# Heavy quarkonium at finite temperature

## (from lattice QCD)

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**International Workshop on High Energy Physics**
*"Hard Problems of Hadron Physics: Non-Perturbative QCD & Related Quests"*
Logunov Institute, Protvino, Russia, 11/10/2021

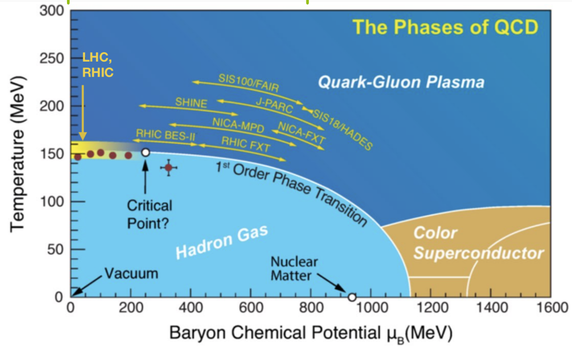
Bottomonium . . . using . . . quantum trajectories . . . :
JHEP 05 (2021) 136; arXiv:2107.06147[physics.comp-ph]; Phys.Rev.D ? (2021)
Bottomonium melting from screening correlators at high temperature,
Phys.Rev.D 104 (2021) 5, 054511
**Static quark anti-quark interactions at non-zero temperature from lattice QCD, arXiv:2110.11659[hep-lat]**

# Outline

1. Appetizer: link to heavy-ion phenomenology
   - Motivation
   - Historical perspective on "Heavy quarkonium at $T > 0$"
2. Main course: modern perspective on "Heavy quarkonium at $T > 0$"
   - In-medium quarkonium at weak coupling
   - Lattice QCD
   - Relativistic bottomonium
   - Nonrelativistic $q\bar{q}$ pair on the lattice
   - In-medium static quarkonium
3. Dessert: bringing "Heavy quarkonium at $T > 0$" full circle

# Phase diagram of QCD & heavy-ion collisions

Weak-coupling picture may eventually work at very high $T$ or $\mu_B$




Neutron stars

- High temperature phase of nuclear matter: quark-gluon plasma (QGP)
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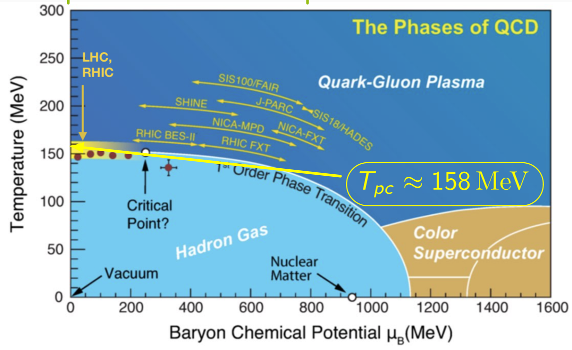
# Phase diagram of QCD & heavy-ion collisions

Weak-coupling picture may eventually work at very high $T$ or $\mu_B$




Neutron stars

- High temperature phase of nuclear matter: quark-gluon plasma (QGP)
- Primordial state of nuclear matter before the hadronic freezeout
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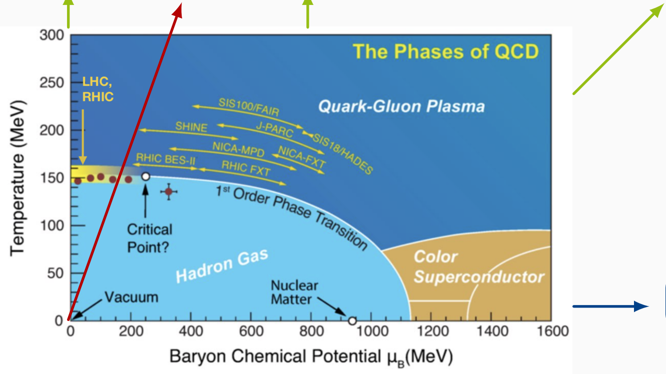
# Phase diagram of QCD & heavy-ion collisions

Weak-coupling picture may eventually work at very high $T$ or $\mu_B$

Lattice Gauge Theory

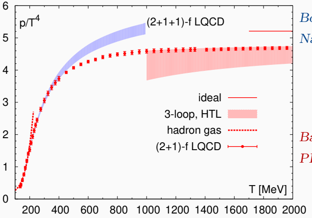



Neutron stars

- High temperature phase of nuclear matter: quark-gluon plasma (QGP)
- Primordial state of nuclear matter before the hadronic freezeout
- QGP can be produced in heavy-ion collision (HIC) experiments
- How to define thermodynamic state variables for such dynamic media?

# Interplay between lattice gauge theory and heavy-ion collisions

- Fruitful interplay of lattice gauge theory & heavy-ion collisions
- Search for the critical point and scan of the QCD phase diagram
- or **equation of state**, QNS, ...
- But: many heavy-ion collision experiments shift their focus




*Borsanyi, et al., Nature 539 (2016)*

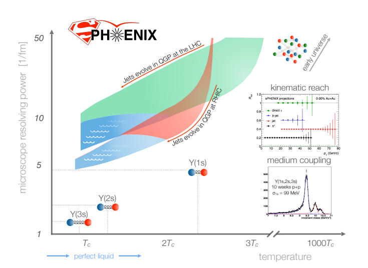
*Bazavov, et al., PRD 97 (2018)*

Recent results → *Bazavov, et al., aXiv:2110.03606 [hep-lat]*

Questions @ *ALICE*, *CMS*, *sPhenix*, ...

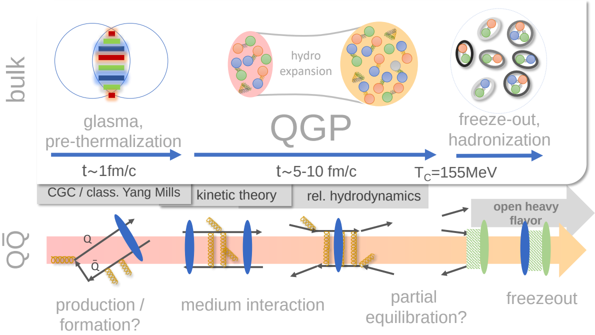
- How do **parton showers** develop and propagate in QGP?
- How to reconcile asymptotic freedom and observed strongly-coupled QGP
- Which **dynamical degrees of freedom** play a role in QGP?

Answers in terms of models or PQCD...




source: *sPhenix proposal, arXiv:1501.06197 [nucl-ex]*

# Why focus on hard probes in heavy-ion collisions?

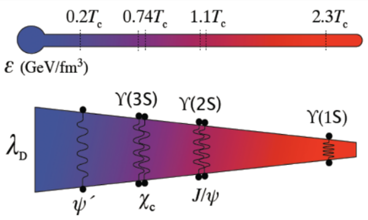



source: *Rothkopf, Phys.Rept. 858 (2020) 1-117*

- Hard probes are produced in a few **hard processes** in initial collision, neither created or destroyed afterwards, but can alter their nature
- Most important probes: jets, open heavy flavor & **heavy quarkonium**
- **What happens to quarkonium if we increase the temperature?**

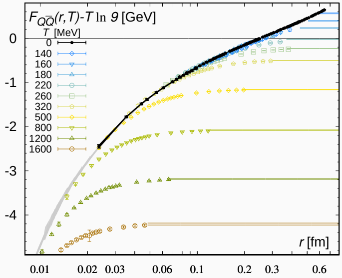
# Heavy quarkonium in the hot medium as a local thermometer

- Idea to look at **quarkonium** in the QGP is old and famous
  *Matsui, Satz, PLB 178 (1986)*
- **Debye screening** of electric gluons ($A_0$) dictates a limit of the radius of hadronic bound states
- Consequence: QGP formation ⇔ **quarkonium suppression**




source: *USQCD whitepaper 2018, EPJ A 55 (2019)*

- **Color screening** usually studied via Polyakov loop correlator
  $$C_P(r,T) = \langle P(0)P^\dagger(\boldsymbol{r})\rangle_T^{\mathrm{ren}} = e^{-F_{Q\bar{Q}}(r,T)/T}$$
- $rT \ll 1$: **singlet**/**octet** decomposition
  $$C_P(r,T) = {}^1\!/_9 e^{-F_S(r,T)/T} + {}^8\!/_9 e^{-F_O(r,T)/T}$$
- $rm_D \gtrsim 1$: screening regime; decompose
  $$C_P(r,T) = \langle \mathrm{Re}\,P(0)\mathrm{Re}\,P^\dagger(\boldsymbol{r})\rangle_T^{\mathrm{ren}}$$
  $$+ \langle \mathrm{Im}\,P(0)\mathrm{Im}\,P^\dagger(\boldsymbol{r})\rangle_T^{\mathrm{ren}}$$
  into $\mathcal{C}$ **even** or **odd** contributions
- QCD: $F_{Q\bar{Q},S,O}(r,T)$ **screened** @ $T=0$



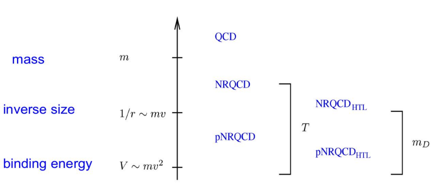

source: *Brambilla, et al., PRD 98 (2018)*

# Screening is not the whole story. . . (at weak coupling)

Matsui & Satz's idea of the **quarkonium suppression mechanism** was turned inside out by **weak-coupling EFT results** emerging 15 years ago

NR hierarchy:

$v \sim \alpha_s$




Thermal hierarchy:

$m_D \sim gT$

- For ${}^1\!/_r \sim m_D \ll T$: $\mathrm{Re}\,[V_s] = F_S + \mathcal{O}(g^4)$ and $\mathrm{Im}\,[V_s] \sim \mathcal{O}(g^2 T)$

$$V_s(T,r) = -C_F\alpha_s \left\{ \frac{e^{-rm_D}}{r} + m_D + \mathrm{i}T\phi(rm_D) \right\}, \phi(x) = 2\int_0^\infty \frac{dz\, z}{(z^2+1)^2}\left\{1 - \frac{\sin(zx)}{zx}\right\}$$

*Laine, et al., JHEP 03 (2007)*

- For $\Delta V \ll {}^1\!/_r \ll m_D \ll T$: $\mathrm{Re}\,[V_s] = V_s + \mathcal{O}(g^4)$ and $\mathrm{Im}\,[V_s] \sim \mathcal{O}(g^4 r^2 T^3, g^6 T)$

$$V_s(T,r) = \frac{-C_F\alpha_s}{r} + r^2T^3 \left\{ \mathcal{O}(g^4) + \mathrm{i}\mathcal{O}\left(g^4, \frac{g^6}{(rT)^2}\right) \right\}$$

*Brambilla, et al., PRD 78 (2008)*

But an imaginary part leads to **dissociation** – is **screening** even relevant?

# In-medium quarkonium as an open quantum system

- Treat in-medium quarkonium in **OQS+pNRQCD** approach

*Brambilla, et al., PRD 96 (2017) + PRD 97 (2018)*

- Density matrix $\rho \equiv \rho_{\mathrm{QGP}} \otimes \rho_{q\bar{q}}$: trace out environment $\Rightarrow$ **OQS**
- Tower of EFTs: **QCD** $\stackrel{\alpha_s M \ll M}{\longrightarrow}$ **NRQCD** $\stackrel{\alpha_s/r \ll 1/r}{\longrightarrow}$ **pNRQCD**

$$\mathcal{L}_{\mathrm{pNRQCD}} = \int d^3\boldsymbol{r}\ \mathrm{tr}\left\{ S^\dagger \left[ i\partial_0 - \left( \frac{\boldsymbol{D}^2}{2M} + \sum_{j=0}^{\infty} \frac{V_s^{(j)}(r)}{M^{j-1}} \right) \right] S + O^\dagger \left[ iD_0 + \frac{\boldsymbol{D}^2}{2M} + \sum_{j=0}^{\infty} \frac{V_o^{(j)}(r)}{M^{j-1}} \right] O \right\}$$
$$+ V_A(r)\ \mathrm{tr}\left\{ O^\dagger \boldsymbol{r} g \boldsymbol{E} S + S^\dagger \boldsymbol{r} g \boldsymbol{E} O \right\} + V_B(r)\ \mathrm{tr}\left\{ O^\dagger \boldsymbol{r} g \boldsymbol{E} O + O^\dagger O \boldsymbol{r} g \boldsymbol{E} \right\}$$
$$+ \mathcal{O}\left( r^2, \frac{1}{M^2} \right) + \mathcal{L}_{light}$$

- **Coupled master equations** for the two-component density matrix

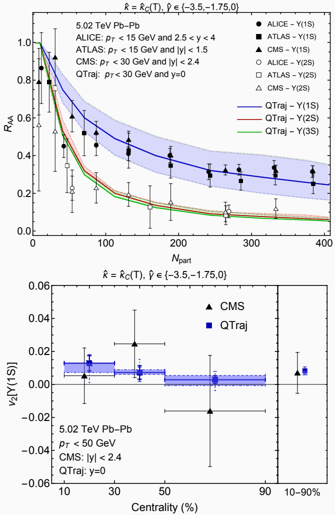
$$\dot{\rho}_s(t;t) = -\mathrm{i}[h_s, \rho_s(t;t)] - \Sigma_s(t)\rho_s(t;t) + \rho_s(t;t)\Sigma_s^\dagger(t) + \Xi_{so}(\rho_o(t;t), t)$$
$$\dot{\rho}_o(t;t) = -\mathrm{i}[h_o, \rho_o(t;t)] - \Sigma_o(t)\rho_o(t;t) + \rho_o(t;t)\Sigma_o^\dagger(t) + \Xi_{os}(\rho_s(t;t), t) + \Xi_{oo}(\rho_o(t;t), t)$$

thermal self-energies $\Sigma_{\cdot}$, dipole transitions by QGP via $\Xi_{\cdot\cdot}(\rho_{\cdot})$

- The **dilute limit** (bottomonium) – $\Xi_{\cdot\cdot}(\rho_{\cdot})$ is **linear** in $\rho$.
- If Markovian + quantum Brownian motion $\Rightarrow$ **Lindblad equation**

Lindblad, CMP 48 (1976); V. Gorini et al., JMP 17 (1976)

# Modern understanding of quarkonium melting from lattice+EFT




source: *Brambilla, et al., arXiv:2107.06222*

If $M \gtrsim 1/a_0 \gg \pi T \sim m_D \gg E$

$\Rightarrow$ master equation has a Lindblad form, is discretized and solved stochastically[a] $\longrightarrow$ `QTraj`

- Temperature dependence from hydrodynamics evolution using lattice QCD **equation of state**
- For strongly-coupled plasma: $T$ dependence via **heavy-quark transport coefficients** $\kappa$, $\gamma$
- Lattice transport coefficients & EoS in OQS+pNRQCD approach: **quarkonium suppression**

[a] *Brambilla, et al., JHEP 05 (2021) + arXiv:2107.06222 [hep-ph]; Ba Omar, et al., arXiv:2107.06147 [physics.comp-ph]*

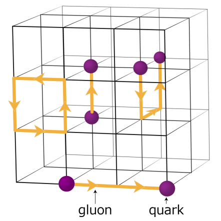
# QCD on a lattice

$$S_{QCD}[U,\bar\psi,\psi] = a^4 \sum_x \sum_{f=1}^{N_f} \bar\psi^f(x)\left(\not{D}[U(x)] + m_f\right)\psi^f(x)$$
$$- a^4 \sum_x \sum_{\mu<\nu} \frac{2}{g_0^2} \mathrm{Re\ tr}\left\{1 - U_{\mu,\nu}(x) + \mathcal{O}(a^2)\right\}$$

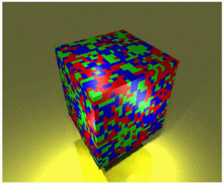
$$D_\mu[U_\mu(x)]\psi^f(x) = \frac{U_\mu(x)\psi^f(x+a\hat\mu) - U_\mu^\dagger(x-a\hat\mu)\psi^f(x-a\hat\mu)}{2a} + \mathcal{O}(a^2)$$

$$U_\mu(x) = \exp[\mathrm{i}ag_0 A_\mu(x)] \qquad \text{gauge link}$$

$$U_{\mu,\nu}(x) = U_\mu(x)U_\nu(x+a\hat\mu)U_\mu^\dagger(x+a\hat\nu)U_\nu^\dagger(x) \qquad \text{plaquette}$$




$\overset{\text{HPC}}{\Longrightarrow}$



# Lattice QCD simulations in a box on a computer

Stochastically sample the (Euclidean) QCD path integral

$$\langle O \rangle_{\mathrm{QCD}} = \frac{1}{Z}\frac{1}{N}\sum_{\{U\}}^{N} O[U] \prod_{f=1}^{N_f} \det\left(\not{D}[U] + m_f\right) \exp\left(-S_g[U]\right) + \mathcal{O}\left(\frac{1}{\sqrt{N}}\right)$$

using MCMC algorithm with importance sampling

QCD on a lattice with spacing $a$ in a box of $N_\sigma^3 \times N_\tau$ points

- scale setting: lattice spacing $a$ is determined a posteriori
  **control the approach to the continuum limit $a \to 0$**
- time (Euclidean): periodic for gluons, antiperiodic for quarks
- space: periodic for gluons and quarks
  **always at finite temperature and in finite volume**
  $aN_\tau = 1/T$ **(volumes only must be large enough)**
- quark masses: light quarks at the physical point are expensive
  **control the quark mass dependence through $\chi$PT**
- quark flavors: usually $N_f = 2+1$ or $N_f = 2+1+1$, or $N_f = 0$

# At which $T$ are there either bound states or melted $q\bar{q}$ pairs?

- **Euclidean Correlators** are towers of exponential decays $G(\tau) = \sum_i A_i e^{-E_i \cdot \tau}$

  For **mesons**: same $E_0$ in temporal or spatial directions

- **Spatial $q\bar{q}$ pair correlators** are a **model-independent** analysis tool

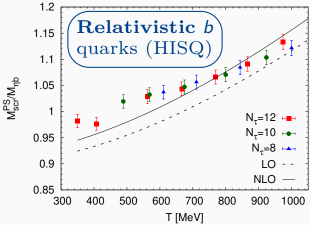
  *Bazavov, et al., PRD 91 (2015)*

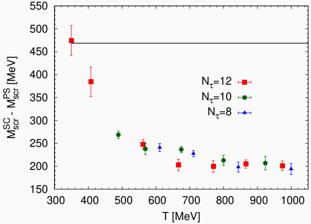
$$G(z,T) = \int_0^{1/T} d\tau \int d^2x_\perp \left\langle \mathcal{J}(\tau, \boldsymbol{x}_\perp, z)\mathcal{J}^\dagger(0)\right\rangle$$

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

with **spectral function** $\rho(\omega, p_z, T)$

$$\sim \begin{cases} \delta\left[\omega^2 - p_z^2 - M_0^2\right] & \text{mesons} \\ \delta\left[\omega - \sum_{q_i} \sqrt{m_{q_i}^2 + [\pi T]^2}\right] & \text{free quarks} \end{cases}$$




source: *Petreczky, et al., PRD 104 (2021)*

- Lowest pseudoscalar & vector are hardly modified at $T \lesssim 450$ MeV
- Lowest scalar & axialvector are hardly modified at $T \lesssim 350$ MeV
- How can we understand the **melting mechanism** at work?

# Nonrelativistic bottomonium with extended sources (HotQCD)

- NRQCD correlator study on $T = 0$ or $N_\tau = 12$ lattices: **extended sources**

  *Larsen, et al., ...*

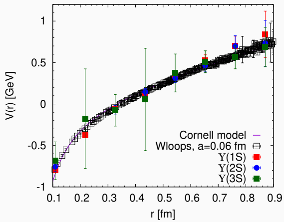
- Lattice NRQCD: no continuum limit $\Rightarrow$ upper limit on $T$ for fixed $N_\tau$
  1. Point source vs Gaussian smearing, new scheme for removing UV part: **thermal width**, small mass shift

     *PRD 100 (2019)*
  2. Cornell pot. eigenstates $\rightarrow$ GEVP $\Rightarrow$ obtain lattice **BS amplitudes**
  3. BS amp. allow recovering potential

$$\left(\frac{-\Delta}{m_b} + V(r)\right)\phi_\alpha = E_\alpha \phi_\alpha$$

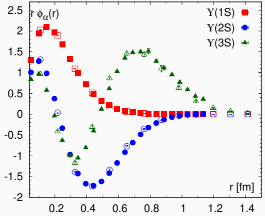
     *PLB 800 (2020) + PRD 102 (2020)*
  4. Small $\tau$: BS amplitudes at $T = 0$ and $T > 0$ almost indistinguishable
  5. Large $\tau$: BS amplitudes at $T > 0$ visibly modified $\Leftrightarrow$ thermal width

$T = 0$, $a = 0.06$ fm: NRQCD vs static $q\bar{q}$




source: *Larsen, et al., PRD 102, (2020)*

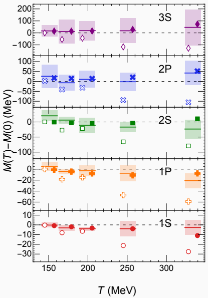
$N_\tau = 12$, $T = 334$ MeV vs $T = 151$ MeV



# Machine learning the potential from NRQCD amplitudes

Machine learning (DNN) applied to lattice BS amp.: $T > 0$ potential

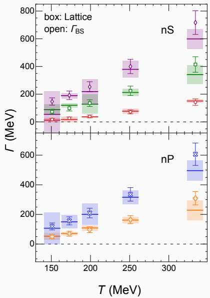
*Shi, et al., arXiv:2105.07862*




BS amp. fed into DNN ⇒ reconstruct potential

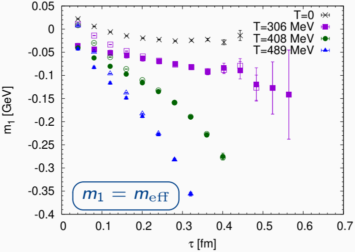
Unscreened real part of potential, but its imaginary part implies a large thermal width

Clearly smaller thermal mass shift and larger width than in **Hard Thermal Loop** (HTL) perturbation theory



# Static $q\bar{q}$ pair at $T > 0$ on the lattice

$a \approx 0.04\,\mathrm{fm},\ {}^{r}/_{a} = 6,\ N_\tau = 64,\ 16,\ 12,\ 10$




source: *Bala, et al., arXiv:2110.11659*

- **Static $q\bar{q}$** interaction is encoded in (real-time) **Wilson loops**[a]

$$W_{[r,T]}(t) = \left\langle e^{\,\mathrm{i}g \oint_{r\times t} dz^\mu A_\mu} \right\rangle_{\mathrm{QCD},T}$$

- Stable (ground) state $\Omega_r$ exists if

$$\Omega_{[r,T]} \equiv -\mathrm{i} \lim_{t\to\infty} \partial_t W_{[r,T]}(t)$$

[a] We use Wilson line correlators in Coulomb gauge.

- Same **spectral functions** yield real- or imaginary-time correlators

$$W_{[r,T]}\begin{pmatrix} t \\ \tau \end{pmatrix} = \int d\omega \begin{pmatrix} e^{+\mathrm{i}\omega\tau} \\ e^{-\omega\tau} \end{pmatrix} \rho_{[r,T]}(\omega)$$

- Motivates **generic decomposition**

$$\rho_{[r,T]}(\omega) = \rho^{\{\Omega;\mathcal{O}(T)\}}_{[r,T]}(\omega) + \rho^{\mathrm{tail}}_{[r,T]}(\omega) + \rho^{\mathrm{UV}}_{[r,T]}(\omega)$$

- UV continuum $\rho^{\mathrm{UV}}_{[r,T]}(\omega)$ is far above **lowest feature $\Omega$ + effects of $\mathcal{O}(T)$**

$\Rightarrow$ Guess $\rho^{\mathrm{UV}}_{[r,T]}(\omega)$ via $\rho^{\mathrm{UV}}_{[r,0]}(\omega)$ $\Rightarrow$ subtract

**Note:** "tail" due to backward propagating UV physics (vacuum excited states) at $\tau \lesssim {}^{1}/T$.

# Cumulants of spectral functions – what can we expect?

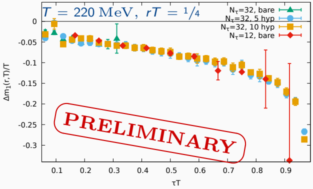
- Access **cumulants of** $\rho_{[r,T]}(\omega)e^{-\omega\tau}$ via $\tau$ **(log) derivatives** of $W_{[r,T]}(\tau)$

$$m_1^{[r,T]}(\tau) = -\partial_\tau \ln W_{[r,T]}(\tau) \quad [\equiv m_{\mathrm{eff}}^{[r,T]}(\tau)],$$

$$m_n^{[r,T]}(\tau) = -\partial_\tau m_{n-1}^{[r,T]}(\tau), \quad n > 1$$

- For $N_\tau \leq 16$ obtain up to $m_3^{[r,T]}(\tau)$: supports $\leq 5$ parameters for $\rho_{[r,T]}(\omega)$
- Higher cumulants at small $\tau$ need at least $N_\tau > 16$: bad signal-to-noise

Fully vacuum-subtracted result




see: *Hoying, et al., arXiv:2110.00565 [hep-lat]*

Feasibility study with $N_\tau = 32$: $m_n^{[r,T]}$, $n > 2$ ?

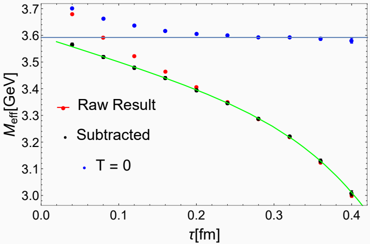
- Fine lattices: $a^{-1} \approx 7\,\mathrm{GeV}$ $m_\pi \approx 0.3\,\mathrm{GeV}$
- UV filtering (HYP) for **noise reduction**

→ distortions cancel in vacuum subtraction

- Definitely still work in progress

# Lowest spectral feature from fits using Gaussian approximation

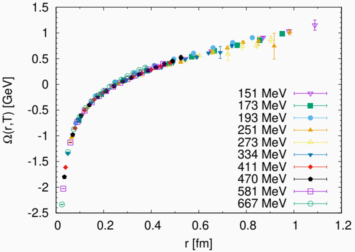
$N_\tau = 12,\ T = 408$ MeV, $r/a = 9$

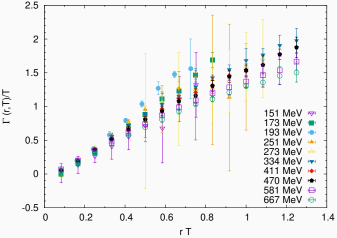



- Quasiparticles are represented as Breit-Wigner in $\rho_{[r,T]}(\omega)$
- Ansatz: approximate BW of $\rho_r^{\{\Omega;\mathcal{O}(T)\}}(\omega)$ locally as Gaussian, include delta function for $\rho_r^{\rm tail}(\omega)$

$$W_{[r,T]}(\tau) = A_{[r,T]}^{\{\Omega;\mathcal{O}(T)\}} e^{-\Omega_{[r,T]}\tau + (\Gamma^G_{[r,T]})^2\tau^2/2} + A^{\rm tail}_{[r,T]} e^{-\omega^{\rm tail}_{[r,T]}\tau}, \quad \omega^{\rm tail}_{[r,T]} \ll \Omega_{[r,T]}$$

$N_\tau = 12,\quad \Omega(r,T) \equiv \Omega_{[r,T]},\quad \Gamma(r,T) \equiv \sqrt{2\ln 2}\,\Gamma^G_{[r,T]},$ subtracted correlators



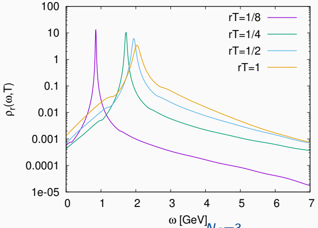




source: *Bala, et al., arXiv:2110.11659*

- Almost no $T$ dependence in $\Omega_{[r,T]}$ (naive correspondence: $\mathrm{Re}\,V_s(r,T)$)
- Naively expected scaling of $\Gamma(r,T)/T \approx \Gamma(rT)/T$ down to $T \approx T_{pc}$

# Comparison: lattice QCD vs HTL

**HTL spectral function** for $T = 667$ MeV




[NLO, 2-loop $\alpha_s(2\pi T)$, $\Lambda_{\overline{\rm MS}}^{N_f=3} = 332$ MeV]

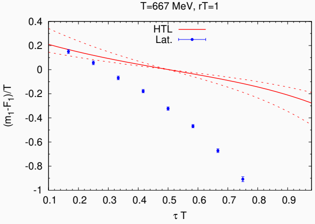
source: *Bala, et al., arXiv:2110.11659*

- **HTL** is an attractive proposition: **motivated & regularized BW**
- **HTL** result is **antisymmetric** around the midpoint $\tau = {}^1\!/_{2T}$:

$$\log W_{[r,T]}(\tau) = -\mathrm{Re}\, V_s(r,T) \times \tau + \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \left\{ e^{-\omega\tau} + e^{-\omega(1/T-\tau)} \right\} \times \{1 + n_B(\omega)\}\, \sigma_{[r,T]}(\omega)$$

- Leading **singularity** of $\sigma_{[r,T]}(\omega)$ (transv. gluon spec. fun.) fixes $\mathrm{Im}\, V_s(r,T)$

$N_\tau = 12$, $r/a = 12$, subtracted correlator



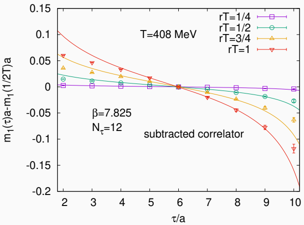

source: *Bala, et al., arXiv:2110.11659*

- **HTL** should work at $r \sim 1/m_D$
- *Subtleties* due to renormalons and regulators: consider $(m_1 - F_S)/T$

  Reminder: $\mathrm{Re}\,[V_s] = F_S + \mathcal{O}(g^4)$ in **HTL**
- No large UV component in HTL, compare UV-subtracted result
- $m_1$ at midpoint lower than **HTL**, and $m_2$ is much more negative

# Lowest spectral feature from fits using HTL-motivated Ansatz

$N_\tau = 12,\ T = 408$ MeV, $r/a = 9$



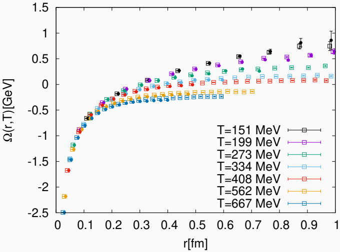

- Fit via HTL-motivated Ansatz

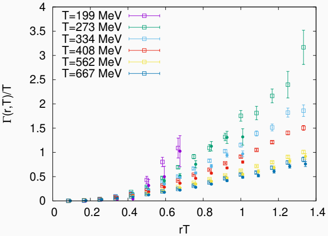
  *Bala, Datta, PRD 101 (2020)*

$$W_{[r,T]}(\tau) = A^{BD}_{[r,T]} e^{-\Omega^{BD}_{[r,T]}\tau - i\frac{\Gamma^{BD}_{[r,T]}}{\pi}\log\sin(\pi\tau T)}$$

- Note: similar result via Gaussian around midpoint $\tau = 1/2T$

$N_\tau = 12$, $\Omega(r,T) \equiv \Omega^{BD}_{[r,T]}$, $\Gamma^{BD}(r,T) \equiv \Gamma^{BD}_{[r,T]}$, (un-)subtracted correlators

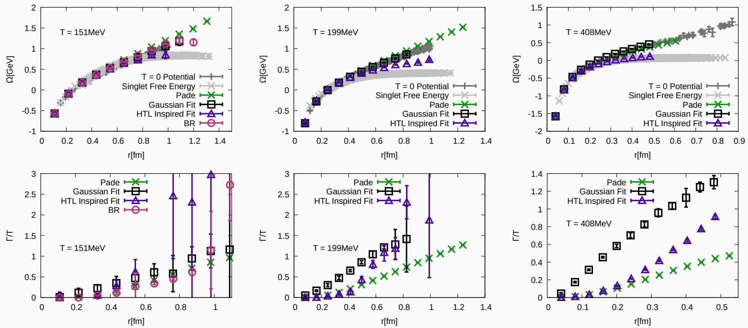



source: *Bala, et al., arXiv:2110.11659*

- Significant $T$ dependence in $\Omega_{[r,T]}$ (naive correspondence: Re $V_s(r,T)$)
- Weaker than naive scaling of $\Gamma(r,T)/T \approx \Gamma(rT)/T$

# Comparison: lowest spectral feature from four different methods




source: *Bala, et al., arXiv:2110.11659*

- Applied two further, independent methods (Padé rational approximation, Bayesian reconstruction) not discussed in detail
- $T \approx 150$ MeV conclusive: $\Omega_{[r,T]} \approx F_S(r,T) \approx V_s(r)$ for $r \lesssim 0.8$ fm
- $T \lesssim 250$ MeV: all three methods yield $\Omega_{[r,T]} \gg F_S(r,T)$
- $T \approx 400$ MeV inconclusive: $\Omega^{BD}_{[r,T]} \approx F_S(r,T)$ vs $\Omega^{G}_{[r,T]} \approx \Omega^{P}_{[r,T]} \approx V_s(r)$
- All methods find for all $T$ nontrivial $\Gamma_{[r,T]}$ that increases with $r$ or $T$

# Heavy quarkonium at finite temperature

Modern picture: quarkonium suppression is **NOT** due to screening.

- **OQS+pNRQCD** ($\longrightarrow$ `QTraj`): first-principles, non-Abelian evolution
- Use of gradient flow for **heavy-quark transport coefficients**
- Spatial correlation functions of **relativistic bottomonium**
  - Model-independent study of quarkonium melting in LQCD
  - $\eta_b$ or $\Upsilon(1S)$ largely unmodified at $T \approx 400\,\text{MeV}$; $\chi_{b0}$ or $h_b$ already gone
- **Nonrelativistic bottomonium**
  - Extended sources or BS wave functions boost resolving power of LQCD
  - Spectral features are fully **consistent with static $q\bar{q}$ pair**
- **Static quarkonium ($q\bar{q}$ pair)**
  - Lowest spectral feature $\{\Omega; \mathcal{O}(T)\}$ + tail + UV continuum
  - Model-independent cumulant analysis $\rightarrow$ clear evidence for a large **thermal width being the main cause of quarkonium melting**
  - Consistent with minimal (Gaussian fit) or major (HTL-motivated fit) medium modification of real part $\rightarrow$ insufficient resolution with $N_\tau \leq 16$

The lattice + EFT is in good shape to deliver more accurate and more realistic results needed for HIC phenomenology in the coming years.

Thank you for your attention!