# The 2025 Beijing Particle Physics and Cosmology: early Universe, GW templates, collider phenomenology

# DYNAMICAL QUASIGLUON

For confinement phase transition

Zhaofeng Kang,09/26/2025, based on Works with Jiang Zhu, Jun Guo & Shinya Matsuzaki

1. Dark colored sectors are popular in new physics, e.g., composite Higgs and glueball DM

2. Inspired by GW physics which provides a way to probe the cosmic **first order confinement PT**

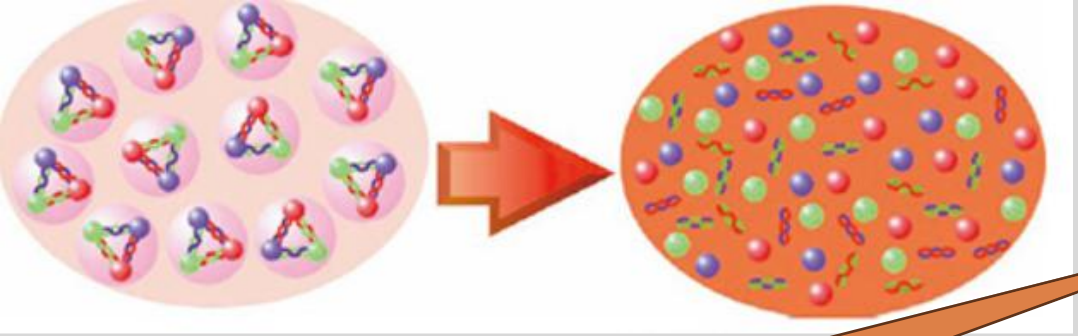
# Part I: Towards the dynamical quasigluon in thermal QFT

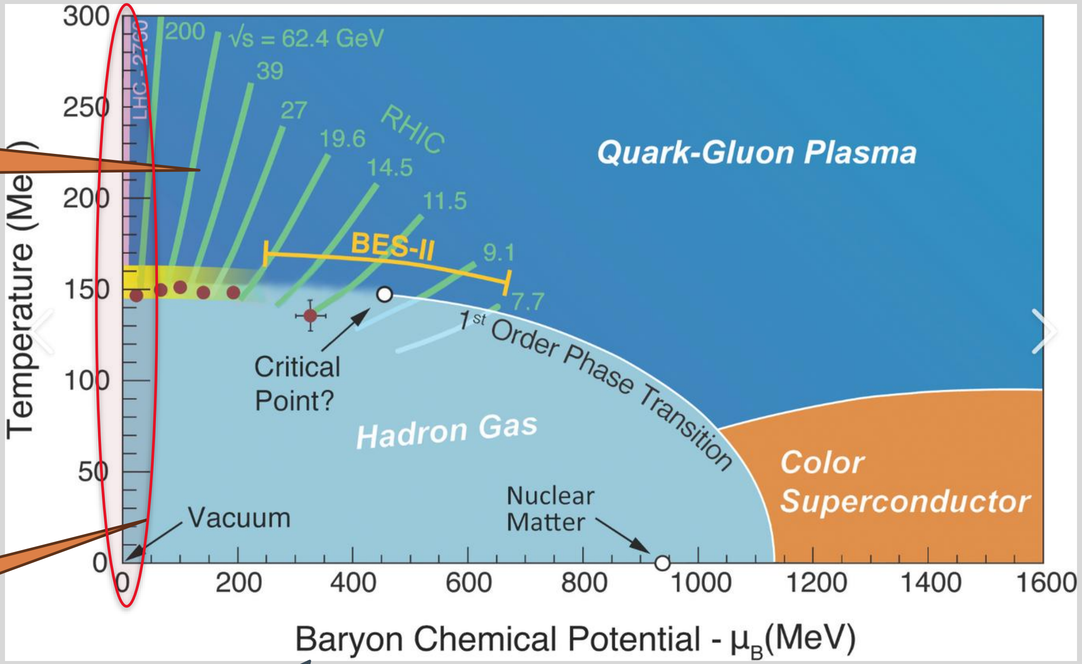
3. Very different than the electroweak-like PT and lack of a perturbative understanding on the confinement PT dynamics

# What are the phases of strongly interacting matter?

Lessons from the real QCD phase diagram (lattice+nonpertubtive approach)

High temperature or/and high density in **a QGP phase** due to asymptotic freedom






Low temperature in the **hadron phase** due to color confinement

How does the transition happen?

In real QCD, it is a crossover in the early universe with $\mu \ll T$, but not the case in the dark QCD

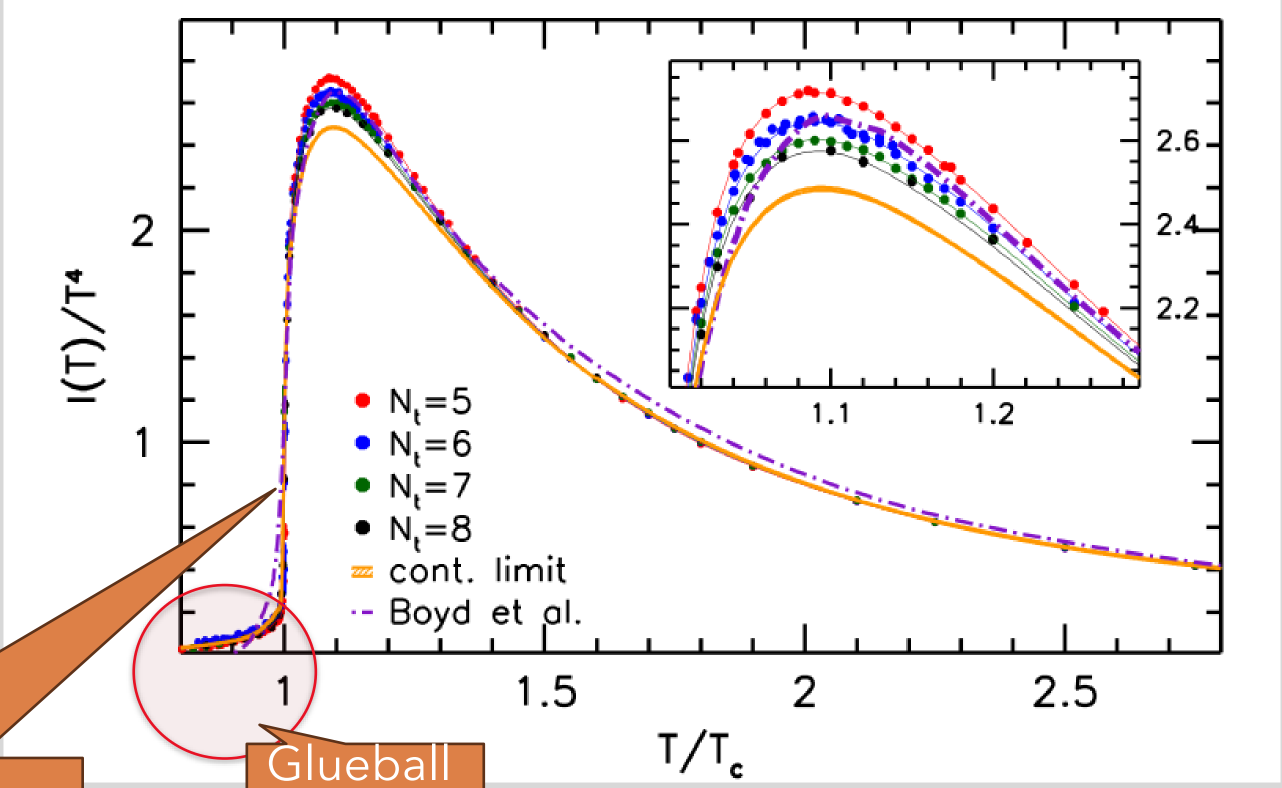
ZK & JiangZhu, JHEP 09 (2025) 005, Large $\mu$ to enhance GW

# How to describe a hot PYM system?

A simpler system: pure gluon system of PYM

Confinement is due to the nonlinear dynamics from the non-Abelian gluon dynamics, so this system provides an easier tiral to understand how confinement happens

Lattice tells us that transition from gluon to glueball is first order for $SU(N > 2)$, moreover, giving thermodynamics




Trace anomaly $\boldsymbol{I \equiv \epsilon - 3p}$ reflects the deviation from ideal gluon gas

Glueball phase

Sz. Borsanyi etc., 2012 for $SU(3)$

# How to describe a hot PYM system?

## Bird view of the hot PYM system

Stefan Boltzmann limit at $T > 10^7$GeV described by a free gluon gas

HTL 重求和

J.O. Andersen, E. Braaten, and M. Strickland, 1999

1. $(T_C, 2-4T_C)$, the strongly coupled QGP regime, with trace anomaly $P(T) \sim c_1(T^4 - c_2 T_c^2 T^2)$

2. For $N$=3,4,6, pressure/energy/entropy density exhibit scaling laws related to $N$

3. The latent heat released also seems to exhibit a scaling law

$$\frac{L_N}{N^2-1} \approx (0.388 - \frac{1.61}{N^2})T_c^4$$

Non-perturbative (NP) effect dominates: **semi-QGP**

Confinement phase decribed by a gas of glueballs

# How to describe a hot PYM system $\sim(T_c, 4T_c)$?

Statistic viewpoint for thermodynamics: Weakly interacting quasi-gluon gas, with mass $M_g(T)$?

V. Goloviznin and H. Satz 1993;
A. Peshier, B. Kampfer, etc., 1996

Dressed gluon with $T$-dependent mass may ``absorb" the NP effect

$$M_g^2(T) = \frac{N}{6} G^2(T) T^2, \quad G^2(T) = \frac{48\pi^2}{11N \log\left(\frac{T}{T_c(\lambda)} + \frac{T_s}{T_c}\right)^2}$$

A form inspired by HTL resummation

$$p(T) = \frac{g(T)}{6\pi^2} \int_0^\infty f_B(E_k) \frac{k^4}{E_k} dk - B(T),$$

$M(T)$ violates the thermodynamic relation for ideal gas, the Gibbs-Duhem relation $\epsilon + p = sT$ with $s = \frac{\partial p}{\partial T}$, and adding $B(T)$ recovers it

Does not involve the order parameter

# How to describe a confinement PT?

order parameter: traced Polyakov loop (PL)

A. M. Polyakov. PLB, 1978

$$L(\vec{x}) = \mathcal{P} \exp\left[ ig \int_0^{1/T} dx_4 A_4(\vec{x}, x_4) \right],$$

Related to the thermal free energy of heavy static quarks
$e^{-F_q/T} = \langle \mathrm{tr}_c L(\vec{x}) \rangle \equiv l(\vec{x}) \Rightarrow l \to 0$, color confinement;
otherwise deconfinement

Svetitsky, L. G. Yaffe.
NPB, 1982

Charged under global center $Z_N \subset SU(N)$ :
$l \to z_k l, \quad z_k = e^{\frac{i2k\pi}{N}} I_{N\times N}$

Center symmetry breaking/conservation
$\Leftrightarrow$ Deconfinement/confinement

How to handle the **centerless gauge group such as** $G_2$ ?

# How to describe a confinement PT?

To get a $Z_N$-invariant Landau free energy $L[\ell]$

Haar measurement inspired by strong coupling expansion

$$\frac{\mathcal{V}_{\text{Haar},0}(L,T)}{T^4} = C_2(N)\left[6\exp(-C_1(N)/T)N^2 l l^\dagger + \log H_N[L]\right],$$

$$H_N[L(\vec{x})] = \Pi_{i<j}|e^{i2\pi q_i(\vec{x})} - e^{i2\pi q_j(\vec{x})}|^2.$$

$$\mathcal{U}(l,T) = \frac{V(l,T)}{T^4} = -\frac{a(T)}{2}|l|^2 + b|l|^4 + c|l|^6,$$

Completely by construction, .e.g., polynomial model

ZK, Jiang Zhu & Shinya Matsuzaki, JHEP 21

W. C. Huang, M. Reichert, F. Sannino & Z. W. Wang, PRD21

To develop a **unified** description of confinement PT!

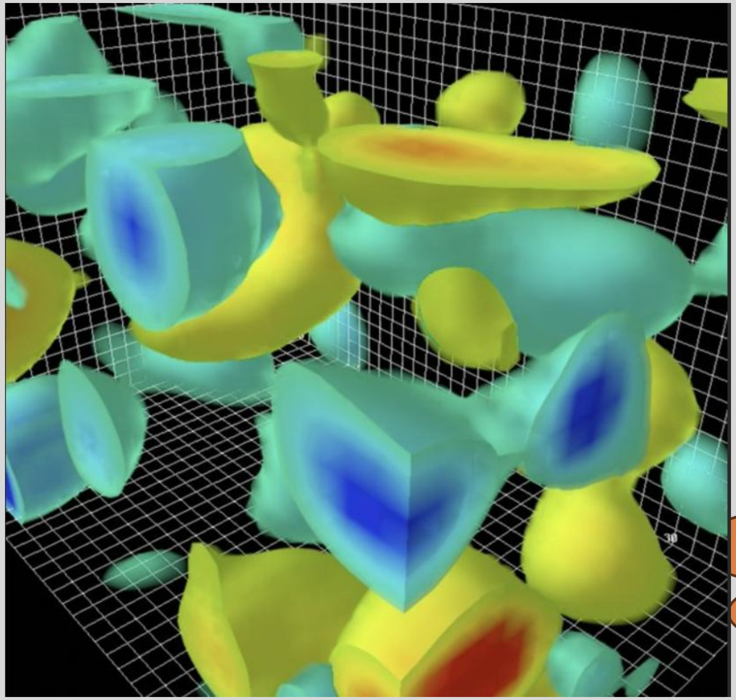
both the order of PT and thermodynamics for any $SU(N)$

# PYM with dynamical quasigluon mass

Towards the massive PYM in the thermal QFT

At $T = 0$, it is traced back to Fradkin et al. (1969)

refined by M. Tissier & N. Wschebor (2010) for addressing the infrared dynamics of YM to remove Gribov copy in the FP procedure



Modern picture of Yang-Mills vacuum medium: full of gluon fluctuations

Lattice data reveals that the **gluon propagates in such a vacuum gains a dynamical mass**, whether at finite or zero $T$, while the ghost field does not

# PYM with dynamical quasigluon mass

Junguo, Zhaofeng Kang & Jiang Zhu, PRD23

Quasigluon massive PYM

$$\mathcal{L} = -\frac{1}{2g^2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{D}_\mu \bar{c}^a D^\mu c^a + i h^a \bar{D}_\mu \hat{A}^{\mu,a} + \frac{1}{2}M_g^2(T)\hat{A}^a_\mu \hat{A}^{a,\mu},$$

FP Lagrangian with massive gluon fluctuations

provide a way to perturbatively calculate the free energy from deep UV to deep IR?

$$\log Z = VT\left[3\int \frac{d^3p}{(2\pi)^3}\log\det\left(1-\hat{L}_A e^{-\frac{E_g}{T}}\right) - \int \frac{d^3p}{(2\pi)^3}\log\det\left(1-\hat{L}_A e^{-\frac{|\vec{p}|}{T}}\right)\right],$$

PL in the adjoint representation

$$\hat{L}_A = \mathrm{diag}[1, 1, ..., 1, e^{i2\pi q_{ij}}, ..., e^{-i2\pi q_{ij}}],$$

Ghost-driven PT mechanism: In the IR, the large quasigluon mass suppresses the contribution of gluon thermal fluctuations, thereby enhancing the ghost

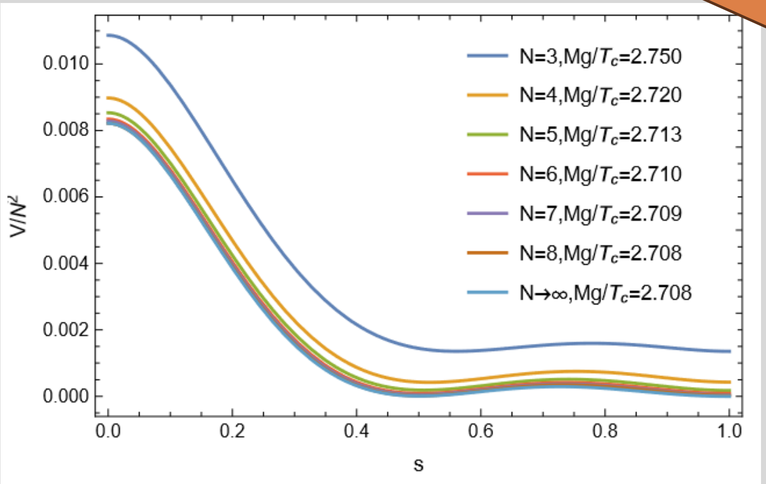
# PYM with dynamical quasigluon mass

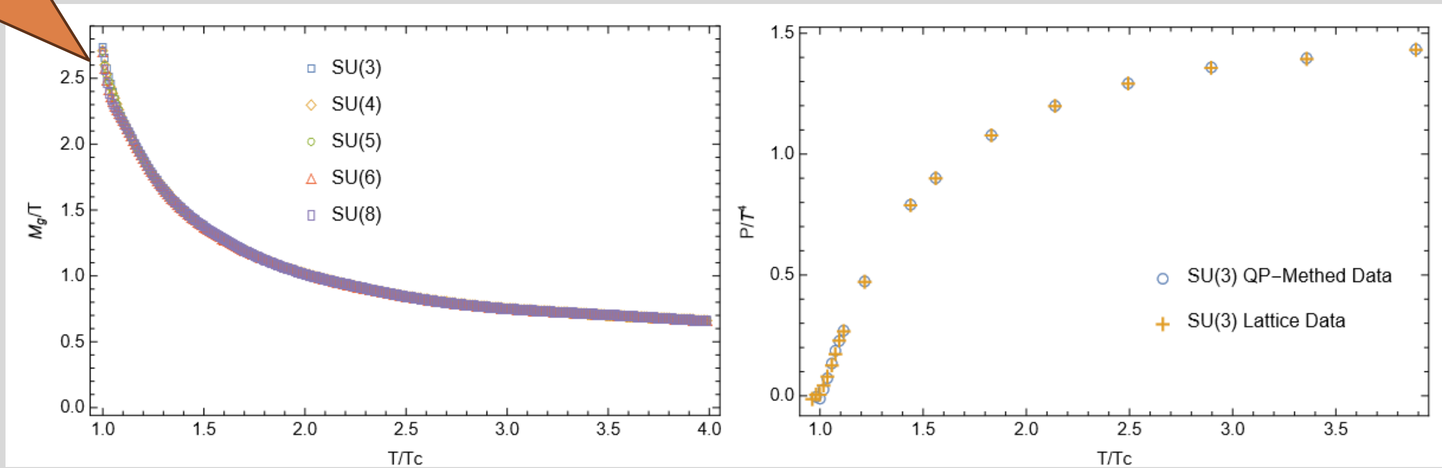
Junguo, Zhaofeng Kang & Jiang Zhu, PRD23

$$\frac{\mathcal{V}_N(s,T)}{N^2/2} \simeq -\frac{3T^4}{\pi^2}\left(\frac{M_g}{T}\right)^2 K_2(M_g/T)\left[\frac{\sin(\pi s)}{\pi s}\right]^2 + \frac{\pi^2 T^4}{45}(s-1)^2(1+2s-2s^2),$$

the assumption of equal eigenvalues (eigenvalue repulsion principle) of PL, which is a matrix

Using machine learning to fit the quasigluon masses, which are normal and **show unified behavior for $N$?**



1. Wall velocity is the key to theoretical prediction of gravitational wave spectrum

2. Difficult for the confinement PT where origin of plasma friction is unknown microscopically

# Part II: Towards the bubble wall velocity of confinement PT

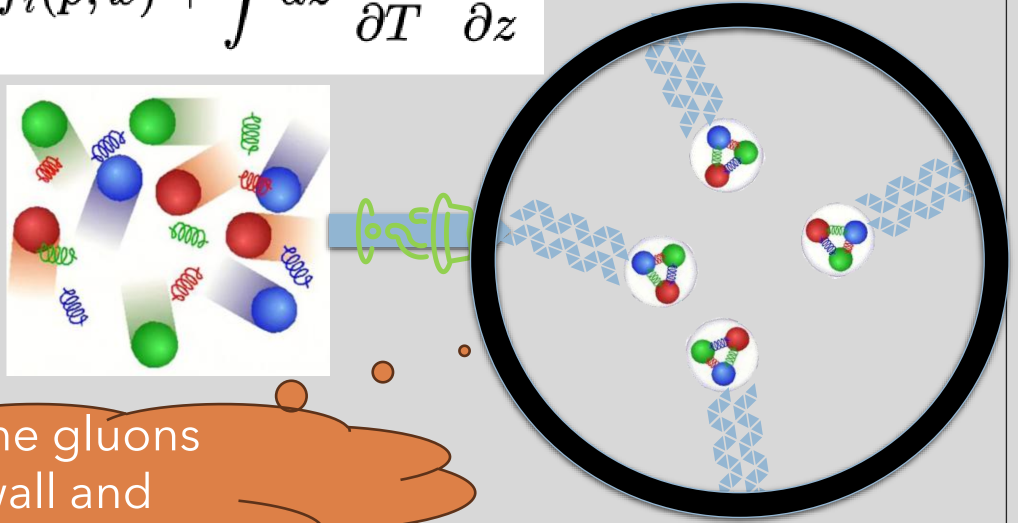
3. The dynamical quasigluon picture **incorporating both particle and order parameter** provides a microscopic way to do this job

# Usual bubble wall velocity

In the EW-like PT, the bubble wall velocity $v_w$ in the plasma is relatively clear, due to the balance between free energy difference and plasma friction by mass changing

$$\frac{F_{\text{pressure}}}{A} = \Delta V_T = \frac{F_{\text{back}}}{A} = -\sum_i \frac{\mathrm{d}m_i^2(\phi)}{\mathrm{d}\phi} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{1}{2E_{\vec{p}}} \delta f_i(p,x) + \int dz \frac{\partial V_T}{\partial T} \frac{\partial T}{\partial z}$$

The order parameter field, the Higgs wall, feedbacks to plasma via mass changing

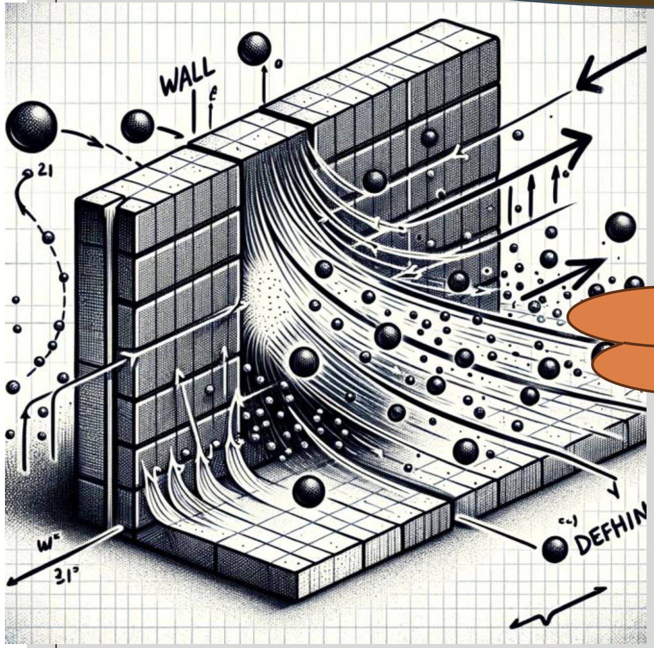


What happened as the gluons pass through the wall and become glueball?

# Dynamical quasipartile determination of $v_w$

Zhaofeng Kang & Jiang Zhu, 05 (2025) 056

Calculate the momentum transfer of incident particles from both sides.




Calculated in the wall frame

$$\frac{dF_W}{A} = \frac{d^3\vec{p}}{(2\pi)^3} v_z f(p) \Delta p_z P(\Delta p_z)$$

probability of a particle passing the wall

$$\mathcal{R} = \frac{(p_z^d - p_z^c)^2}{(p_z^d + p_z^c)^2} \text{ and } \mathcal{T} = \frac{4 p_z^d p_z^c}{(p_z^d + p_z^c)^2}$$

The incident particle flux factor, **determining the distribution function $f_W$ is crucial**

The change in momentum of particles passing through wall

$$\frac{F_W}{A} = \int \frac{d^3\vec{p}_d}{(2\pi)^2} v_z^d f(p^d)[2p_z^d \mathcal{R} + (p_z^d - p_z^c)\mathcal{T}]\Theta(p_z^d) - \int \frac{d^3\vec{p}_c}{(2\pi)^2} v_z^c f(p^c)[2p_z^c \mathcal{R} + (p_z^c - p_z^d)\mathcal{T}]\Theta(-p_z^c)$$

# Dynamical quasipartile determination of $v_w$

Zhaofeng Kang & Jiang Zhu, 05 (2025) 056

Non-ideal fluid with an imaginary chemical potential

An effective distribution function obtained from the free energy

$$f_{W,a}(v_w, p, z) = 1/(\exp\beta[\gamma(E - v_w p_z) + \mu_a(z)] - 1)$$

The PL background enters as an imaginary chemical potential $\mu_a \sim \frac{is}{N} T$, reflecting the suppression of quasigluon density in the confined phase with $s_c = 1$

$\langle A_0 \rangle$ changes the quasigluon dispersion relation thus momentum change

$$(p_0 - \mu_a)^2 = |\vec{p}|^2 + M_g^2,$$

$$(p_0 - \mu_a)^2 = |\vec{p}|^2.$$

$$\Delta p_z^a = \sqrt{(p_0 - \mu_d^a) - |\vec{p}|^2 - m^2} - \sqrt{(p_0 - \mu_c^a) - |\vec{p}|^2 - m^2}$$

# Dynamical quasipartile determination of $v_w$

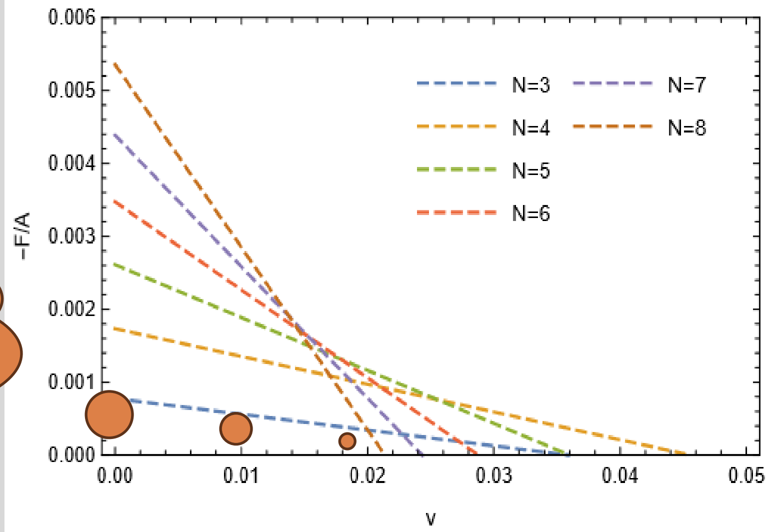
Zhaofeng Kang & Jiang Zhu, 05 (2025) 056

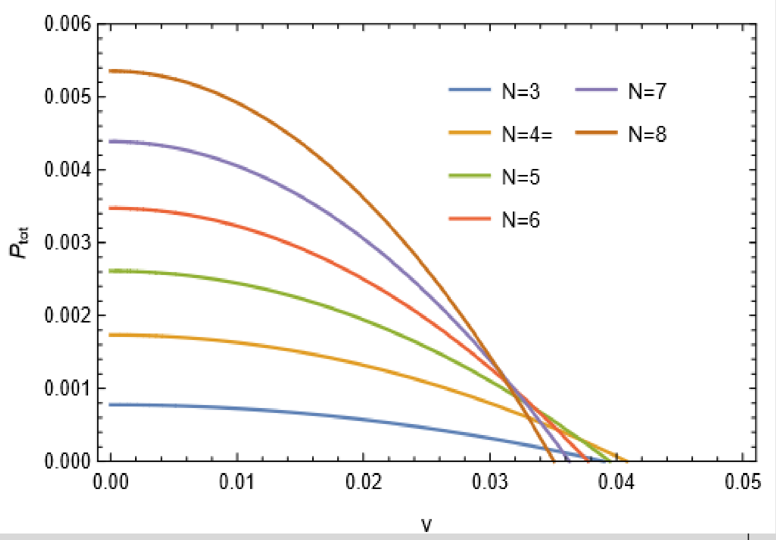
## Wall velocity in low $v_w$ expansion

$$\frac{F_W}{A} = \mathcal{P}(s_d) - \mathcal{P}(s_c) + 2 v_w \beta \int \frac{d^2 p_\perp}{(2\pi)^2} \int_0^{\Re[p'_z]} \frac{dp_z^d}{2\pi} f(p_0)[f(p_0)+1] p_z^{d\,2} + v_w \beta \int \frac{d^3 \vec{p}^d}{(2\pi)^3} \frac{p_z^d}{\sqrt{|\vec{p}^d|^2 + M_g^2}} f(p_0)[f(p_0)+1](p_z^d - p_z^c)^2,$$

In $v_w \to 0$, the two-phase pressure difference was successfully reproduced

Non-relativistic wall with $v_w \sim 0.01$, qualitatively consistent with other methods



# SUMMARY & OUTLOOK

We propose to modify YM near $T_c$ by considering massive gluon fluctuations with dynamical mass $M(T)$, successfully accounting for the $SU(N)$ confinement dynamics

To dig the more profound version of this effective model, e.g. dynamical mass from the gluon condensation; to see if it is consistent with the usual nonperturbative approach such as functional renormalization group

Thanks for your attention!