Spatial meson correlators and screening masses at finite temperature in lattice simulations with HISQ

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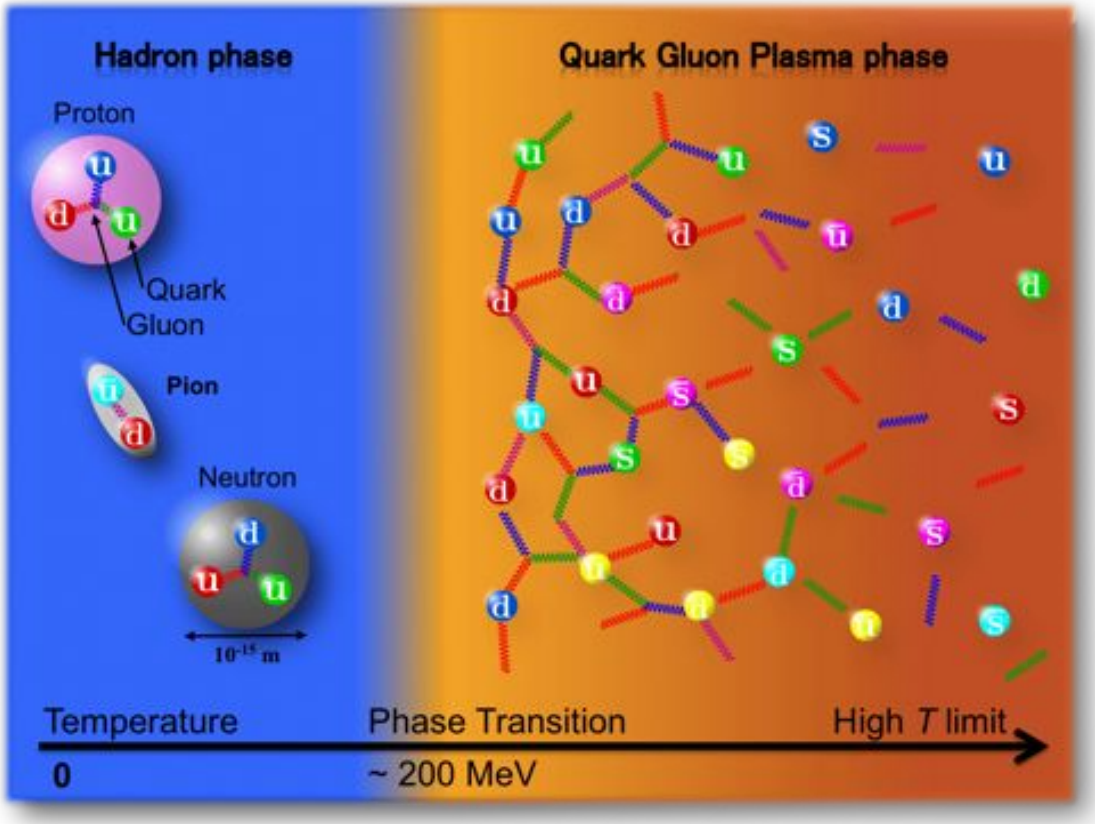
At $T \sim T_c$, modification of meson bound state in QGP

At high T, comparison with thermal perturbation theory

Momentum on charmonium

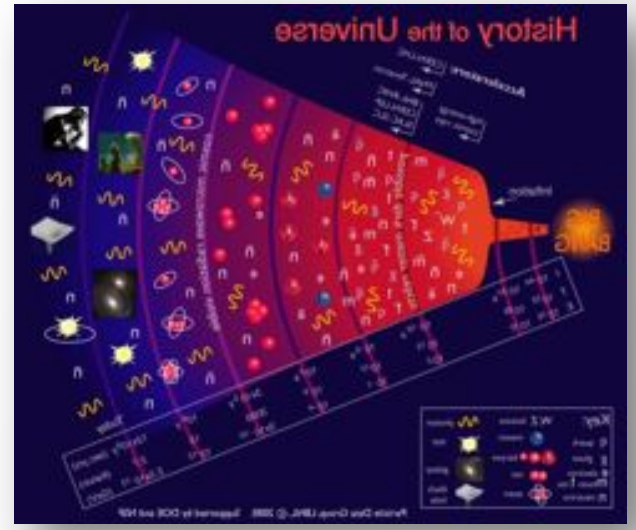
Summary

Hot QCD world

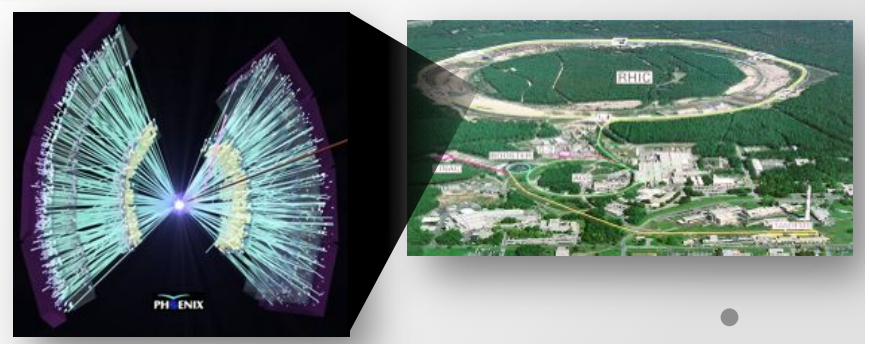


Time

Big Bang



Little Bang

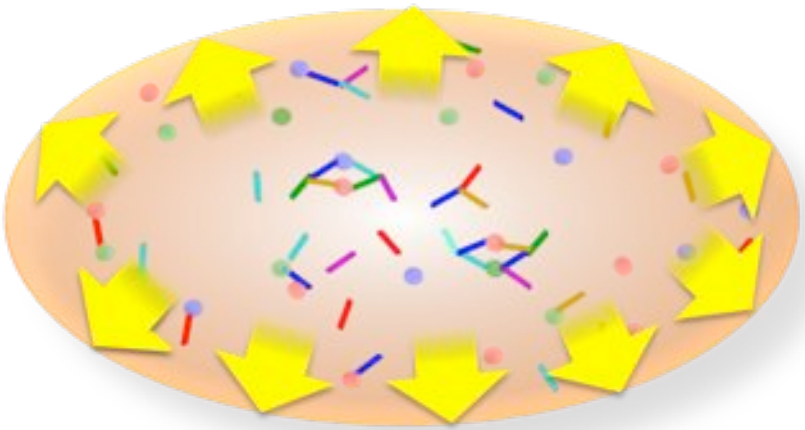


Amazing plasma of quarks and gluons…

➡ QCD thermodynamics

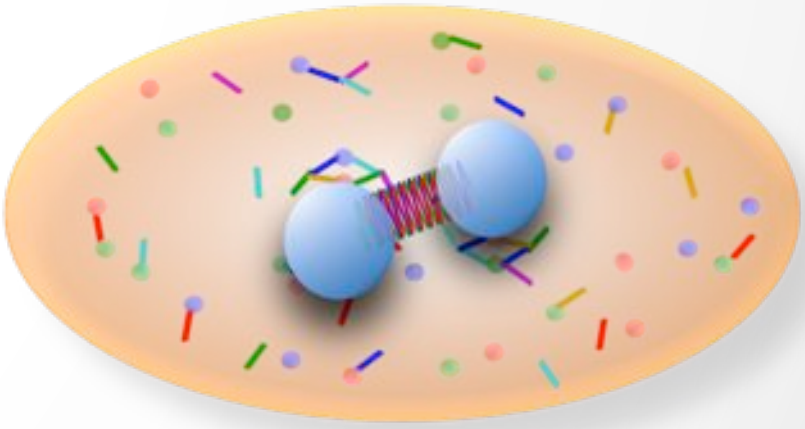
QCD thermodynamics

Bulk properties of QGP



- ✓ Phase transition
  - chiral, deconfinement, T_C, scaling
- ✓ Equation of state
  - pressure, energy density
- ✓ Fluctuation
  - B, Q, S susceptibilities

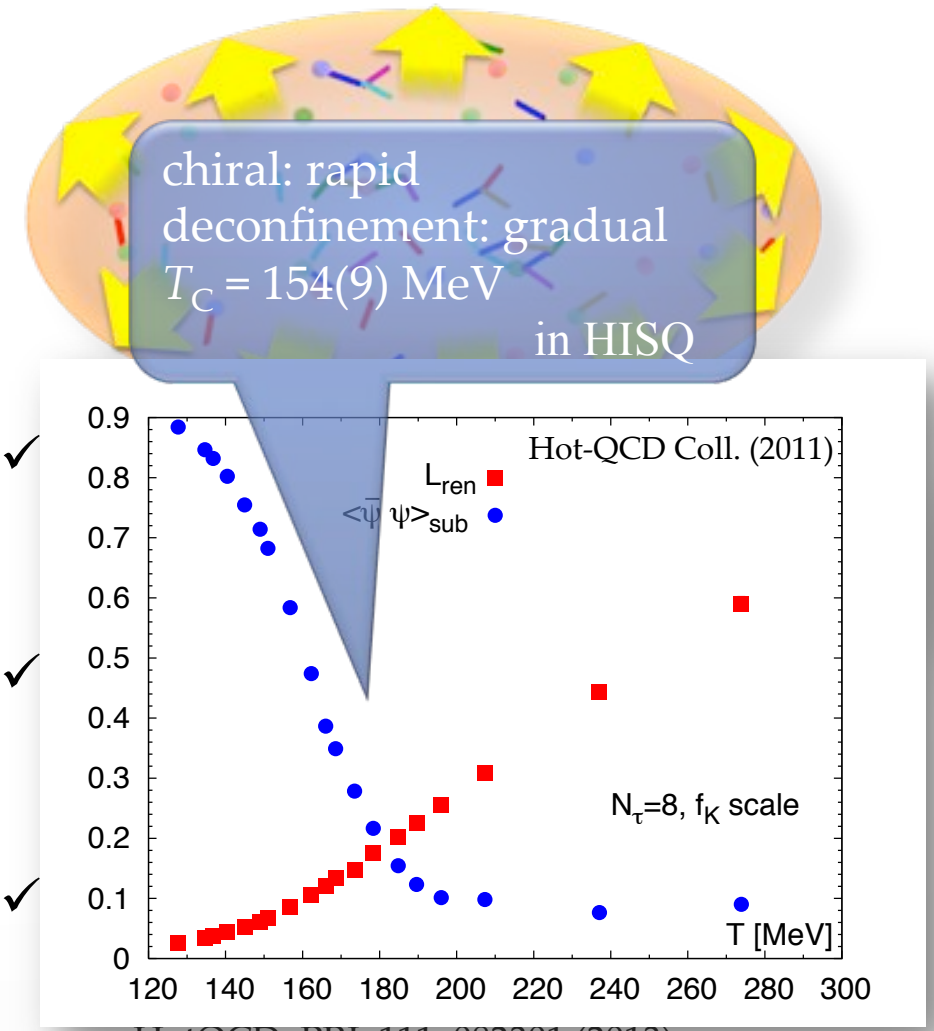
Internal properties of QGP



- ✓ Hadron excitation
  - dissociation of hadrons
  - color screening in plasma
- ✓ Quark-gluon correlation
  - transport coefficients
  - dilepton emission
  - …

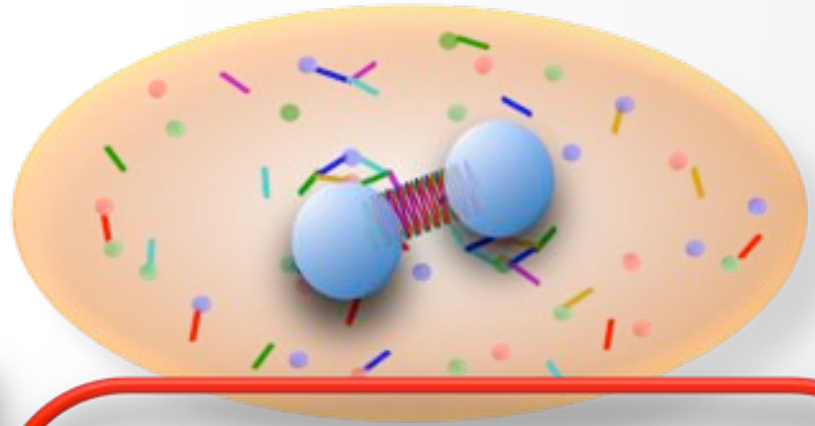
QCD thermodynamics

Bulk properties of QGP



HotQCD, PRL 111, 082301 (2013)

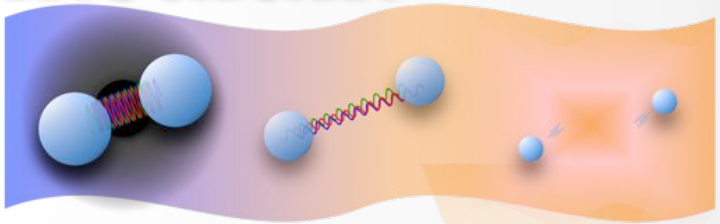
Internal properties of QGP



- ✓ Hadron excitation
  - dissociation of hadrons
  - color screening in plasma

  in lattice simulations
- ✓ Quark-gluon correlation
  - transport coefficients
  - dilepton emission
  - …

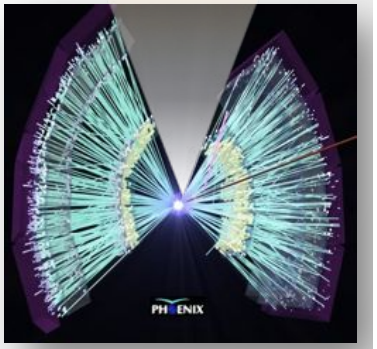
Meson in thermal medium



Low T: bound state

High T: screened due to thermal fluctuation and dissociate in medium

- charmonium: purely created after collision
  direct probe in HIC experiments

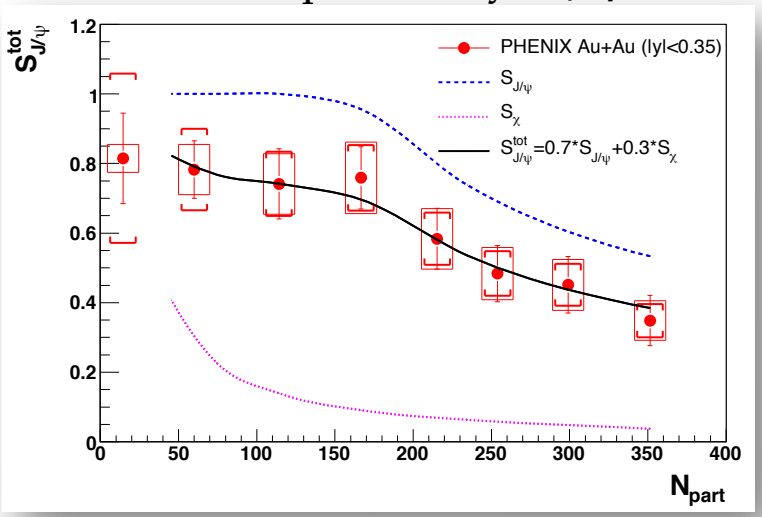


J/ψ suppression

⇒ direct signal that Quark-Gluon plasma is created

Matsui and Satz (1986)

Survival probability of J/ψ



Gunji et al. PRC 76, 051901 (2007)

in PHENIX experiment at RHIC…

Suppression of survival probability of J/ψ

⇓

Theoretical understanding properties of hadronic excitation in QGP

- ✓ modification temperature
- ✓ charm, strangeness…

Lattice QCD at finite temperature

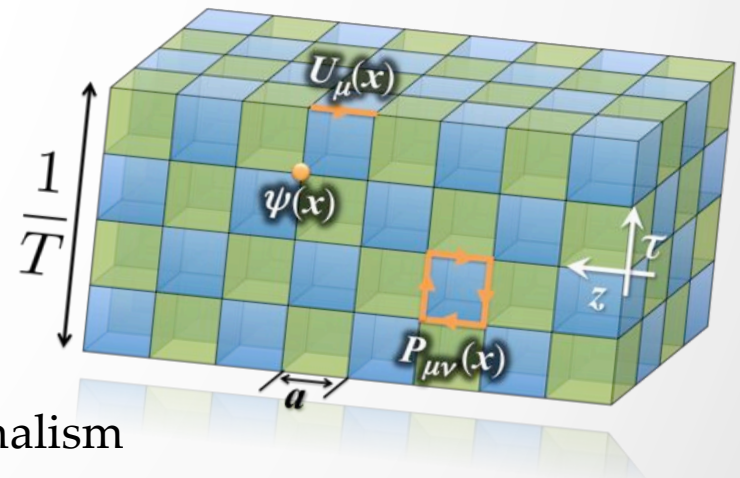
QCD: Strong non-linearity and multi-dimensional integration

➡ Numerical simulations with probability distribution on finite lattice

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int dU d\bar{\psi} d\psi \mathcal{O}(U, \bar{\psi}, \psi) e^{-S_g - S_q}$$

$$\simeq \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(U_i)$$

U_i: configurations



<u>Lattice formulation:</u> imaginary time (Euclidian) formalism

$$S = \int_0^{1/T} d\tau \int d^3x \mathcal{L}(\tau, \mathbf{x}) \to \sum_{n_\tau, n_\mathbf{x}} \mathcal{L}(n_\tau, n_\mathbf{x})$$

limitations of temporal size at finite temperature

<u>Hadrons on lattice</u>: temporal correlation function

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

e.g.) meson

$J_\mathrm{H}(\tau, \mathbf{x}) = \bar{q} \Gamma_\mathrm{H} q(\tau, \mathbf{x})$

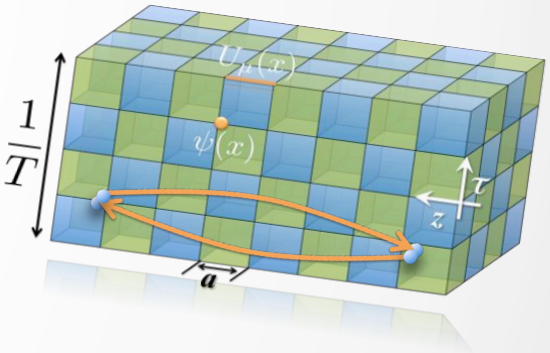
m_0: mass of ground state

…difficult to extract meaningful signal at $\tau < 1/T$

Lattice QCD at finite temperature

<u>Meson correlation function to spatial direction</u>

$$G(z,T) = \int dxdy \int_0^{1/T} d\tau \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{z\to\infty} Ae^{-M_\Gamma z}$$



Screening mass: response to meson due to thermal effect
advantage $z < L_z$

$$\Rightarrow \quad G(z,T) = \int_0^\infty \frac{2d\omega}{\omega} \int_{-\infty}^{\infty} dp_z e^{iP_z z} \underline{\rho(\omega,p_z,T)}$$

Spectral function

At low T: $\rho(\omega,p_z,T) \sim \delta(\omega^2 - p_z^2 - M^2)$ ➡ screening mass = peak position

At high T: zero mode $\omega\delta(\omega)$ ➡ contact term of free quarks

Estimation of survival and/or modification temperature of meson states

e.g.) temporal correlation function

$$G(\tau,T) = \int d^3x \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle = \int_0^\infty d\omega K(\tau,\omega,T)\rho(\omega,T)$$

$$K(\tau,\omega,T) = \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}$$

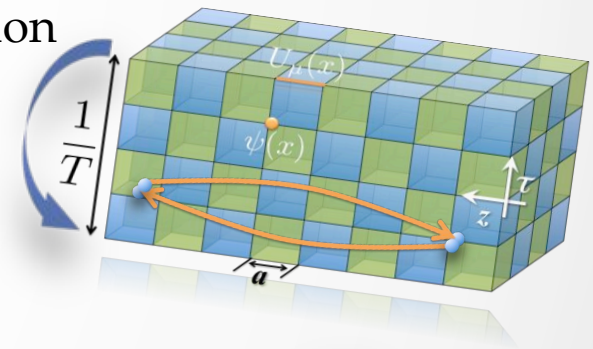
zero mode ➡ non-decaying constant contribution

Meson screening mass at finite T

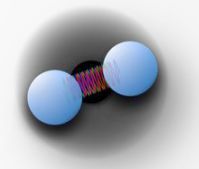
Boundary Condition: Investigation of hadronic modification

Anti-periodic BC: $q(\vec{x}, 1/T) = -q(\vec{x}, 0)$

Periodic BC: $q(\vec{x}, 1/T) = q(\vec{x}, 0)$

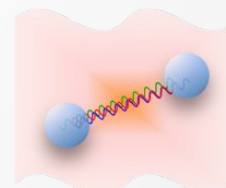


<u>Screening mass in thermal medium…</u>



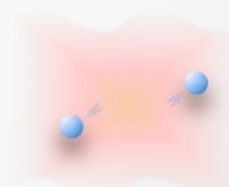
at $T \sim 0$, meson bound state: pole mass at $T = 0$: $M(T) \sim m_0$

➡ Bosonic state: no BC dependence



at $T \sim T_c$, bound states broaden: sensitive to quark structure

Fermionic contribution: $M^{\mathrm{APB}} \neq M^{\mathrm{PB}}$



at $T \to \infty$, free meson with two quark propagators

which have the lowest Matsubara mode:

$$M_{\mathrm{free}}^{\mathrm{APB}} \to 2\sqrt{(\pi T)^2 + m_q^2}$$

$$M_{\mathrm{free}}^{\mathrm{PB}} \to 2m_q$$

Previous results on charmonium in lattice

Temporal correlation in quenched QCD (a part is full-QCD)

- 1S charmonium state survives at $T < 1.6T_c$

  in maximum entropy method

  Asakawa et al. (2001) (2004), Wetzorke et al. (2002), Umeda et al. (2005), Datta et al. (2004), Jakovac et al. (2007), Aarts et al. (2007)

  in variational method

  Iida et al. (2006), Ohno et al. (2011)

- no peak of bound state at $T \sim 1.46T_c$ with $a = 0.01$ fm in MEM

  Ding et al (2010)

Spatial correlation in full-QCD

- significant modification at $T \sim 1.5T_c$ in staggered-p4 action

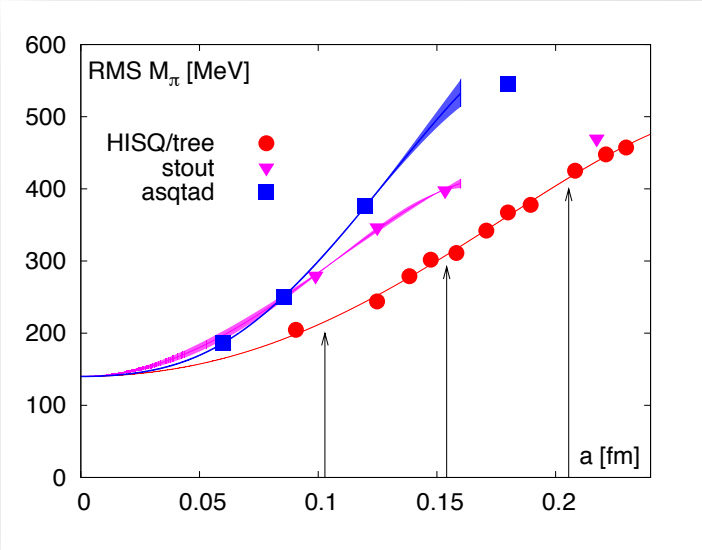
  Karsch et al. (2012)

<u>in this study</u>: spatial correlation in 2+1 flavors of HISQ

charmonium, open-charm and strangeness sectors

Lattice simulations with HISQ

Highly Improved Staggered Quarks



HISQ action Bazavov et al. (2011)

Reduction of the taste violation

Control of the cutoff effects

Bulk thermal properties: investigated

Hot-QCD Coll. (2011)

abundant statistics with widely T range: utilizable

Lattice setup

2+1 flavor QCD (charm quenched)

$m_l/m_s = 0.05$ (m_π~160 MeV, m_K~504 MeV)

48^3x48 or 64 at $T = 0$

48^3x12, $\beta = 6.664—7.280$ ($T = 138—245$ MeV, 15 points)

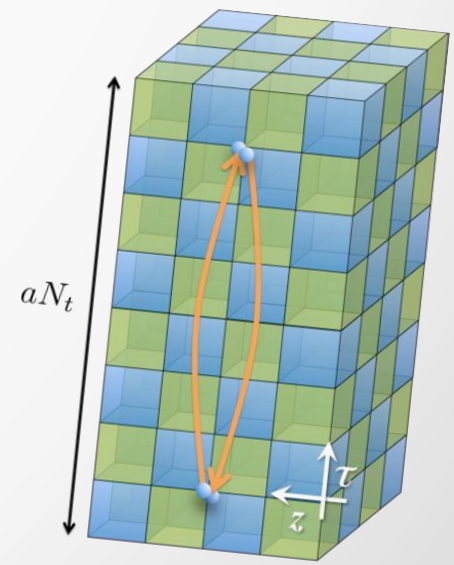
N_τ=10, 8, 6, 4 at $\beta = 7.280$, N_s/N_τ=4 ($T = 297—743$ MeV)

scale: f_k input

meson propagators: point and wall sources (5000—10000 traj.)

$T = 0$

- Meson propagators in HISQ
- Meson spectrum in strange and charm



Meson correlators in staggered action

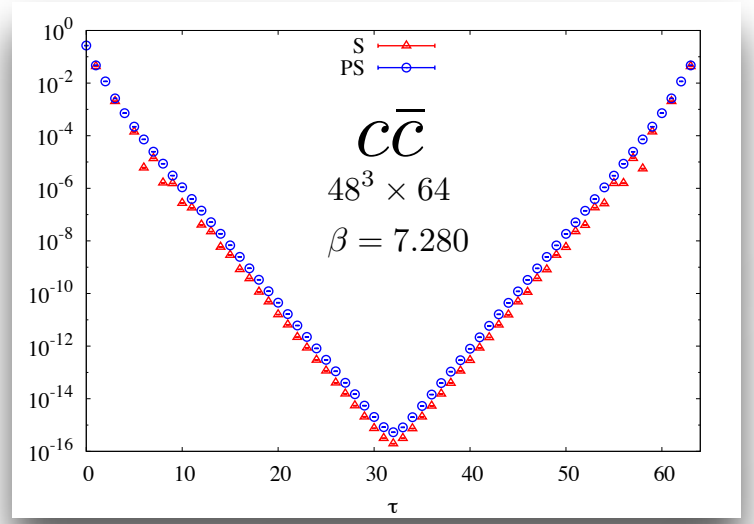
Staggered propagator: mixture of parities

$$C(\tau) = A_{\rm NO} e^{-m_- \tau} - (-)^\tau A_{\rm O} e^{-m_+ \tau}$$

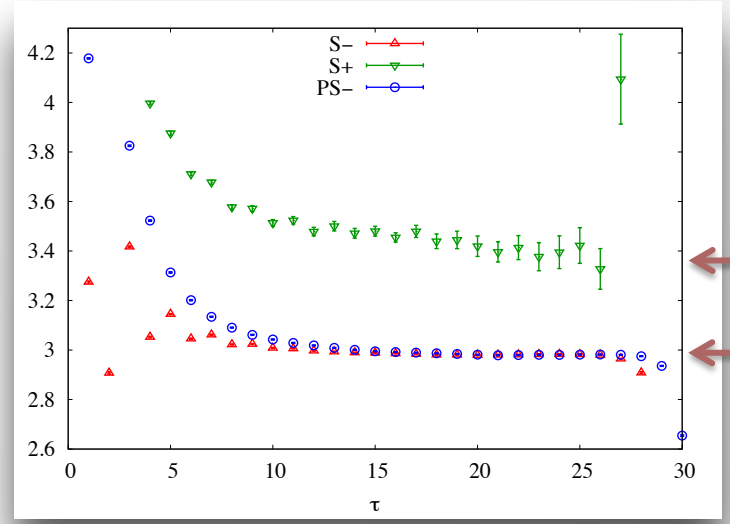
	S		PS		AV		V	
Γ	$\gamma_4\gamma_5$	1	γ_5	γ_4	$\gamma_i\gamma_4$	$\gamma_i\gamma_5$	γ_i	$\gamma_j\gamma_k$
J^{PC}	0^{-+}	0^{++}	0^{-+}	0^{+-}	1^{--}	1^{++}	1^{--}	1^{+-}
$s\bar{s}$	$\eta_{s\bar{s}}$		$\eta_{s\bar{s}}$	$-$	ϕ		ϕ	
$s\bar{c}$	D_s	D^*_{s0}	D_s	D^*_{s0}	D^*_s	D_{s1}	D^*_s	D_{s1}
$c\bar{c}$	η_c	χ_{c0}	η_c	$-$	J/ψ	χ_{c1}	J/ψ	h_c

Taste different meson

Meson propagator: S and PS



Effective masses



0^{++}

0^{-+}

Artifacts due to the taste violation:

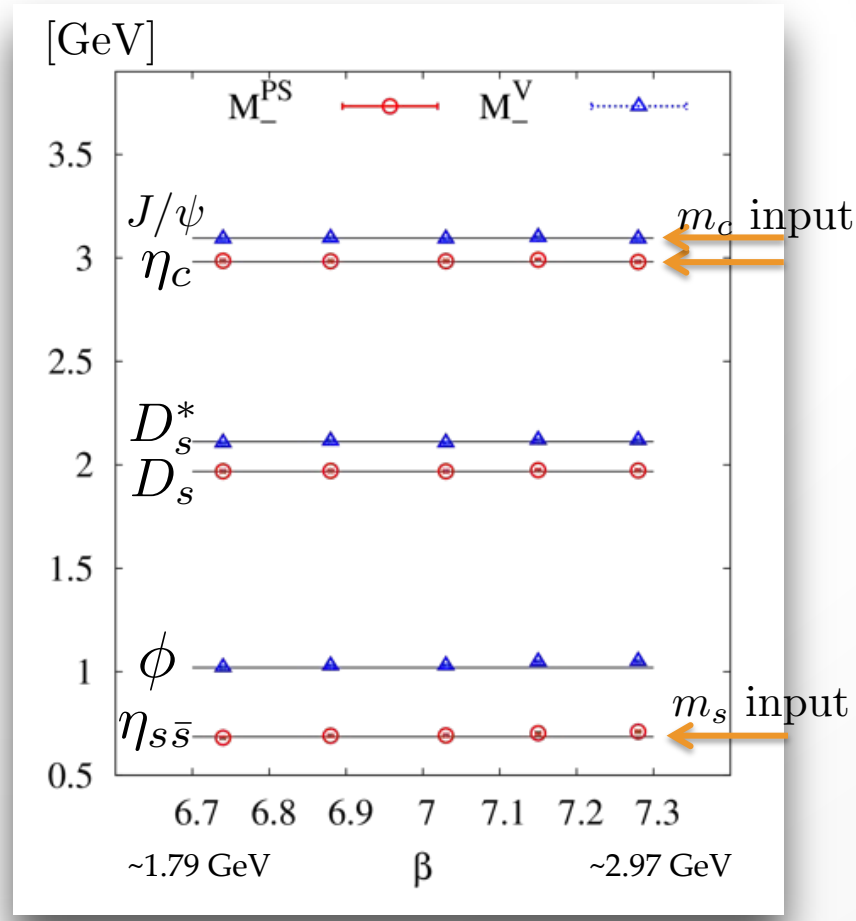
- well suppressed at large distance in HISQ action

Meson spectrum at $T = 0$

Ground states with negative parity

$$M_-^{\mathrm{PS}},\ M_-^{\mathrm{V}}$$

	S		PS		AV		V	
Γ	$\gamma_4\gamma_5$	1	γ_5	γ_4	$\gamma_i\gamma_4$	$\gamma_i\gamma_5$	γ_i	$\gamma_j\gamma_k$
J^{PC}	0^{-+}	0^{++}	0^{-+}	0^{+-}	1^{--}	1^{++}	1^{--}	1^{+-}
$s\bar{s}$	$\eta_{s\bar{s}}$		$\eta_{s\bar{s}}$	$-$	ϕ		ϕ	
$s\bar{c}$	D_s	D_{s0}^*	D_s	D_{s0}^*	D_s^*	D_{s1}	D_s^*	D_{s1}
$c\bar{c}$	η_c	χ_{c0}	η_c	$-$	J/ψ	χ_{c1}	J/ψ	h_c



Determination of quark mass at $T = 0$

Strange-quark mass:

$$m_{\eta_{\bar{s}s}} = \sqrt{2m_K^2 - m_\pi^2}$$ Hot-QCD (2011)

Charm-quark mass:

$$\frac{1}{4}m_{\eta_c} + \frac{3}{4}m_{J/\psi}$$

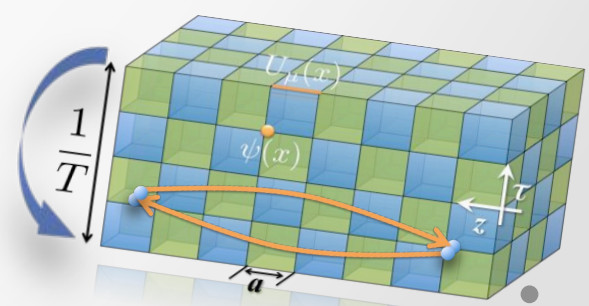
No significant β dependence:

well improvement of

the cutoff effect in HISQ action

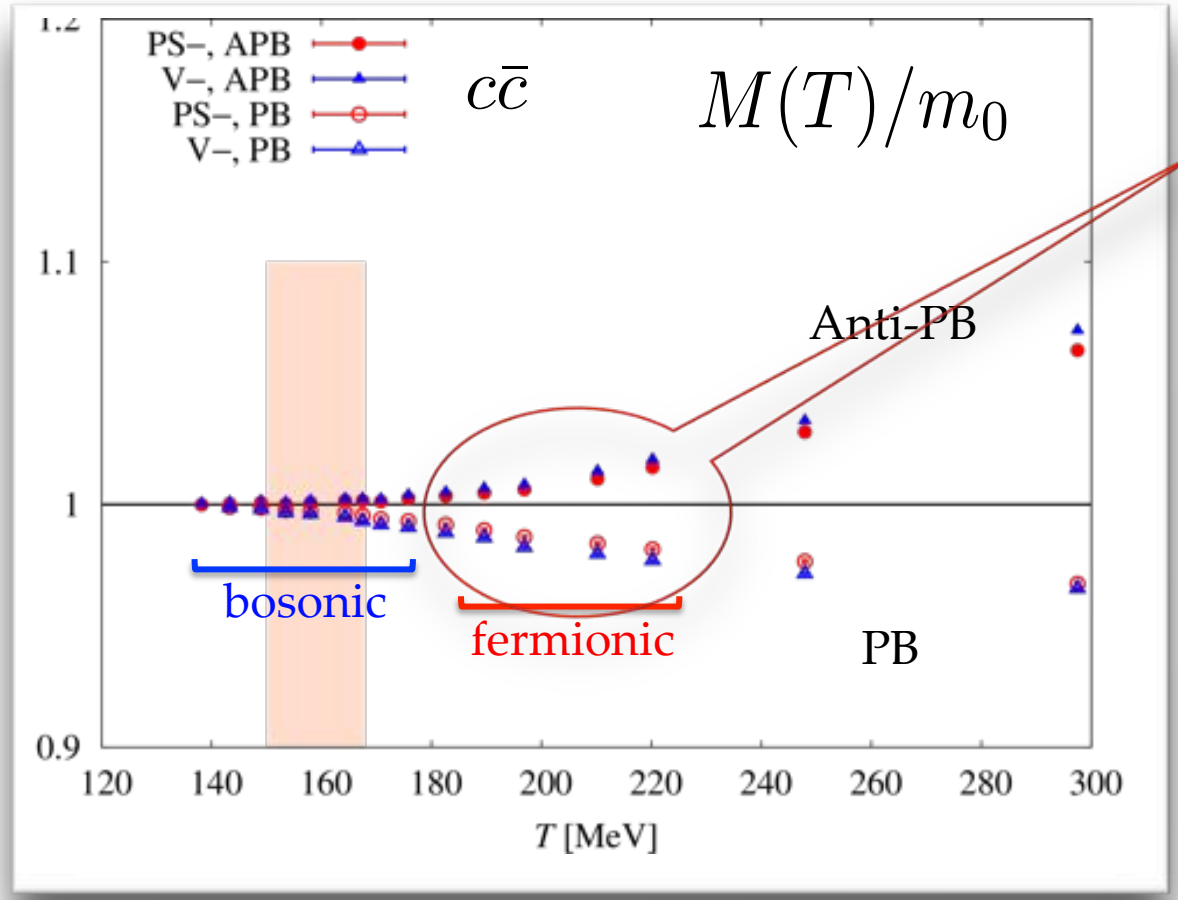
Finite temperature

- Screening mass: Anti-periodic BC and periodic BC
  - Charmonium
  - Open-charm and strangeness
- At high temperature
  - comparison with thermal perturbation theory
- Momentum on charmonium



Charmonium screening mass at $T \sim T_c$

Screening mass divided by pole mass at $T = 0$



at low T: $M(T)/m_0 = 1$

at $T \sim 200-220$ MeV:

APB: increases
PB: decreases

at high T:

$$M^{\mathrm{APB}} \sim 2\sqrt{(\pi T)^2 + m_c^2}$$

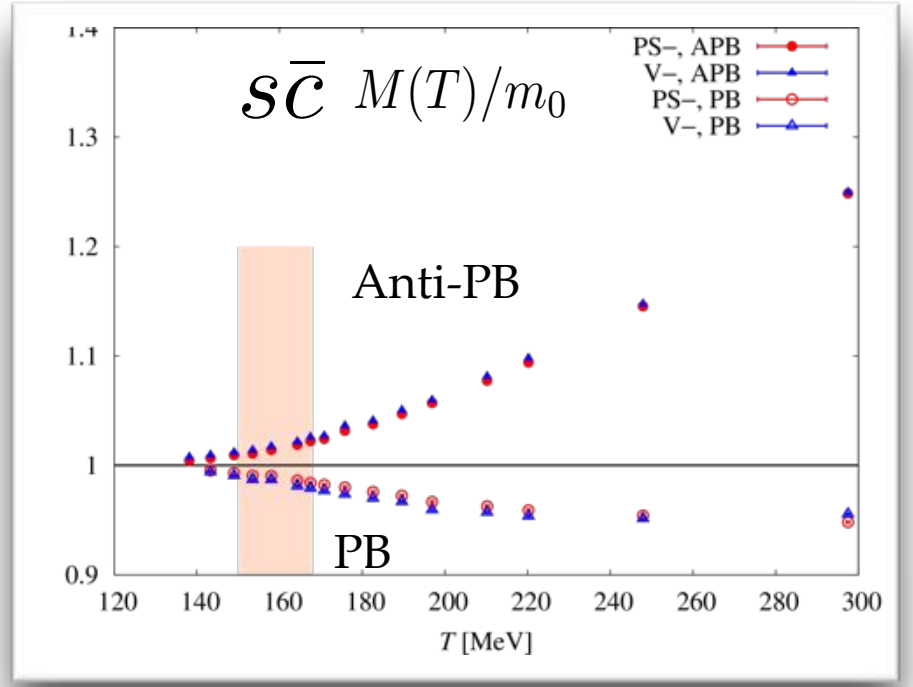
$$M^{\mathrm{PB}} \sim 2m_c$$

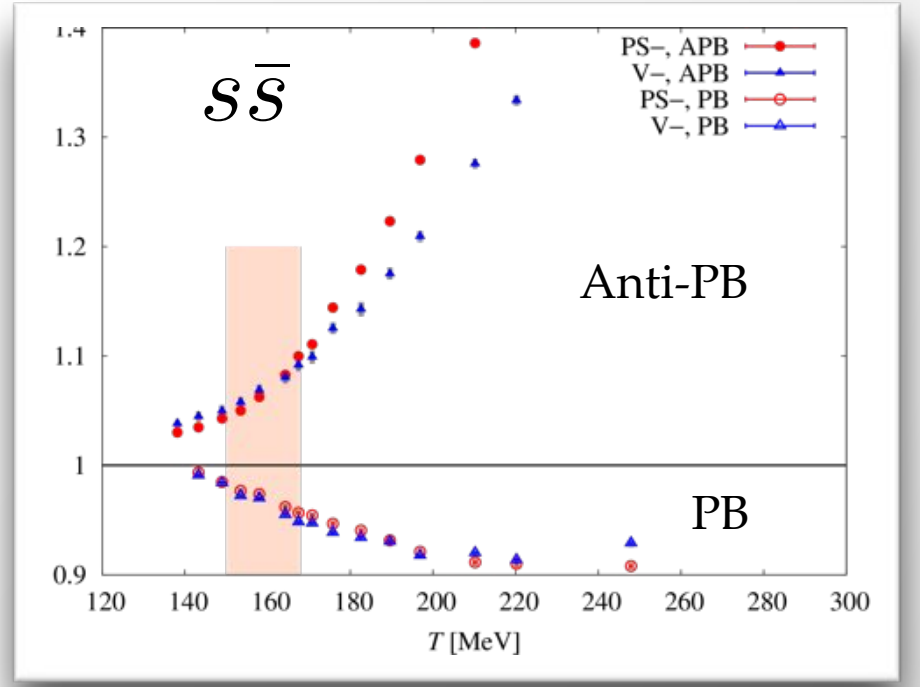
η_c, J/ψ survive at $T < 1.3T_c$

and modified at $T > 1.3-1.4T_c$

bosonic: meson bound state
fermionic: sensitive to quark structure

Open-charm and strangeness: $T \sim T_c$





at $T \sim 160$ MeV:

discrepancy btw APB and PB

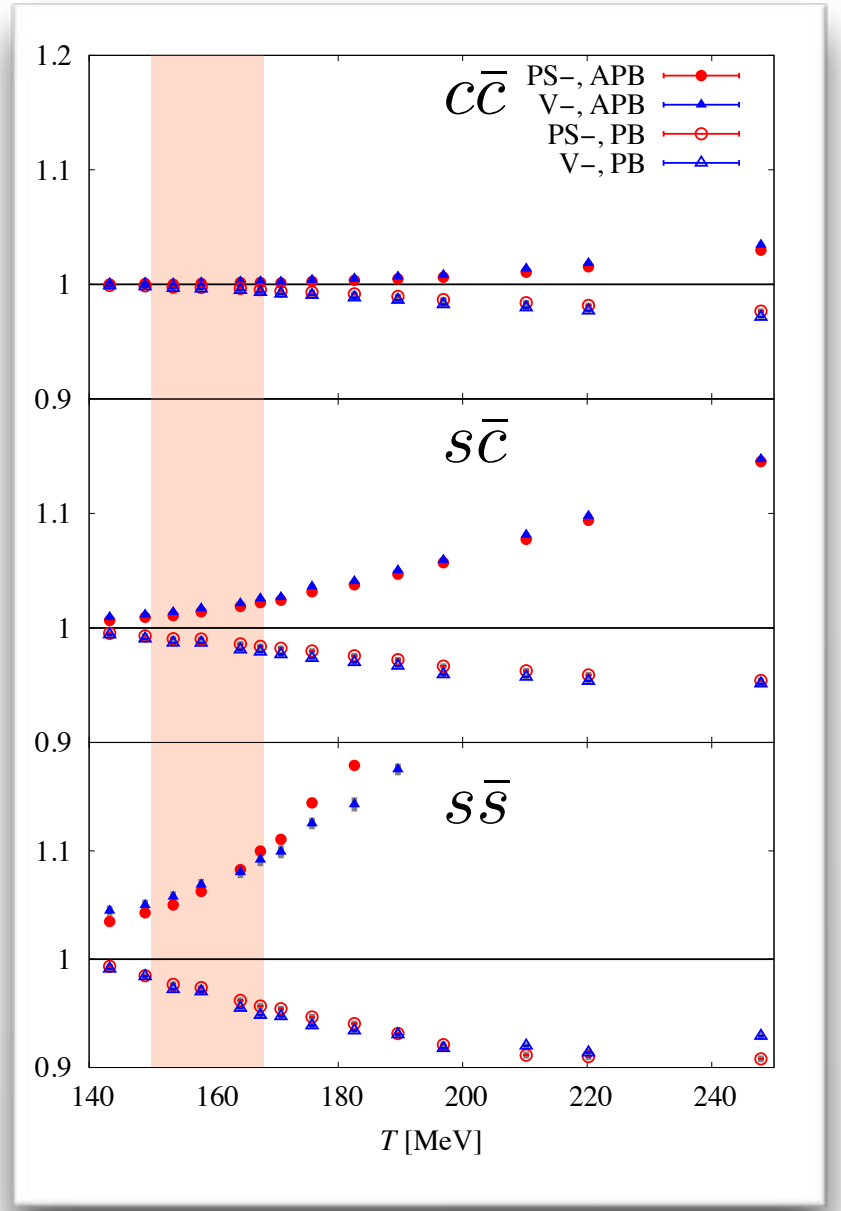
even at $T < 140$ MeV:

discrepancy btw APB and PB

➡ D_s, D_s^* modified at $T > T_c$ $(\eta_{s\bar{s}})$, ϕ significant modification at $T < 0.8T_c$

5% mass shift at $T \sim T_c$

Screening mass vs. pole mass



$$M(T)/m_0$$

near critical temperature (T_{pc} = 159 MeV)

modifications due to thermal effect appear

$c\bar{c}$: T ~ 200—220 MeV (~ 1.3 T_{pc})

$s\bar{c}$: T ~ 160 MeV

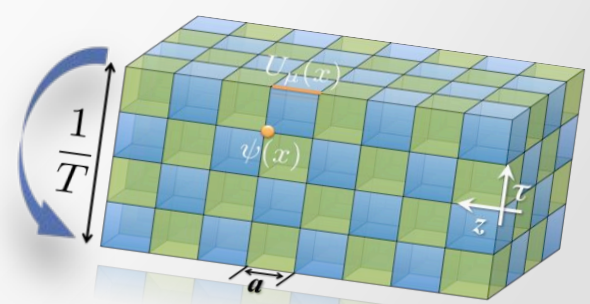
$s\bar{s}$: T < 140 MeV

η_c, J/ψ survive above T_{pc}
(similar to p4 action)

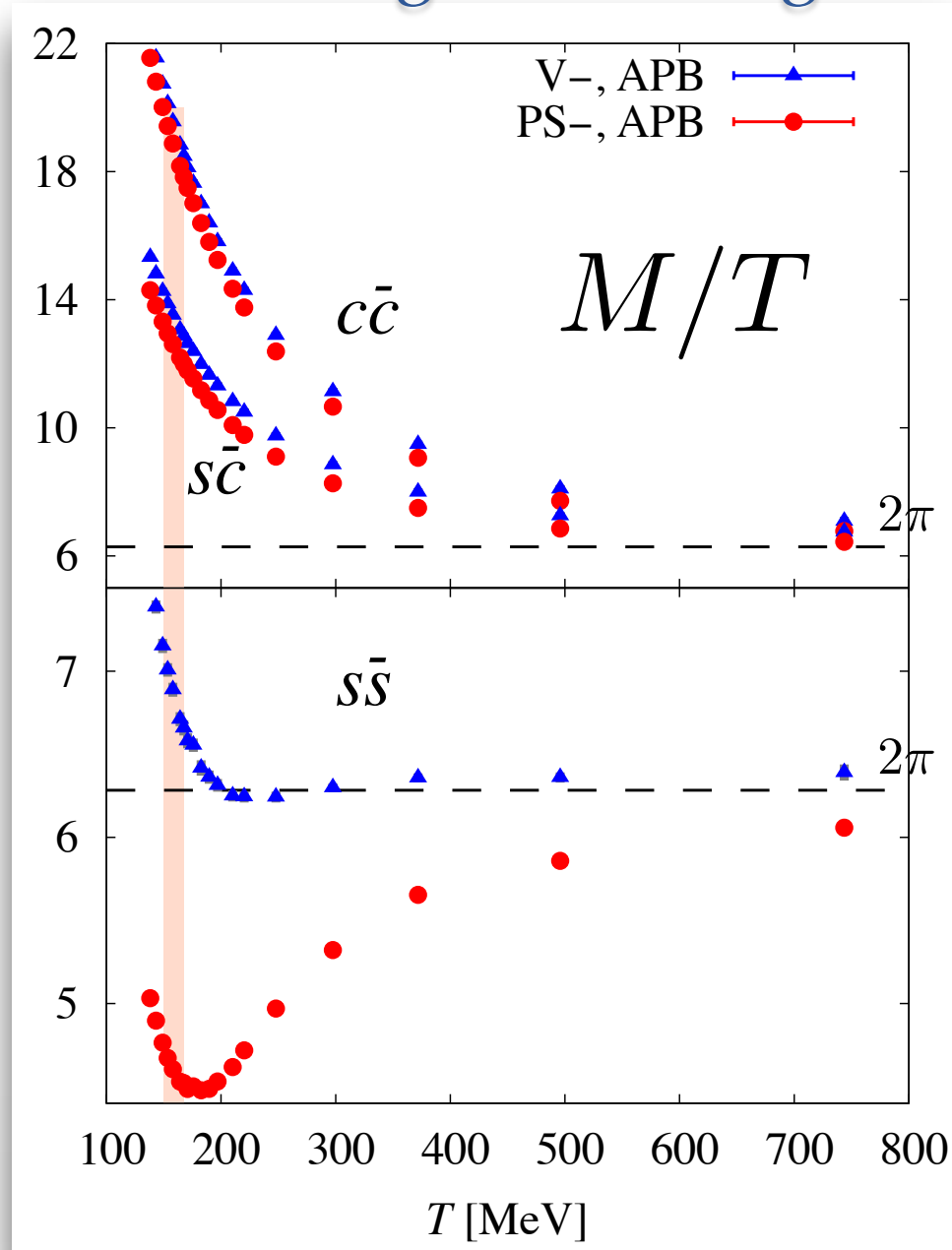
$(\eta_{s\bar{s}})$, ϕ significant modification
even below T_{pc}

Finite temperature

- Screening mass: Anti-periodic BC and periodic BC
  - Charmonium
  - Open-charm and strangeness
  - Discrepancy btw APB and PB
- At high temperature
  - comparison with thermal perturbation theory
- Momentum on charmonium



Screening mass at high T vs. thermal perturbation



with T increasing… $M_{\rm free}^{\rm APB} \to 2\sqrt{(\pi T)^2 + m_q^2}$

$c\bar{c},\ \ s\bar{c}$

M/T decreases and converges to 2π

$s\bar{s}$

Significant T dependent slightly above T_c

Convergence to 2π

PS: from below

V: from above

Thermal perturbation Laine et al 2004

- all channel converges
- described by

$$M_{\rm weak} = 2\pi T(1 + g^2 \times \begin{cases} 0.022(N_f = 0) \\ 0.033(N_f = 3) \end{cases})$$

on lattice: no convergence

similar results in p4 (2011)

precise investigations at high T: future

Finite temperature

- Screening mass: Anti-periodic BC and periodic BC
  - Charmonium
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  - Discrepancy btw APB and PB
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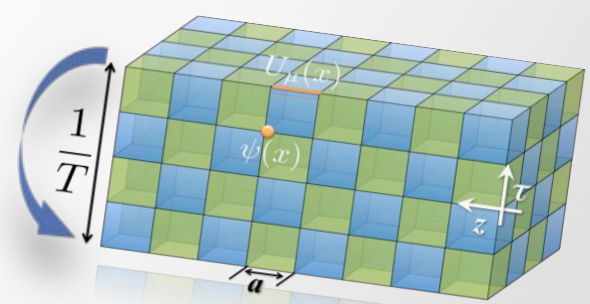
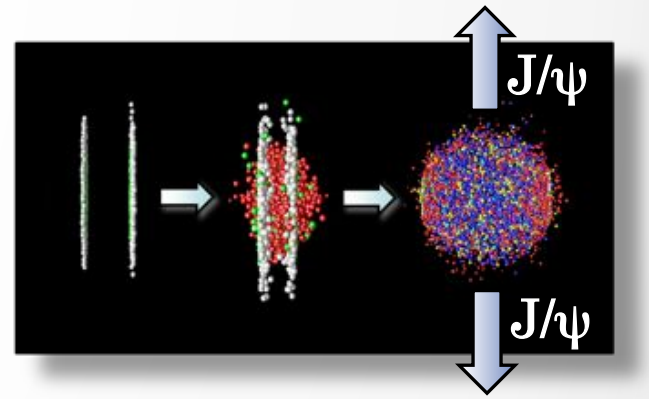


Momentum on charmonium



<u>J/ψ produced in heavy-ion collision:</u>

$p_{J/\psi}$ ~ 3--10 GeV in Au+Au @ STAR
1107.0532

$p_{J/\psi}$ ~ 2--4 GeV in pb+pb @ ALICE
1208.5401

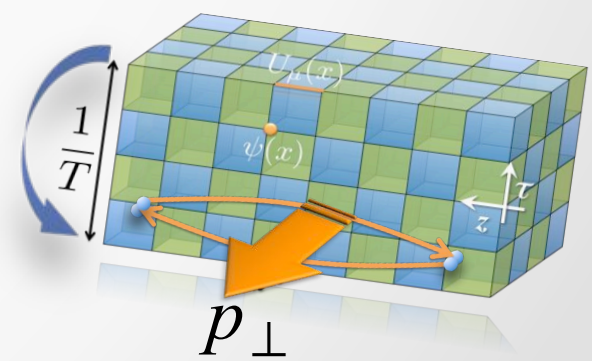
<u>Theoretical investigation:</u>

bound state of J/ψ suppressed at large momentum

in meson effective model, weak coupling effective theory and AdS/CFT
Haglin et al (2001) Escobedo et al (2011) Aarts et al. (2012) Liu et al (2007)

<u>Meson propagators with finite momentum on lattice</u>

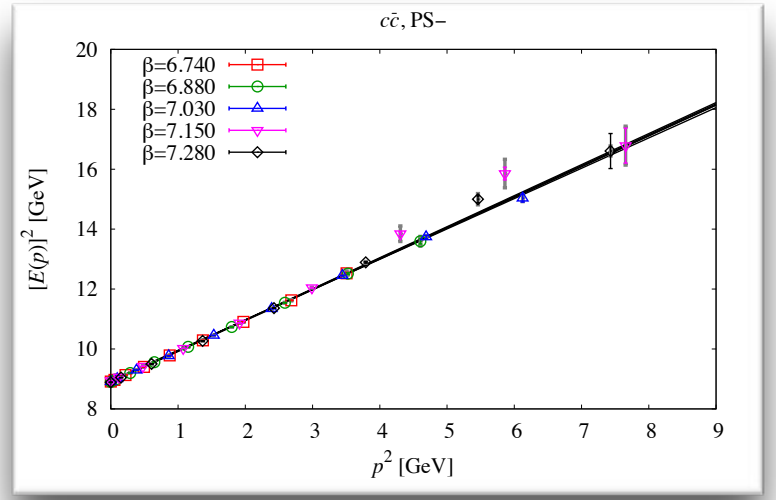
$$G(z,T) = \int dx dy e^{-ip_x x - ip_y y} \int_0^{1/T} d\tau \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle$$
$$\xrightarrow{z\to\infty} A e^{-E(p,M_H)z}$$



momentum on lattice

$$p_\perp^2 = p_x^2 + p_y^2, \quad a p_i = \frac{2\pi k_i}{L_i}, \quad k_i = 0\text{–}N_i/2$$

Dispersion relation of η_c at $T = 0$

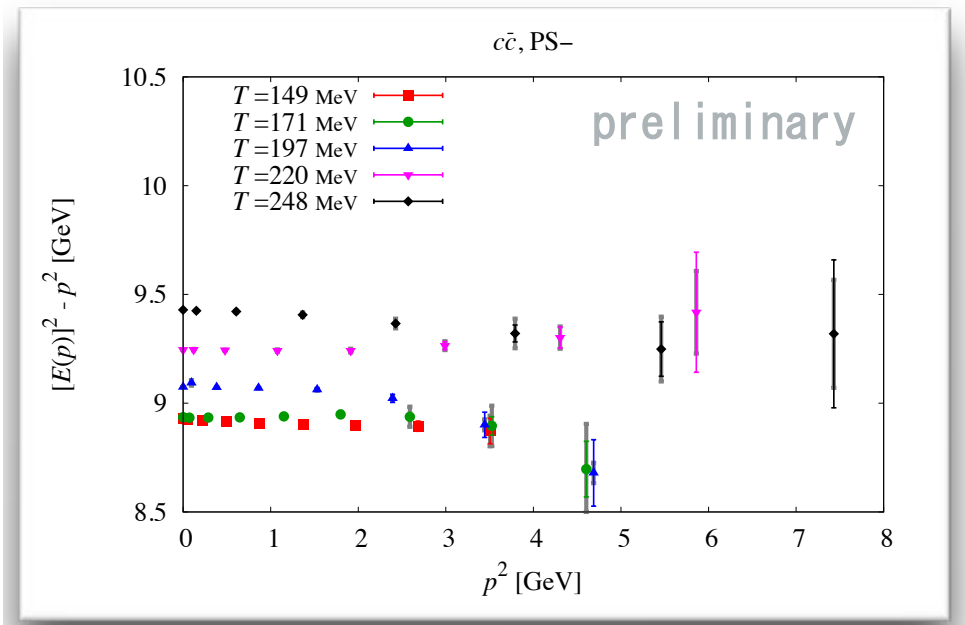


$$E^2 = p^2 + m_{\eta_c}^2$$

satisfied well at $p \lesssim 2\text{–}3$ GeV

data noisy at $p > 3$ GeV

Screening mass at finite temperature



Screening mass with finite momentum

$$M^2(T,p) \equiv E^2 - p_\perp^2$$

no significant momentum dependence at $p_\perp \lesssim 2\text{–}3$ GeV

momentum: $p_\perp \sim m_{\eta_c}$

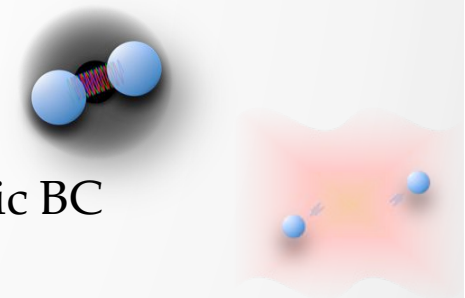
too small to expect strong modification…

larger momentum: in future

Summary

Meson screening masses in Highly Improved Staggered Quarks

for charmonium, open-charm and strangeness



at low T: corresponding to pole mass at $T = 0$

at high T: convergence to $2\sqrt{(\pi T)^2 + m_q^2}$ with Anti-periodic BC

$2m_q$ with periodic BC

Modification due to thermal medium

$\eta_c,\ J/\psi$ survive at $T \sim 1.3\ T_c$

D_s, D_s^* modified at $T \sim T_c$

$(\eta_{s\bar{s}}),\ \phi$ significant modification even at $T < 0.8\ T_c$

Comparison with thermal perturbation: $s\bar{s}$ V— is similar, but PS— is not

➡ no convergence: precise investigation at higher T

No significant momentum dependence on charmonium at $p_\perp < 2$-3 GeV

Future… charmonium: ABC-BC relation to spectral function (MEM)?

strangeness: role in strange fluctuation and deconfinement?