

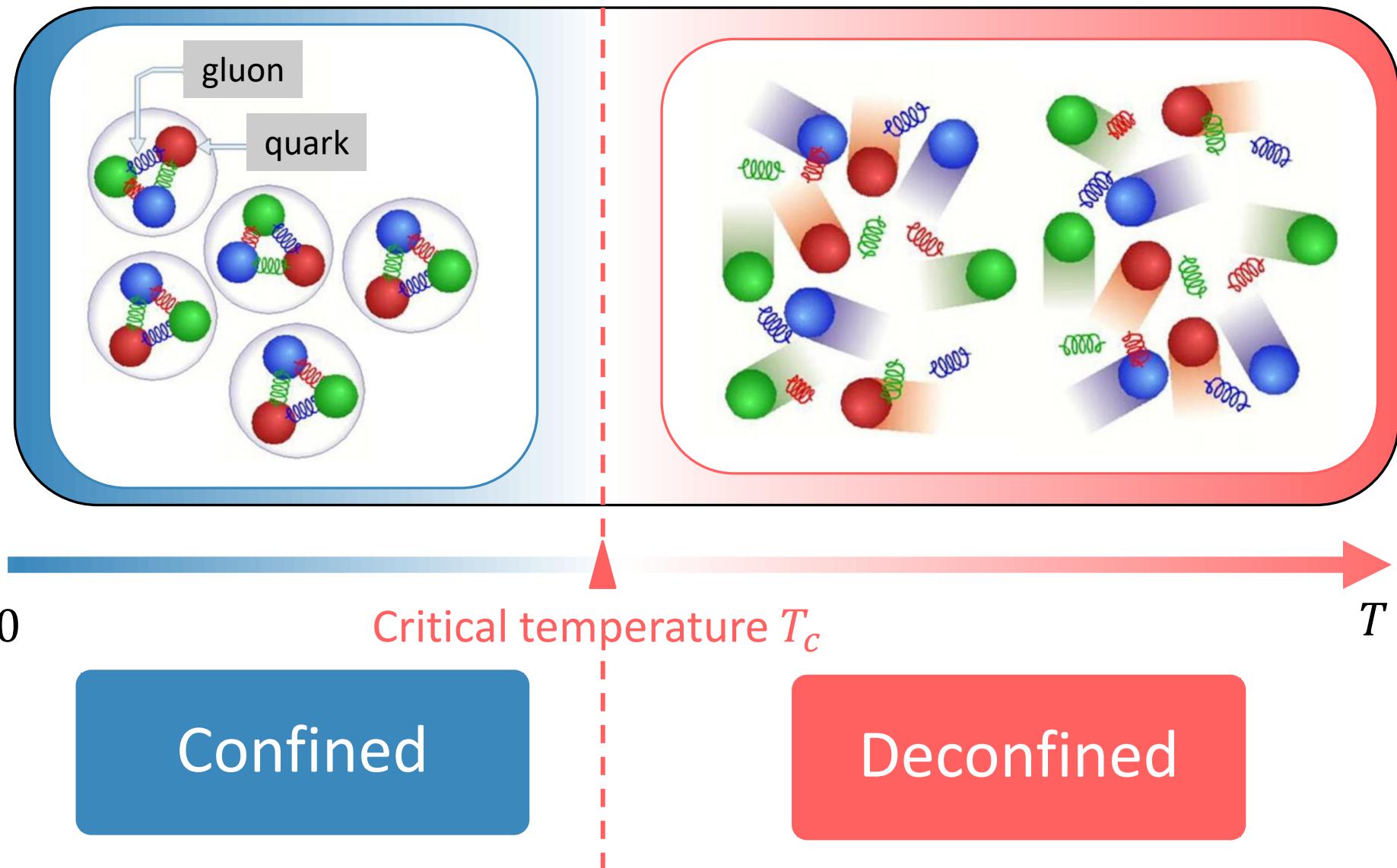
有限温度系における 静的カラー電荷周辺のエネルギー応力分布

柳原 良亮 (阪大理)

For FlowQCD collaboration

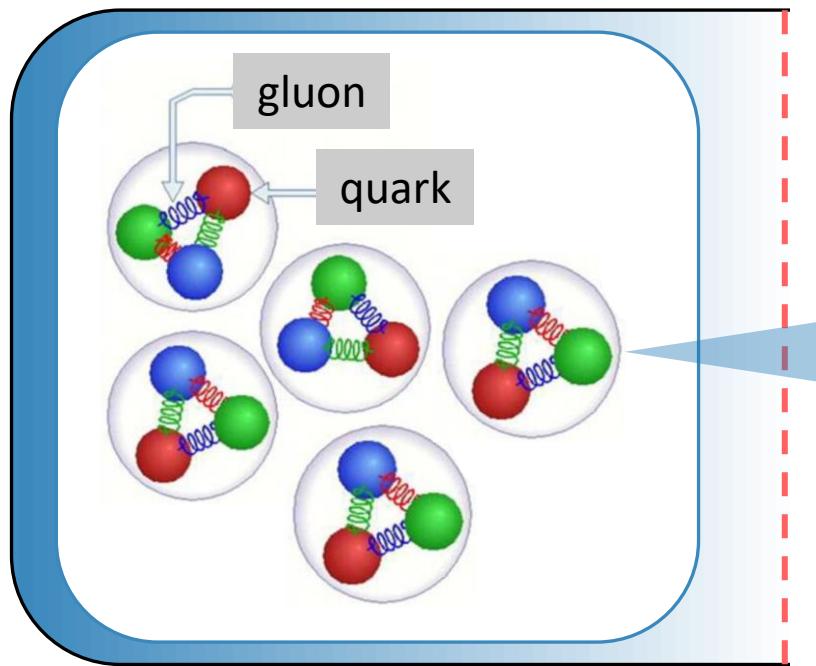
北沢 正清、浅川 正之、初田 哲男

閉じ込め・非閉じ込め



閉じ込め・非閉じ込め

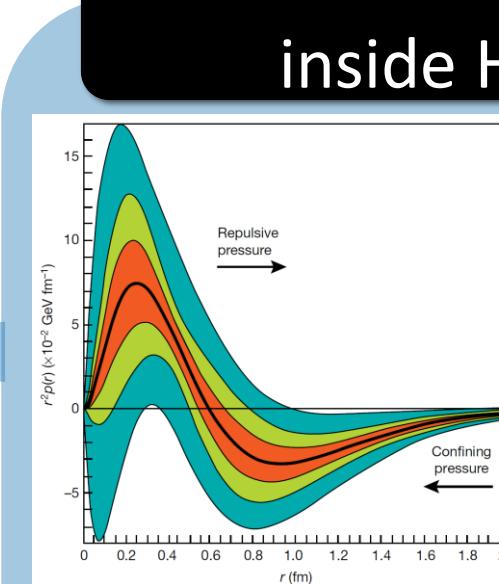
Pressure distribution inside Hadrons



0

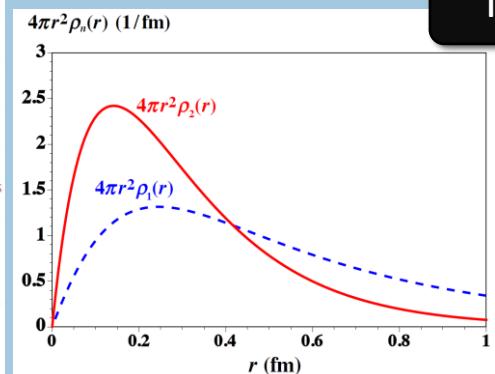
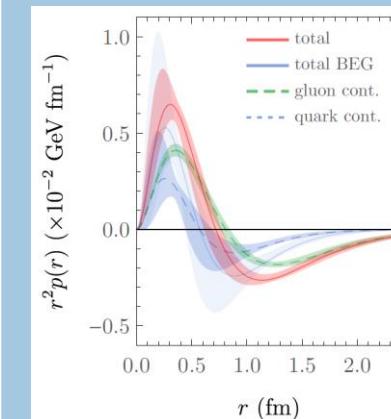
Confined

T_c



Exp.

Burkert *et al.*,
Nature 557 (2018) 396.

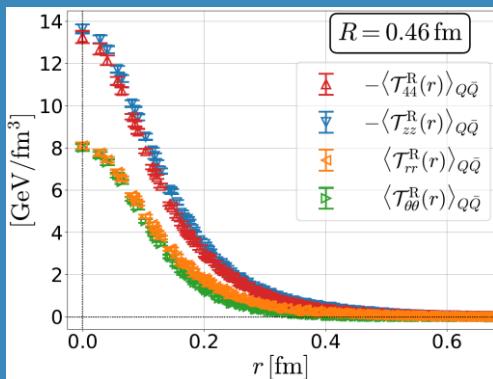
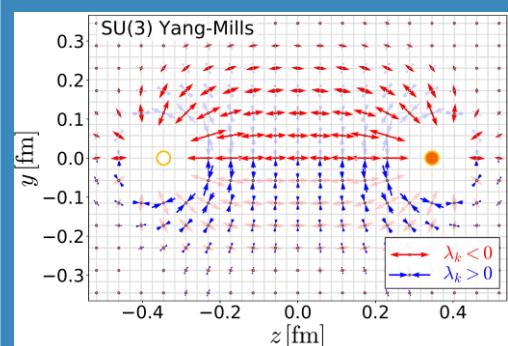


Th.

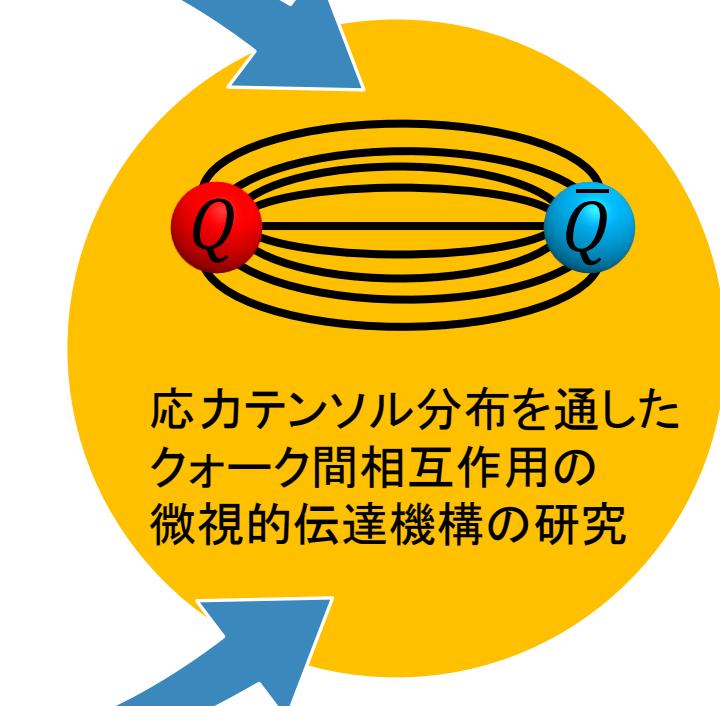
Shanahan *et al.*, PRL 122 (2019) no7, 072003.
Kumano *et al.*, PRD 97 (2018) 014020.

これまでの研究成果 (真空の $Q\bar{Q}$ 系)

1 Stress distribution around $Q\bar{Q}$ on the lattice

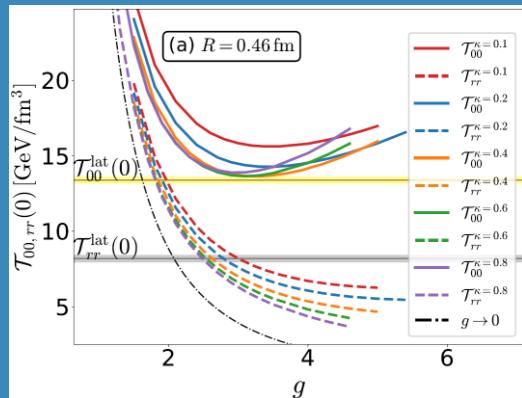
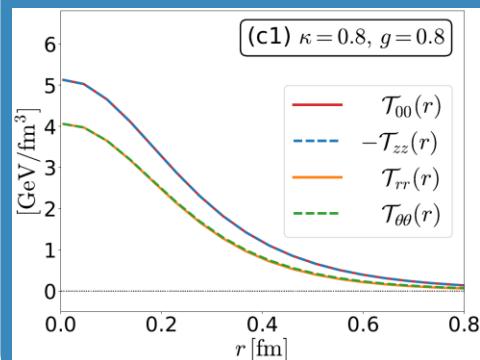


RY et al. (Flow QCD collab.), PLB789 (2019) 210.



応力テンソル分布を通した
クオーク間相互作用の
微視的伝達機構の研究

2 Stress distribution around $Q\bar{Q}$ in AH model



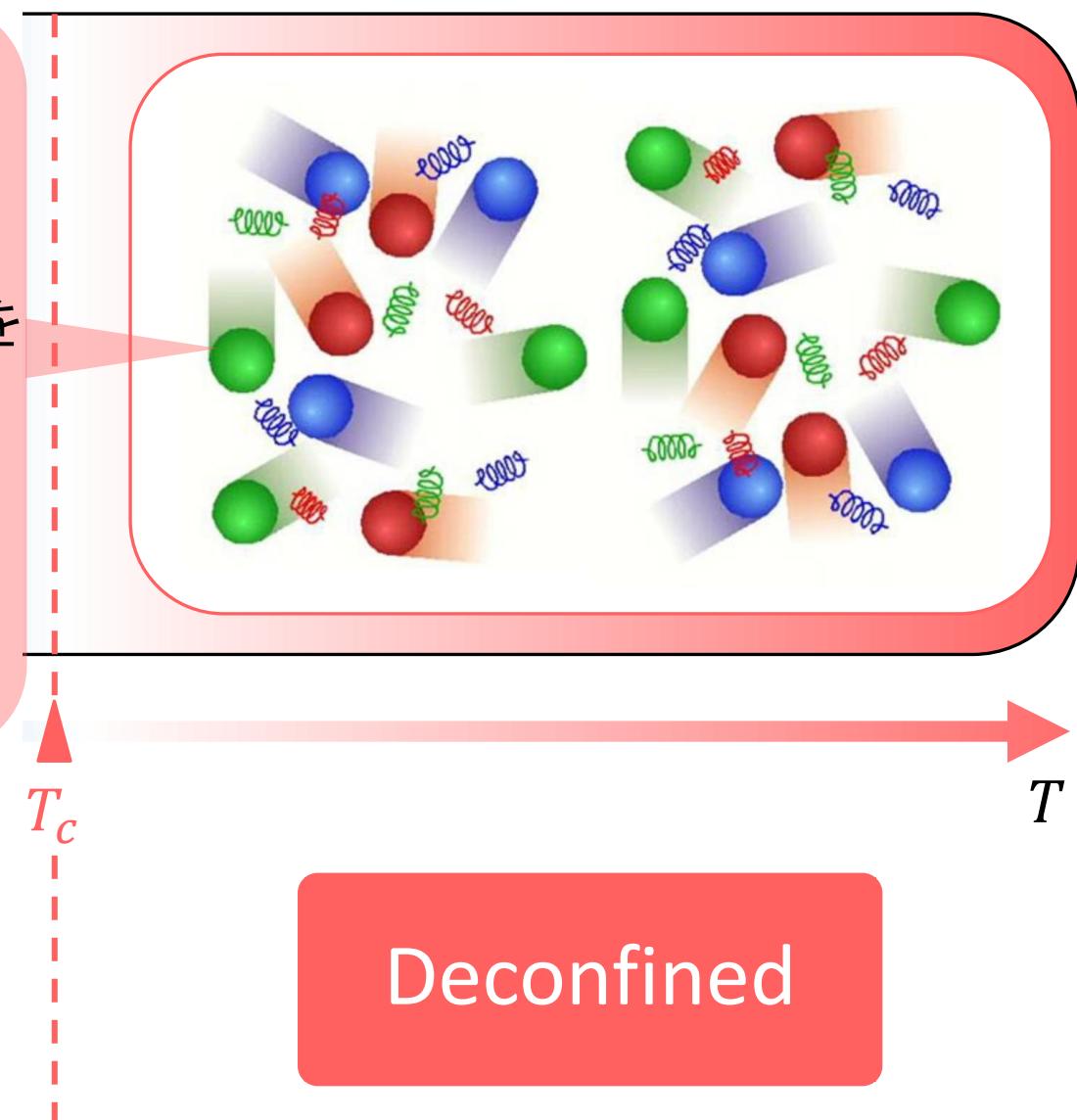
RY and M. Kitazawa, PTEP2019 (2019) 093B02.

有限温度系へ

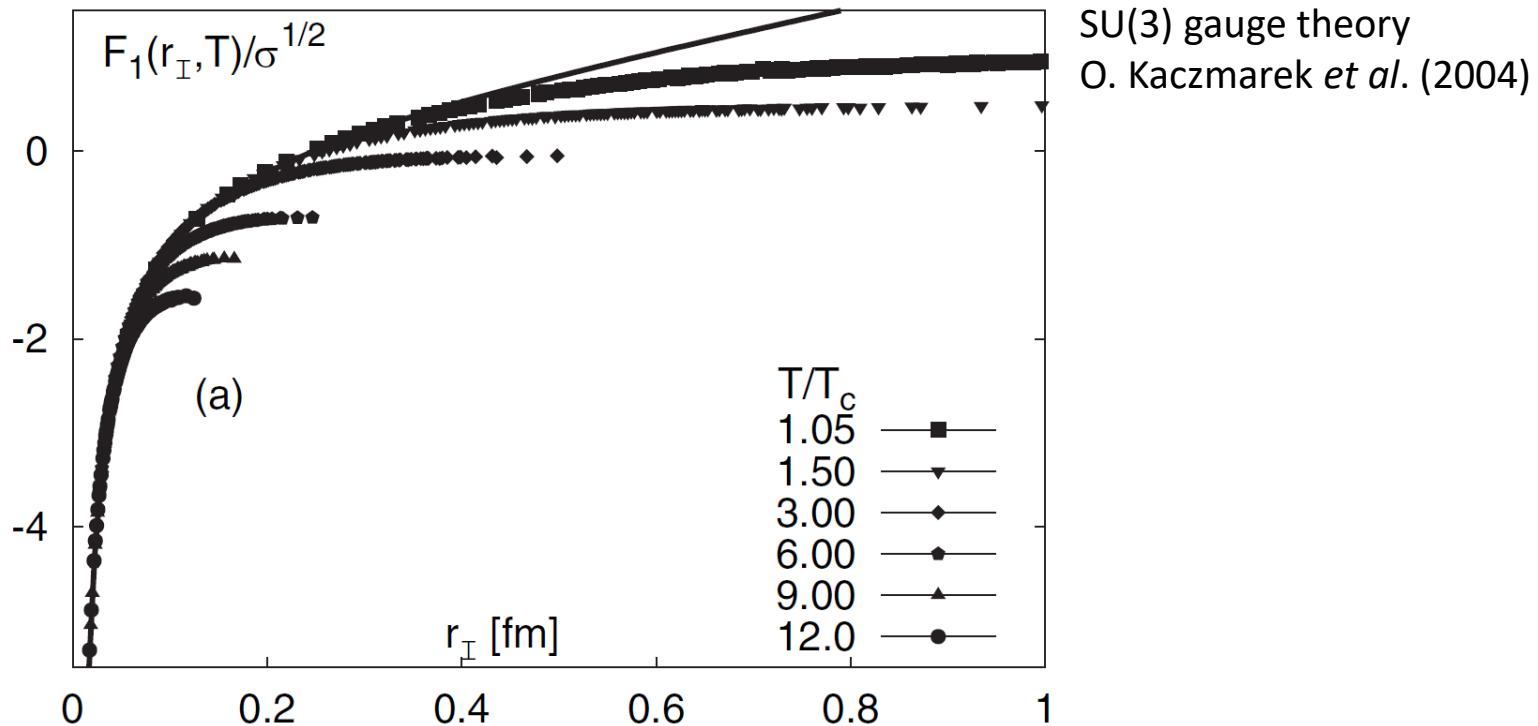
3

本研究

有限温度媒質中に置かれた
静的カラー電荷周辺の応力分布を
SU(3)格子ゲージ理論に基づいて
数値的に解析することで、
プラズマの局所的な性質(力学的情報)を調べる。



熱力学 —有限温度媒質のバルクの性質—



自由エネルギー (1重項)

✓ $e^{-F_1(r)/T} = \frac{1}{3} \langle \text{Tr } \Omega^\dagger(\vec{x}) \Omega(\vec{y}) \rangle$

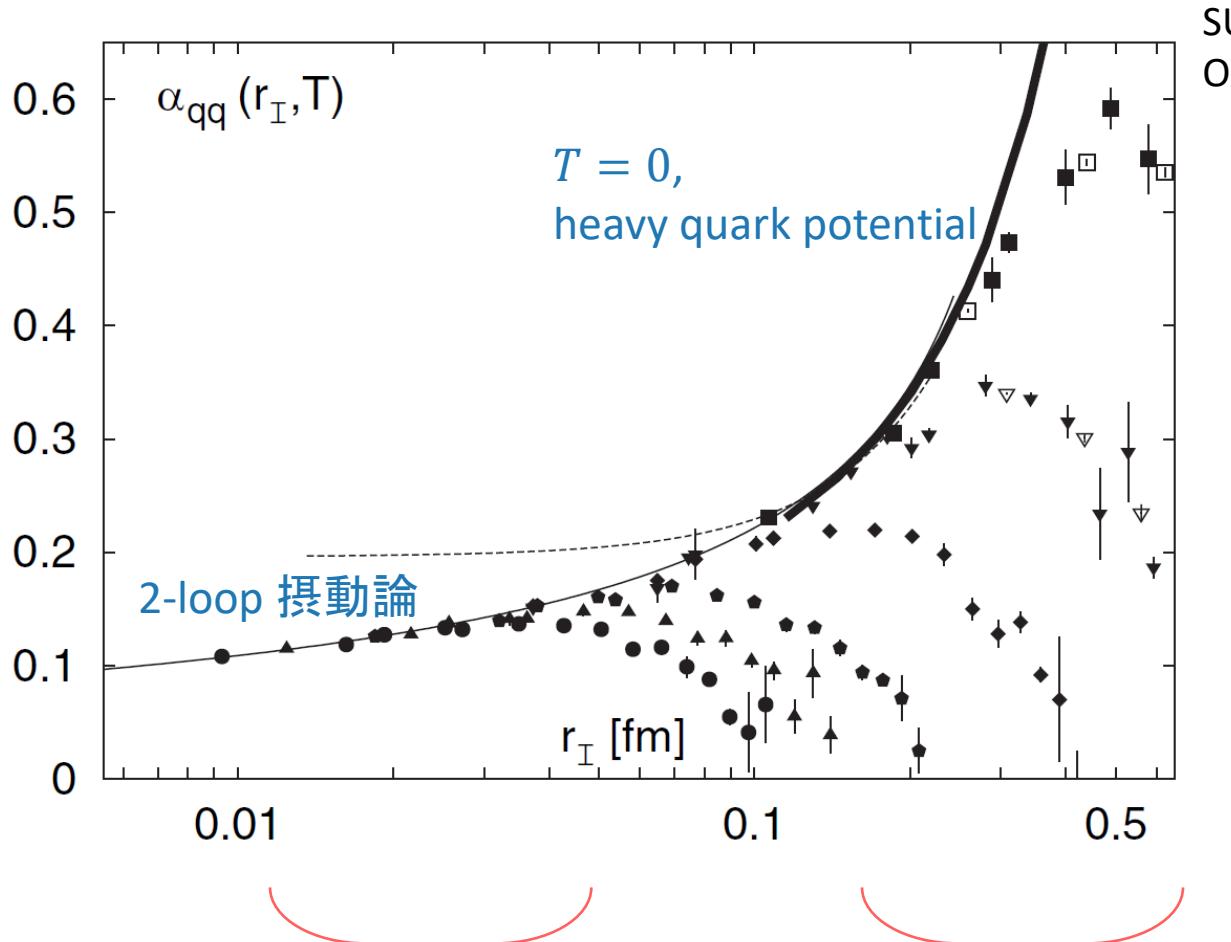


$$F_1(r) = \begin{cases} -\frac{4}{3} \cdot \frac{\alpha(r)}{r} & rT \ll 1 \\ -\frac{4}{3} \cdot \frac{\alpha(T)}{r} e^{\sqrt{4\pi\alpha(T)}rT} & rT \gg 1 \end{cases}$$

$rT \ll 1$

$rT \gg 1$

Running coupling



SU(3) gauge theory
O. Kaczmarek *et al.* (2004)

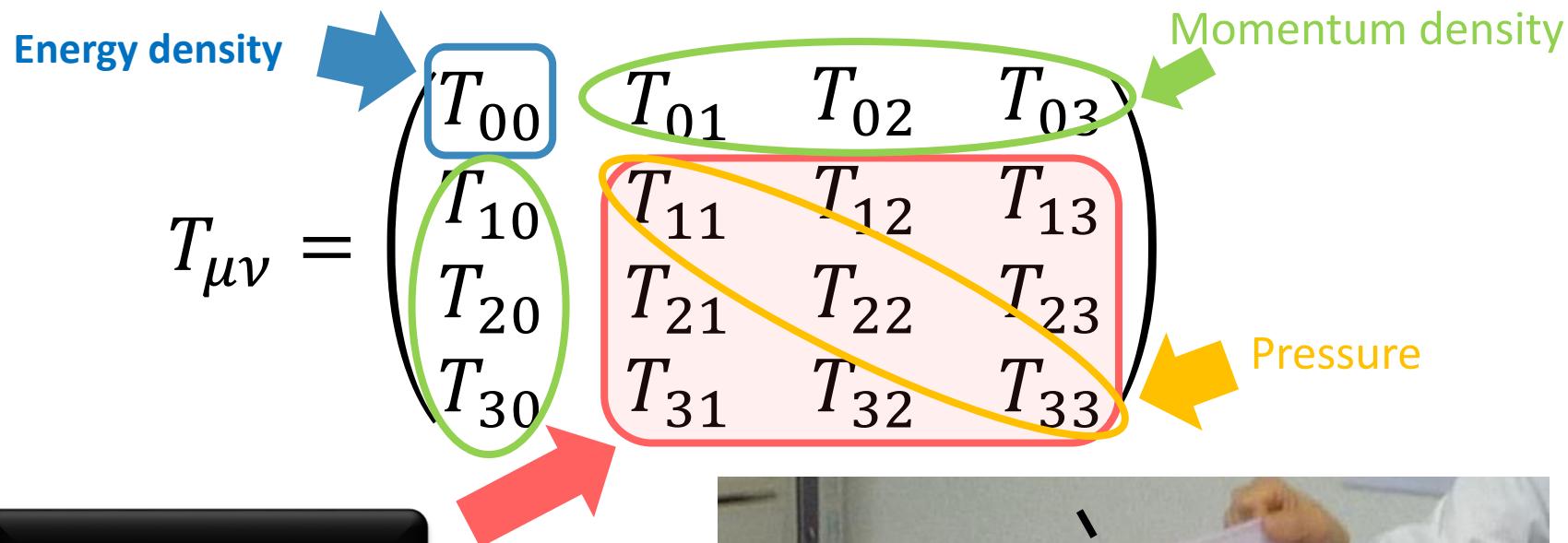
Running couplingの定義

✓ $\alpha_{qq}(r, T) = \frac{3r^2}{4} \cdot \frac{dF_1(r, T)}{dr}$

$r \lesssim 0.1\text{fm}$:
ゼロ温度摂動論に一致

$r \gtrsim 0.1\text{fm}$:
有限温度媒質の効果

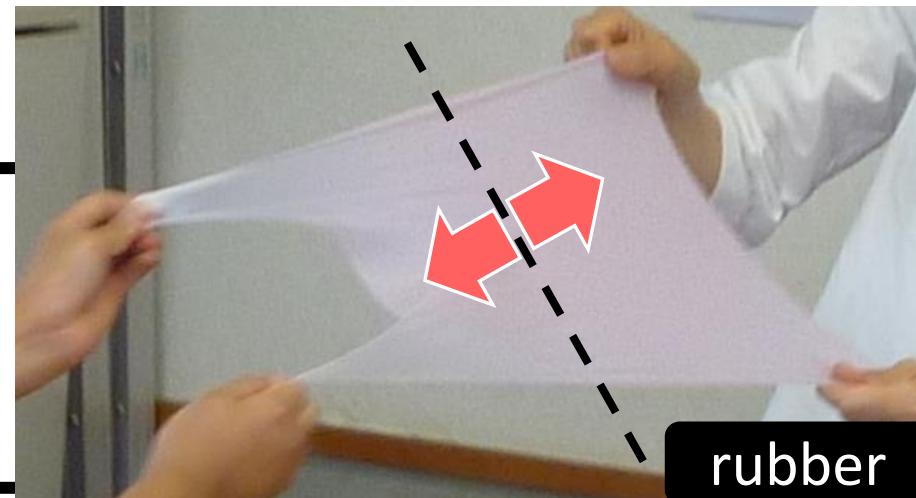
局所的な性質へ：エネルギー運動量テンソル



✓ Stress is force per unit area

$$f_i = \sigma_{ij} n_j ; \sigma_{ij} = -T_{ij}$$

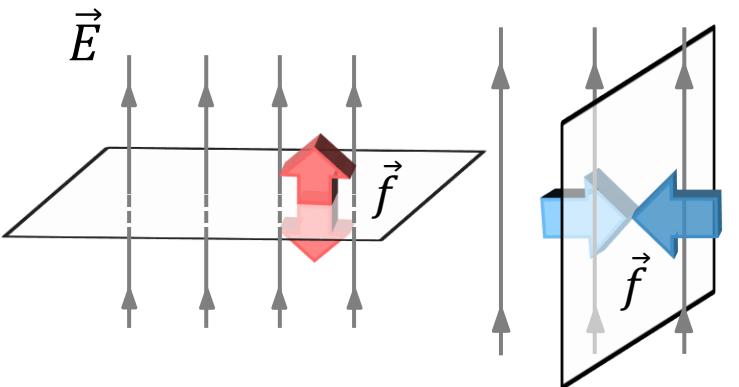
Landau and Lifshitz



rubber

Maxwell応力

$$T_{ij} = \epsilon_0 \left(E_i E_j - \frac{\delta_{ij}}{2} E^2 \right) + \frac{1}{\mu_0} \left(B_i B_j - \frac{\delta_{ij}}{2} B^2 \right)$$

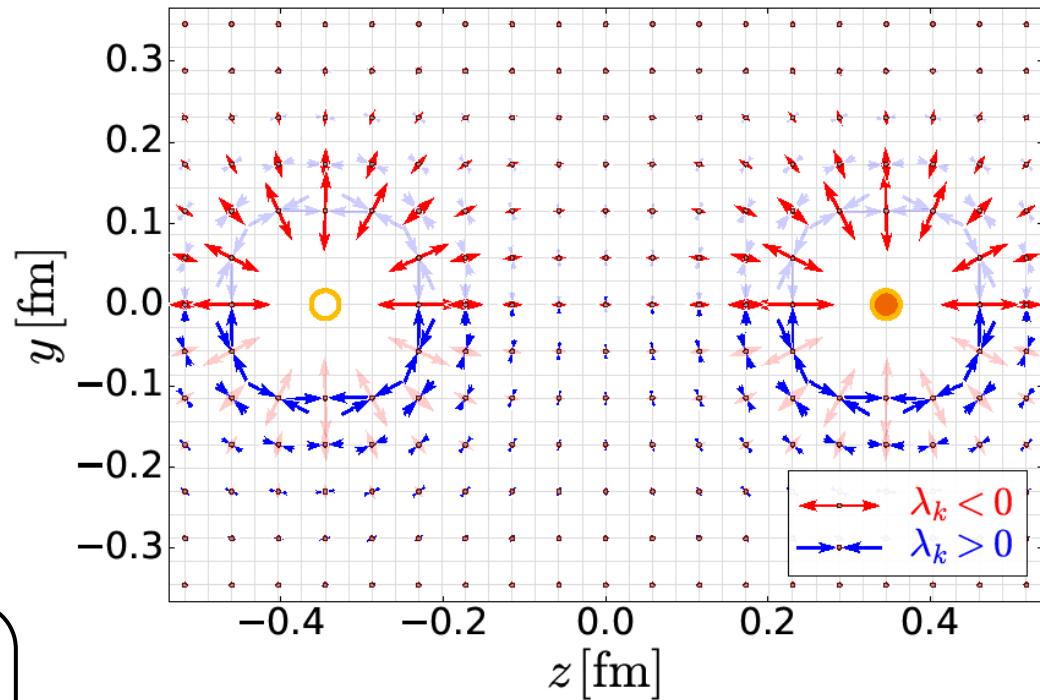


- ✓ Perpendicular plane: $\lambda_k < 0$
- ✓ Parallel plane: $\lambda_k > 0$

✓ Stress tensor

$$T_{ij} n_j^{(k)} = \lambda_k n_i^{(k)}$$

$$(i, j = 1, 2, 3 ; k = 1, 2, 3)$$



Length of arrows = $\sqrt{|\lambda_k|}$

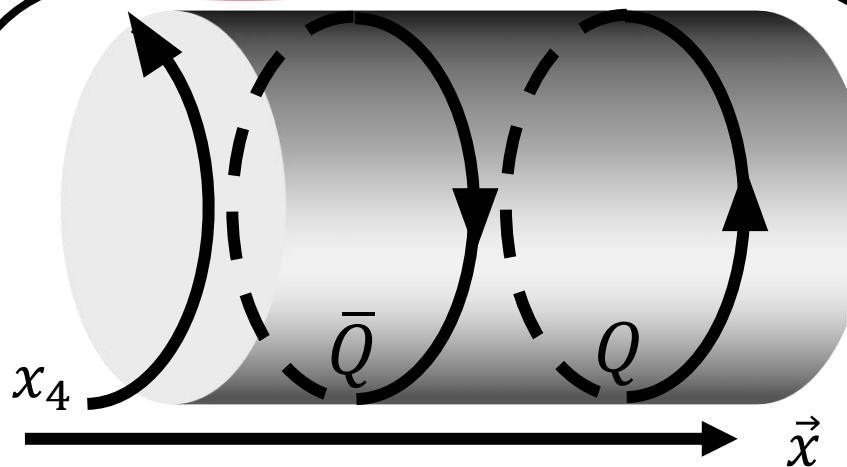
格子上での測定

To do

① Prepare $Q(\bar{Q})$ on the lattice

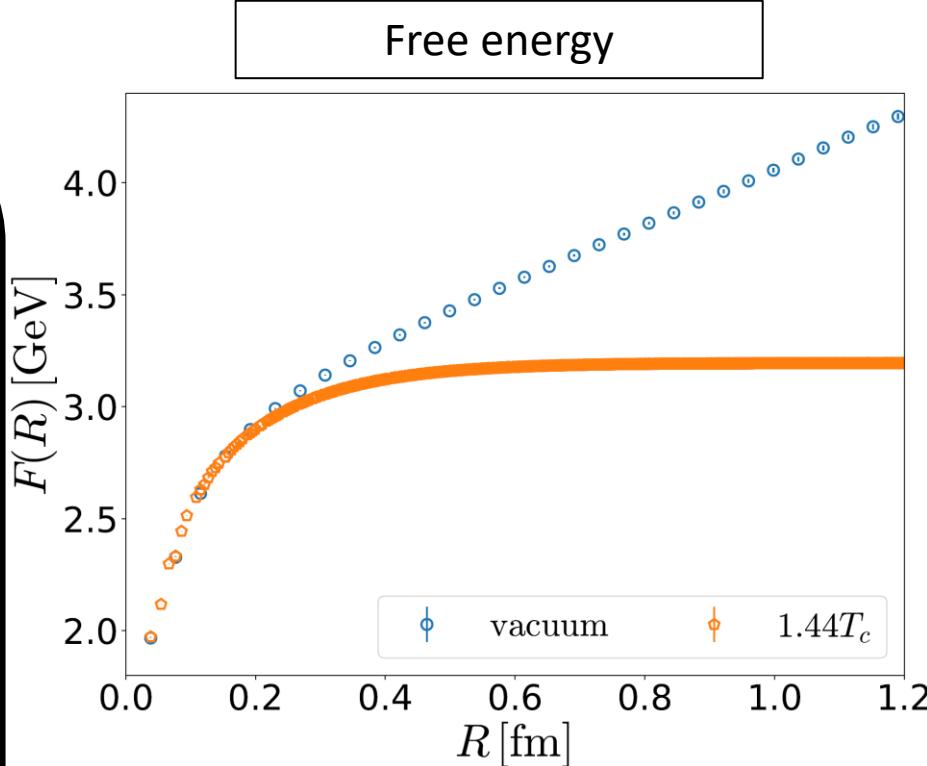
② Measure EMT around Q/\bar{Q}

Polyakov Loop



$$e^{-F(R)/T} = \frac{1}{3} \langle \text{Tr } \Omega^\dagger(\vec{x}) \Omega(\vec{y}) \rangle$$

Color singlet free energy
(eg. Coulomb gauge fixing)



- ✓ quenched SU(3) Yang-Mills
- ✓ $\beta = 6.600$ ($a = 0.038$ fm)

格子上での測定

To do

① Prepare $Q(\bar{Q})$ on the lattice

② Measure EMT around Q/\bar{Q}

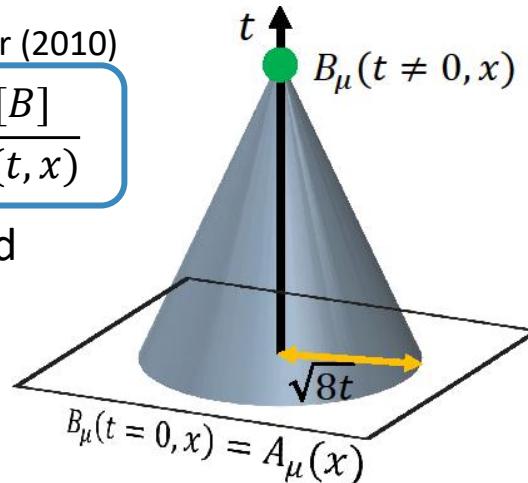
Gradient flow

Flow eq.

Lüscher (2010)

$$\frac{\partial B_\mu(t, x)}{\partial t} = -g_0^2 \frac{\delta S[B]}{\delta B_\mu(t, x)}$$

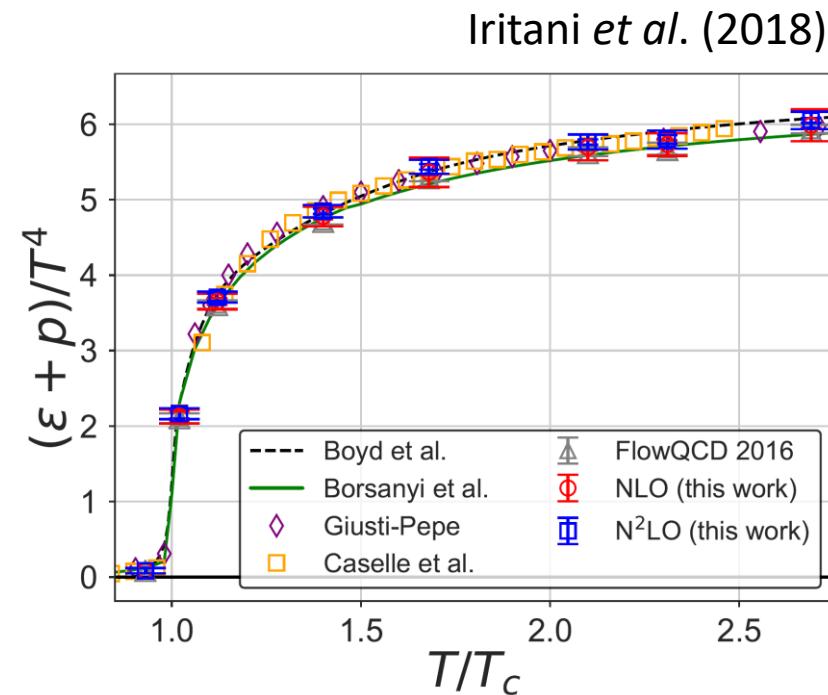
B_μ : smeared field



EMT defined via gradient flow

Suzuki (2013)

$$T_{\mu\nu}(t, x) = \frac{1}{\alpha_U(t)} U_{\mu\nu}(t, x) + \frac{\delta_{\mu\nu}}{4\alpha_E(t)} [E(t, x) - \langle E(t, x) \rangle] + O(t)$$



Entropy density vs. temperature

✓ 2-loop coefficient is now available !

Harlander *et al.* (2018)

セットアップ

- ✓ Quenched SU(3) Yang-Mills gauge theory
- ✓ Wilson gauge action
- ✓ Clover operator
- ✓ 4 temperatures above T_c
- ✓ Multihit improvement in temporal links
- ✓ Simulation using OCTOPUS, Reedbush

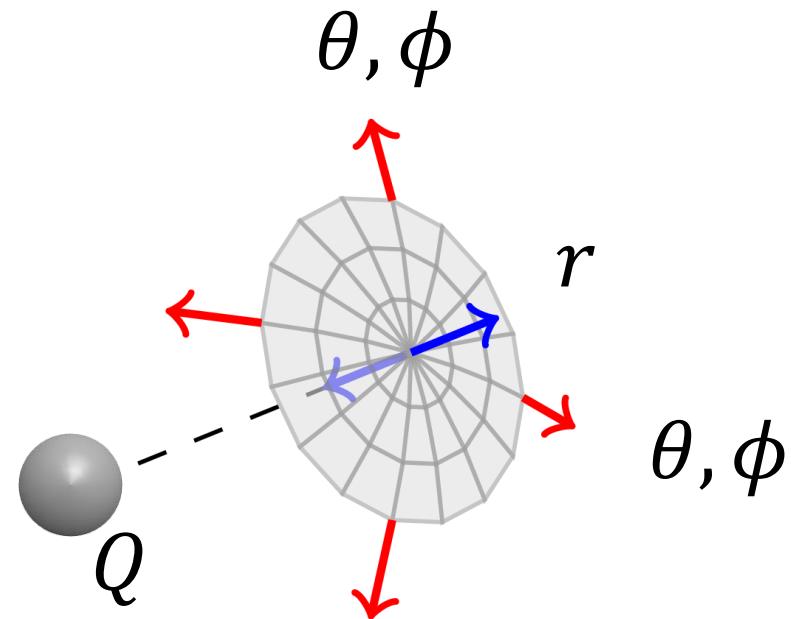
β	Lattice spacing	Spatial size	Temporal size	T/T_c	# of statistics
6.600	0.0384 fm	48^3	12	1.44	650
6.716	0.0329 fm	56^3	14		840
6.819	0.0288 fm	64^3	16		1,000
6.910	0.0256 fm	72^3	18		1,000

球座標系

$$T_{\mu\nu} = \begin{pmatrix} T_{44} & & & \\ & T_{rr} & & \\ & & O & \\ & & & T_{\theta\theta} \end{pmatrix}$$

Diagonalized EMT

(Spherical symmetry)

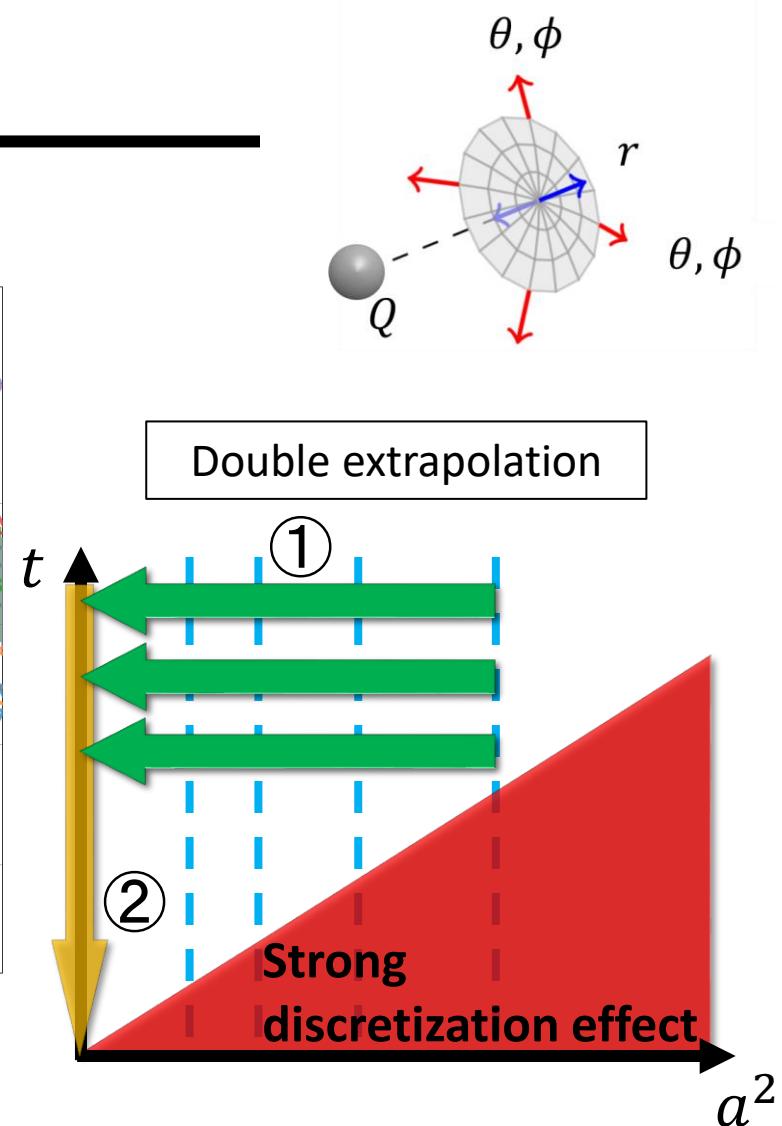
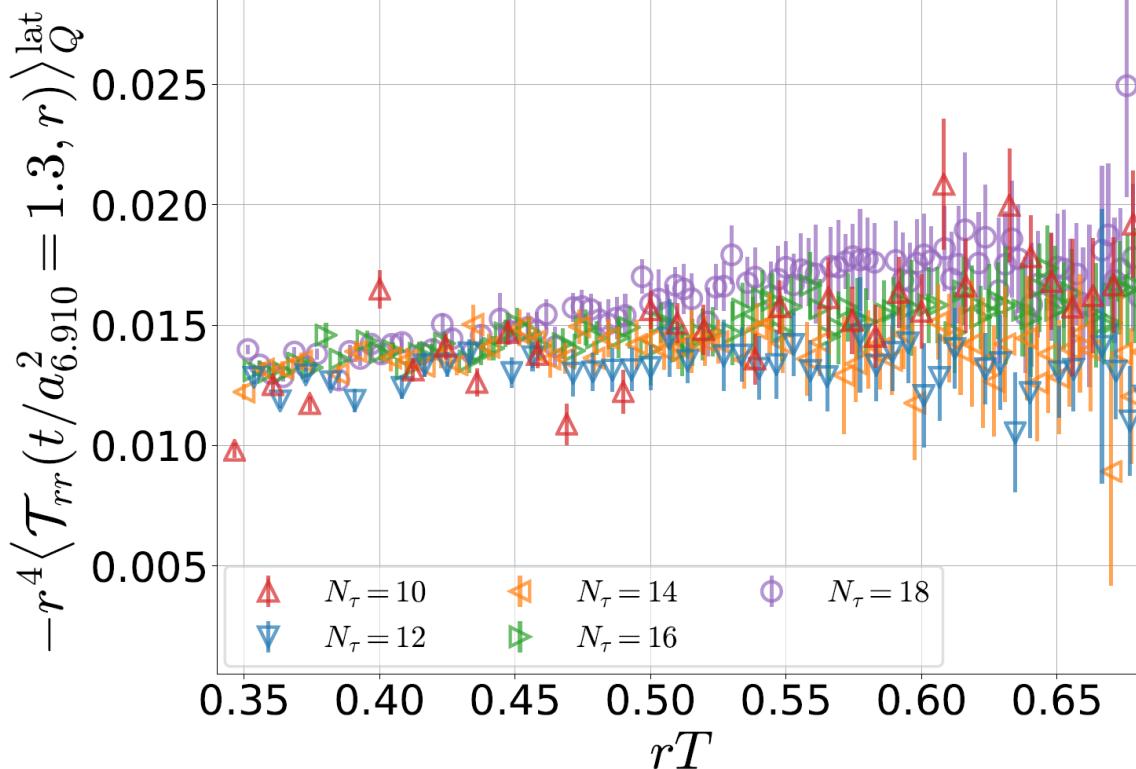


Degeneracy (Maxwell Theory)

$$|T_{44}| = |T_{rr}| = |T_{\theta\theta}|$$

$$(T_{\theta\theta} = T_{\phi\phi})$$

Double extrapolation

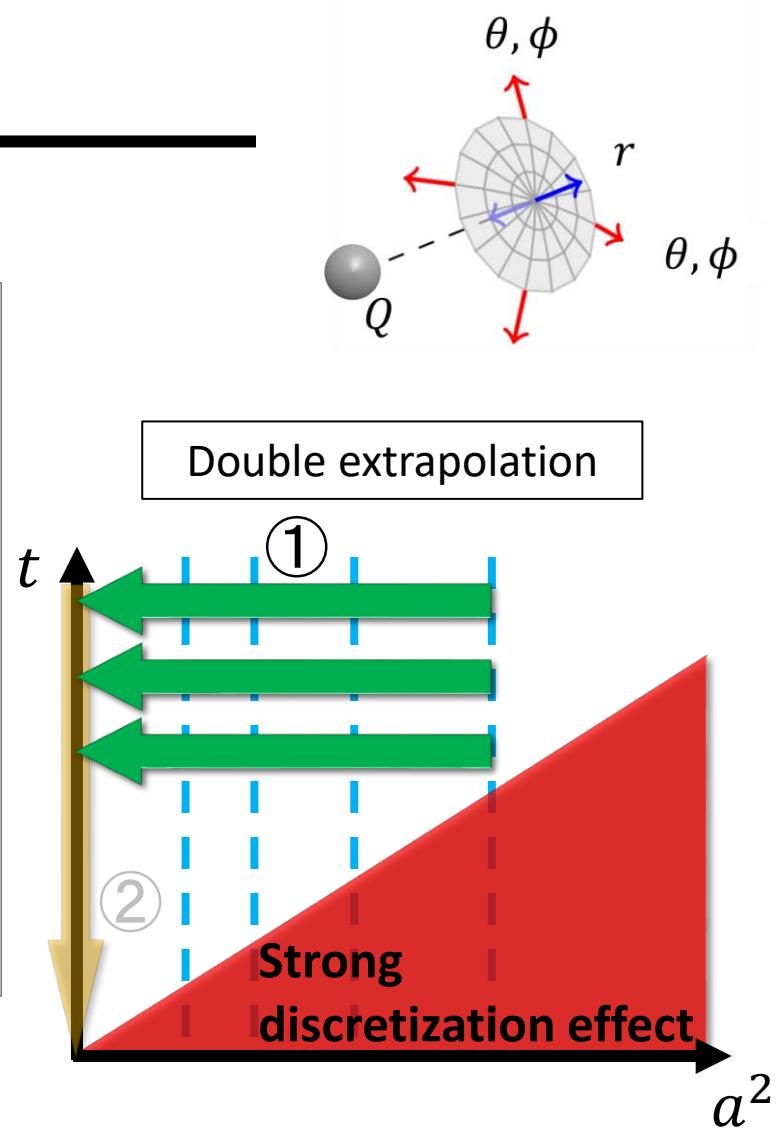
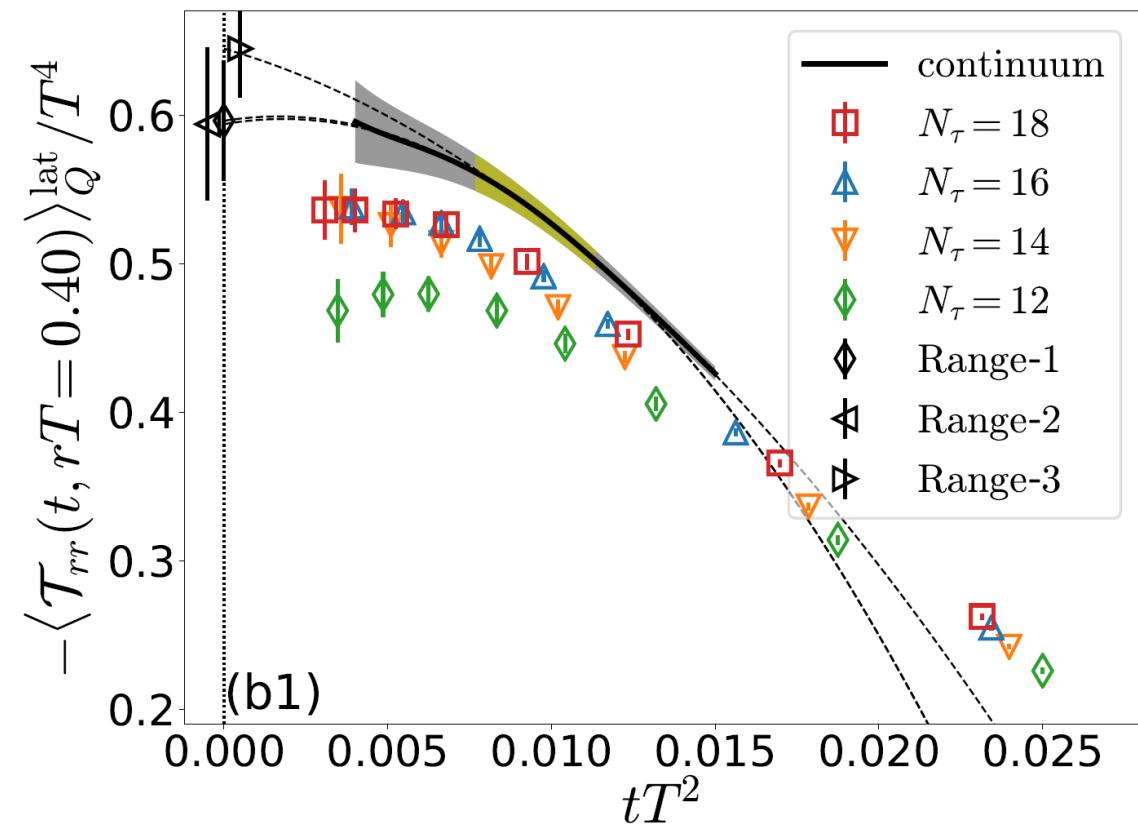


$$O_{\text{cont}} = O_{\text{lat}} + A_1(t)a^2 + A_1 t + A_2 t^2$$

①

②

Double extrapolation @ $rT = 0.40$

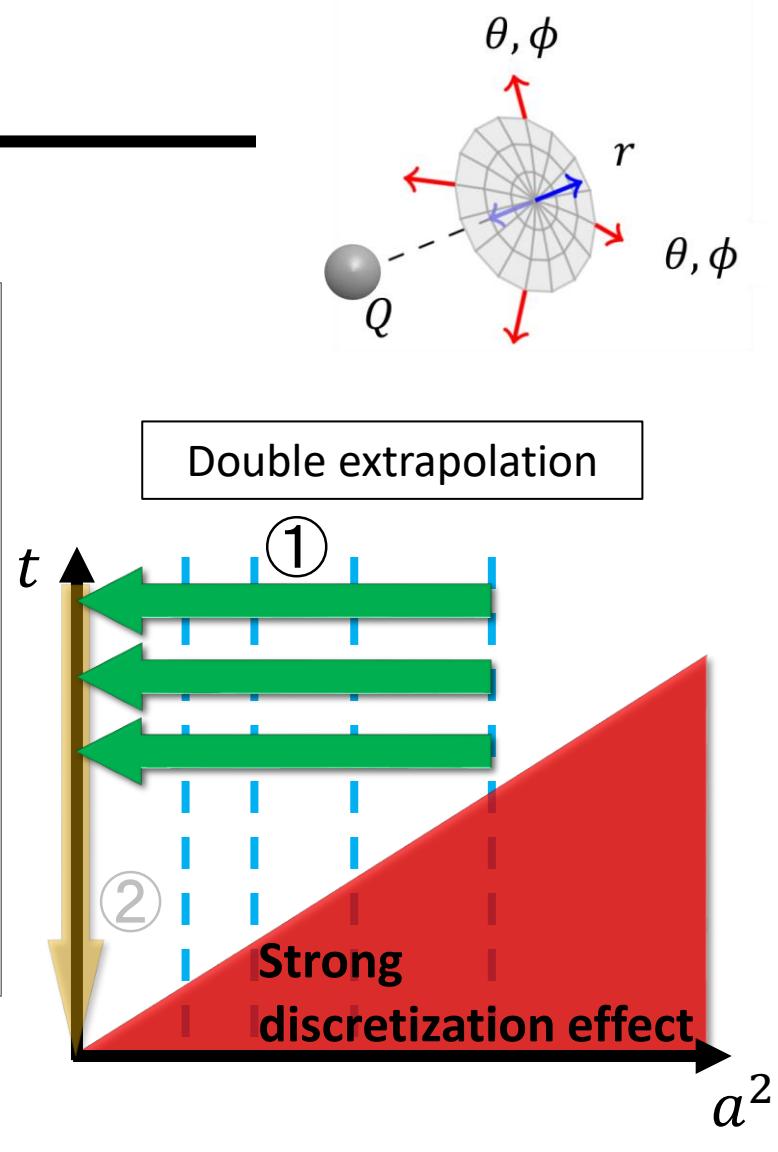
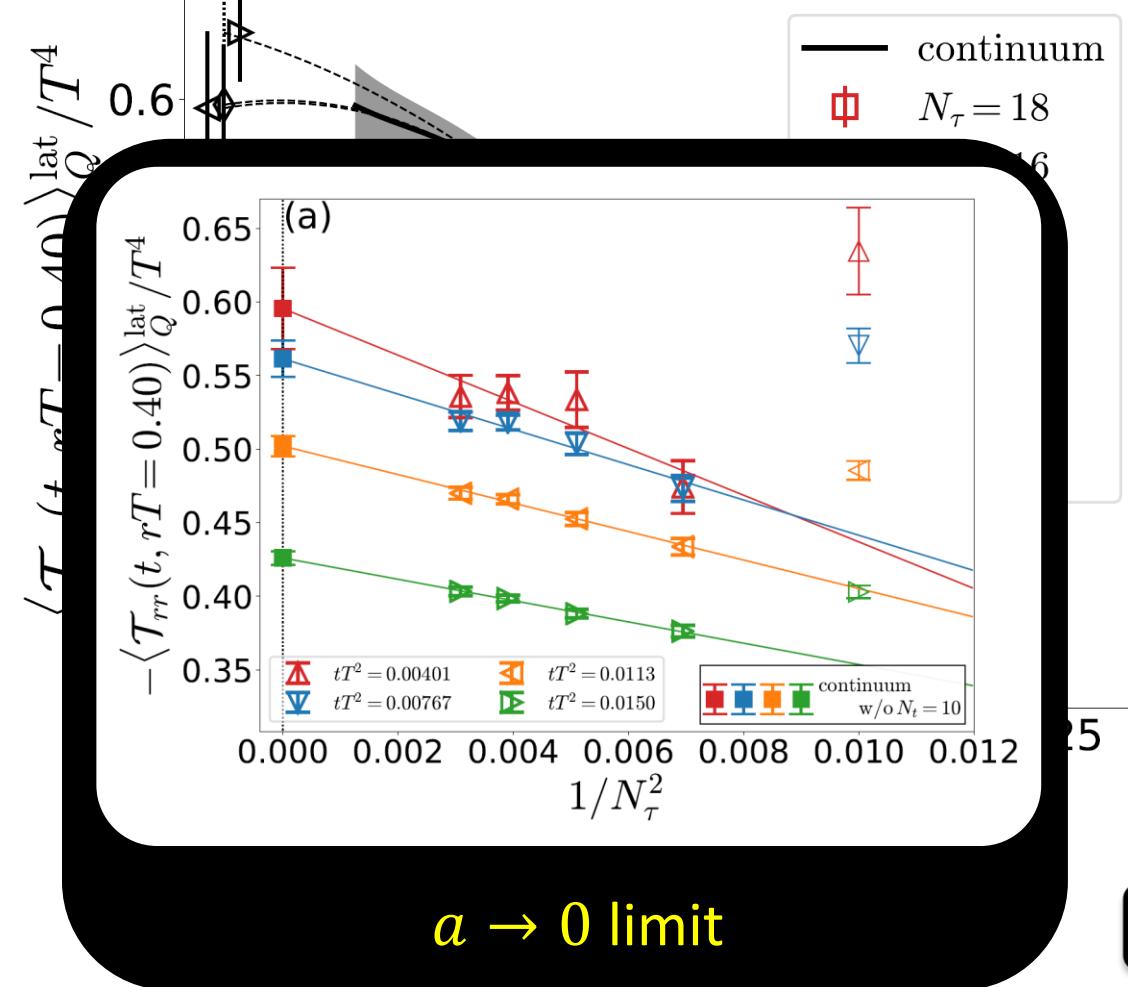


$$O_{\text{cont}} = O_{\text{lat}} + A_1(t)a^2 + A_1t + A_2t^2$$

①

②

Double extrapolation @ $rT = 0.40$

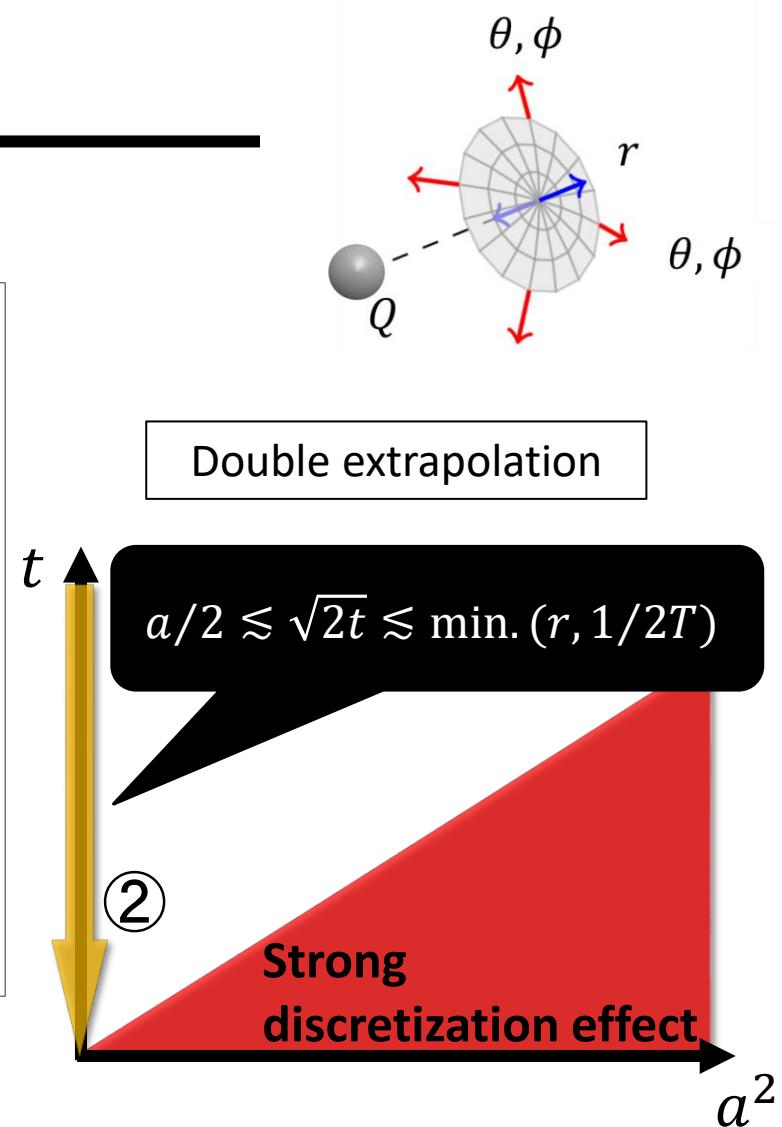
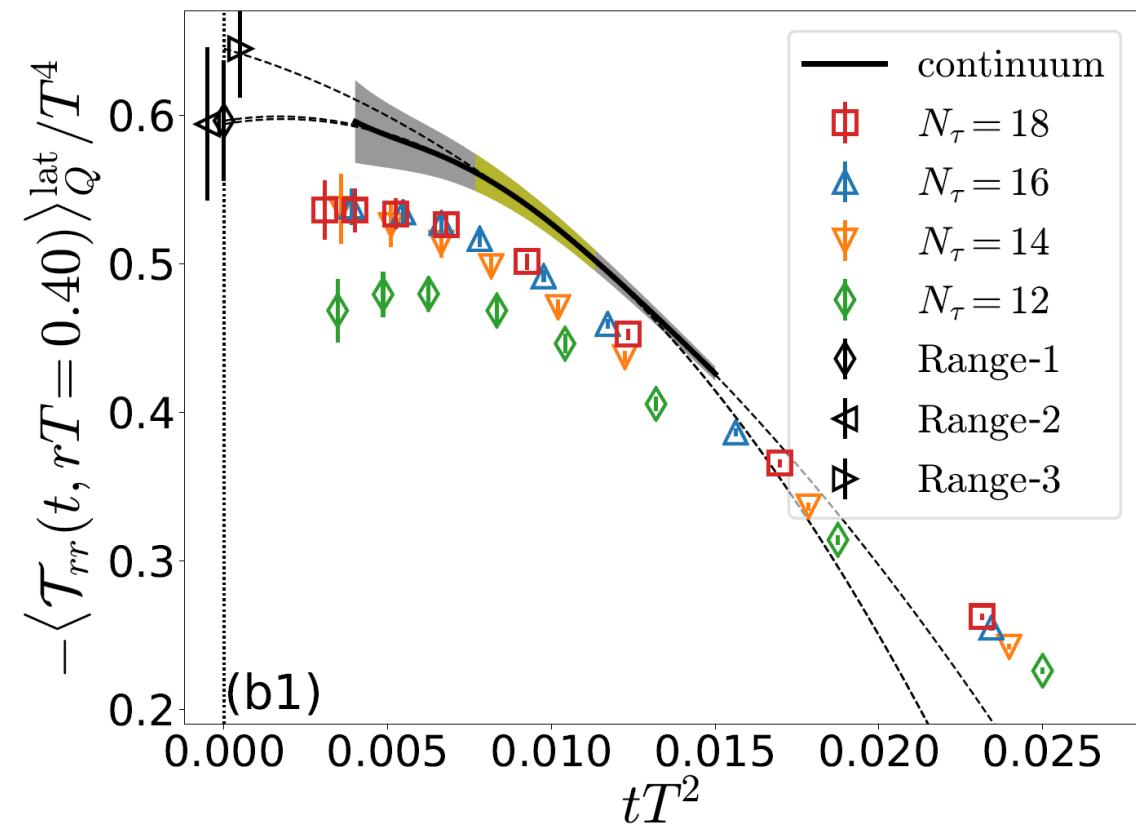


$$O_{\text{cont}} = O_{\text{lat}} + A_1(t)a^2 + A_1t + A_2t^2$$

①

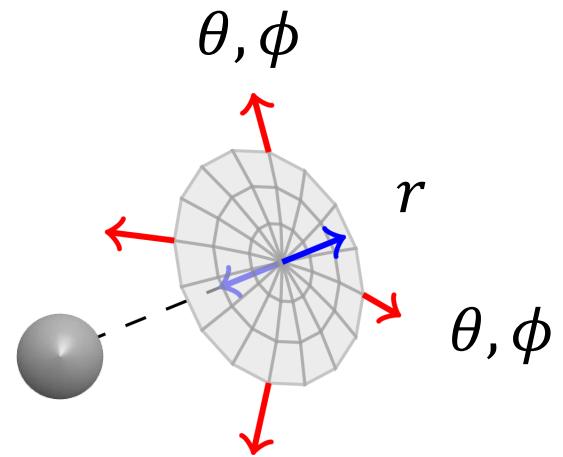
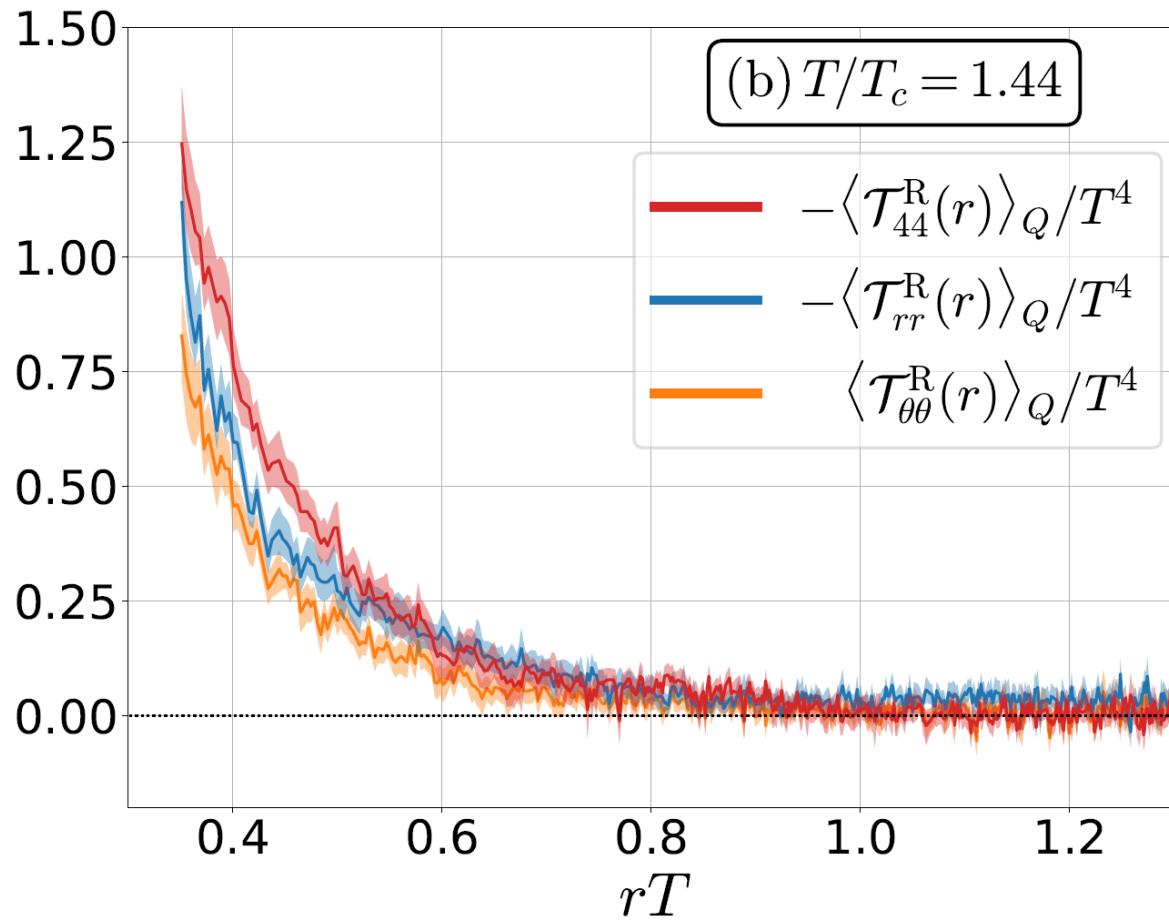
②

Double extrapolation @ $rT = 0.40$



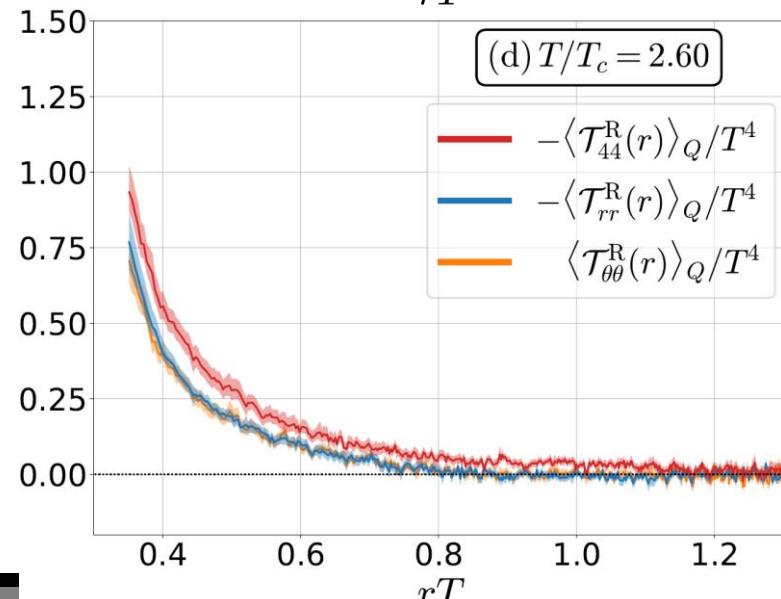
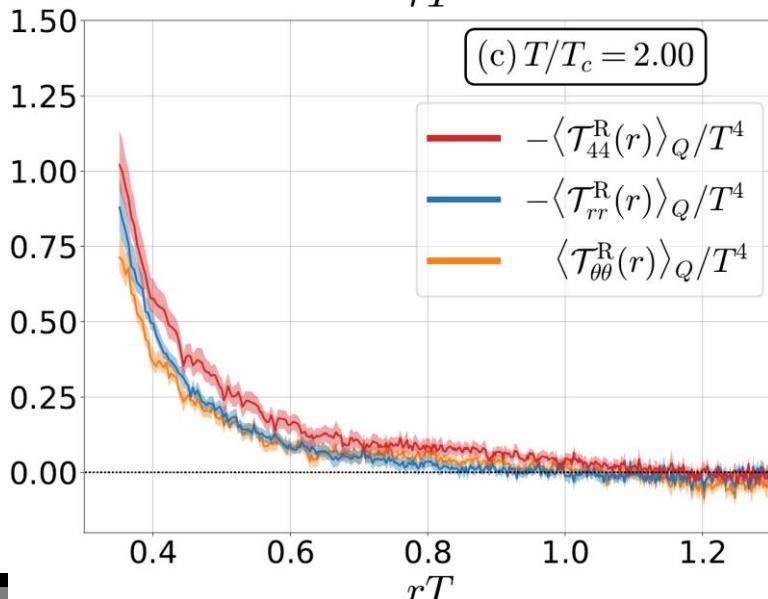
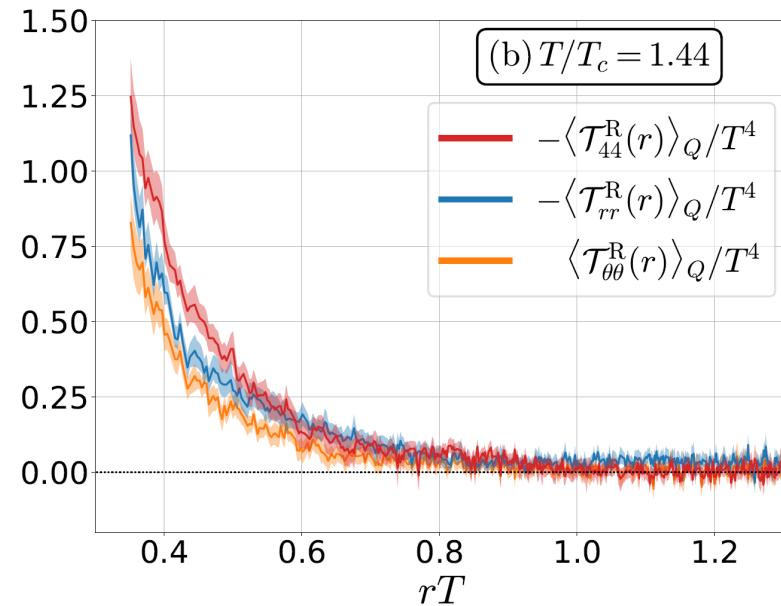
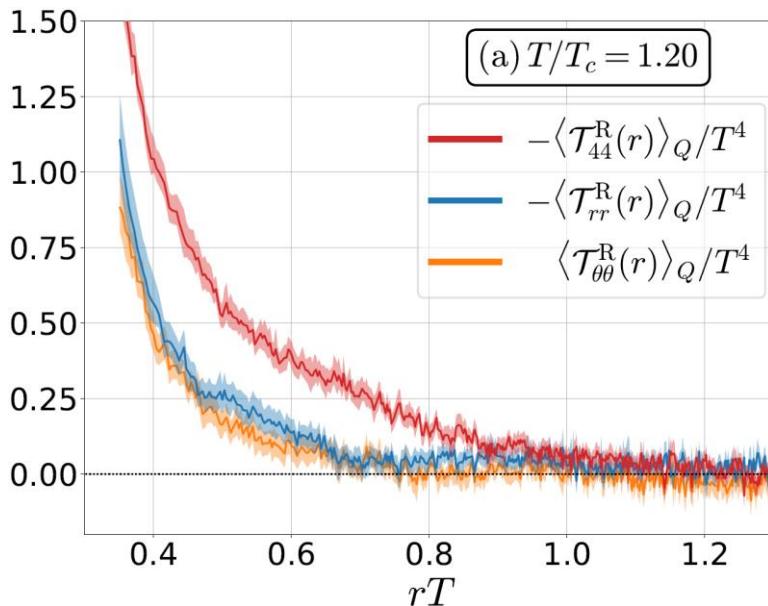
$$O_{\text{cont}} = O_{\text{lat}} + A_1(t)a^2 + A_1t + A_2t^2$$

静的クオーク1体周辺の応力分布

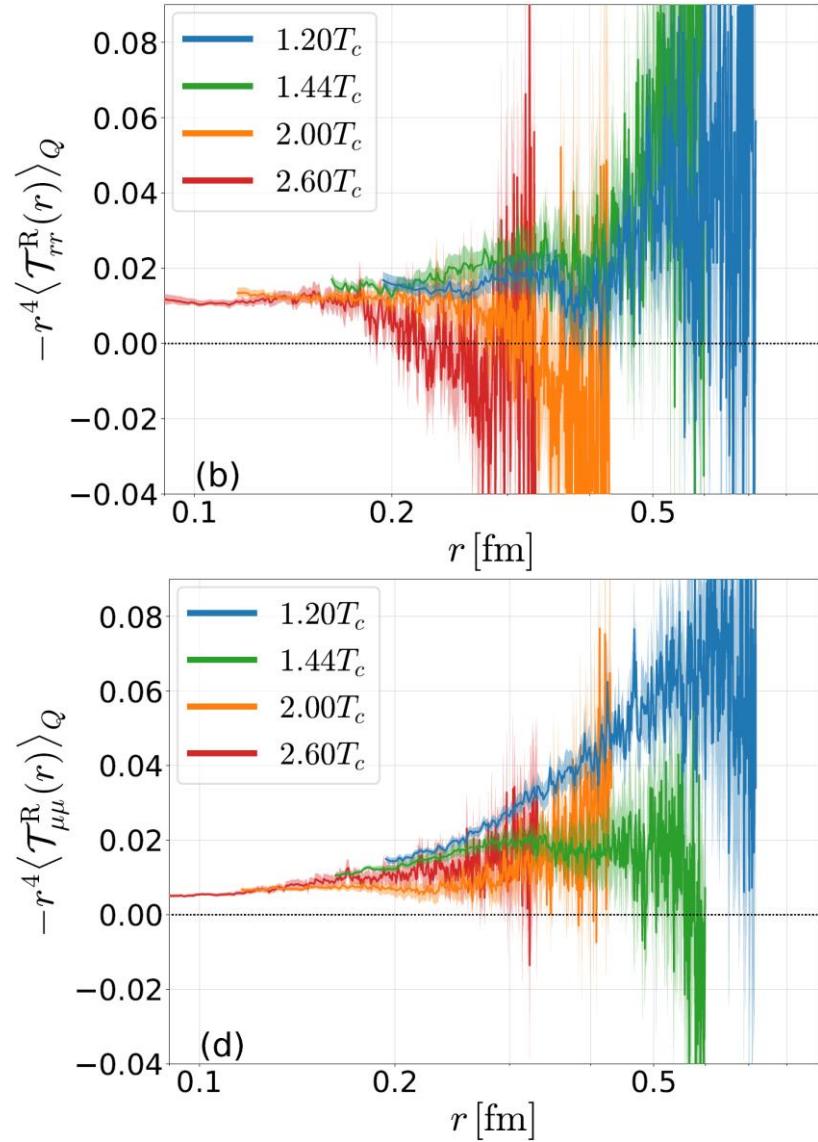
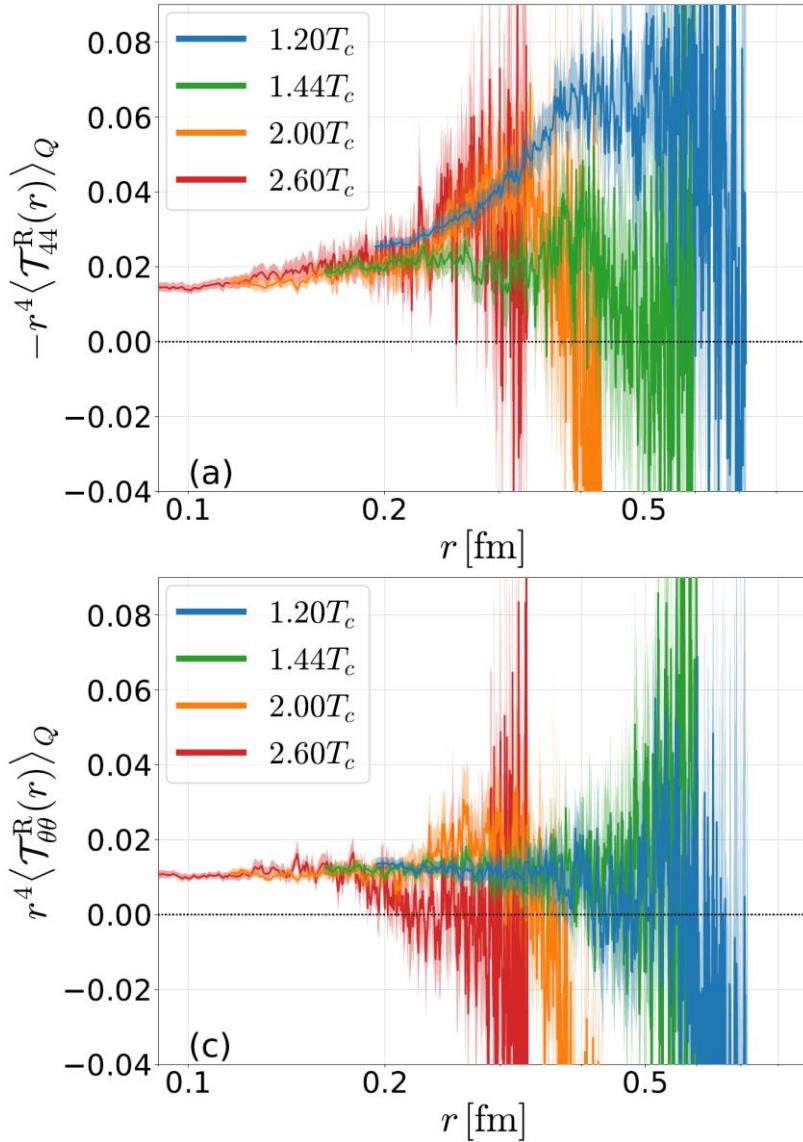


- ✓ Overlap : $r \lesssim \sqrt{2t}$
- ✓ Separation
- ✓ Around origin $\propto \alpha_s(r)/r^4$
- ✓ Damping $\sim e^{-2m_D r}$
- ✓ Conservation law :
$$\partial_r(r^2 T_{rr}) = r T_{\theta\theta}$$

静的クオーク1体周辺の応力分布



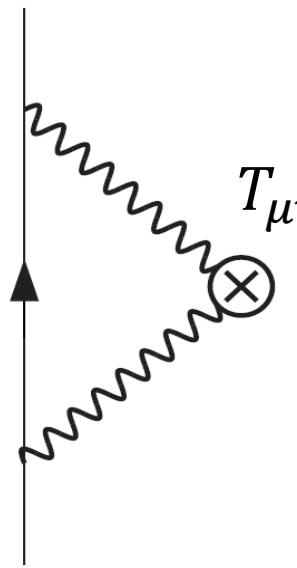
静的クオーク1体周辺の応力分布(温度依存性)



$$T_{\mu\mu} = T_{44} + T_{rr} + 2T_{\theta\theta}$$

摂動計算との比較

エネルギー運動量テンソル (L.O.)


$$T_{\mu\nu} \text{ L. O. } = \frac{C_F \alpha_s}{8\pi} \frac{(m_D r + 1)^2}{r^4} e_E^{-2m_D r} + O(g^4)$$

トレース (L.O.)

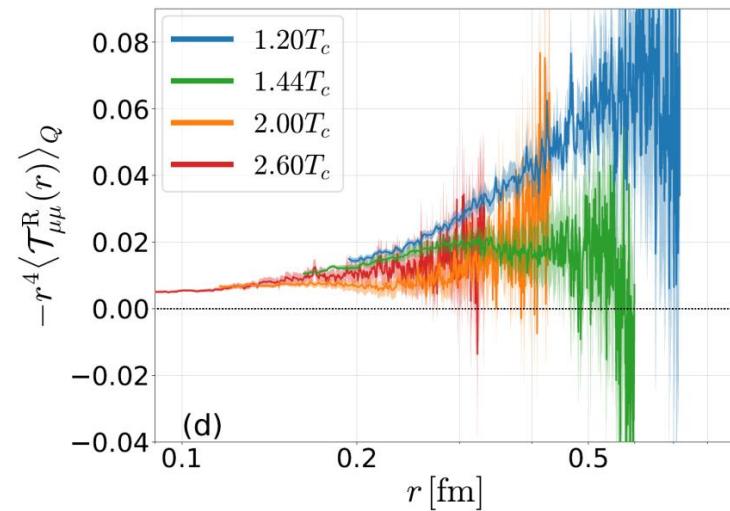
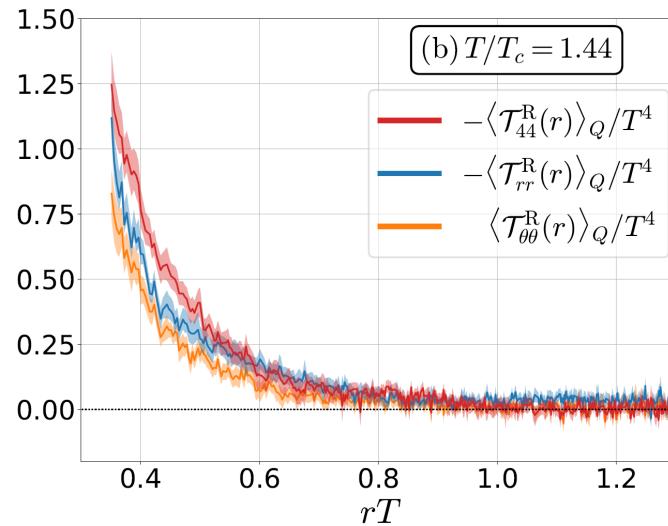
$$-\langle T_{\mu\mu}(r) \rangle_Q = \frac{11}{3} \frac{C_A C_F}{(4\pi)^2} \alpha_s^2 \frac{(m_D r + 1)^2}{r^4} e_E^{-2m_D r} + O(g^6)$$

($T_{\mu\mu} = (\beta/2g) F_{\mu\nu} F_{\mu\nu}$)

まとめと展望

まとめ

- ✓ 有限温度媒質中の静的クオーク周辺の応力分布を格子数値解析に基づいて調べた
- ✓ EMTのchannel間の分離・縮退
- ✓ 摂動論のLOとの比較



展望

- ✓ Coupling constant, Debye mass
- ✓ Application: QQ , QQQ , glueball, hadron (full QCD)...

補足

データセット

T/T_c	N_s	N_τ	β	a [fm]	N_{conf}
1.20	40	10	6.336	0.0551	500
	48	12	6.467	0.0460	650
	56	14	6.581	0.0394	840
	64	16	6.682	0.0344	1,000
	72	18	6.771	0.0306	1,000
1.44	40	10	6.465	0.0461	500
	48	12	6.600	0.0384	650
	56	14	6.716	0.0329	840
	64	16	6.819	0.0288	1,000
	72	18	6.910	0.0256	1,000
2.00	40	10	6.712	0.0331	500
	48	12	6.853	0.0275	650
	56	14	6.973	0.0236	840
	64	16	7.079	0.0207	1,000
	72	18	7.173	0.0184	1,000
2.60	40	10	6.914	0.0255	500
	48	12	7.058	0.0212	650
	56	14	7.182	0.0182	840
	64	16	7.290	0.0159	1,000
	72	18	7.387	0.0141	1,000

格子補正

- ✓ 格子の離散化に由来する回転対称性の破れを補正(特に原点近傍で重要)
- ✓ 格子ゲージ理論に基づくtreeの計算と連続理論におけるtreeの計算から

$$\langle E(t, \vec{x}_n) \rangle_Q^{\text{imp}} = c(t, \vec{x}_n) \langle E(t, \vec{x}_n) \rangle_Q$$

$$\langle U_{\gamma\gamma'}(t, \vec{x}_n) \rangle_Q^{\text{imp}} = c(t, \vec{x}_n) \left\langle U_{\gamma\gamma'}(t, \vec{x}_n) \right\rangle_Q + \left\langle \delta U_{\gamma\gamma'}(t, \vec{x}_n) \right\rangle_Q$$

ただし

$$\left\langle U_{\gamma\gamma'}(t, \vec{x}_n) \right\rangle_Q = \left\langle U_{\gamma\gamma'}(t, \vec{x}_n) \right\rangle_Q + \left\langle \delta U_{\gamma\gamma'}(t, \vec{x}_n) \right\rangle_Q$$

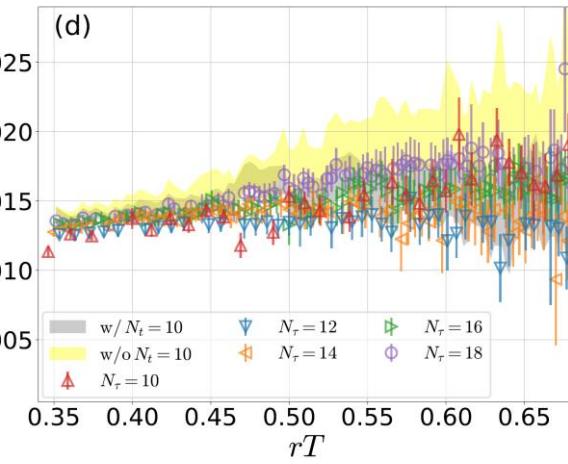
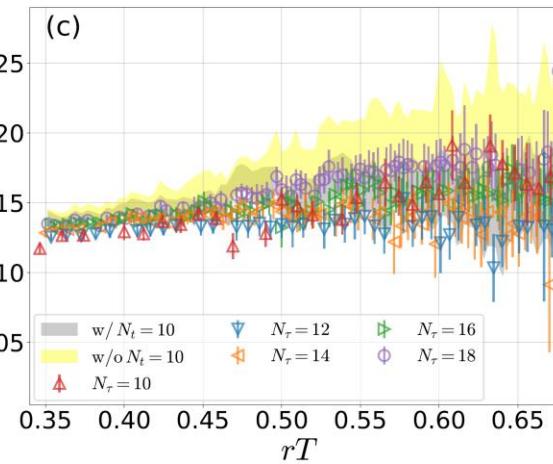
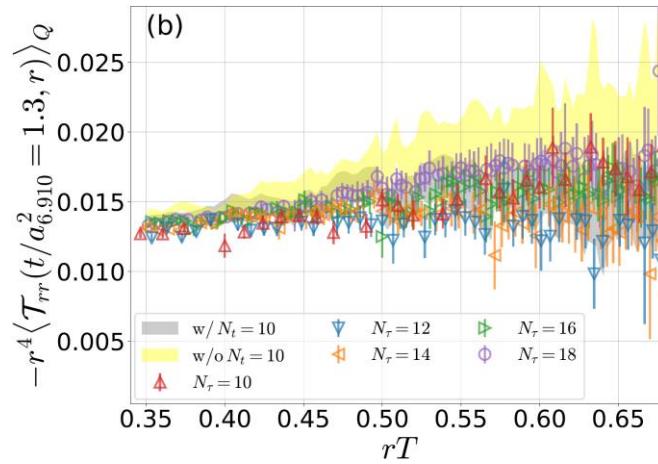
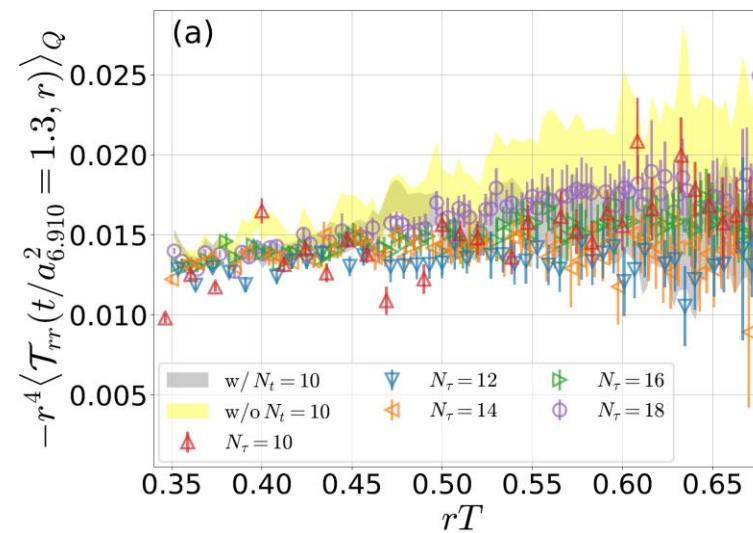
であり、第1項は補正係数のかかるtreeの部分

$$\langle U_{44}(t, \vec{x}_n) \rangle_Q = \langle U_{rr}(t, \vec{x}_n) \rangle_Q = -\langle U_{\theta\theta}(t, \vec{x}_n) \rangle_Q$$

一方の第2項は格子データから縮退部分を除いた残り

- ✓ 今回は $\langle E(t, \vec{x}_n) \rangle_Q = \langle E(t, \vec{x}_n) \rangle_Q^{\text{lat}}$ で、 $\left\langle U_{\gamma\gamma'}(t, \vec{x}_n) \right\rangle_Q = \langle U_{44}(t, \vec{x}_n) \rangle_Q^{\text{lat}}$,
 $\langle U_{rr}(t, \vec{x}_n) \rangle_Q^{\text{lat}}, -\langle U_{\theta\theta}(t, \vec{x}_n) \rangle_Q^{\text{lat}}$ の3種類を考える

格子補正



格子補正による連続極限への影響

