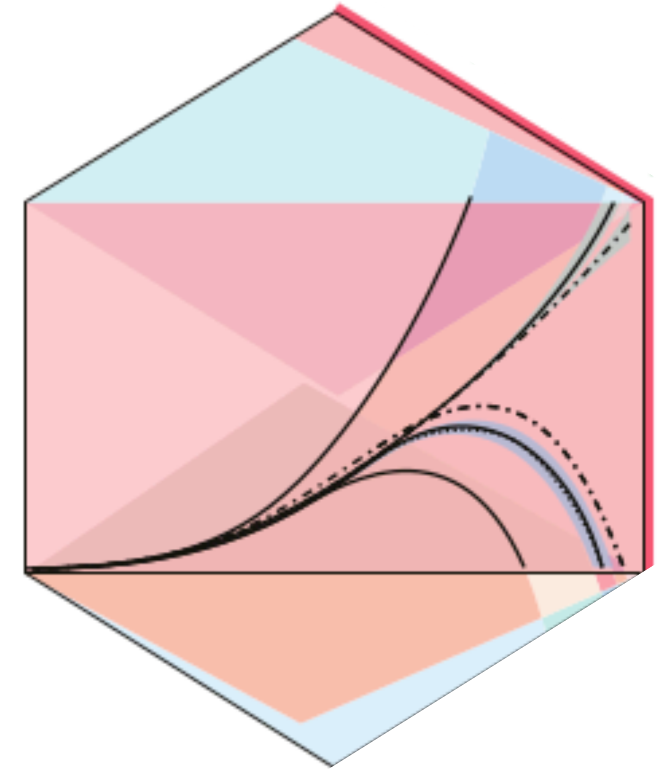
Lawrence Livermore National Laboratory

JÜLICH FORSCHUNGSZENTRUM



Probing D0-brane Black Holes

Evan Berkowitz
MCSMC: Monte Carlo String + M-Theory Collaboration
Forschungszentrum Jülich

Numerical Approaches to Holography, Quantum Gravity, and Cosmology
2018-05-24
Higgs Centre for Theoretical Physics

1606.04948 1606.04951 EB, Enrico Rinaldi, Masanori Hanada, Pavlos Vranas, Goro Ishiki, Shinji Shimasaki
1709.01932 Rinaldi, EB, Hanada, Maltz, and Vranas
+ forthcoming work

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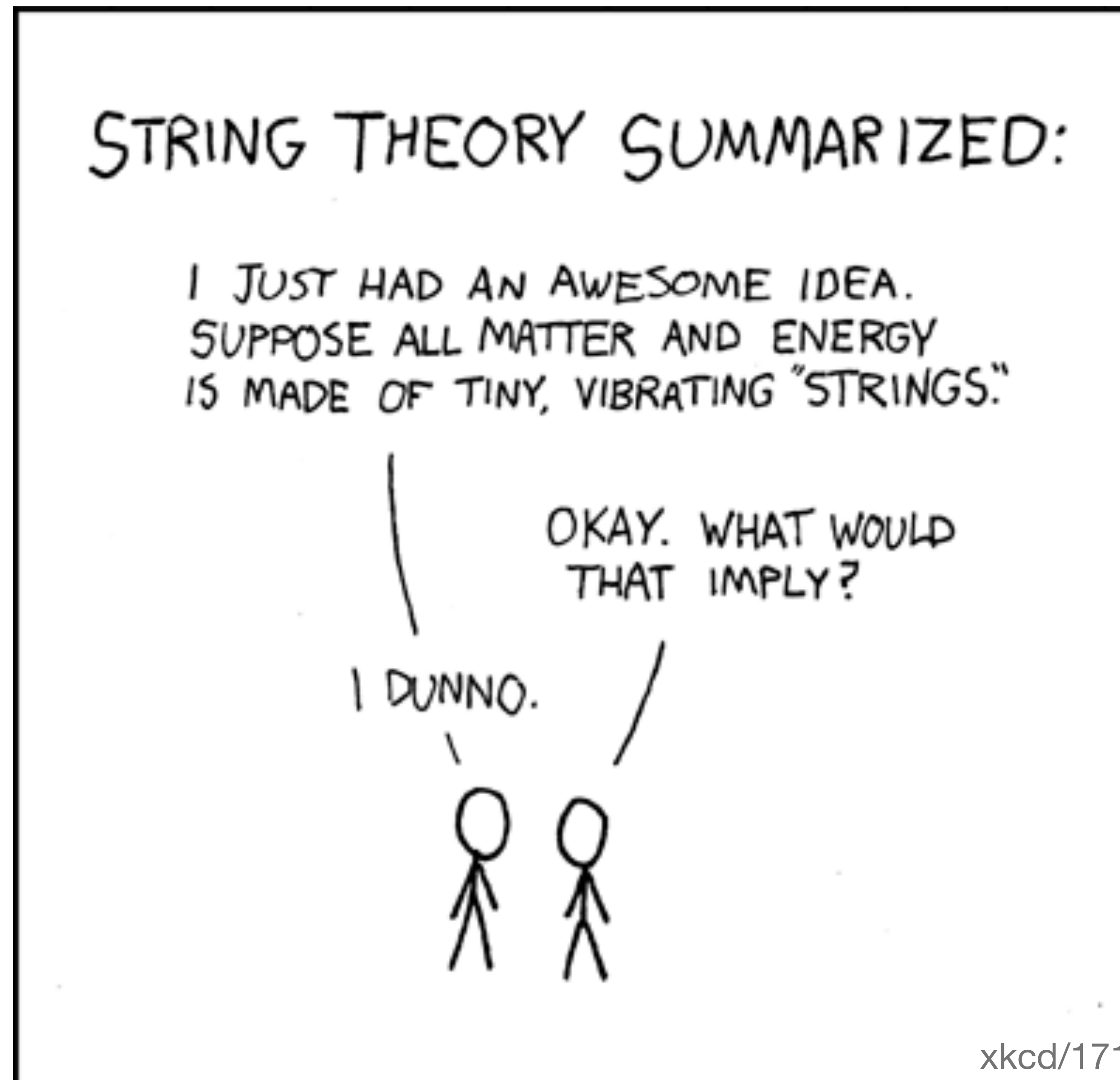
Outline

- Gauge/Gravity Duality & Motivation
- The BFSS / D0 Matrix Model
- Monte Carlo, Fitting
- Tests of Holography
- Probes of Geometry



xkcd/171

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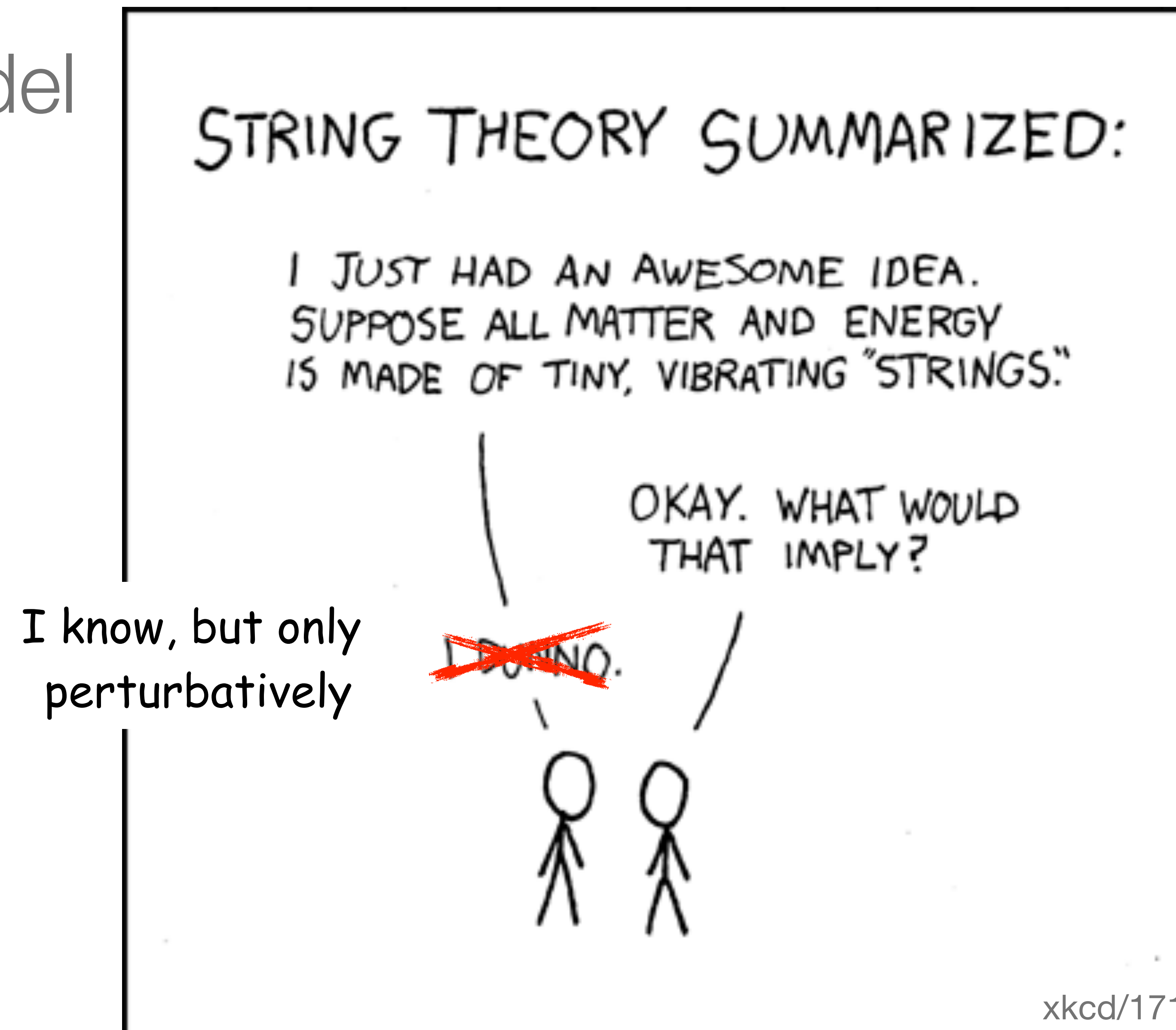

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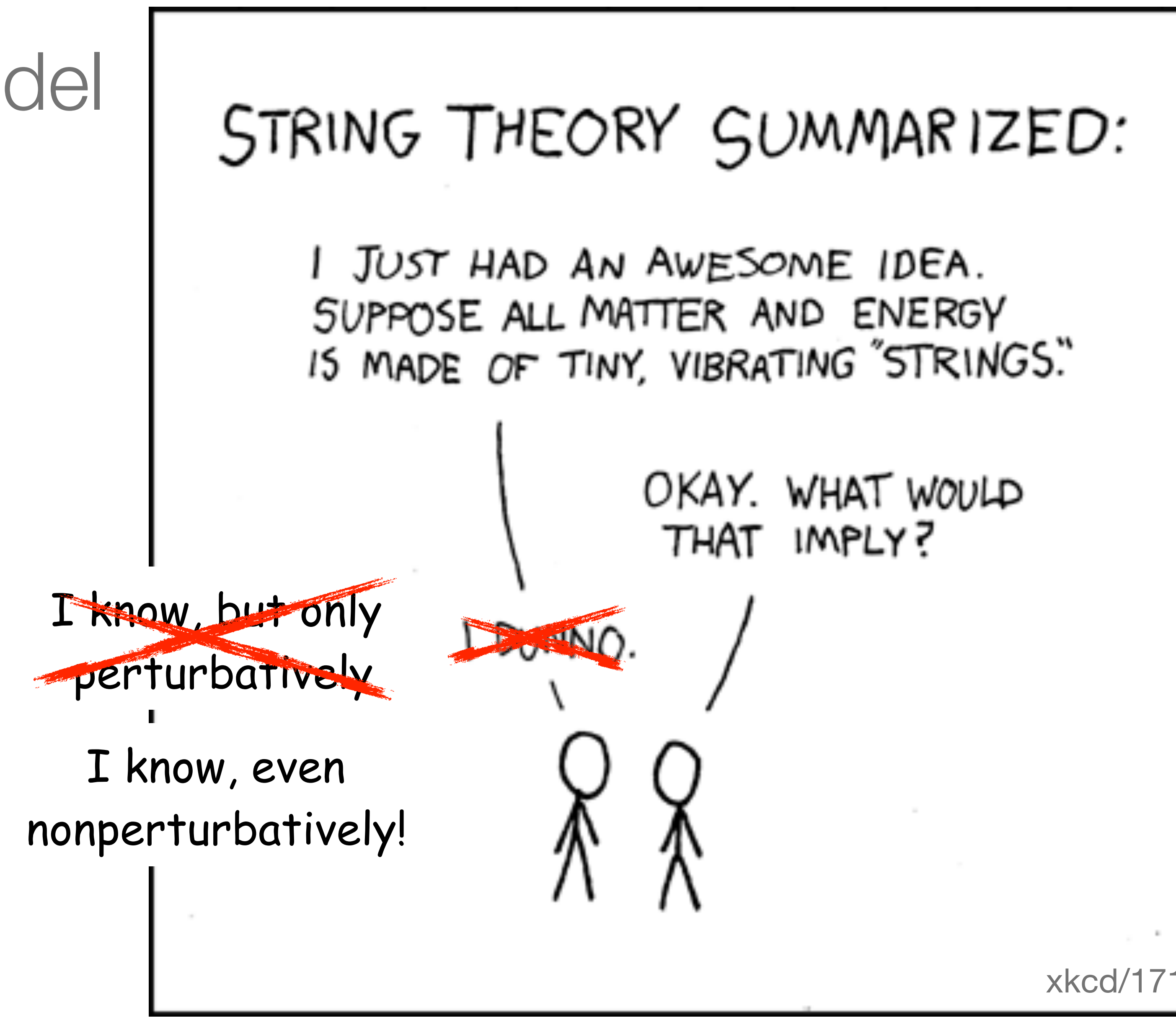

xkcd/171

0+1 D0 Brane QM / BFSS Matrix Model

Banks Fischler Shenker Susskind hep-th/9610043

$$L = \frac{1}{2g_{YM}^2}\mathrm{Tr}\left\{(D_t X_M)^2 + i\bar{\psi}^\alpha D_t \gamma^{10}_{\alpha\beta}\psi^\beta + \bar{\psi}^\alpha \gamma^M_{\alpha\beta}[X_M, \psi^\beta] + [X_M, X_{M'}]^2\right\}$$

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$D_t \cdot = \partial_t \cdot - i[A_t, \cdot]$

γ^M left-handed part of 9+1D γs

X_M 9 bosonic

ψ^α 16 fermionic

$N \times N$ matrices

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Yukawa Self-interaction

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$N \times N$ matrices

- Obvious nonperturbative definition (discretized quantum mechanics)
- Defined for all N and g_{YM}
- Manifestly unitary

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- 10D SUGRA at low temperature
- Dimensionful coupling, easy scale setting!
- Low T = strong coupling

BFSS Conjecture:
This theory ≡ M theory

IIA is in here too!

0+1 D0 Brane QM / BFSS Matrix Model

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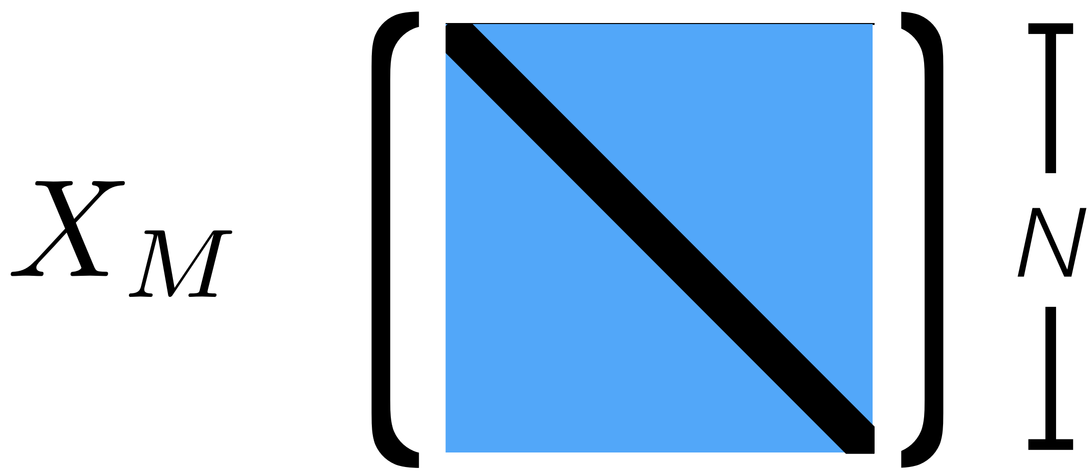
Quote everything in terms of dimensionful coupling $\lambda = g_{YM}^2 N$

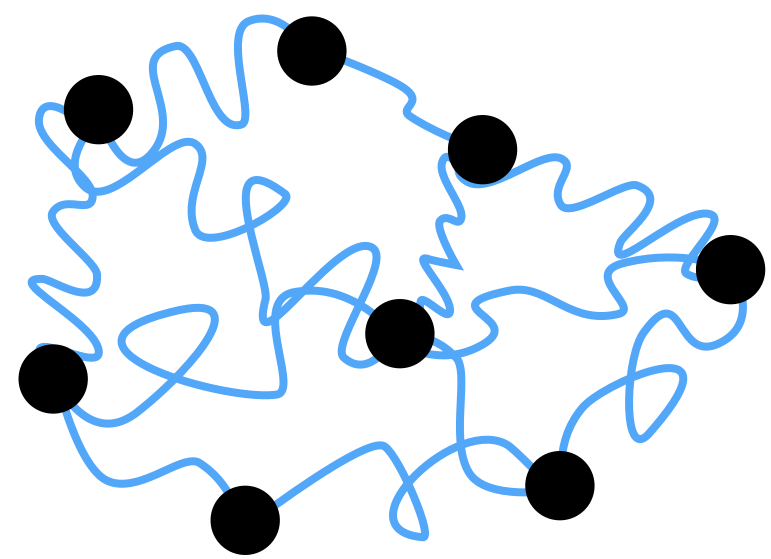
eg. T is actually $\lambda^{-1/3} T$

BFSS Cartoon

Witten hep-th/9510135

$$L = \frac{1}{2g_{YM}^2}\mathrm{Tr}\left\{ (D_t X_M)^2 + i\bar{\psi}^\alpha D_t \gamma^{10}_{\alpha\beta}\psi^\beta + \bar{\psi}^\alpha \gamma^M_{\alpha\beta}[X_M, \psi^\beta] + [X_M, X_{M'}]^2 \right\}$$





coordinates

couplings

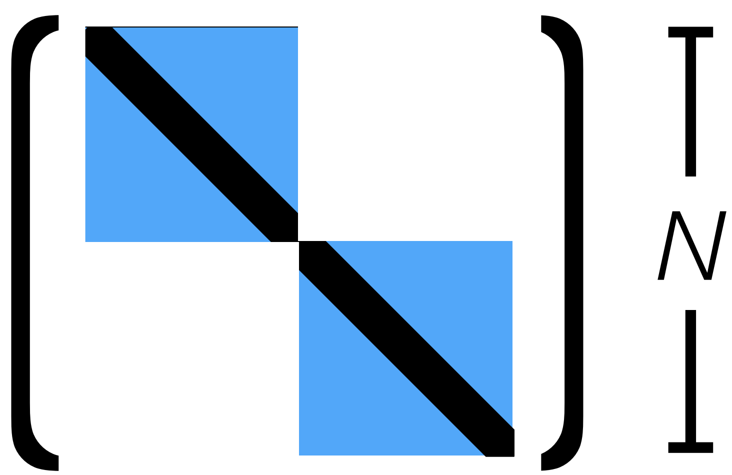
One big bunch ~ black 0-brane ~ BH

BFSS Cartoon

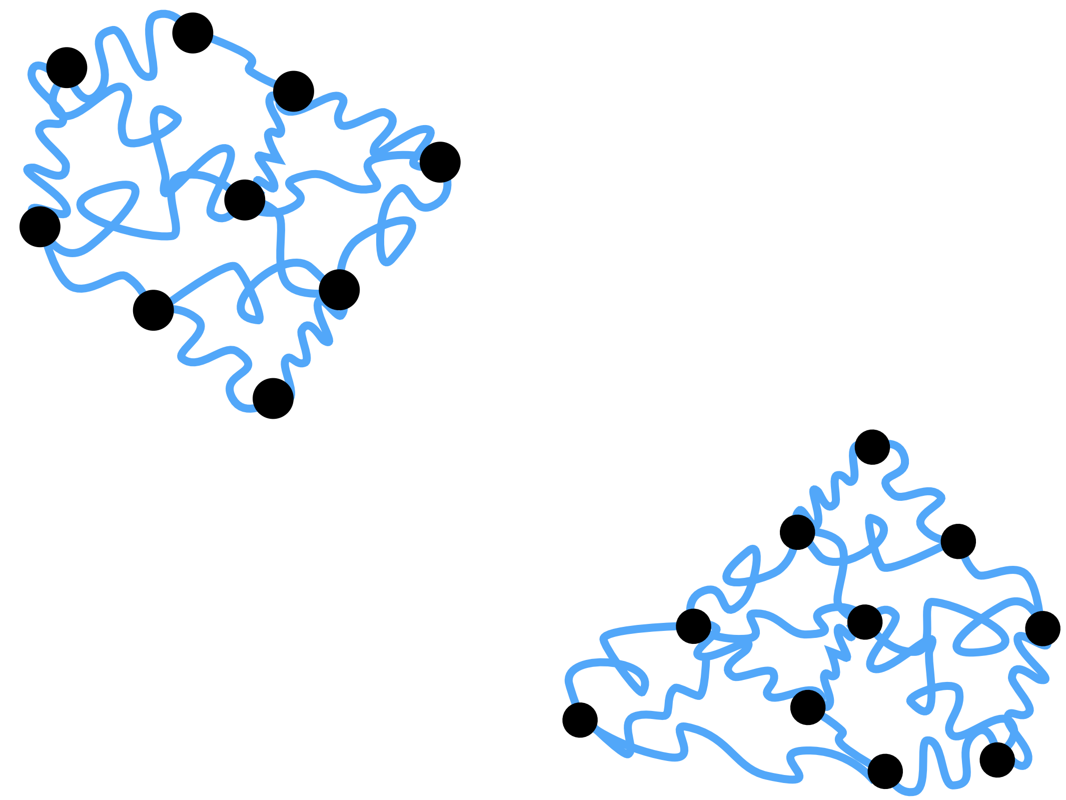
Witten hep-th/9510135

$$L = \frac{1}{2g_{YM}^2}\mathrm{Tr}\left\{(D_t X_M)^2 + i\bar{\psi}^\alpha D_t \gamma^{10}_{\alpha\beta}\psi^\beta + \bar{\psi}^\alpha\gamma^M_{\alpha\beta}[X_M,\psi^\beta] + [X_M, X_{M'}]^2\right\}$$

$$X_M$$



2 BHs



At large *N* BFSS is a 2nd quantized theory!

BFSS Cartoon

Witten hep-th/9510135

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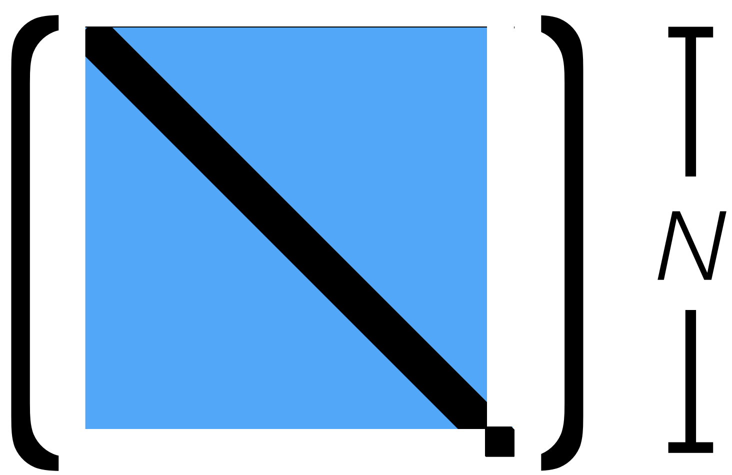
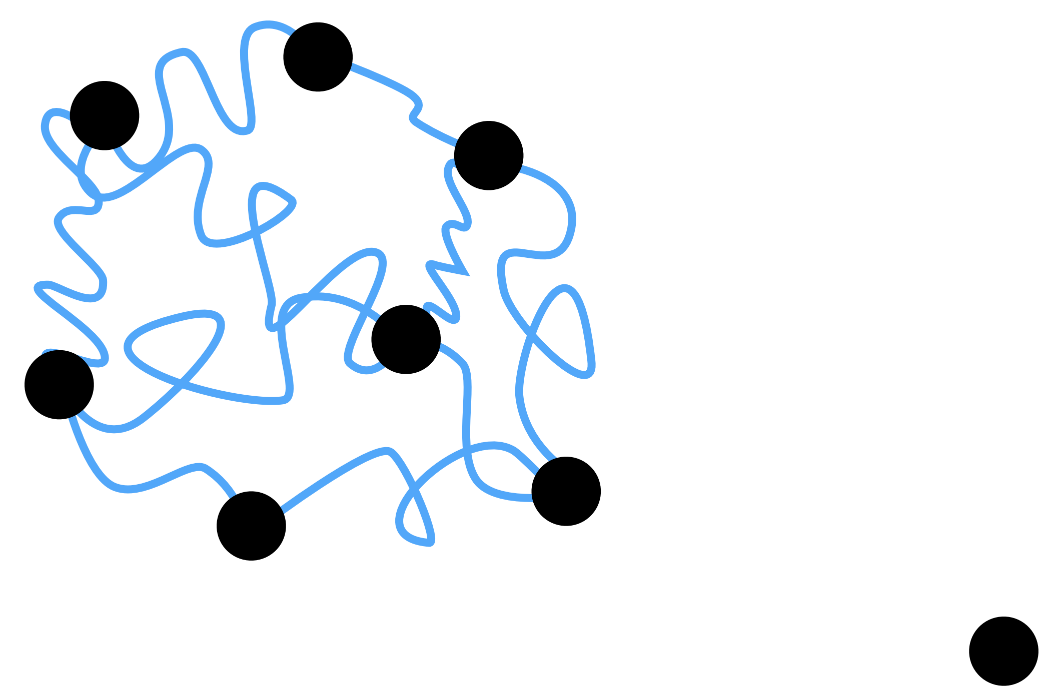
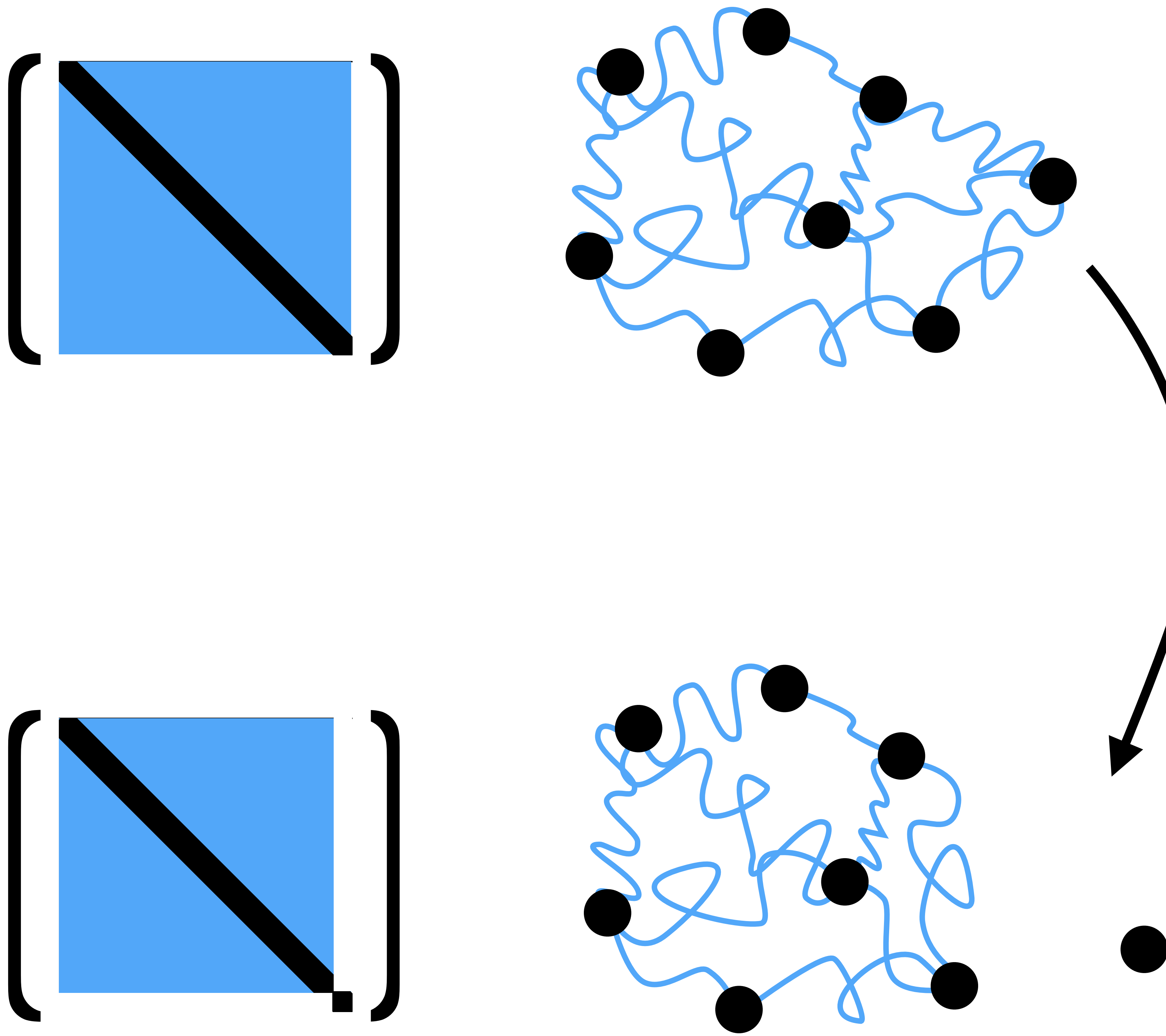


BH + D0 radiation



Monte Carlo Study of Metastable State?



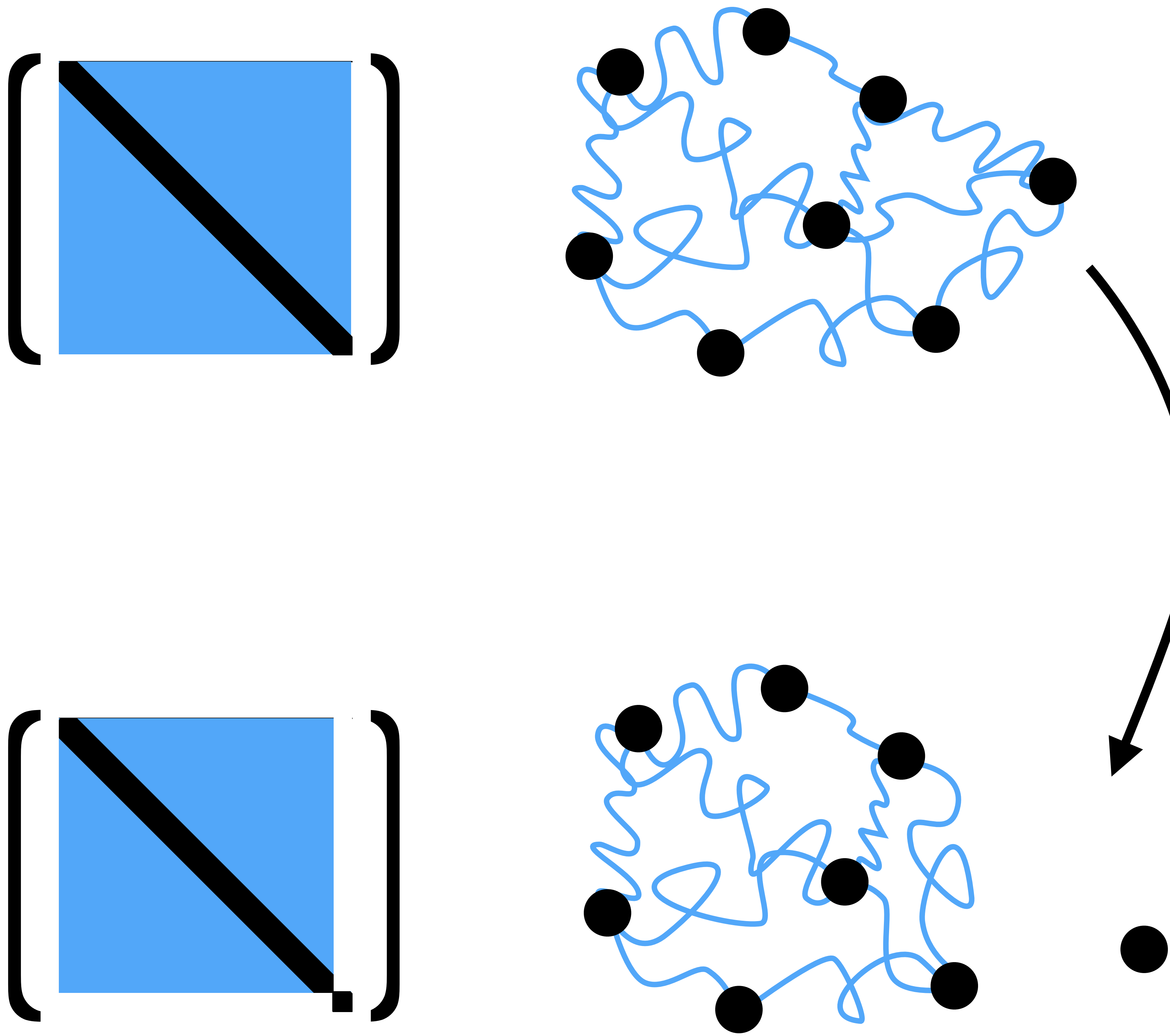
DOF ~ N^2

$t_{recurrence} \sim e^{+N^2}$

$\tau \sim e^{+N}$

DOF ~ $(N-1)^2$

Monte Carlo Study of Metastable State?



DOF $\sim N^2$

$t_{\text{recurrence}} \sim e^{+N^2}$

$\tau \sim e^{+N}$

DOF $\sim (N-1)^2$

$+ \# \log(V)$

Possible Observables

Likely an incomplete list!

Fast Scrambling	arXiv:1512.00019 Gur-Ari, Hanada, Shenker	$t_{\mathrm{scramble}} \sim \log N$
SUGRA	0707.4454 Anagnostopoulos et al. 0803.4273 Catterall+Wiseman 1503.08499 Kadoh, Kamata 1506.01366 Filev, O'Connor	
Finite N	0811.3102 Hanada, Hyakutake, Nishimura, Takeuchi 1311.5603 1603.00538 Hanada, Hyakutake, Ishiki, Nishimura 1606.04948 1606.04951 MCSMC	
Polyakov loop	0811.2081 Hanada, Miwa, Nishimura, Takeuchi	
2-point functions	1108.5153 Hanada, Nishimura, Sekino, Yoneya, 2009, 2011	
Force	1709.01932 Rinaldi, Berkowitz, Hanada, Maltz, Vranas	

Test: BH Internal Energy

$$E/N^2 = \underbrace{\frac{(a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8} + \cdots)}{N^0}}_{\frac{E_0(T)}{N^0}} + \underbrace{\frac{(b_0 T^{0.4} + b_1 T^{2.2} + \cdots)}{N^2}}_{\frac{E_1(T)}{N^2}} + \mathcal{O}\left(\frac{1}{N^4}\right)$$

$$\frac{E_0(T)}{N^0} + \frac{E_1(T)}{N^2} + \ldots$$

Expand in $\frac{\alpha'}{R_{BH}^2} \sim T^{3/5}$

$(\alpha')^{1,\ 2,\ \text{and}\ 4}$ terms vanish

Gross + Witten, Nucl Phys B 277:1 1986
Gross + Sloan, Nucl Phys B291:41-89, 1987
Grisaru, van de Ven, + Zanon PLB 173:423-428, 1986

Green + Vanhove PRD61:104011, 2000
Green, Russo + Vanhove JHEP 02:099, 2007

Hyakutake PTEP 2014:033B04, 2014
Hyakutake JHEP 09:075, 2014

$a_0 = 7.41$

hep-th/980242 Itzhaki, Maldacena, Sonnenschein, Yankielowicz

$b_0 = -5.77$

1311.7526 Hyakutake

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$$\frac{E_0(T)}{N^0} + \frac{E_1(T)}{N^2} + \ldots$$

't Hooft counting still valid, even in discretized theory

Expand in $\dfrac{\alpha'}{R_{BH}^2} \sim T^{3/5}$

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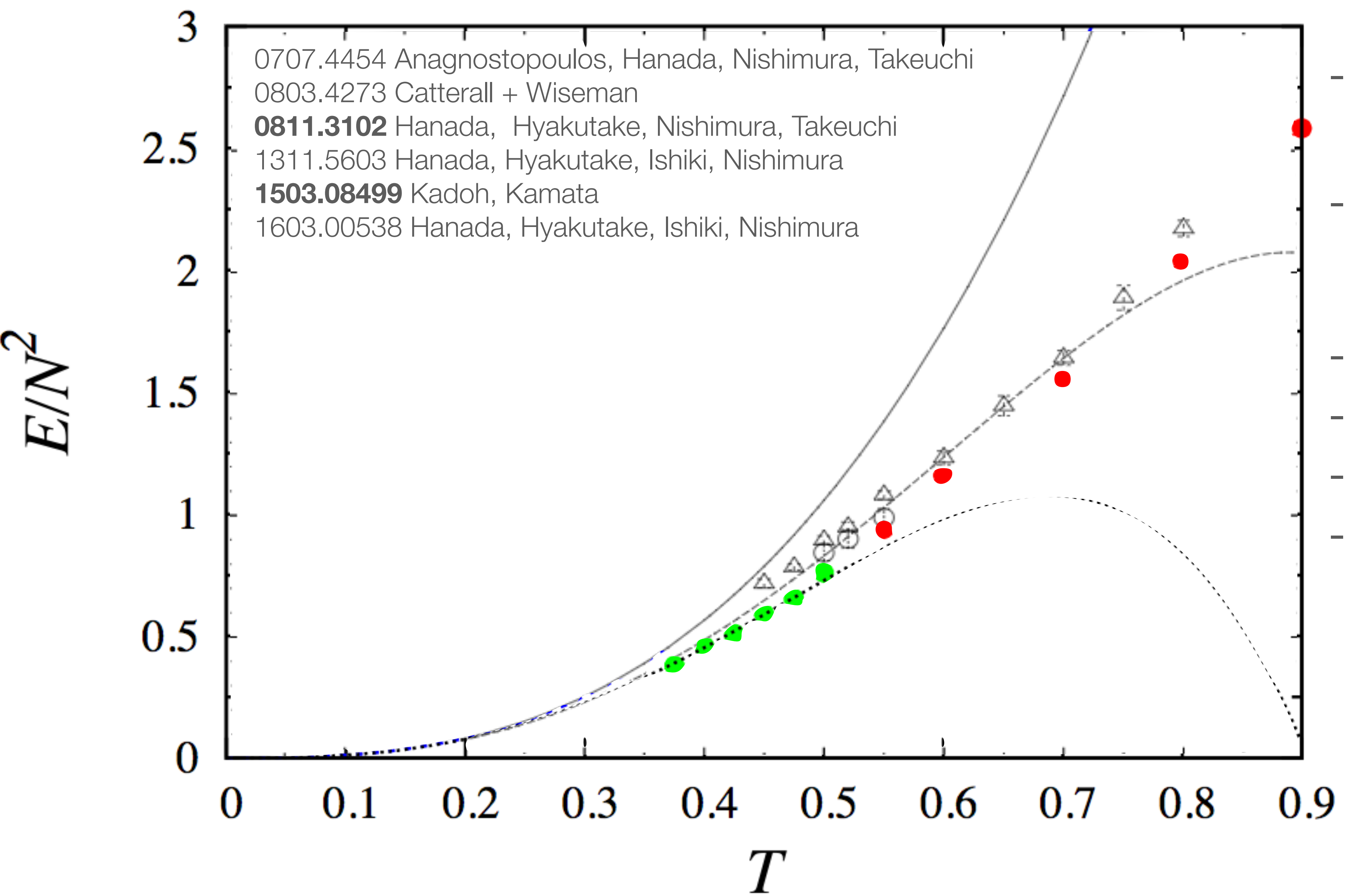

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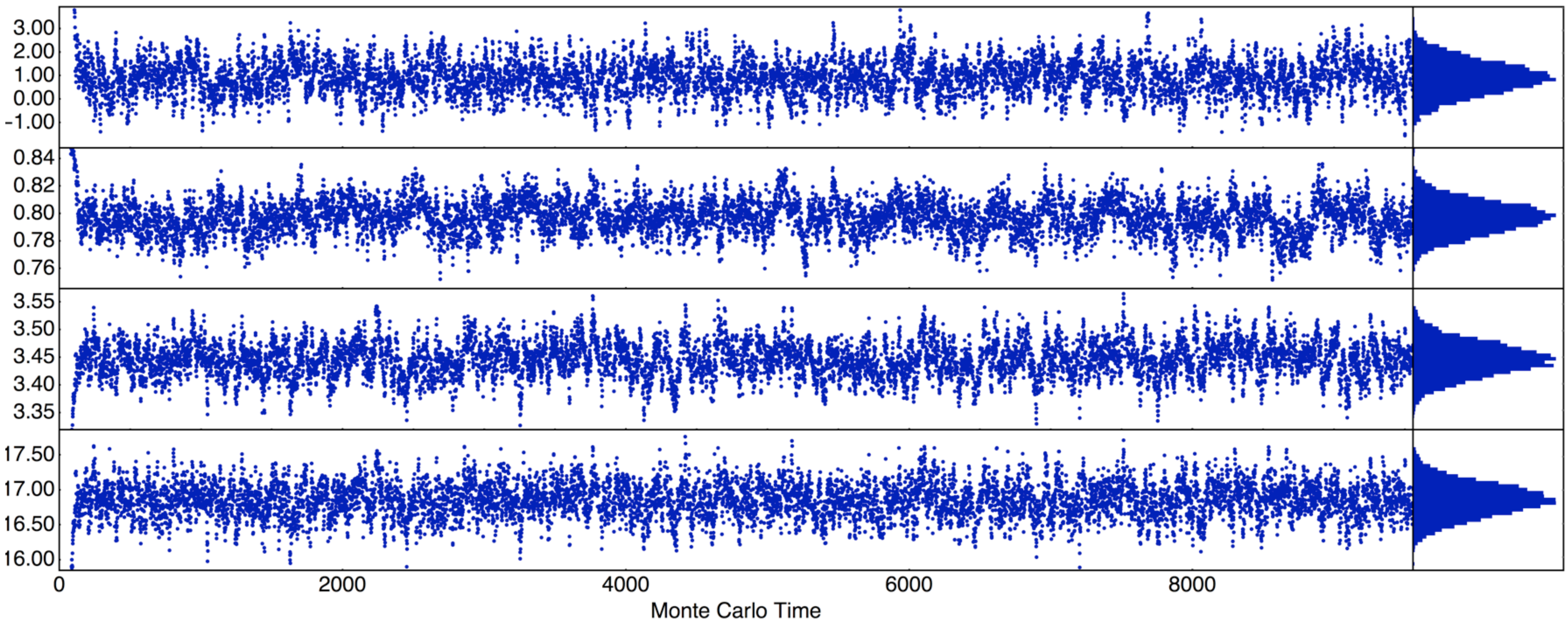
  hep-th/980242 Itzhaki, Maldacena, Sonnenschein, Yankielowicz
- $b_0 = -5.77$
  1311.7526 Hyakutake

- No large N
- No continuum limit
- a_0 fixed by hand
- NLO tension

Example Monte Carlo History

MCSMC 1606.04948 1606.04951

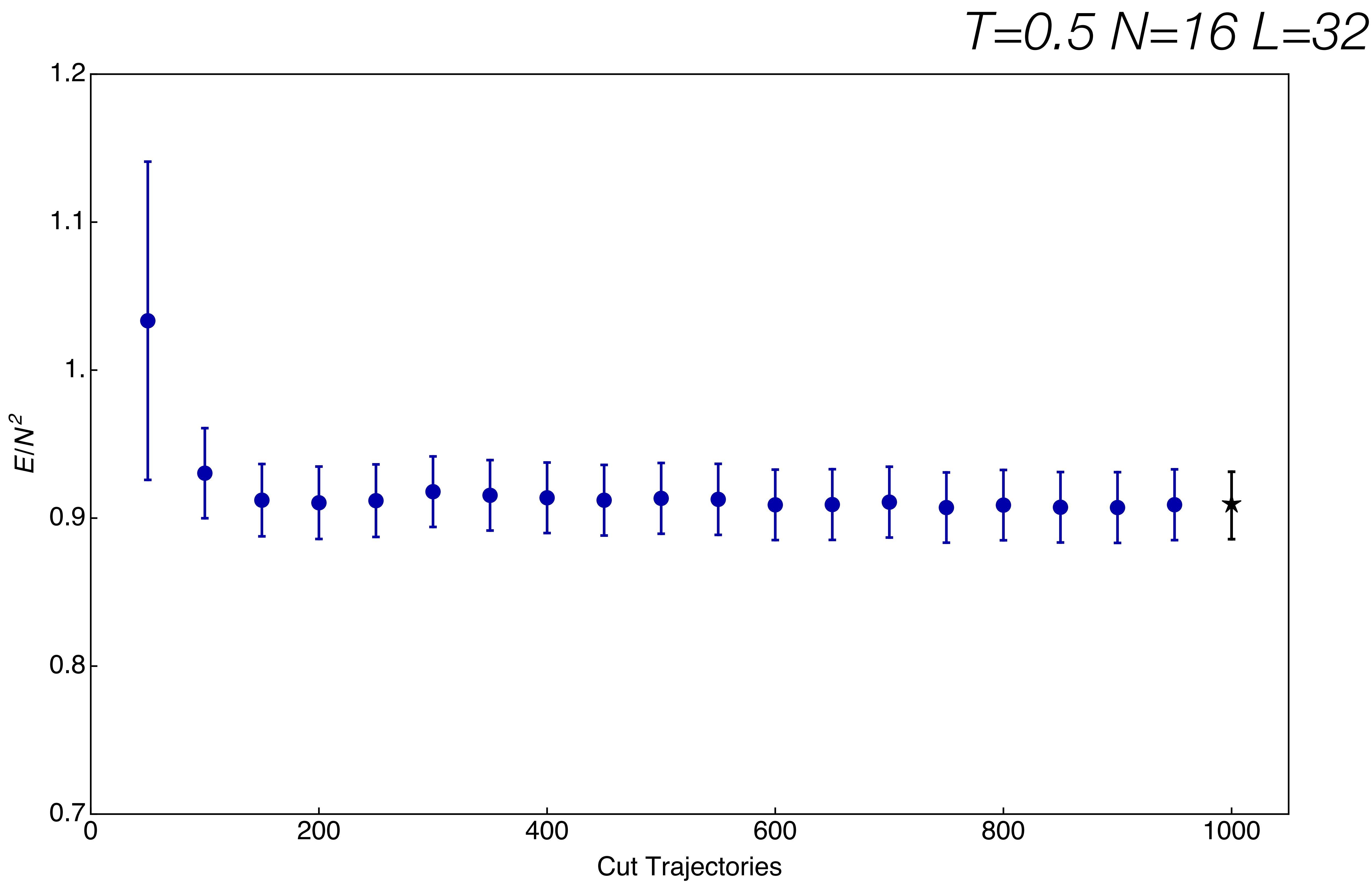
T=0.5 N=24 L=32



Long correlations can be seen in each observable.

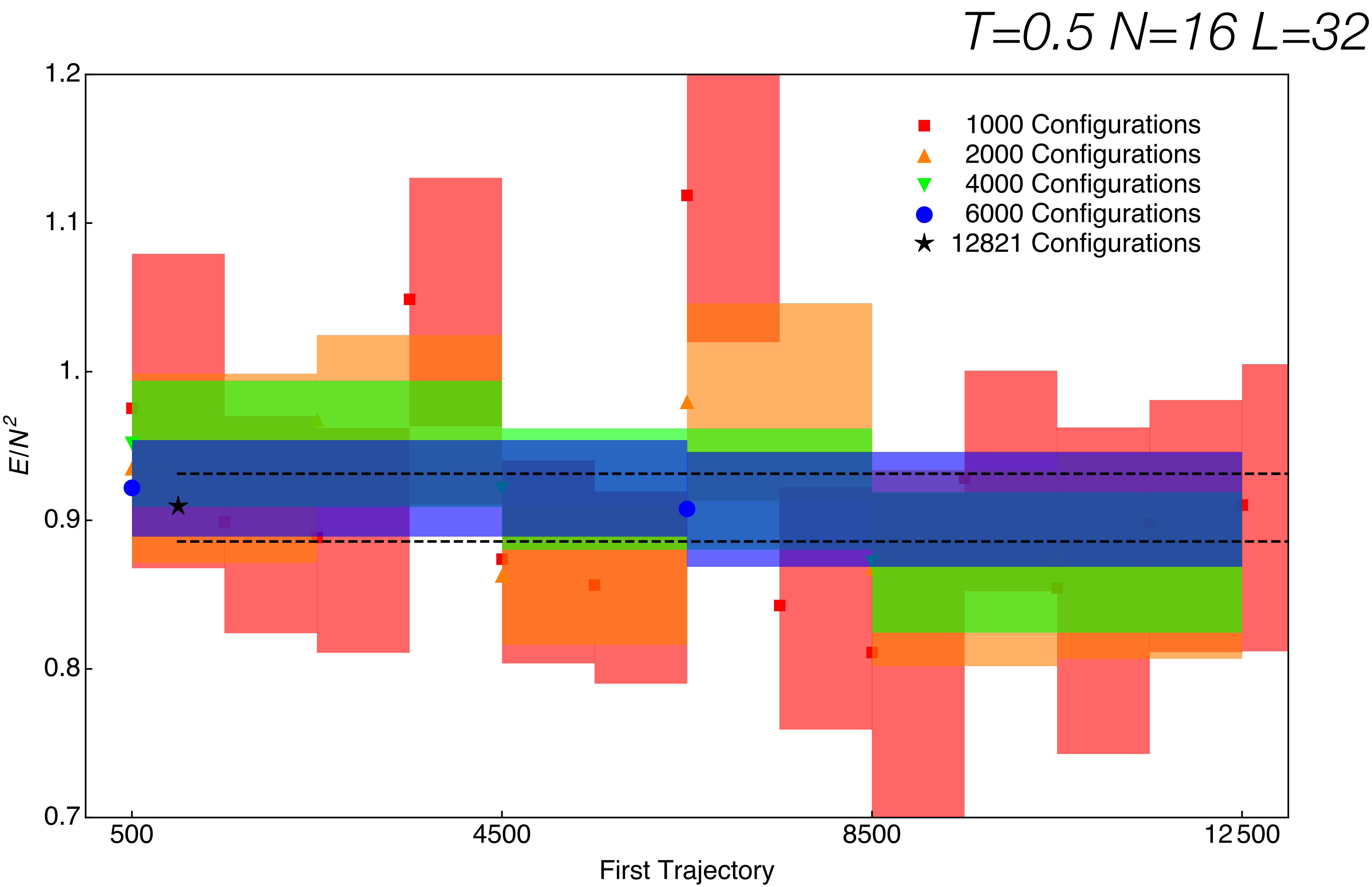
Thermalization Cut

MCSMC 1606.04948 1606.04951



Statistical Stability

MCSMC 1606.04948 1606.04951



Compute!

Ensembles

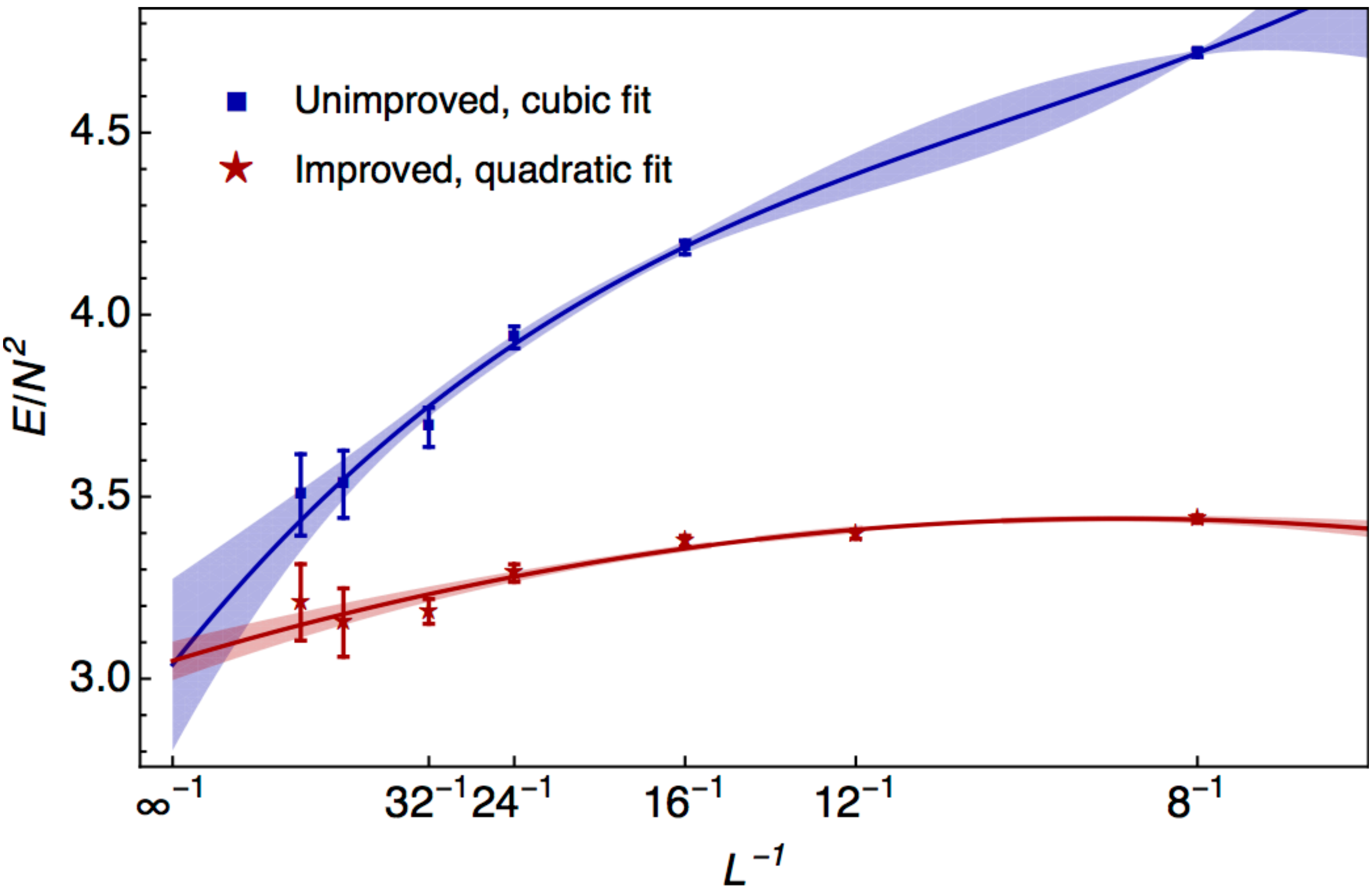
T	N	L	action	N_{cfg}	E/N^2	$\|P\|$	R^2	F^2
0.4	24	16	improved	15935	0.827±0.005	0.72770±0.00035	3.2504±0.0015	14.530±0.002
		24	improved	2321	0.719±0.031	0.72888±0.00129	3.3459±0.0039	15.627±0.011
		32	improved	6625	0.657±0.027	0.72721±0.00116	3.4110±0.0020	16.319±0.008
	32	8	improved	3057	0.903±0.009	0.74150±0.00348	4.8789±0.0967	13.846±0.006
		12	improved	2491	0.907±0.010	0.72754±0.00089	3.1663±0.0024	13.651±0.005
		16	improved	8242	0.835±0.007	0.72732±0.00054	3.2387±0.0012	14.518±0.003
		24	improved	1331	0.692±0.052	0.72919±0.00453	3.3414±0.0025	15.635±0.012
		32	improved	1888	0.629±0.029	0.72849±0.00142	3.4016±0.0018	16.311±0.008
0.5	16	8	improved	21101	1.229±0.004	0.78847±0.00031	3.1104±0.0026	13.068±0.003
		12	improved	17201	1.140±0.007	0.79566±0.00032	3.2304±0.0014	14.374±0.003
		16	improved	17933	1.081±0.009	0.79599±0.00035	3.3086±0.0012	15.207±0.004
		32	improved	15101	0.907±0.020	0.79689±0.00049	3.4747±0.0017	16.897±0.006
	24	8	improved	20951	1.243±0.004	0.78964±0.00028	3.0776±0.0007	13.038±0.002
		16	improved	19765	1.092±0.006	0.79718±0.00020	3.2883±0.0005	15.194±0.002
		24	improved	14957	0.979±0.010	0.79741±0.00029	3.3898±0.0006	16.240±0.003
		32	improved	10469	0.941±0.024	0.79727±0.00051	3.4457±0.0012	16.851±0.007
	32	8	improved	16253	1.248±0.003	0.78995±0.00020	3.0712±0.0006	13.032±0.002
		12	improved	3569	1.155±0.010	0.79600±0.00049	3.2012±0.0010	14.357±0.004
		16	improved	7885	1.093±0.009	0.79730±0.00034	3.2830±0.0007	15.196±0.003
		24	improved	2873	0.946±0.047	0.79852±0.00123	3.3815±0.0032	16.223±0.012
		32	improved	5469	0.955±0.023	0.79833±0.00044	3.4386±0.0011	16.841±0.006
0.6	16	8	improved	27221	1.560±0.005	0.83423±0.00018	3.1410±0.0006	13.728±0.002
		12	improved	19051	1.475±0.007	0.84077±0.00021	3.2708±0.0008	15.001±0.003
		16	improved	18141	1.432±0.010	0.84156±0.00023	3.3477±0.0010	15.790±0.004
		24	improved	8977	1.339±0.021	0.84184±0.00034	3.4410±0.0020	16.754±0.008

T	N	L	action	N_{cfg}	E/N^2	$\|P\|$	R^2	F^2
0.6	16	32	improved	18677	1.267±0.021	0.84181±0.00028	3.4951±0.0014	17.327±0.006
	24	8	improved	23971	1.569±0.004	0.83474±0.00017	3.1290±0.0005	13.731±0.002
		12	improved	19171	1.481±0.007	0.84083±0.00018	3.2602±0.0007	15.012±0.003
		16	improved	19961	1.429±0.008	0.84205±0.00018	3.3349±0.0006	15.790±0.003
		24	improved	25249	1.346±0.009	0.84176±0.00015	3.4262±0.0006	16.753±0.003
		32	improved	12577	1.276±0.025	0.84212±0.00030	3.4780±0.0012	17.309±0.007
	32	8	improved	19017	1.575±0.005	0.83539±0.00024	3.1248±0.0007	13.731±0.003
		16	improved	10071	1.442±0.009	0.84182±0.00022	3.3306±0.0006	15.787±0.004
0.7	16	8	improved	30641	1.959±0.005	0.86564±0.00013	3.1941±0.0006	14.377±0.003
		12	improved	20051	1.885±0.008	0.87096±0.00014	3.3145±0.0008	15.579±0.004
		16	improved	20187	1.843±0.011	0.87181±0.00015	3.3891±0.0009	16.333±0.005
		24	improved	10605	1.763±0.022	0.87126±0.00024	3.4702±0.0018	17.214±0.009
		32	unimproved	21633	2.344±0.031	0.86981±0.00017	3.5681±0.0015	18.615±0.007
			improved	19921	1.672±0.023	0.87191±0.00021	3.5193±0.0014	17.739±0.007
	24	8	improved	20701	1.968±0.005	0.86574±0.00014	3.1854±0.0005	14.385±0.003
		12	improved	19997	1.893±0.008	0.87095±0.00013	3.3088±0.0007	15.601±0.004
		16	improved	21451	1.849±0.007	0.87203±0.00012	3.3789±0.0006	16.338±0.004
		24	improved	28925	1.755±0.011	0.87126±0.00012	3.4634±0.0007	17.237±0.004
		32	improved	16135	1.682±0.025	0.87186±0.00019	3.5069±0.0012	17.726±0.008
	32	8	improved	18989	1.966±0.006	0.86612±0.00017	3.1837±0.0007	14.394±0.004
		16	improved	10849	1.850±0.010	0.87187±0.00015	3.3771±0.0008	16.341±0.004
0.8	16	8	unimproved	19281	3.674±0.009	0.89048±0.00013	3.5758±0.0028	17.845±0.008
			improved	19171	2.400±0.008	0.88790±0.00012	3.2468±0.0007	14.994±0.004
		12	improved	22001	2.356±0.009	0.89220±0.00011	3.3601±0.0008	16.138±0.005
		16	unimproved	24081	3.283±0.016	0.89113±0.00011	3.5305±0.0011	18.305±0.006
			improved	21421	2.309±0.012	0.89318±0.00011	3.4295±0.0010	16.856±0.005
		24	unimproved	21591	3.000±0.025	0.89069±0.00012	3.5588±0.0012	18.663±0.007
			improved	17521	2.214±0.019	0.89292±0.00014	3.5070±0.0013	17.687±0.008
		32	unimproved	14157	2.710±0.044	0.89119±0.00017	3.5803±0.0016	18.880±0.010

T	N	L	action	N_{cfg}	E/N^2	$\|P\|$	R^2	F^2
0.8	16	32	improved	20187	2.107±0.024	0.89261±0.00015	3.5452±0.0014	18.131±0.009
	24	8	improved	22151	2.417±0.006	0.88779±0.00011	3.2416±0.0006	15.010±0.003
		12	improved	18175	2.346±0.009	0.89207±0.00011	3.3553±0.0008	16.155±0.005
		16	improved	20721	2.303±0.010	0.89317±0.00009	3.4232±0.0007	16.868±0.004
		24	improved	9153	2.216±0.020	0.89239±0.00015	3.4968±0.0012	17.681±0.008
		32	improved	13867	2.176±0.028	0.89287±0.00015	3.5366±0.0015	18.134±0.009
	32	8	improved	19213	2.424±0.007	0.88809±0.00014	3.2394±0.0008	15.012±0.004
		16	improved	13495	2.340±0.017	0.89302±0.00018	3.4216±0.0014	16.869±0.008
0.9	16	8	unimproved	20411	4.221±0.010	0.90519±0.00009	3.5113±0.0012	17.926±0.005
			improved	20401	2.895±0.009	0.90433±0.00009	3.3002±0.0008	15.599±0.004
		12	improved	20501	2.863±0.011	0.90783±0.00009	3.4048±0.0009	16.679±0.005
		16	unimproved	37701	3.710±0.014	0.90689±0.00007	3.5475±0.0007	18.635±0.005
			improved	21461	2.796±0.014	0.90856±0.00009	3.4717±0.0010	17.377±0.006
		24	unimproved	21851	3.450±0.028	0.90639±0.00010	3.5807±0.0013	19.001±0.008
			improved	17955	2.716±0.021	0.90826±0.00011	3.5400±0.0014	18.139±0.009
		32	unimproved	12221	3.243±0.049	0.90720±0.00013	3.6037±0.0019	19.209±0.012
			improved	14601	2.673±0.031	0.90849±0.00013	3.5750±0.0017	18.545±0.011
	24	8	improved	24331	2.931±0.006	0.90413±0.00008	3.2958±0.0006	15.613±0.004
		12	improved	17557	2.872±0.010	0.90785±0.00009	3.4025±0.0009	16.707±0.006
		16	improved	24441	2.822±0.010	0.90861±0.00007	3.4658±0.0007	17.384±0.005
		24	improved	8917	2.761±0.023	0.90774±0.00013	3.5349±0.0014	18.156±0.009
		32	improved	16709	2.719±0.028	0.90824±0.00010	3.5663±0.0014	18.538±0.009
	32	8	improved	18695	2.931±0.008	0.90441±0.00011	3.2948±0.0009	15.620±0.005
		16	improved	12061	2.835±0.019	0.90836±0.00016	3.4643±0.0016	17.388±0.009
1.0	16	8	unimproved	21291	4.719±0.011	0.91705±0.00007	3.5139±0.0010	18.245±0.006
			improved	20641	3.439±0.010	0.91672±0.00008	3.3515±0.0009	16.185±0.005
		12	improved	20751	3.397±0.012	0.91968±0.00008	3.4485±0.0010	17.217±0.006
			unimproved	25379	4.185±0.019	0.91907±0.00007	3.5769±0.0010	19.034±0.007
		16	improved	21641	3.378±0.015	0.92033±0.00008	3.5115±0.0011	17.876±0.007

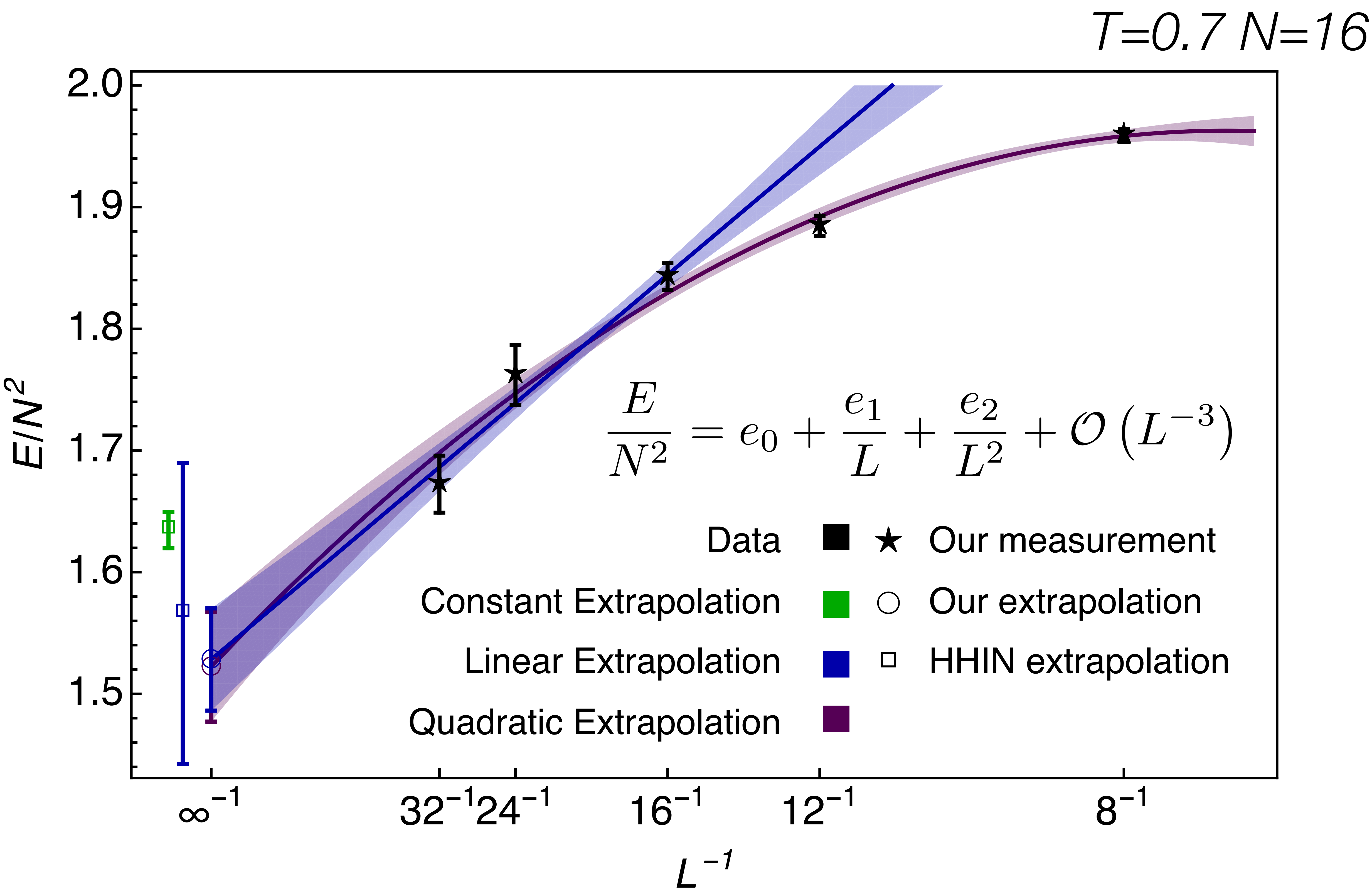
T	N	L	action	N_{cfg}	E/N^2	$\|P\|$	R^2	F^2
1.0	16	24	unimproved	23391	3.937±0.030	0.91855±0.00008	3.6099±0.0013	19.376±0.009
			improved	17469	3.290±0.024	0.91979±0.00009	3.5755±0.0017	18.600±0.011
		32	unimproved	13503	3.690±0.054	0.91895±0.00012	3.6323±0.0019	19.582±0.013
			improved	15555	3.185±0.034	0.91985±0.00011	3.6068±0.0018	18.971±0.013
		48	unimproved	12026	3.534±0.092	0.92064±0.00014	3.6592±0.0028	19.810±0.021
			improved	5772	3.154±0.094	0.92101±0.00025	3.6431±0.0042	19.401±0.027
		64	unimproved	15024	3.505±0.112	0.92051±0.00015	3.6808±0.0029	19.999±0.020
			improved	7280	3.210±0.105	0.92070±0.00021	3.6752±0.0042	19.715±0.030
	24	8	improved	22605	3.467±0.007	0.91663±0.00007	3.3490±0.0007	16.208±0.004
		12	improved	19817	3.413±0.011	0.91956±0.00007	3.4478±0.0009	17.251±0.006
		16	improved	20655	3.363±0.013	0.92041±0.00007	3.5084±0.0009	17.901±0.006
		24	improved	21725	3.283±0.019	0.91964±0.00008	3.5705±0.0011	18.609±0.008
		32	improved	19383	3.268±0.028	0.91997±0.00009	3.5993±0.0014	18.964±0.010
	32	8	improved	17881	3.469±0.008	0.91684±0.00009	3.3482±0.0009	16.216±0.006
		16	improved	14915	3.386±0.019	0.92018±0.00011	3.5078±0.0013	17.902±0.009

Derivative Improvement



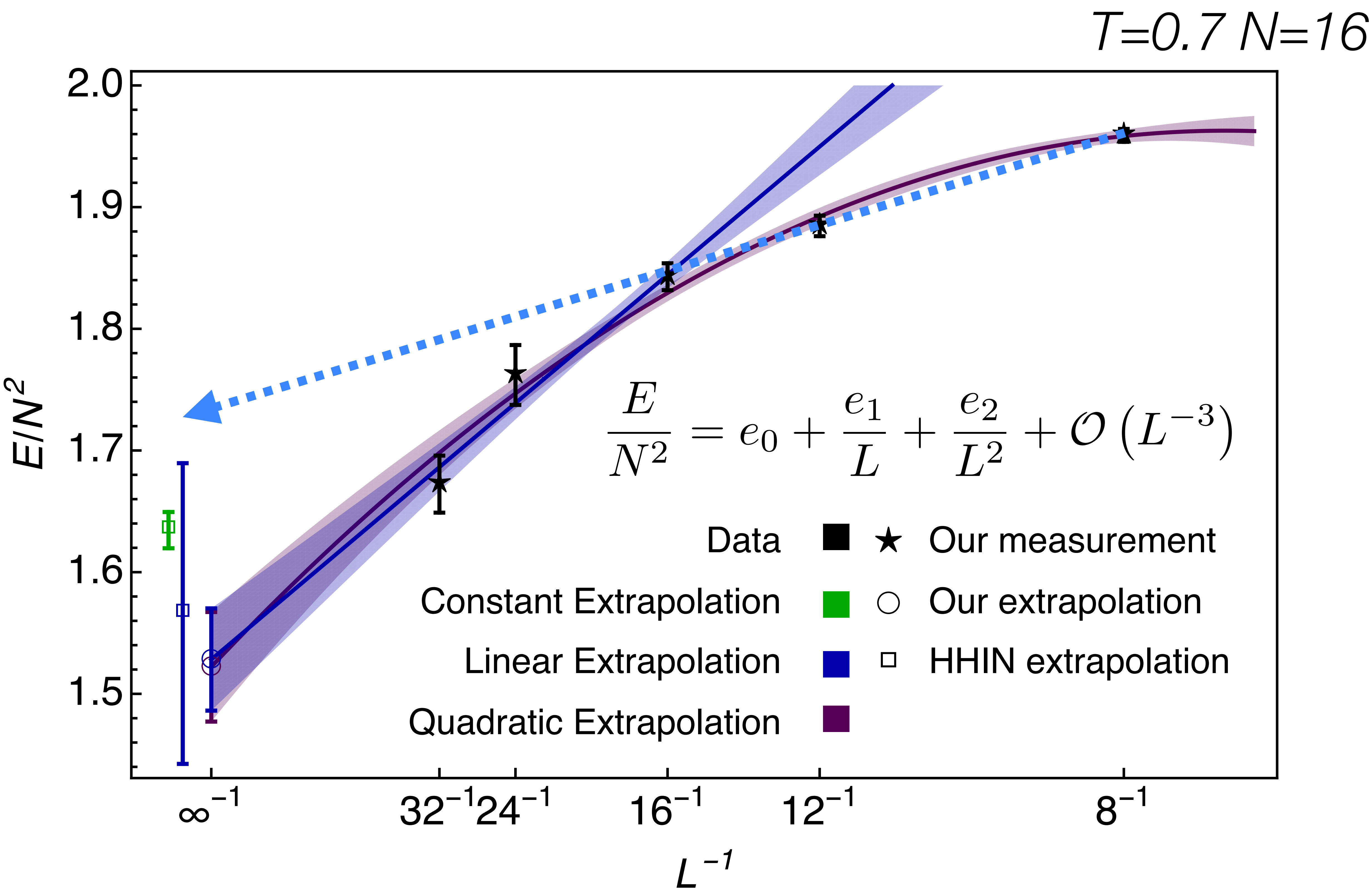
Fixed-*N* Continuum Extrapolation

MCSMC 1606.04948 1606.04951



Fixed-N Continuum Extrapolation

MCSMC 1606.04948 1606.04951

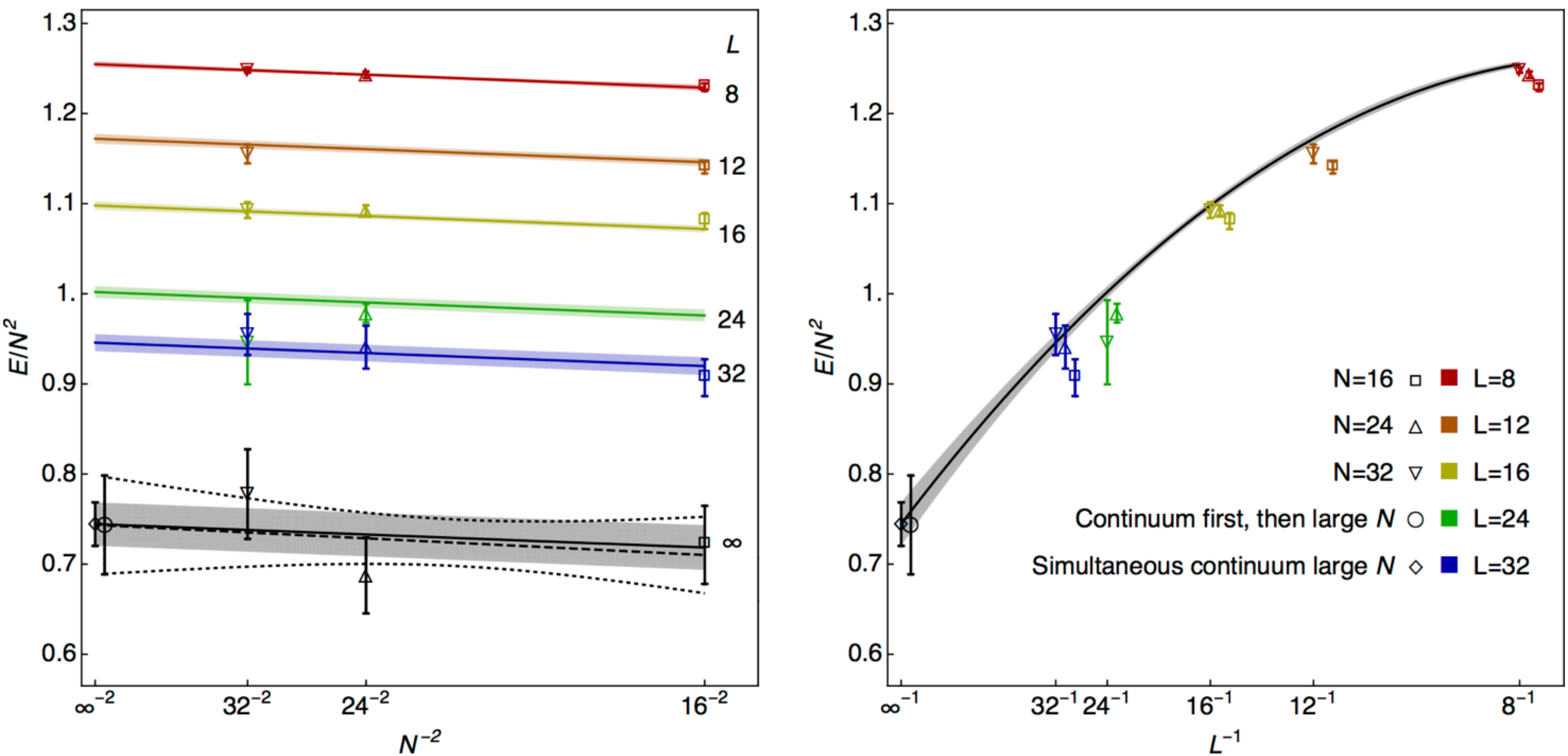


Simultaneous Continuum + Large-N Extrapolation

MCSMC 1606.04948 1606.04951

T=0.5

$$\frac{E}{N^2} = \sum_{ij\geq 0} \frac{e_{ij}}{N^{2i}L^j} \qquad e_{00}, e_{01}, e_{02}, e_{10}$$

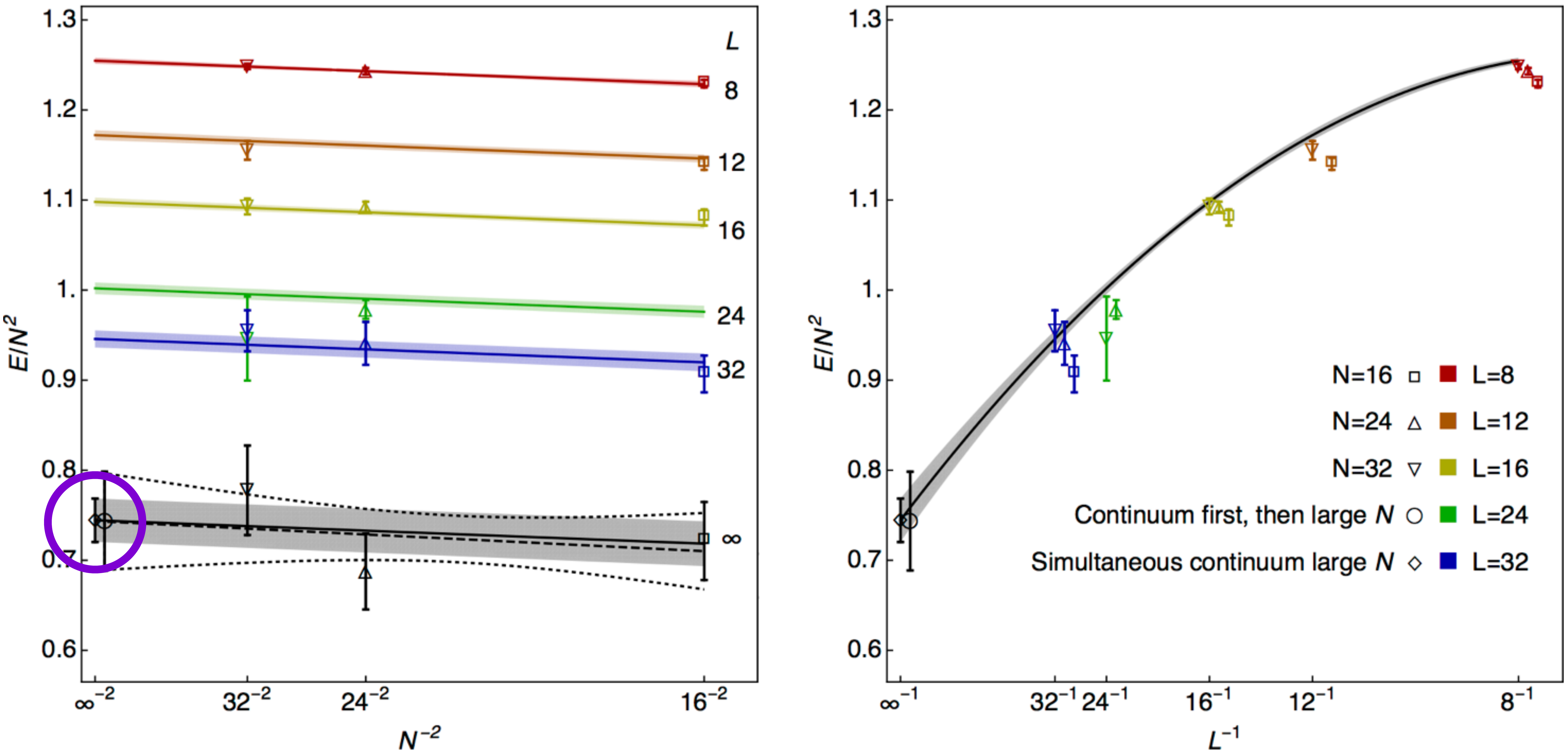


Simultaneous Continuum + Large-N Extrapolation

MCSMC 1606.04948 1606.04951

T=0.5

$$\frac{E}{N^2} = \sum_{ij\geq 0} \frac{e_{ij}}{N^{2i}L^j} \qquad e_{00}, e_{01}, e_{02}, e_{10}$$



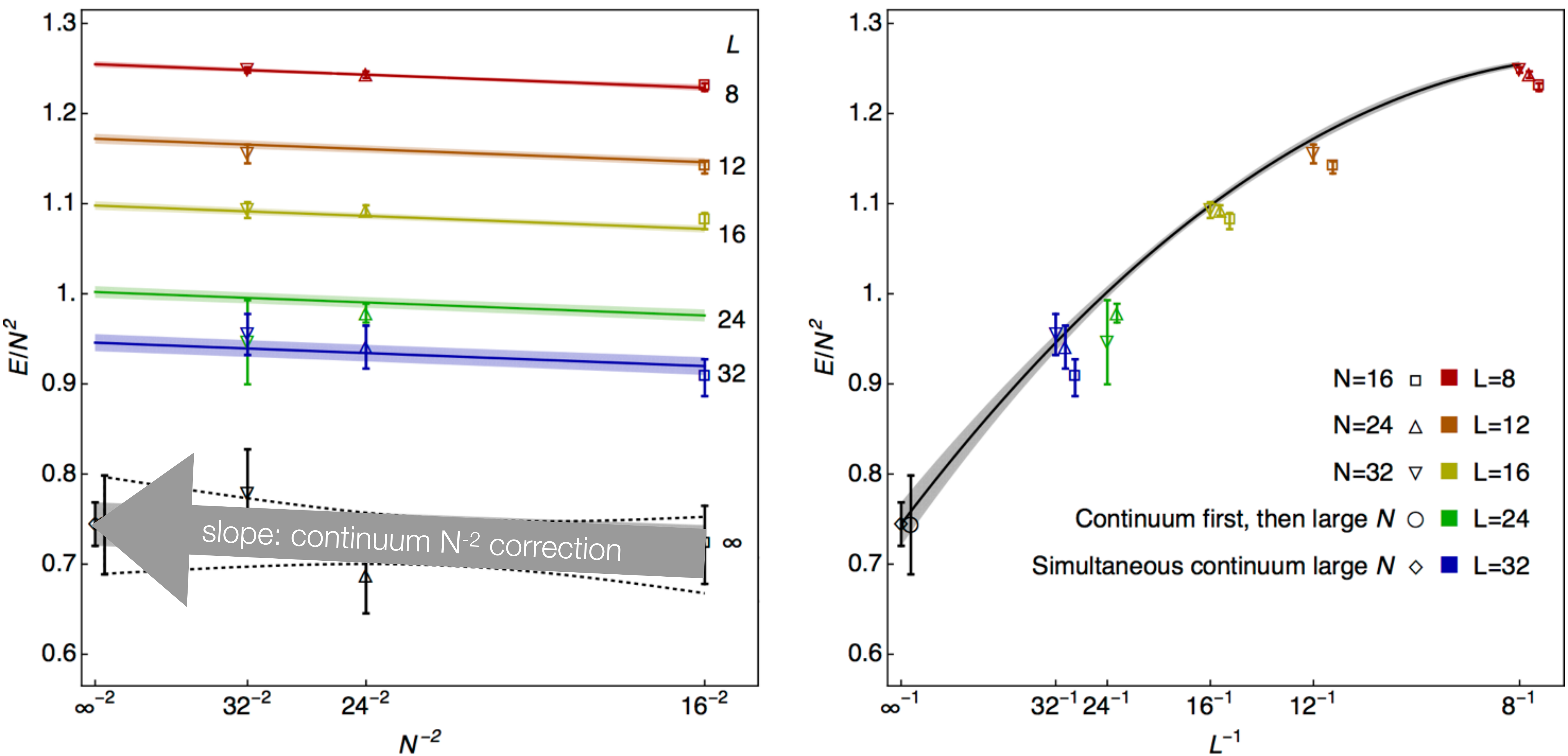
Simultaneous Continuum + Large-N Extrapolation

MCSMC 1606.04948 1606.04951

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

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

T=0.5

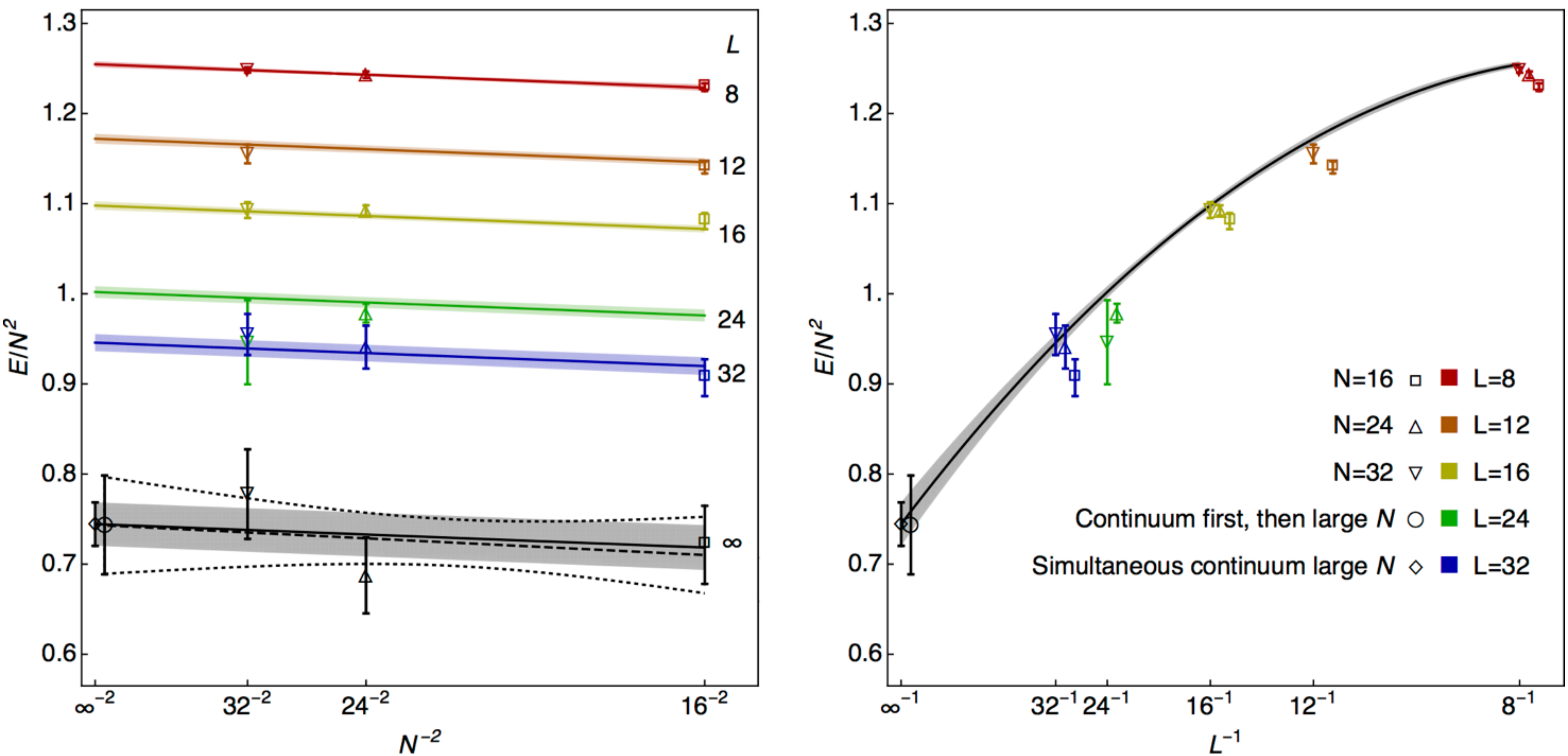


Simultaneous Continuum + Large-N Extrapolation

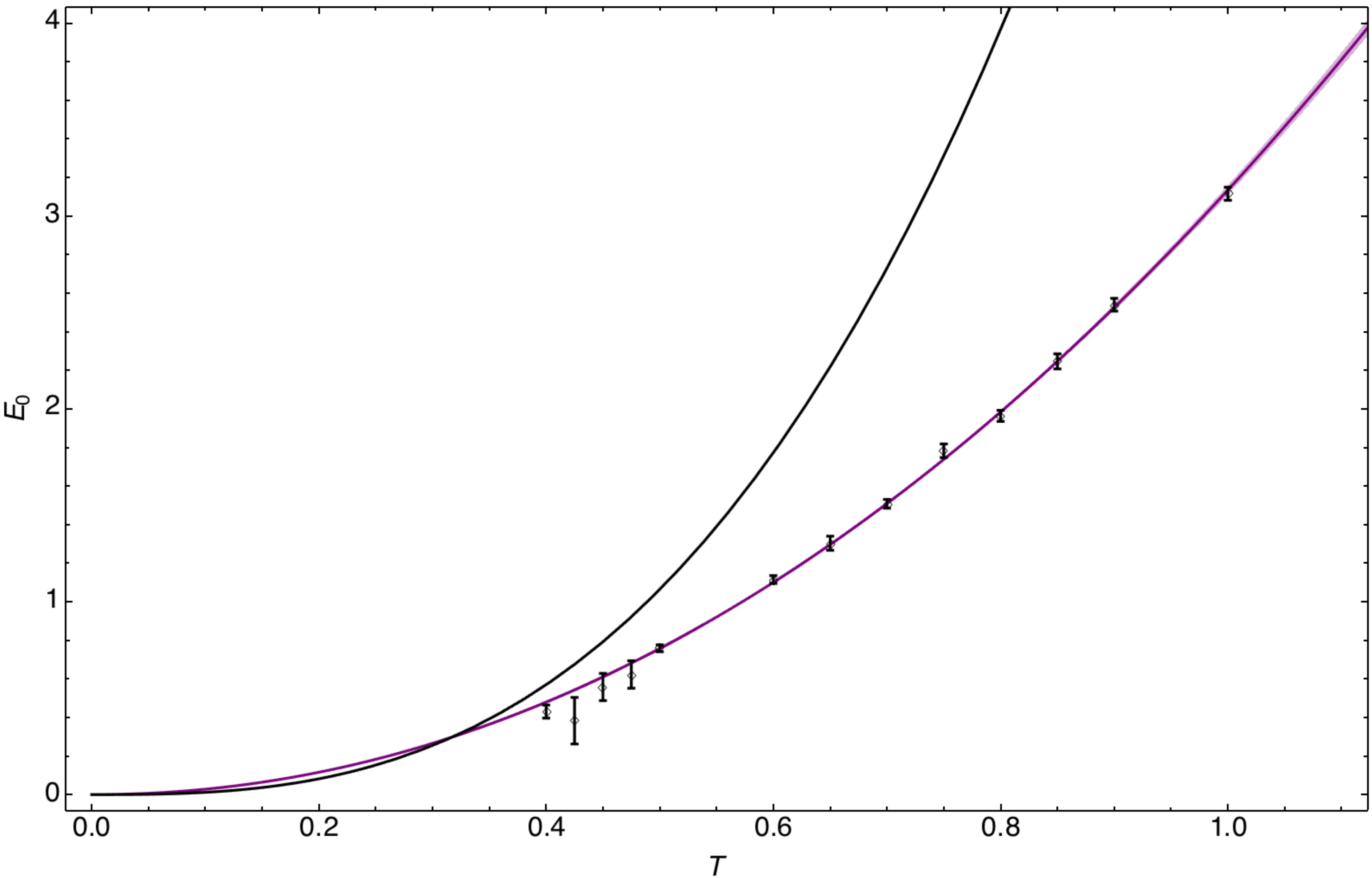
MCSMC 1606.04948 1606.04951

T=0.5

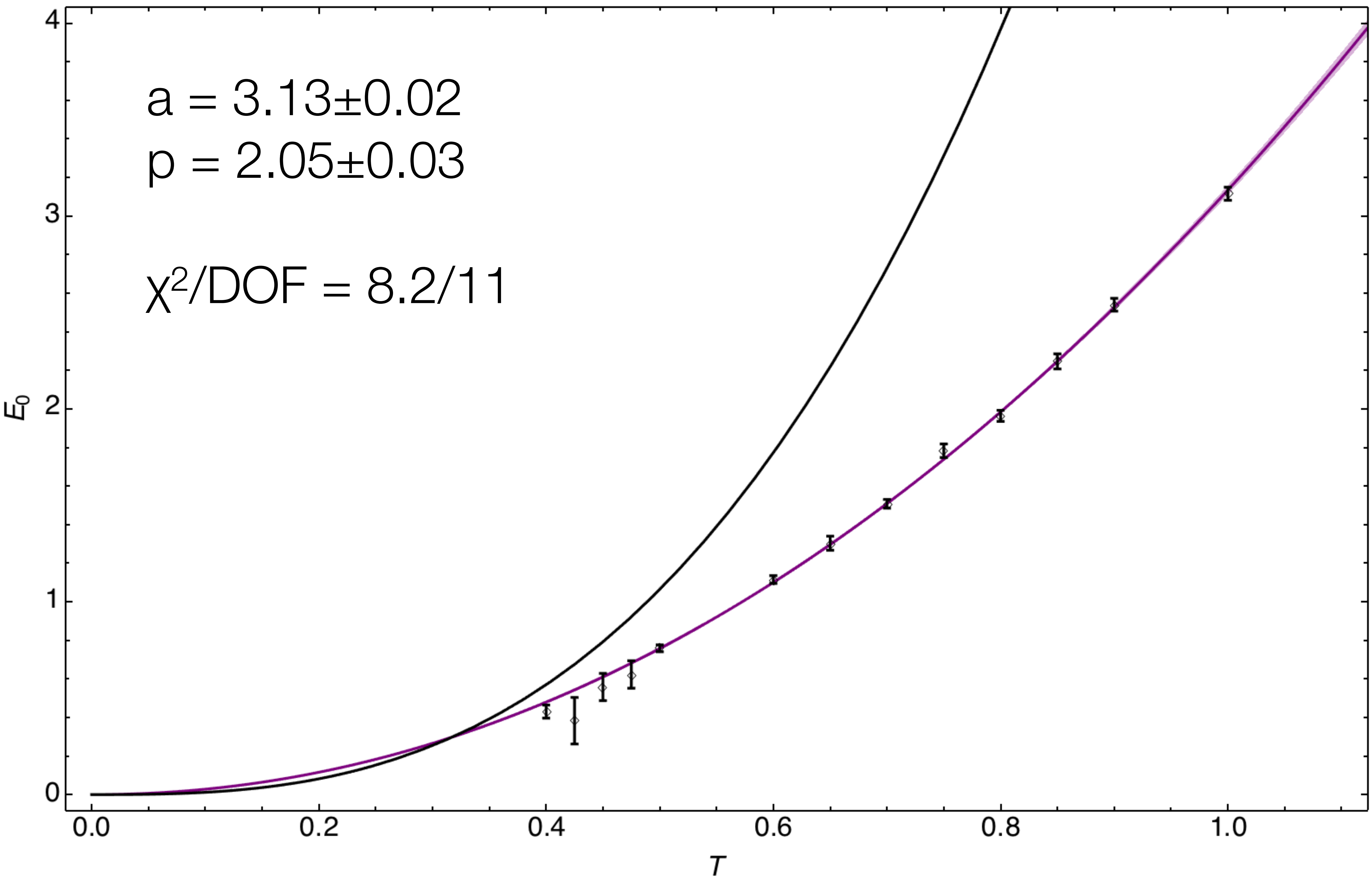
$$\frac{E}{N^2} = \sum_{ij\geq 0} \frac{e_{ij}}{N^{2i}L^j} \qquad e_{00}, e_{01}, e_{02}, e_{10}$$



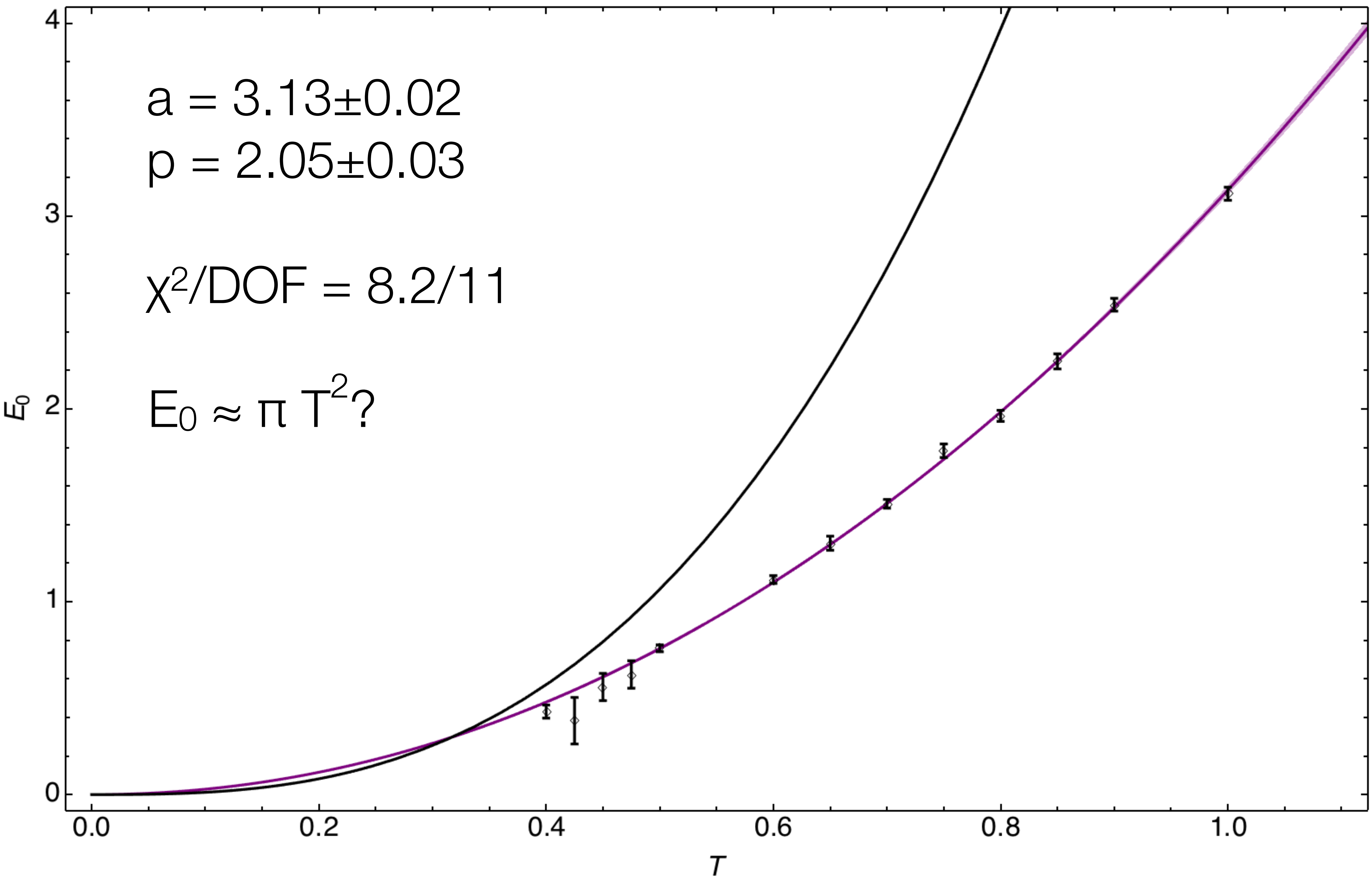
No stringy input: a T^p ?



No stringy input: a T^p ?

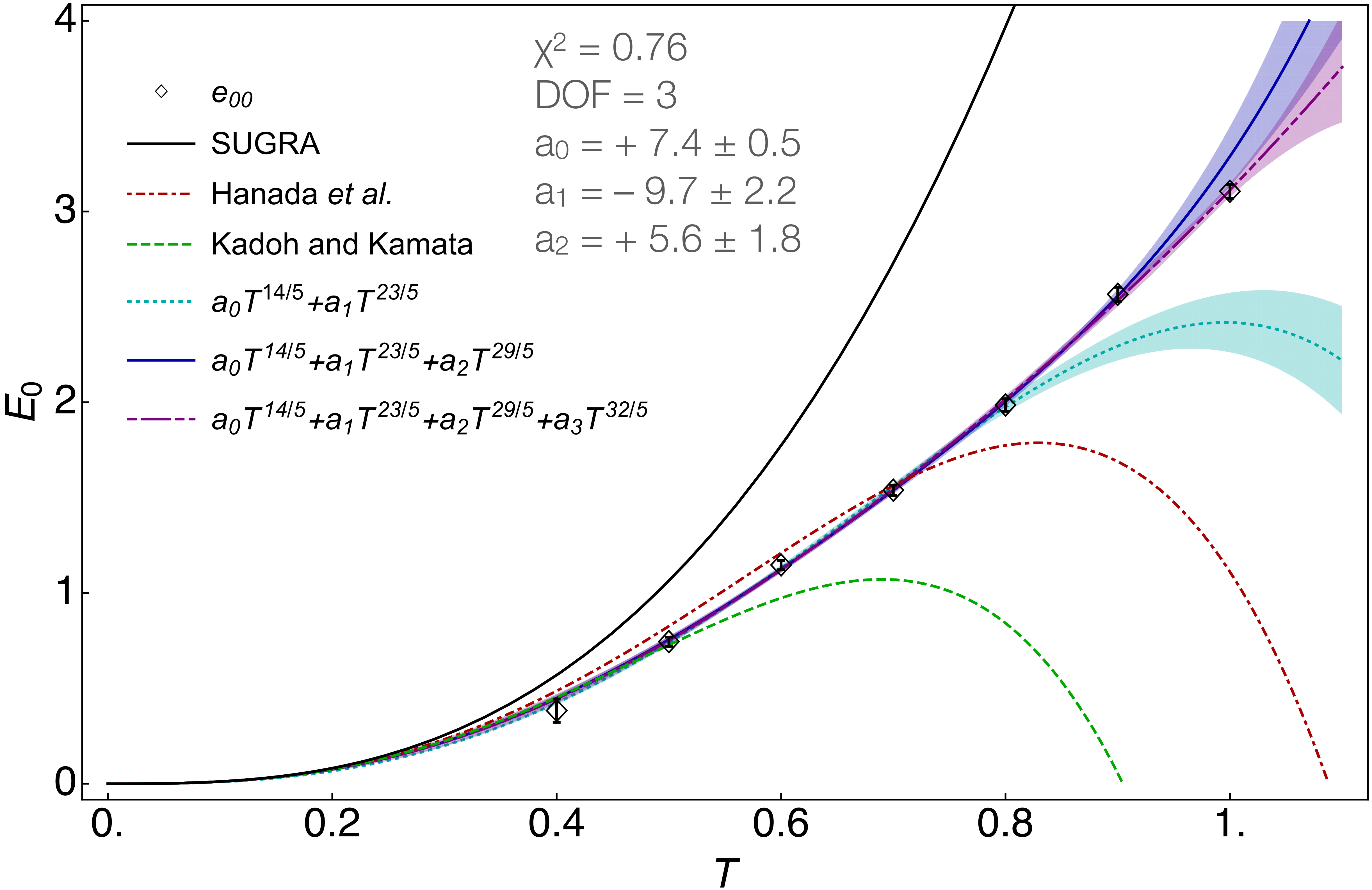


No stringy input: $a\,T^{p}$?



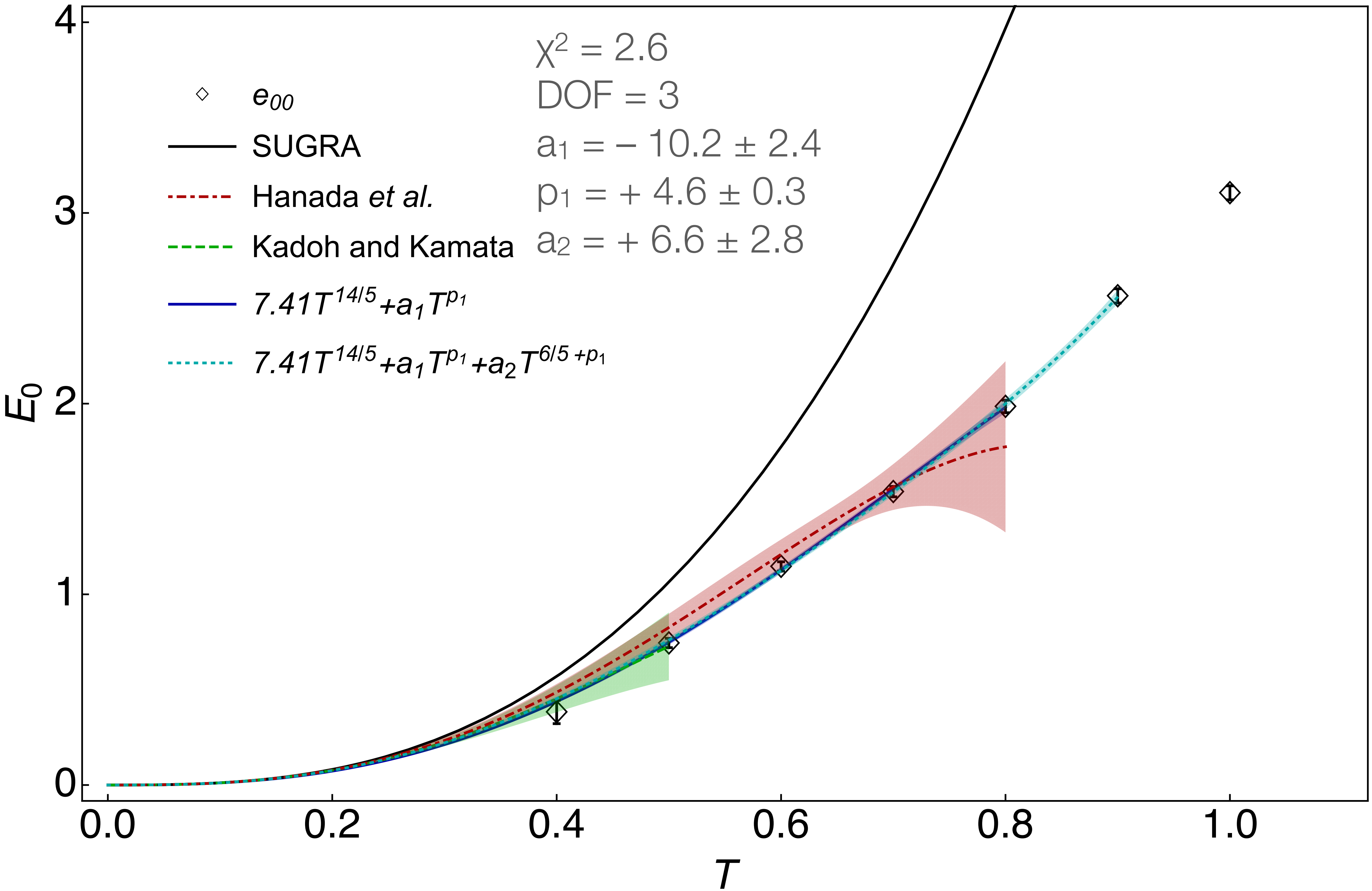
$$E/N^2 = N^0 \left(a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8} + \cdots\right) + \mathcal{O}\left(N^{-2}\right)$$

MCSMC 1606.04948 1606.04951



$$E/N^2 = N^0\left(a_0 T^{2.8} + a_1 T^{4.6} + a_2 T^{5.8} + \cdots\right) + \mathcal{O}\left(N^{-2}\right)$$

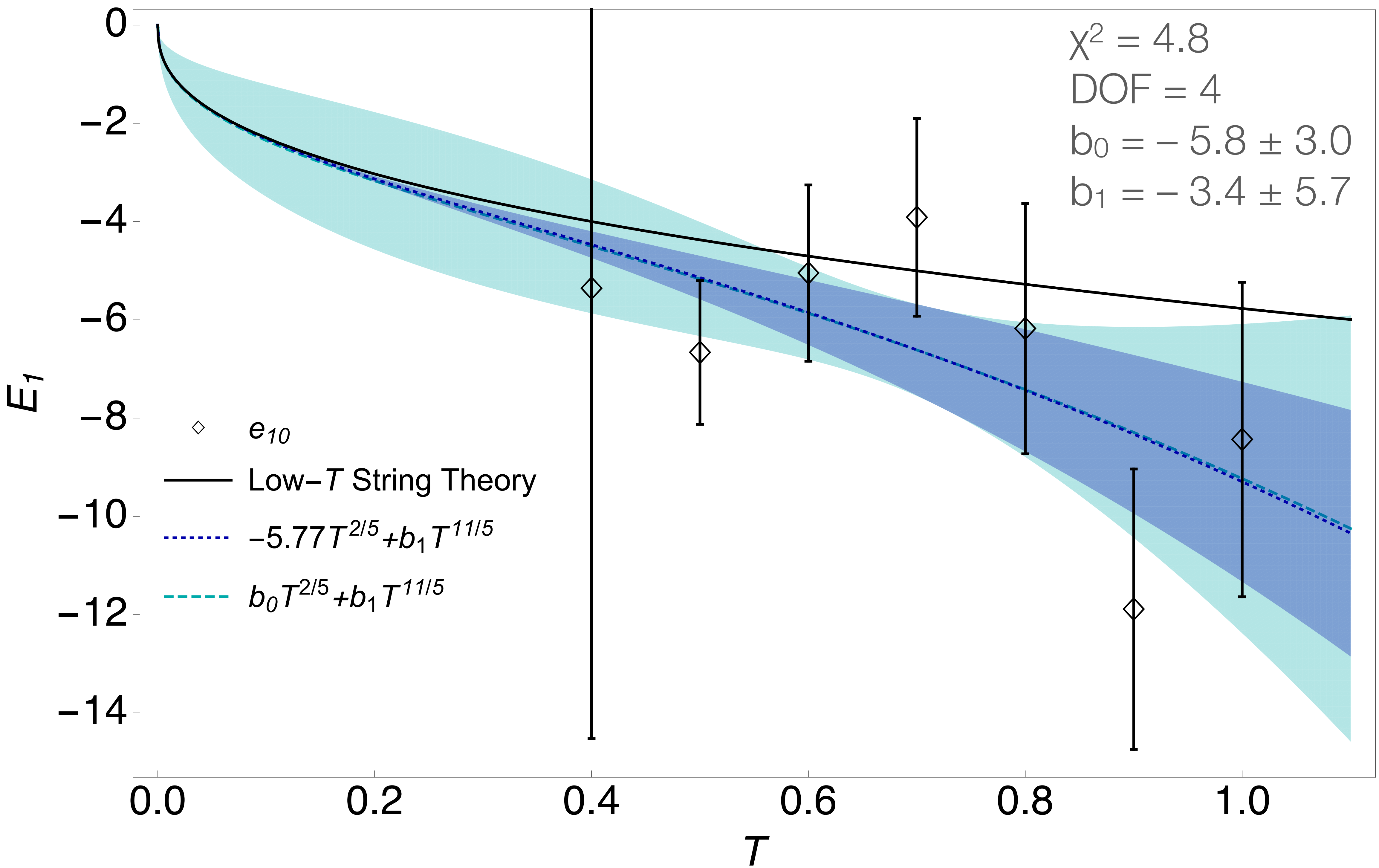
MCSMC 1606.04948 1606.04951



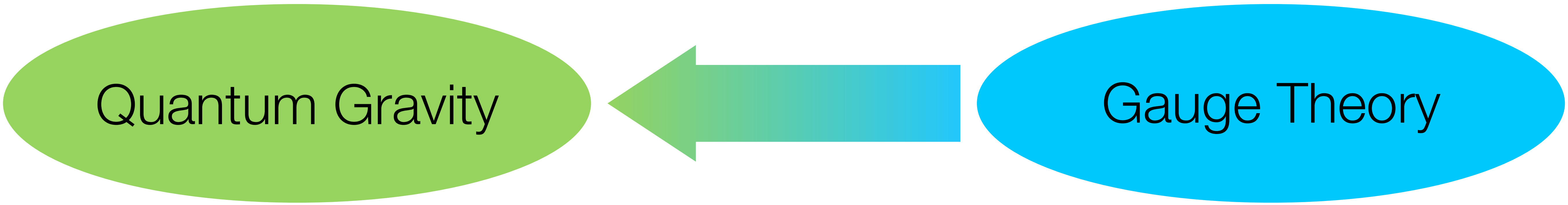
$$\mathcal{O}(N^{-2}) = N^{-2}\left(b_0 T^{0.4} + b_1 T^{2.2} + \cdots\right)$$

slope: continuum N-2 correction

MCSMC 1606.04948 1606.04951



Summary

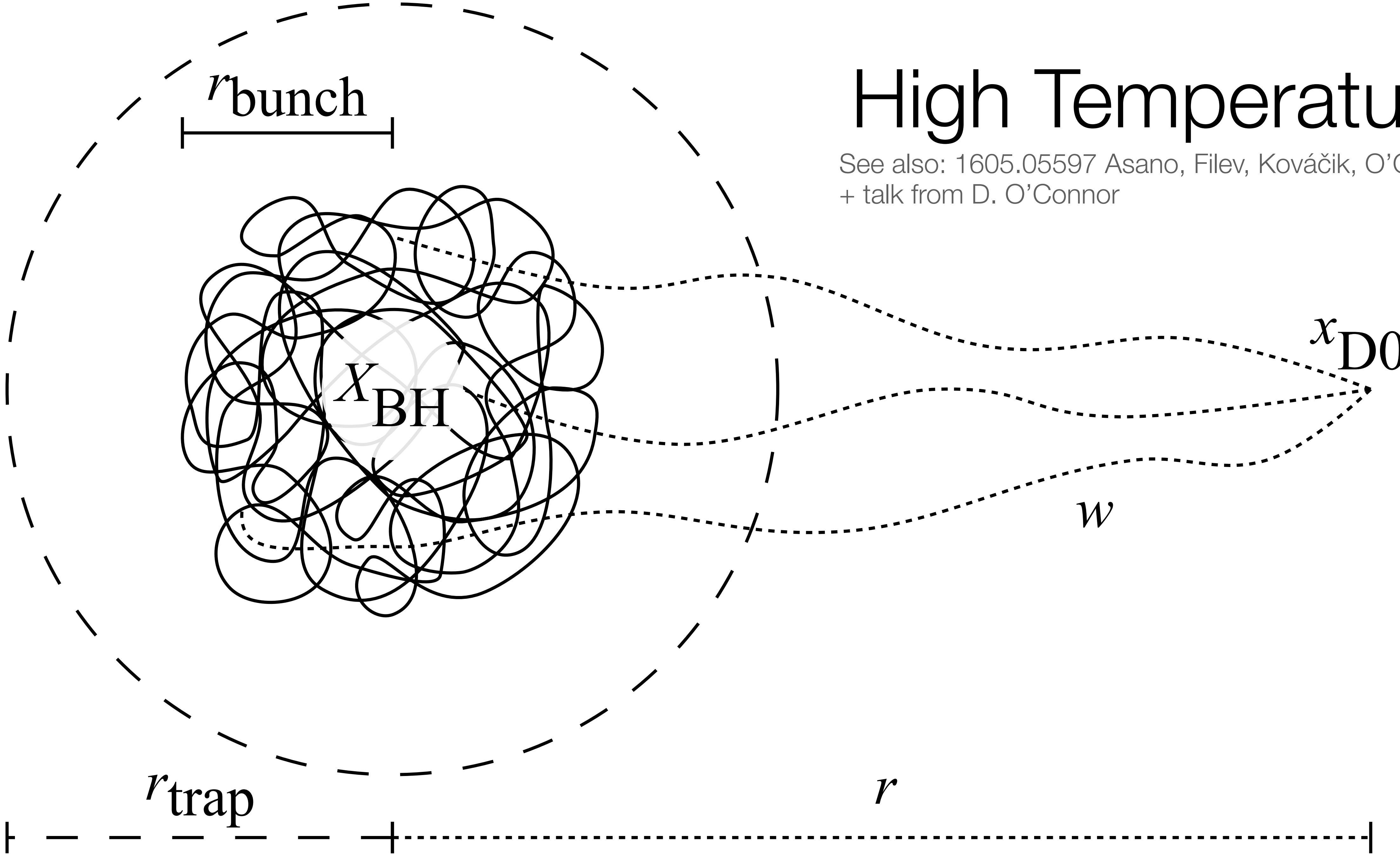


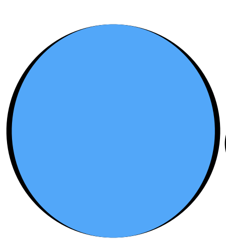
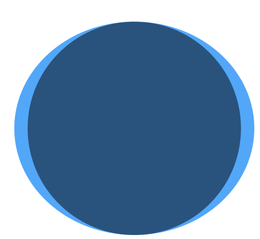
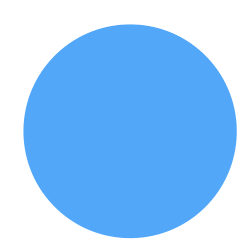
- 0+1D BFSS reproduces known 10D SUGRA result
- Nontrivial checks of gauge / gravity duality
- Predictions about (quantum!) stringy corrections.

Probes of Geometry

High Temperature

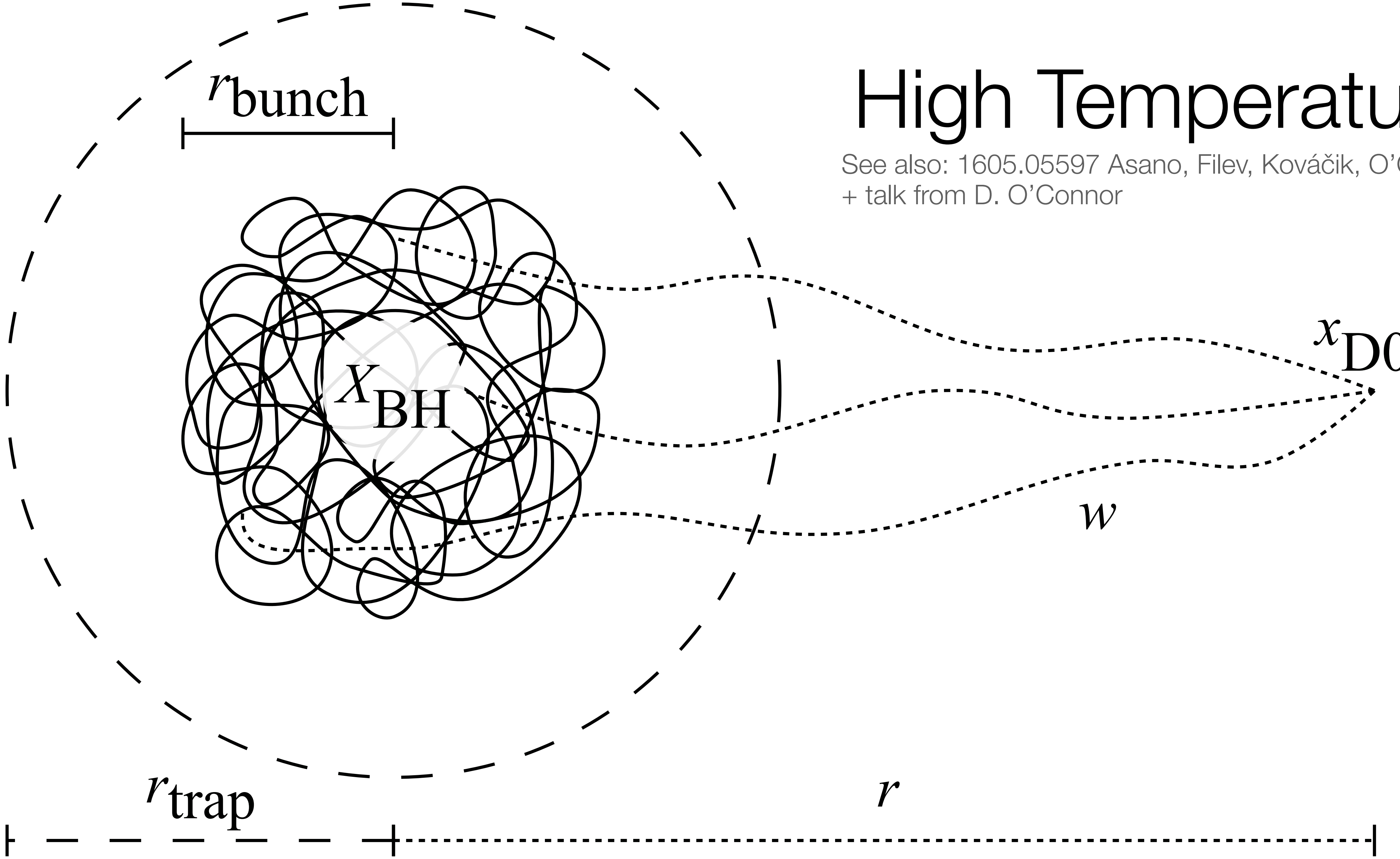
See also: 1605.05597 Asano, Filev, Kováčik, O'Connor
+ talk from D. O'Connor



r→0	Intermediate r	Large r
Commutator	Tidal	Weak
 oblate	 prolate	 spherical

High Temperature

See also: 1605.05597 Asano, Filev, Kováčik, O'Connor
+ talk from D. O'Connor



$r \to 0$

force vanishes
by rotational sym.
open strings excited
F ~ N

oblate

Intermediate r

$r \lesssim T$: strings excited, strong attraction
$r \sim T$: D0s are trapped by entropic suppression
$r \gtrsim T$: stringy excitations suppressed

prolate

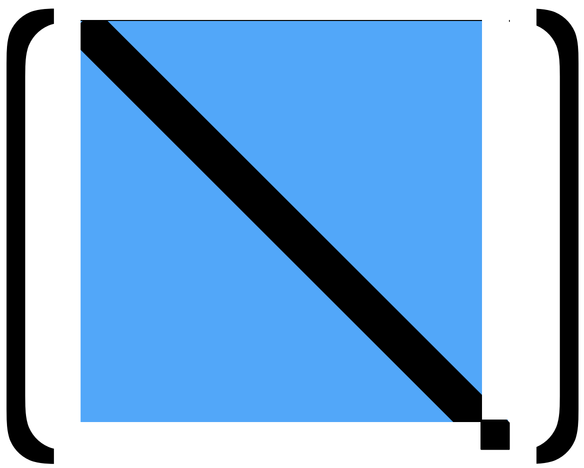
Large r

$f(T)\, N\, r^{-8}$
$f(T) \to 0$ as $T \to 0$

spherical

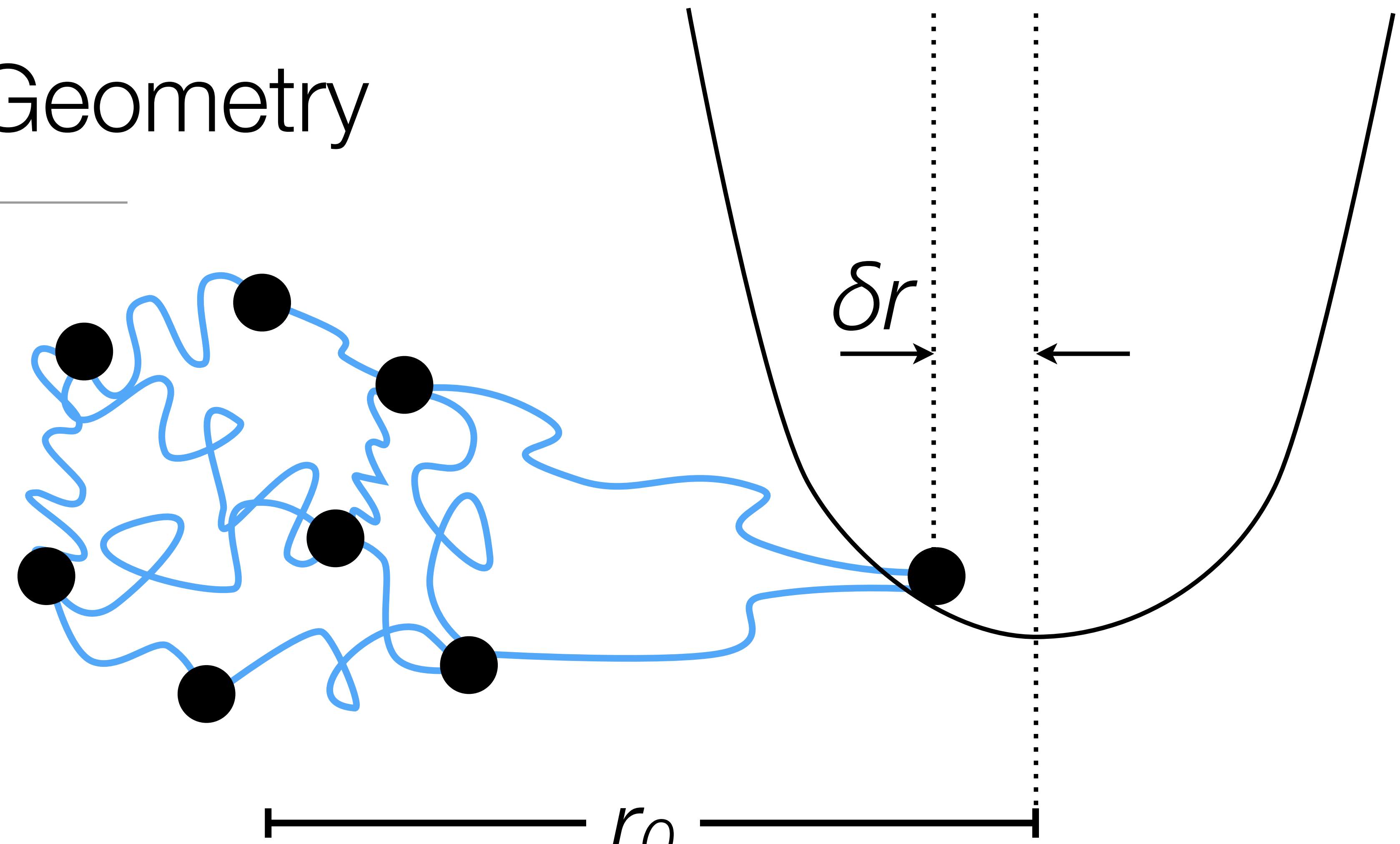
Force / Emergent Geometry

MCSMC 1709.01932



BH + probe D0

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



No unphysical longitudinal modes

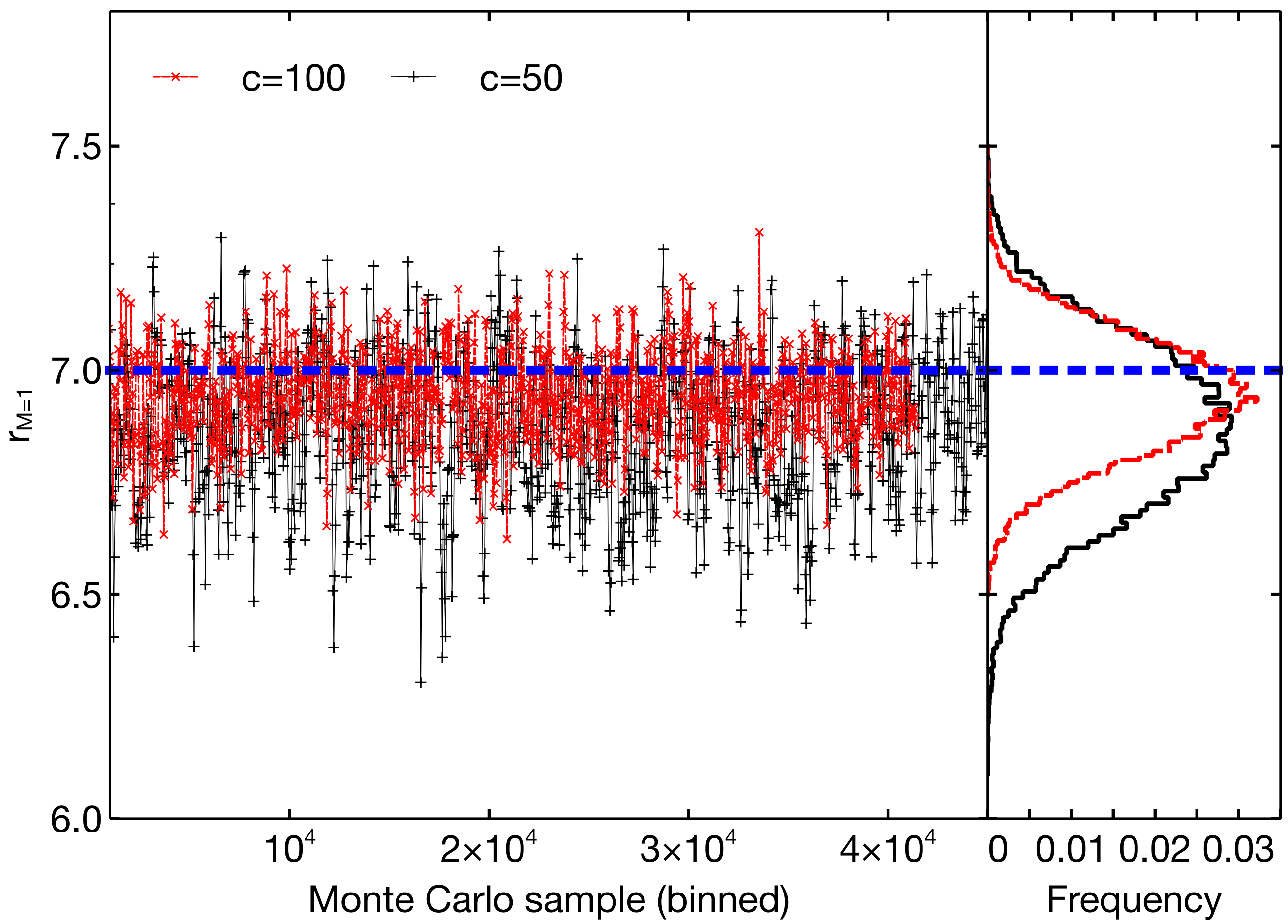
$$\Delta L = -c \left\{ \underbrace{\left(\frac{\mathrm{Tr} X^1_{\mathrm{BH}}}{N-1} - x^1_{\mathrm{D0}} - r_0 \right)}_{\delta r}^2 + \sum_{M=2}^{9} \left(\frac{\mathrm{Tr} X^M_{\mathrm{BH}}}{N-1} - x^M_{\mathrm{D0}} \right)^2 \right\} - c' \, |w_1|^2$$

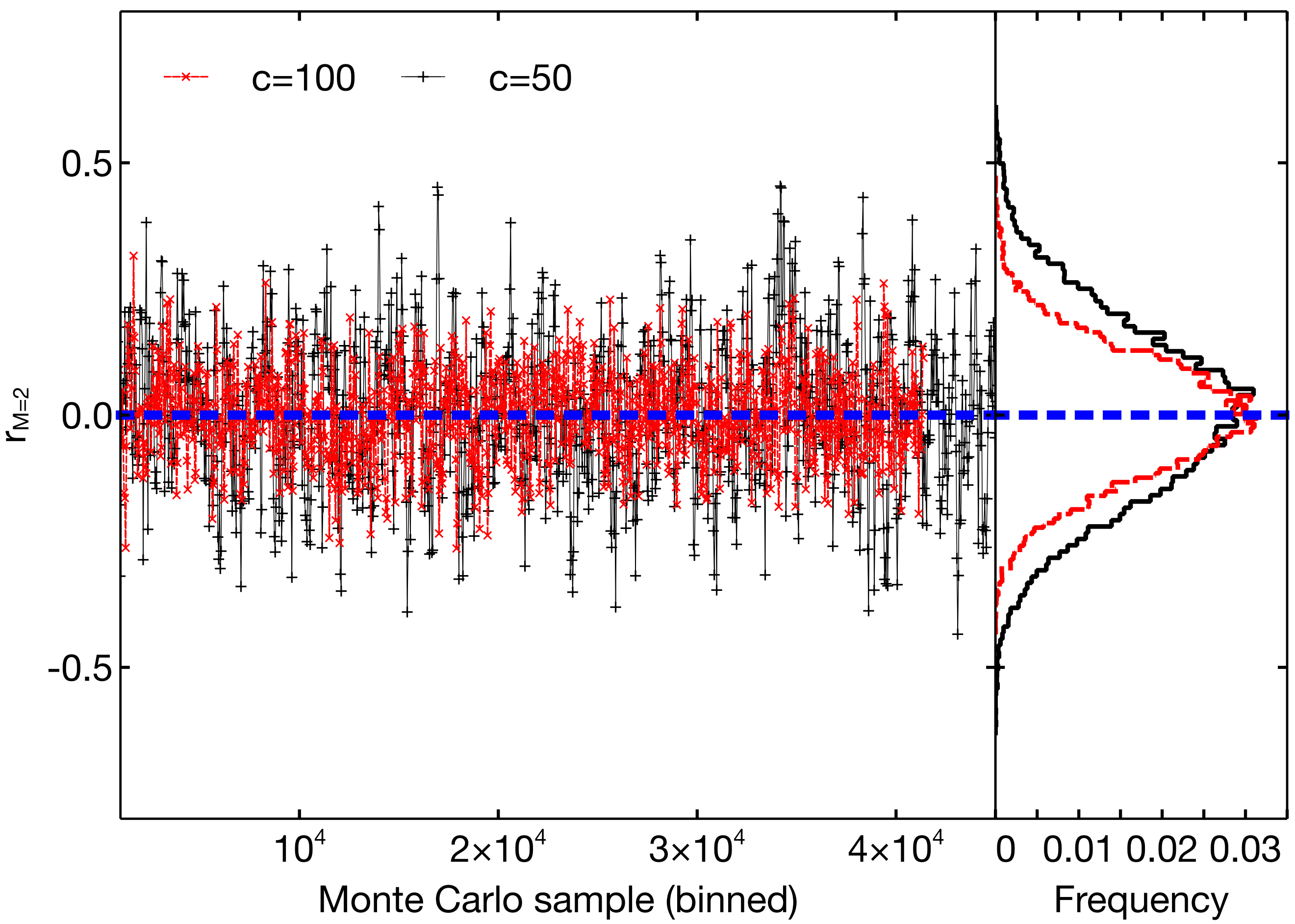
$$F(N, L, r_0) = 2\, c\, \langle \delta r \rangle$$

$A_t = 0$ gauge

⟨δr⟩ in different directions

r_0=7 T=3.0 N=8 L=8





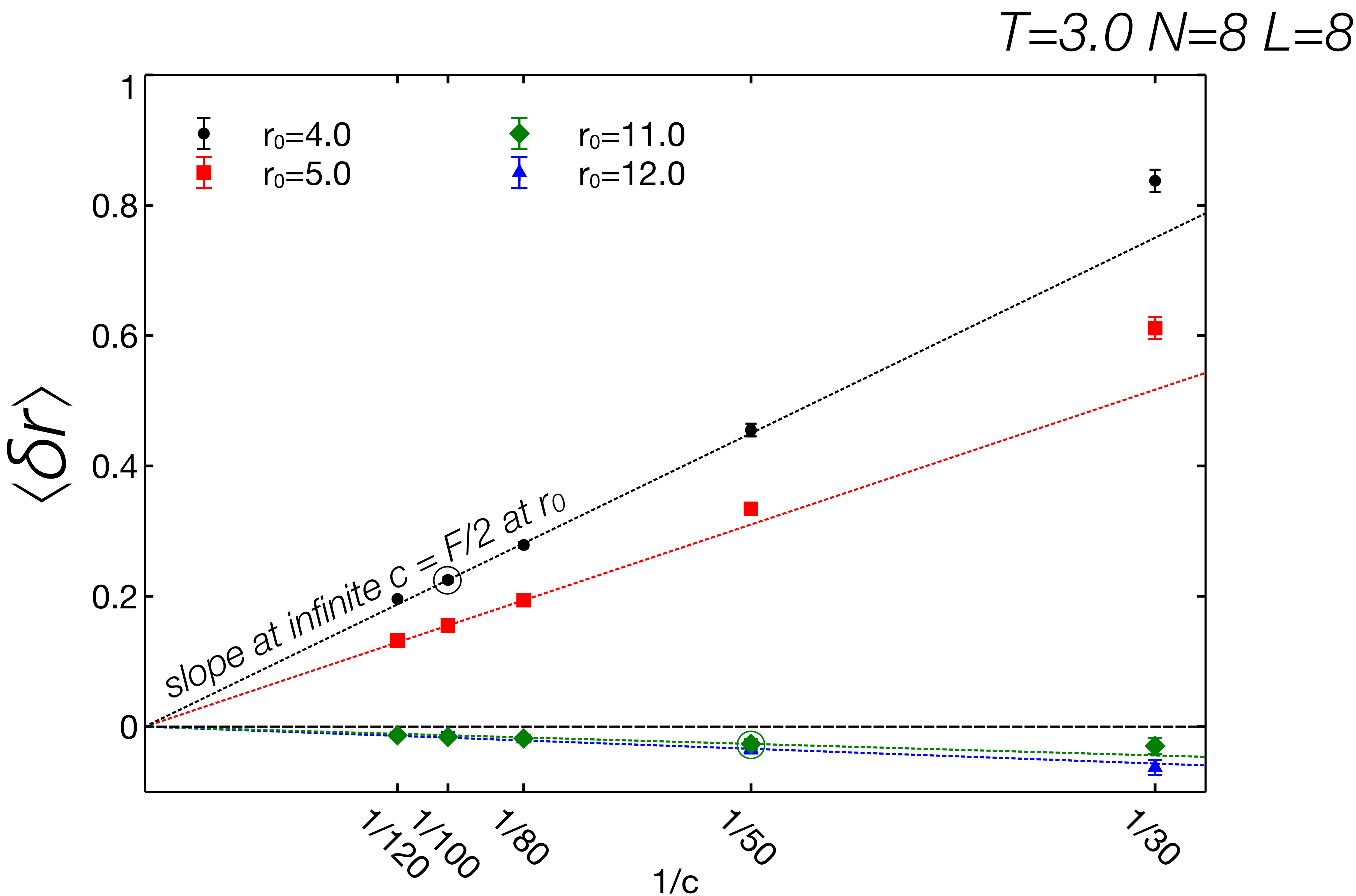
probe displacement direction

perpendicular direction

c=100

c=50

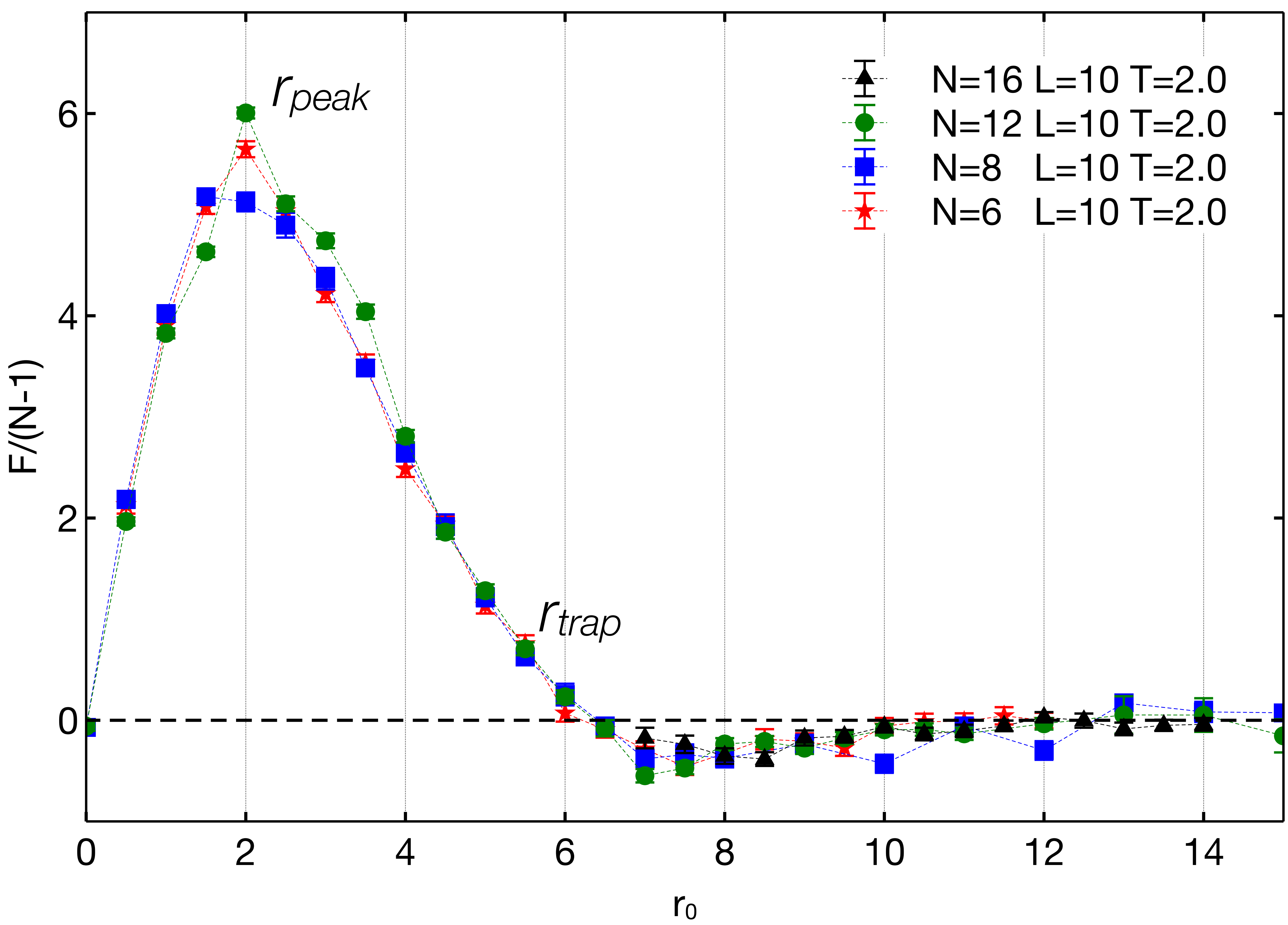
⟨δr⟩= F(N,L,r0) / 2 c



T=3.0 N=8 L=8
r0=4.0
r0=5.0
r0=11.0
r0=12.0
slope at infinite c = F/2 at r0
⟨δr⟩
1/c
1/120
1/100
1/80
1/50
1/30
0
0.2
0.4
0.6
0.8
1

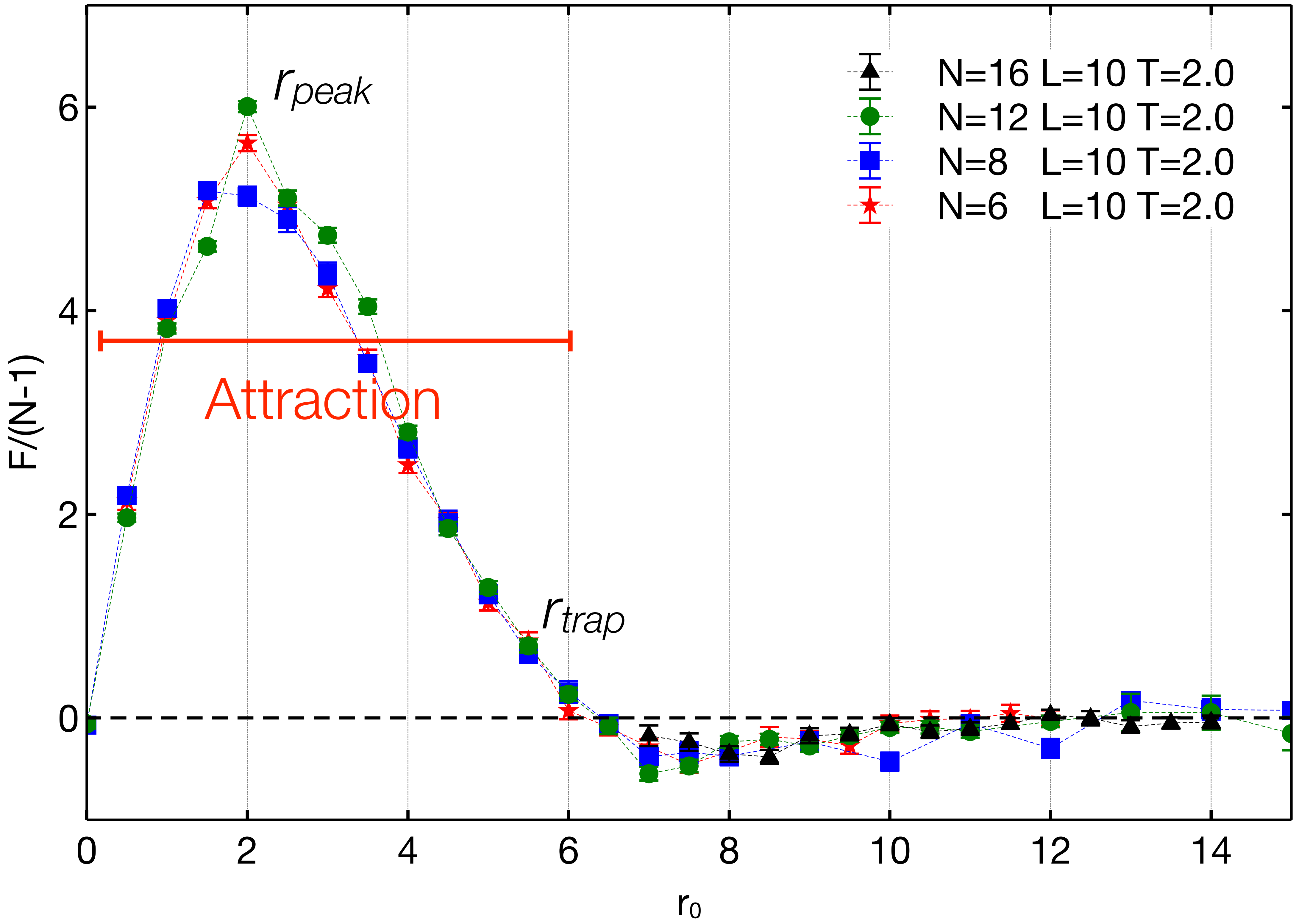
Force on probe D0 brane

MCSMC 1709.01932



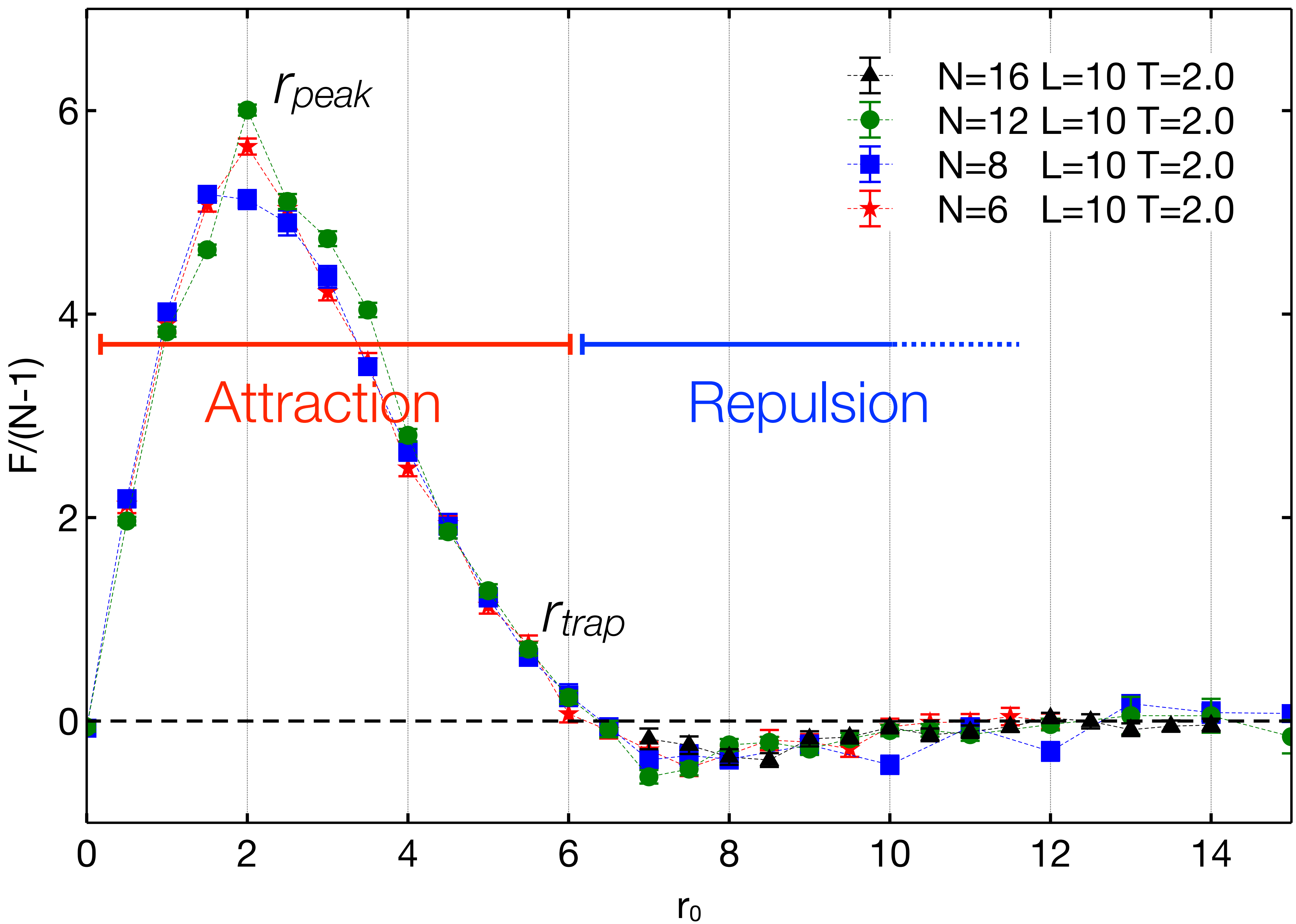
Force on probe D0 brane

MCSMC 1709.01932



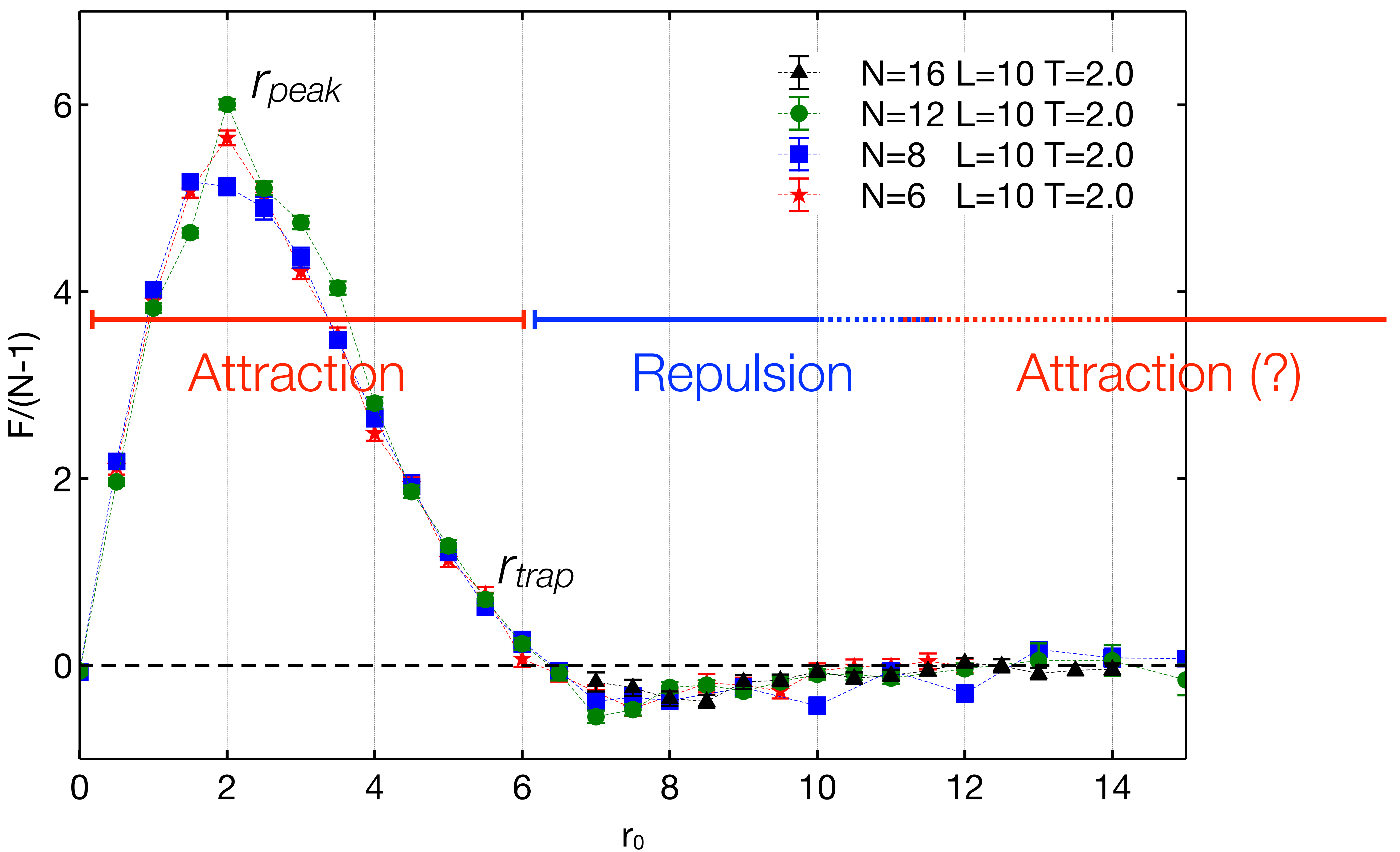
Force on probe D0 brane

MCSMC 1709.01932



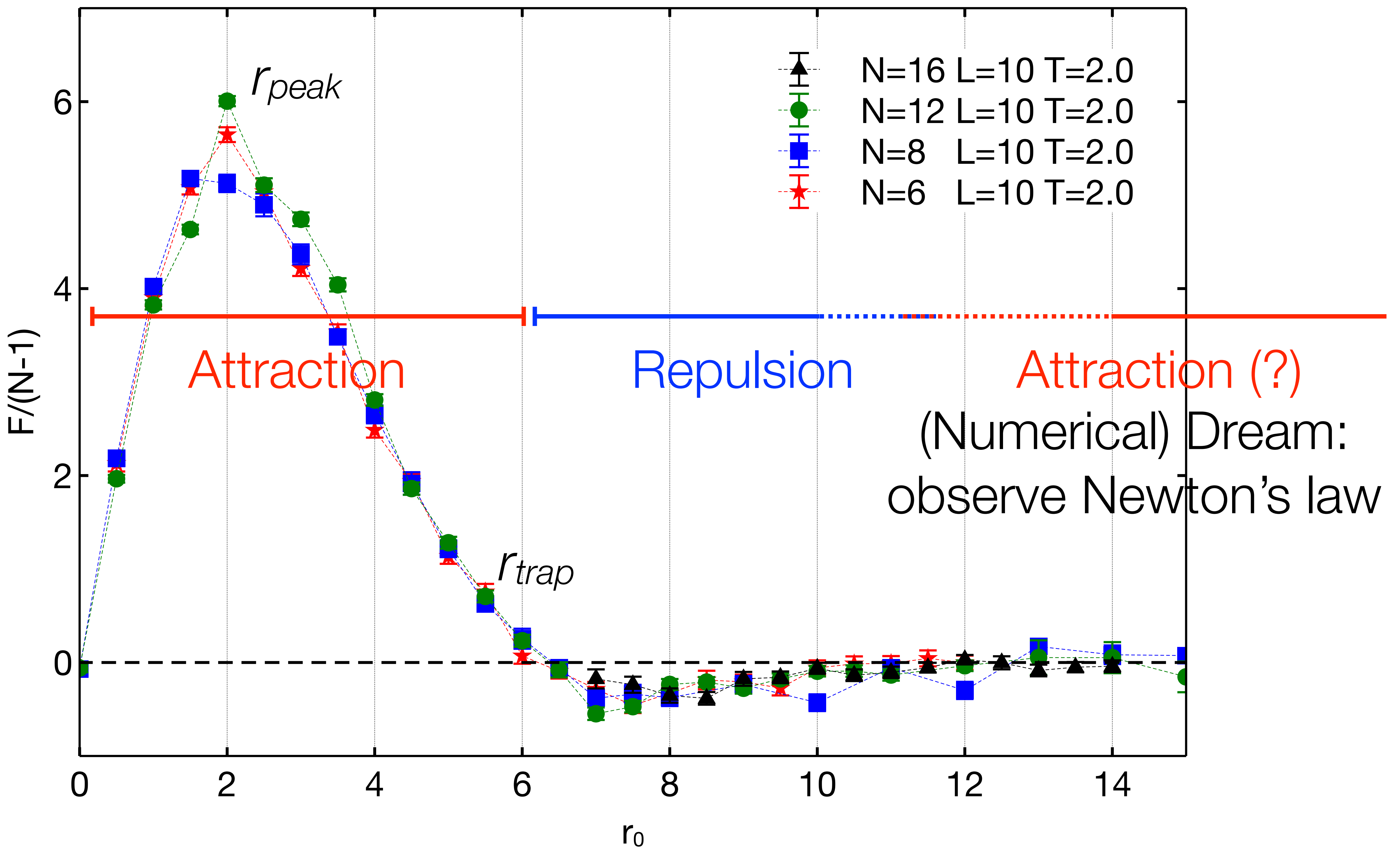
Force on probe D0 brane

MCSMC 1709.01932



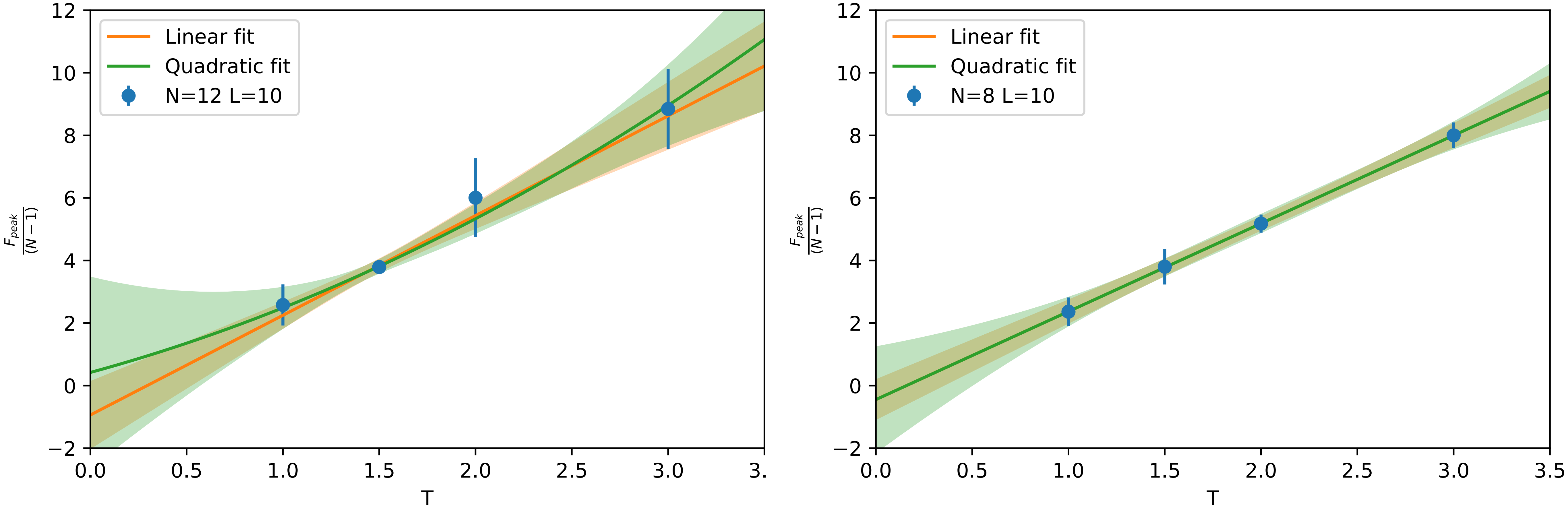
Force on probe D0 brane

MCSMC 1709.01932



(Numerical) Dream:
observe Newton's law

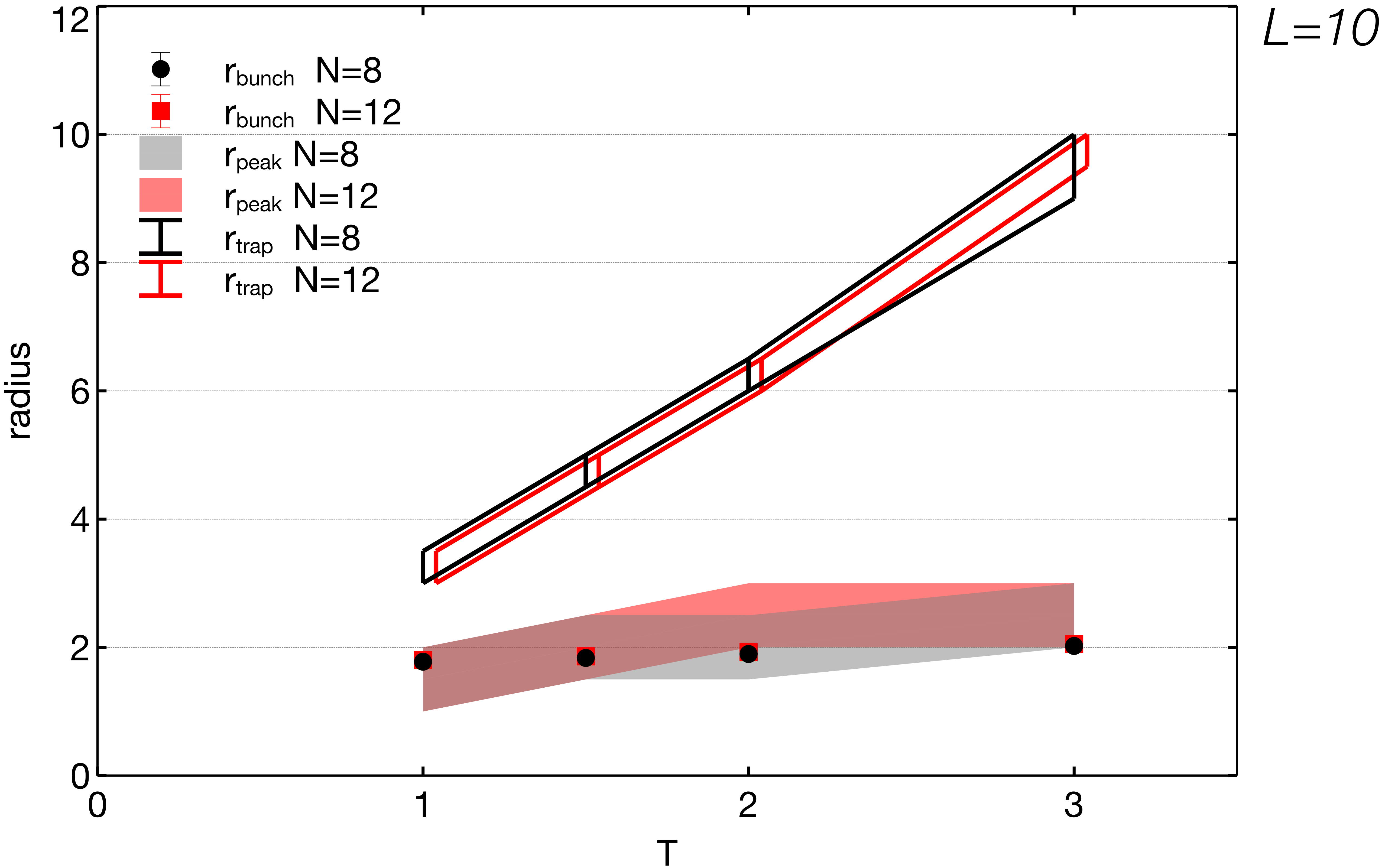
Hints of T=0 Supersymmetry



At T=0 fermionic and bosonic contributions should cancel.

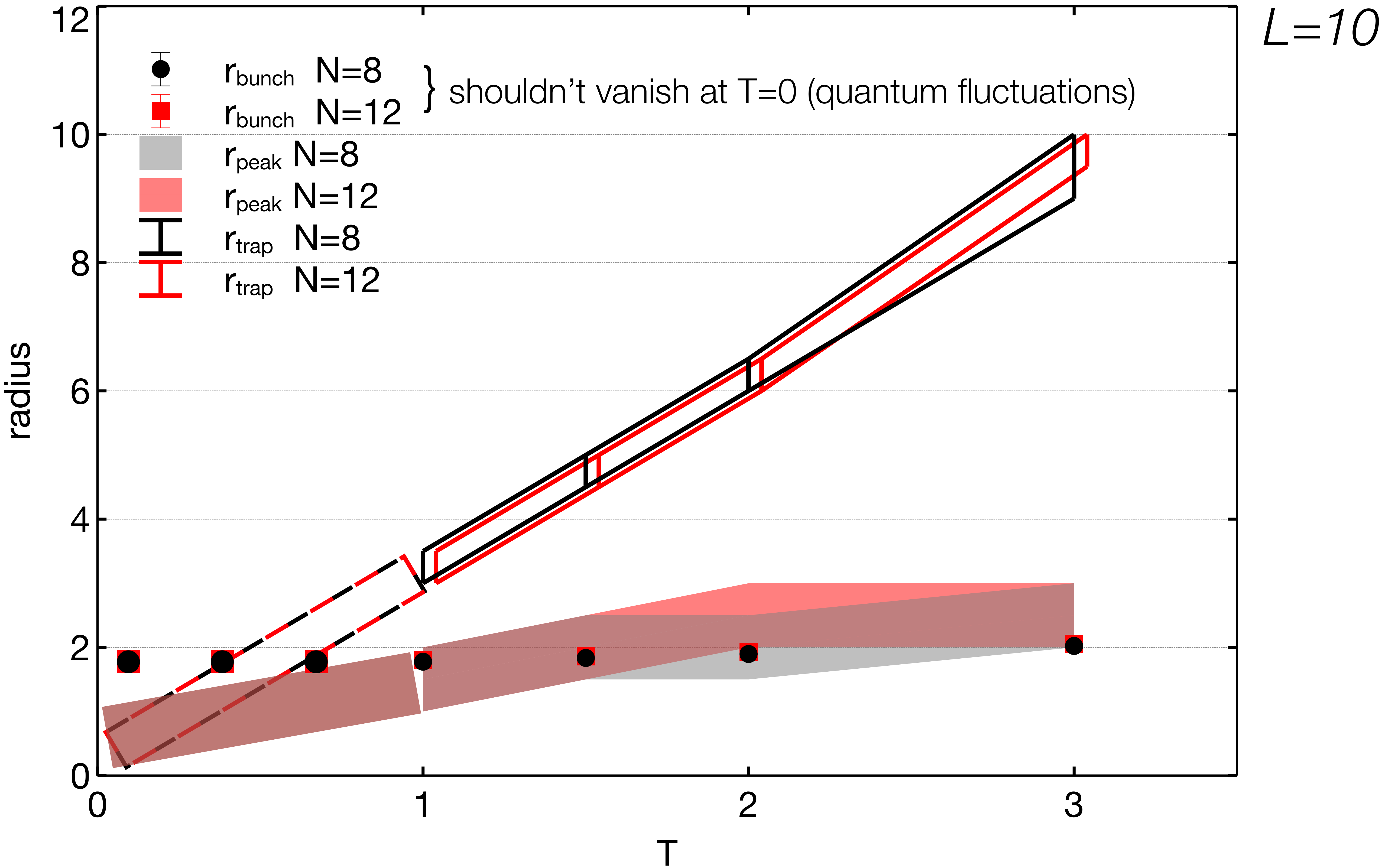
Length Scales

MCSMC 1709.01932



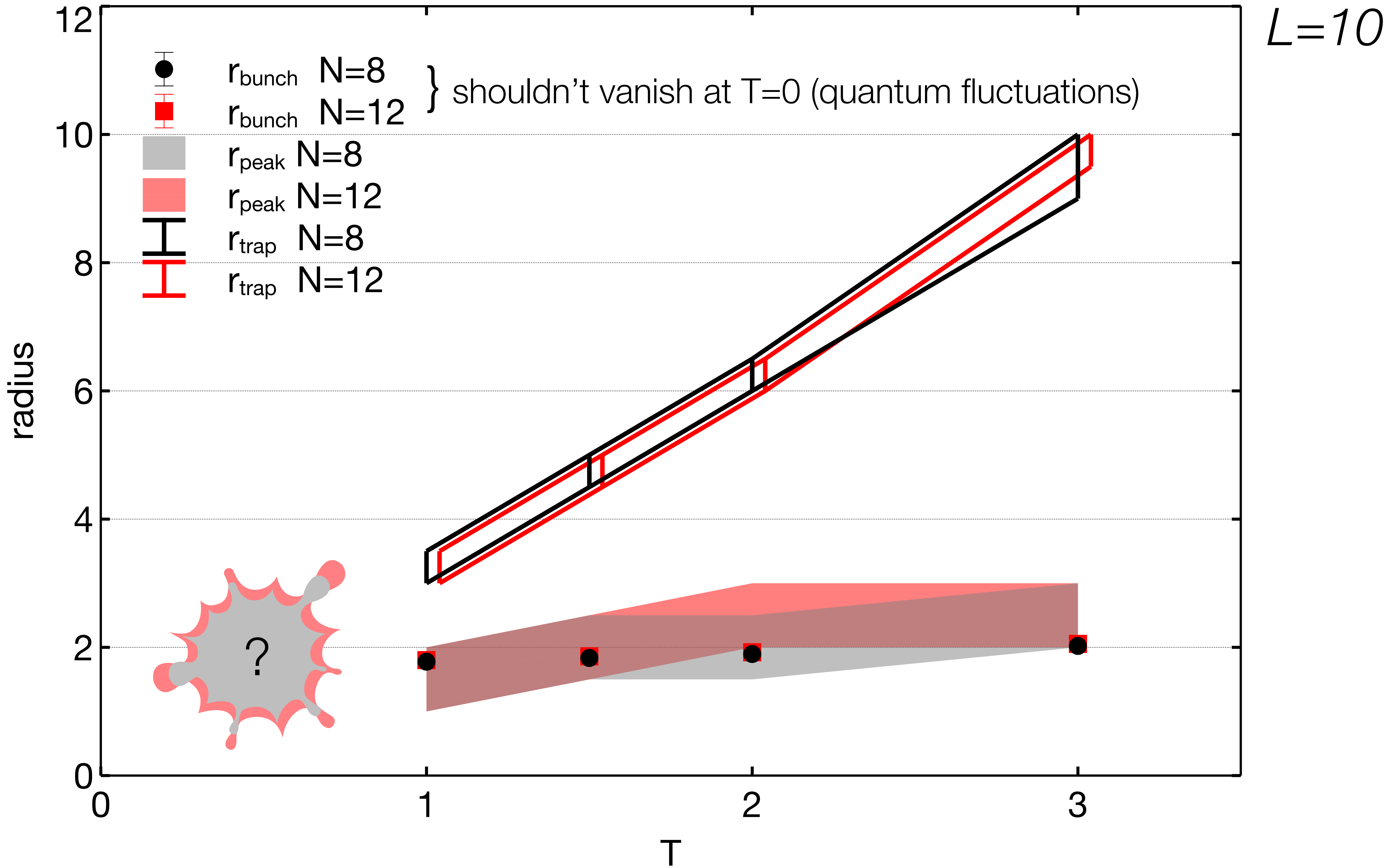
Length Scales

MCSMC 1709.01932



Length Scales

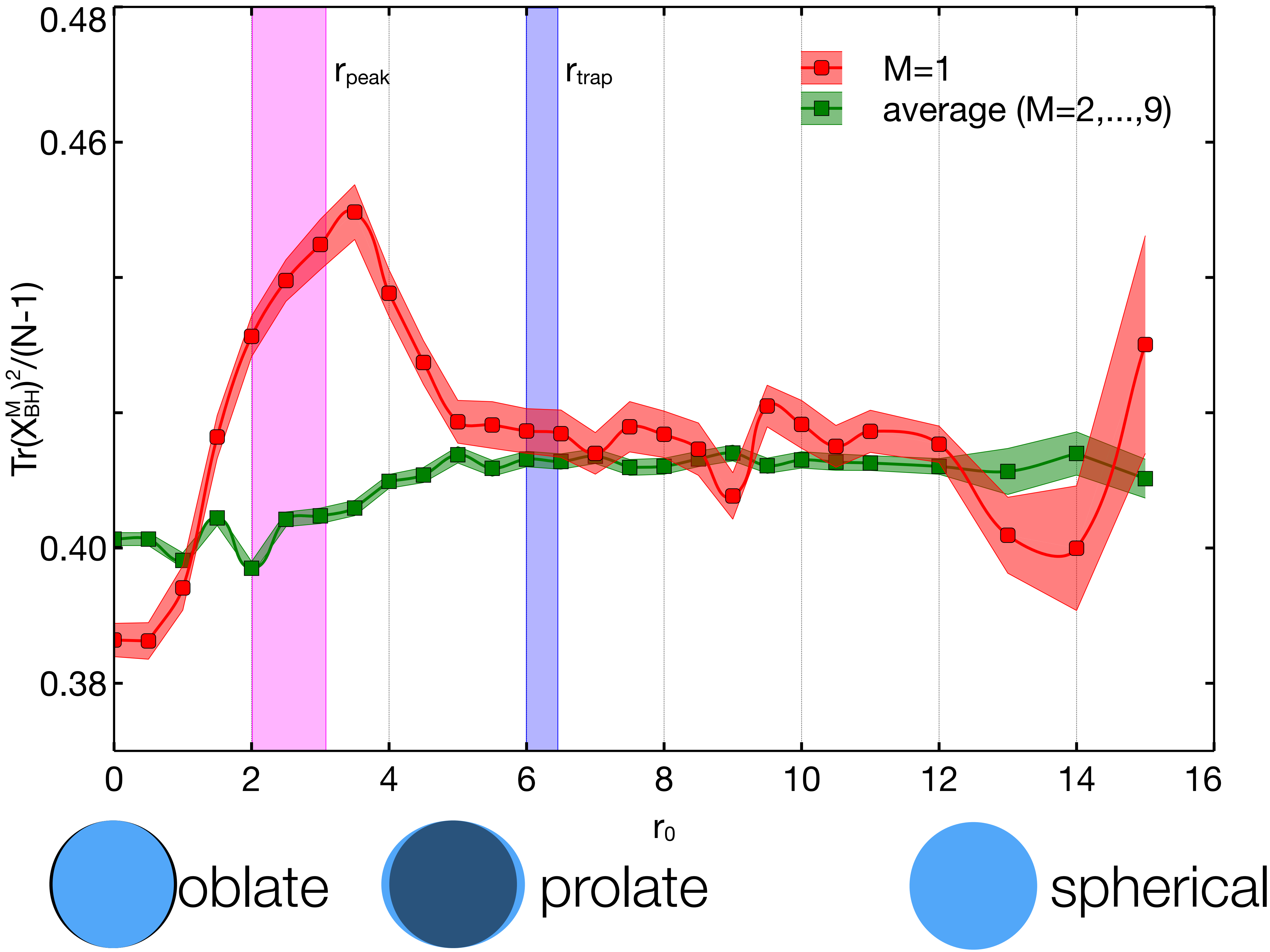
MCSMC 1709.01932



Bunch Deformation

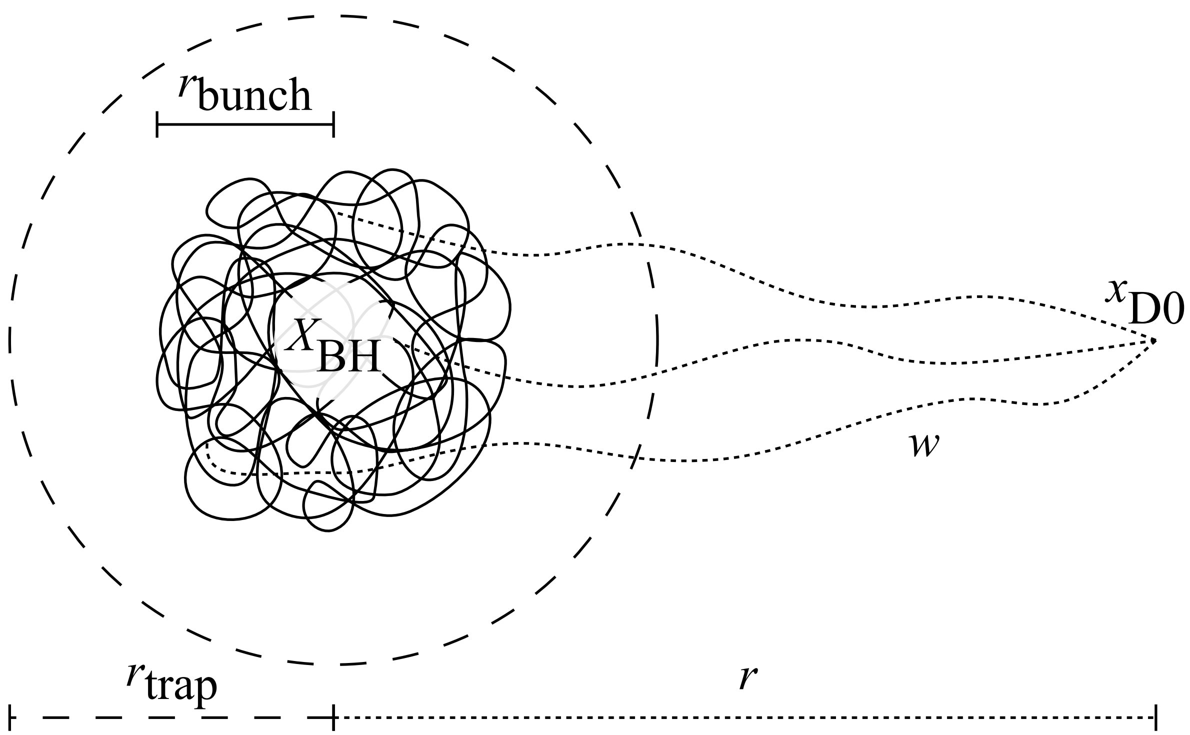
MCSMC 1709.01932

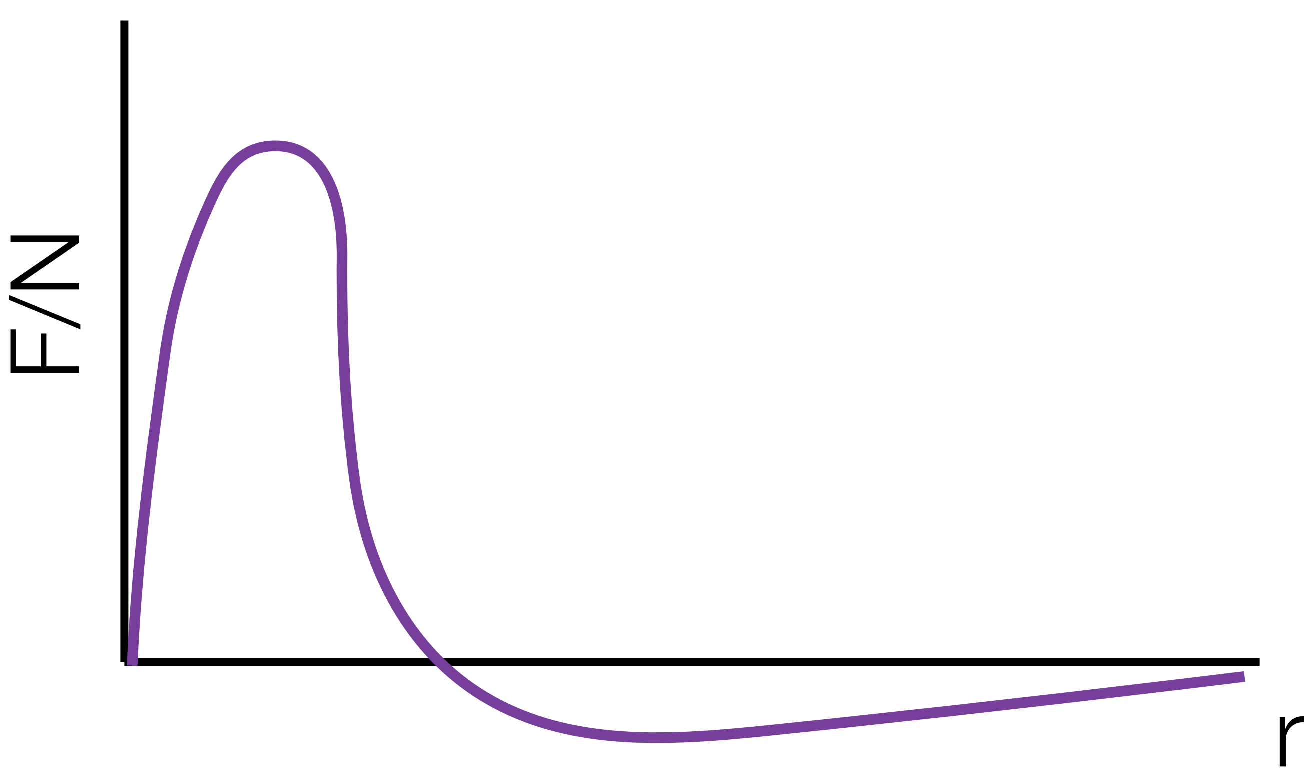
T=2.0 N=12 L=10



Where is the Horizon? (High Temperature)

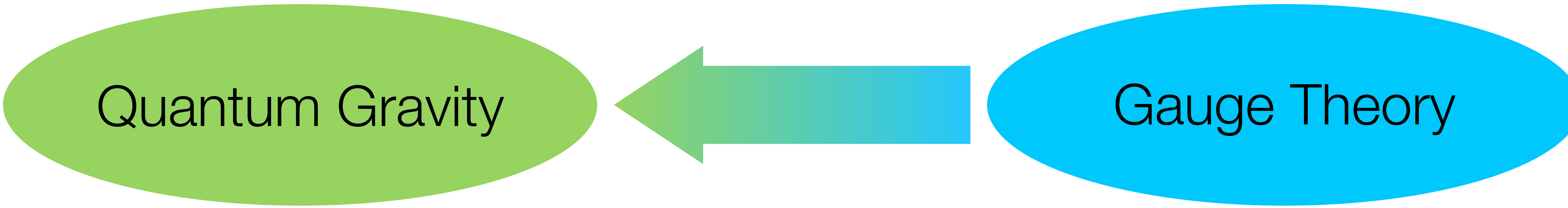
See also: 1512.02536, 1612.09281 Filev + O'Connor





- The whole bunch?
  - ✓ Carries all the information
  - ✓ Light modes become massless near r_{bunch}
  - ✓ Open string condensation needed for fast scrambling
  - ✓ Euclidean signature's dual does not have an 'interior'
- r_{trap}?
  - ✓ Repulsive force seems naturally 'outside'.
  - ✓ Off-diagonal elements are excited / emission increases the temperature
  - ✓ Stringy effects happen inside r_{trap}
  - ✗ Euclidean theory knows about interior, against lore
  - ✗ Can pass through the horizon in finite gauge theory time
- Elsewhere?

Summary

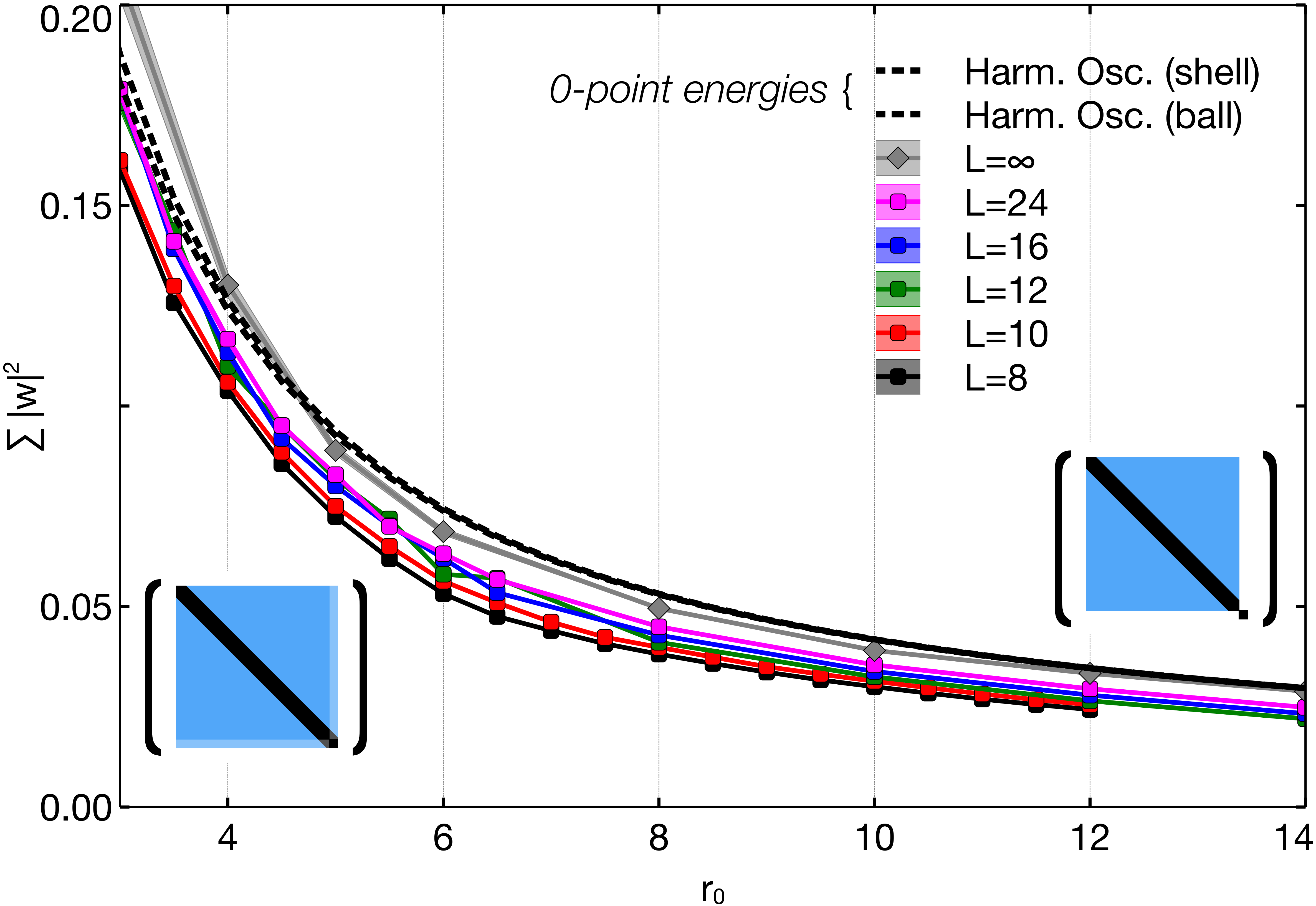


- Geometrical story seems good at long and maybe even intermediate distances.
- Where exactly IS the horizon? r_{bunch}? r_{trap}? The whole bunch is the horizon?
- Velocity dependence of the force?
- LOTS TO DO!

Backup Slides

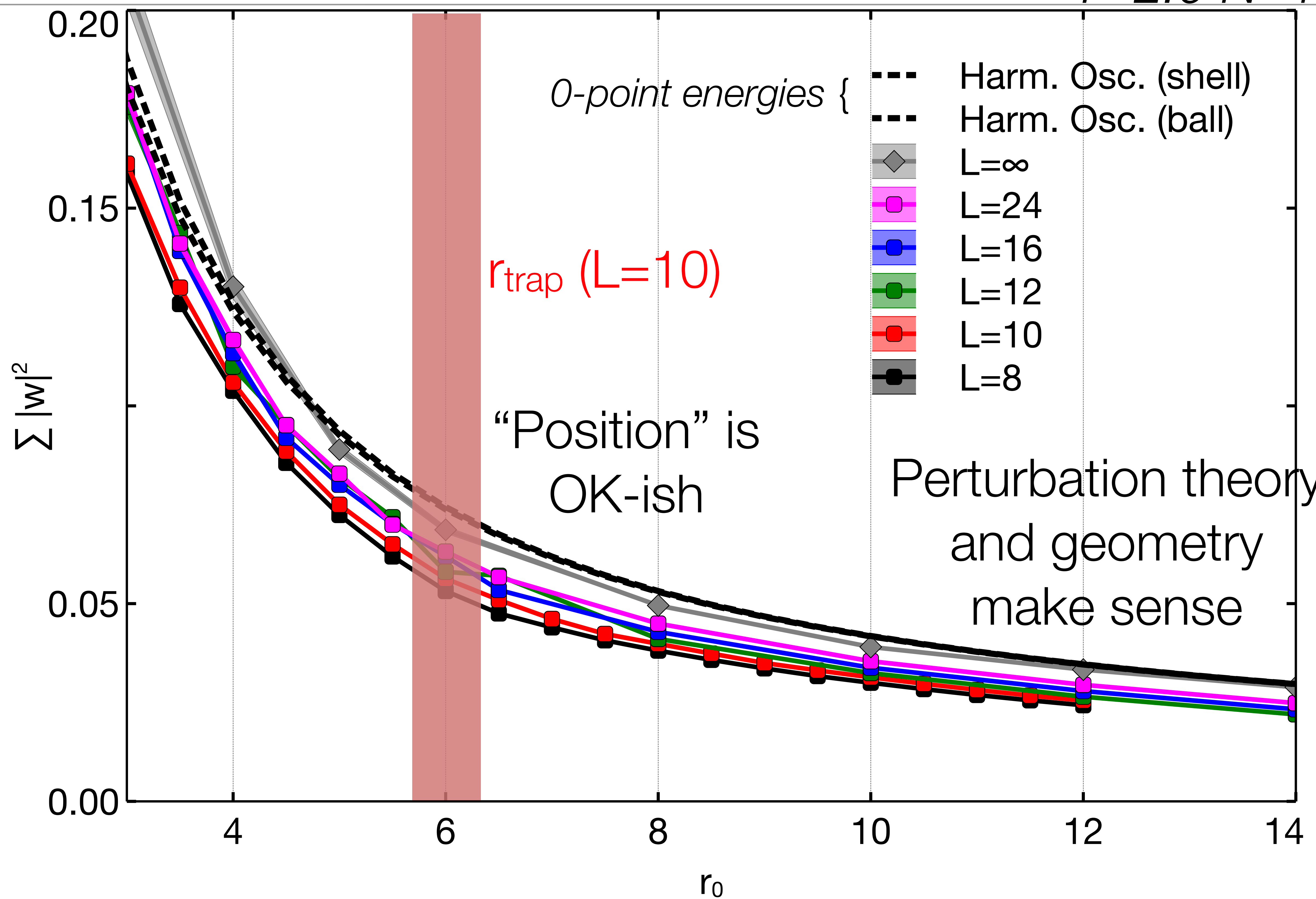
Off-diagonal Elements

T=2.0 N=12



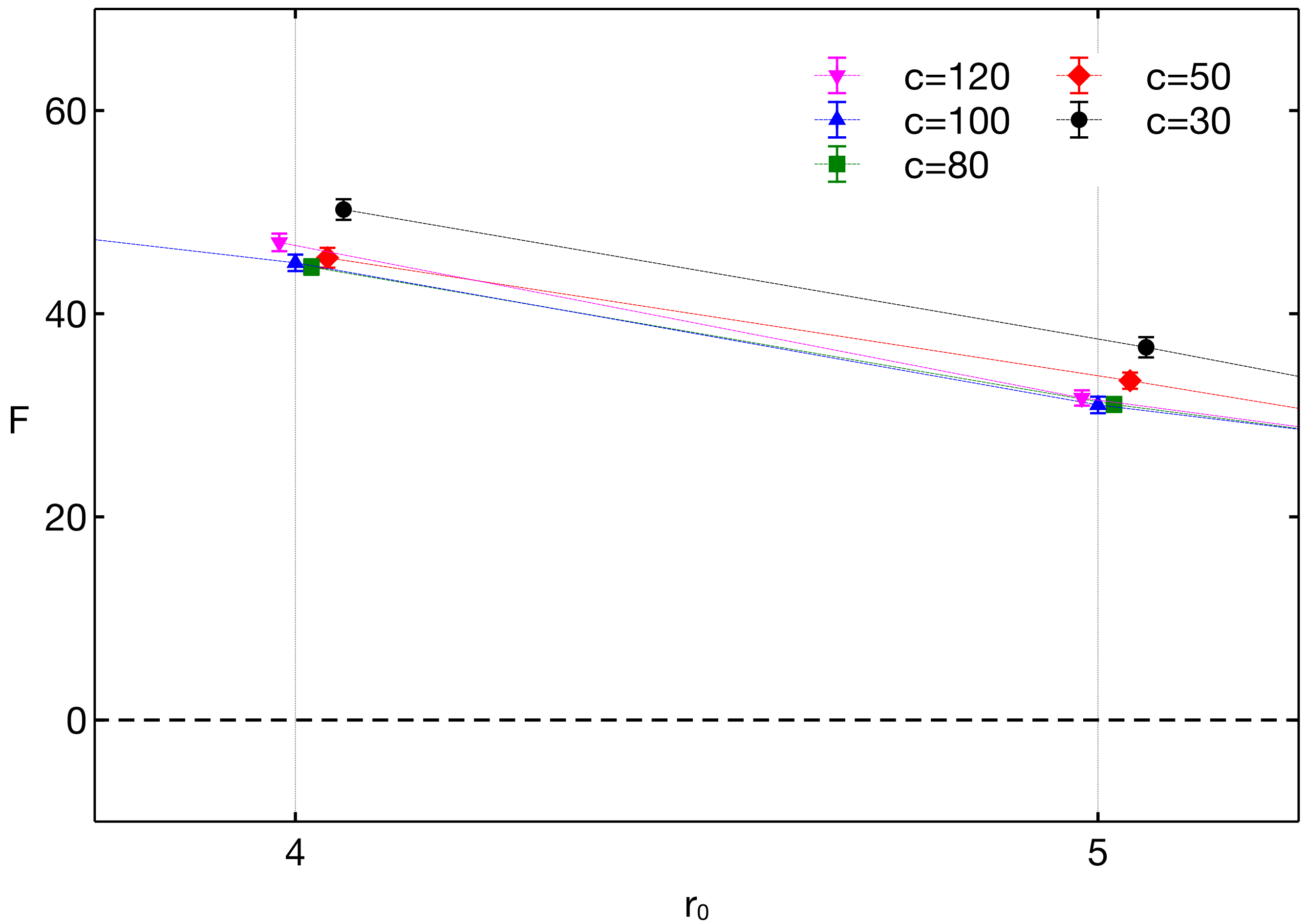
Off-diagonal Elements (Open String Diagnostic)

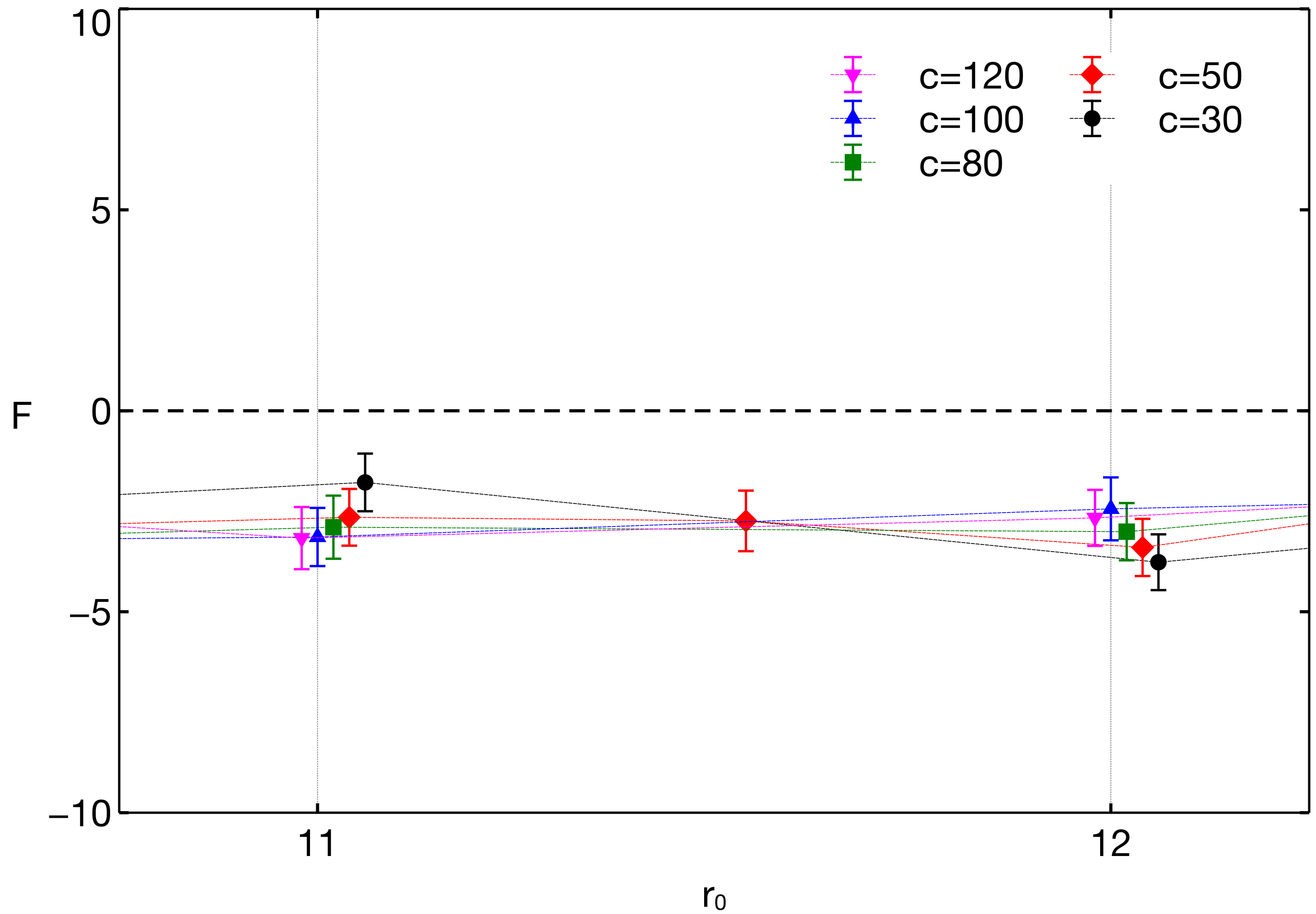
T=2.0 N=12

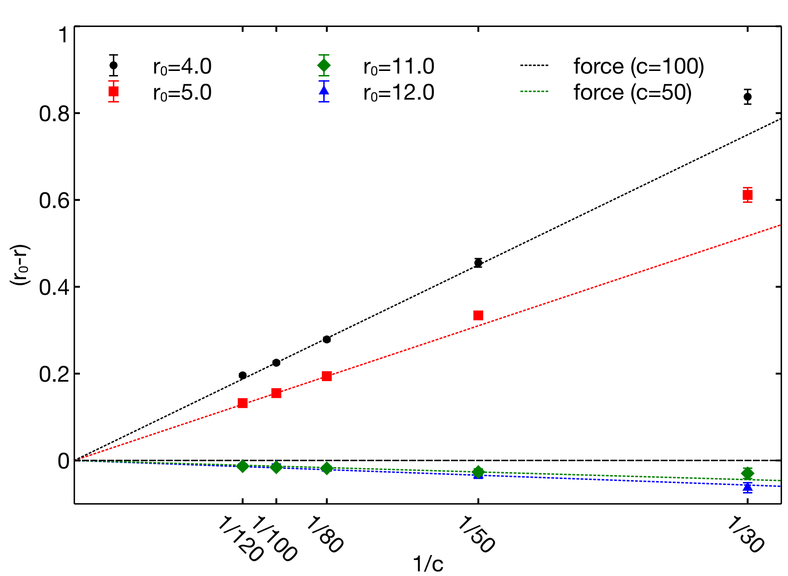


Choice for Potential Strength

T=3.0 N=8 L=8







c ≳ 50 is fine for cases we studied

We set c = 100

Phase Quench