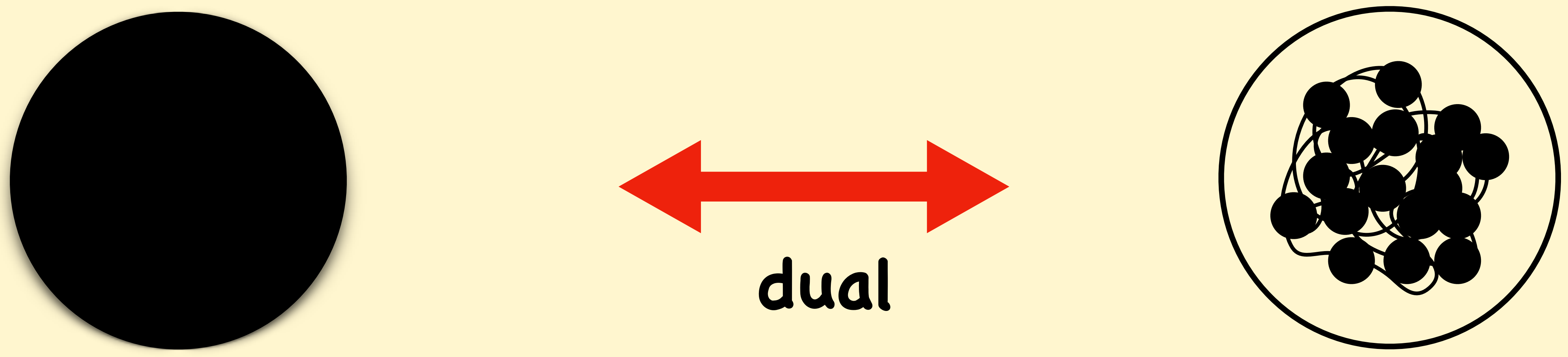


Gauge/gravity duality in string theory



Black p-brane
in IIA/IIB string

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

In this talk p=0

For p=-1 ⟶ IKKT model Anagnostopoulos, Azuma, Ito, Kim, Nishimura, Okubo, Papadoudis, Tsuchiya,...

The curious case of p=0

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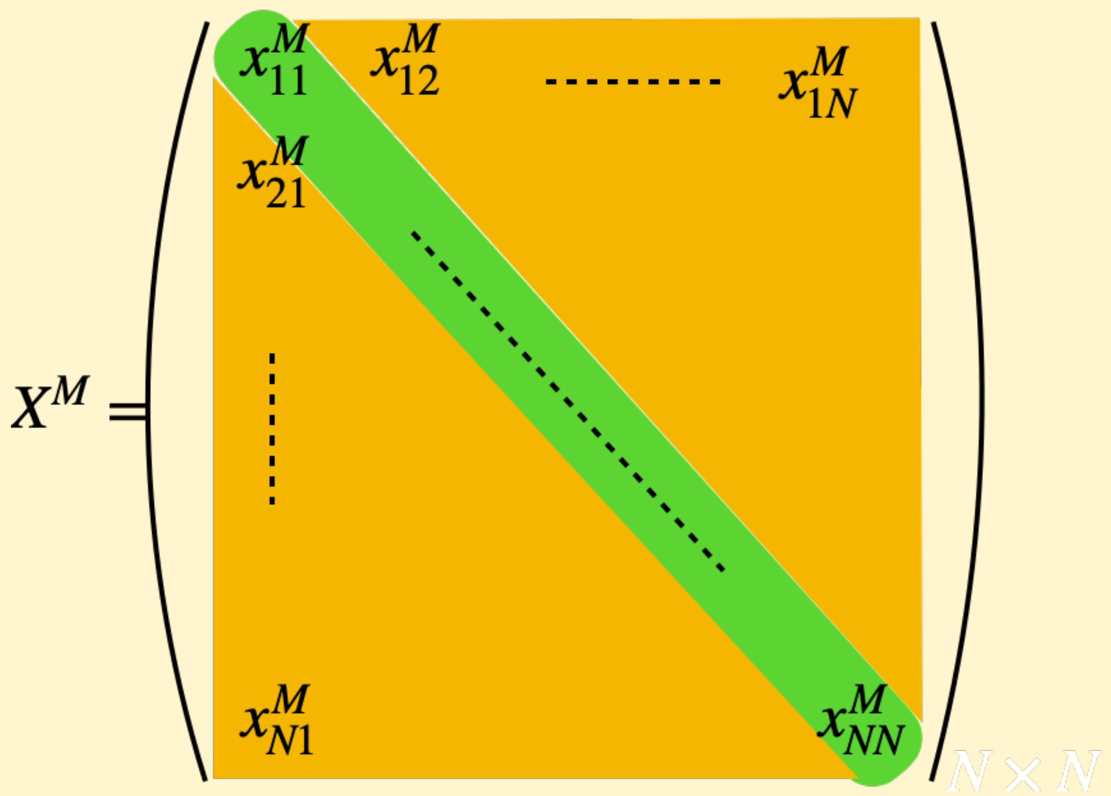
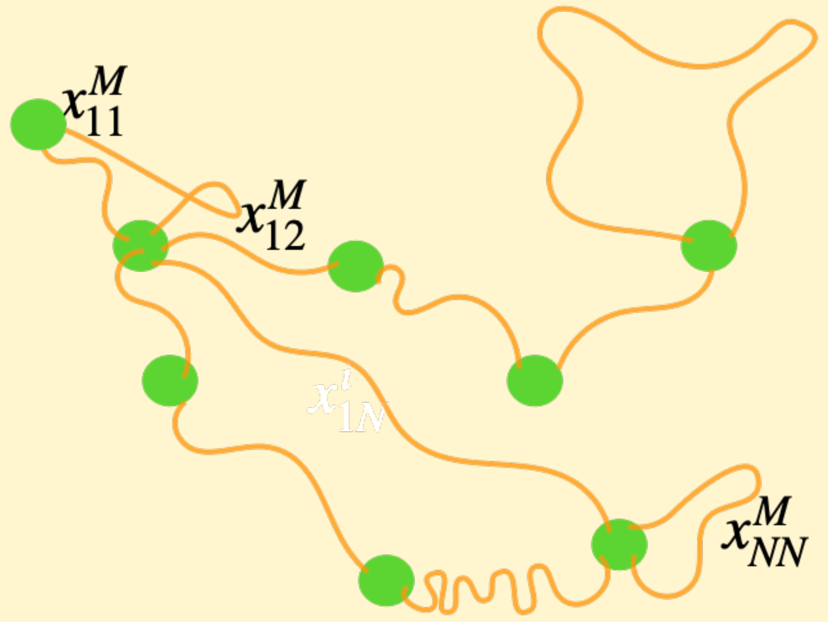
$$V_B = [X_M, X_N]^2 \sim X_M^4$$

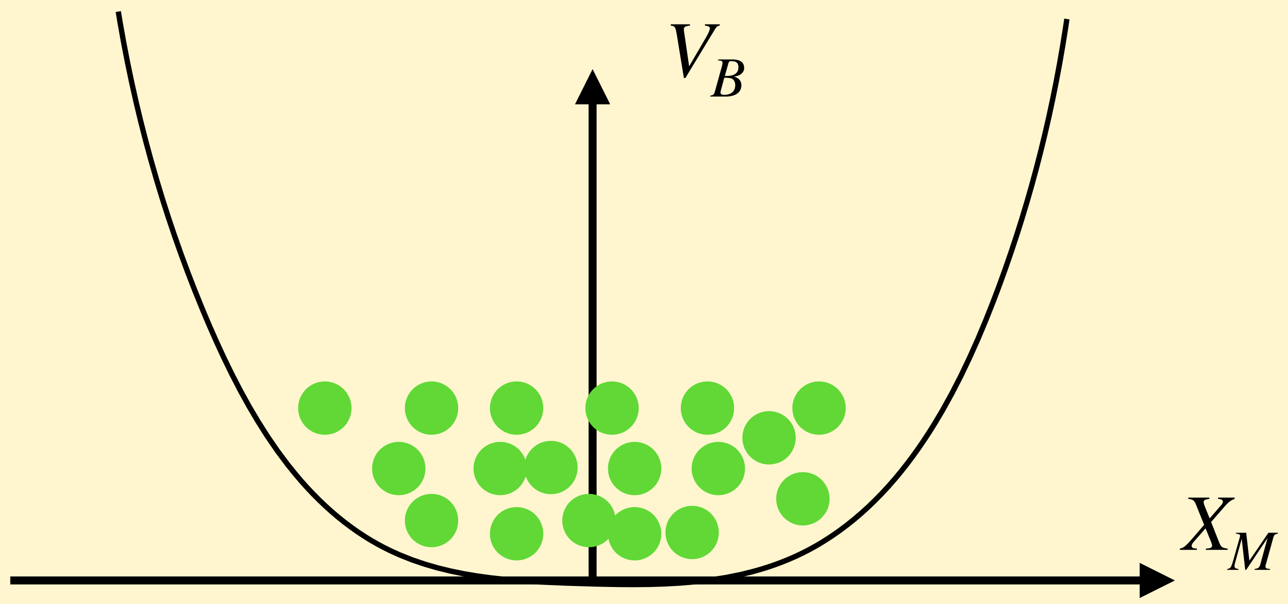


Witten 1995



$\mathbb{R}^9$

$M = 1,\cdots,9$



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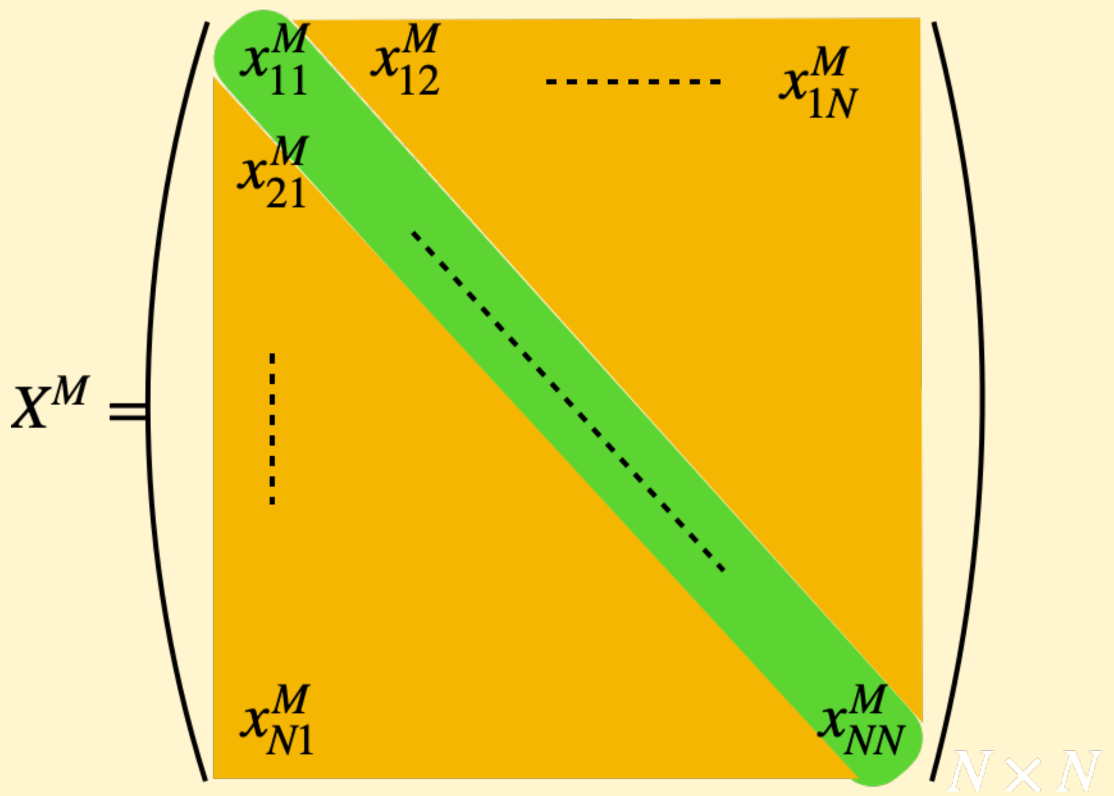

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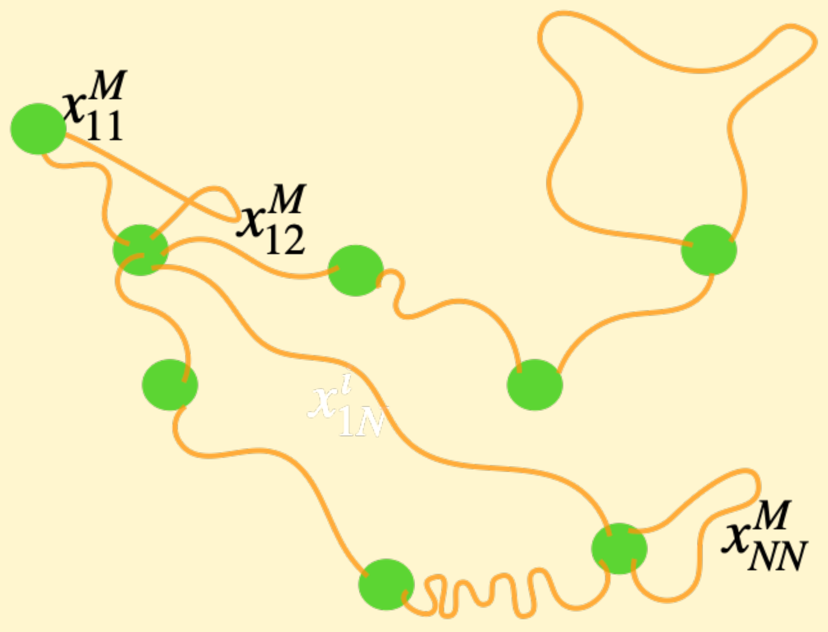

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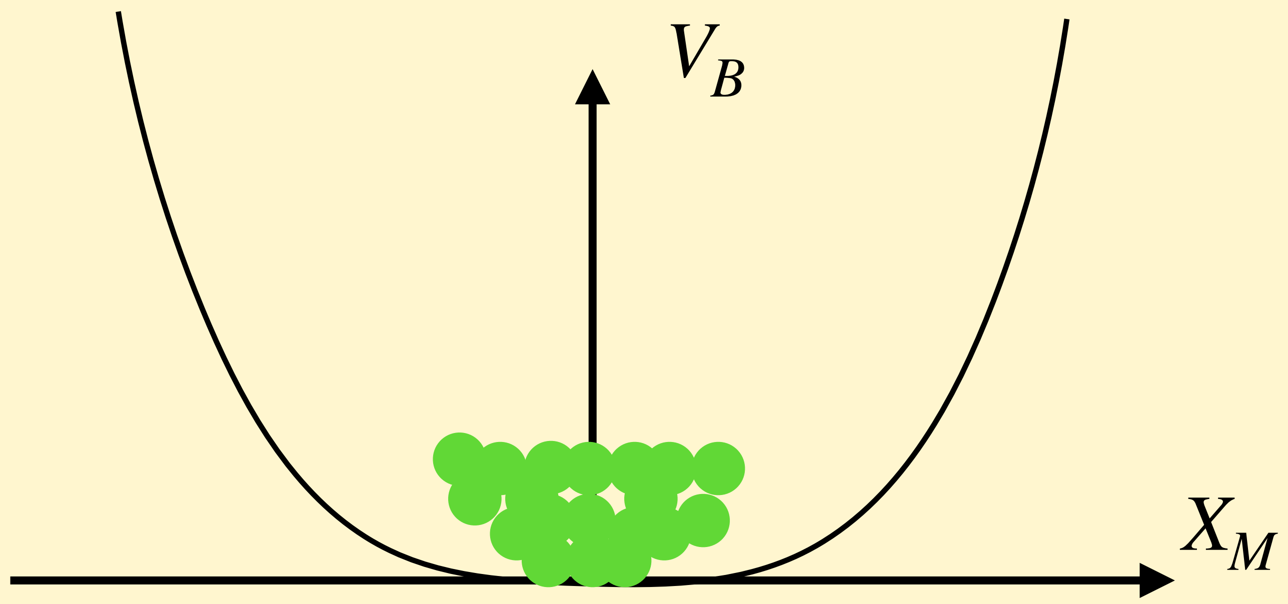


What does this correspond to in the gravity side?

Deformation of the D0-matrix model

The BMN model

Berestein, Maldacena, Nastase, 2002

$$S_{BMN} = S_b + S_f + \Delta S_b + \Delta S_f$$

BFSS

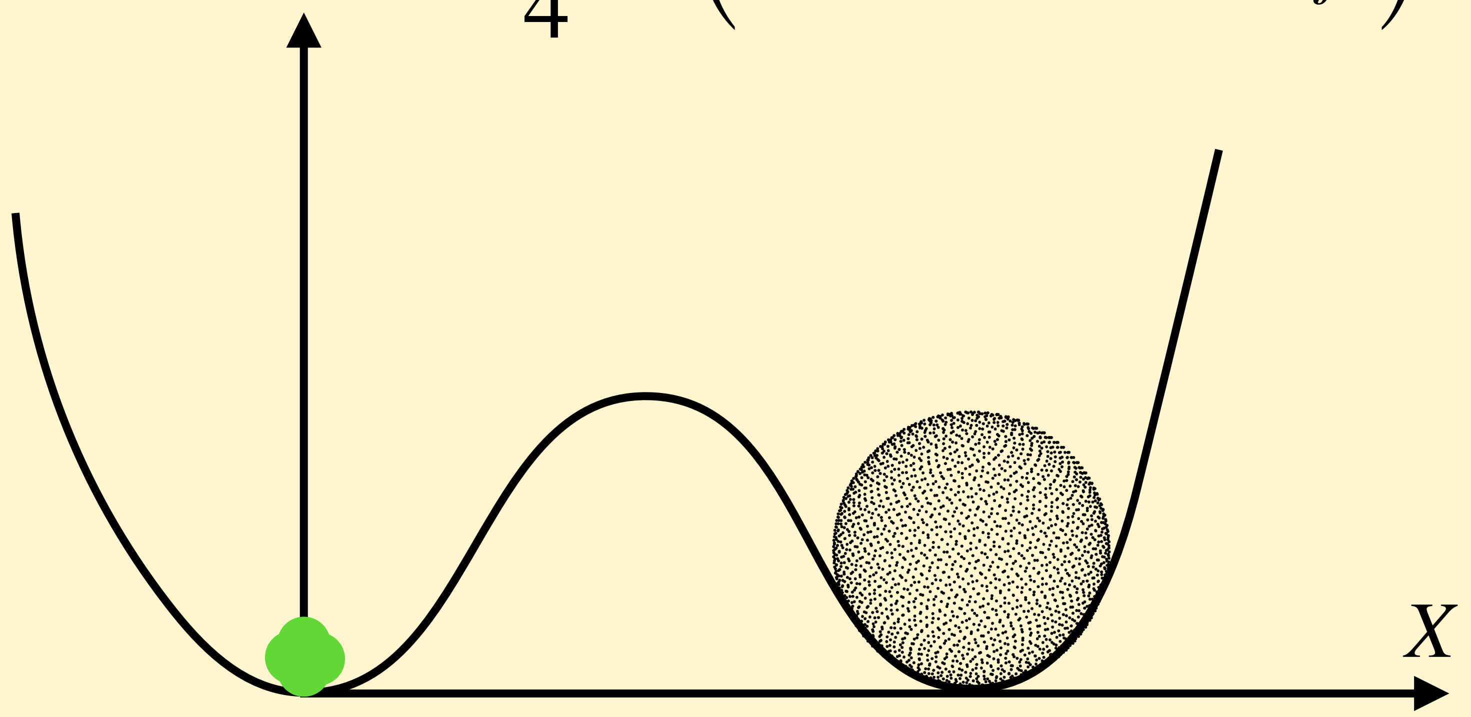
$$S_b = \frac{N}{\lambda}\int_0^\beta dt Tr \left\{ \frac{1}{2}\sum_{I=1}^{9}(D_tX_I)^2 - \frac{1}{4}\sum_{I,J=1}^{9}[X_I, X_J]^2 \right\},$$

$$S_f = \frac{N}{\lambda}\int_0^\beta dt Tr \left\{ i\bar{\psi}\gamma^{10}D_t\psi - \sum_{I=1}^{9}\bar{\psi}\gamma^I[X_I, \psi] \right\},$$

$$\Delta S_b = \frac{N}{\lambda}\int_0^\beta dt Tr \left\{ \frac{\mu^2}{2}\sum_{i=1}^{3}X_i^2 + \frac{\mu^2}{8}\sum_{a=4}^{9}X_a^2 + i\mu\sum_{i,j,k=1}^{3}\epsilon^{ijk}X_iX_jX_k \right\},$$

$$\Delta S_f = \frac{3i\mu N}{4\lambda}\int_0^\beta dt Tr\left(\bar{\psi}\gamma^{123}\psi\right),$$

$$V_{SO(3)} = \frac{1}{4}Tr\left(\mu\epsilon^{ijk}X_k + i[X_i, X_j]\right)^2$$



- Mass terms for bosons, fermions
- $SO(9) \rightarrow SO(3) \times SO(6)$
- $SU(2)$ vacua, i.e fuzzy spheres

The curious case of p=0

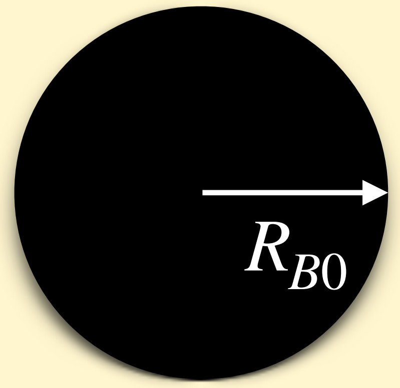
$$g_{eff} = \frac{\lambda}{E^3}$$

Strong coupling ⟷ Low energies

Black zero-brane in IIA SUGRA

$$\frac{ds^2}{\alpha'} = H(r)^{-\frac{1}{2}} f(r) dt^2 + H(r)^{\frac{1}{2}} \left(\frac{dr^2}{f(r)} + r^2 d\Omega_8^2 \right)$$

$$H(r) = \frac{240\pi^5 \lambda}{r^7}, \ f(r) = 1 - \left(\frac{r_0}{r} \right)^7$$



$$E = 7.41 N^2 \lambda^{-3/5} T^{14/5}, \quad S = 11.52 N^2 \lambda^{-3/5} T^{9/5}$$

$$\frac{R_{B0}^2}{\alpha'} \sim g_{eff}^{\frac{1}{2}} \sim \sqrt{\frac{\lambda}{E^3}}$$

$$e^{\phi}\Big|_{horizon} \sim \frac{g_{eff}^{7/4}}{N}$$

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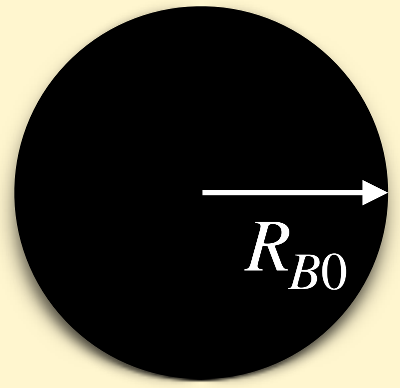

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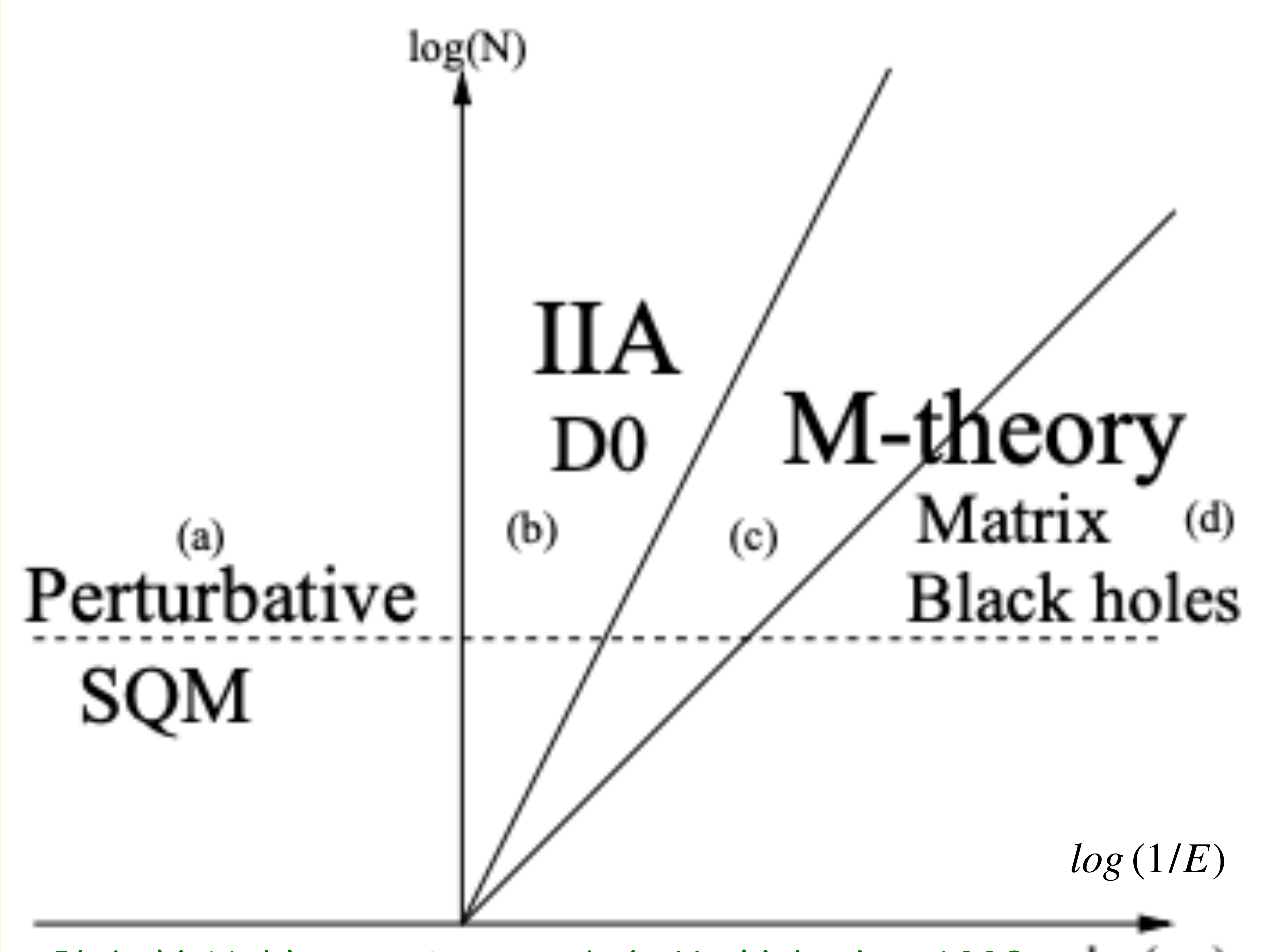

Itzhaki-Maldacena-Sonnenschein-Yankielowicz, 1998

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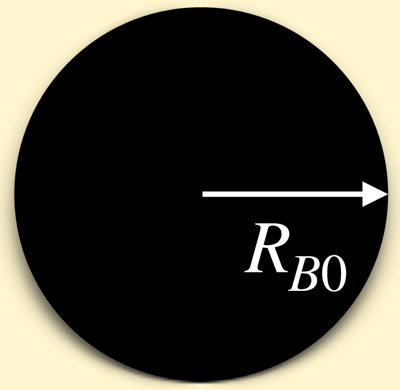

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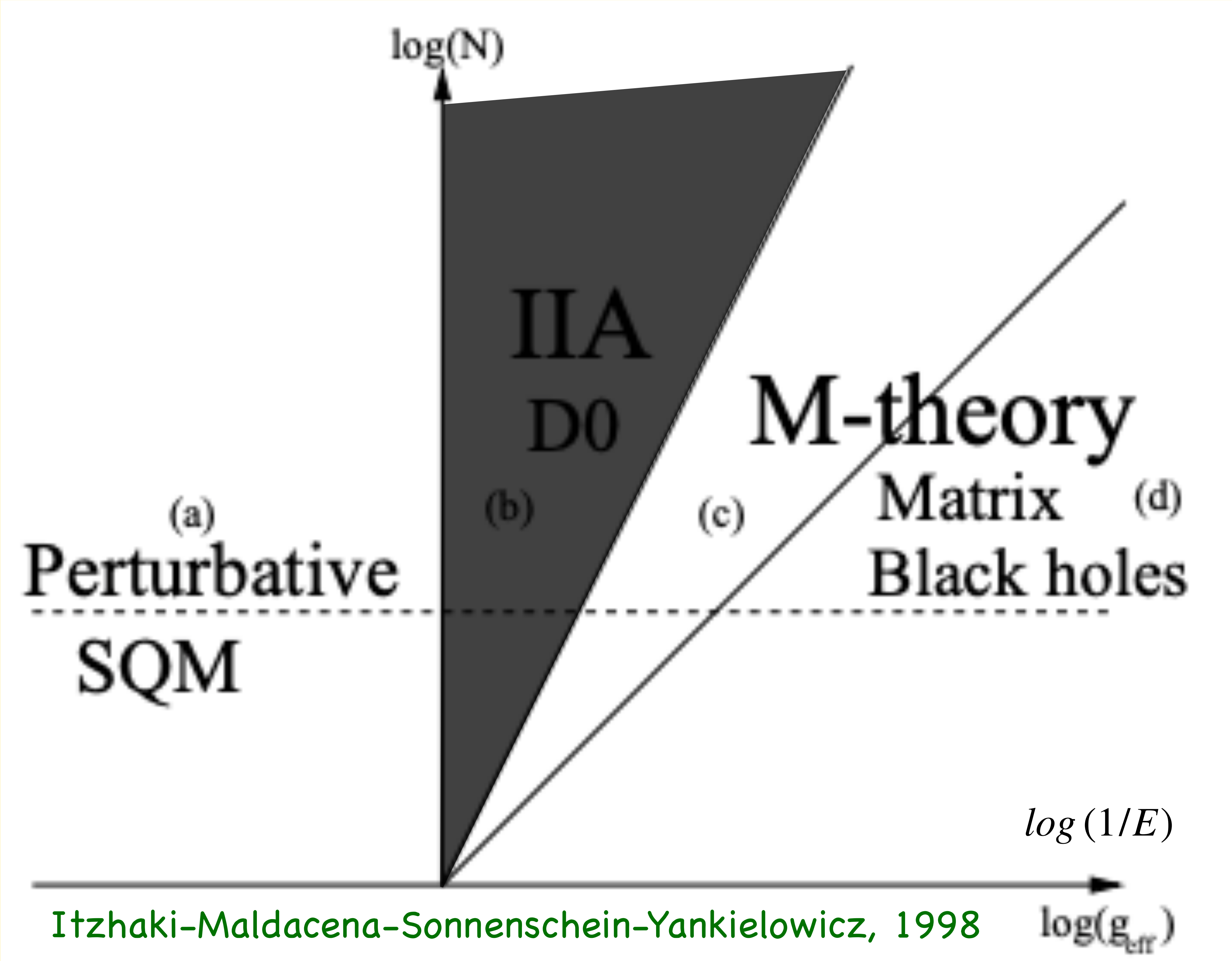

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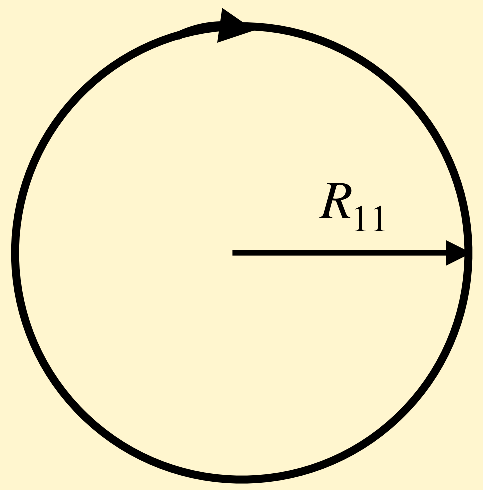
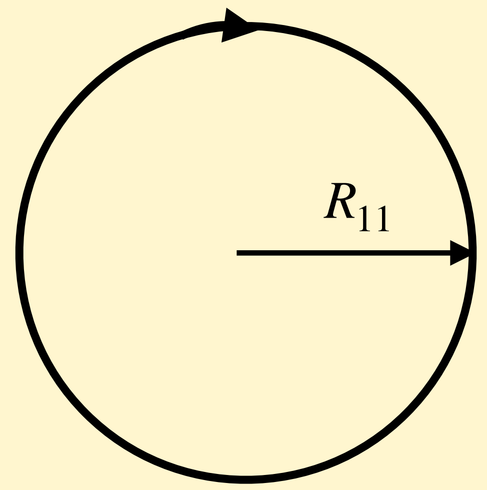


Type IIA string theory is defined as M-theory compactified on a circle $\mathbf{S}^1$

$R_{11} \sim 2\pi g_s l_s = 2\pi l_s e^{\phi} \simeq l_s \frac{g_{\text{eff}}^{7/4}}{N}, \quad g_{\text{eff}} = \frac{\lambda}{E^3}$ Strong coupling/low energies corresponds to the M-theory region

To probe M-theory region $E \ll 1$ $(E = 7.41 N^2 \lambda^{-3/5} T^{14/5})$ ⟶ Low temperatures

The curious case of p=0



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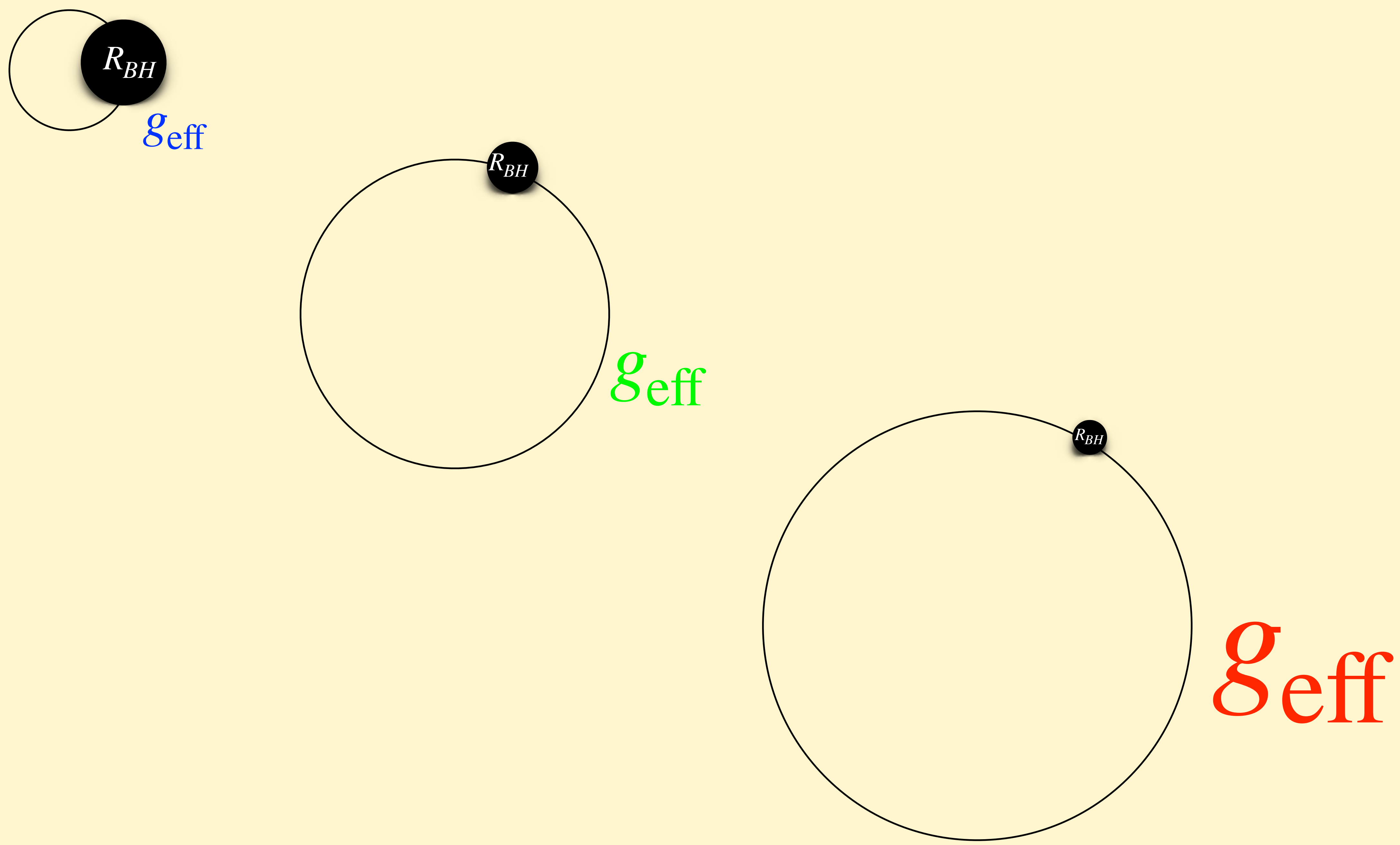
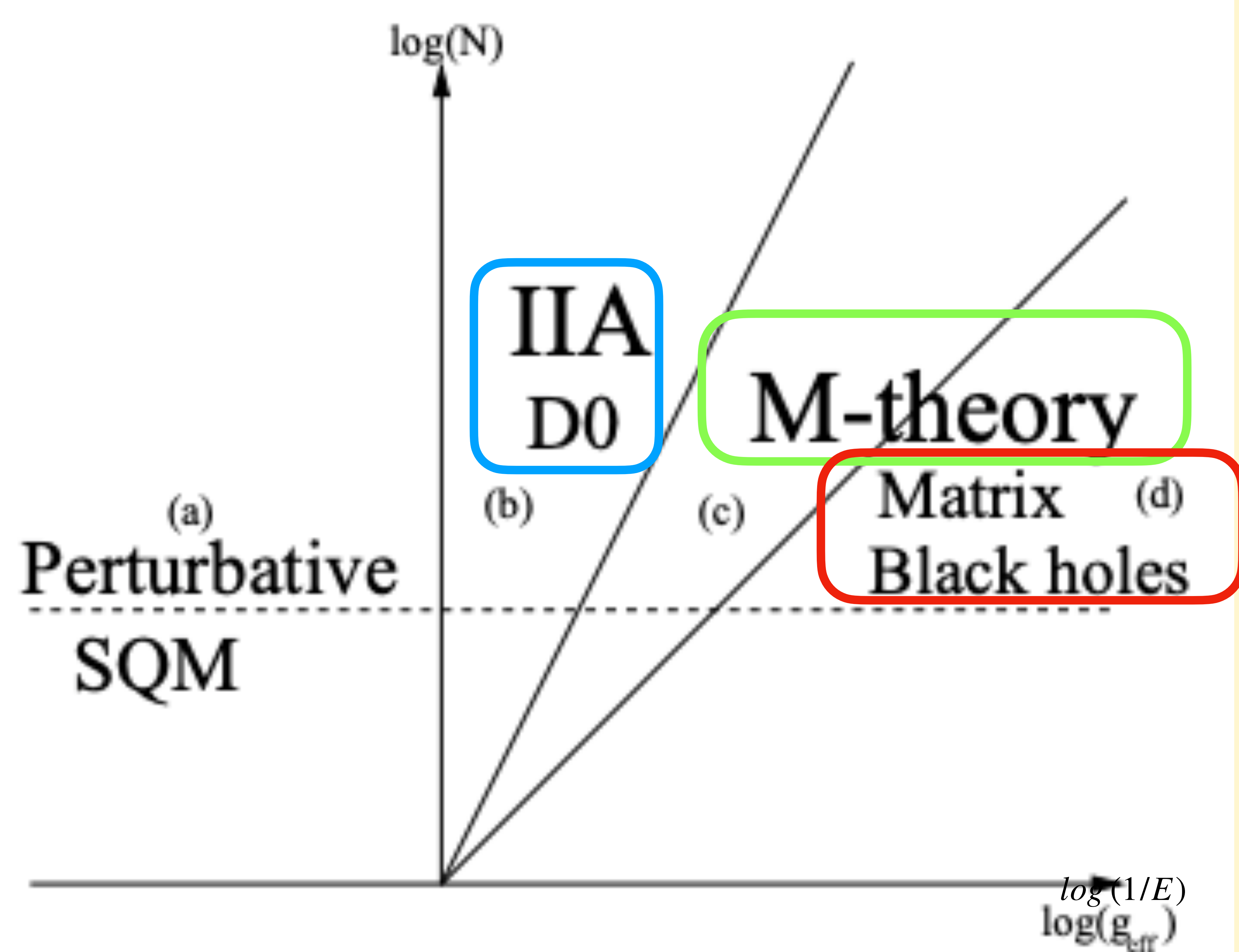
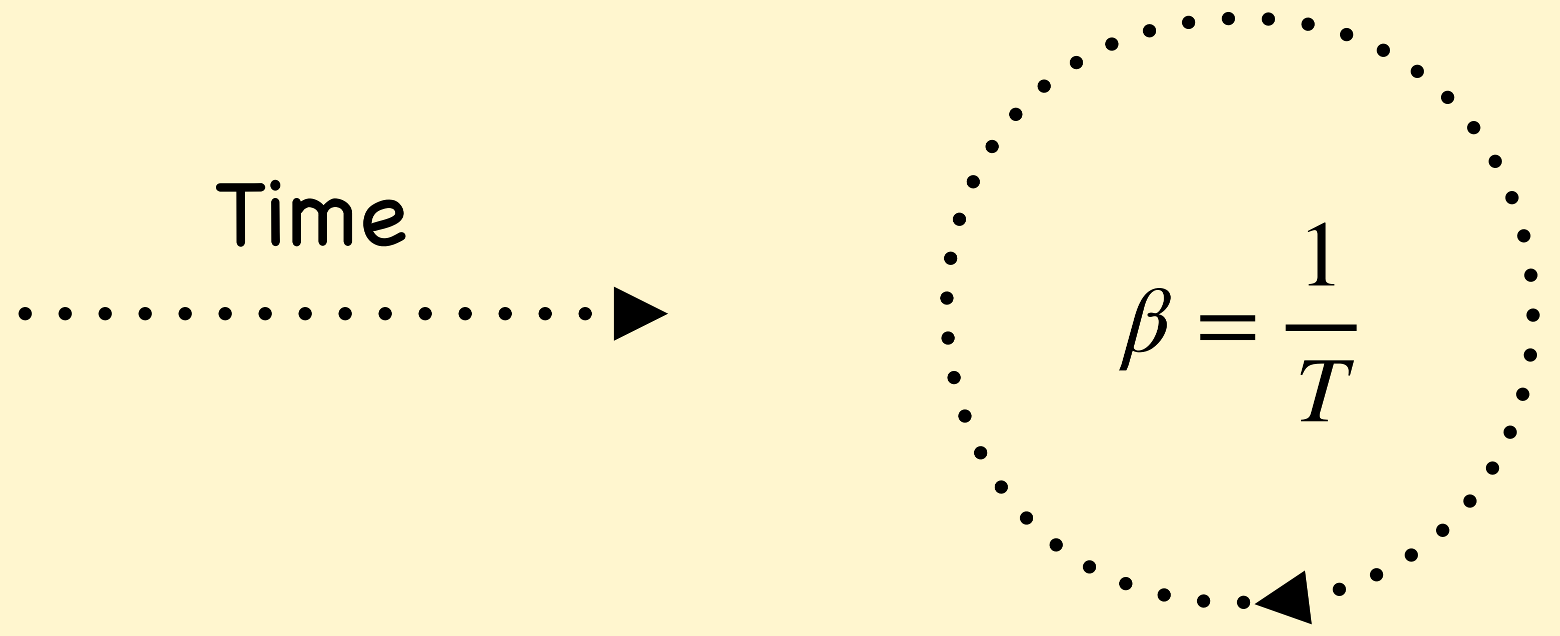




Switch to simulations

Model on the lattice

- We can do Monte Carlo simulations
- Borrow techniques from lattice QCD
- (0+1)-d matrix quantum mechanics



- Parameters

$N \longrightarrow X_{N\times N}$

$S \longrightarrow$ Lattice points

$T \longrightarrow$ Temperature

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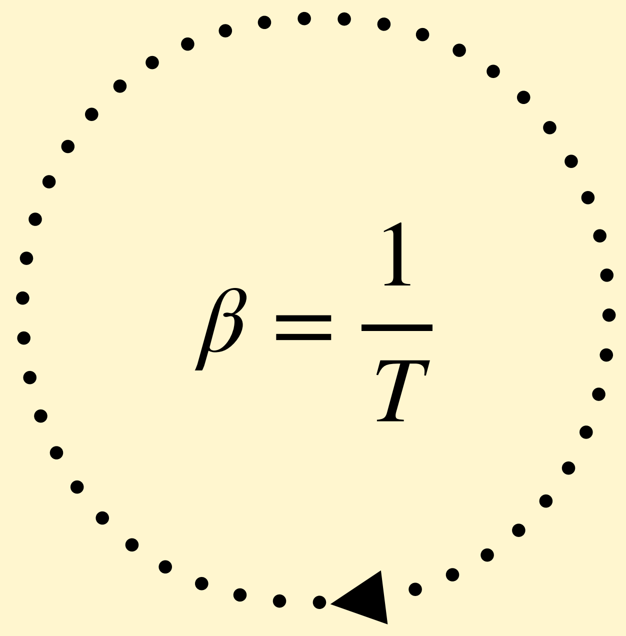
Time



- Parameters

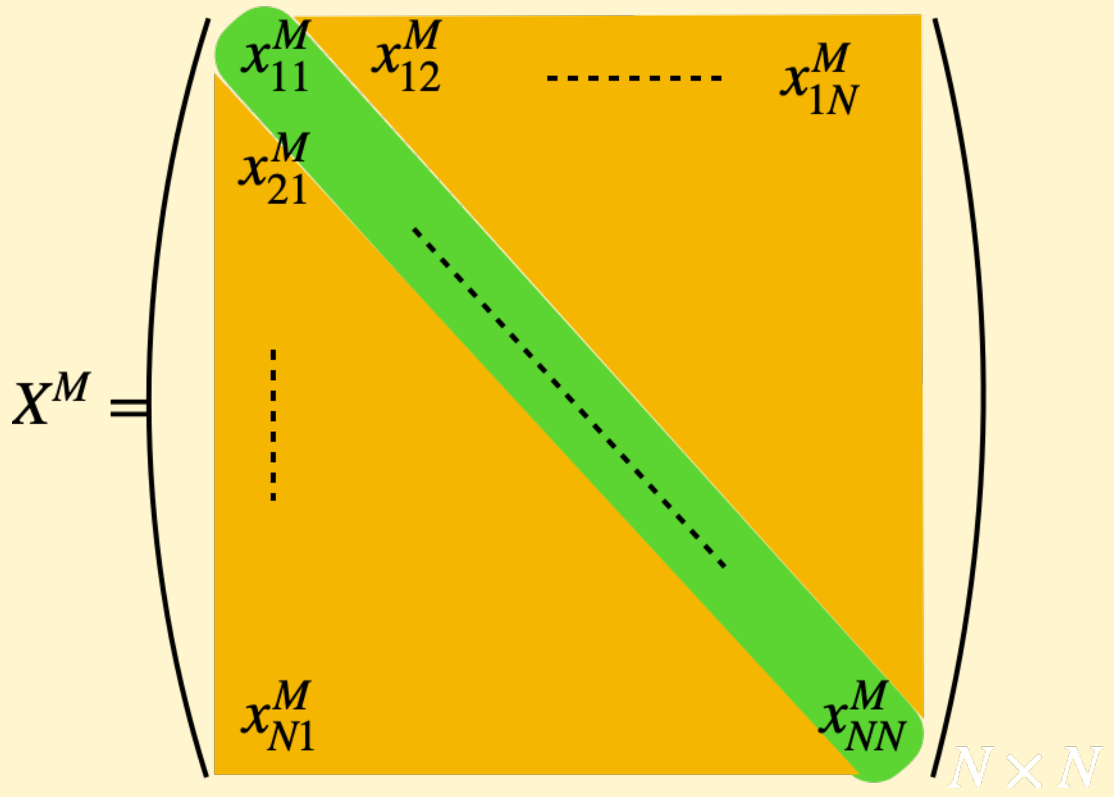
N ⟶ $X_{N\times N}$

S ⟶ Lattice points

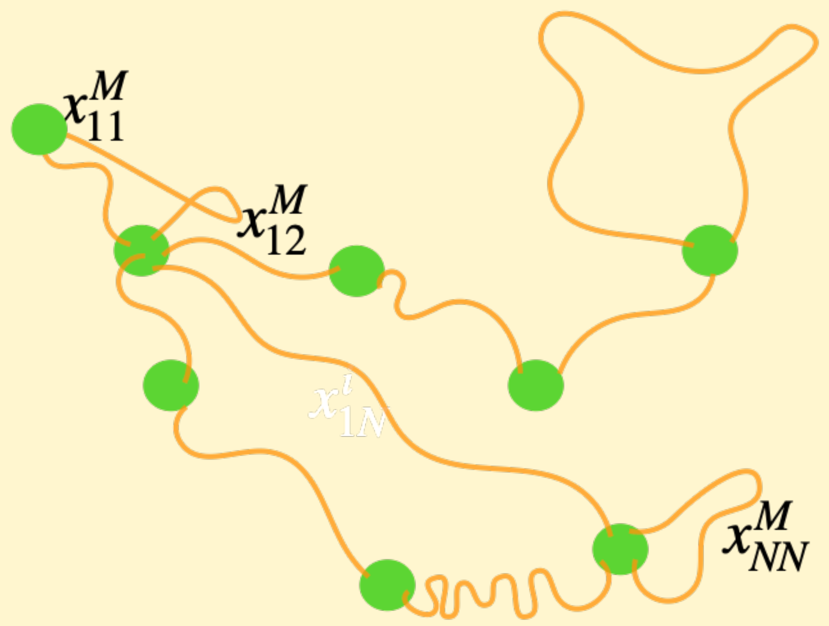
T ⟶ Temperature

large N limit

$\lambda \sim N^0$, $T \sim N^0$ ⟷ $\lambda = 1$: **fix**, $\lambda^{-\frac{1}{3}} T \sim N^0$: **fix**



Witten 1995



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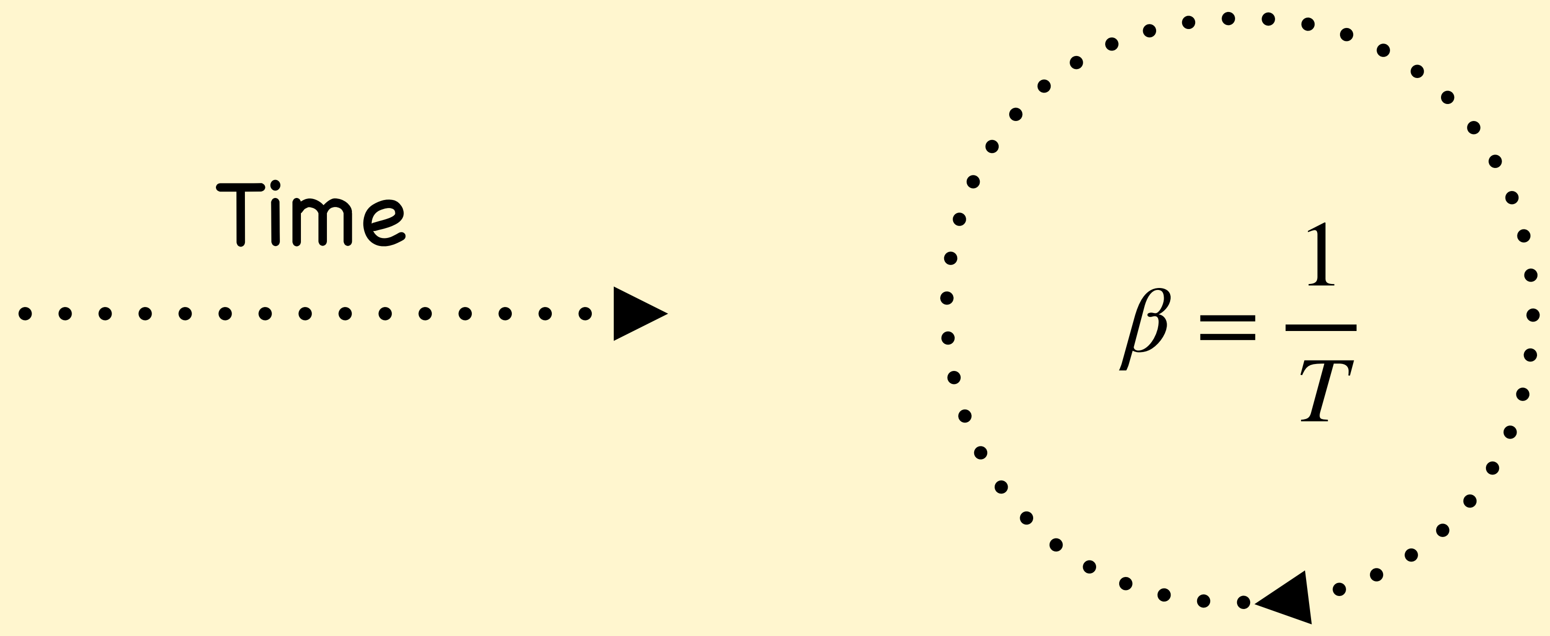

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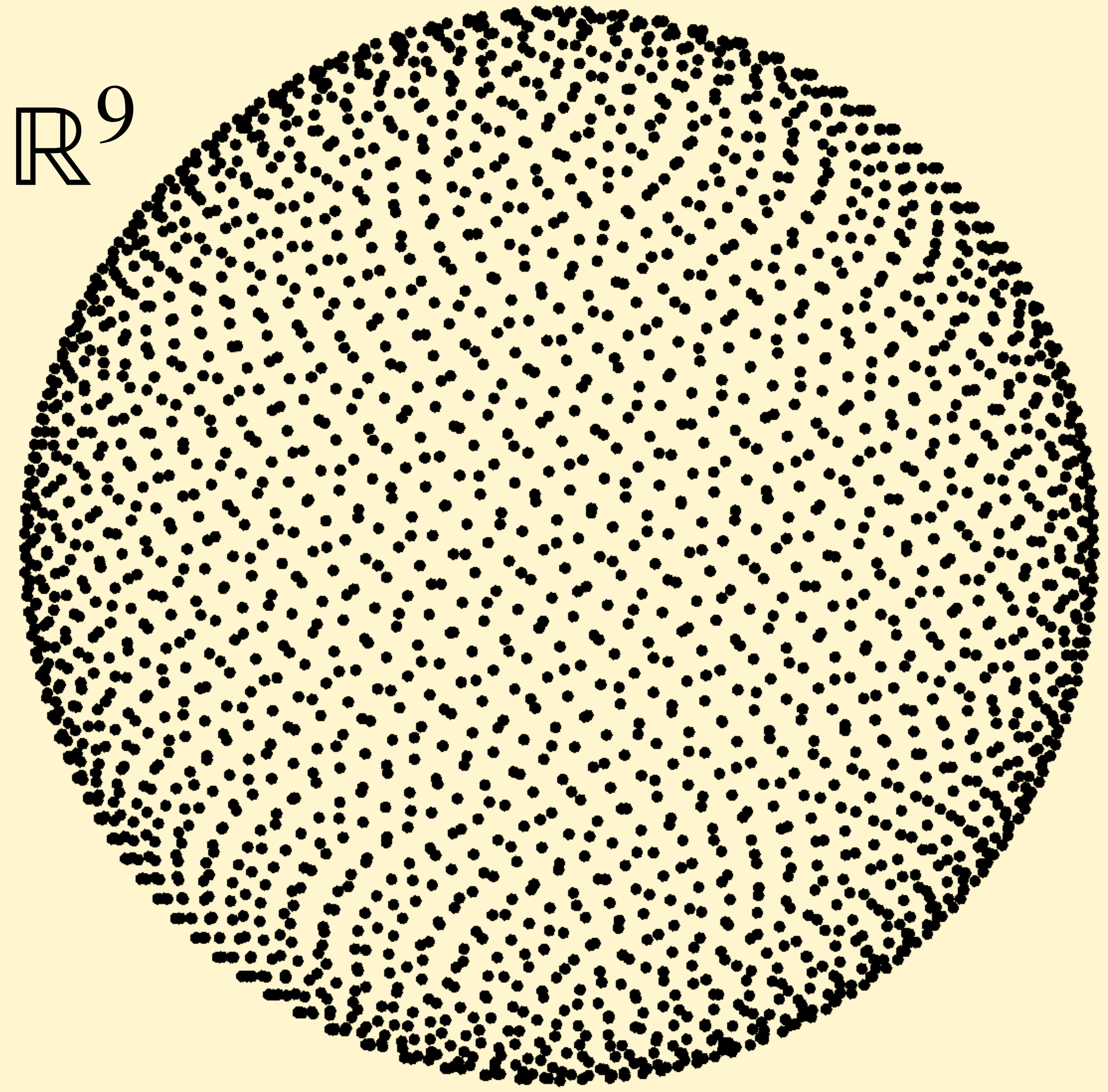
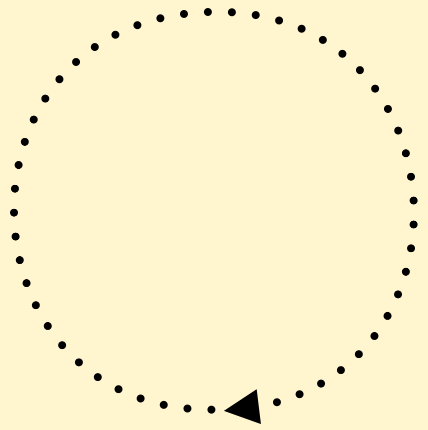


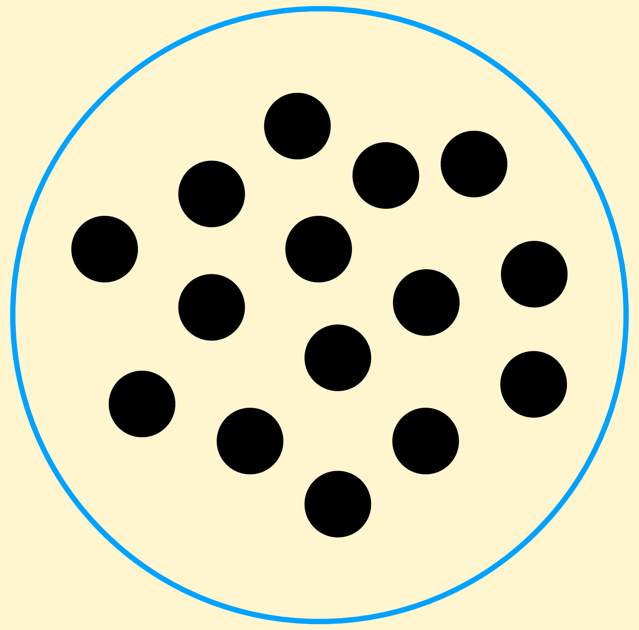
Confinement/deconfinement

- Polyakov loop $P = \frac{1}{N} Tr\left(\mathscr{P}exp\left(i\int_0^\beta dtA_t\right)\right) = \frac{1}{N}\sum_{j=1}^{N} e^{i\theta_j}$ On the lattice

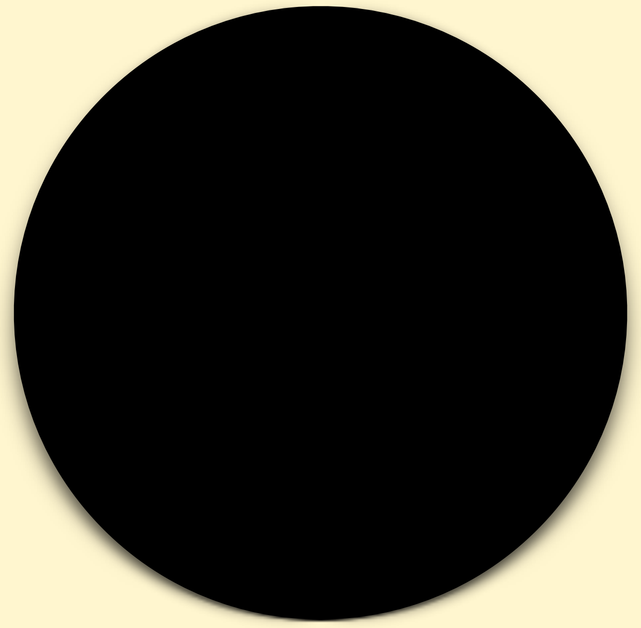


- Restoration/breaking of $U(1)$ symmetry

- Intuition from $AdS_5 \times S^5$



Gravity side



$E, P = 0$

Confinement
Graviton gas

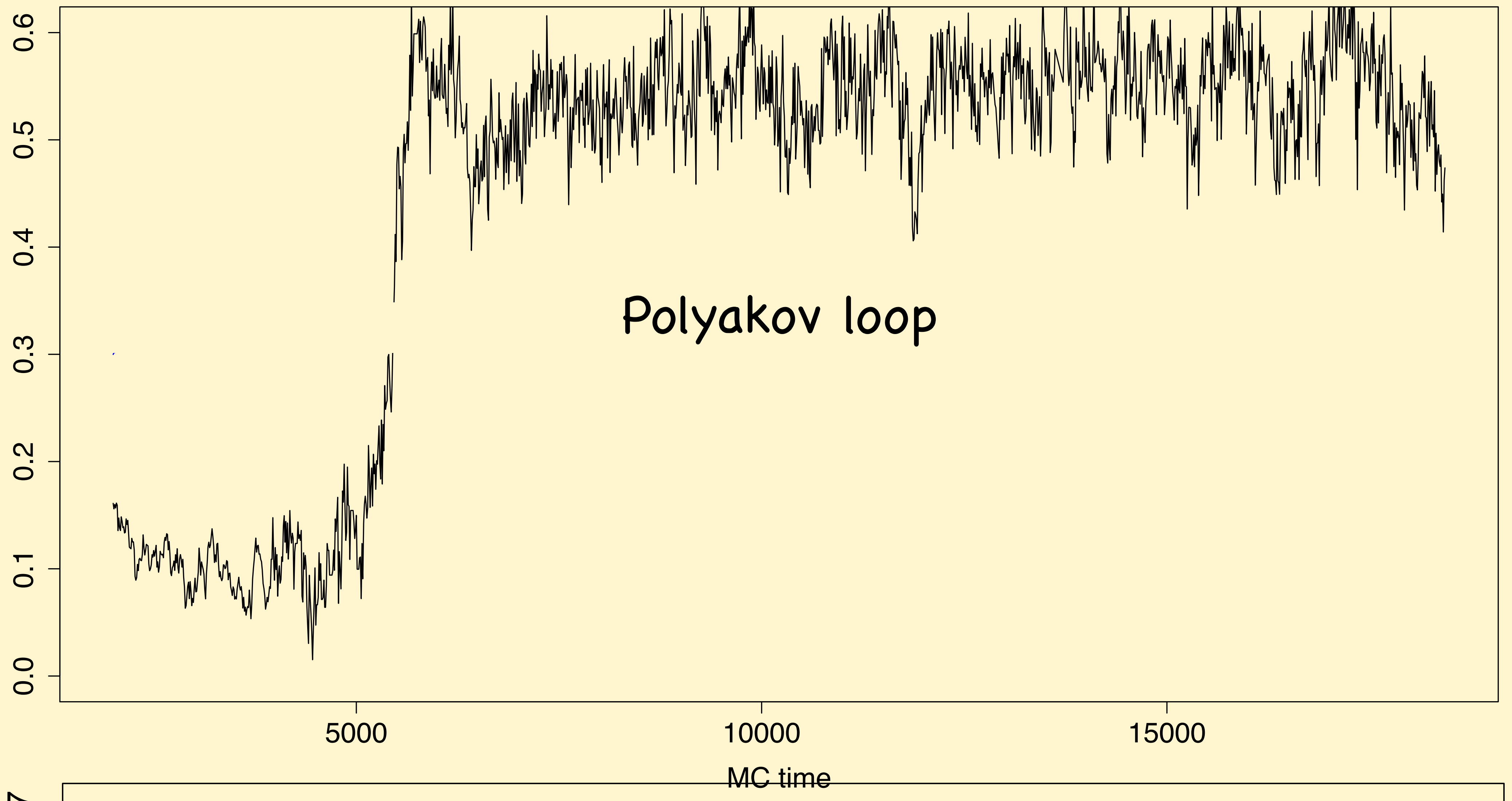
MAGOO, Witten, Sundborg

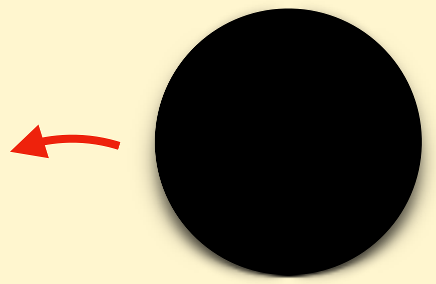
Aharony-Marsano-Minwalla-Papadodimas-Van Raamsdonk, 2003

$E \neq 0,\ P \gtrsim \frac{1}{2}$

Deconfinement
Black holes

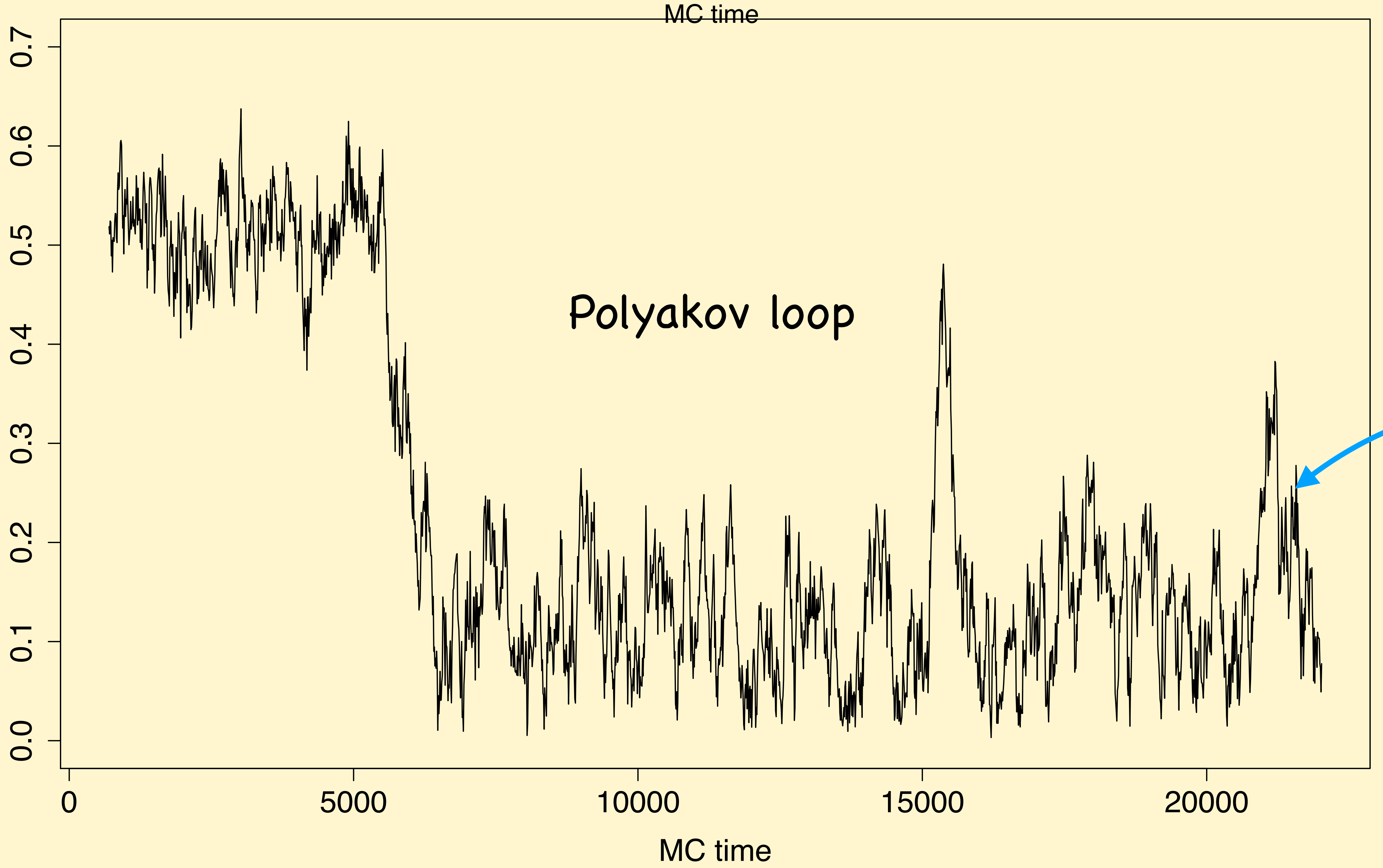
Confinement/deconfinement



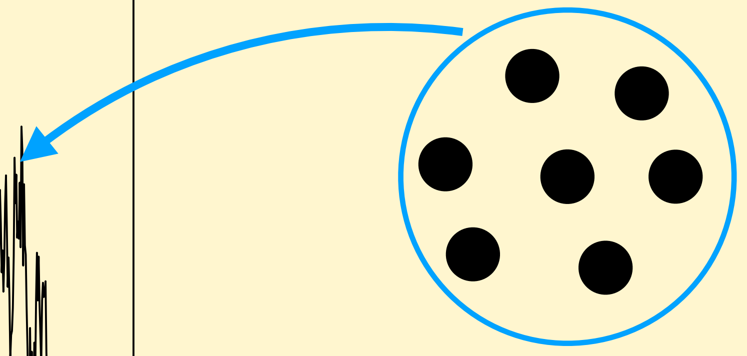


deconfined

$$P \gtrsim \frac{1}{2}$$

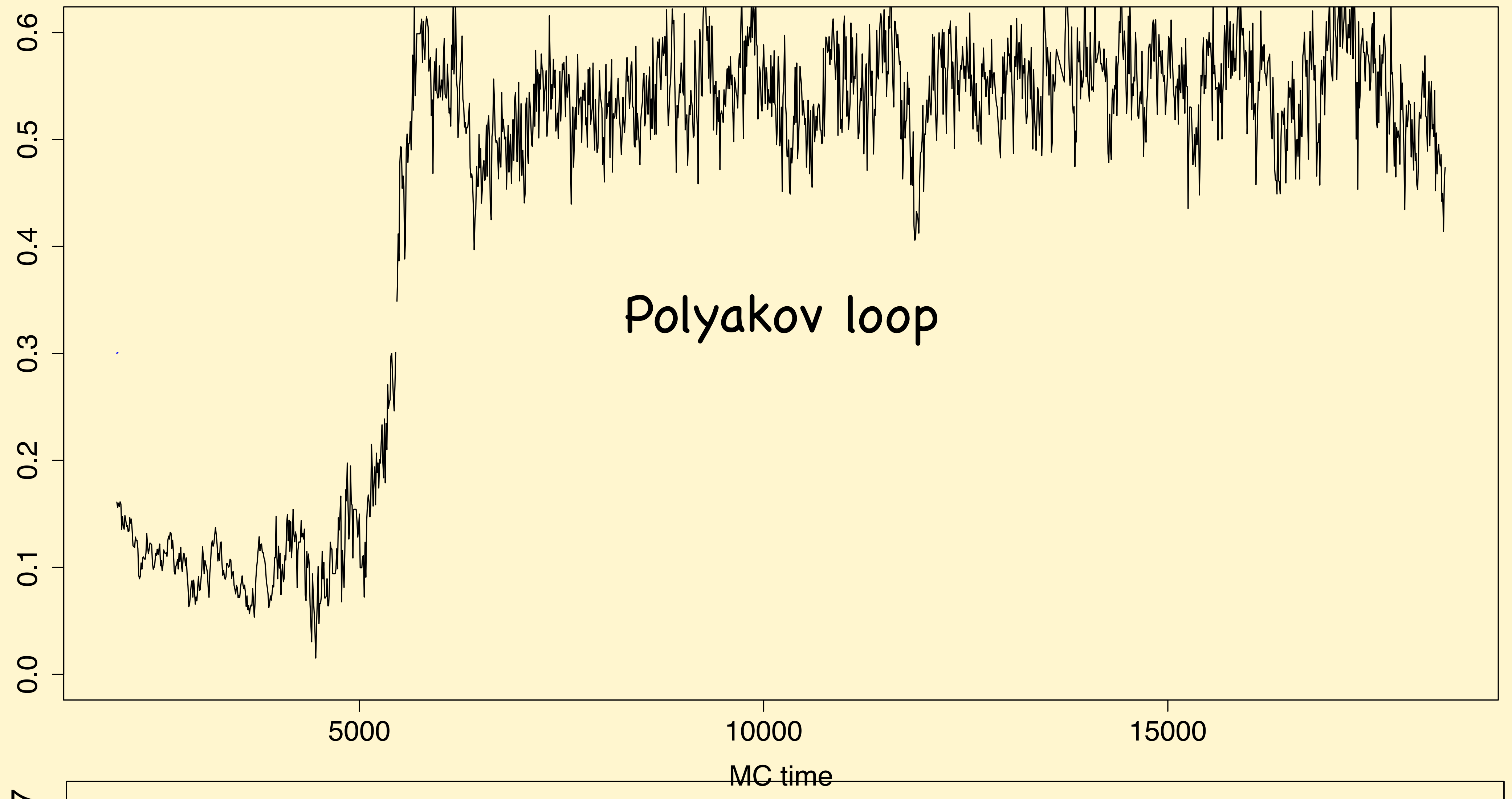


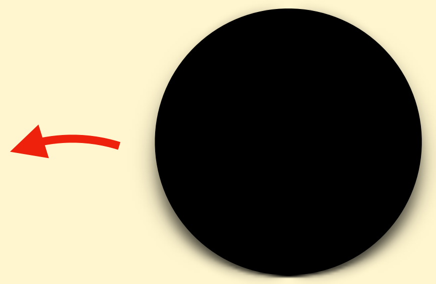
Confined



$$P \approx 0$$

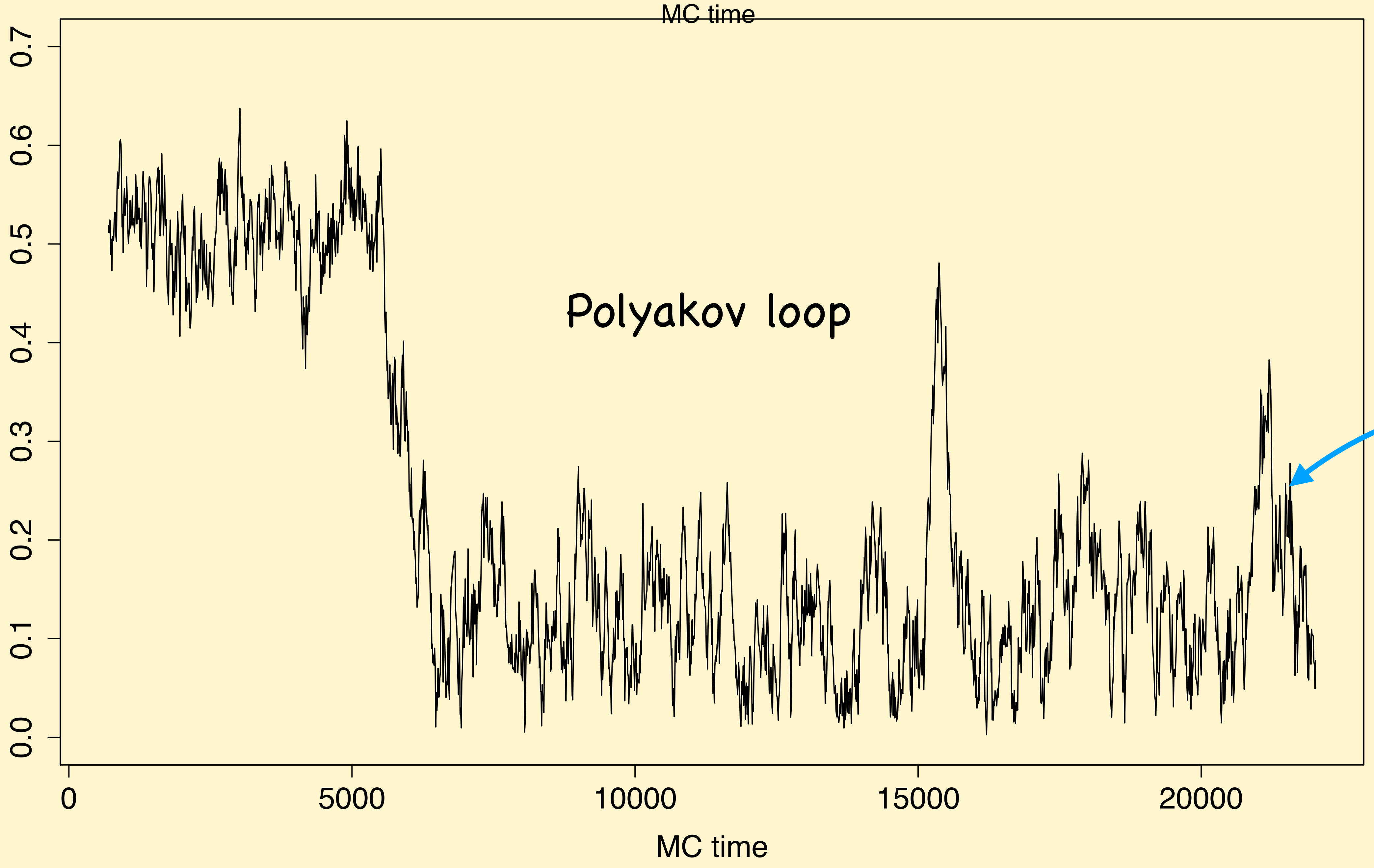
Confinement/deconfinement



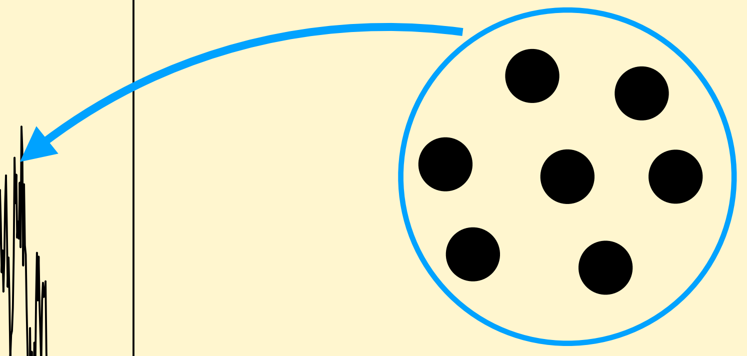


deconfined

$P \gtrsim \frac{1}{2}$



Confined



$P \approx 0$

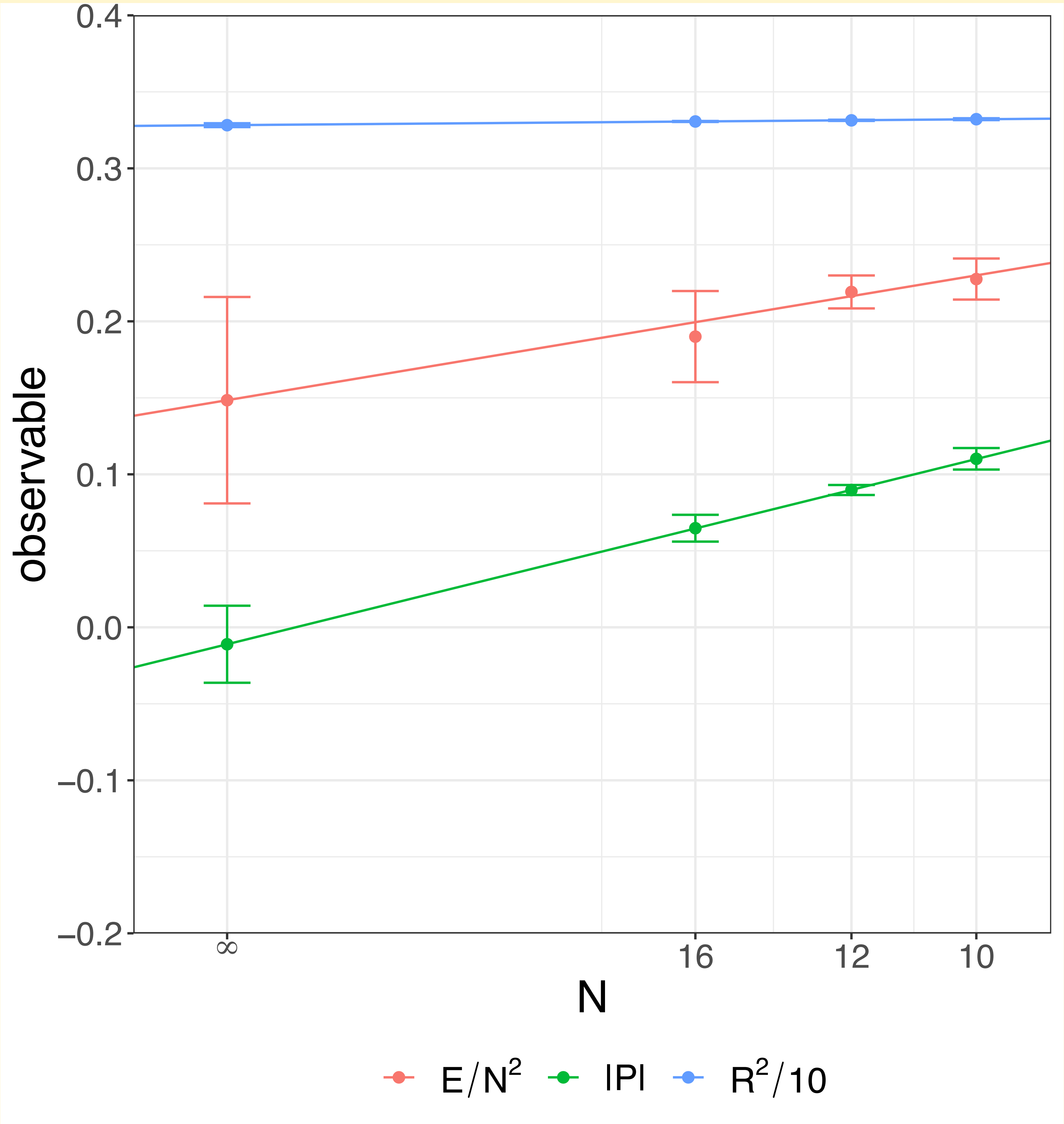
The gravity theory predicts always deconfinement

$(E = 7.41 N^2 \lambda^{-3/5} T^{14/5})$

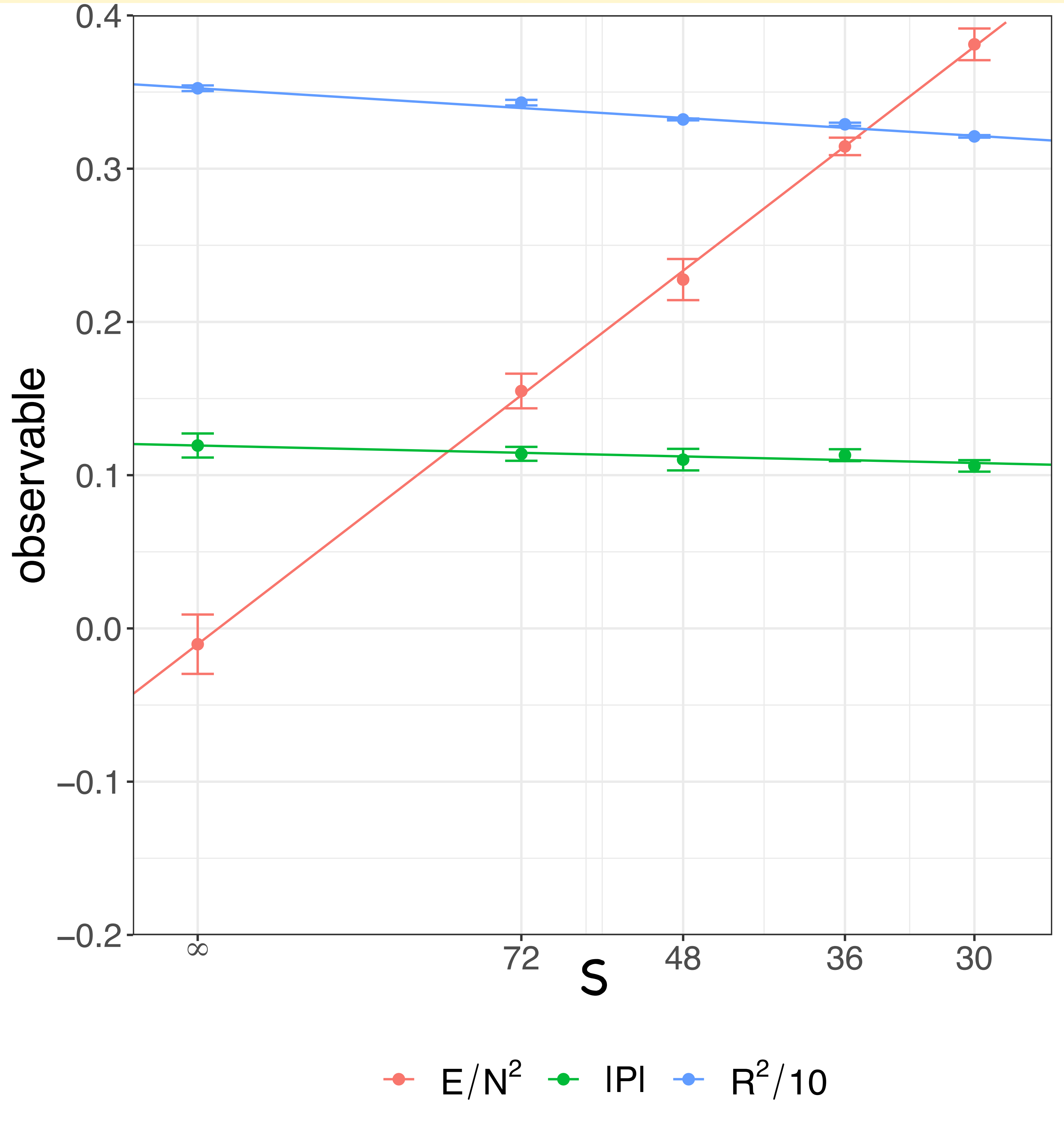
How to understand this?

Confined studies of D0-matrix model

Large N and S=48 @ T=0.2



Continuum and N=10 @ T=0.2



Combine both

Deconfined phase

$$\frac{E}{N^2} \simeq 7.41 T^{\frac{14}{5}} \simeq 0.0818 \qquad @\ T=0.2$$

$$P \simeq 0.5 \qquad @\ T=0.2$$

Confined phase

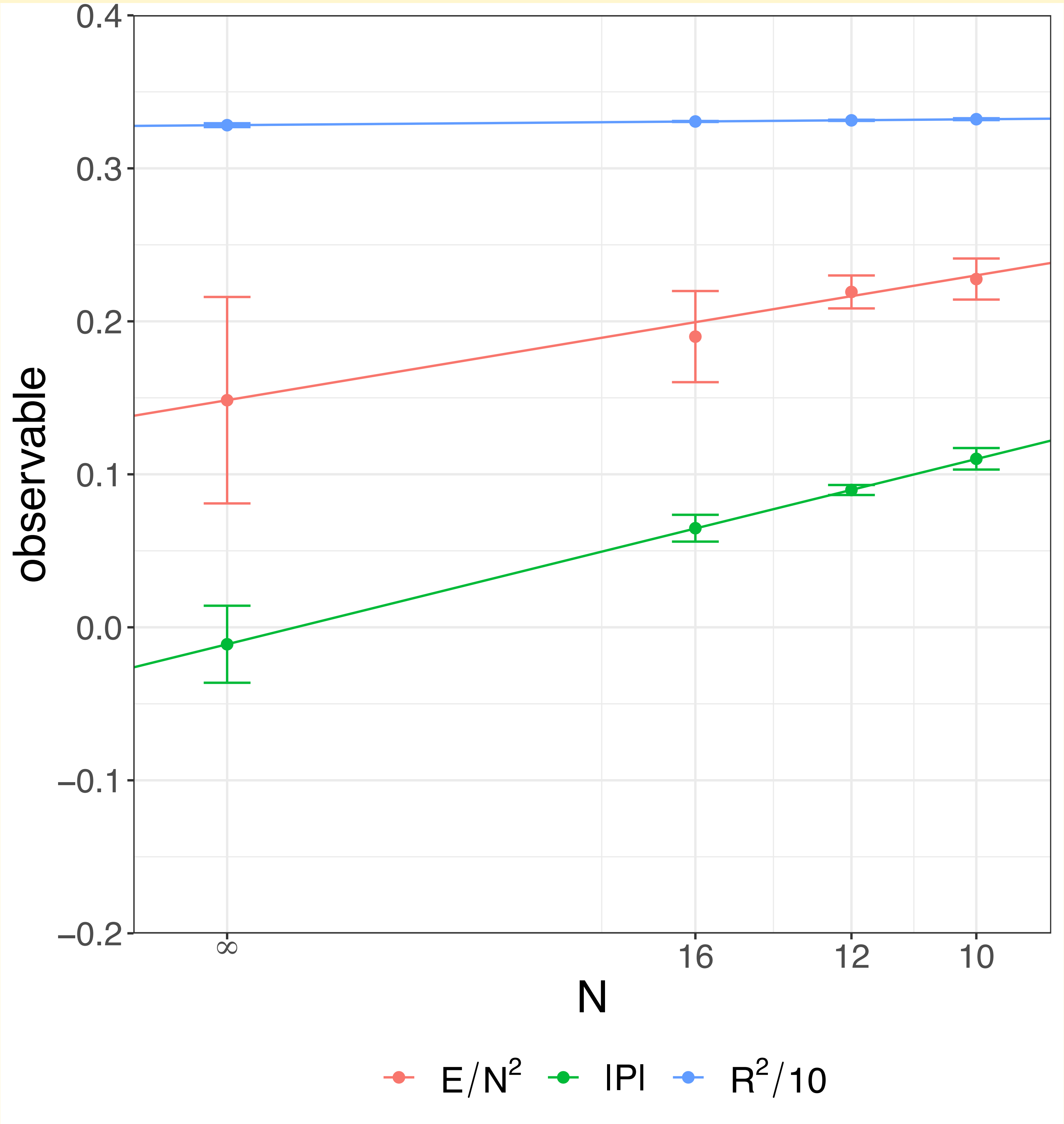
$$E \simeq 0$$

$$P \simeq 0$$

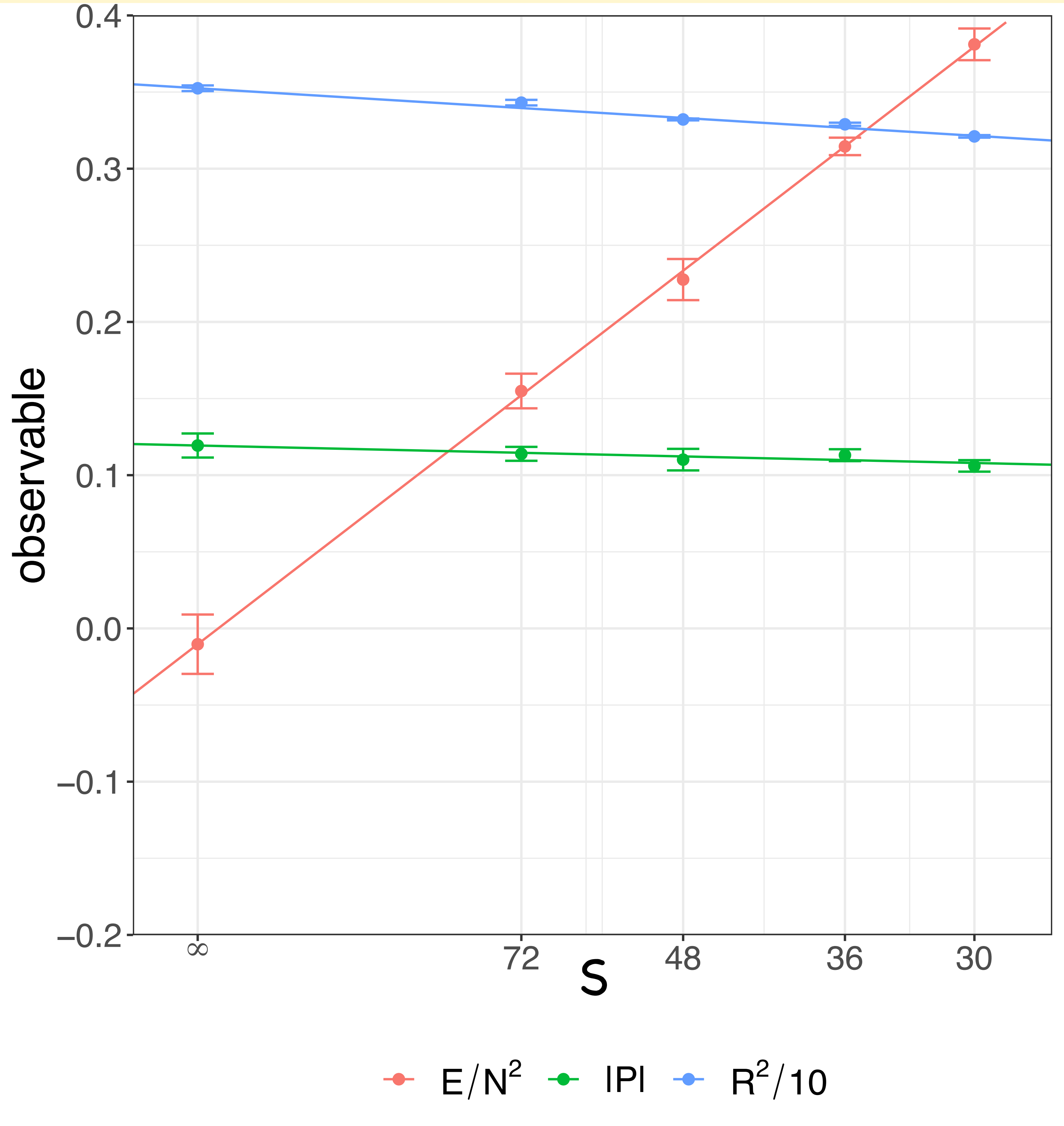
@ large N and continuum

Confined studies of D0-matrix model

Large N and S=48 @ T=0.2



Continuum and N=10 @ T=0.2



Combine both

Deconfined phase ✗

$$\frac{E}{N^2} \simeq 7.41 T^{\frac{14}{5}} \simeq 0.0818 \quad \text{@ T=0.2}$$

$$P \simeq 0.5 \quad \text{@ T=0.2}$$

Confined phase

$$E \simeq 0$$

$$P \simeq 0$$

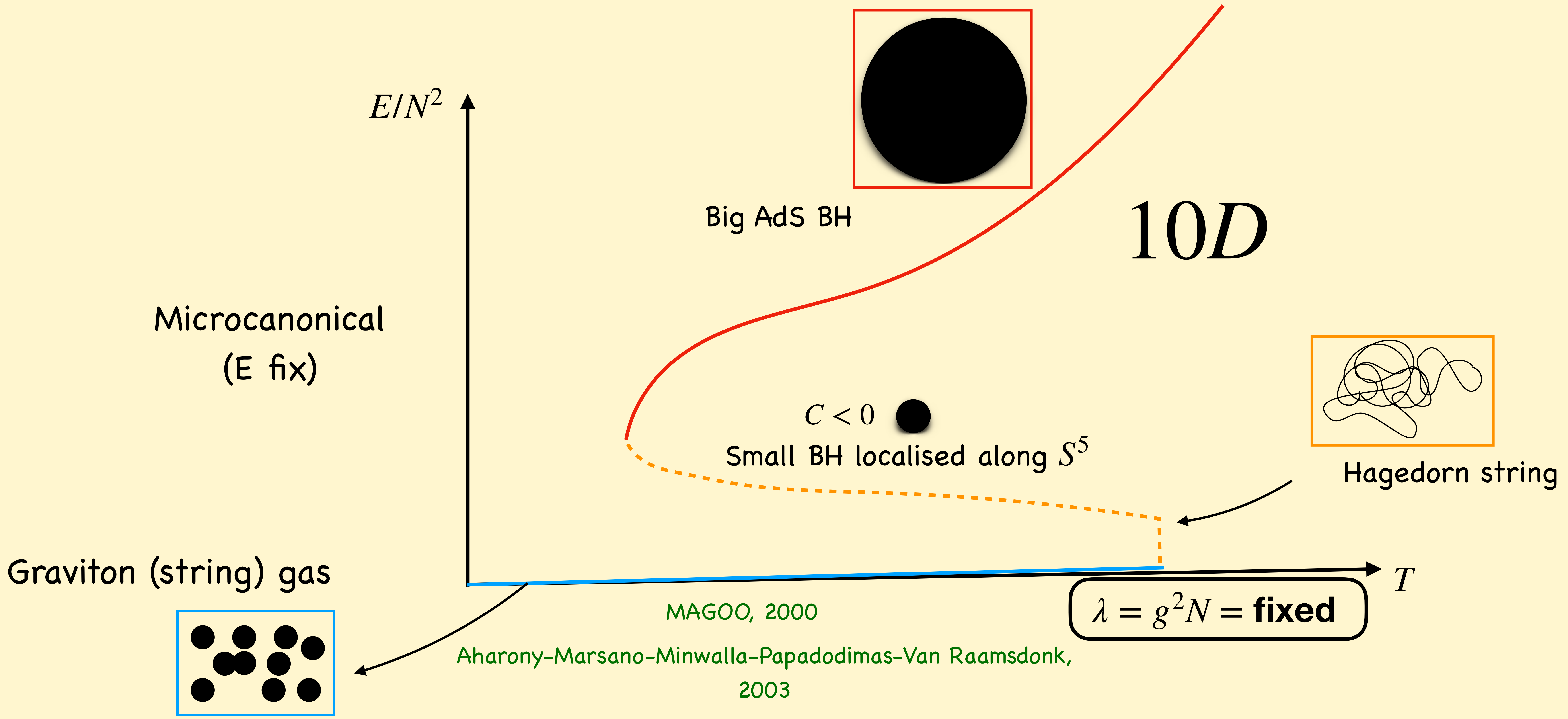
@ large N and continuum

Conventional holography

How to understand confinement?

Motivation from
$AdS_5 \times S^5$

Microcanonical
(E fix)



MAGOO, 2000

Aharony-Marsano-Minwalla-Papadodimas-Van Raamsdonk, 2003

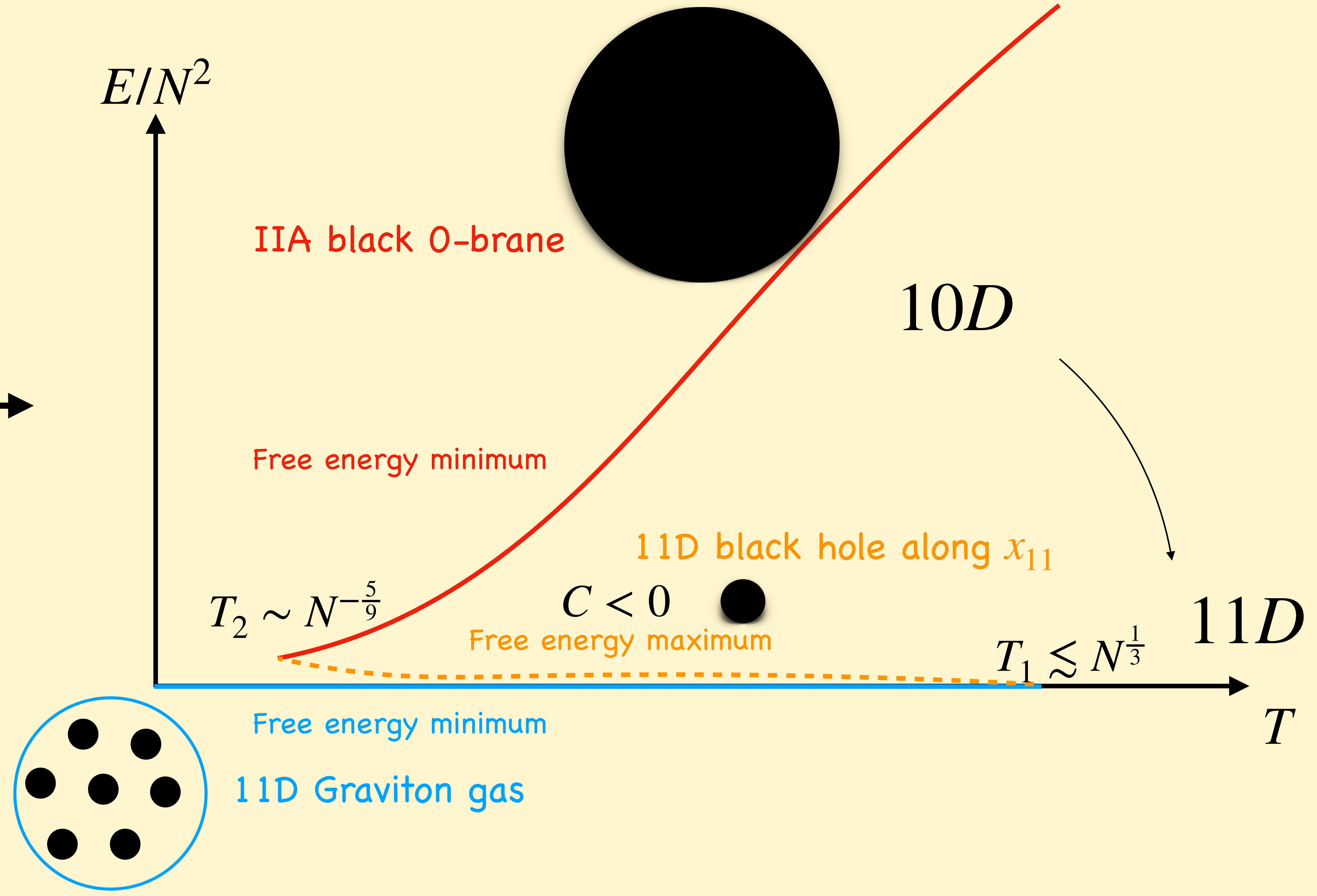
Confinement in the D0-matrix model

How to understand confinement?

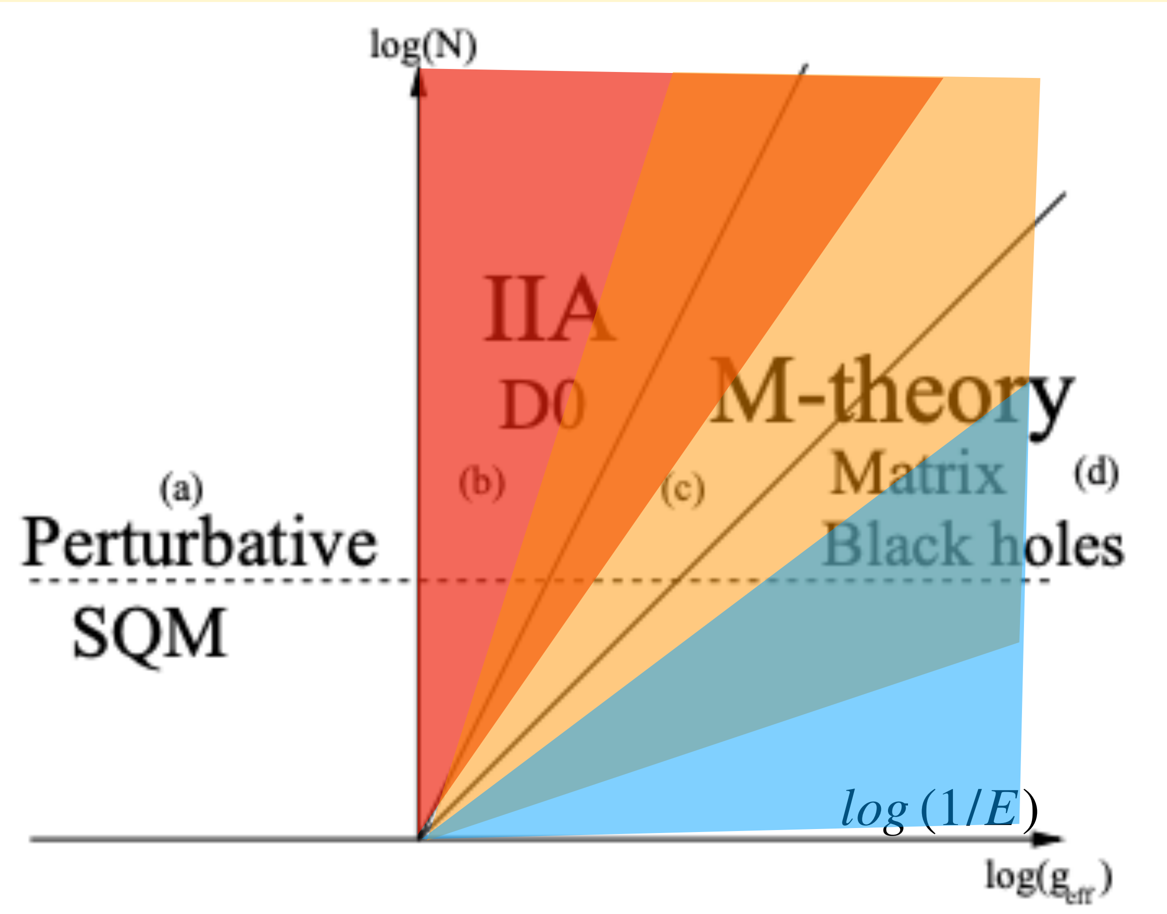
Large N

Gravity limit

$$g_{eff} = \frac{1}{E^3}$$



Confinement in the D0-matrix model



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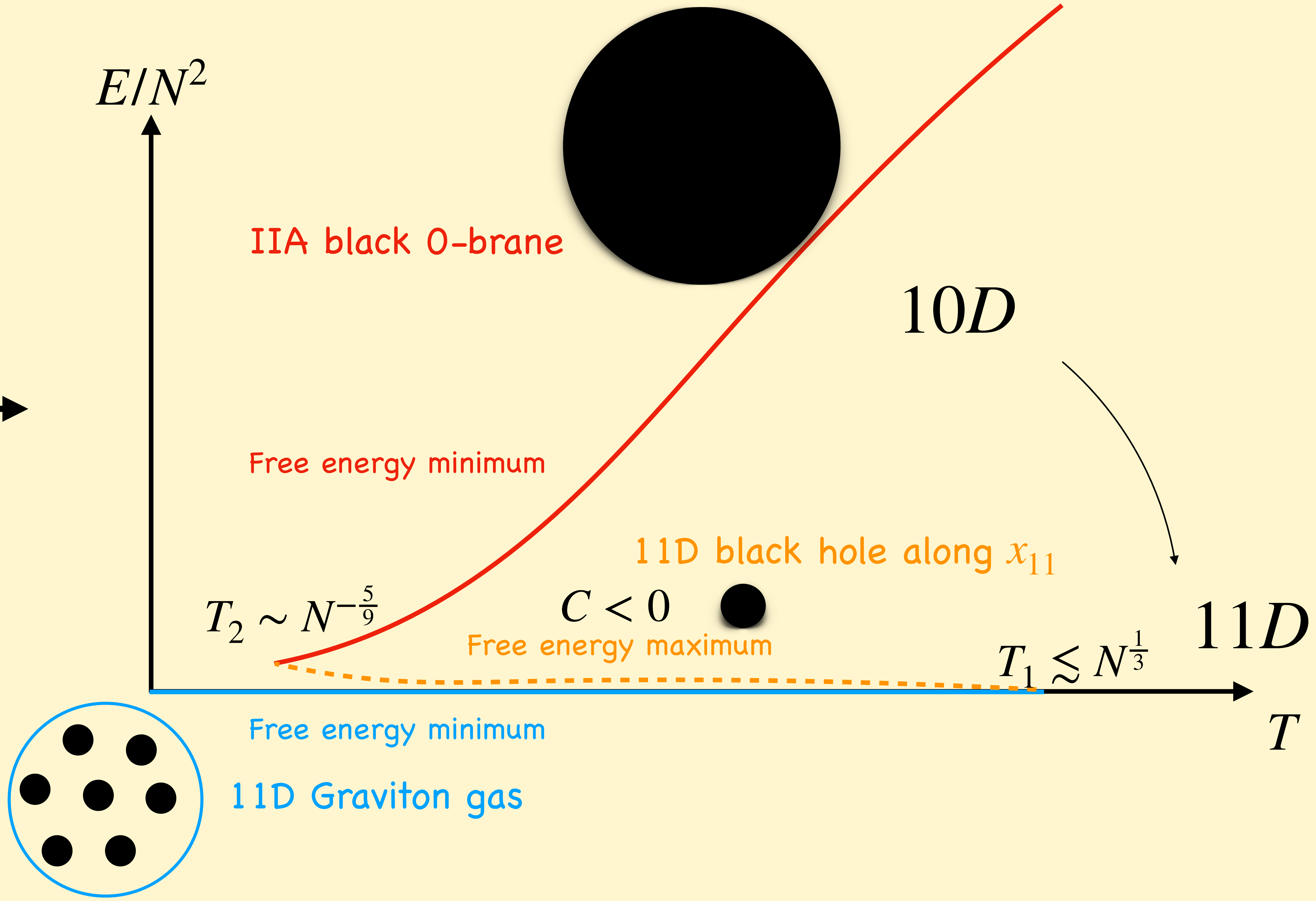
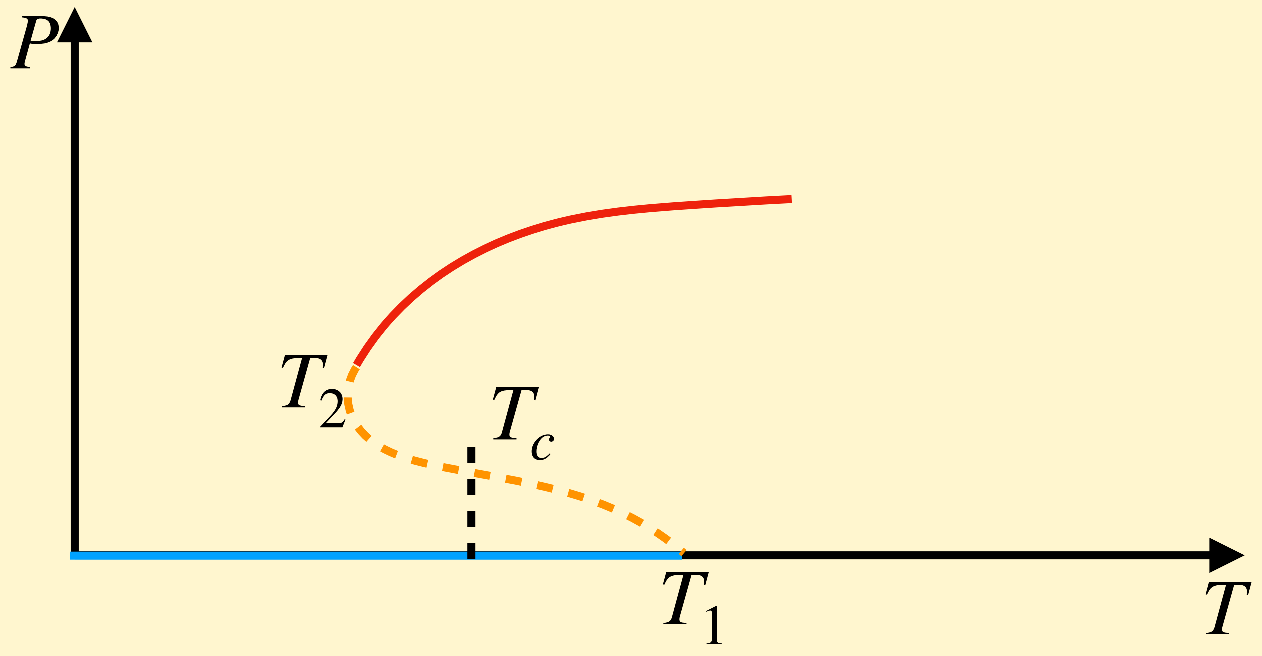


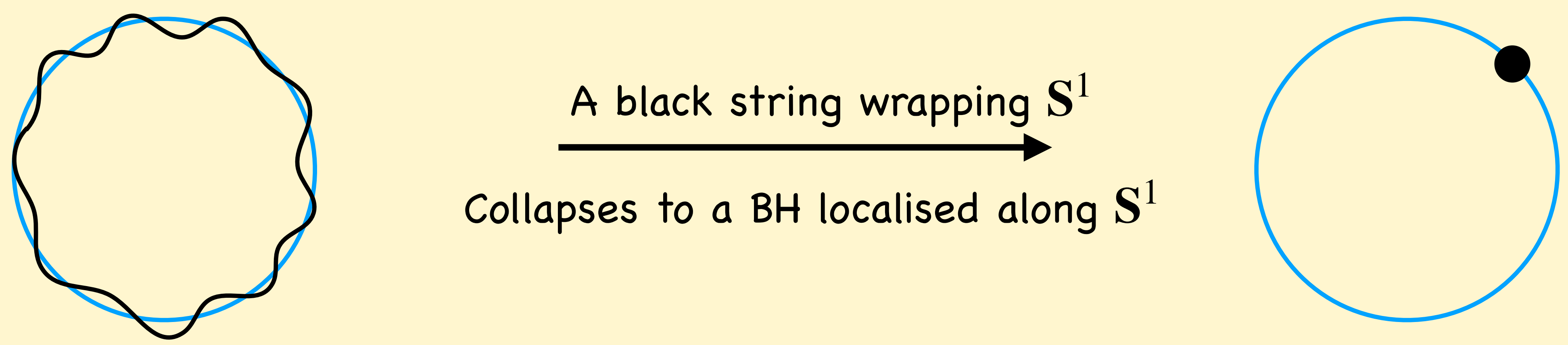
Confinement in the D0-matrix model



How to determine T_1 and T_2 ?

- T_2 corresponds to Gregory-Laflamme transition (or Gross-Witten-Wadia)

Gregory-Laflamme 1994, Gubser-Mitra 2001, Harmark-Niarchos-Obers 2004, Figueras, Kudoh-Wiseman 2004, Horowitz-Martinec 1997, Gross-Witten, Wadia, ...

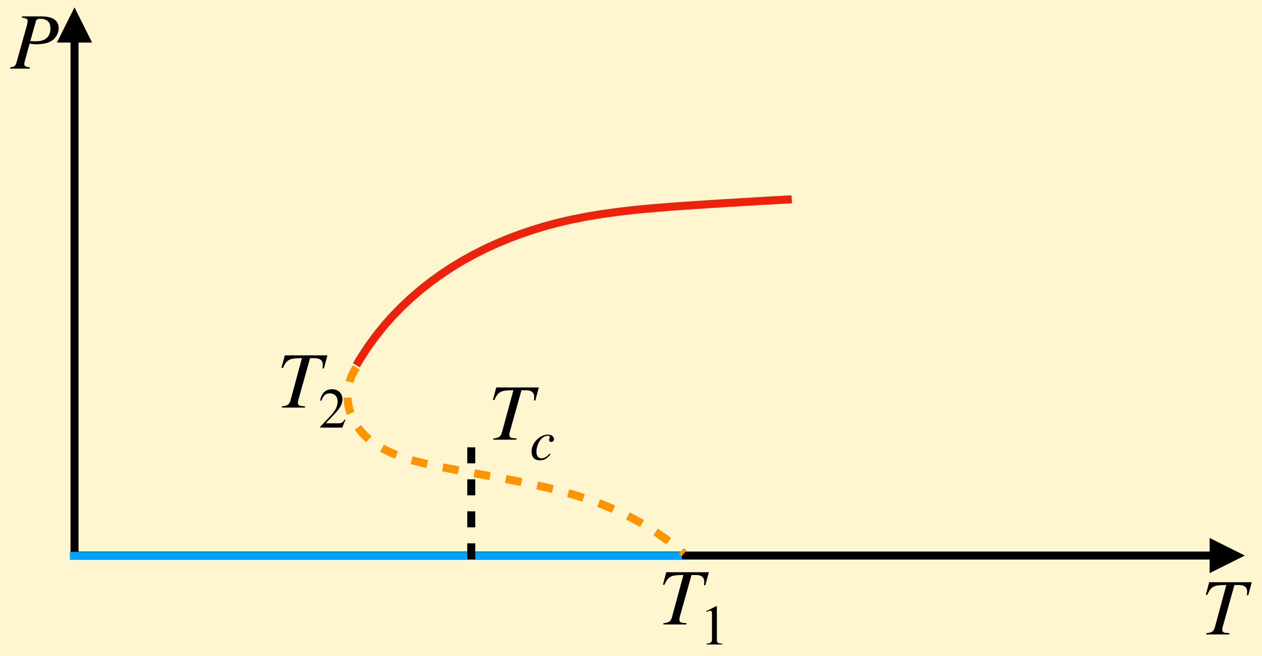


$$T_2 \sim N^{-5/9}$$

- T_1 corresponds to maximum/minimum confinement/deconfinement temperature

Schwarzschild BH in 11D with $M = M_{Pl}$ $\longrightarrow$ $T_1 \lesssim N^{1/3}$

Confinement in the D0-matrix model



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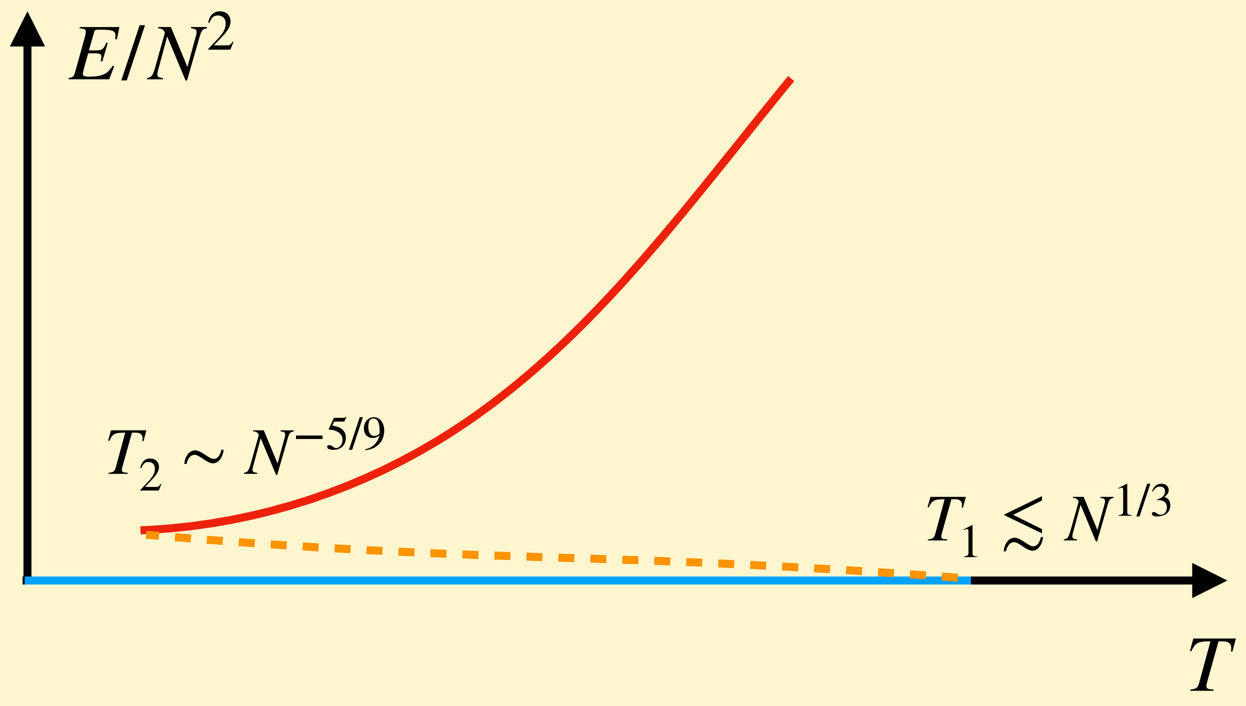

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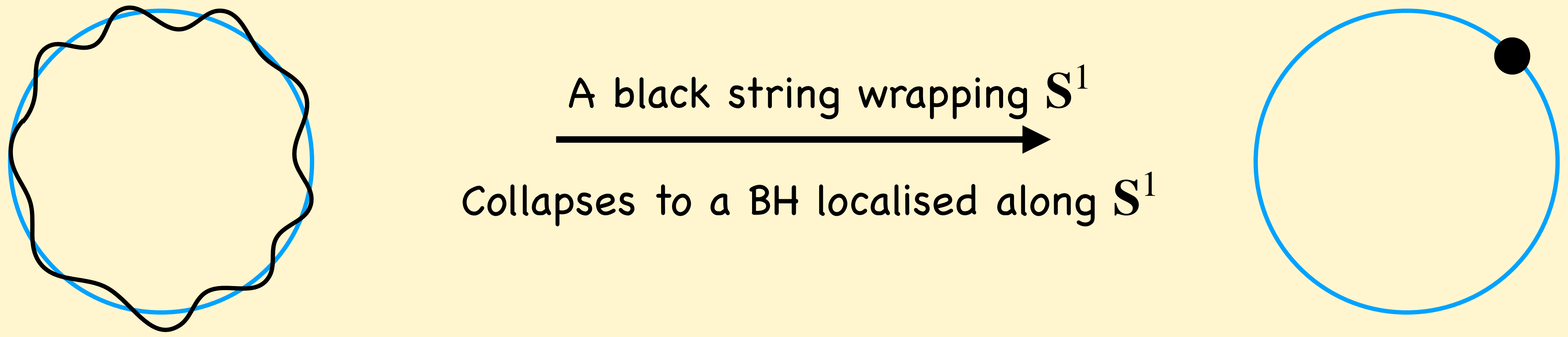

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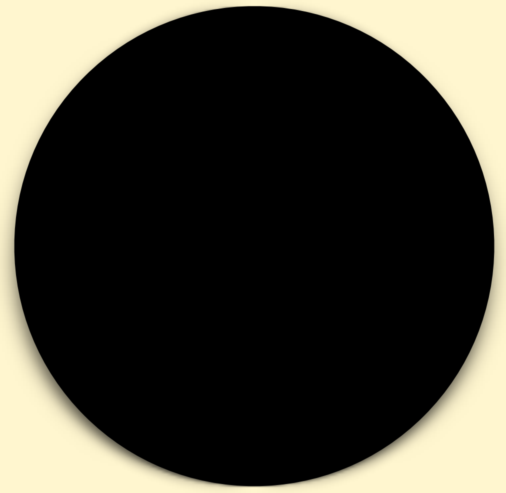
Deconfined studies in the D0-matrix model

Tests of gauge/gravity duality

- One of the most precise tests of holography appeared in arxiv/1606.04951



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Deconfined studies in the D0-matrix model

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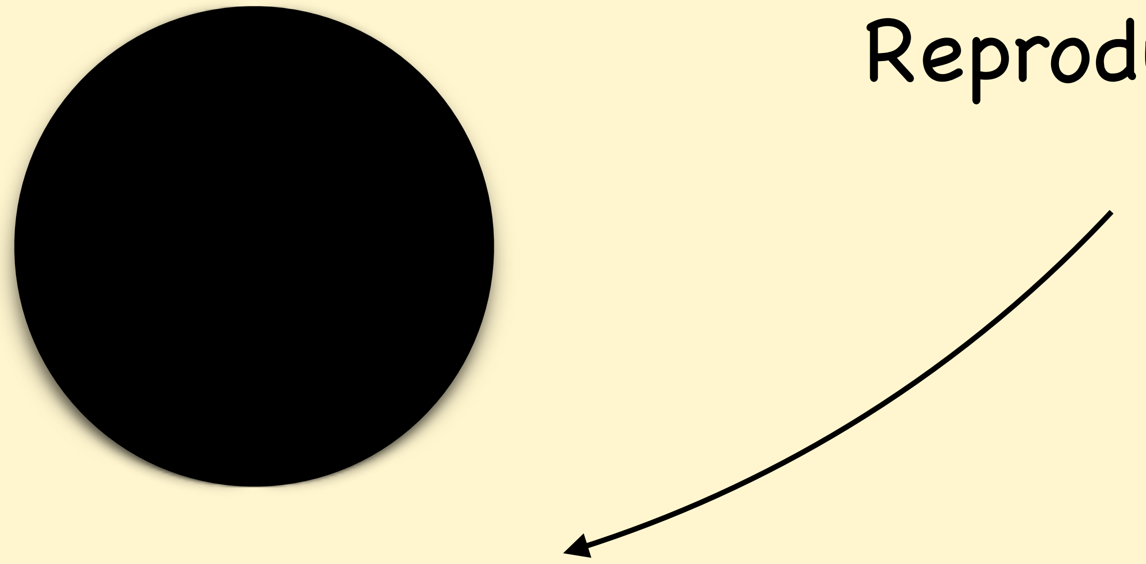
Reproduced by simulations of matrix quantum mechanics



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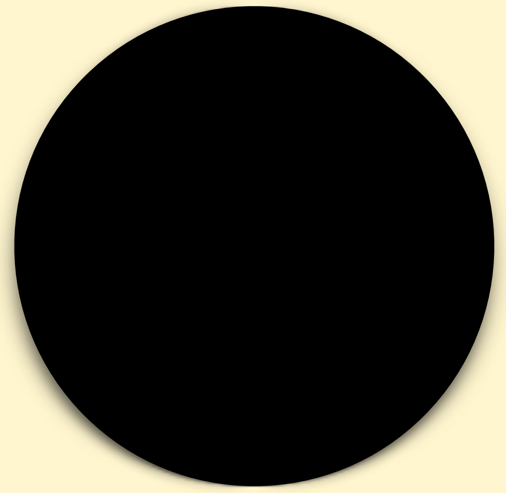

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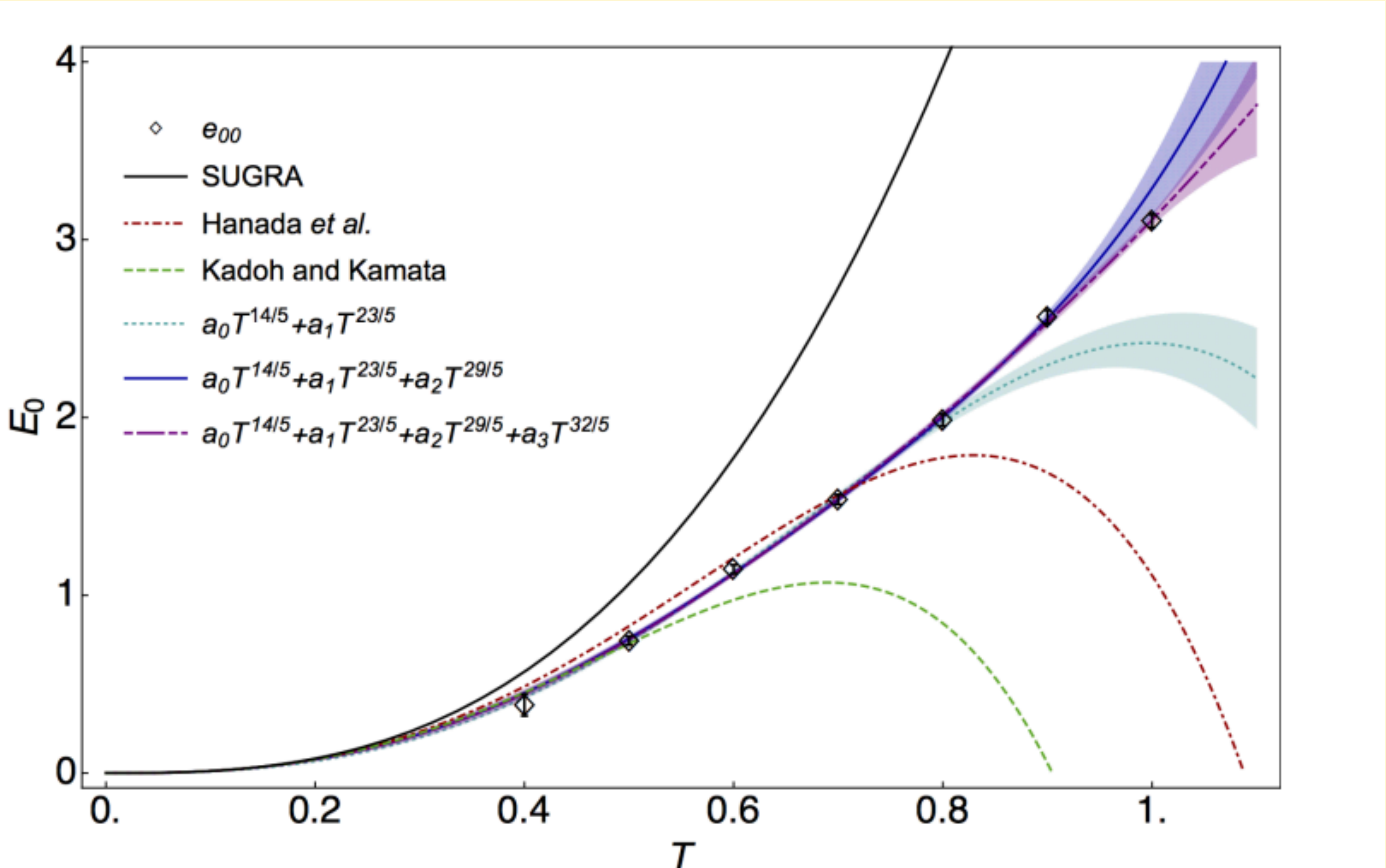

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Rinaldi, Berkowitz, Watanabe, Vranas, Berger, Bodendorfer, Schäfer, Dhindsa, Jha, Joseph, Samlodia, Schaich, Costa, Greenspan, Penedones, Santos, SP, ...

$$\frac{E}{N^2} = \frac{\left(a_0 T^{\frac{14}{5}} + a_1 T^{\frac{23}{5}} + a_2 T^{\frac{29}{5}} + \cdots\right)}{N^0} + \frac{\left(b_0 T^{\frac{2}{5}} + b_1 T^{\frac{11}{5}} + \cdots\right)}{N^2} + \mathcal{O}(N^{-4})\,.$$

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Finite μ corrections for BMN supergravity

$$\frac{E}{N^2} \simeq a_0 T^{\frac{14}{5}} f(\mu)$$

Costa, Greenspan, Penedones, Santos

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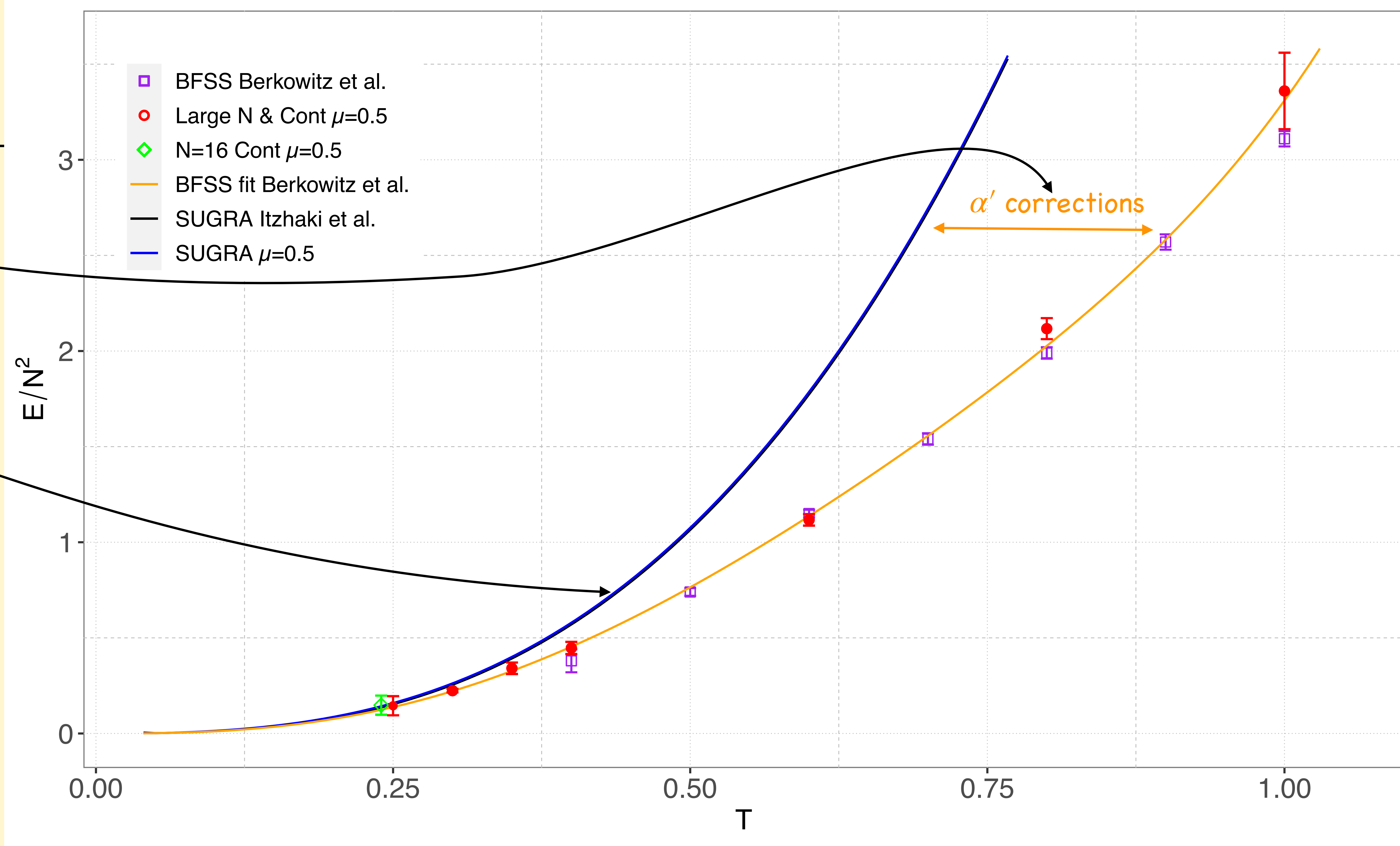
Ongoing work



Is the singlet constraint important?

Maldacena-Milekhin conjecture

$$Z_{\text{gauged}} = \int [dX][d\psi][dA_t]e^{-S_{\text{matrix}}[X,\psi,A_t]}$$ → Gauge singlet constraint: $\mathcal{G} := \frac{iN}{2\lambda}\left(2[\dot{X}_M, X_M] + [\bar{\psi}_\alpha, \psi_\alpha]\right) = 0$

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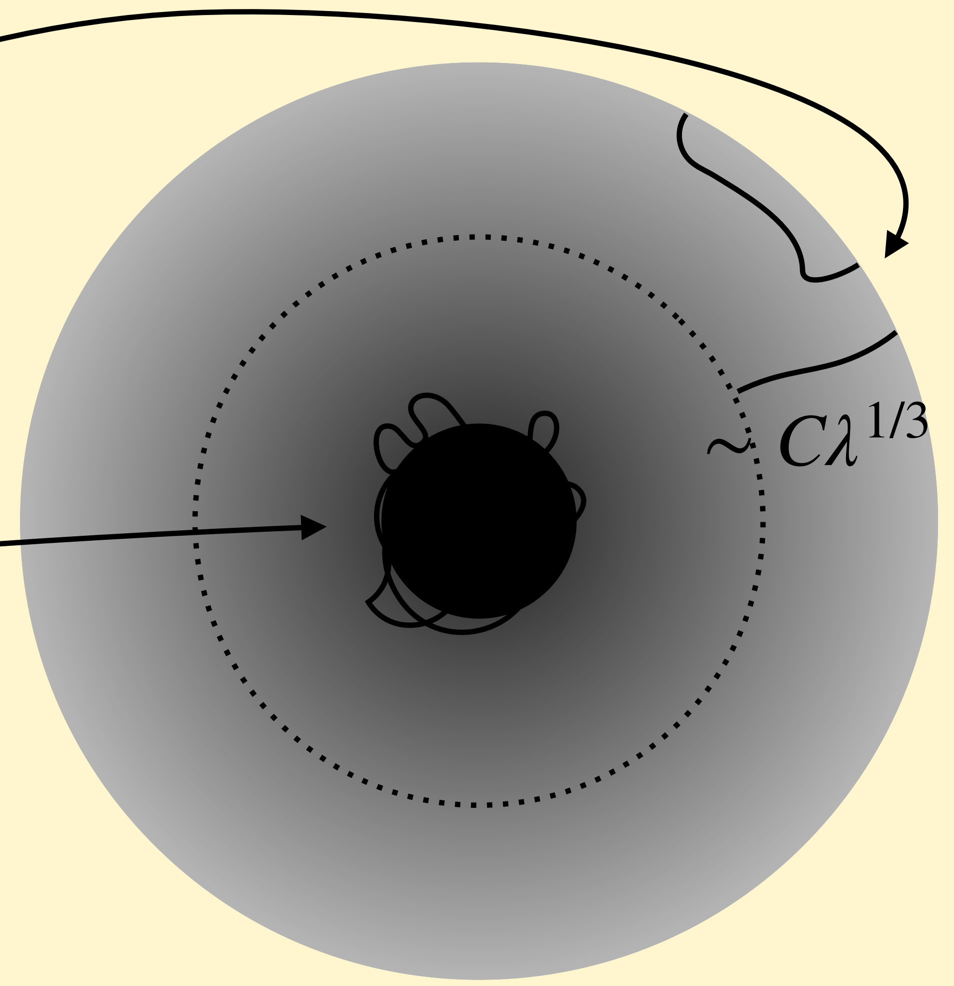
$$\mathscr{H}_{\text{total}} = \mathscr{H}_{\text{singlets}} \otimes \mathscr{H}_{\text{non-singlets}}$$



- Non-singlets do not contribute at low temperatures

$$\Delta Z = Z_{\text{gauged}} - Z_{\text{ungauged}} \simeq e^{-\frac{C\lambda^{1/3}}{T}} \quad , \quad T \to 0$$

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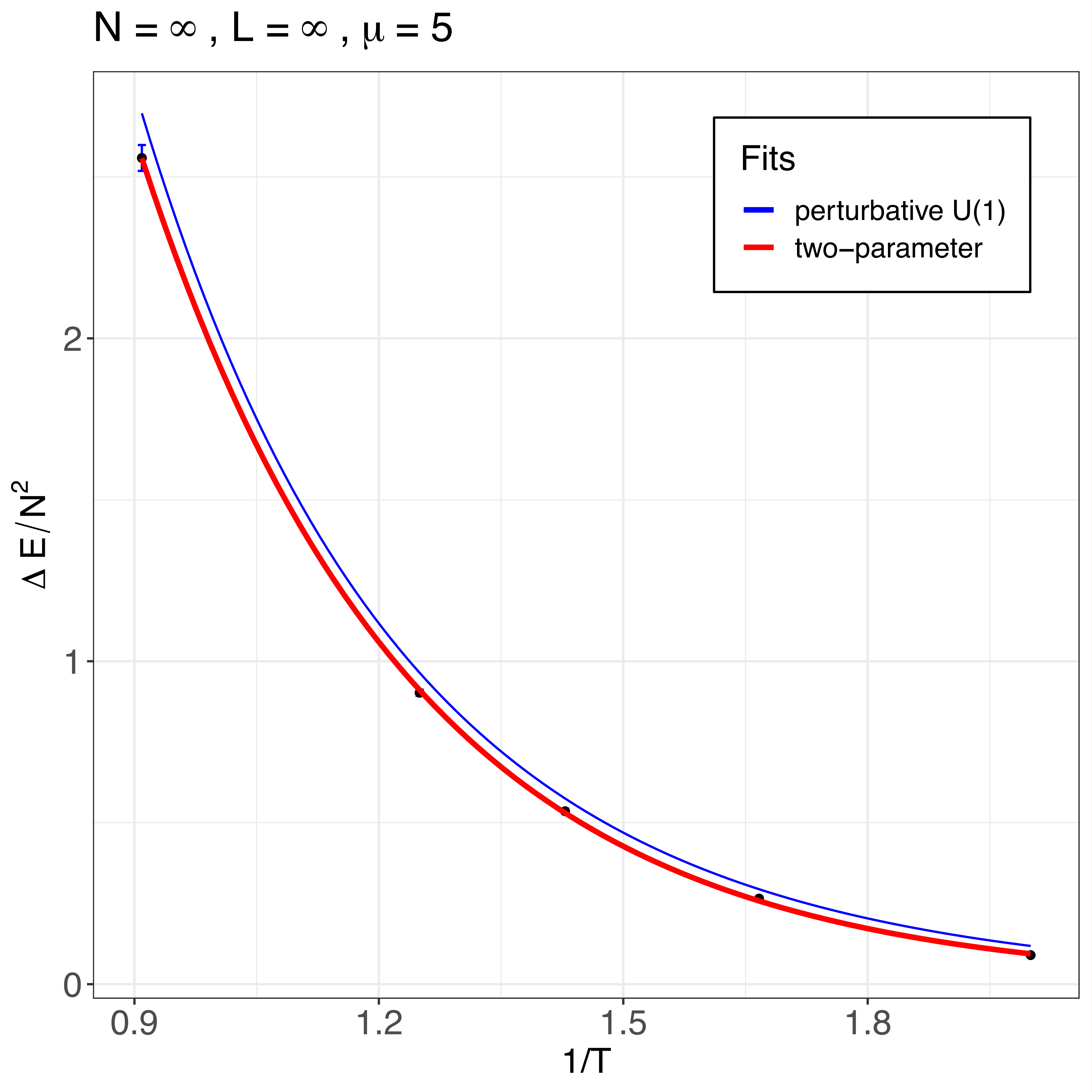

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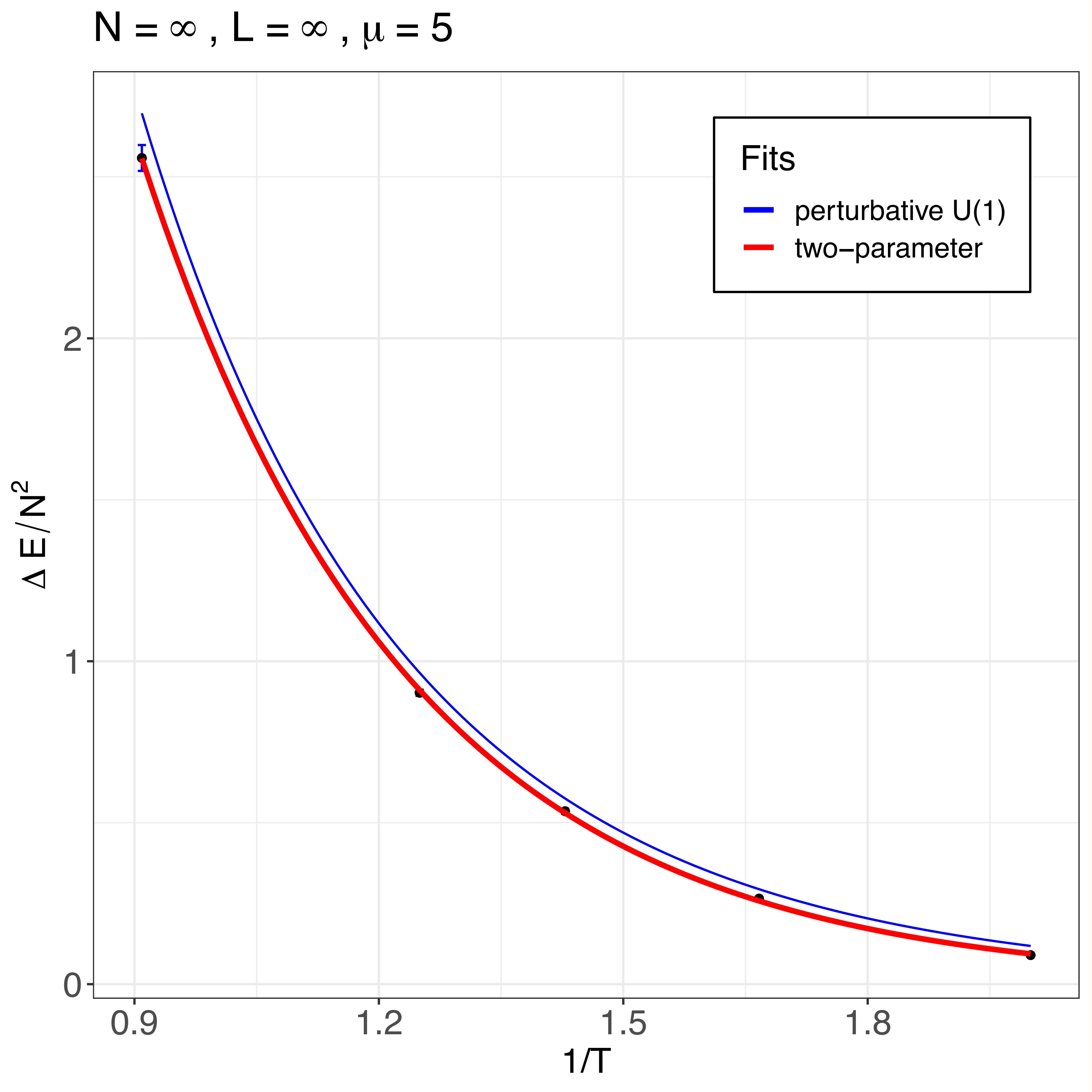
$$\frac{E_{U(1)}}{N^2} = 6 \cdot \frac{\mu}{2} e^{-\frac{\mu}{2}\frac{1}{T}} + 8 \cdot \frac{3\mu}{4} e^{-\frac{3\mu}{4}\frac{1}{T}} + 3 \cdot \mu e^{-\frac{\mu}{T}} \quad , \quad \frac{\lambda}{T^3} \gg 1 \, , \, \frac{\mu^3}{\lambda} \gg 1$$

$$\frac{\Delta E}{N^2} = E_{\text{ungauged}} - E_{\text{gauged}} = D \cdot e^{-\frac{C}{T}} \quad , \quad \frac{\lambda}{T^3} \gg 1 \quad , \frac{\mu^3}{\lambda} \ll 1$$



What do we learn?

- D0-matrix models interesting test examples for holography
- A stable confined phase has been observed for the first time
- Interesting possibility to probe contents of M-theory.

Study better the Schwarzschild BH. Membrane? Fivebrane?

- Low temperature precision test for holography (internal energies)
- Non-AdS/non-CFT, non-gauge/gravity, stringy corrections
- More studies (confined and deconfined) are important

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Thank you