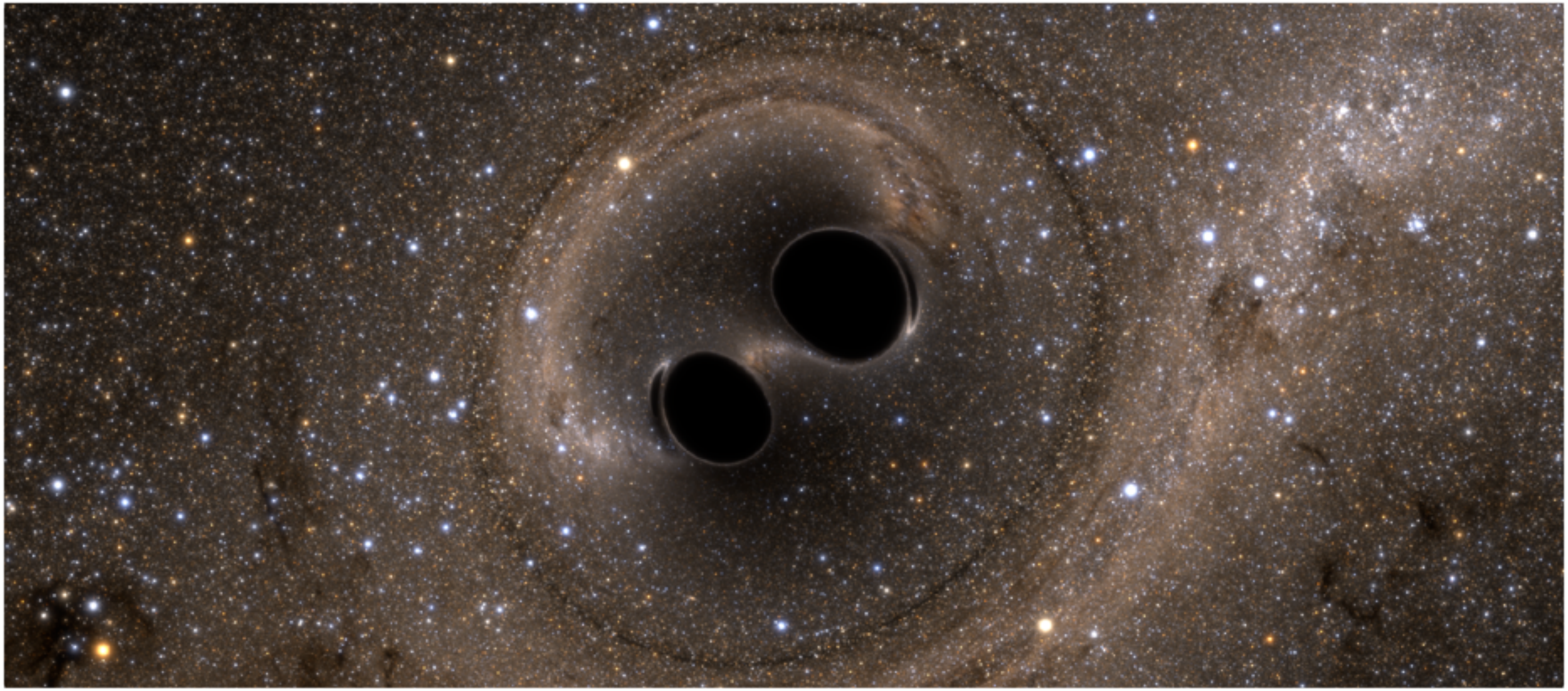
[SXS - black-holes.org]



Lattice for Beyond the Standard Model Physics - 4/6/2018 - University of Colorado, Boulder, CO

High-precision tests of the gauge/gravity duality and new applications

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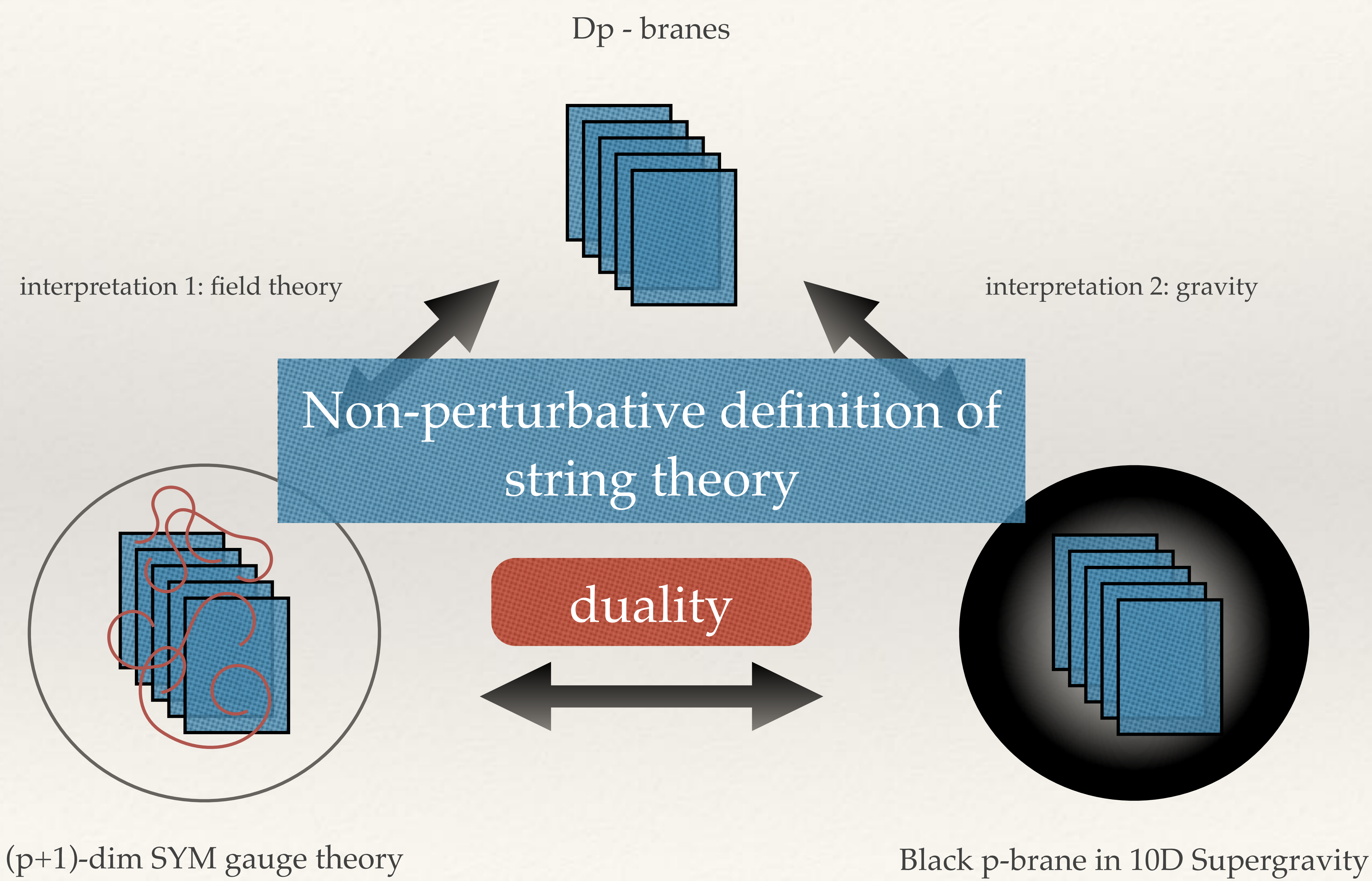
✴ *with the Monte-Carlo String+M-theory Collaboration (MCSMC)*

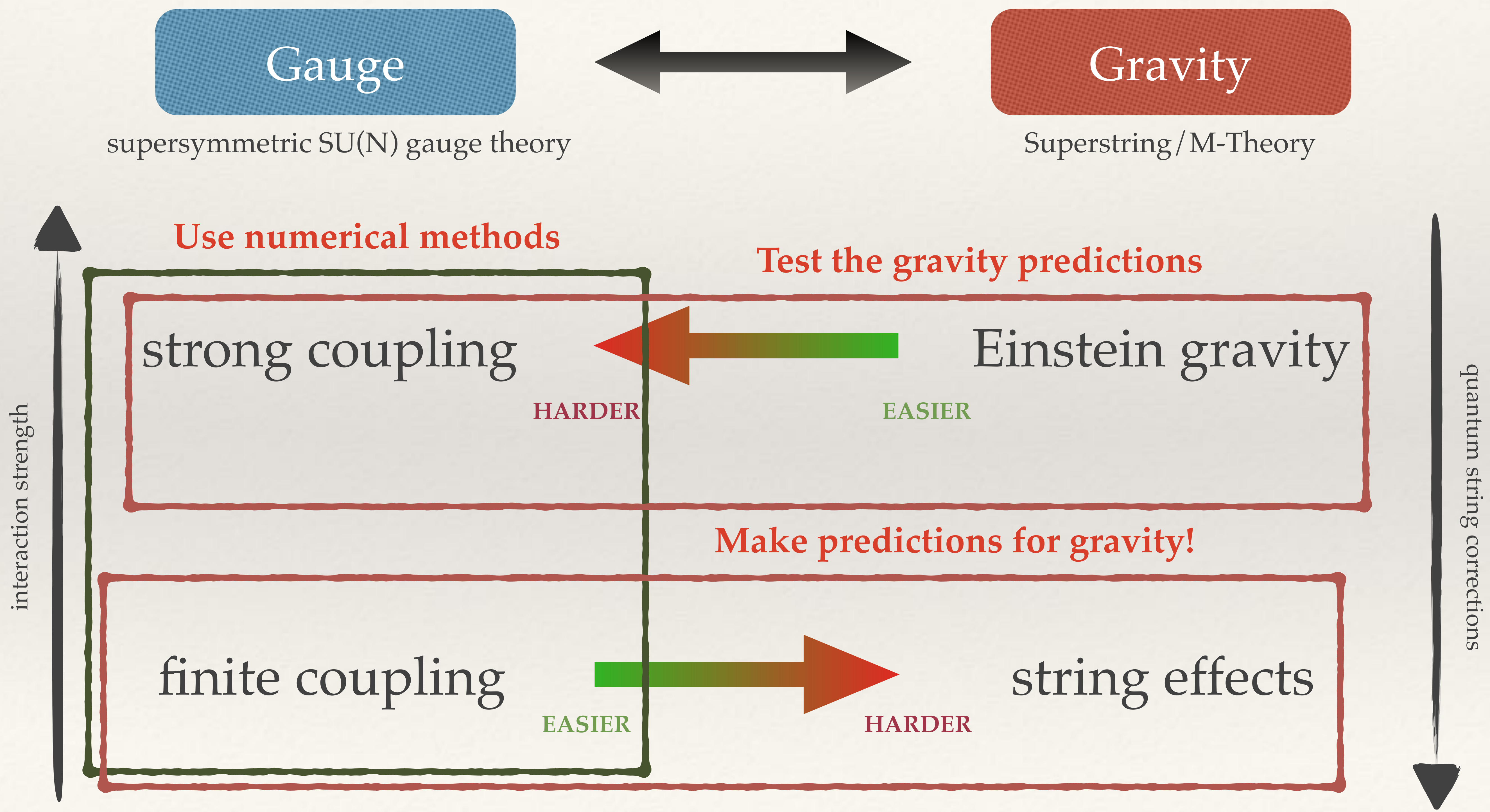
[Maldacena '97, Itzhaki,Maldacena,Sonnenschein,Yankielowic '98]

Gauge/Gravity duality

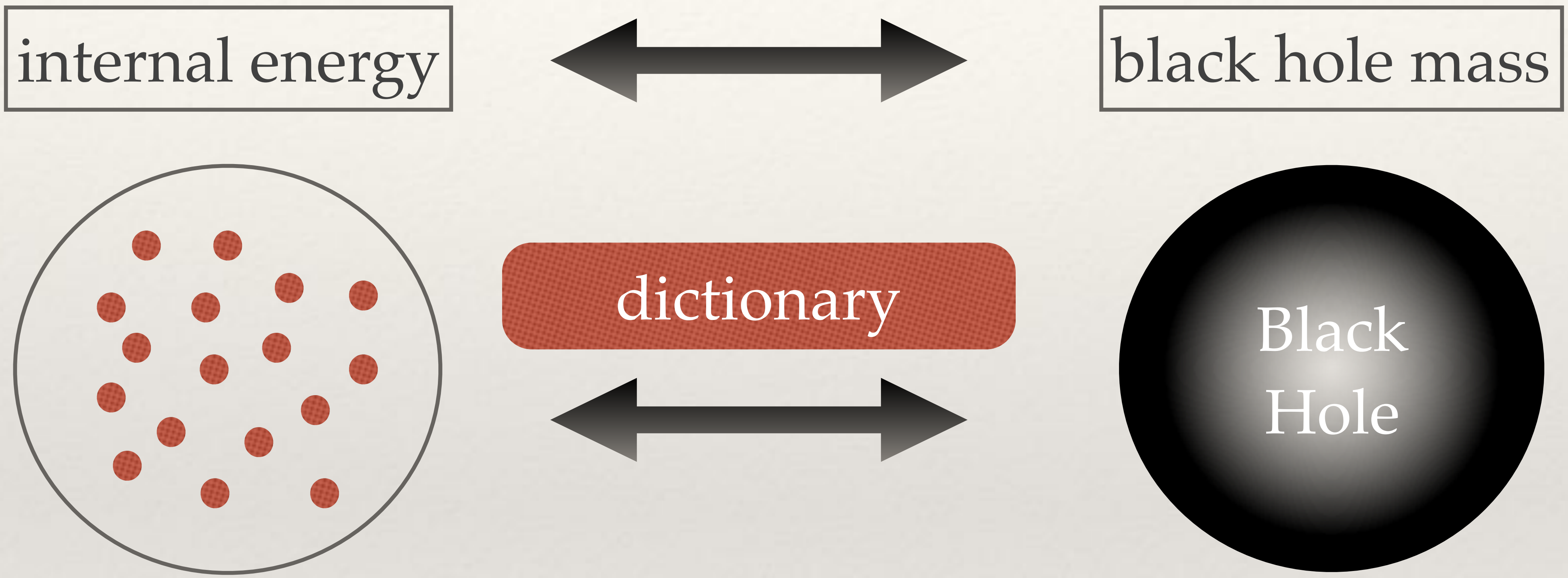


['t Hooft, Susskind, Maldacena …]

Gauge/Gravity duality



Testing the gauge/gravity duality



(0+1)-dim maximally supersymmetric gauge theory

Type IIA superstring theory
in the near horizon limit of
a black 0-brane geometry

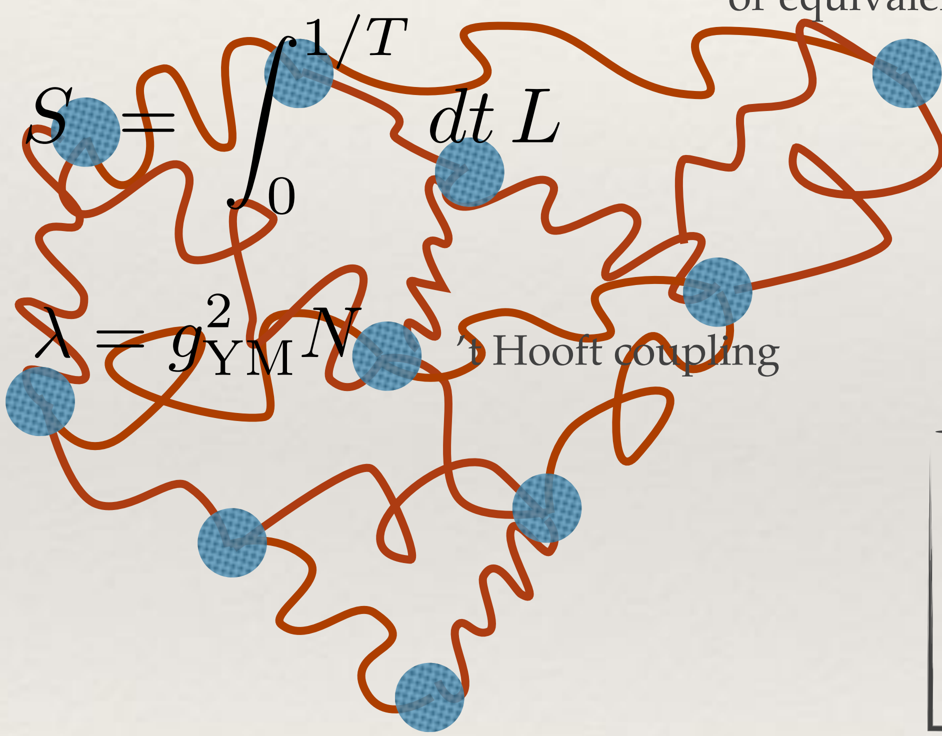
Compute observables that are dual to each other on both sides and compare in an easy case (low-d)

Supersymmetric quantum mechanics

$$L = \frac{1}{2g_{YM}^2}\mathrm{Tr}\left\{(D_t X_M)^2 + [X_M, X_{M'}]^2 + i\bar{\psi}^\alpha D_t \psi^\beta + \bar{\psi}^\alpha \gamma^M_{\alpha\beta}[X_M, \psi^\beta]\right\}$$

obtained from $\mathcal{N}$=1 U(N) SYM in (9+1)d via dimensional reduction to (0+1)d

or equivalently from $\mathcal{N}$=4 U(N) SYM in (3+1)d



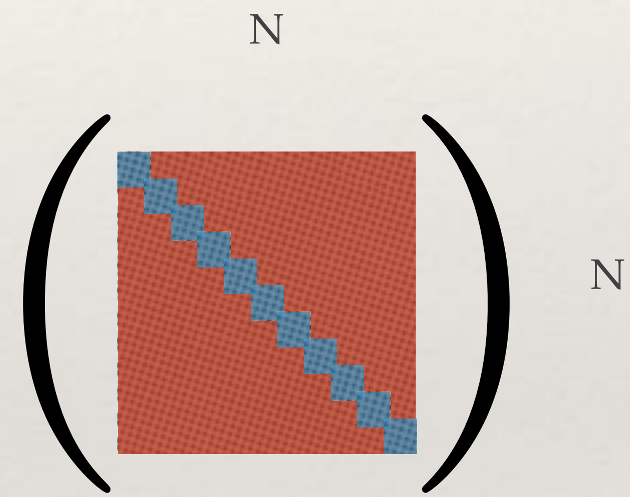
$$S = \int_0^{1/T} dt\, L$$

$$\lambda = g^2_{\mathrm{YM}} N$$ 't Hooft coupling

D0-branes

coordinates

couplings



$X_M \,, M = 1, \ldots, 9 \;(N \times N) \;\rightarrow$ hermitian scalars

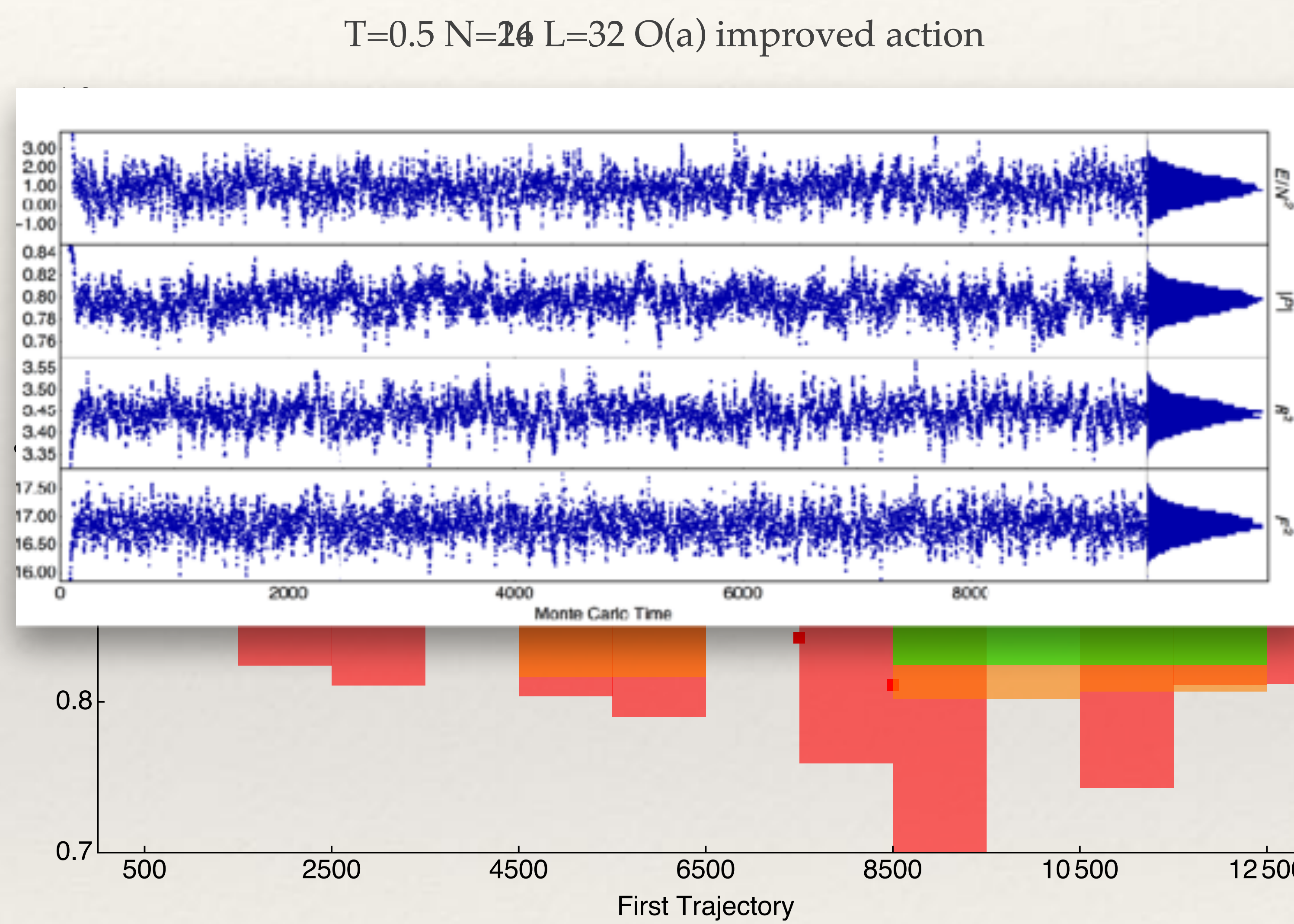
$\psi^\alpha \,, \alpha = 1, \ldots, 16 \;(N \times N) \;\rightarrow$ adjoint fermions

$D_t \cdot \;=\; \partial_t \cdot - i[A_t, \cdot] \;\rightarrow$ gauge covariant derivative

conjectured to be equivalent to M-theory

Monte Carlo simulations

- Observables: E/N^2, $|P|$, $R^2=\mathrm{Tr}[X^2]/N$, $F^2=\mathrm{Tr}([X_i,X_j]^2)/N$
- Large statistics for all parameters (N,L,T) is needed
- Dedicated autocorrelation analysis is paramount due to long fluctuations
- All data is published in tables and can be used for future benchmarks!



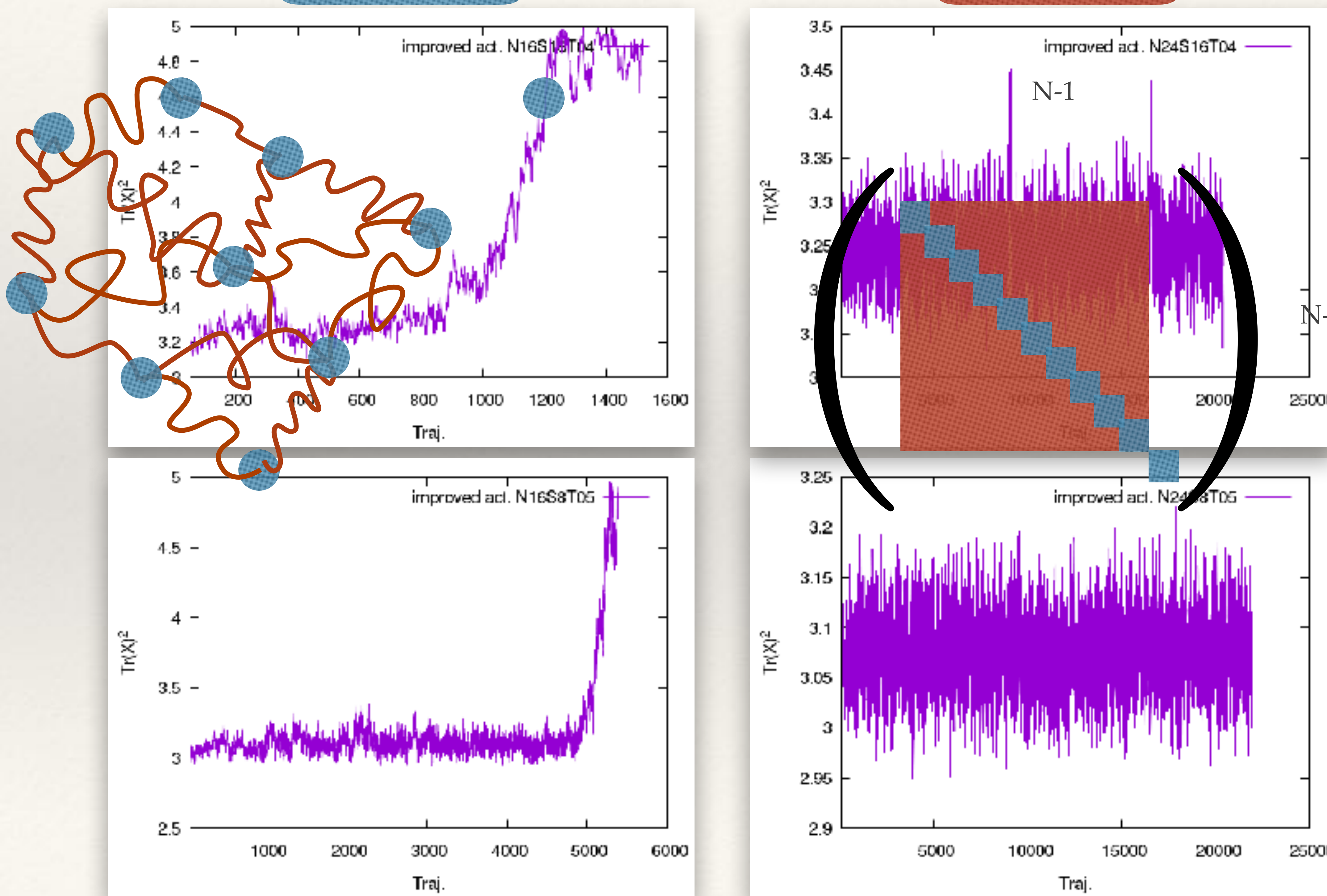
Challenge: flat direction

N=16

N=24

T=0.4

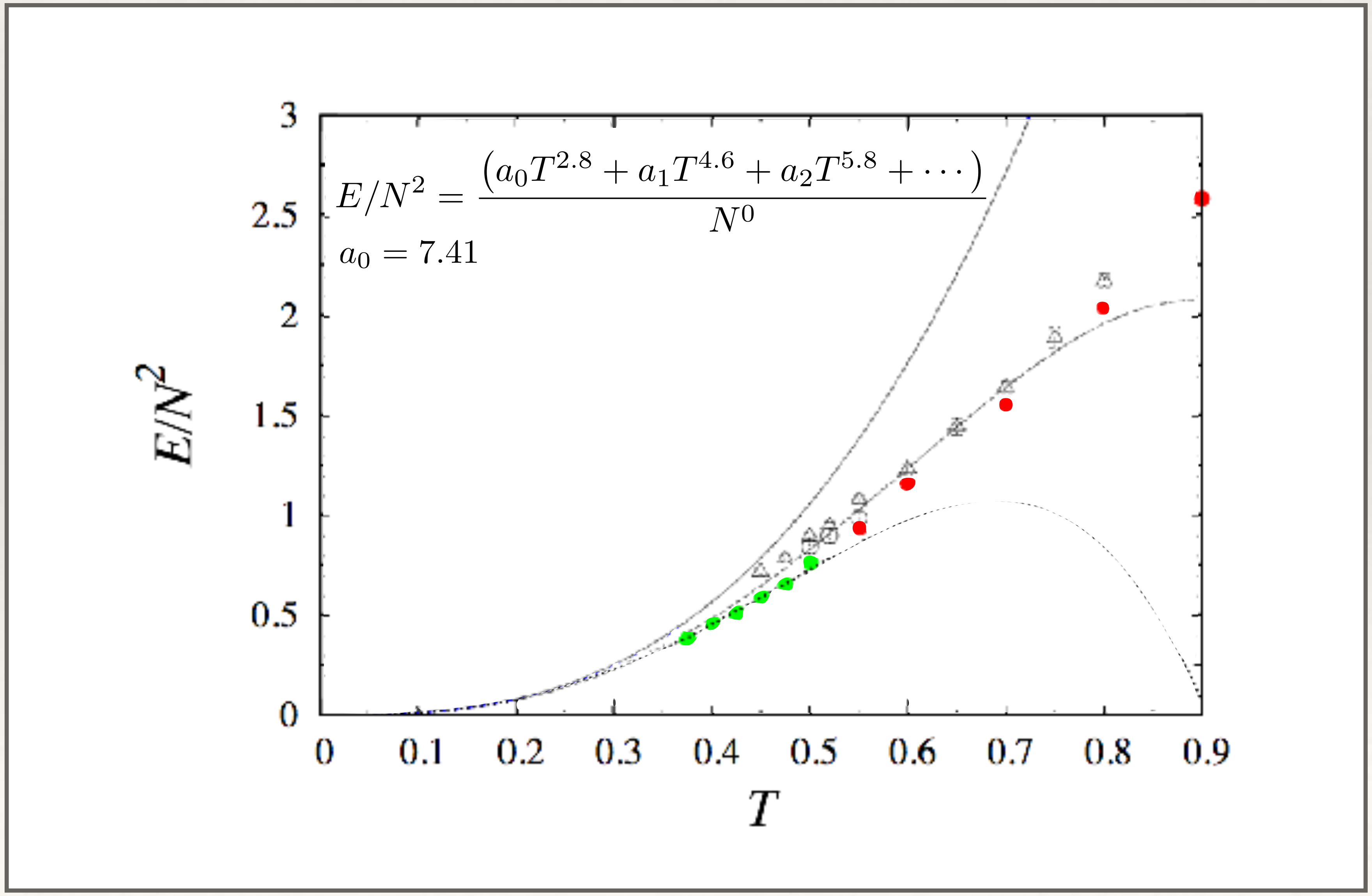
T=0.5



Previous results

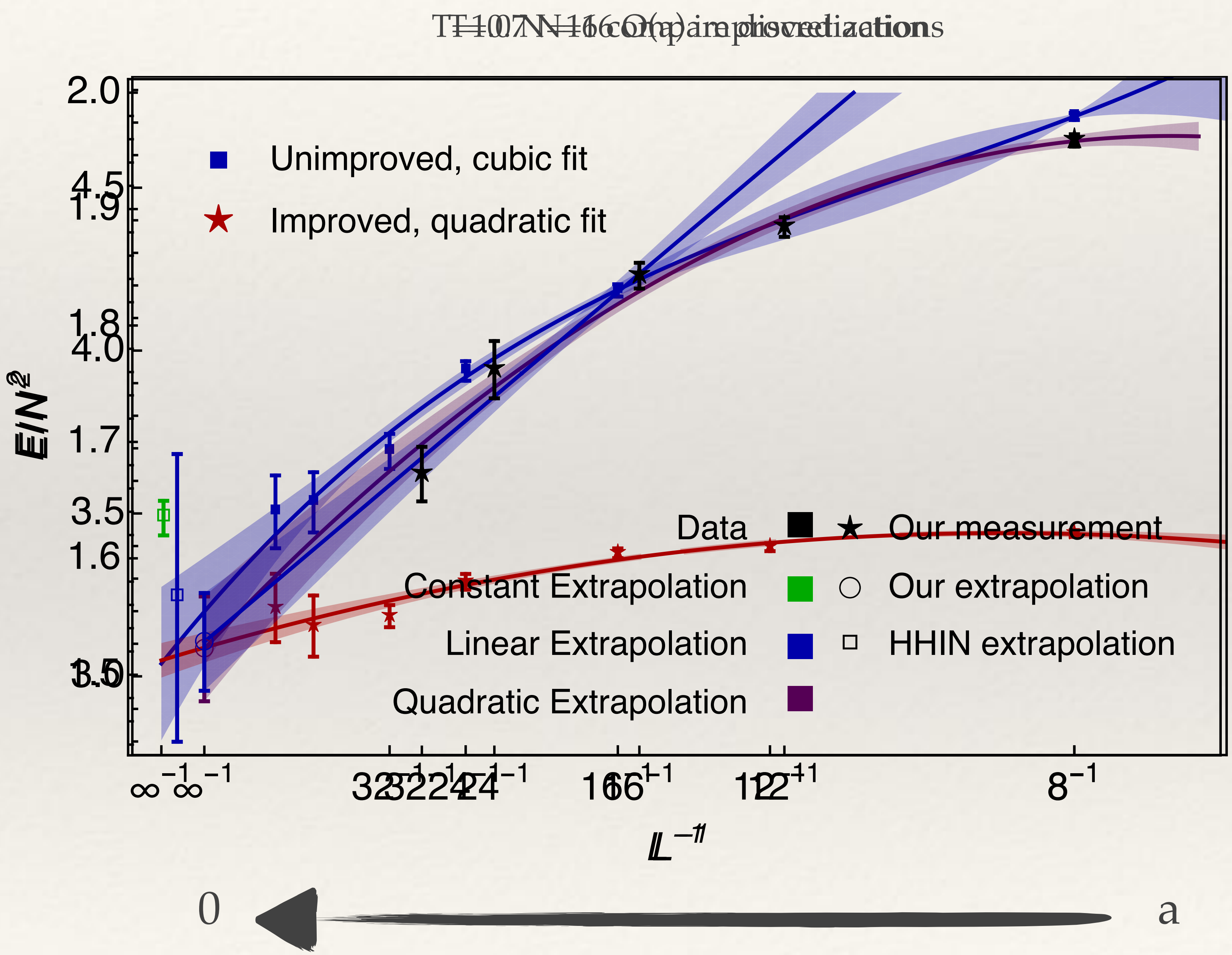
[Agnastopoulos et al. arxiv:0707:4454]
[Catteral, Wiseman arxiv:0803.4273]
[Hanada et al. arxiv:0811.3102]
[Hanada et al. arxiv:1311.5603]
[Kadoh, Kamata arxiv:1503.08499]
[Filev, O'Connor arxiv:1506.01366]
…

- Different cutoff regulator
- Different discretizations
- Finite N
- Finite cutoff
- Qualitative agreement
- Not enough precision for quantitative predictions



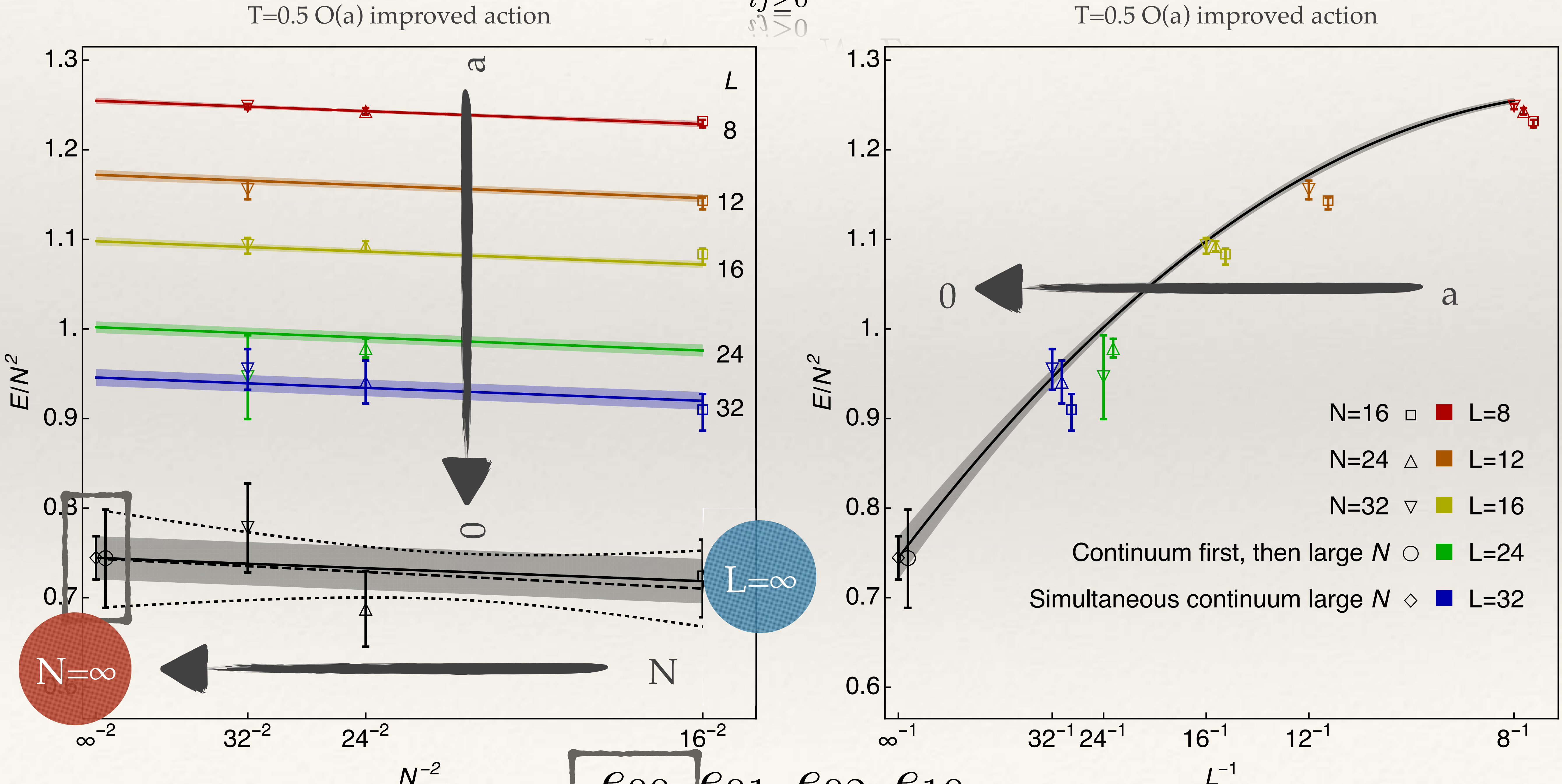
Remove regularization effects

- Numerical simulations are done at fixed cutoff e.g. a
- Need to remove regulator effects
- Different discretization forms give consistent results
- Compare with previous results in the literature
- Physics is independent of the regulator once cutoff effects are accurately removed



Towards the large-N limit

$$\frac{E}{N^2} = \sum_{ij\geq 0} \frac{e_{ij}}{N^{2i}L^j}$$



$e_{00}, e_{01}, e_{02}, e_{10}$

Extract predictions on the gauge side

TEST

- LO $E_0 = a_0 T^{2.8}$
- NLO $E_0 = a_0 T^{2.8} + a_1 T^{4.6}$
- NNLO $E_0 = a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8}$
- NNNLO $E_0 = a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8} + a_3 T^{6.4}$
- NLOP1(fixed LO) $E_0 = 7.41 T^{2.8} + a_1 T^{p_1}$
- NNLOP1(fixed LO) $E_0 = 7.41 T^{2.8} + a_1 T^{p_1} + a_2 T^{p_1+1.2}$
- NNLOP0 $E_0 = a_0 T^{p_0} + a_1 T^{p_0+1.8} + a_2 T^{p_0+3}$

PREDICT

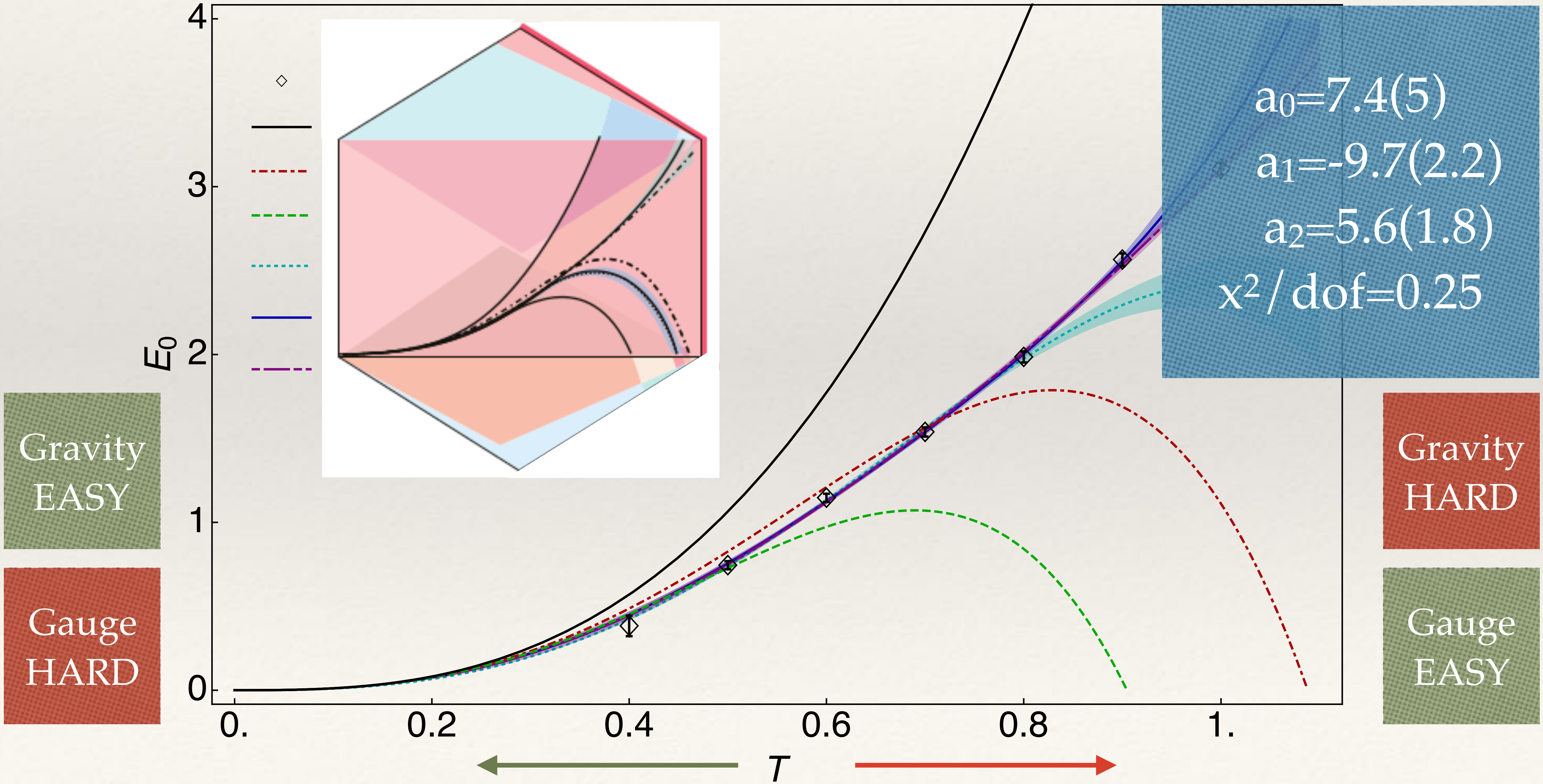
TEST

Large-N and continuum limit results

$$\frac{E}{N^2} = a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8}$$

$a_0 = 7.41$ Supergravity

$a_1 = ?\ a_2 = ?$ String effects



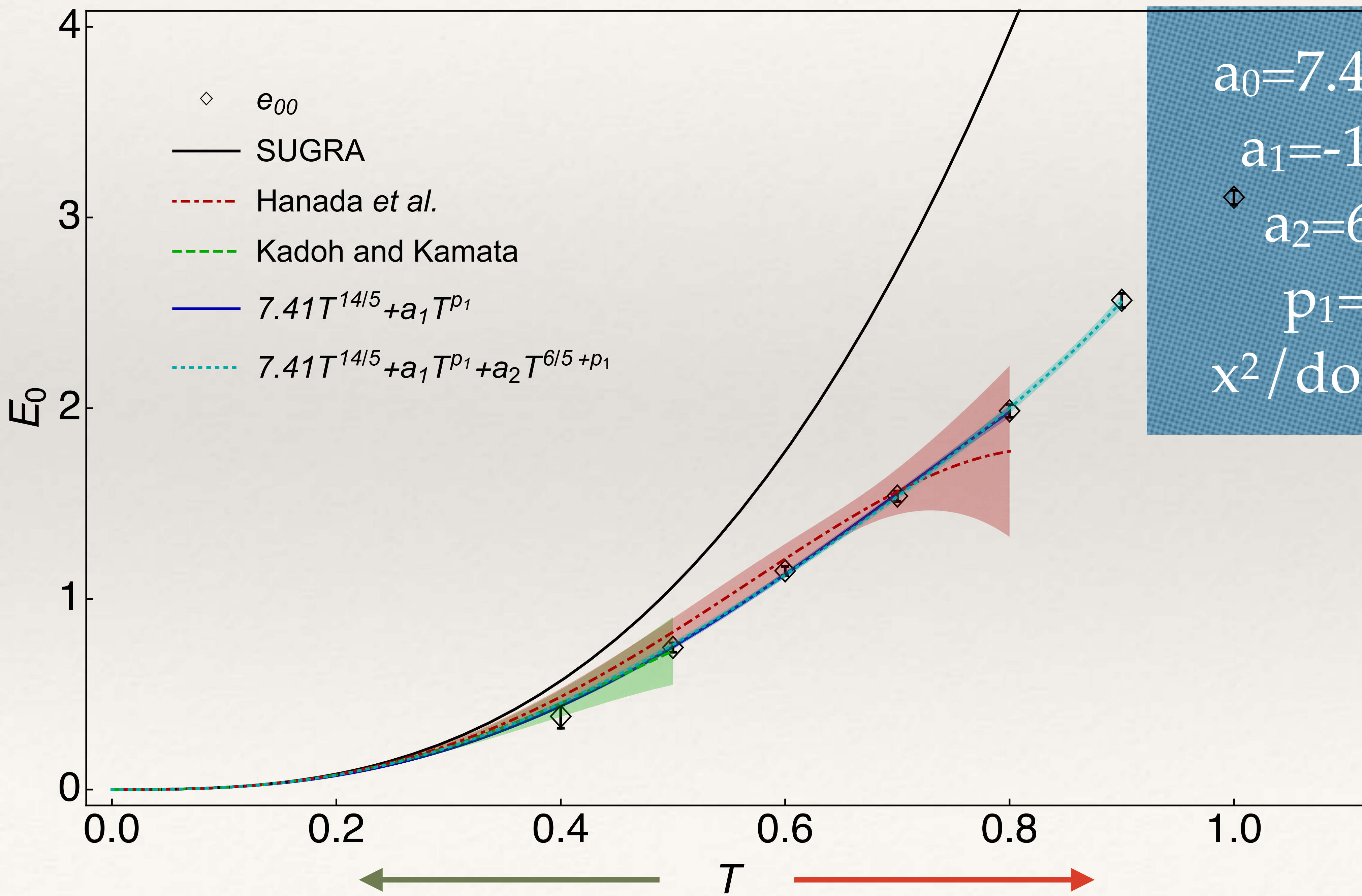
[Hanada et al. arxiv:0811.3102, Kadoh and Kamata arxiv:1503.08499] [MCSMC, Phys. Rev. D94 (2016) 094501]

Large-N and continuum limit results

$$\frac{E}{N^2} = a_0 T^{2.8} + a_1 T^{p_1} + a_2 T^{p_1+6/5}$$

$a_0 = 7.41$ Supergravity

$a_1 = ?\ p_1 = 4.6$ String effects



a_0=7.41 (fix)
a_1=-10.2(2.4)
a_2=6.2(2.6)
p_1=4.6(3)
x^2/dof=0.87

Gravity EASY

Gauge HARD

Gravity HARD

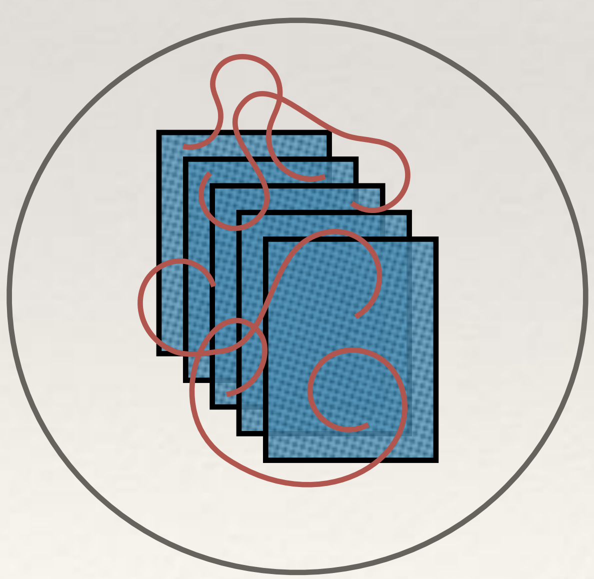
Gauge EASY

Caveat: This part is more speculative, and makes use of the conjectured duality [MCSMC, JHEP 1802 (2018) 042]

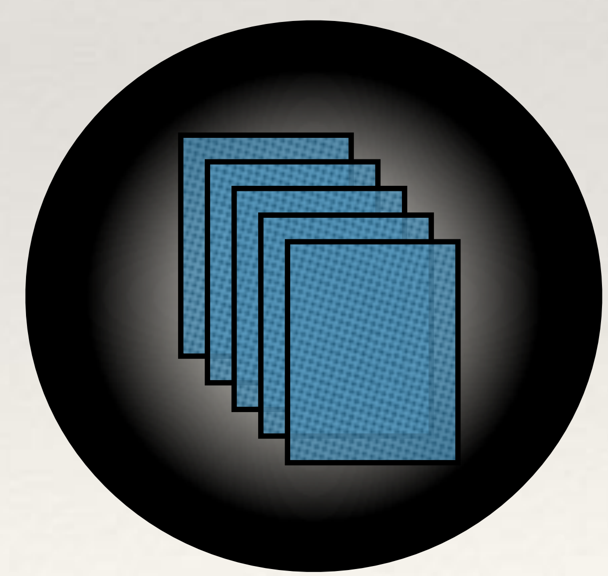
Geometry from gauge theories

Goal: determine how geometry emerges from the dual gauge theory

- ★ interior
- ★ exterior
- ★ horizon
- ★ evaporation



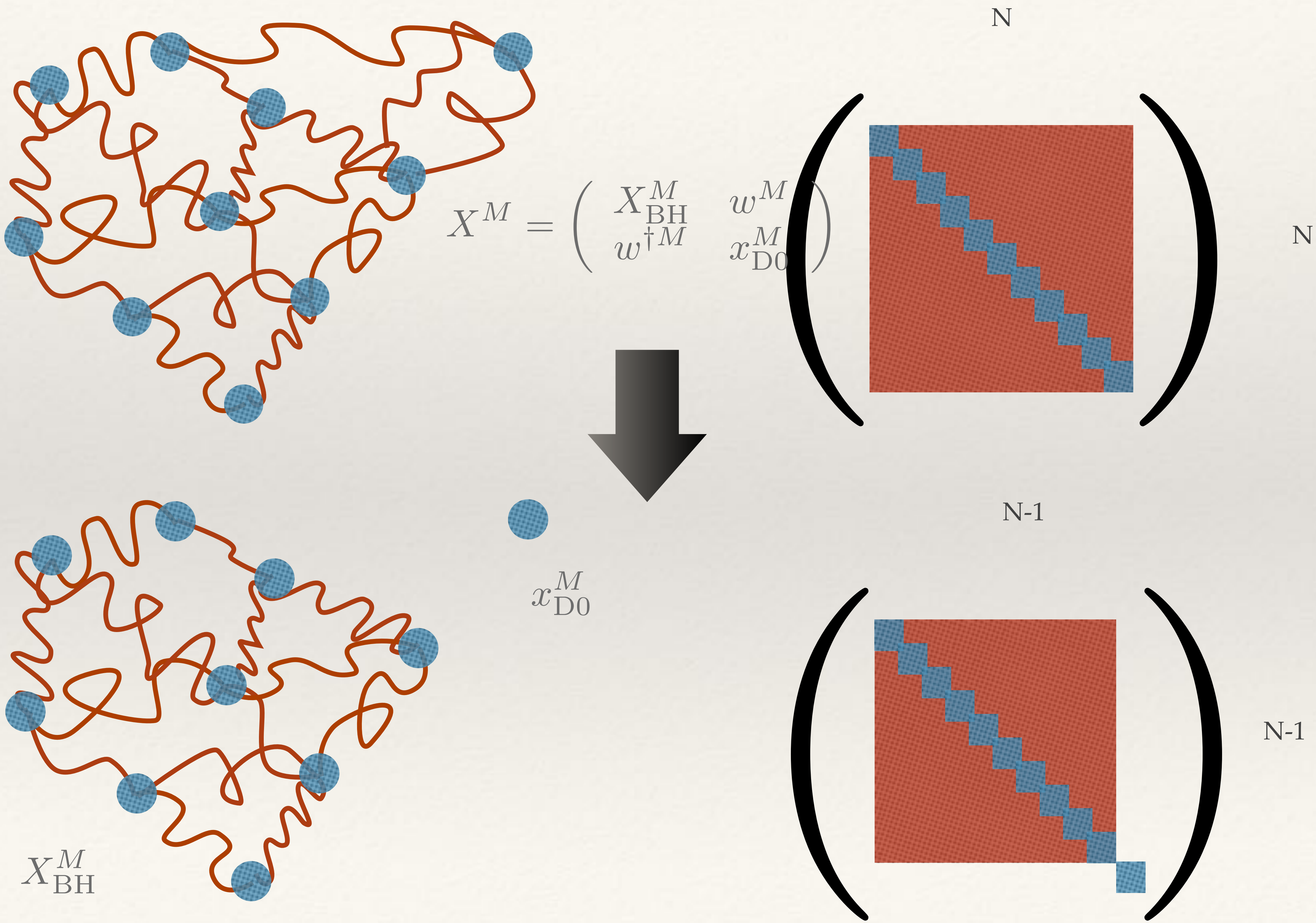
(p+1)-dim SYM gauge theory



Black p-brane in 10D Supergravity

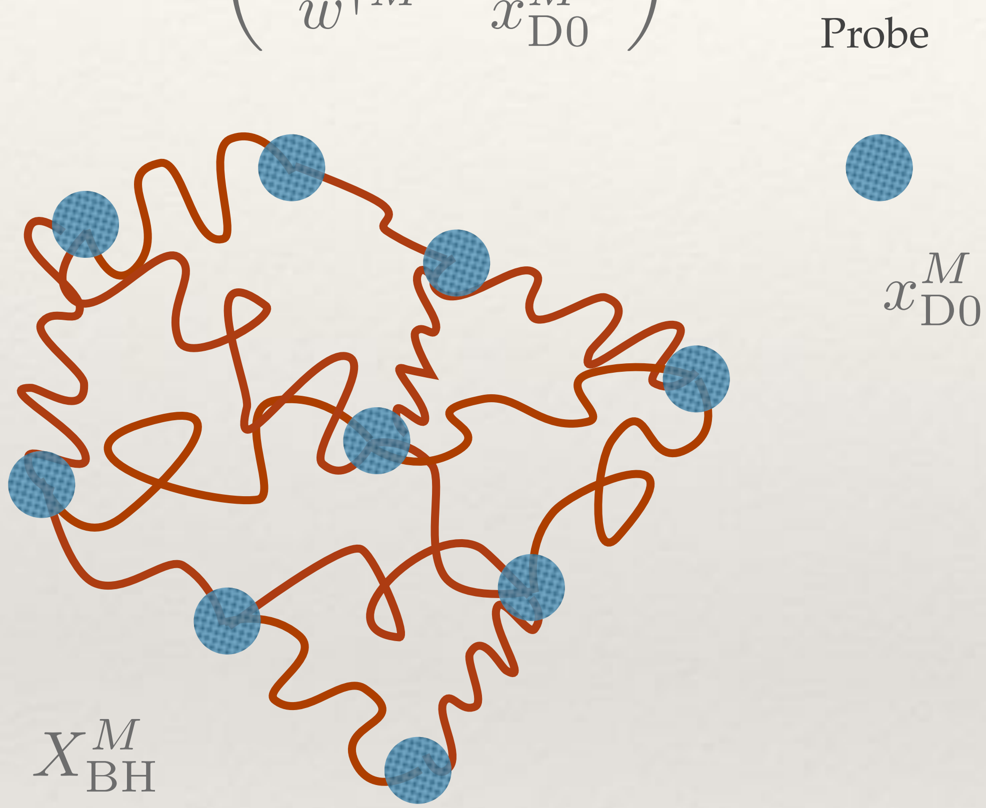
[Witten ’94, Banks, Fischler, Shenker, Susskind ’96]

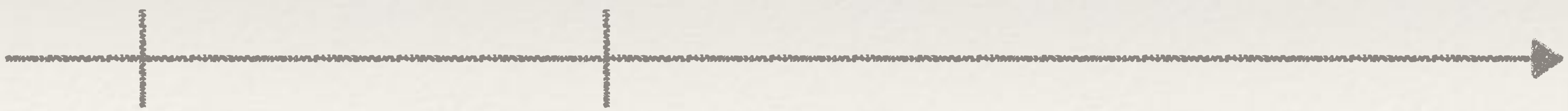
Numerical approach



"Probing" the force

$$X^M = \begin{pmatrix} X^M_{\rm BH} & w^M \\ w^{\dagger M} & x^M_{\rm D0} \end{pmatrix}$$

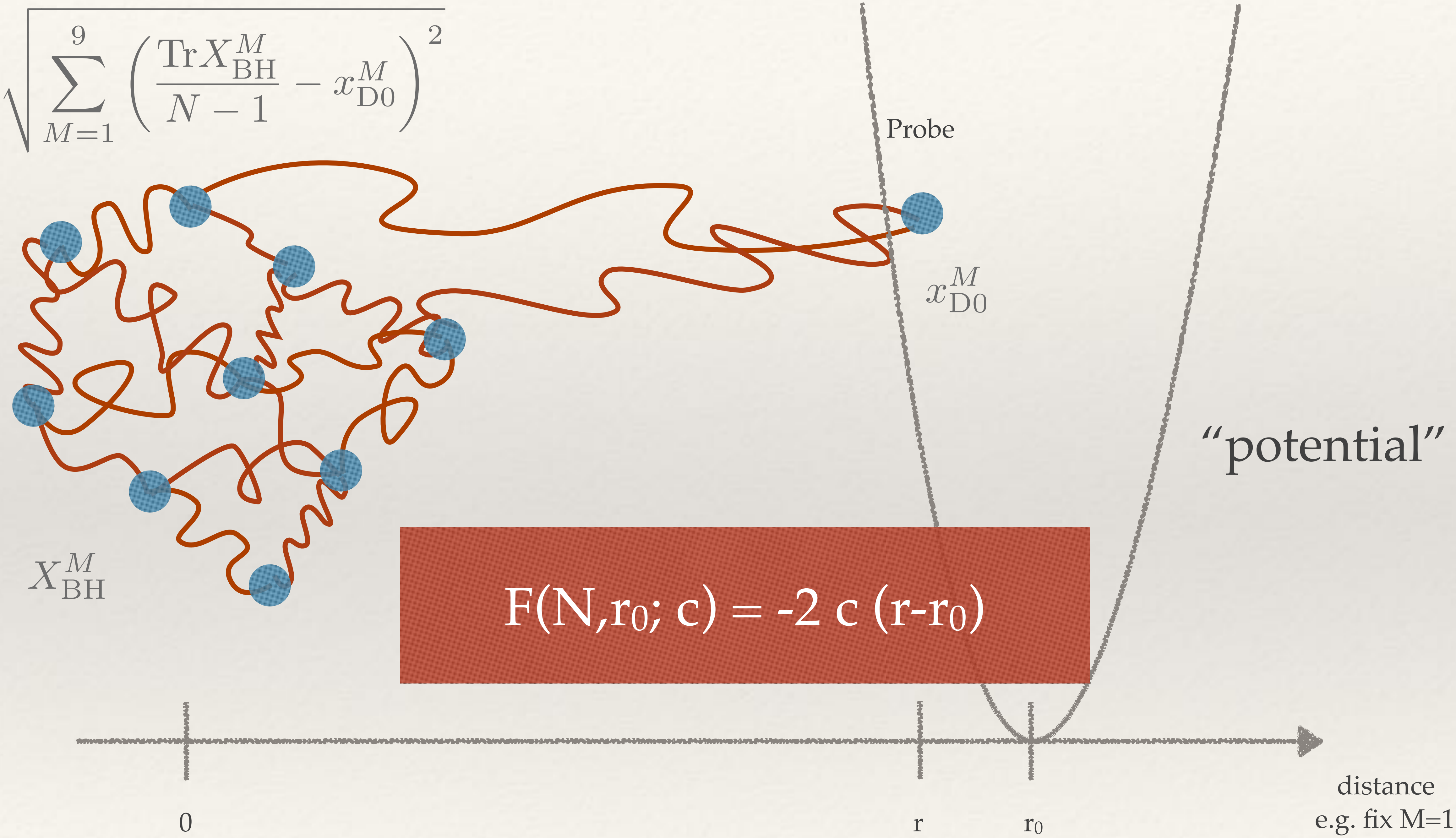




$$r \equiv \sqrt{\sum_{M=1}^{9} \left(\frac{{\rm Tr} X^M_{\rm BH}}{N-1} - x^M_{\rm D0} \right)^2}$$

"Measure" the force

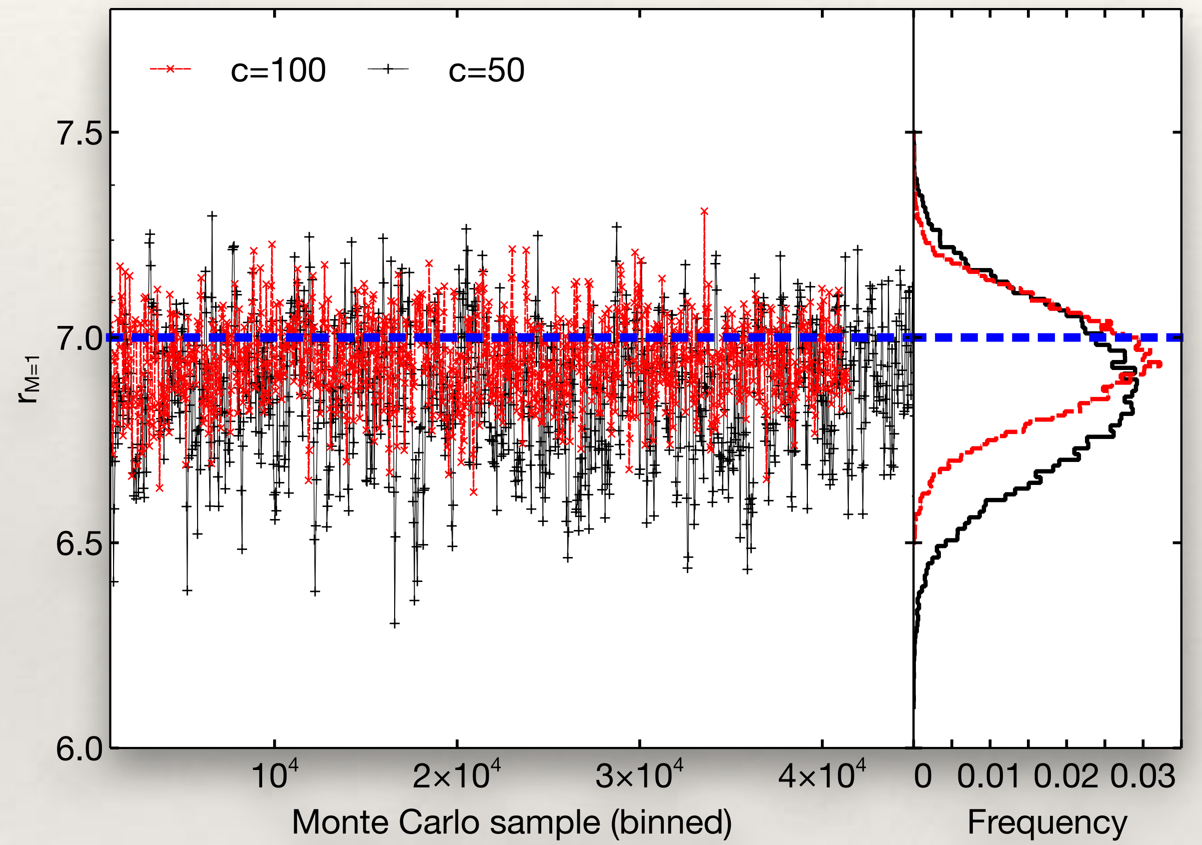
$$r \equiv \sqrt{\sum_{M=1}^{9}\left(\frac{\mathrm{Tr}X^{M}_{\mathrm{BH}}}{N-1} - x^{M}_{\mathrm{D0}}\right)^{2}}$$



$$\Delta L = -c\left\{\left(\frac{\mathrm{Tr}X^{1}_{\mathrm{BH}}}{N-1} - x^{1}_{\mathrm{D0}} - r_0\right)^{2} + \sum_{M=2}^{9}\left(\frac{\mathrm{Tr}X^{M}_{\mathrm{BH}}}{N-1} - x^{M}_{\mathrm{D0}}\right)^{2}\right\} - c'|w_1|^2$$

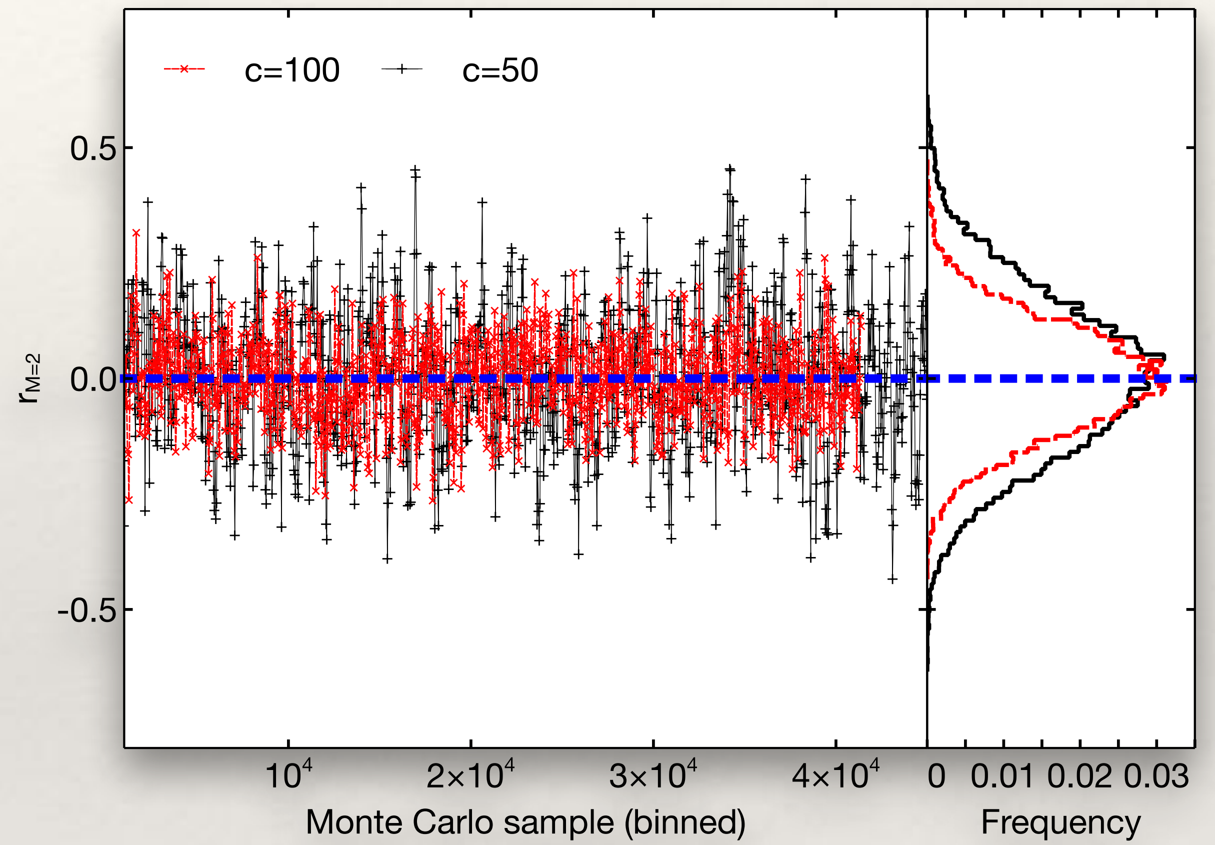
Numerical demonstration

distance
in M=1 direction



r_0=7.0

distance
in M=2 direction

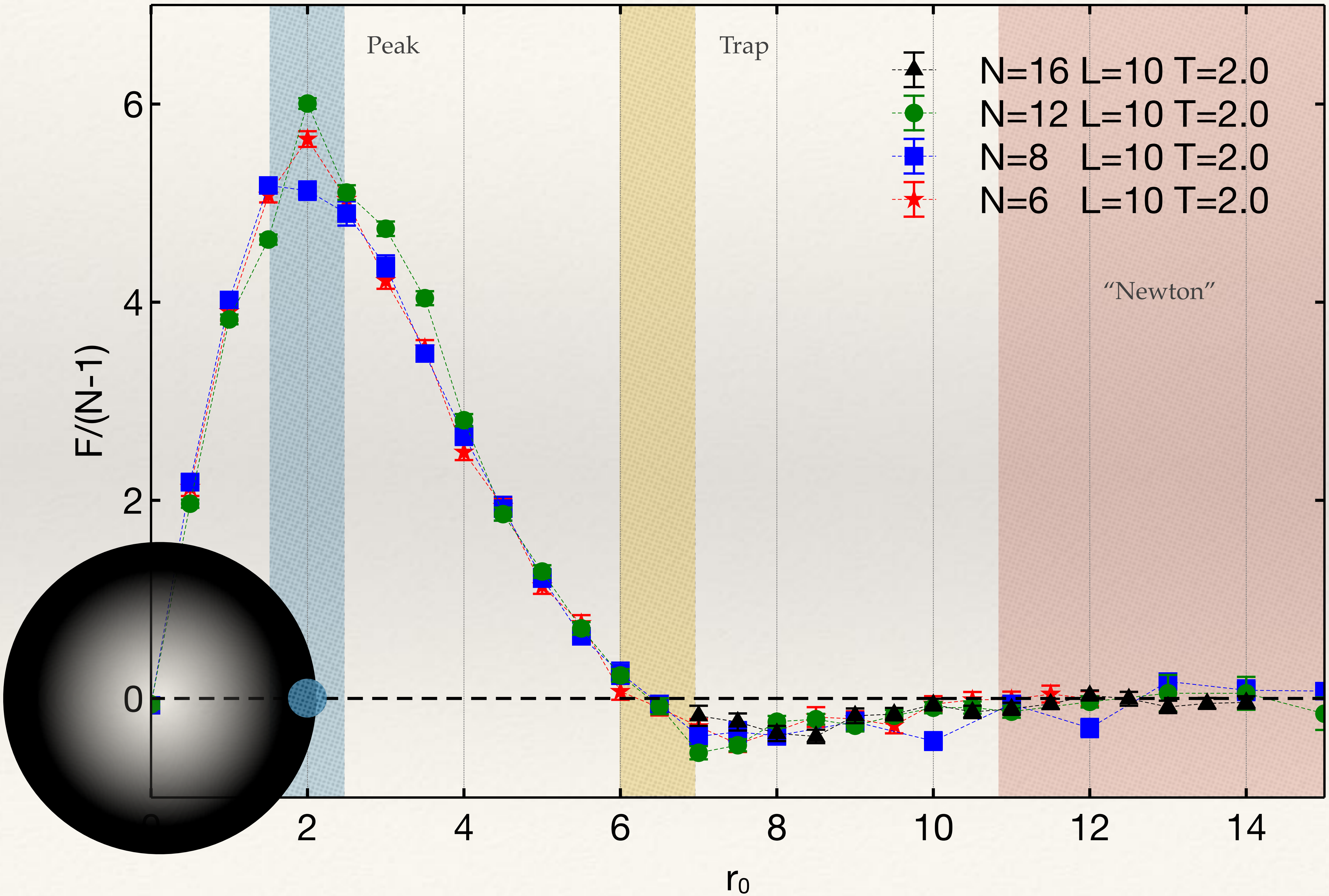


r_0=0.0

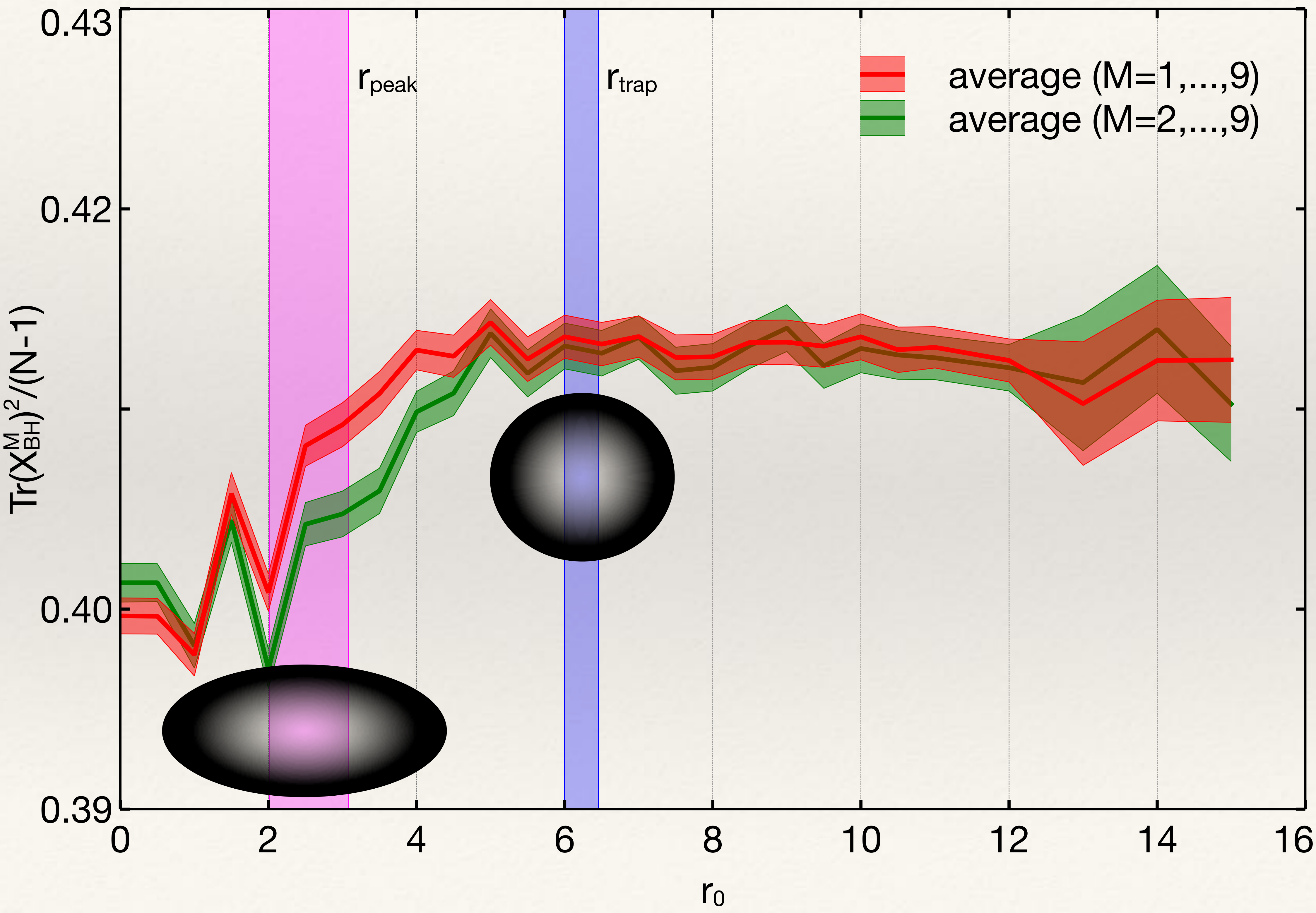
c=100

c=50

Lattice Monte Carlo results



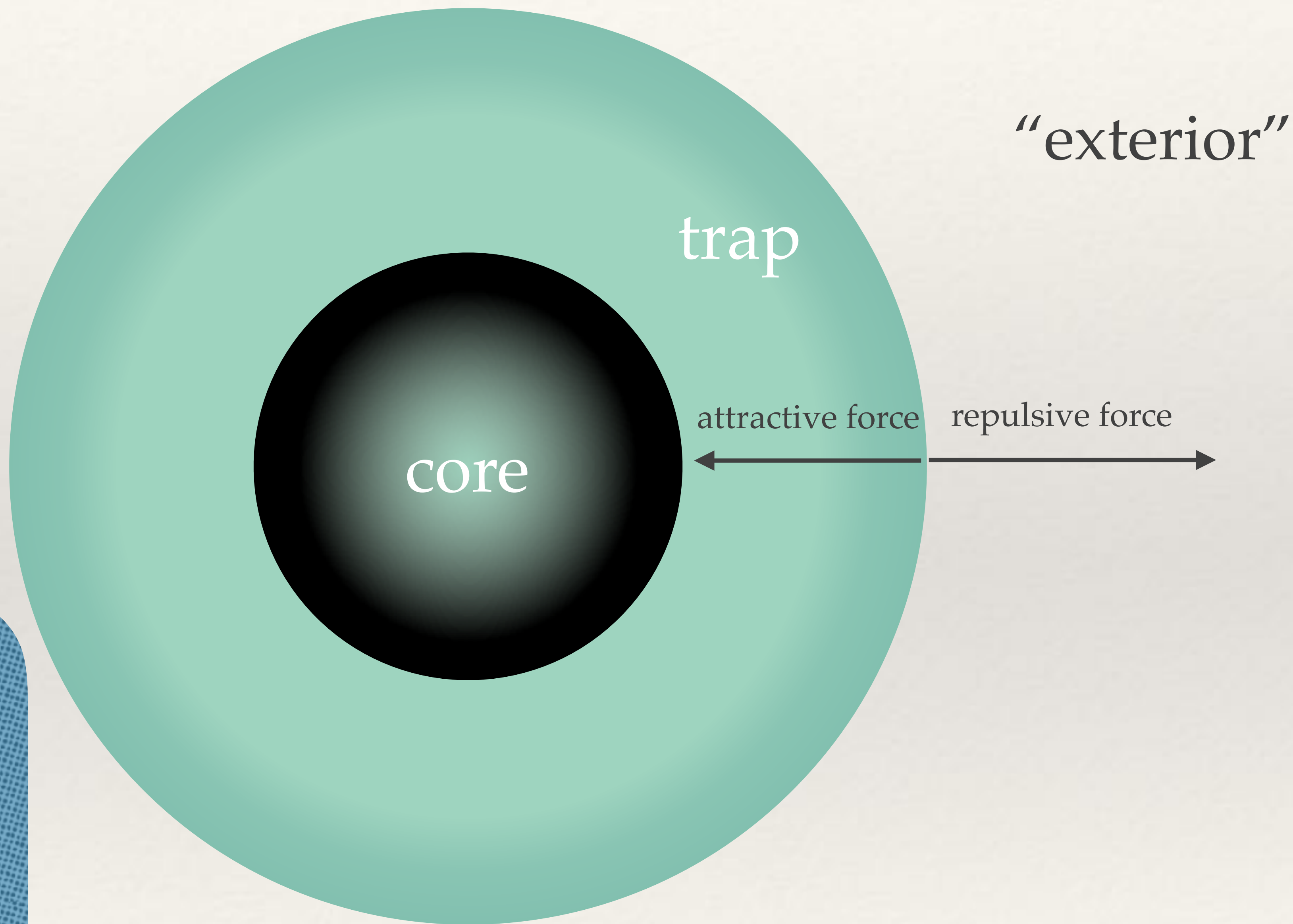
Core radius



0.43
0.42
0.40
0.39
0
2
4
6
8
10
12
14
16
r_{peak}
r_{trap}
average (M=1,...,9)
average (M=2,...,9)
$\mathrm{Tr}(X^M_{BH})^2/(N-1)$
r_0

[MCSMC, JHEP 1802 (2018) 042]

Possible interpretations



Caveats:

- not accounting the potential
- no continuum limit
- no large-N limit

trap = horizon

[see also: Filev, O'Connor arXiv: 1512.02536, 1612.09281]

Summary and future work

- Testing the gauge/gravity duality is the first step towards using it to define a quantum theory of gravity
- Numerical tests are now mature for low-dimensional systems: control over continuum and planar limit (only for p=0)
- Lower temperatures are needed to directly extract the leading SUGRA behavior from data (unless assumptions are made)
- New numerical simulations can help extracting bulk geometrical properties of gravity theories
- New conjectures can be tested non-perturbatively in relatively short time [see MCSMC 1802.02985 and Maldacena, Milekhin 1802.00428]

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BROOKHAVEN NATIONAL LABORATORY

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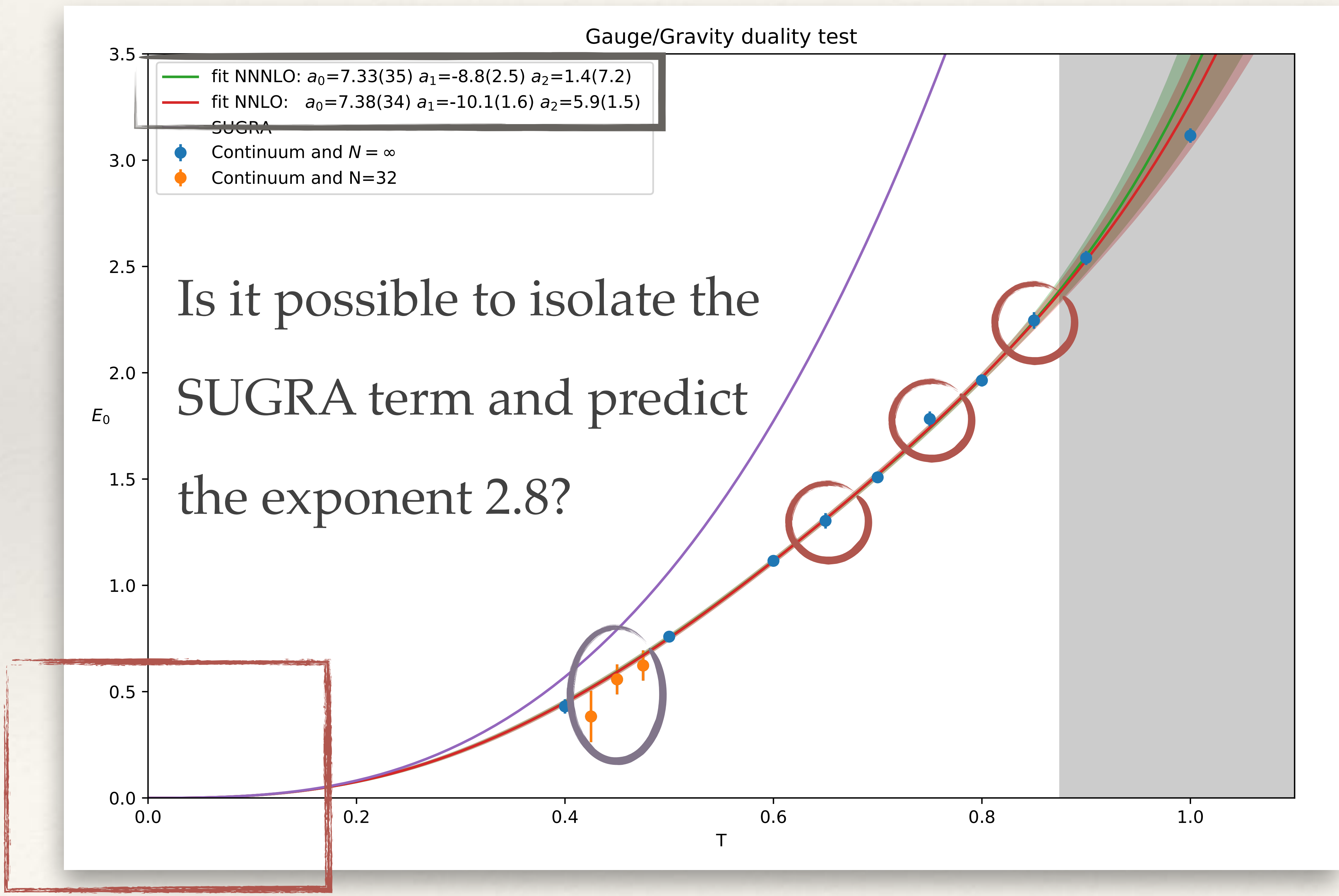
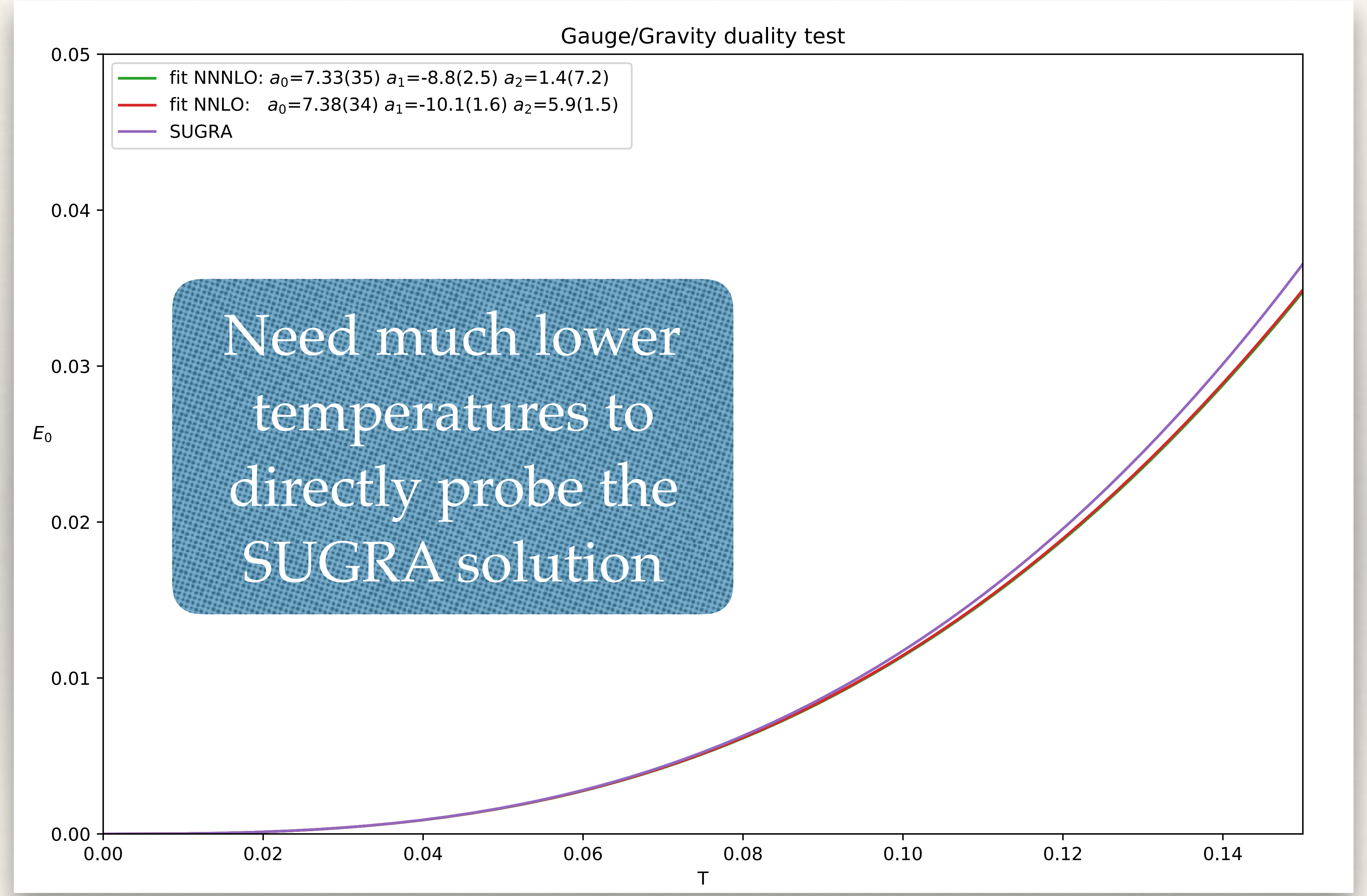
Extra slides

Preliminary new results

$$\frac{E}{N^2} = a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8}$$



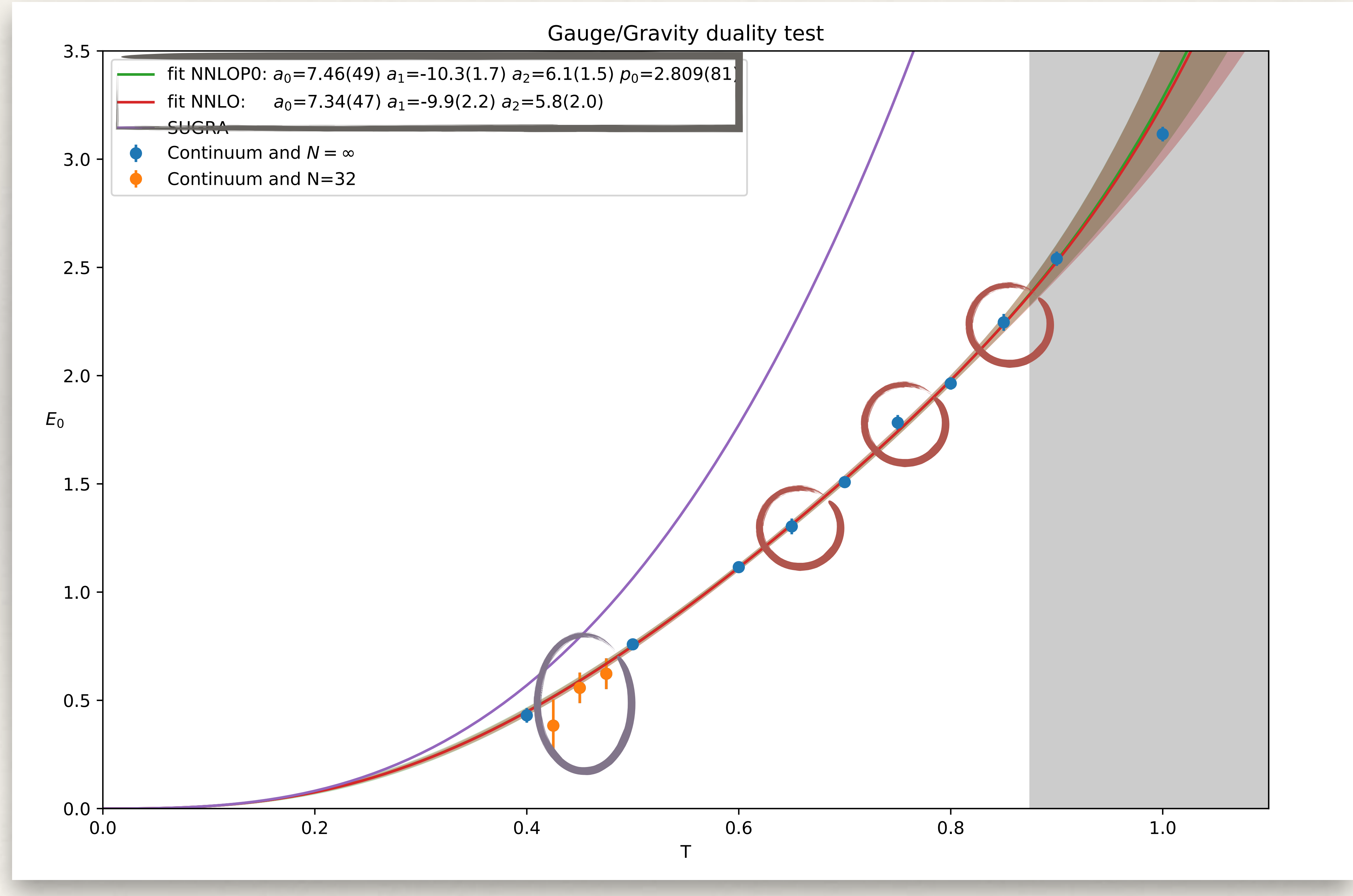
Preliminary new results



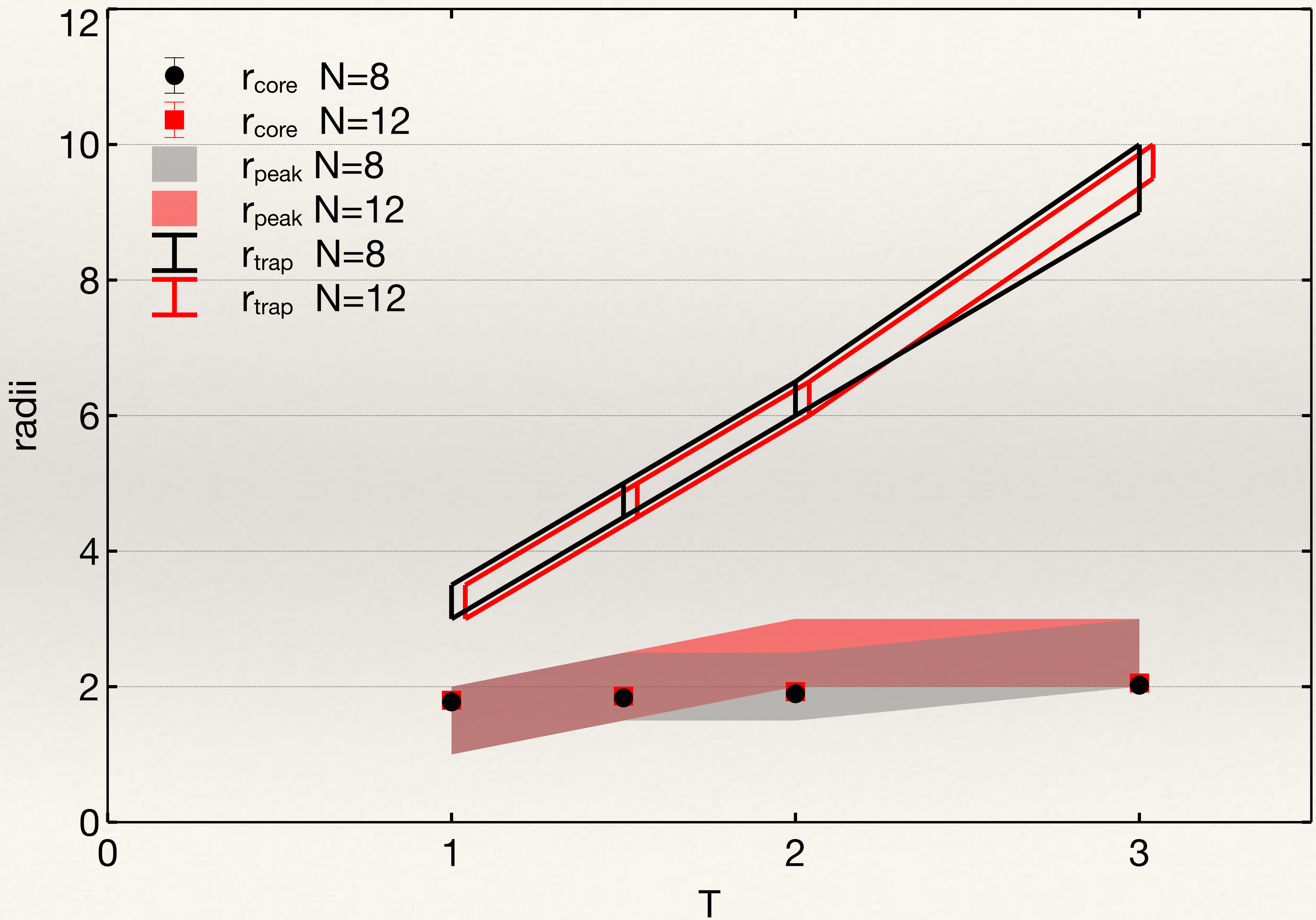
Preliminary new results

$$\frac{E}{N^2} = a_0 T^{p_0} + a_1 T^{p_0+1.8} + a_2 T^{p_0+3}$$

- Bayesian priors are used
- Assumptions on the low-energy gravity theory are used



Temperature dependence



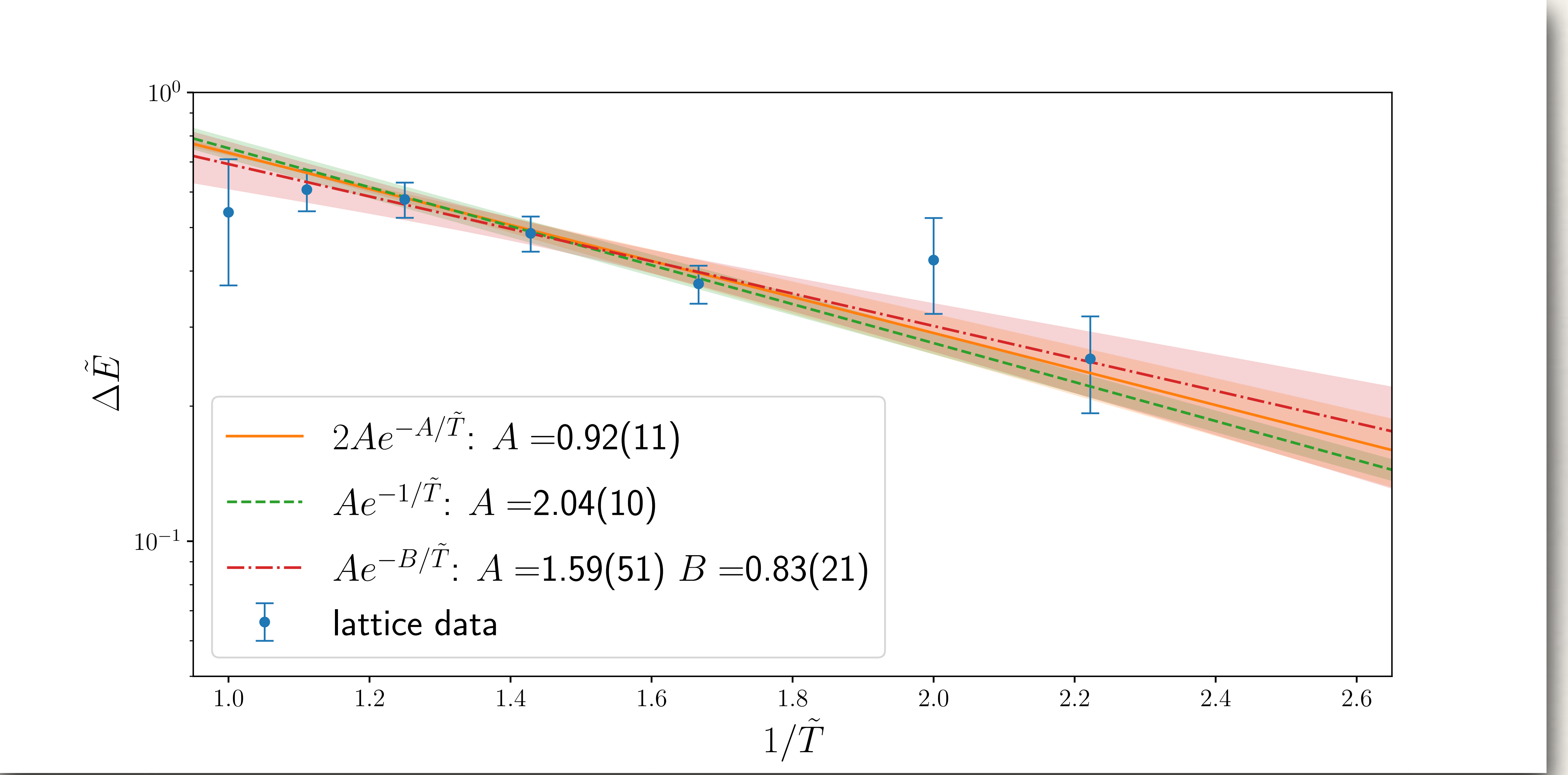
"to gauge or not to gauge"

"un"gauge / gravity duality

Easier to simulate on a quantum computer!

- ★ D0-brane matrix model (and its string theory dual)
- ★ SU(N) symmetry is just a global symmetry in quantum mechanics
- ★ Remove gauge singlet constraint (Gauss Law)
- ★ Introduce non-singlet states
- ★ Effects on non-singlets are suppressed at low energy
- ★ Where the gravity solution is valid, gauge singlets dominates

Energy difference

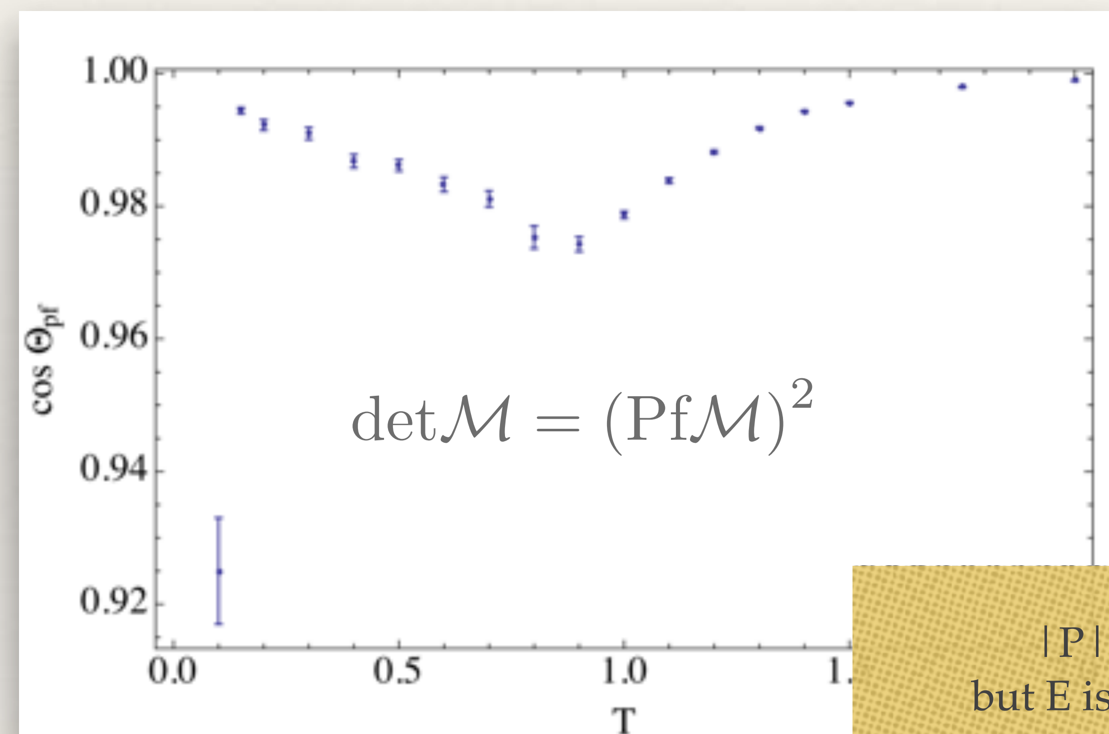


$$\Delta E = E_{\text{ungauged}} - E_{\text{gauged}} = d_{\text{adj}} C_{\text{adj}} N^2 e^{-C_{\text{adj}}/T} + \cdots$$

Challenge 2: Pfaffian

phase reweighting: $$\langle \mathcal{O} \rangle_{\mathrm{F}} = \frac{\langle \mathcal{O} \cdot e^{i\theta} \rangle_{\mathrm{PQ}}}{\langle e^{i\theta} \rangle_{\mathrm{PQ}}}$$

N=3 L=4 (+ small regulator mass)



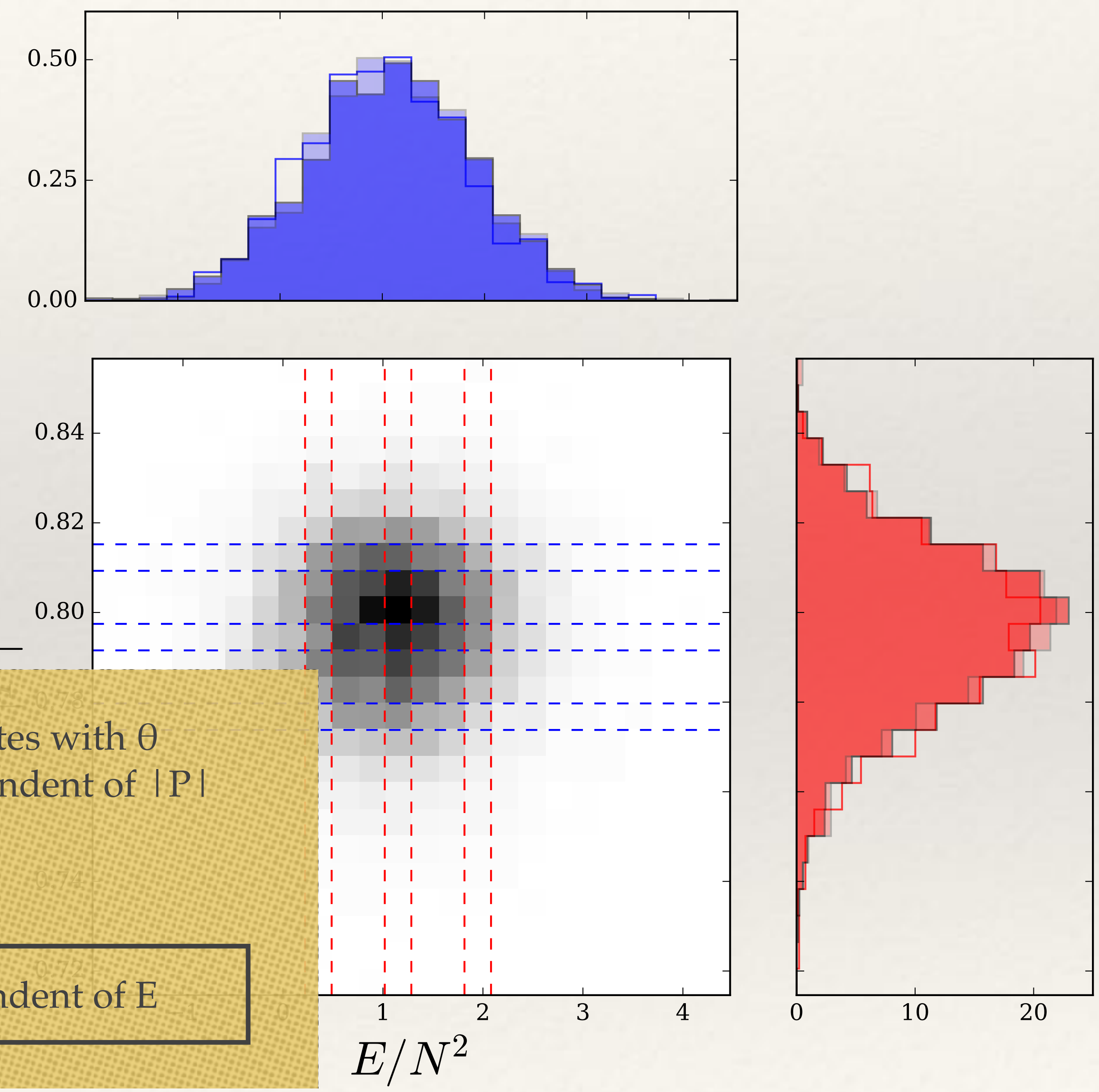
$$\det \mathcal{M} = (\mathrm{Pf}\mathcal{M})^2$$

$$\langle \mathcal{O} \rangle_{\mathrm{PQ}} = \int dx \; x\rho(x)$$

$$\langle \mathcal{O} \cdot e^{i\theta} \rangle_{\mathrm{PQ}} = \int dx \; x\rho(x) w_x$$

$$\langle e^{i\theta} \rangle_{\mathrm{PQ}} = \int dx \; \rho(x) w_x$$

T=0.5 N=16 L=16 O(a) improved action



|P| correlates with θ
but E is independent of |P|

θ is independent of E

No correlations between |P| and E

Perturbative treatment of type IIA superstring: type IIA supergravity + higher derivative corrections e.g. Hanada et al. arxiv:1603.00538

Analytical expectations at finite T

$$E/N^2 = \frac{(a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8} + \cdots)}{N^0} + \frac{(b_0 T^{0.4} + b_1 T^{2.2} + \cdots)}{N^2} + \mathcal{O}\left(\frac{1}{N^4}\right)$$

small T, infinite N, strong coupling — $a_0 = 7.41$

finite T, infinite N, finite coupling — ${\ell_s}^6 \cdots$

Include effects of finite string length

small T, finite N, strong coupling — $b_0 = -5.77$

Include effects of finite string coupling

small T, finite N, strong coupling — $\sim {\ell_s}^{12} {g_s}^2$

quantum string corrections