Heavy Probes in Heavy-Ion Collisions
Theory Part IV

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Heavy quarkonia in the vacuum

1. “Stable” charmonium and bottomonium states ($M < 2m_D$)
2. Non-relativistic potential models

Heavy quarkonia in the sQGP

1. $J/\psi$ suppression
2. Heavy-quarkonium dissociation
3. In-medium modification of bound-state potentials
4. Heavy-quarkonia dissociation and regeneration in the QGP
5. Dissociation Cross Sections
Charmonium states

- no **flavor-changing neutral currents** in weak interactions ⇒ prediction of fourth quark
  - GIM mechanism (Glashow, Iliopolous, Maiani)
  - CKM-quark-mixing matrix (Cabibbo, Kobayashi, Maskawa)
  - discovered as \( \bar{c}c \) bound state
  - simultaneously by Ting (BNL) and Richter (RHIC) ⇒ name \( J/\psi \)

- today many charmonia known (only “stable” states)
- higher excitations can decay strongly to \( \bar{D} + D \)

<table>
<thead>
<tr>
<th>Name</th>
<th>( \eta_c )</th>
<th>( J/\psi )</th>
<th>( \chi_{c0} )</th>
<th>( \chi_{c1} )</th>
<th>( \chi_{c2} )</th>
<th>( \psi' )</th>
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</thead>
<tbody>
<tr>
<td>mass (GeV)</td>
<td>2.98</td>
<td>3.10</td>
<td>3.42</td>
<td>3.51</td>
<td>3.56</td>
<td>3.69</td>
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<tr>
<td>( E_B ) (GeV)</td>
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<td>0.64</td>
<td>0.32</td>
<td>0.22</td>
<td>0.18</td>
<td>0.05</td>
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<td>state</td>
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<td>1S</td>
<td>1P</td>
<td>1P</td>
<td>1P</td>
<td>2S</td>
</tr>
<tr>
<td>( J^{PC} )</td>
<td>0−+</td>
<td>1−−</td>
<td>0++</td>
<td>1++</td>
<td>2++</td>
<td>1−−</td>
</tr>
</tbody>
</table>

[L. Kluberg, H. Satz, Landolt-Börnstein 23/I, 6-1 (2010)]
Bottomonium states

- $\Upsilon$ as first $\bar{b}b$-bound state discovered by Ledermann (Fermi Lab) 1977
- even more “stable” bottomonium states (due to stronger binding)
- higher excitations $\Rightarrow$ can decay strongly to $\bar{B} + B$

<table>
<thead>
<tr>
<th>Name</th>
<th>$\Upsilon$</th>
<th>$\chi_{b0}$</th>
<th>$\chi_{b1}$</th>
<th>$\chi_{b2}$</th>
<th>$\Upsilon'$</th>
<th>$\chi'_{b0}$</th>
<th>$\chi'_{b1}$</th>
<th>$\chi'_{b2}$</th>
<th>$\Upsilon''$</th>
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<tr>
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<td>9.86</td>
<td>9.89</td>
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<td>10.23</td>
<td>10.26</td>
<td>10.27</td>
<td>10.36</td>
</tr>
<tr>
<td>$E_B$ (GeV)</td>
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<td>0.70</td>
<td>0.67</td>
<td>0.64</td>
<td>0.53</td>
<td>0.34</td>
<td>0.3</td>
<td>0.29</td>
<td>0.20</td>
</tr>
<tr>
<td>state</td>
<td>$1S$</td>
<td>$1P$</td>
<td>$1P$</td>
<td>$1P$</td>
<td>$2S$</td>
<td>$1P$</td>
<td>$1P$</td>
<td>$1P$</td>
<td>$3S$</td>
</tr>
<tr>
<td>$J^{PC}$</td>
<td>$1^{--}$</td>
<td>$0^{++}$</td>
<td>$1^{++}$</td>
<td>$2^{++}$</td>
<td>$1^{--}$</td>
<td>$0^{++}$</td>
<td>$1^{++}$</td>
<td>$2^{++}$</td>
<td>$1^{--}$</td>
</tr>
</tbody>
</table>

[L. Kluberg, H. Satz, Landolt-Börnstein 23/I, 6-1 (2010)]

- light-quark mesons: mass from strong interaction (confinement)
- heavy quarkonia: mass due to quark masses
- can be treated as (quasi-)non-relativistic bound states
Non-relativistic potential models

- use phenomenological static potentials, e.g., Cornell potential
  \[ V(r) = \sigma r - \frac{\alpha}{r} \]

- long-range scale: confining (non-perturbative QCD), string tension, \( \sigma \approx 0.2 \text{ GeV}^2 \)

- short-range scale: Coulomb-like (pQCD), \( \alpha \approx \pi/12 \)

- heavy-quarkonium states from non-relativistic Schrödinger equation
  \[
  \left[ 2m_Q - \frac{1}{m_Q} \Delta + V(r) \right] \Phi_i(\vec{r}) = M_i \phi_i(r)
  \]

- fit to spin-averaged heavy-quarkonium spectra
  \[ m_c = 1.25 \text{ GeV}, \quad m_b = 4.65 \text{ GeV}, \quad \sqrt{\sigma} = 0.445 \text{ GeV}, \quad \alpha = \pi/12 \]

- from wave function \( \langle r_i^2 \rangle = \langle \Phi_i | \vec{r} | \Phi_i \rangle \)

<table>
<thead>
<tr>
<th>Name</th>
<th>J/ψ</th>
<th>χc</th>
<th>ψ′</th>
<th>γ</th>
<th>χb</th>
<th>γ′</th>
<th>χb′</th>
<th>γ′′</th>
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</thead>
<tbody>
<tr>
<td>mass (GeV)</td>
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<td>3.53</td>
<td>3.68</td>
<td>9.46</td>
<td>9.99</td>
<td>10.02</td>
<td>10.26</td>
<td>10.36</td>
</tr>
<tr>
<td>( E_B ) (GeV)</td>
<td>0.64</td>
<td>0.20</td>
<td>0.05</td>
<td>1.10</td>
<td>0.67</td>
<td>0.54</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>( \Delta M_i ) (GeV)</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.036</td>
<td>-0.06</td>
<td>-0.06</td>
<td>-0.08</td>
<td>-0.07</td>
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<tr>
<td>( r_0 ) (fm)</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
<td>0.28</td>
<td>0.44</td>
<td>0.56</td>
<td>0.68</td>
<td>0.78</td>
</tr>
</tbody>
</table>
$J/\psi$ suppression as probe for QGP formation

- **heavy quarkonia** break up in sQGP
  - dissociation through inelastic scattering with medium particles
  - gluon dissociation, quasi-free knock-out reactions
  - in-medium modification of strong interaction; color screening

- suppression of **heavy quarkonia** as signal for QGP formation
  [T. Matsui, H. Satz, $J/\psi$ PLB 178, 416 (1986)]
  - caveat! already suppression in pA collisions compared to pp
  - absorption, shadowing, Cronin effect as cold-nuclear-matter effects
  - must be taken into account to determine “anomalous suppression”
Heavy-quarkonium dissociation

- from non-rel. potential models: tightly bound states of small size
- need hard parton to dissociate heavy quarkonia
- leading-order process via hard gluon
- hot hadron gas

- hadron of high momentum $p_h \Rightarrow$ distribution of gluons with momentum $xp_h$:

$$g(x) \propto (1-x)^2$$

- average gluon-momentum fraction

$$\langle x \rangle = \frac{\int_0^1 dx x g(x)}{\int_0^1 dx g(x)} = \frac{1}{5}$$

- in hadronic medium with $T < T_c$ average momentum

$$\langle p_{\text{gluon}} \rangle = 3T/5 \leq 0.1 \text{ GeV} \ll E_B \simeq 0.6 \text{ GeV}$$

- deconfined matter (QGP)

  - $p_{\text{gluon}} \simeq 3T \Rightarrow$ for $T \gtrsim 1.2T_c$ gluo dissociation of $J/\psi$ possible
Heavy-quarkonium dissociation

- dissociation cross section (similar to photo effect in QED)

\[ g + J/\psi \rightarrow \bar{c} + c \]

\[ \sigma_{g+J/\psi \rightarrow \bar{c}+c} \propto \frac{1}{m_c^2} \frac{(k/E_B - 1)^{3/2}}{(k/E_B)^5} \]

- for hadron: convolution with parton-distribution function \( g(x) \)

[L. Kluberg, H. Satz, Landolt-Börnstein 23/I, 6-1 (2010)]
Potential models in the medium

- modify Cornell potential by Debye screening
- confining part: Laplace equation in 1D
- perturbative part: Laplace equation in 3D
- Debye-screened Cornell potential

\[ V(r, T) \simeq \sigma r \frac{1 - \exp(-\mu_D r)}{\mu_D r} - \frac{\alpha}{r} \exp(-\mu_D r) \]

- shortcomings of this model
  - confining part treated as “1D-gauge theory” \( \Rightarrow \) different in 3D
  - \( \mu_D \) taken in high-energy form \( \mu \propto T \)
  - lQCD \( \mu_D \) different close to \( T_c \) (strong interactions \( \Rightarrow \) sQGP!)

Static heavy-quark potentials from lattice QCD

- lattice QCD at finite temperature: calculate free energy \( F = U - TS \)
- calculate difference between \( F_{QQ} \) with \( Q \) and \( \bar{Q} \) at distance, \( r \) and \( F \)
- average Hamiltonian for static \( \bar{QQ} \): \( \langle H \rangle_T = U = -T^2 \partial (F/T) / \partial T \)
  \( \Rightarrow M_{\text{quarkonium}} \)
- long-distance limit: \( 2M_D(T) \simeq 2m_c + U(\infty, T) \)
- can be reinterpreted as medium-modified heavy-quark mass
- short-distance: polarization zones overlap \( \Rightarrow \) enhancement of \( U \) over \( T = 0 \) Cornell potential
- “right” potential \( V = xU + (1 - x)F \)?

**Diagram:**
- Plot of \( V \) vs. \( r \) with data points and fits for different temperatures.
- Lines representing different temperature values: \( 1.09T_c \), \( 1.13T_c \), \( 1.19T_c \), \( 1.29T_c \), \( 1.43T_c \), \( 1.57T_c \), \( 1.89T_c \).
- Key metrics: \( F(r, T=0) \), \( U(r, T) \), \( T S(r, T) \), \( r_D \), \( T > T_c \).
Heavy-quarkonium spectral functions from lQCD

- lQCD: thermal expectation values of imaginary-time operators
- Monte Carlo evaluation of path integrals of discreticed QCD action
- current-correlation function for heavy quarkonia

\[ G_\alpha(\tau, \vec{r}) = \langle j_\alpha(\tau, \vec{r}) j_\alpha^+(0, 0) \rangle_T \]

- connection with spectral function

\[ G_\alpha(\tau, p; T) = \int_0^\infty dE \sigma_\alpha(E, p; T) K(E, \tau; T) \quad \text{with} \]

\[ K(E, \tau; T) = \frac{\cosh[E(\tau - \beta/2)]}{\sinh(\beta E/2)} \]

- inversion problematic on (discretized) imaginary time \(0 \leq \tau \leq \beta\)
- statistical maximum-entropy method (MEM)
T-matrix approach for quarkonium-bound-state problem

- **T-matrix Brückner approach** for heavy quarkonia as for HQ diffusion
- consistency between HQ diffusion and $\bar{Q}Q$ suppression!

\[ T = V + \frac{1}{2\pi} \int_0^\infty dk k^2 V(q', k) G_{Q\bar{Q}}(E; k) T(E; k, q) \times \left\{ 1 - n_F[\omega_1(k)] - n_F[\omega_2(k)] \right\} \]

- **4D Bethe-Salpeter equation** → **3D Lippmann-Schwinger equation**
- relativistic interaction → **static heavy-quark potential** (lQCD)

\[ T_\alpha(E; q', q) = V_\alpha(q', q) + \frac{2}{\pi} \int_0^\infty dk k^2 V_\alpha(q', k) G_{Q\bar{Q}}(E; k) T_\alpha(E; k, q) \times \left\{ 1 - n_F[\omega_1(k)] - n_F[\omega_2(k)] \right\} \]

- $q, q', k$ relative 3-momentum of initial, final, intermediate $\bar{Q}Q$ state

The potential

- non-perturbative static gluon propagator
  \[ D_{00}(\vec{k}) = 1/(\vec{k}^2 + \mu_D^2) + m_G^2/(\vec{k}^2 + \tilde{m}_D^2)^2 \]

- finite-T HQ color-singlet-free energy from Polyakov loops
  \[
  \exp[-F_1(r, T)/T] = \left\langle \text{Tr}[\Omega(x)\Omega^\dagger(y)]/N_c \right\rangle \\
  = \exp \left[ \frac{g^2}{2N_cT^2} \left\langle A_{0,\alpha}(x)A_{0,\alpha}(y) - A_{0,\alpha}^2(x) \right\rangle \right] + \mathcal{O}(g^6)
  \]

- identify \( \left\langle A_{0,\alpha}(x)A_{0,\alpha}(y) \right\rangle = D_{00}(x - y) \)

- color-singlet free energy
  \[ F_1(r, T) = -\frac{4}{3} \alpha_s \left\{ \frac{\exp(-m_D r)}{r} + \frac{m_G^2}{2\tilde{m}_D} \left[ \exp(-\tilde{m}_D r) - 1 \right] + m_D \right\} \]

- in vacuo \( m_D, \tilde{m}_D \to 0 \)
  \[ F_1(r) = -\frac{4}{3} \frac{\alpha_s}{r} + \sigma r, \quad \sigma = \frac{2\alpha_s m_G^2}{3} \]

Heavy quarkonia

- fit parameters, $\alpha_s(T), m_D(T), \tilde{m}_D(T), \tilde{m}_G(T)$ to lQCD
- calculate internal energy $U(r, T) = F(r, T) - T \frac{\partial}{\partial T} F(r, T)$
- solve Lippmann-Schwinger equation $\Rightarrow$ adjust $m_Q$ to get $s$-wave charmonia/bottomonia masses in vacuum

In the following
  - potential 1: $N_f = 2 + 1$ [O. Kaczmarek]
  - potential 2: $N_f = 3$ [P. Petreczky]
  - BbS: Blancenblecler-Sugar reduction scheme
  - Th: Thompson reduction scheme

- Vacuum-mass splittings
  - Uncertainty for charmonia: 50-100 MeV
  - Uncertainty for bottomonia: 30-70 MeV
  - Overall uncertainty $\simeq 10\%$

- Melting temperatures with $U$ and $F$
  - $s$-wave ($\eta_c, J/\psi$): $2-2.5T_c, \gtrsim 1.3T_c$,
    $\Upsilon: > 2T_c, \gtrsim 1.7T_c, 1T_c, \gtrsim 2T_c, 1T_c, 1T_c$
  - $p$-wave ($\chi_c$): $\gtrsim 1.2T_c, \gtrsim 1T_c, \chi_b: \gtrsim 1.7T_c, 1.2T_c, \text{all } \gtrsim 1T_c$

Quarkonium-spectral functions in the vacuum

\[ \frac{\sigma}{[\text{GeV}^2]} \]

\[ E_{\text{cm}} [\text{GeV}] \]

\( \mathcal{J}/\Psi, \; \eta_c \)

\( \chi_c \)

\( \Upsilon \)

\( \chi_b \)

BbS / Pot. 1 — Th / Pot. 1 — BbS / Pot. 2 — Th / Pot. 2
In-medium charmonium-spectral functions (s states)

Potential 1
BbS-Scheme

Potential 2
BbS-Scheme

Potential 1
Th-Scheme

Potential 2
Th-Scheme

$\sigma$ [GeV$^2$]

$J/\psi, \eta_c$

$E_{cm}$ [GeV]

$\tau$ [fm]

$T=0$ $T_c$ (solid)

$T=1.2$ $T_c$ (red dashed)

$T=1.5$ $T_c$ (blue dotted)

$T=1.75$ $T_c$ (green dashed-dotted)

$T=2$ $T_c$ (purple dotted-dashed)

Hendrik van Hees (JLU Gießen)
In-medium charmonium-spectral functions (p states)

Potential 1
BbS-Scheme

Potential 2
BbS-Scheme

Potential 1
Th-Scheme

Potential 2
Th-Scheme

$\chi_c$

$\sigma [\text{GeV}^2]$ vs $E_{cm} [\text{GeV}]$

$T=0 \ T_c$

$T=1.2 \ T_c$

$T=1.5 \ T_c$

$T=1.75 \ T_c$

$T=2 \ T_c$

$T=1.35 \ T_c$
$J/\psi$ suppression and regeneration

- dissociation rate

\[ \Gamma_{\Psi} = \sum_i \int \frac{d^3 k}{(2\pi)^3} f_i(\omega_k, T) v_{rel} \sigma_{\Psi_i}^{(diss)}(s) \]

- $g + \Psi \rightarrow \bar{Q} + Q$ ("gluon dissociation")

\[ \sigma_{g\Psi}(k_0) = \frac{2\pi}{3} \left( \frac{32}{3} \right)^2 \left( \frac{m_Q}{E_b} \right)^{1/2} \frac{1}{m_Q^2} \frac{(k_0/E_B - 1)^{3/2}}{(k_0/E)^5} \]

- for decreasing binding energy: cross section sharply peaked at low $k_0$
- gluon dissociation becomes inefficient for loosely bound states
- additional channel: quasi-free dissociation $g + \Psi \rightarrow g + \bar{Q} + Q$

[L. Granchamp, R. Rapp, PLB 523, 60 (2001); R. Rapp EPC 43, 91 (2005)]
Dissociation Cross Sections

- need **dissociation cross sections** to evaluate $\Upsilon$ yield
- Usual mechanism: **gluon dissociation** (in dipole approximation)
- Problem: becomes **inefficient** for loosely bound states

\[ \Gamma_\Upsilon = \tau_\Upsilon^{-1} = \int \frac{d^3k}{(2\pi)^3} f_{q,g}(\omega_k, T) v_{\text{rel}} \sigma_\Upsilon^{\text{diss}}(s) \]

\[ m_\Upsilon = 2m_b(T) - \epsilon_\Upsilon(T) = \text{const} \]

- $\epsilon_\Upsilon(T)$ from Schrödinger eq. with **screened Cornell potential**
  
  [Karsch, Mehr, Satz 88]
Dissociation Cross Sections

- breakup mechanism for loosely bound states: quasifree dissociation

- use LO pQCD cross sections for elastic scattering [Combridge 79]

- Color screening reduces $\Upsilon$ lifetime by factor of 10!
$J/\psi$ suppression and regeneration

- **use of in-medium binding energies:**
  - need both gluon absorption + quasi-free scattering

[L. Granchamp, R. Rapp, PLB 523, 60 (2001); R. Rapp EPC 43, 91 (2005)]
Quarkonium transport in heavy-ion collisions

- **Quarkonium transport in the sQGP**

\[
\frac{p^\mu}{p_0} \partial_\mu f_\Psi(x, \vec{p}) = -\Gamma_\Psi(x, \vec{p}) + \beta_\Psi(x, \vec{p})
\]

- **Gain/regeneration term** (e.g., for \(Q + \bar{Q} \rightarrow g + \Psi\))

\[
\beta_\Psi(x, \vec{p}) = \frac{1}{2p_0} \int \frac{d^3\vec{k}}{(2\pi)^3 2\omega_k} \int \frac{d^3\vec{p}_Q}{(2\pi)^3 2\omega_Q} \int \frac{d^3\vec{p}_{\bar{Q}}}{(2\pi)^3 2\omega_{\bar{Q}}} \times f_Q(x, \vec{p}_Q) f_{\bar{Q}}(x, \vec{p}_{\bar{Q}}) W_{Q\bar{Q}}^{g\Psi}(s) \Theta[T_{\text{diss}} - T(x)]
\]

\[
\times (2\pi)^4 \delta^{(4)}(p + q - p_Q - p_{\bar{Q}})
\]

\[
W_{Q\bar{Q}}^{g\Psi} = \sigma_{Q\bar{Q} \rightarrow g\Psi} v_{\text{rel}} 4\omega_Q \omega_{\bar{Q}}
\]

- **Cross section must be the same as for dissociation (up to kinematics)**

- **Detailed balance**
Rate equations for quarkonia

- Integrate Boltzmann equation over $x, \vec{p}$
- Assume thermalized $Q/\bar{Q}$ distributions in the sQGP
- Rate equation
  \[
  \frac{dN_{\Psi}}{d\tau} = -\Gamma_{\Psi}(N_{\Psi} - N_{\Psi}^{(eq)})
  \]
- Detailed balance ensures correct equilibrium limit
- Conservation of heavy-quark number $N_{Q\bar{Q}} = N_Q = N_{\bar{Q}}$ over whole evolution of the medium
- HQ fugacity factors

\[
N_{Q\bar{Q}} = \frac{1}{2} N_{\text{op}} \frac{I_1(N_{\text{op}})}{I_0(N_{\text{op}})} + V_{FB} \gamma_Q^2 \sum_{\Psi} n_{\Psi}^{(eq)}(T)
\]

\[
N_{\text{op}} = \begin{cases} 
V_{FB} \gamma_Q 2 n_Q^{(eq)}(m_Q^*, T) & \text{for QGP} \\
V_{FB} \gamma_Q \sum_\alpha n_\alpha^{(eq)}(T, \mu_B) & \text{for hadron gas}
\end{cases}
\]
Initial conditions

- **QQ pairs** produced in primordial hard collisions only
- subject to **cold-nuclear-matter effects**
  - **nuclear absorption**: dissociation by interaction with surrounding nucleons
  - **Cronin effect**: broadening of $\Psi-p_T$ spectra due to rescattering of gluons before charmonium formation
  - **(anti-)shadowing**: modification of the parton-distribution functions in nuclei
- after formation time: assume equilibrium distributions
- $p_T$ distributions
  - **direct part**: from $pp$ + cold-nuclear-matter effects
  - **regenerated part**: boosted Boltzmann distribution (blast wave)

$$
\frac{dN_\Psi}{p_T dp_T} \propto m_T \int_0^R dr \ r \ K_1 \left( \frac{m_T \cosh y_T}{T} \right) I_0 \left( \frac{p_T \sinh y_t}{T} \right)
$$
Centrality dependence of $J/\psi$ in AA collisions

- mid rapidity

[X. Zhao, R. Rapp, EPC 62, 109 (2009)]
Centrality dependence of $J/\psi$ in AA collisions

- forward rapidity
- with and without shadowing

\[ |y|: [1.2, 2.2] \]

[X. Zhao, R. Rapp, EPC 62, 109 (2009)]
$p_T$ dependence of $J/\psi$ $R_{AA}$

- **mid rapidity**

  ![Graphs showing $R_{AA}$ vs. $p_T$ for different centrality bins.](image)

  [X. Zhao, R. Rapp, EPC 62, 109 (2009)]
$p_T$ dependence of $J/\psi$ $R_{AA}$

- **forward rapidity**

![Graphs showing $p_T$ dependence of $J/\psi$ $R_{AA}$ at different rapidity intervals](graphs)

[Reference: X. Zhao, R. Rapp, EPC 62, 109 (2009)]
Instead of a summary: questions

- How are heavy quarkonia in the vacuum theoretically described?
- What can we learn from that about fundamental properties of QCD?
- Which cold-nuclear matter (initial state) effects are important for heavy quarkonia?
- What are the main mechanisms behind “heavy-quarkonium suppression” in the sQGP?
- How are the bound-state properties of heavy quarkonia in the medium described?
- How are the heavy-quarkonium observables in heavy-ion collisions described?
Summary

- **Heavy quarkonium states**
  - (non-relativistic) bound $\bar{Q}Q$ states
  - potential: “color-Coulomb” (pert.) + “confining” (non-pert.) part
  - good description of charmonia, $J/\psi$, $\chi_C$,... and bottomonia, $\Upsilon$, $\chi_b$,...
  - tightly bound states with small size

- **Heavy quarkonia in the medium**
  - dissociation via scattering with medium particles
  - main mechanism: gluon dissociation, quasi-free break-up reaction
  - $J/\psi$ suppression as signal for QGP formation in HICs
  - cold-nuclear-matter effects (absorption, shadowing Cronin effect)
  - “anomalous suppression” QGP signal
Summary

- **Potential models in the medium**
  - heavy quarkonia with IQCD
  - difficult to extract spectral properties (MEM)
  - ⇒ potential models in the medium
  - use in-medium potentials from the lattice
  - free energy or internal energy?
  - use screened color-Coulomb + confining ansatz for potential
  - fit medium dependent parameters to IQCD
  - leads to survival of some quarkonia above $T_c$ ⇒ regeneration important

- **Dissociation/Regeneration of heavy quarkonia in the QGP**
  - initial conditions: production cross sections, cold-nuclear matter effects
  - dissociation cross sections for gluon absorption + quasi-free scattering
  - Transport approach to dissociation and regeneration of heavy quarkonia
  - in-medium bound-state properties