Volodymyr Magas

X(3872) in relativistic heavy ion collisions

Collaborators: Martin Cleven, Angels Ramos
The X(3872)

The story of X(3872) starts in 2003

[Belie collaboration],

The first exotic meson!

\[ M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV} \]

Exotic (non-standard) quarkonium states,

inconsistent with pure \( \bar{b} \bar{b} \)
\( c \bar{c} \) states
Exotic spectroscopy

\((X, Y)\) and \(Z^+\) meson-like and \(P_c^+\) baryon-like states

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Olsen, Skwarnicki, Zieminska, Rev. Mod. Phys. 90 (2018) 015003
Exotic spectroscopy

$(X, Y)$ and $Z^+$ meson-like and $P_c^+$ baryon-like states
Observation of $J/\Psi p$ resonances consistent with pentaquark states in $\Lambda_b \rightarrow J/\psi \ K^- \ p$ decays


<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M_R$ [MeV]</th>
<th>$\Gamma_R$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)$</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$205 \pm 18 \pm 86$</td>
</tr>
<tr>
<td>$P_c(4450)$</td>
<td>$4449.8 \pm 1.7 \pm 2.5$</td>
<td>$39 \pm 5 \pm 19$</td>
</tr>
</tbody>
</table>
More detailed reanalysis of the pentaquark states in $\Lambda_b \to J/\psi \, K^- \, p$ decays


<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>(95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>$4311.9 \pm 0.7^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
<td>(&lt; 27)</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>$4440.3 \pm 1.3^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
<td>(&lt; 49)</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>$4457.3 \pm 0.6^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
<td>(&lt; 20)</td>
</tr>
</tbody>
</table>

![Graph showing weighted candidates vs. $m_{J/\psi}$ distribution with peaks labeled $P_c(4312)^+$, $P_c(4440)^+$, and $P_c(4457)^+$]
Experiments involved
Production processes

- B decays
  \[ J^P = 0^+ \text{ or } 2^+ \]

- Initial state radiation/ e^+ e^-
  \[ J^P = 1^- \]

- Double charmonium production

- γγ-fusion

- Decays of Y(4260) and higher charmonia

- p\bar{p} inclusive
- pp inclusive
- (virtual) photo production
The X(3872)
### The $X(3872)$

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (decay mode)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>3871.69 ± 0.17</td>
<td>&lt; 1.2</td>
<td>$1^{++}$</td>
<td>$B \to K(J/\psi \pi^+ \pi^-)$</td>
<td>Belle (Choi et al., 2011), BABAR (Aubert et al., 2005c), LHCb (Aaij et al., 2013a, 2015d)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>CDF (Acosta et al., 2004; Abulencia et al., 2006; Aaltonen et al., 2009b), D0 (Abazov et al., 2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p\bar{p} \to (J/\psi \pi^+ \pi^-) + \cdots$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(J/\psi \pi^+ \pi^-)$</td>
<td>Belle (Abe et al., 2005), BABAR (del Amo Sanchez et al., 2010a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(D^0 \bar{D}^0 \pi^0)$</td>
<td>Belle (Gokhroo et al., 2006; Aushev et al., 2010b), BABAR (Aubert et al., 2008c)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(J/\psi \gamma)$</td>
<td>BABAR (del Amo Sanchez et al., 2010a), Belle (Bhardwaj et al., 2011), LHCb (Aaij et al., 2012a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(\psi' \gamma)$</td>
<td>BABAR (Aubert et al., 2009b), Belle (Bhardwaj et al., 2011), LHCb (Aaij et al., 2014a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$pp \to (J/\psi \pi^+ \pi^-) + \cdots$</td>
<td>LHCb (Aaij et al., 2012a), CMS (Chatrchyan et al., 2013a), ATLAS (Aaboud et al., 2017)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \to \gamma(J/\psi \pi^+ \pi^-)$</td>
<td>BESIII (Ablikim et al., 2014d)</td>
</tr>
</tbody>
</table>

The $X(3872)$ is also known as $\chi_{c1}(3872)$. This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non-$q\bar{q}$ states.
The X(3872)

- $J^{PC} = 1^{++}$ established

- Mass $m = 3871.69 \pm 0.17$ MeV (in X(3872) $\rightarrow J/\psi \ X$ decays)

- $D \bar{D}^*$ threshold: $3871.81 \pm 0.09$ MeV

- Mass difference $m_X - m_{J/\psi} = 775 \pm 4$ MeV

- Width $\Gamma < 1.2$ MeV Belle [PRD84(2011)052004]

- Mass and decay mode disfavor $c\bar{c}$ state.

- $J^{PC} = 1^{++}$: $D^0 D^*$ molecule, Tetra-quark

- No charged partner, no $C = -1$ partner found
The $X(3872)$ structure

Tetraquark

Compact


Meson molecule

Large and loosely bound

Swanson, Phys. Rept. 429 (2006) 243;

Recent Overview: Guo et al., Rev. Mod. Phys. 90 (2018) 015004
Production processes

- B decays
- Initial state radiation/$e^+e^-$
- Double charmonium production
- $\gamma\gamma$-fusion
- Decays of $Y(4260)$ and higher charmonia
- $p\bar{p}$ inclusive
- $pp$ inclusive
- (virtual) photo production

Nothing in the Nucleus-Nucleus collisions

$J^P = 0^+$ or $2^+$

Why?
Nucleus-Nucleus collisions

- **More charm:** charm quarks are produced in the initial quark-gluon plasma phase

- **Tetraquarks:** are produced via quark coalescence during hadronization

- **Bound meson-meson states:** are produced via meson coalescence during freeze out

Can we detect the difference?

Nature of X(3872)

[ExHIC Coll.] PRL 106 (2011)212001; PRC 84 (2011) 064901
Quark coalescence during hadronization

Quark coalescence

X(3872)
$X(3872)$ in the hadronic phase

Hadron gas

$X$ production by meson fusion

$X$ production by meson coalescence

$X$ absorption by light hadrons
X(3872) in the hadronic phase

Production

\[ D + \bar{D} \rightarrow X + \pi \]
\[ D + \bar{D}^* \rightarrow X + \pi \]
\[ D^* + \bar{D}^* \rightarrow X + \pi \]

Absorption

\[ X + \pi \rightarrow D + \bar{D} \]
\[ X + \pi \rightarrow D + \bar{D}^* \]
\[ X + \pi \rightarrow D^* + \bar{D}^* \]

Cross sections are calculated using chiral SU(4) effective Lagrangians.
X(3872) in the hadronic phase

Production

\[
\begin{align*}
D + \bar{D} &\rightarrow X + \pi \\
D + \bar{D}^* &\rightarrow X + \pi \\
D^* + \bar{D}^* &\rightarrow X + \pi 
\end{align*}
\]

Absorption

\[
\begin{align*}
X + \pi &\rightarrow D + \bar{D} \\
X + \pi &\rightarrow D + \bar{D}^* \\
X + \pi &\rightarrow D^* + \bar{D}^* 
\end{align*}
\]

Cross sections are calculated using chiral SU(4) effective Lagrangians

\[
\phi = \left(\begin{array}{cccc}
\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\
-\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 & D^- \\
K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & D^- \\
D^0 & D^+ & \eta & D_s^+ \\
\end{array}\right)
\]

\[
V_\nu = \left(\begin{array}{cccc}
\frac{1}{\sqrt{2}}(\rho^0 + \omega) & \rho^+ & K^{*+} & \bar{D}^{*0} \\
\rho^- & \frac{1}{\sqrt{2}}(-\rho^0 + \omega) & K^0 & D^{*-} \\
K^{*-} & \bar{K}^0 & \phi & D_s^{*-} \\
D^{*0} & D^{*+} & D_s^{*+} & J/\psi \\
\end{array}\right)_\nu
\]

\[
J_\mu = (\partial_\mu \phi) \phi - \phi (\partial_\mu \phi)
\]

\[
\mathcal{J}_\mu = (\partial_\mu V_\nu) V^\nu - V_\nu (\partial_\mu V^\nu)
\]

\[
\mathcal{L}_{PPV} = -ig_{PPV} \text{Tr} \left( V^\mu J_\mu \right)
\]

\[
\mathcal{L}_{VVV} = ig_{VVV} \text{Tr} \left( V^\mu \mathcal{J}_\mu \right)
\]
X(3872) in the hadronic phase

\[ \mathcal{L}_{D^*D\pi} = ig_{D^*D\pi}(D^*_\mu \partial^\mu \pi \bar{D} - D \partial^\mu \pi \bar{D}^*_\mu) \]

\[ \mathcal{L}_{XD^*D} = g_{XD^*D} X \mu \bar{D}^*_\mu D \]

\begin{align*}
\bar{D}^* & \quad D^* & \quad \bar{D} & \quad D \\
X & \quad \pi & \quad X & \quad \pi 
\end{align*}

More elaborated works:
- Martinez Torres et al., PRD 90 (2014) 114023
Results of ExHIC collaboration

[ExHIC Coll.]
PRL 106 (2011) 212001; PRC 84 (2011) 064901; 
Prog. Part. Nucl. Phys. 95 (2017) 279

Table 3.4: Summary of particle yields for heavy hadrons (cf. Table 2.4).

<table>
<thead>
<tr>
<th>Particle</th>
<th>$q\bar{q}/qqq$</th>
<th>multiquark</th>
<th>$q\bar{q}/qqq$</th>
<th>multiquark</th>
<th>Mol.</th>
<th>Stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>scenario 1</td>
<td>scenario 2</td>
<td>scenario 1</td>
<td>scenario 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_s(2317)$</td>
<td>$2.3 \times 10^{-2}$</td>
<td>$2.4 \times 10^{-3}$</td>
<td>$2.3 \times 10^{-2}$</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$6.5 \times 10^{-3}$</td>
<td>$6.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$5.0 \times 10^{-5}$</td>
<td>$5.6 \times 10^{-4}$</td>
<td>$5.3 \times 10^{-5}$</td>
<td>$9.1 \times 10^{-4}$</td>
<td>$5.7 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

At RHIC and LHC energies the $X(3872)$ production yield is about 18 times smaller for a tetraquark configuration than for a molecular structure.
Tetraquark $X(3872)$ has to survive through hadronic phase.

Absorption is much stronger than production.

Tetraquark X(3872) has to survive though hadronic phase

The abundance of a tetraquark X drops by a factor 4 during the hadronic phase

Summary

We want to use HIC to know the structure of the X

X tetraquark is produced at the end of the plasma phase by quark coalescence

In the hadron phase X can be produced and destroyed

This is described by Effective Lagrangians.

Here we have introduced terms with anomalous couplings

Cross sections much larger

Significant reduction of the X abundance

X molecule is produced at the end of the hadron phase by meson coalescence

Conjecture: if we see any X in HIC, then it is a molecule!
The non-observation of $X(3872)$ in heavy ion experiments favors its interpretation as a compact tetraquark state.
However,

If \( X(3872) \) is a molecular state of \( DD^* \)

We know that \( D \) and \( D^* \) meson are acquire a substantial width in hot pionic matter.

This will necessarily affect the properties of the composite \( X \) state and its production yields.

Cleven, Magas, Ramos, PRC96 (2017) 045201
Pseudoscalar–vector meson interaction

\[ \phi = \begin{pmatrix} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{3}} \eta + \frac{1}{\sqrt{6}} \eta' \\ \pi^- \\ K^- \\ D^0 \end{pmatrix} \quad \begin{pmatrix} \pi^+ \\ K^+ \\ D^0 \end{pmatrix} \quad \begin{pmatrix} K^0 \\ D^- \\ \bar{D}^0 \end{pmatrix} \quad \begin{pmatrix} \rho^0 + \omega \\ \rho^- \\ K^{*-} \end{pmatrix} \quad \begin{pmatrix} K^0 \\ \bar{K}^* \end{pmatrix} \quad \begin{pmatrix} K^*+ \\ D^{*0} \end{pmatrix} \quad \begin{pmatrix} \frac{1}{\sqrt{2}} (\rho^0 + \omega) \\ \rho^- \\ K^{*-} \end{pmatrix} \quad \begin{pmatrix} \frac{1}{\sqrt{2}} (-\rho^0 + \omega) \\ K^{*0} \end{pmatrix} \quad \begin{pmatrix} K^{*+} \\ D^{*-} \end{pmatrix} \]

\[ V_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} (\rho^0 + \omega) \\ \rho^- \\ K^{*-} \end{pmatrix} \quad \begin{pmatrix} \frac{1}{\sqrt{2}} (-\rho^0 + \omega) \\ K^{*0} \end{pmatrix} \quad \begin{pmatrix} K^{*+} \\ D^{*-} \end{pmatrix} \]

\[ J_\mu = (\partial_\mu \phi) \phi - \phi (\partial_\mu \phi) \quad J_\mu = (\partial_\mu V_\nu) V^\nu - V_\nu (\partial_\mu V^\nu) \]

\[ \mathcal{L}_{PPVV} = -\frac{1}{4f^2} \text{Tr} (J_\mu J^\mu) \]

SU(4) symmetry breaking corrections:

charm meson exchange - factor \( \gamma = \left(\frac{m_L}{m_H}\right)^2 \)

charm & light & J/\Psi exchange - factor \( \psi = -1/3 + 4/3 \left(\frac{m_L}{m'_H}\right)^2 \)

\[ V_{ij}(s, t, u) = -\frac{\xi_{ij}}{4f^2} (s - u) \epsilon \cdot \epsilon' \]

Pseudoscalar-vector meson interaction

$X(3872)$ as a molecular state

2 channels: $D \bar{D}^* + c.c.$ $D_s \bar{D}_s^* + c.c.$

$$V_{ij}(s, t, u) = -\frac{\xi_{ij}}{4f^2}(s - u) \epsilon \cdot \epsilon'$$

$$\xi = \begin{pmatrix} -\psi - 2 & -\sqrt{2} \\ -\sqrt{2} & -\psi - 1 \end{pmatrix}$$

$f = f_D = 165$ MeV
$m_L = 800$ MeV; $m_{H'} = 3000$ MeV

Pseudoscalar-vector meson interaction

$X(3872)$ as a molecular state

2 channels:  \[ D \bar{D}^* + c.c. \quad D_s \bar{D}_{s}^* + c.c. \]

\[
V_{ij}(s, t, u) = -\frac{\xi_{ij}}{4f^2} (s - u) \epsilon \cdot \epsilon'
\]

\[
\xi = \begin{pmatrix}
-\psi - 2 & -\sqrt{2} \\
-\sqrt{2} & -\psi - 1
\end{pmatrix}
\]

\[ f = f_D = 165 \text{ MeV} \]
\[ m_L = 800 \text{ MeV}; \quad m_{H'} = 3000 \text{ MeV} \]

Bethe-Salpeter equation

\[ T = (1 - VG)^{-1} V \cdot \epsilon' \]

Bethe-Salpeter equation

\[ T = (1 - VG)^{-1} V \varepsilon \cdot \bar{\varepsilon}' \]

Meson-meson loop function

\[
G_{ii}(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{[q^2 - m_1^2 + i\epsilon][(P-q)^2 - m_2^2 + i\epsilon]}
\]

\[
= \frac{1}{16\pi^2} \left[ \alpha + \log \frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s} \log \frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}} \left( \log \frac{s - m_2^2 + m_1^2 + 2p\sqrt{s}}{-s + m_2^2 - m_1^2 + 2p\sqrt{s}} + \log \frac{s + m_2^2 - m_1^2 + 2p\sqrt{s}}{-s - m_2^2 + m_1^2 + 2p\sqrt{s}} \right) \right], \quad \alpha = -1.26
\]

X(3872) is dynamically generated with correct mass

**X(3872) in a hot pionic gas**

**Imaginary Time Formalism:** \( q^0 \rightarrow i \omega_n = i 2 \pi n T, \quad \int \frac{d^4 q}{(2\pi)^4} \rightarrow iT \sum_i \int \frac{d^3 q}{(2\pi)^3} \)

**Meson-meson loop function**

\[
G_{MM'}(P^0, \vec{P}; T) = \int \frac{d^3 q}{(2\pi)^3} \int d\omega \int d\omega' \frac{S_M(\omega, \vec{q}; T)S_{M'}(\omega', \vec{P} - \vec{q}; T)}{P^0 - \omega - \omega' + i\varepsilon} \times \\
\times [1 + f(\omega, T) + f(\omega', T)]
\]

\( f(\omega, T) = [\exp(\omega/T) - 1]^{-1} \) - Bose distribution function

\( S_M(\omega, \vec{q}; T) = -(1/\pi)\text{Im}(D_M(\omega, \vec{q}; T)) \) - spectral function of meson \( M \)

\( D_M(\omega, \vec{q}; T) = [\omega^2 - \vec{q}^2 - m_M^2 - \Pi_M(\omega, \vec{q}; T)]^{-1} \) - meson propagator

\( \Pi_M(p^0, \vec{p}; T) = \int \frac{d^3 q}{(2\pi)^3} \int d\Omega \frac{f(\Omega, T) - f(\omega_\pi, T)}{(p^0)^2 - (\omega_\pi - \Omega)^2 + i\varepsilon} \times \\
\times \left(-\frac{1}{\pi}\right) \text{Im}T_{M\pi}(\Omega, \vec{p} + \vec{q}; T) \) - meson self-energy
\( X(3872) \) in a hot pionic gas

\[ T = V + VGT \]

\[ D_s(D_s) \]

\[ D^*(D_s^*) \]

\[ \Pi_M(p^0, \bar{p}; T) \]

\[ \Pi_M(\omega, \bar{q}; T) = \frac{1}{\omega^2 - \bar{q}^2 - m^2_M - \Pi_M(\omega, \bar{q}; T)} \]
Both $D$ and $D^*$ get a substantial width of 30-40 MeV at $T=150$ MeV

No mass change

$\Gamma_D^{0} = 83$ keV
$X(3872)$ is in a hot pionic gas

$X(3872)$ is a stable bound state at $T=0$ MeV

$X(3872)$ develops a substantial width:

$\Gamma_X \sim 10, \sim 30$ and $\sim 60$ MeV at $T=50, 100$ and $150$ MeV, respectively

the $X(3872)$ peak position is shifted from slightly below $DD^*$ threshold in vacuum to some MeV above it at finite $T$
$X(3872)$ in a hot pionic gas

$X(3872)$ is a stable bound state at $T=0$ MeV

$X(3872)$ can not be considered as a loosely bound (deuteron-like) $DD^*$ bound state

For heavy ion collision simulations $X(3872)$ can not be considered as a loosely bound (deuteron-like) $DD^*$ bound state.

$X(3872) \rightarrow D^0 \bar{D}^{*0}$ decay was not considered.

[Temperature for kinetic freeze out]
- $T_{FO} = 119$ MeV (RHIC)
- $T_{FO} = 115$ MeV (LHC)
- $\Gamma_X \sim 40$ MeV

[Temperature for hadronization]
- $T_H = 162$ MeV (RHIC)
- $T_H = 156$ MeV (LHC)
- $\Gamma_X \sim 65$ MeV
Conclusions

- The study of the X(3872) production in the heavy ion collision experiments may help us to understand its nature.

- D and D* mesons develop a substantial width in a hot medium.

  - If X(3872) is a molecular state its properties can change drastically in a hot medium.

  - The production of the molecular X(3872) state via hadron coalescence has to be recalculated.

- Work in progress.
Back up
statistical model prediction. This can be understood by considering, for example, a simple rate equation for the $K^*$ meson during the hadronic stage,

$$\frac{dN_{K^*}(\tau)}{d\tau} = \frac{1}{\tau_{\text{scat}}^K} N_K(\tau) - \frac{1}{\tau_{\text{scat}}^{K^*}} N_{K^*}(\tau),$$

(3.29)

with $1/\tau_{\text{scat}}^K = \sum_i \langle \sigma_{K^* i} n_{K^* i} \rangle n_i + \langle \Gamma_{K^*} \rangle$, and $1/\tau_{\text{scat}}^{K^*} = \sum_j \langle \sigma_{K^* j} n_{K^* j} \rangle n_j$. Here $i$ and $j$ stand for mostly the light mesons such as the pion and $\rho$ meson, i.e., $1/\tau_{\text{scat}}^K = \langle \sigma_{K^* \rho \rightarrow K\pi \rho} n_{\rho} \rangle + \langle \sigma_{K^* \pi \rightarrow K\pi \pi} n_{\pi} \rangle + \langle \Gamma_{K^*} \rangle$ and $1/\tau_{\text{scat}}^{K^*} = \langle \sigma_{K\rho \rightarrow K^* \rho} n_{\rho} \rangle + \langle \sigma_{K\pi \rightarrow K^* \pi} n_{\pi} \rangle + \langle \sigma_{K\pi \rightarrow K^* \pi} n_{\pi} \rangle + \langle \sigma_{K\pi \rightarrow K^* \pi} n_{\pi} \rangle$ with $\langle \Gamma_{K^*} \rangle$ being the thermally averaged decay width of the $K^*$ meson [268]. In the above, non-linear terms originated from the interaction between $K^*$ mesons or kaons, like $K\bar{K} \rightarrow \rho\pi$, are not considered.

Consider a simple picture where the total number of light mesons and $K$ mesons are fixed as the system expands. The equilibrium number of $K^*$ mesons is given by the asymptotic value obtained by taking the right hand side of Eq. (3.29) to be zero, given as

$$N_{K^*}^{\text{asym}}(\tau) = \frac{\sum_j \langle \sigma_{K^* j} n_{K^* j} \rangle N_j}{\sum_j \langle \sigma_{K^* j} n_{K^* j} \rangle N_j + V(\tau) \langle \Gamma_{K^*} \rangle} N_K.$$

(3.30)

At chemical freeze-out, this value should correspond to that given by the statistical model. As the system expands, while the total number of light hadrons and $K$ meson remain fixed, the $K^*$ number decreases due to decay as the freeze-out volume $V(\tau)$ increases, leading to a suppression factor that depends on the freeze-out volume, a result borne out in the measured $K^*$ number in heavy ion collision [5]. This mechanism becomes relevant only for particles that have natural decay width, which leads to terms in the rate equation that are proportional to their numbers and thus scale with the volume of the system. For bound states composed of hadrons, they do not have natural decay widths and are thus not affected by this suppression mechanism. Although
X(3872) in a hot pionic gas

Figure 3: Real part of the $DD^*$ loop (left panel), imaginary part of the $DD^*$ loop (right panel). All quantities are shown at temperatures 0, 50, 100, 150 MeV. The dashed gray line represents the $DD^*$ threshold.
X(3872) production
# Exotic spectroscopy

<table>
<thead>
<tr>
<th>J/ψπ⁺π⁻</th>
<th>X(3872)</th>
<th>Y(4260)</th>
<th>Y(4008)</th>
<th>p̅p incl.</th>
<th>pp incl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ψ(2S)π⁺π⁻</td>
<td></td>
<td>Y(4360)</td>
<td>Y(4660)</td>
<td>X(3872)</td>
<td>X(3872)</td>
</tr>
<tr>
<td>ΛcΛc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ψγ</td>
<td>X(3872)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>χc1(1P)γ</td>
<td>X(3832)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>χc1(1P)ω</td>
<td></td>
<td></td>
<td></td>
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Dynamically generated hidden charm resonances around 4.3 GeV

Similar states have been predicted theoretically!

**Molecular models**
- Wu, Molina, Oset, Zou,
  PRL 105, 232001 (2010); PRC 84, 015202 (2011)
- Yang, Sun, He, Liu, Zhu,

**Quark models**
- Wang, Huang, Zhang, Zou, PRC 84, 015203 (2011)
- Yuan, Wei, He, Xu, Zou, EPJA 48, 61 (2012)