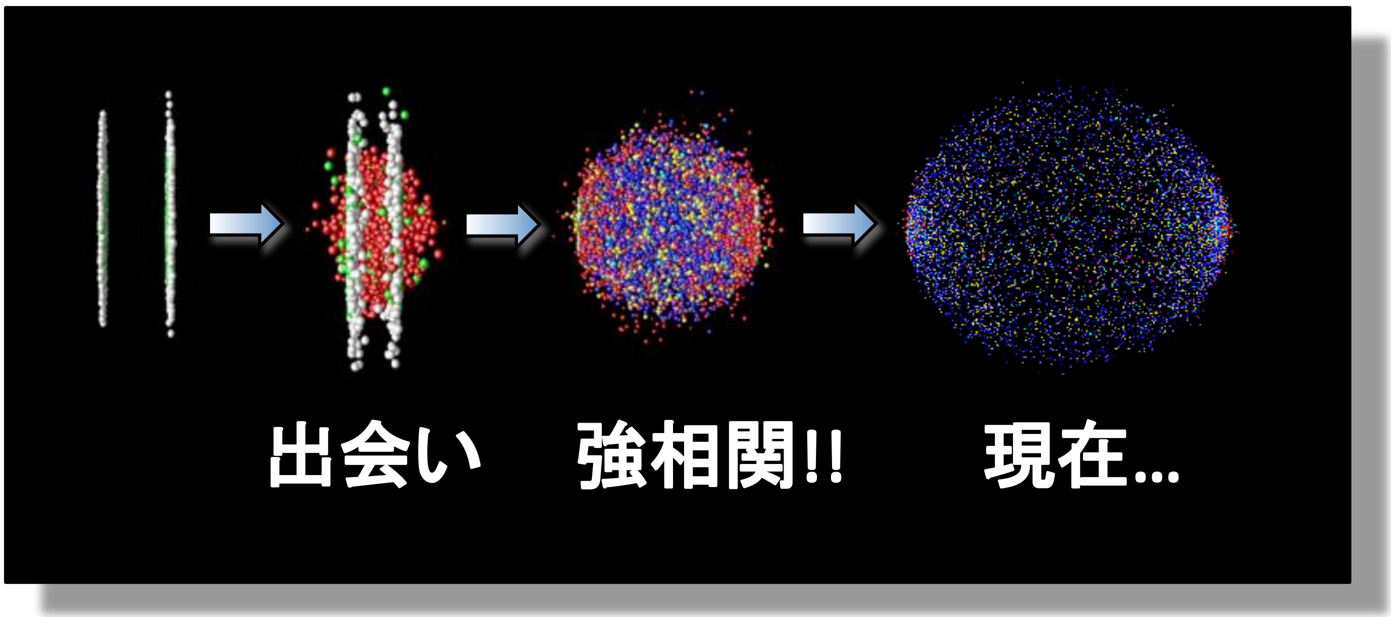
相関関数からみた クォーク・グルーオン・プラズマ: 金谷さんとの強相関

前澤 祐 (YITP)



有限温度密度系の物理と格子QCDシミュレーション、2015年9月5日

小生の研究生活と金谷さん

2003年4月 東大院・初田研

2003年 ペンタクウォーク発見 ➡ 修論:マルチクウォーク模型

2004年 江尻さん: 初田研助教

D1: Lattice QCDゼミ: Creutz, Ukawa…

2005年4月 RHICで完全流体

D1: 2005年8月27日（土） 江尻さんとともに金谷さんを訪問

2004--5年 浮田さん、石井さん: 初田研PD

2005年秋 WHOT-QCD発足
メンバー: 青木慎也, 江尻信司, 初田哲男, 石井理修,
金谷和至, 谷口裕介, 前澤祐, 浮田尚哉

・・・・・・・・・・ Talk @ LATTICE2006 July in Arizona

D3: 2008年3月博士論文
Polyakov loop correlations in quark-gluon plasma
from lattice QCD simulations

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Free energy at finite T and μ

PRD75(2007)074501

PRD82(2010)014508

PTP128(2012)955

Electric and magnetic screening masses

PRD81(2010)091501(R)

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クォーク間自由エネルギー

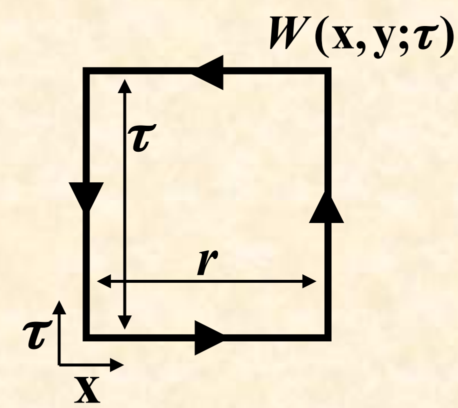
静的なクォーク間相互作用を特徴付けるためには・・・

$\boxed{T = 0}$ 静的なクォーク間ポテンシャル Brown and Weisberger (1979)

⇨ ウィルソン・ループ演算子

$$V(r) = -\lim_{\tau\to\infty}\left[\tau^{-1}\ln\langle W(\mathrm{x},\mathrm{y};\tau)\rangle\right]$$

$$= -\frac{\alpha}{r} + \sigma r$$



$\boxed{T > 0}$ 静的なクォーク間自由エネルギー Nadkarni (1986)

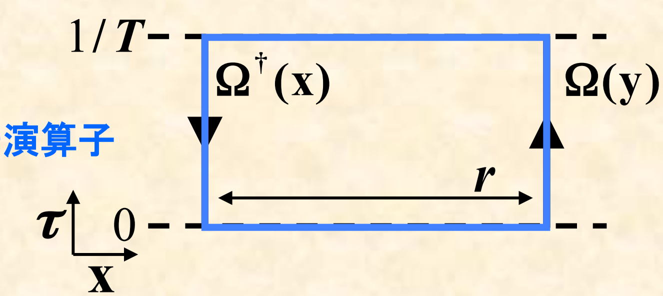
⇨ 有限温度下でのクォーク間ポテンシャルの候補

ポリヤコフ線 $\Omega(\mathrm{x}) = \prod_{\tau=1}^{N_t} U_4(\mathrm{x},\tau)$: 位置 x にある静的なクォーク

クーロンゲージにおけるカラー1重項に射影されたポリヤコフ線間の相関関数

$$\Rightarrow F^1(r,T) = -T\ln\langle \underline{\mathrm{Tr}\Omega^\dagger(\mathrm{x})\Omega(\mathrm{y})}\rangle$$

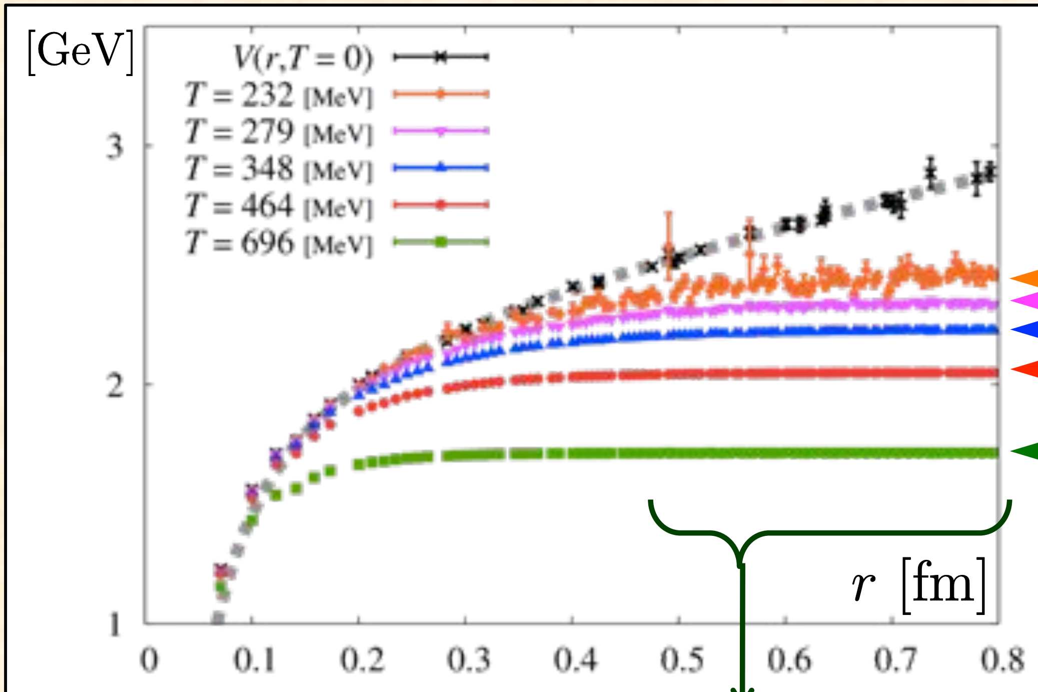
有限温度下でウィルソン・ループと類似の演算子

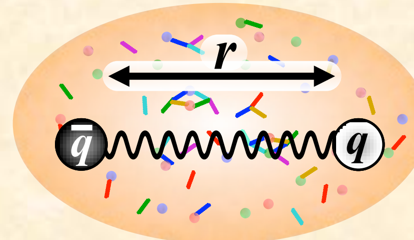


期待されるクォーク間自由エネルギーの振舞い:

- 短距離 r : $F^1(r,T) \sim V(r)$ (媒質の影響をうけないため) ⇨ ウィルソンループとの整合性
- 中距離 r : プラズマによる遮蔽効果
- 遠距離 r : 相互作用のないクォーク単一の自由エネルギー

$T>0$でのクォーク間ポテンシャル(自由エネルギー)





$2F_Q(T)$
= 2 x
(クォーク単一の自由エネルギー)

遠距離領域

$F^1(r,T)$ は平らになり、線形項は現れない ⇒ 熱媒質の効果により閉じ込めが消失

遠距離でポリヤコフ線間の相関が消失する場合

$$F^1(r,T) = -T\ln\langle \mathrm{Tr}\Omega^\dagger(\mathbf{x})\Omega(\mathbf{y})\rangle \xrightarrow{r\to\infty} -T\langle \mathrm{Tr}\Omega\rangle^2 = 2F_Q(T)$$

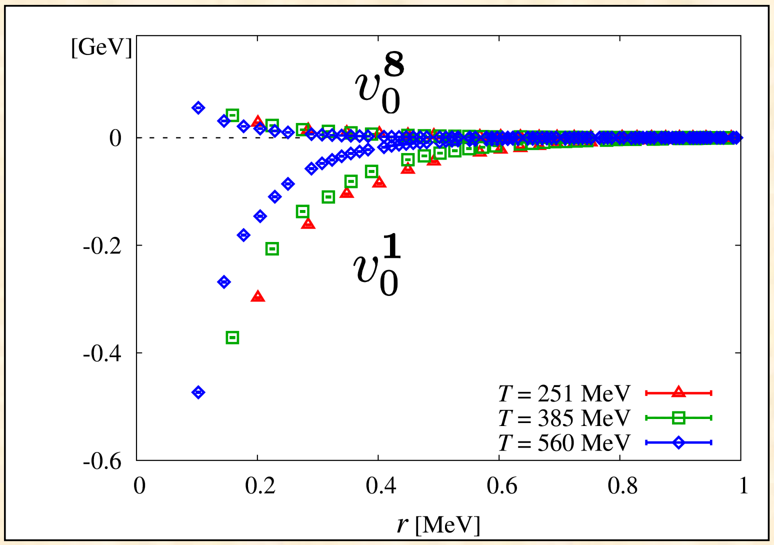
⇒ 遠距離でF^1 は 2 x(クォーク単一の自由エネルギー)に収束する

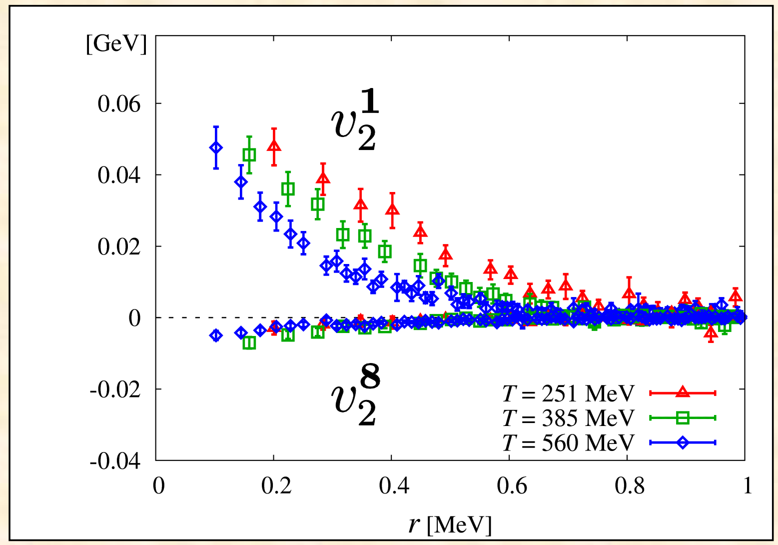
クォーク間自由エネルギー

$Q\bar{Q}$ ポテンシャル

$N_f = 2,\ 16^3 \times 4,\ m_\pi / m_\rho = 0.80,\ T_{pc} \sim 186\,\mathrm{MeV}$

$$V^{Q\bar{Q}}(r,T,\mu_q) = v_0(r,T) + v_2(r,T)\left(\frac{\mu_q}{T}\right)^2 + O(\mu^3)$$





カラー 1_c 重項: 引力

カラー 8_c 重項: 斥力

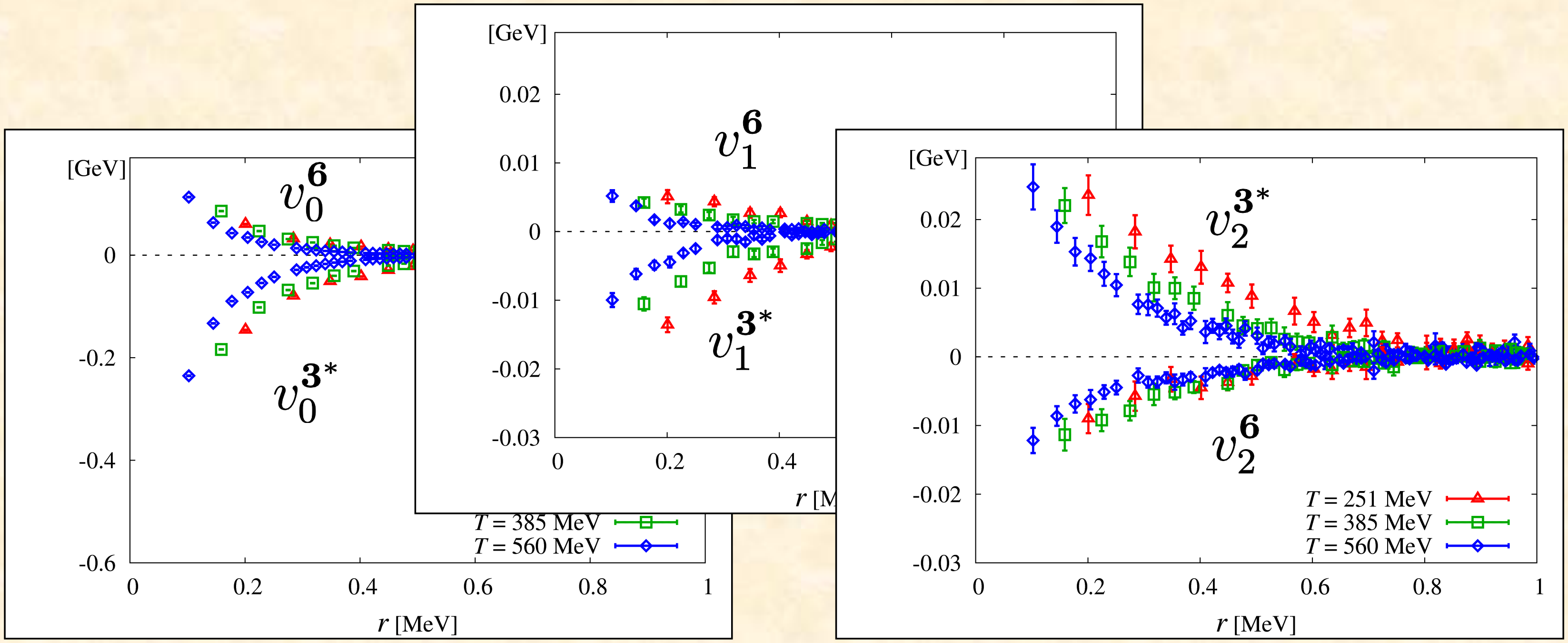
$$v_2 \times v_0 < 0$$

$0 < \mu_q/T << 1$ において

$V^{Q\bar{Q}}(r,T,\mu_q)$ は弱まる

QQ ポテンシャル

$$V^{QQ}(r,T,\mu_q) = v_0(r,T) + v_1(r,T)\left(\frac{\mu_q}{T}\right) + v_2(r,T)\left(\frac{\mu_q}{T}\right)^2 + O(\mu^3)$$



カラー 3^*_c 重項: 引力

カラー 6_c 重項: 斥力

$$v_1 \times v_0 > 0, \quad v_2 \times v_0 < 0$$

$0 < \mu_q/T << 1$ において

$V^{QQ}(r,T,\mu_q)$ は**強まる**

小生の研究生活と金谷さん

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<u>Free energy at finite T and μ</u>

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小生の計算: グルーオンの空間相関

Free energy at finite T and μ

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A. Bazavov,[1] H.-T. Ding,[1,2] P. Hegde,[3] O. Kaczmarek,[4] F. Karsch,[1,4] E. Laermann,[4] Y. Maezawa,[1] Swagato Mukherjee,[1] H. Ohno,[4] P. Petreczky,[1] C. Schmidt,[4] S. Sharma,[4] W. Soeldner,[5] and M. Wagner[4]

[1]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*Physics Department, Columbia University, New York, New York 10027, USA*
[3]*Department of Physics R518, High Energy Physics Lab, National Taiwan University, Taipei 10617, Taiwan*
[4]*Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany*
[5]*Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*

2011年10月 BNL, 2013年10月 Bielefeld

BNL-Bielefeld-CCNU Coll. ∈ HotQCD Coll.

小生の計算: 中間子の空間相関

2015年4月 YITPへ...

格子QCDによる
空間相関から迫る
中間子熱変化と壊れた対称性の回復

前澤 祐 (YITP, Kyoto University)

in collaboration with

Frithjof Karsch (Universität Bielefeld, Brookhaven National Lab.)
Swagato Mukherjee (Brookhaven National Lab.)
Peter Petreczky (Brookhaven National Lab.)

Introduction

Thermal fluctuation in QCD

Modifications of hadrons

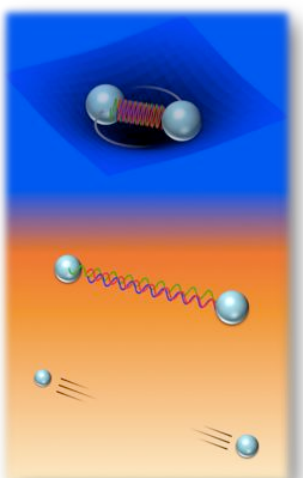
sequential melting pattern
of **quarkonium** and
open-flavor mesons
e.g. J/ψ suppression

Matsui and Satz (1986)

Restorations of broken symmetries

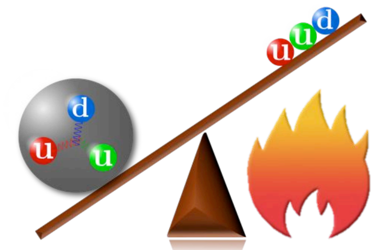
restored pattern
of **chiral** and $\mathrm{U_A(1)}$ symmetries
the nature of phase transition

Pisarski and Wilczek (1984)

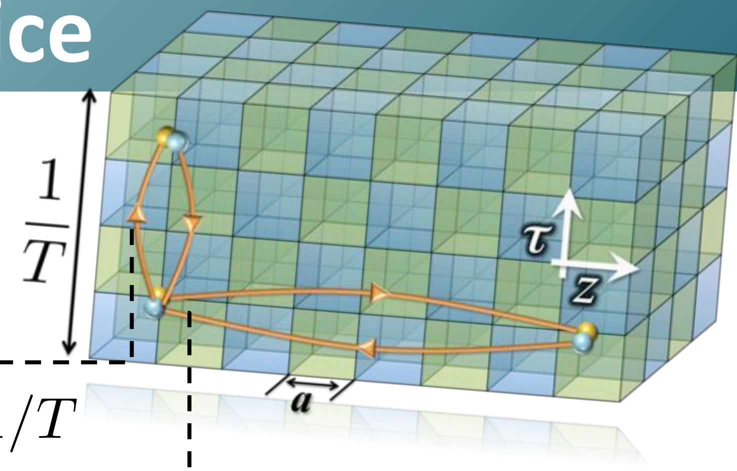


Theoretical understanding in lattice QCD simulations
from spatial correlation functions

Previous: strange-charm PRD91 (2015) 5, 054503
This work: **including up/down at widely *T* range**



Hadronic excitation on Lattice



Temporal correlation function:

$$G^T(\tau, T) = \int d^3x \langle J_H^\dagger(0, \mathbf{0}) J_H(\tau, \mathbf{x}) \rangle \xrightarrow{\tau \to \infty} A e^{-m_0 \tau}$$

...difficult due to the limitation $\tau < 1/T$

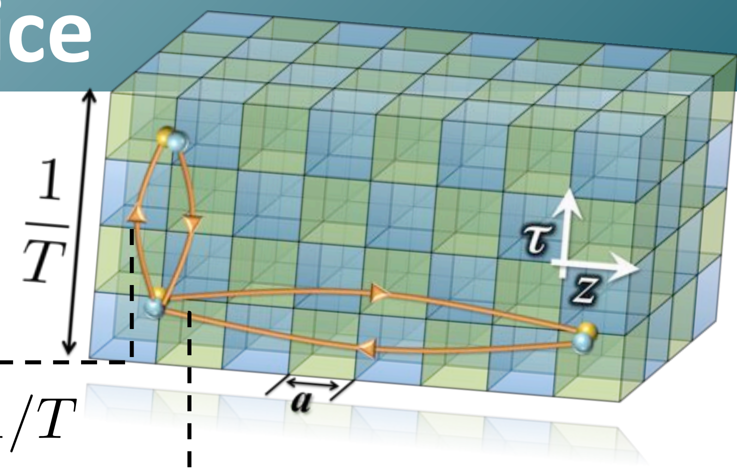
Spatial correlation function:

$$G^S(z, T) = \int_0^{1/T} d\tau \int dx dy \langle J_H^\dagger(0, \mathbf{0}) J_H(\tau, \mathbf{x}) \rangle \xrightarrow{z \to \infty} A e^{-M(T) z}$$

$M(T)$: screening mass

No limitation to spatial direction: more sensitive to in-medium modification

Hadronic excitation on Lattice



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Spectral function

$$G^T(\tau, T) = \int_0^\infty d\omega \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \sigma(\omega, T)$$

e.g.) reconstruction of σ: MEM

$$G^S(z, T) = \int_0^\infty \frac{2d\omega}{\omega} \int_{-\infty}^\infty dp_z e^{ip_z z} \sigma(\omega, p_z, T)$$

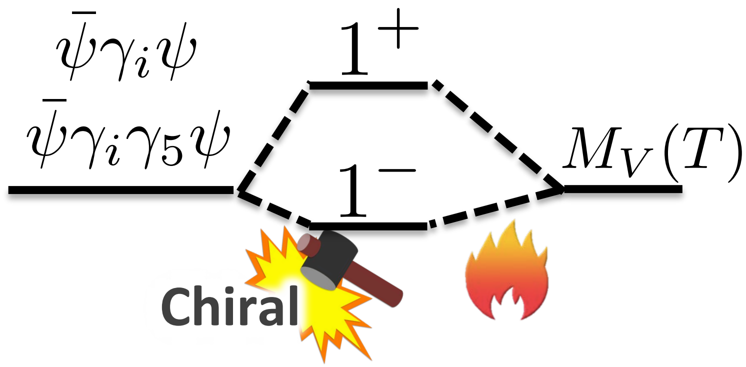
No T dependence in Kernel: direct probe of thermal modification of σ

$$G^S(z, T)/G^S(z, T=0)$$

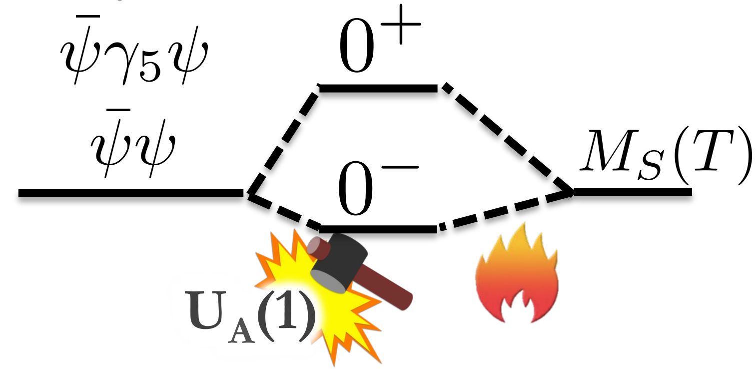
Hadronic excitation on Lattice

Parity partner of meson states

Vector (vector and axial-vector)



Scalar (pseudo-scalar and scalar)



➡ Degeneracy of parity partners: indicator of symmetry restorations

Hadronic excitation on Lattice

Parity partner of meson states

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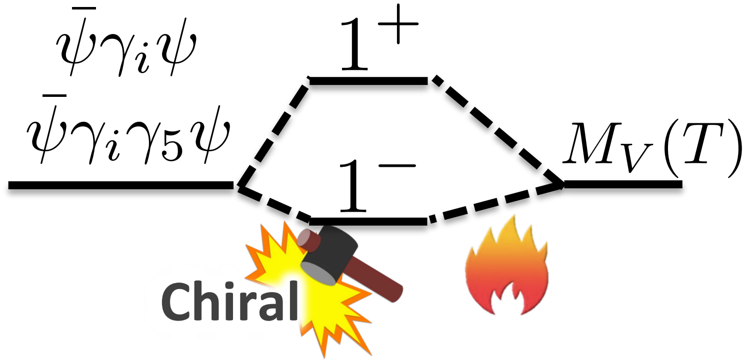

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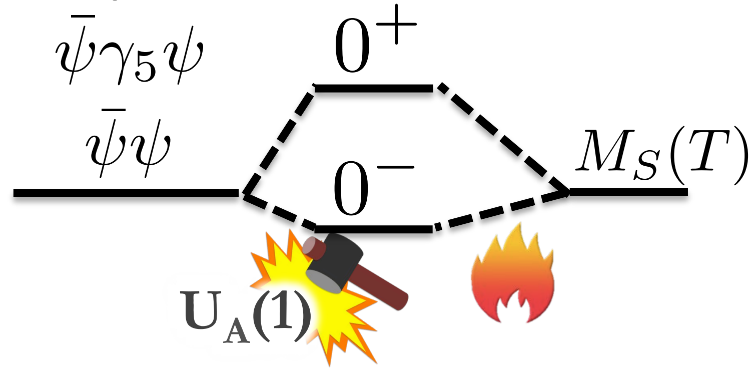


→ Degeneracy of parity partners: indicator of symmetry restorations

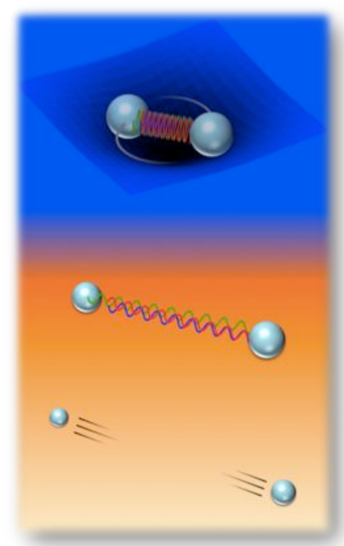
Behavior in limiting cases:

At low T, bound state: $M(T) \sim m_0$ pole mass at $T=0$

$$\sigma(\omega, 0, 0, p_z, T) \sim \delta(\omega^2 - p_z^2 - m_0^2)$$

At $T \sim T_c$, in-medium modification and/or dissolution
degeneracy of parity partner states

At $T \to \infty$, free quark-antiquark pair: $M \to 2\sqrt{m_q^2 + (\pi T)^2}$
with the lowest Matsubara frequency



Lattice simulations

- Setup in HISQ
- Modifications of Mesons
- Restorations of broken symmetries

Highly Improved Staggered Quarks

Reduction of taste violation
Control of cutoff effects

Bazavov et al. `11, Hot-QCD `11, `14

Lattice parameters

- 2+1 flavor QCD (charm quenched)
- m_s: physical, $m_l/m_s = 1/20$ (m_π~160 MeV, m_K~504 MeV)
- $N_\tau = 8$ ($T = 110$—207 MeV)
  10 ($T = 139$—166 MeV)
  12 ($T = 149$—400 MeV)
  keeping $N_s/N_\tau=4$
- 32^4--48^3x64 at $T = 0$
- scale: f_k input
- calculating quark-line connected part of meson correlators

Mesons contents

Γ	J^P	$u\bar{d}$	$u\bar{s}$	$u\bar{c}$	$s\bar{s}$	$s\bar{c}$	$c\bar{c}$
γ_5	0^-	π	K	D	$(\eta_{s\bar{s}})$	D_s	η_c
1	0^+	–	K_0^*	D_0^*	–	D_{s0}^*	χ_{c0}
γ_i	1^-	ρ	K^*	D^*	ϕ	D_s^*	J/ψ
$\gamma_i\gamma_5$	1^+	–	K_1	D_1	$f_1(1420)$	D_{s1}	χ_{c1}

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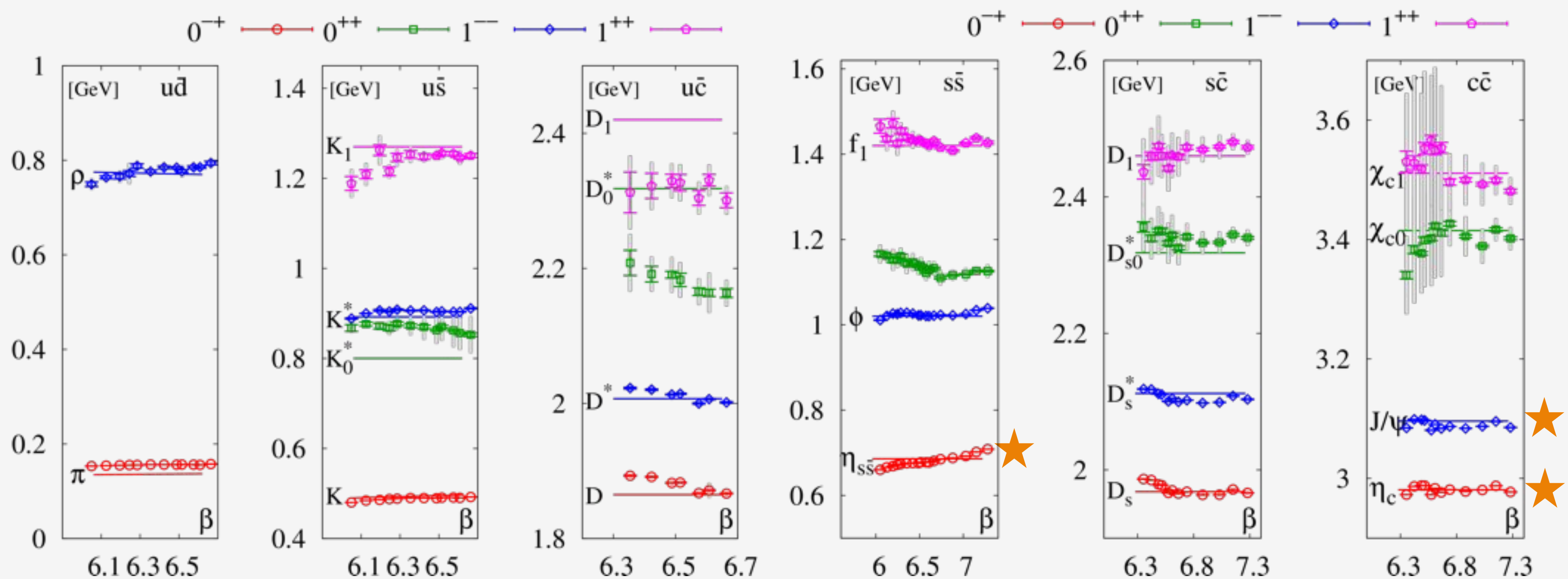
γ_i	1^-	ρ	K^*	D^*	ϕ	D_s^*	J/ψ
$\gamma_i\gamma_5$	1^+	–	K_1	D_1	$f_1(1420)$	D_{s1}	χ_{c1}

Meson spectra at T = 0 (input: ★)



Ratio of spatial correlation functions

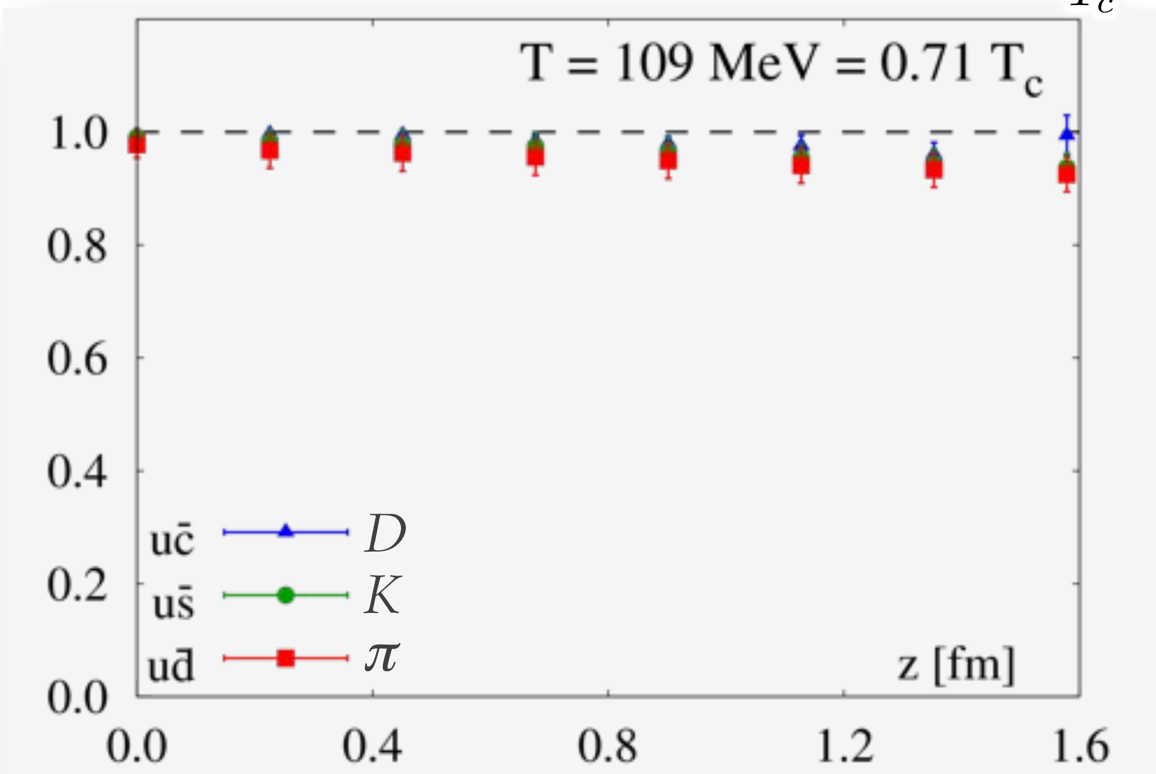
Probe of thermal modifications of spectral function

$G^S(z,T)/G^S(z,T=0) \simeq 1$ the same σ at $T=0$, or $\neq 1$ modified

$T_c = (154 \pm 9)$ MeV

Pseudo-scalar

$J^P = 0^-$



- $G^S(z,T)/G^S(z,0) \simeq 1$ at short distance ➡ physics: not sensitive to T
- $G^S(z,T)/G^S(z,0) \neq 1$ at large distance ➡ thermal modification of σ

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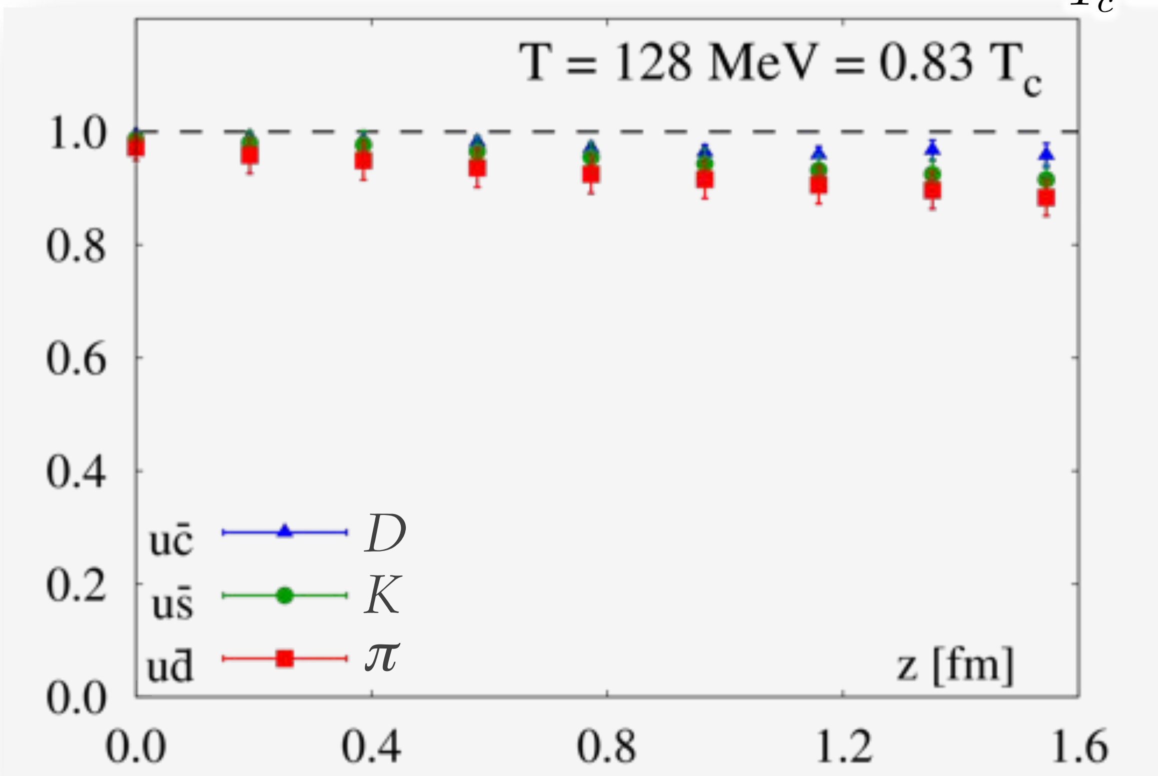

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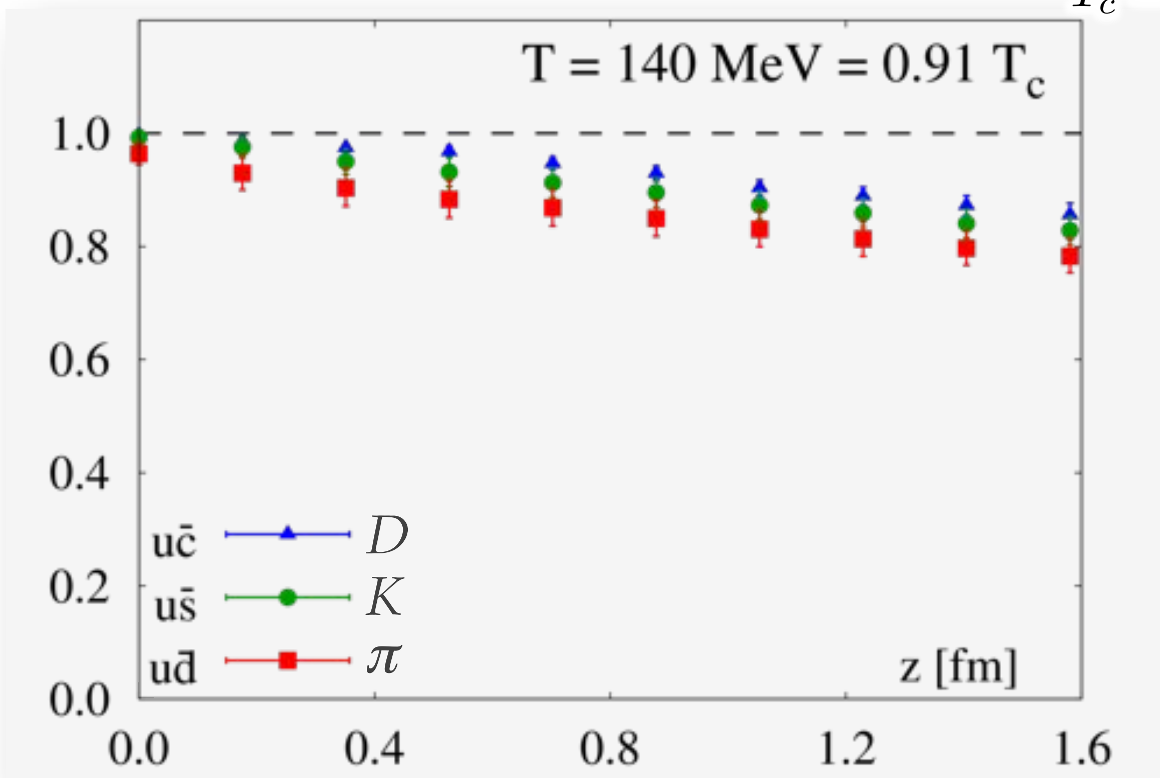

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- modification at $T < T_c$

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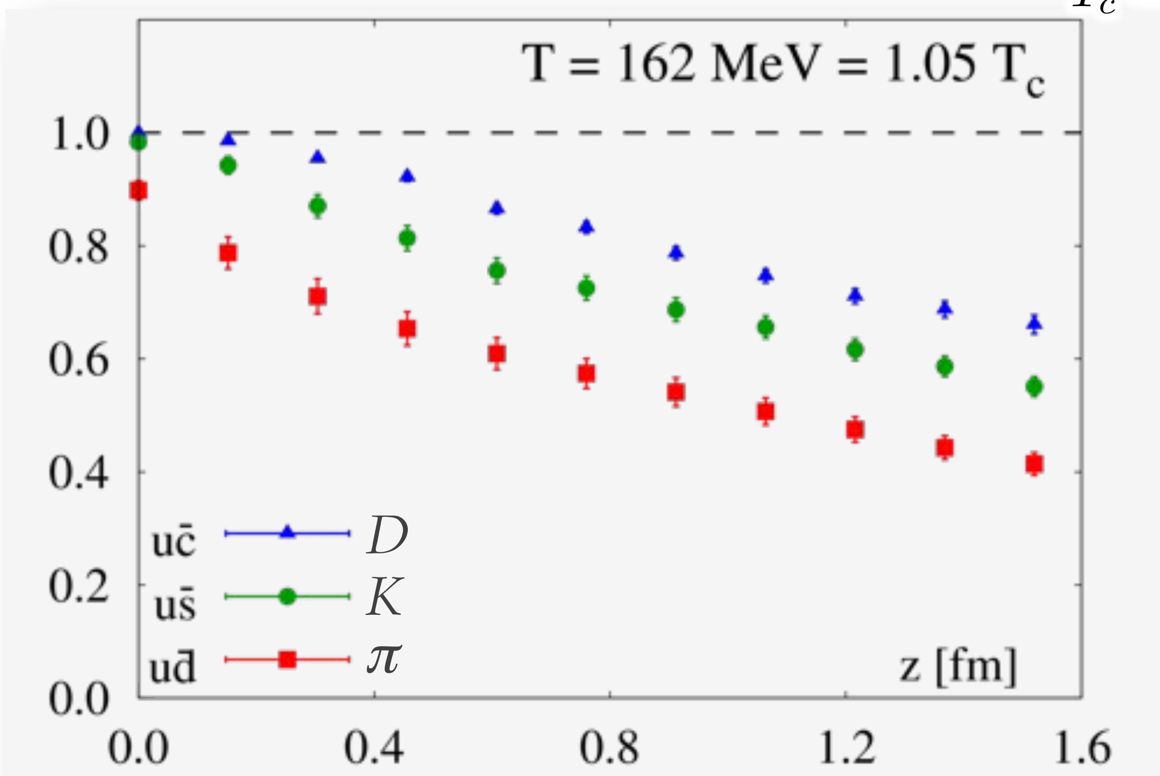

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- modification at $T < T_c$, explicit flavor dependence at $T > T_c$

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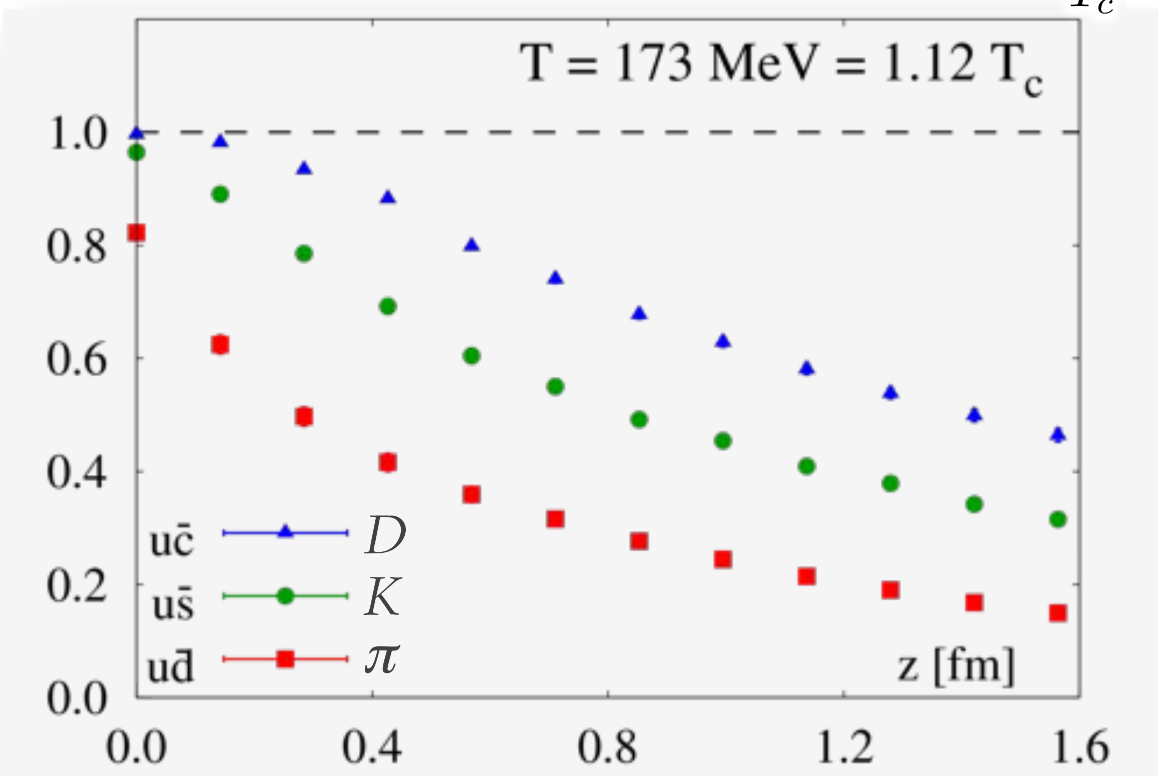

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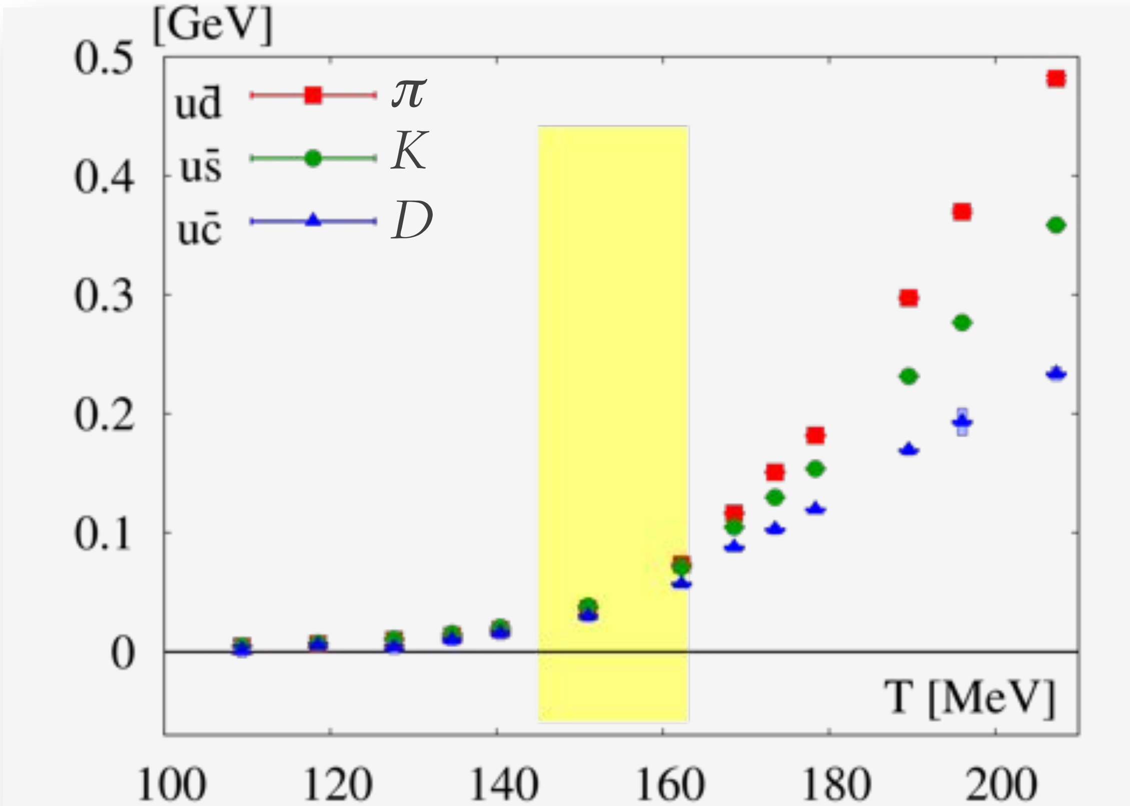
- modification at $T < T_c$, explicit flavor dependence at $T > T_c$

Mass difference

$$\Delta M(T) = M(T) - m_0$$ ~ change of "binding energy"

Pseudo-scalar
$J^P = 0^-$



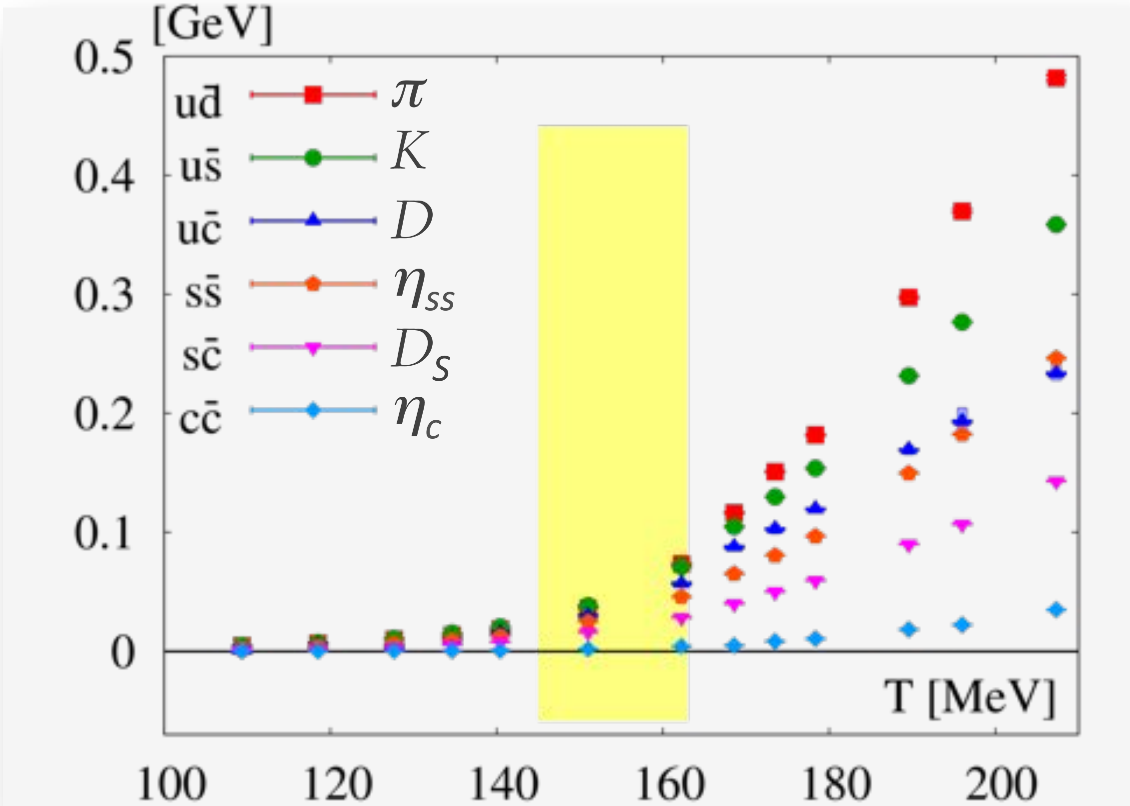
- $u\bar{d},\ u\bar{s},\ u\bar{c}$: explicit thermal modification below T_c,

similar modification pattern at $T < T_c$,
explicit flavor dependence at $T > T_c$

Mass difference

$\Delta M(T) = M(T) - m_0$ ~ **change of "binding energy"**

Pseudo-scalar
$J^P = 0^-$



- $u\bar{d},\ u\bar{s},\ u\bar{c}$: explicit thermal modification below T_c ,
  → similar modification pattern at $T < T_c$,
  explicit flavor dependence at $T > T_c$
- $s\bar{s},\ s\bar{c}$: slight modification below T_c
- $c\bar{c}$: stable beyond T_c

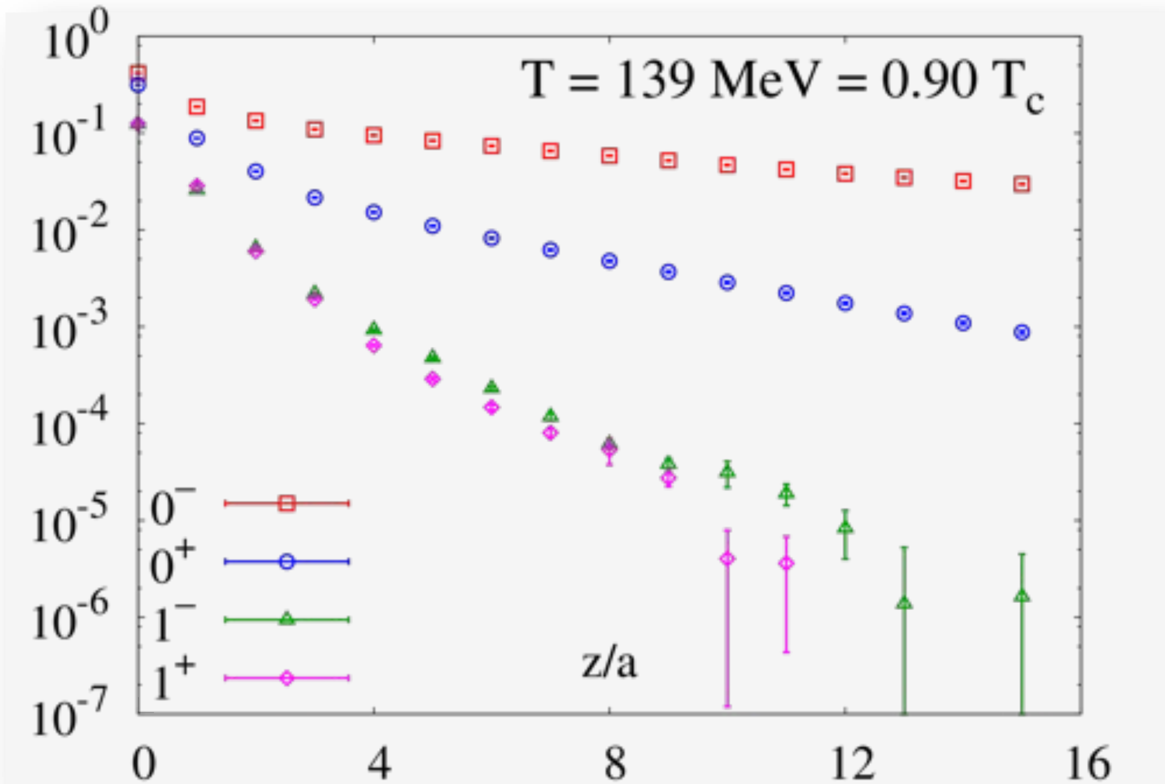
PRD91 (2015) 5, 054503

Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A}(1)$ symmetry

$G^S(z,T)$

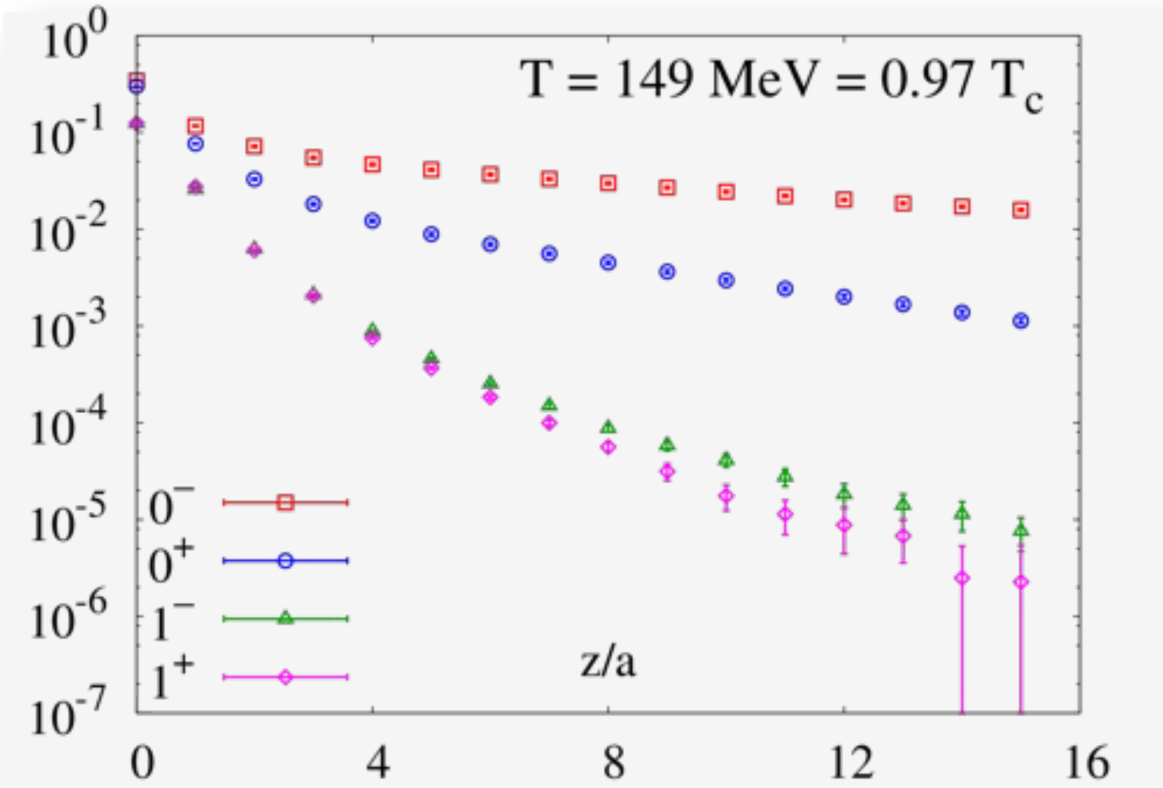


Restoration of broken symmetries

Degeneracy of vector partners ➡ restoration of chiral symmetry

Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A(1)}$ symmetry

$$G^S(z, T)$$



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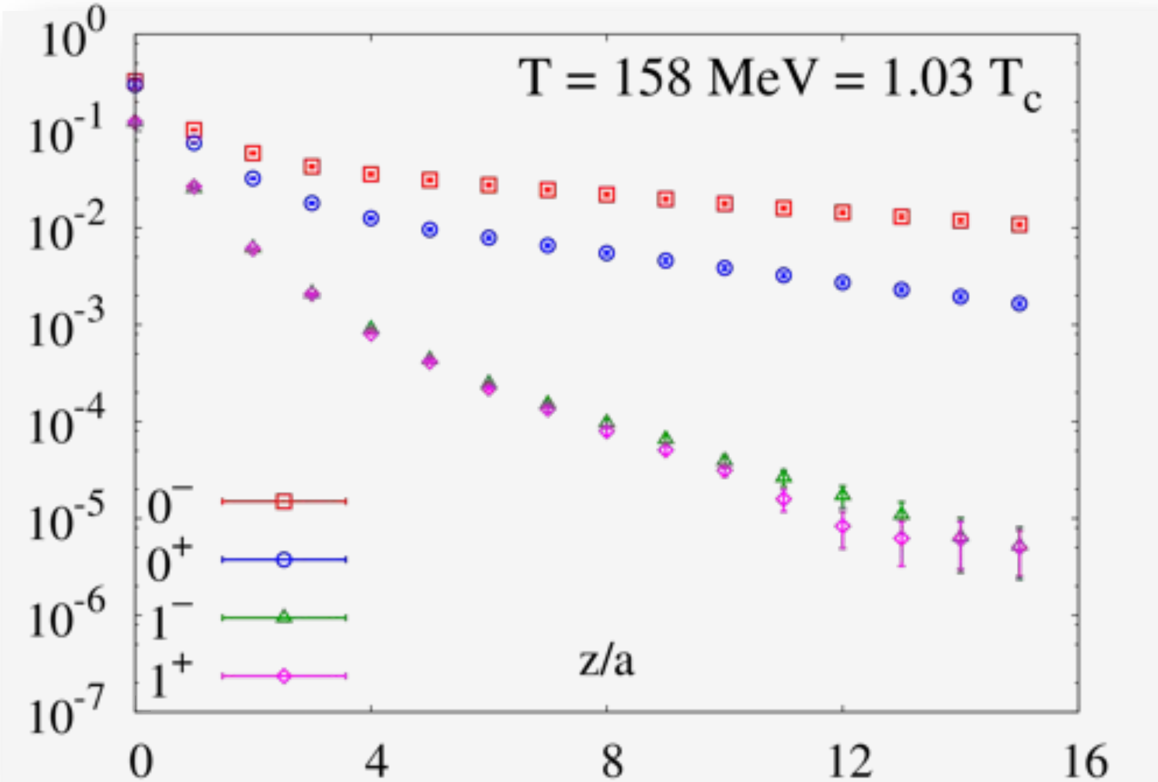

- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$

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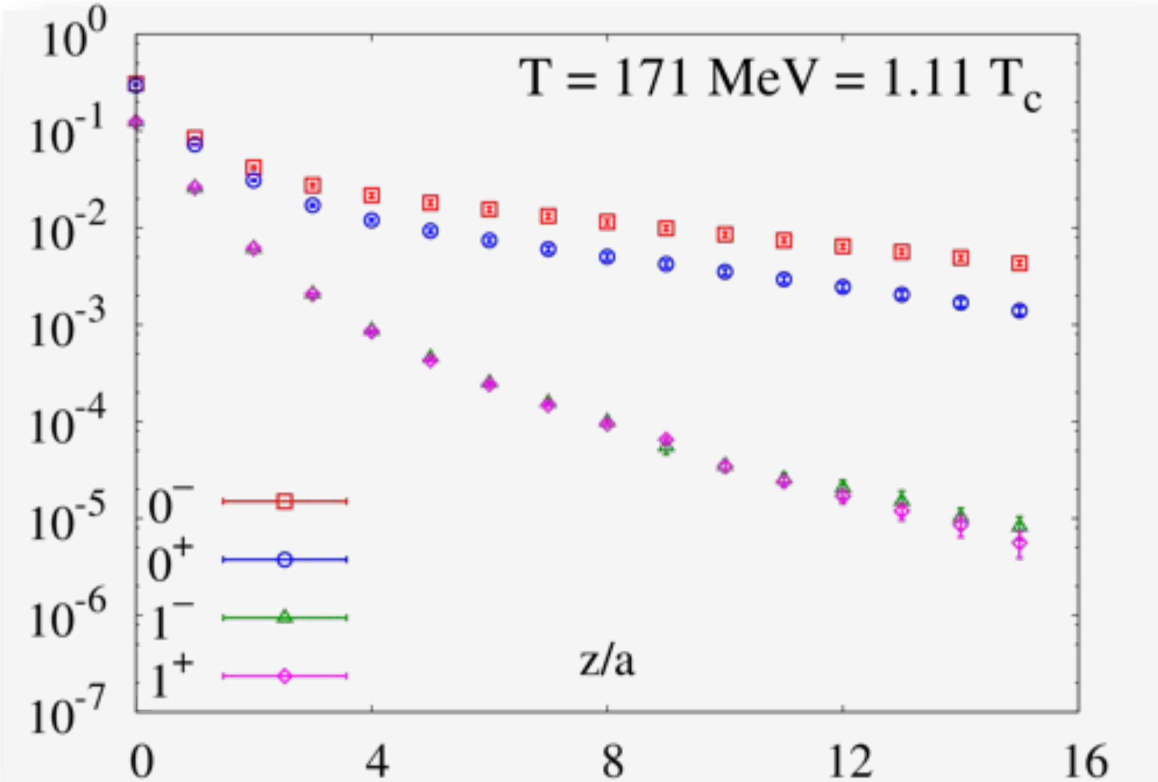

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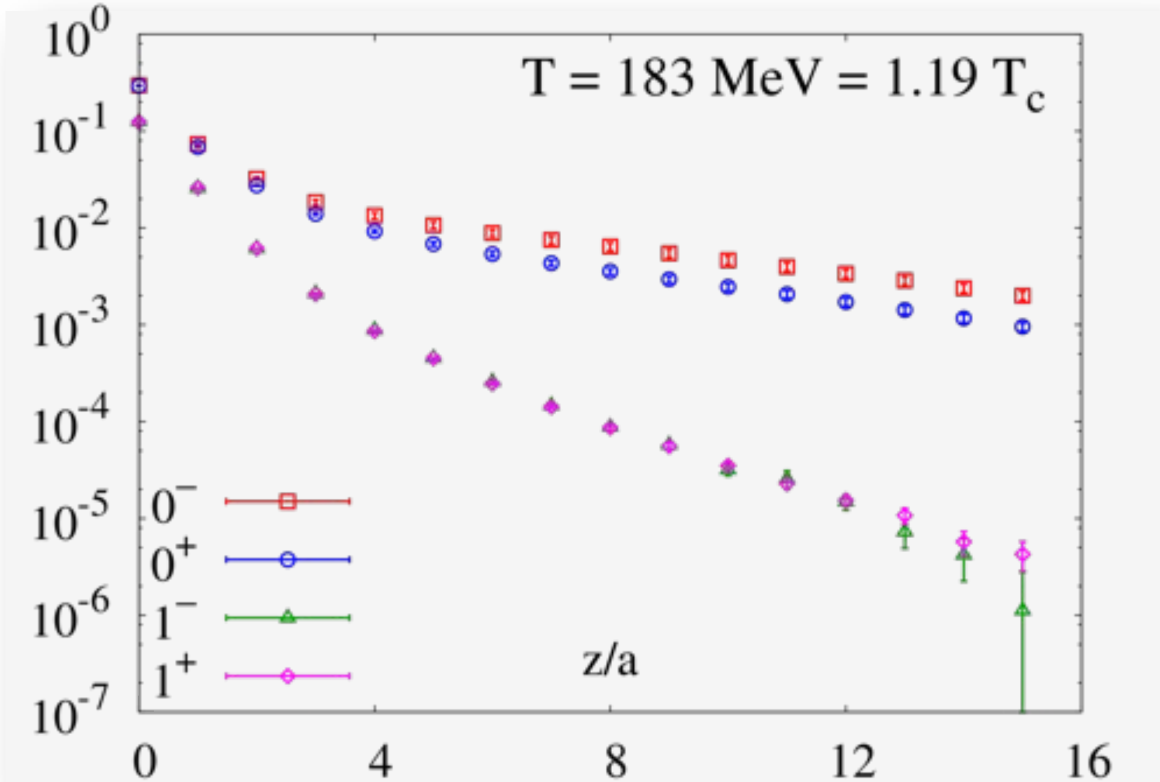

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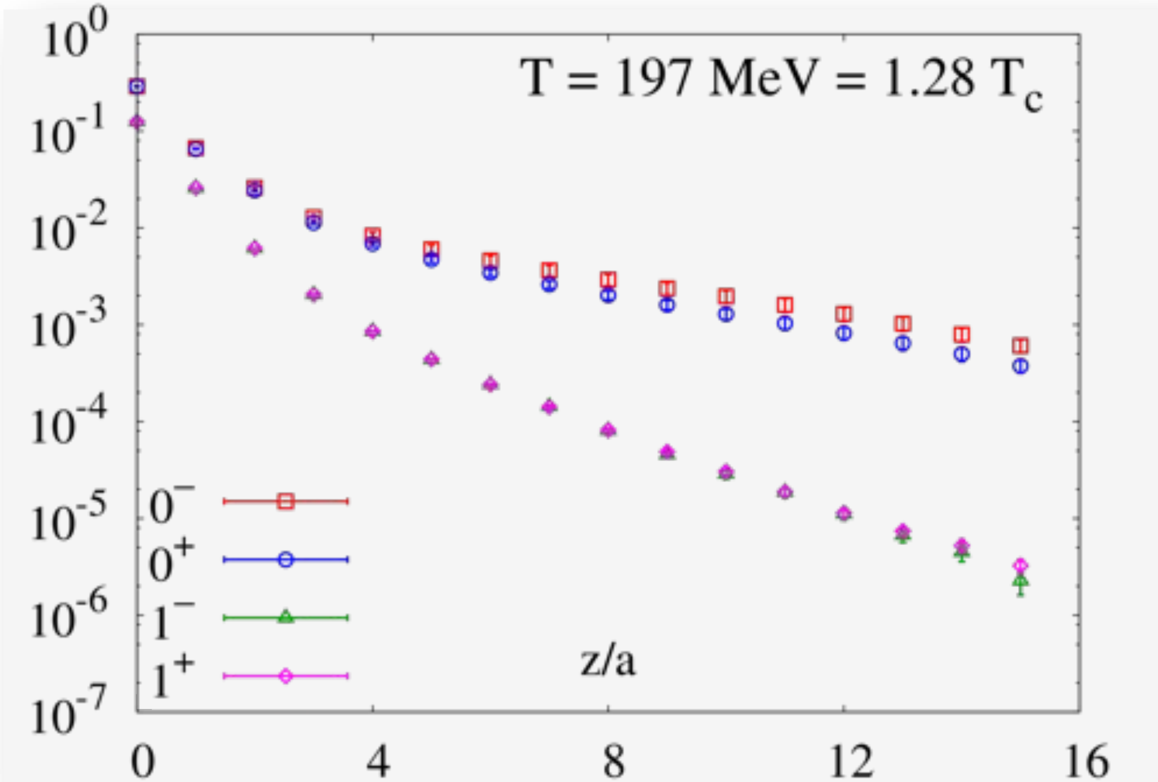

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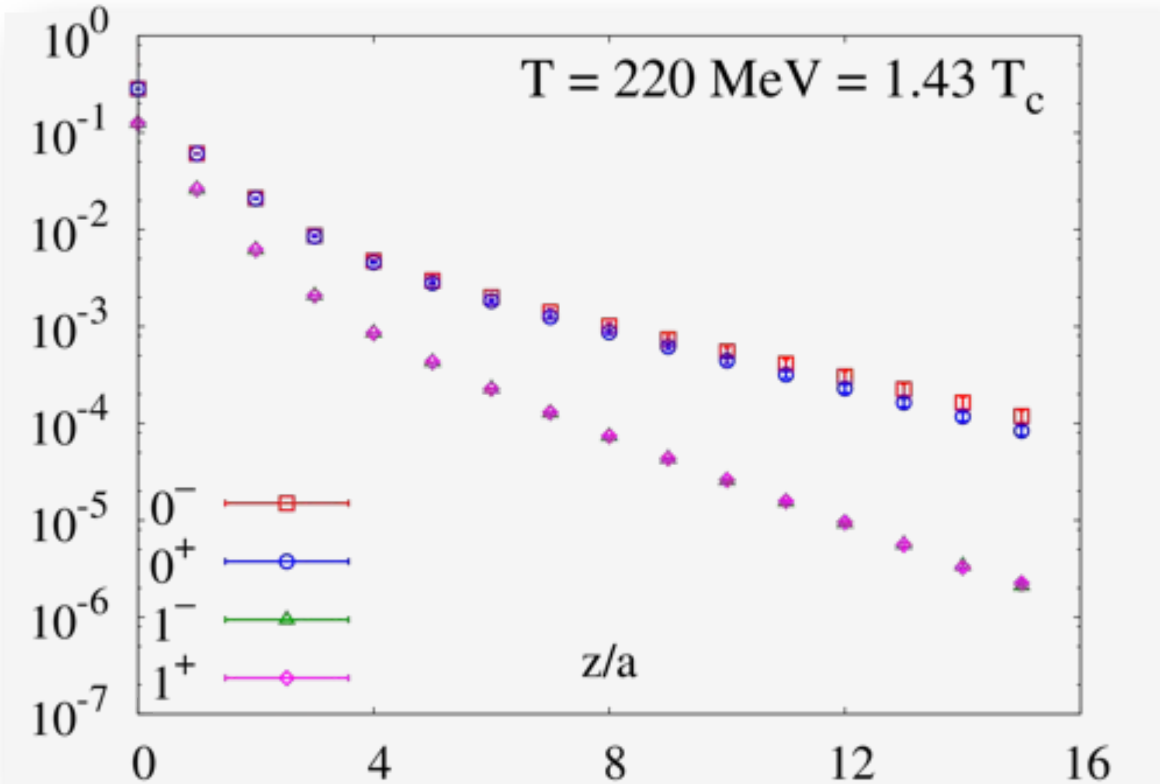

- Vector partner degenerates at $T \sim 1.0T_\mathrm{c}$--$1.1T_\mathrm{c}$
- Scalar partner degenerates at $T \sim 1.4T_\mathrm{c}$--$1.6T_\mathrm{c}$

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Degeneracy of scalar partners ➡ (effective) restoration of $\mathrm{U_A}(1)$ symmetry

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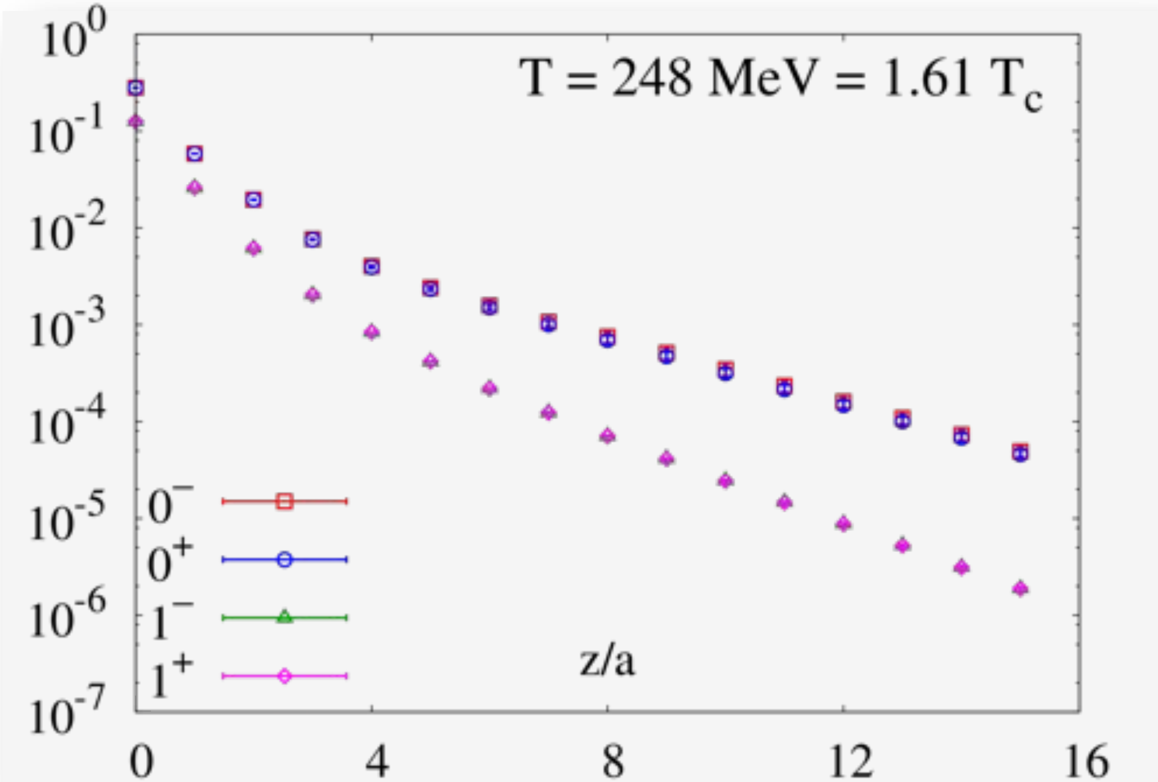

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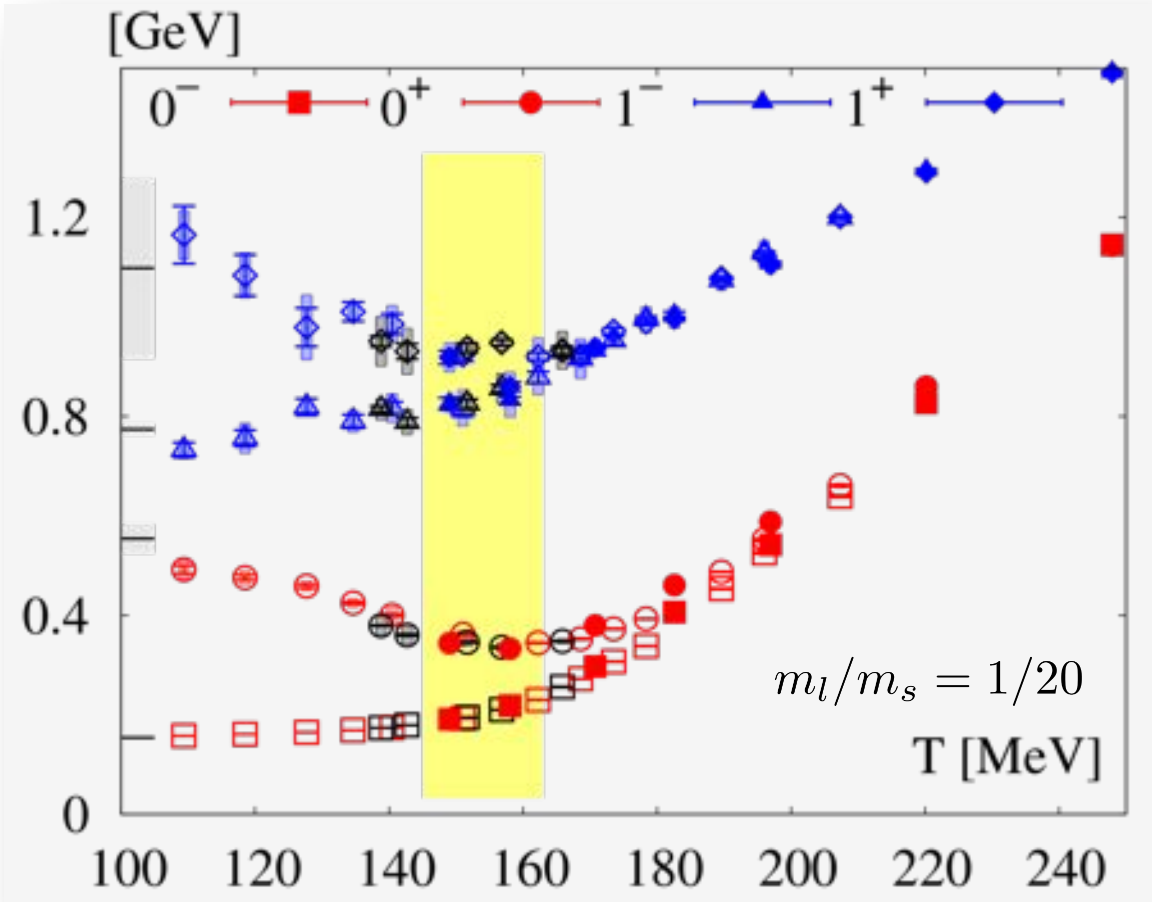
Restoration of broken symmetries

Large distance behavior of spatial correlator $G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

Light-unflavored
$u\bar{d}$



Open: $N\tau = 8$
Black: $N\tau = 10$
Filled: $N\tau = 12$

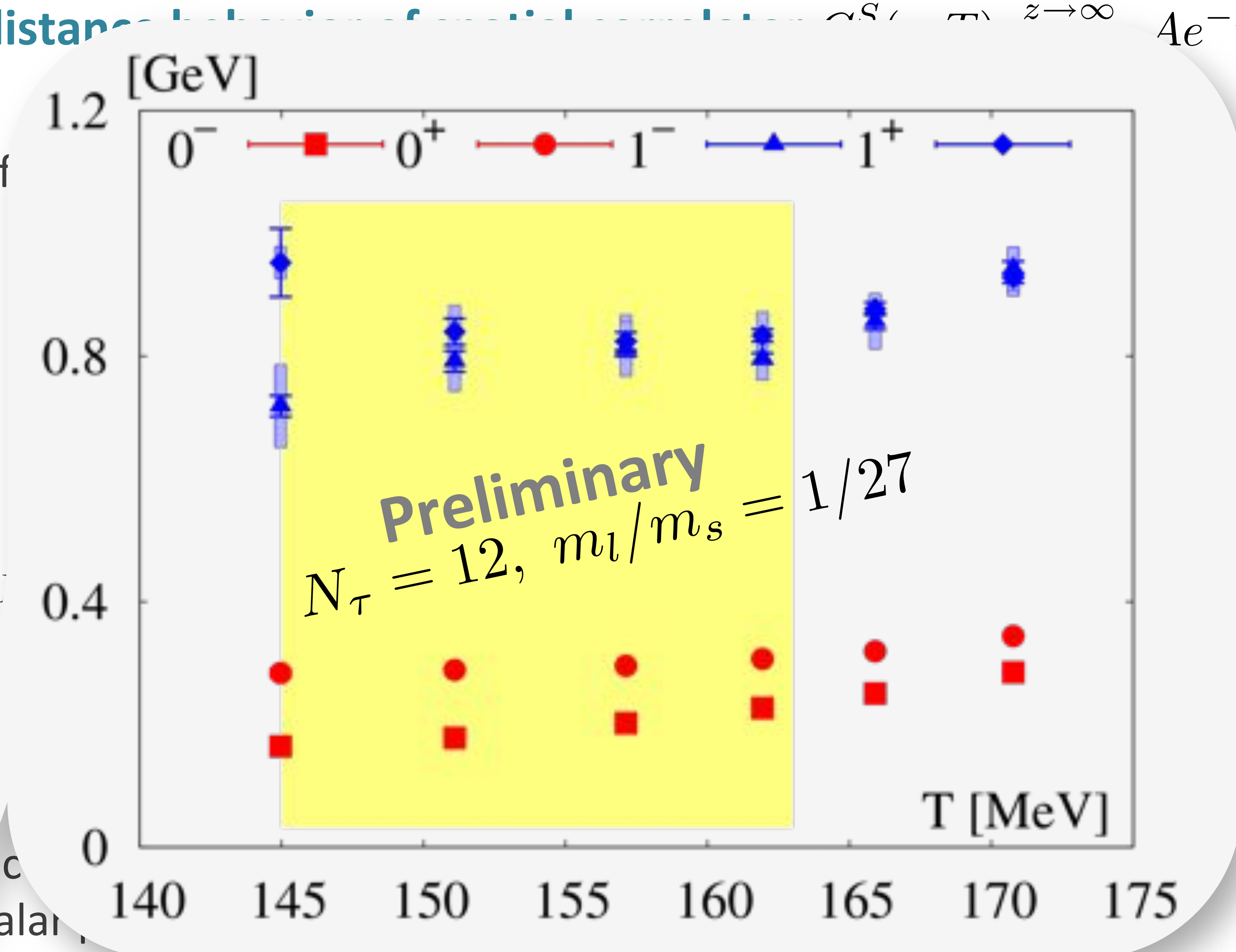
- Vector partner degenerates at $T \sim 1.0T_c$--$1.1T_c$
- Scalar partner degenerates at $T \sim 1.4T_c$--$1.6T_c$

➡ chiral: restored, $\mathrm{U_A}(1)$: broken at T_c, no dependence on lattice spacing

Restoration of broken symmetries

Large distan $\stackrel{z\to\infty}{\longrightarrow}$ $Ae^{-M(T)z}$

Light-unf



Open:

Black:

Filled:

- Vec
- Scalar

➡ chiral: restored, $\mathrm{U_A}(1)$: broken at T_c, no dependence on lattice spacing

Summary

In-medium mesons from spatial correlation function

- Sensitive to thermal effect at finite T on lattice
  - Direct probe of modification of meson spectral function
  - Indicator of restorations of broken symmetries

(2+1)-flavor QCD lattice simulations with HISQ of

ratio: $G^S(z,T)/G^S(z,T=0)$, screening mass: $G^S(z,T) \xrightarrow{z\to\infty} Ae^{-M(T)z}$

- $u\bar{d},\ \ u\bar{s},\ \ u\bar{c}$: explicit thermal modification below $T_{\rm c}$,
  - similar modification pattern below $T_{\rm c}$, explicit flavor dependence above $T_{\rm c}$
- $s\bar{s},\ \ s\bar{c}$: slight modification below $T_{\rm c}$
- $c\bar{c}$: stable beyond $T_{\rm c}$

PRD91 (2015) 5, 054503

- Degeneracies of parity partners
  - chiral: restored, $\mathrm{U_A}(1)$: broken at $T_{\rm c}$

in continuum and physical quark mass (preliminary)