



Quarkonium transport @ SPS energy and below

Exploring high- μ_B matter with rare probes @ ECT* (Hybrid)

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Outline

■ Quarkonium and QGP in low-T high- μ_B

- Relevant scales for quarkonium and pre-equilibrium QGP
- Importance of pre-equilibrium QGP as background to quarkonium transport

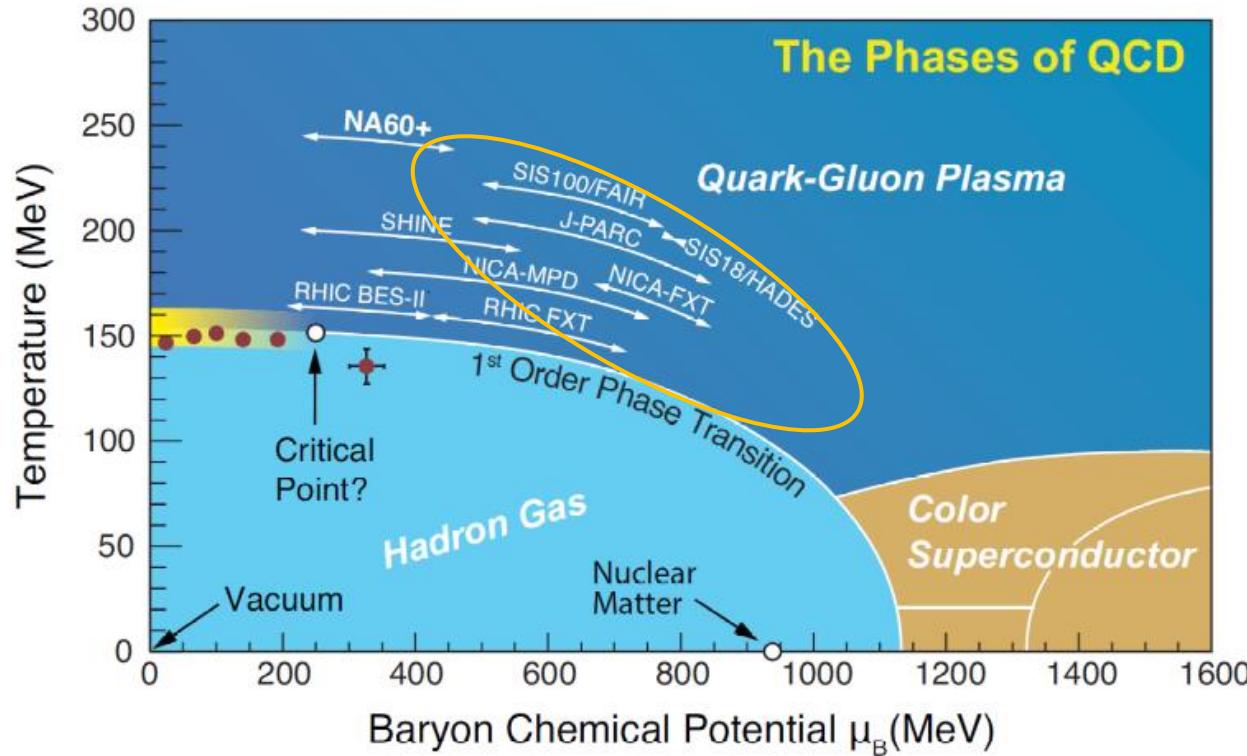
■ Pre-equilibrium QGP description at high- μ_B

- Pre-equilibrium QGP at finite baryon density from effective kinetic theory
- Constraining pre-equilibrium QGP from multiplicity and di-lepton

■ Quarkonium transport in pre-equilibrium high- μ_B matter

- Quarkonium width in plasma modified by pre-equilibrium QGP (chemically, kinetically and anisotropically)
- Relation to heavy quark and phenomenology

Quarkonium and QGP in CBM



De Falco, arXiv:2108.11300

Compressed Baryonic Matter (CBM)

Lower temperature:

Longer QGP formation time, shorter hydro period, kinetics

higher baryon density: baryon rich initial state

Even longer QGP formation time, chemistry

Quarkonium and QGP in CBM

Scales of heavy quark/quarkonium

Heavy quark production:

$$t_{\text{form}}[\text{charm}] \sim 1/m_c = 0.12 \text{ fm}, \quad t_{\text{form}}[\text{bottom}] \sim 1/m_b = 0.04 \text{ fm}$$

Quarkonium production

$$t_{\text{form}}[J/\psi] \sim 1/E_c \sim 0.3 \text{ fm}, \quad t_{\text{form}}[Y(1S)] \sim 1/E_b \sim 0.2 \text{ fm}$$

Scales of plasma

Hydrodynamization time :

$$\tau \simeq 1.3 \text{ fm}/c \left(\frac{4\pi\eta/s}{2} \right)^{\frac{3}{2}} \left(\frac{dN_{ch}/d\eta}{1942} \right)^{-\frac{1}{2}} \left(\frac{S_\perp}{138 \text{ fm}^2} \right)^{\frac{1}{2}} \left[1 + \sum_f \left(\frac{\mu_f}{T} \right)^2 \right]^{\frac{1}{2}}$$

XD, Schlichting, PRL127(2021)122301

1. At CBM, there is $\sim O(\mu_B)$ correction to the above formula (nonlinear)

2. For instance at SPS PbPb@17AGeV, multiplicity $dN_{ch}/d\eta < 400$

$t_{\text{form}}[\text{QGP}] > 1 \text{ fm}$ (even for holographic limit of $\eta/s \sim 1/4\pi$)

Low energy, CBM, larger η/s increase the QGP formation time: $t_{\text{form}}[\text{QGP}] \gg 1 \text{ fm}$

$t_{\text{form}}[\text{QGP}] \gg t_{\text{form}}[J/\psi]$: Pre-equilibrium QGP description is needed

QGP at high- μ_B : Transport

Simulation with QCD Effective Kinetic Theory (EKT)

$$\left(\frac{\partial}{\partial \tau} - \frac{p_{\parallel}}{\tau} \frac{\partial}{\partial p_{\parallel}} \right) f_a(\tau, p_T, p_{\parallel}) = -C_a^{2 \leftrightarrow 2}[f](\tau, p_T, p_{\parallel}) - C_a^{1 \leftrightarrow 2}[f](\tau, p_T, p_{\parallel})$$

Arnold, Moore, Yaffe, JHEP01 (2003) 030

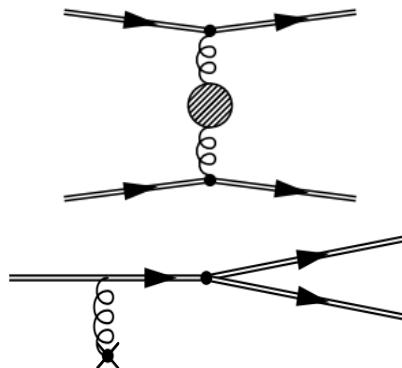
Arnold, Moore, Yaffe, JHEP0206 (2002) 030

Kurkela, Mazeliauskas, PRD99 (2019) 054018

Solving a set of coupled Boltzmann equations

Including all light quarks/antiquarks and gluon $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}$

Including LO $2 \leftrightarrow 2$ elastic scatterings and $1 \leftrightarrow 2$ inelastic scatterings, with back reaction

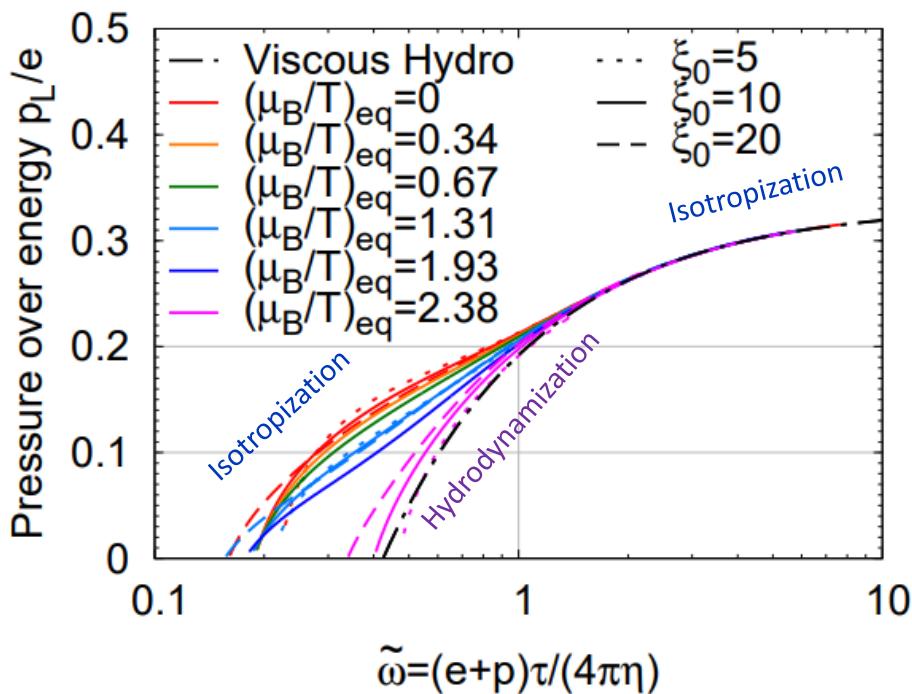
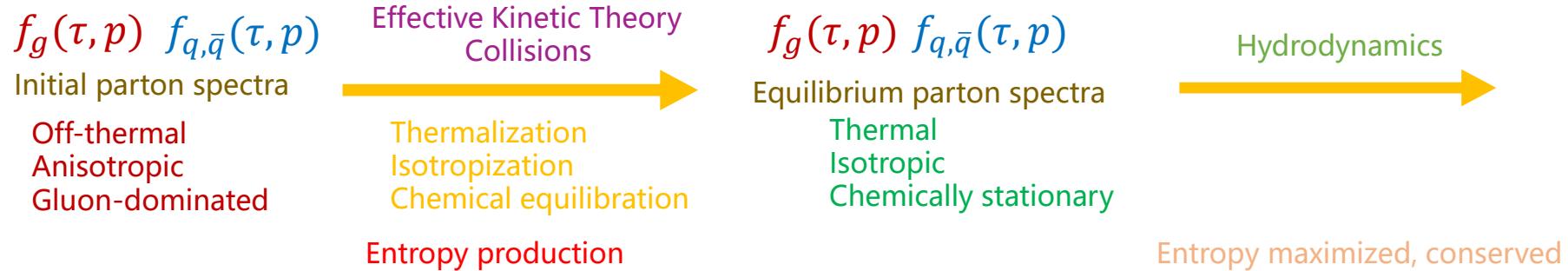


$2 \leftrightarrow 2$: Color screening by Debye mass fit to Hard Thermal Loop (HTL) calculation

$1 \leftrightarrow 2$: Collinear radiation including Landau-Pomeranchuk-Migdal (LPM) effect via effective vertex resummation

Provides first principle calculation of
pre-equilibrium QGP
at finite baryon density

QGP at high- μ_B : Dynamics



Hydrodynamization

1st-order hydro constitutive relation

$$\frac{p_L}{e} = \frac{1}{3} - \frac{4}{9\pi\tilde{\omega}}$$

Universal time scaling: Hydrodynamization finishes $\omega \sim 1$

$$\tilde{\omega} = \frac{(e + p)\tau}{4\pi\eta}$$

Although the isotropization/chemical reaction is not ended

Constrain the dynamics? Match final entropy to data

QGP at high- μ_B : Equilibration

Constrain from multiplicity/baryon density

Entropy density from EKT,
charged particle multiplicity from data

$$(\tau s)_{eq} = \frac{\tau(e + p - \sum_f \mu_f \Delta n_f)}{T}$$

$$\frac{dN_{ch}}{d\eta} = \frac{N_{ch}}{JS} (\tau s)_{eq} S_T \approx 0.12 (\tau s)_{eq} S_T$$

net baryon number from EKT,
entropy per baryon from data

$$\Delta n_B = \frac{1}{3} \Delta n_u + \frac{1}{3} \Delta n_d$$

$$\frac{S}{N_B} = \left(\frac{\tau s}{\tau \Delta n_B} \right)_{eq}$$

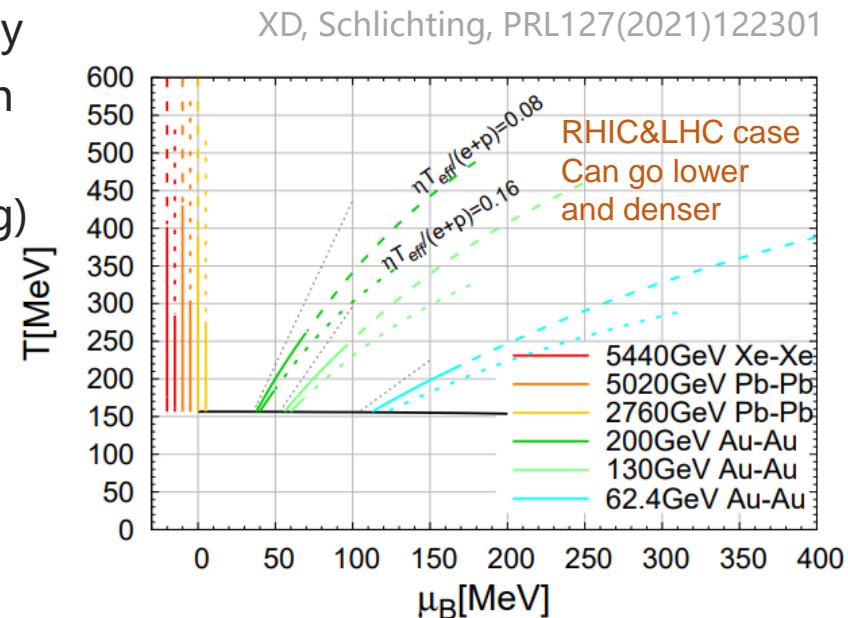
Pre-equilibrium QGP background

1. Estimate initial density with attractor theory
2. Perform QCD matter evolution via EKT with above constraints
3. Define effective T and μ_B (Landau matching)

Further constraints

For instance, η/s ?

some other probes of pre-equilibrium QGP...



QGP at high- μ_B : Di-lepton as a probe

Electromagnetic probes

Coquet, XD, Ollitrault, Schlichting, Winn, PLB821(2021)136626

Produced through-out HICs, not interacted with QGP, photon, di-lepton

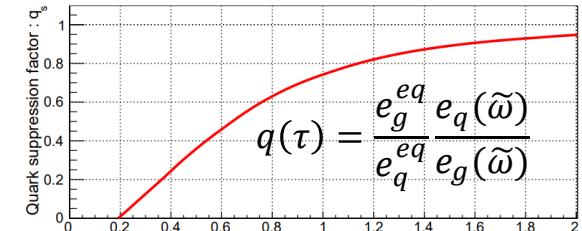
Di-lepton production proportional to $\exp(-M/T)$, important at early stage of HICs

$$\frac{dN^{l+l-}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} 4N_c \sum_f f_q(x, p_1) f_{\bar{q}}(x, p_1) v_{q\bar{q}} \sigma_{q\bar{q}}^{l+l-} \delta^{(4)}(K - P_1 - P_2)$$

Chemical equilibration

Quark abundance increases (YM plasma \rightarrow QCD plasma)

At high baryon density, less obvious?



Di-lepton as a probe of viscosity

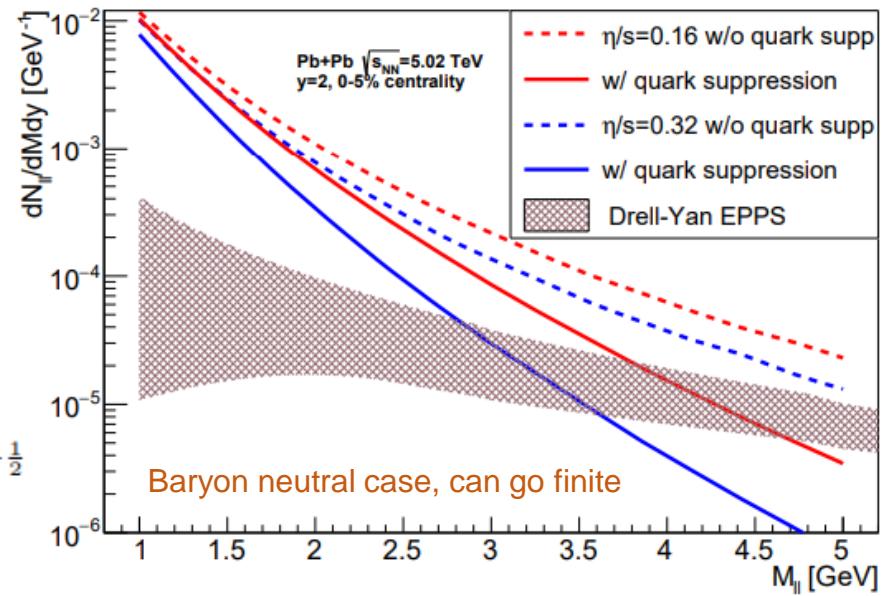
Constraining viscosity, e.g. η/s

larger viscosity, lower temperature

(hydro temperature)

$$T \simeq 300 \text{ MeV} \left(\frac{4\pi\eta/s}{2} \right)^{-\frac{1}{2}} \left(\frac{dN_{ch}/d\eta}{1942} \right)^{\frac{1}{2}} \left(\frac{S_\perp}{138 \text{ fm}^2} \right)^{-\frac{1}{2}}$$

XD, Schlichting, PRL127(2021)122301



Quarkonium at high- μ_B : Transport

Kinetic theory approach

$$\left(\frac{\partial}{\partial \tau} - \nu \cdot \nabla \right) f_\Psi(\tau, p, x) = -(C_{\Psi, LO}^{2 \leftrightarrow 2} + C_{\Psi, NLO}^{2 \leftrightarrow 3})[f](\tau, p, x) = \boxed{-\alpha(\tau, p)} f_\Psi(\tau, p, x) + \boxed{\beta(\tau, p)} \text{ suppression regeneration}$$

gluo-diss quasi-free

Zhao, Rapp PRC82(2010)064905
XD, He, Rapp, PRC96(2017)054901

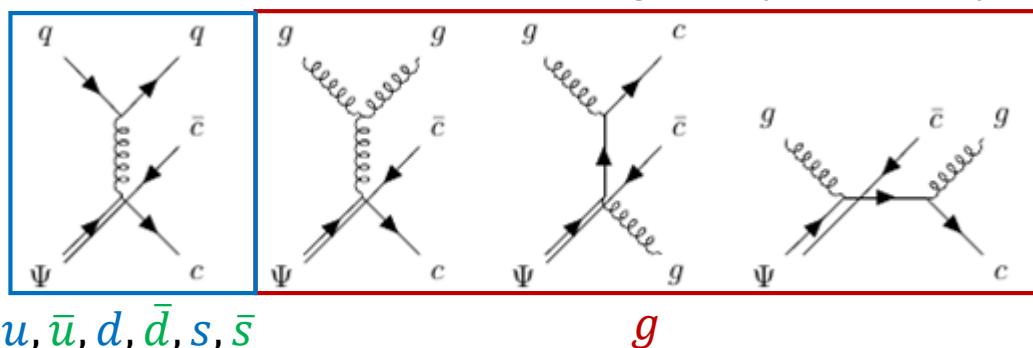
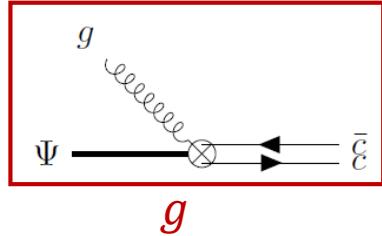
Solving a Boltzmann equation of quarkonium

Including LO $2 \leftrightarrow 2$ singlet-octet transition (gluo-dissociation)

Peskin, NPB156(1979)365,
Bhanot, Peskin, NPB156(1979)391

and NLO $2 \leftrightarrow 3$ Landau damping (quasi-free), with back reaction

Grandchamp, Rapp, PLB523(2001)60



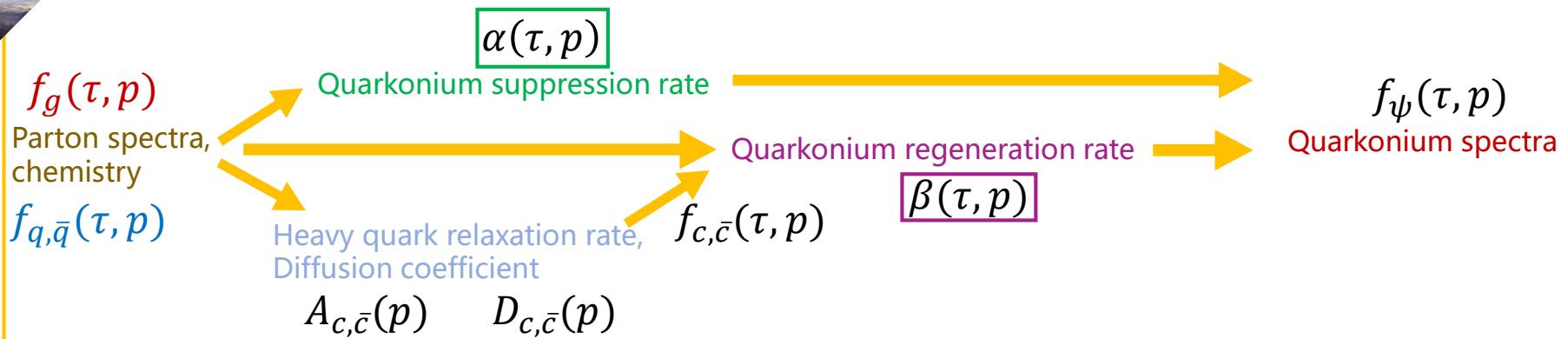
CBM as its background

Long pre-equilibrium stage: 1. partons not in thermal; 2. quark/gluon abundances change.

High baryon density: quark rich, but anti-quark barren

Needs to have individual evaluation of each process in NLO rate with off-thermal parton scattering.

Quarkonium at high- μ_B : Dynamics



Two types of parton/medium equilibration

Kinetic equilibration (hydrodynamization including thermalization + isotropization):
Initial far-from equilibrium gluon/quark spectra become thermal (finally BE/FD distribution)

Chemical equilibration:

Initial gluon/quark abundances/fractions become stationary (finally BE/FD with chemical potential)

Two types of reaction mechanism with quarkonium

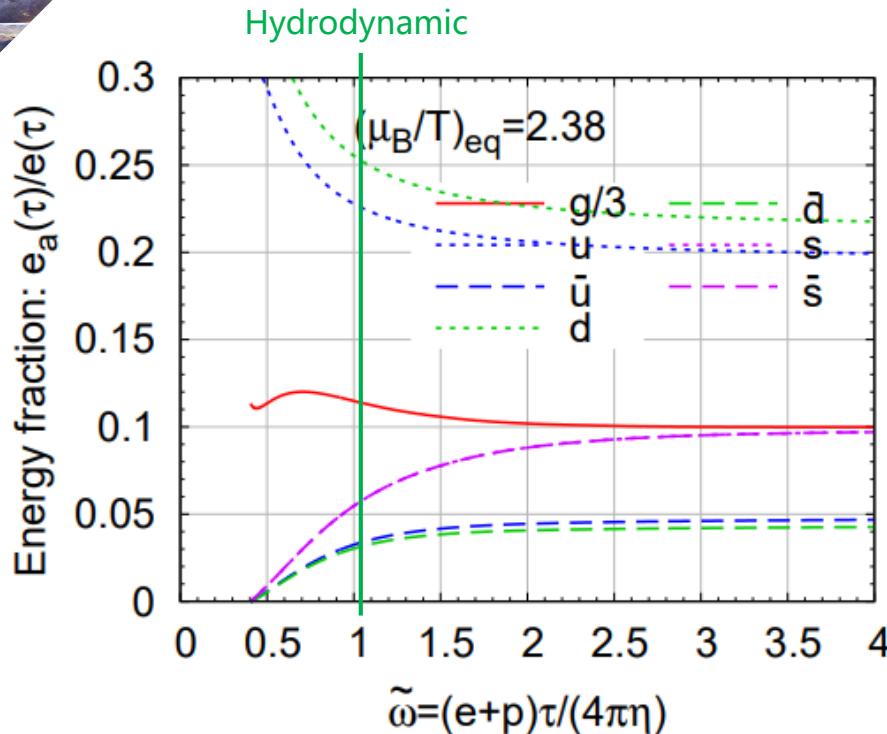
Suppression:

Medium modification to **quarkonium suppression rate** $\alpha(t,p)$

Regeneration:

Medium modification to **charm relaxation rate** $A(t,p)$, further to **onium regeneration rate** $\beta(t,p)$

Quarkonium at high- μ_B : Chemistry

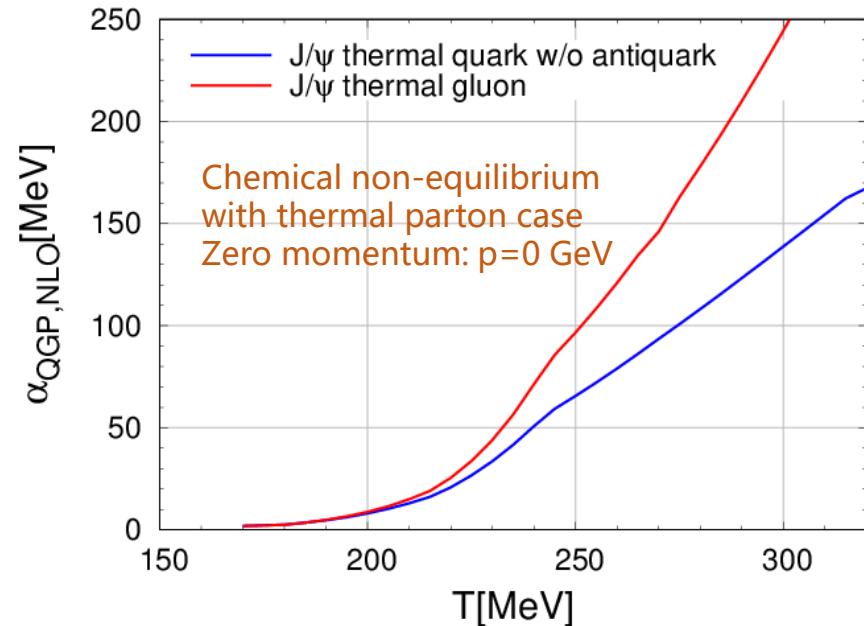


XD, Schlichting, PRD104(2021)054011

Chemical equilibration at high- μ_B
(not subject to any specific collision)

Chemical fraction evolution of
gluon/quark/antiquark depends on initial
condition/collision systems

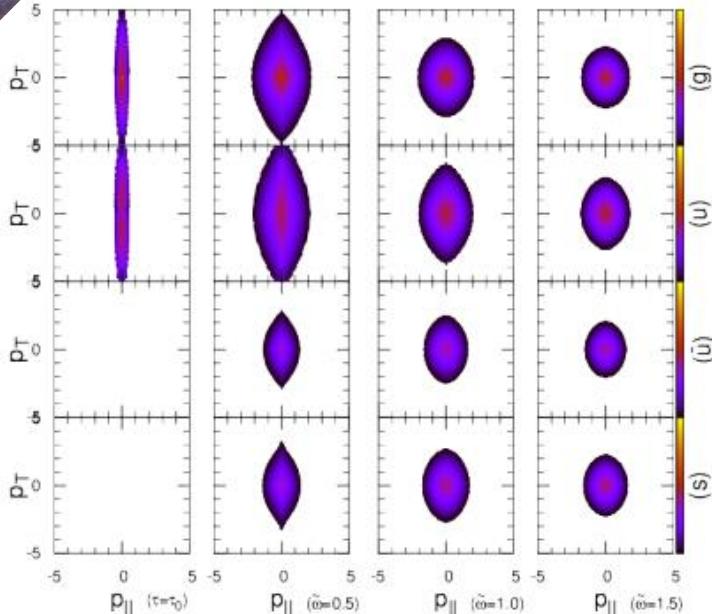
Chemical equilibration > hydrodynamization



Quarkonium width at high- μ_B
Effects even with thermal parton:
(More effects with off-thermal parton)

QGP chemistry also important in (thermal)
hydrodynamic stage

Quarkonium at high- μ_B : Anisotropy



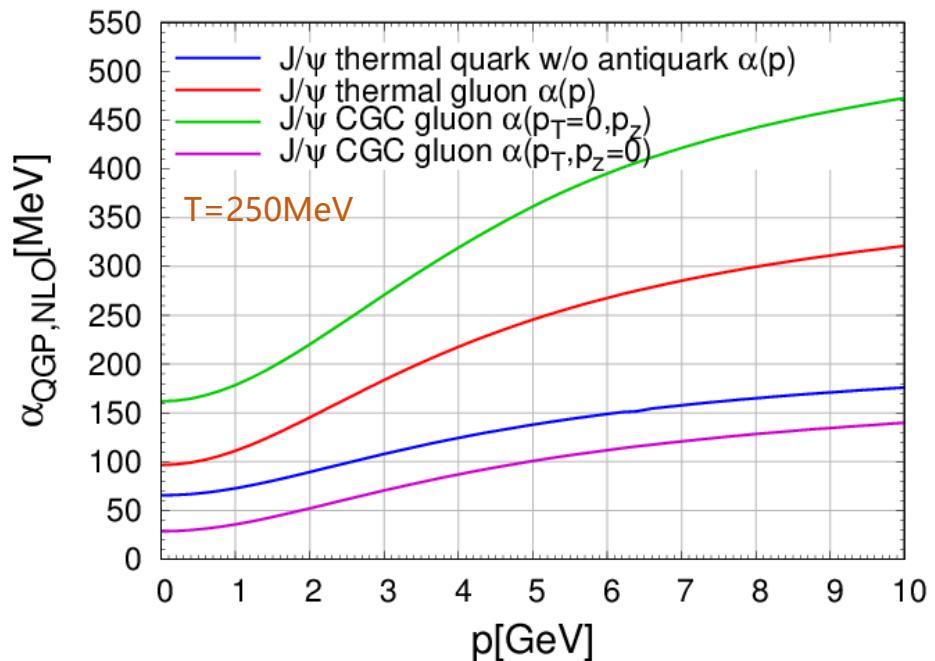
XD, Schlichting, PRD104(2021)054011

Anisotropic initial spectra
(Color glass condensate)

$$f_g(\tau_0, p_T, p_{\parallel}) = f_g^0 \frac{Q_0}{\sqrt{p_T^2 + \xi_0^2 p_{\parallel}^2}} e^{-\frac{2(p_T^2 + \xi_0^2 p_{\parallel}^2)}{3Q_0^2}}$$

Softer in transverse momentum

Harder in longitudinal momentum



Anisotropic reaction rate
Suppressed in transverse momentum
Enhanced in longitudinal momentum

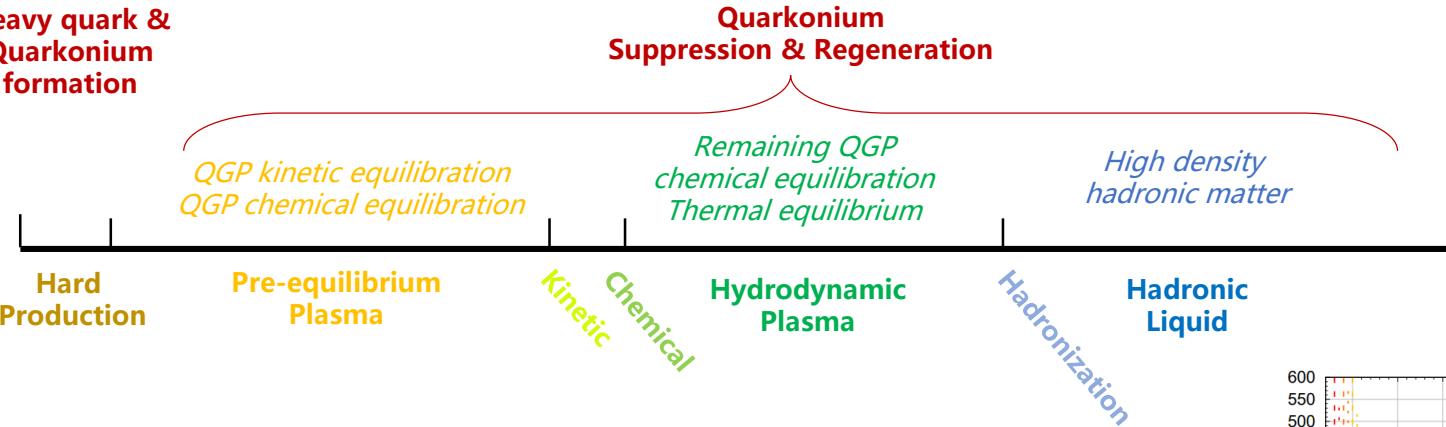
Phenomenology

Contribution to p_T -spectra/ v_2 in two ways:
Less quarkonium suppression in transverse
Less heavy quark energy loss/diffusion in transverse
But in transverse, it will be compensated by chemistry (more gluon in pre-equilibrium stage)

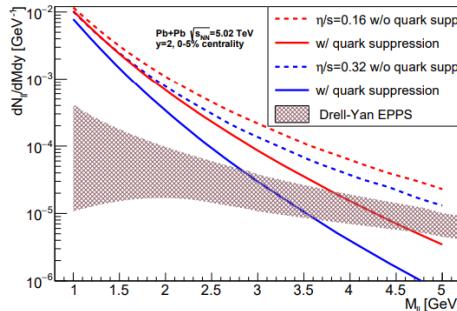
Conclusions

- Pre-eq stage important for quarkonium transport at low energy CBM

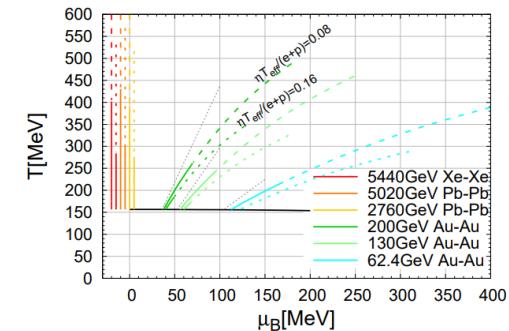
Heavy quark &
Quarkonium
formation



- QCD EKT at finite density for medium description



- Multiplicity and di-lepton data useful to constrain pre-eq QGP (η/s , anisotropy, ..)



- Quarkonium/heavy quark reaction width modified in pre-eq high- μ_B matter, by chemistry, anisotropy, etc.

