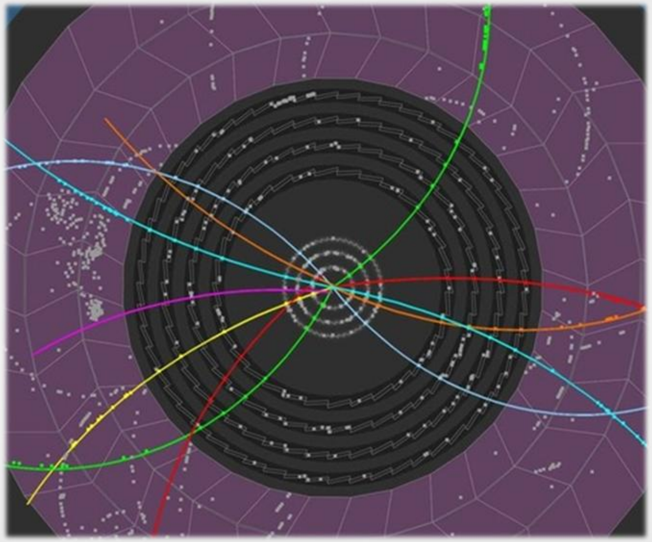
QUANTUM AND SEMI-CLASSICAL APPROACHES TO J/ψ SUPPRESSION



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Summary

- Introduction
- Quantum formalism
- Quantum results
- Semi-classical formalism
- Semi-classical results
- Comparison
- Conclusion

Introduction

Background?

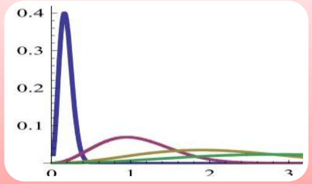
- **Quarkonia suppression was predicted** by Matsui and Satz as a sign of Quark-Gluon Plasma production in heavy-ion collisions.
- Quarkonia suppression has been observed but is **still poorly understood**.

PhD thesis goal ?

- Study the **evolution of a $c\bar{c}$ pair in the QGP** by different means.
- Explain the observed **suppression of the J/ψ suppression** as the collision energy increases.

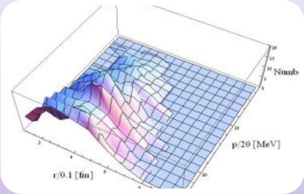
This project goal ?

- **Study** the wavefunction of a $c\bar{c}$ pair in an isotropic QGP at thermal equilibrium through:



Quantum approach

- Non relativistic Schrödinger equation



Semi-classical approach

- Quantum Wigner distribution
- Classical, 1st order in ħ, Wigner-Moyal equation

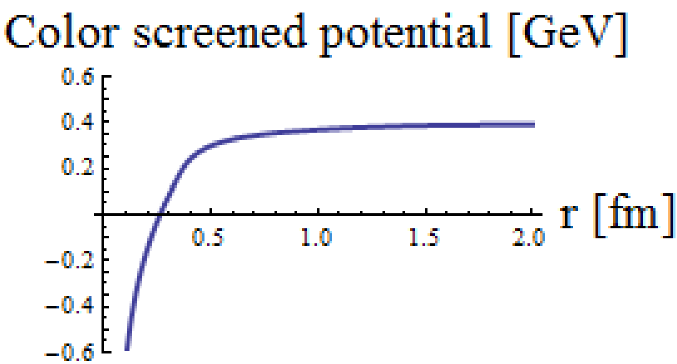
… then **projection** onto the J/ψ state.

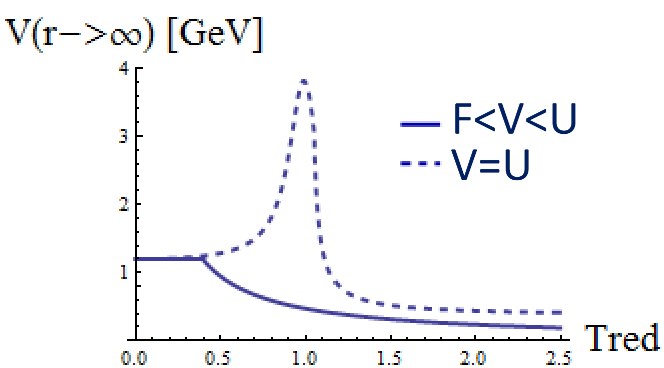
- **Results comparison to validate/unvalidate** Young and Shuryak* semi-classical approach to J/ψ survival with stochastic Langevin equation.

* Phys.Rev.C79:034907,2009

The common tools

The color potentials V(Tred, r)





- "Weak potential F<V<U"

$$V_{\text{close}}(r) = -\frac{\alpha}{r} + \sigma r - \frac{0.8\sigma}{m^2 r},$$

$$V_{\text{int}}(r) = \frac{V0 + g_1(r-r_0) + g_2(r-r_0)^2}{1 + g_3(r-r_0) + g_4(r-r_0)^2},$$

$$V_{\text{far}}(r) = V_\infty - \frac{4}{3}\frac{\alpha_1}{r} e^{-\sqrt{4\pi\ \tilde{\alpha}_1} T r}$$

- "Strong potential V=U"

$$U = \left(-\frac{\alpha}{r} + \sigma r - \frac{0.8\sigma}{m^2 r} \right) \times e^{-(\mu r)^2} + V_0 \times \left(1 - e^{-(\mu r)^2}\right)$$

Evaluated by Mócsy & Petreczky* and Kaczmarek & Zantow** from some lQCD results and reparametrized by Gossiaux

 * Phys.Rev.D77:014501,2008 **arXiv:hep-lat/0512031v1

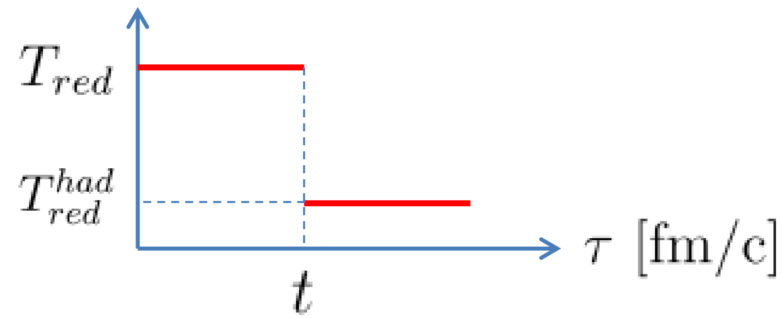
The common tools

The temperature scenarios

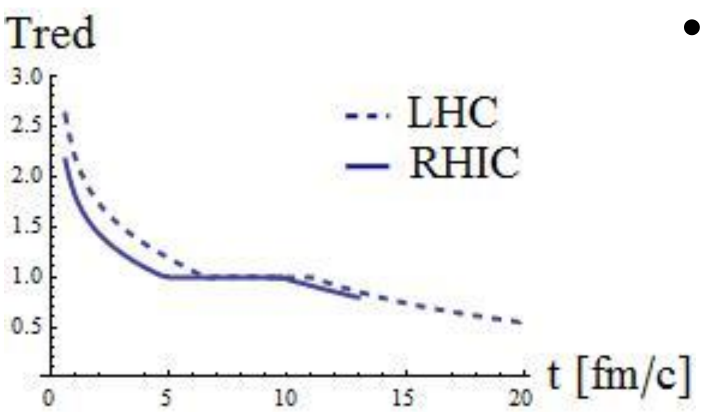
- At fixed temperatures

$$T_{red} = T/T_c,$$

where $T_c = 0.165\ \text{Gev}$



Instantaneous transition from QGP at T_{red} to hadronisation phase at $T^{had}_{red} \leq 0.4$



- Time dependent temperature
  - **Cooling** of the QGP over time by Kolb and Heinz* (hydrodynamic evolution and entropy conservation)
  - At LHC ($\sqrt{s_{NN}} = 2.76\ \text{TeV}$) and RHIC ($\sqrt{s_{NN}} = 200\ \text{GeV}$) energies

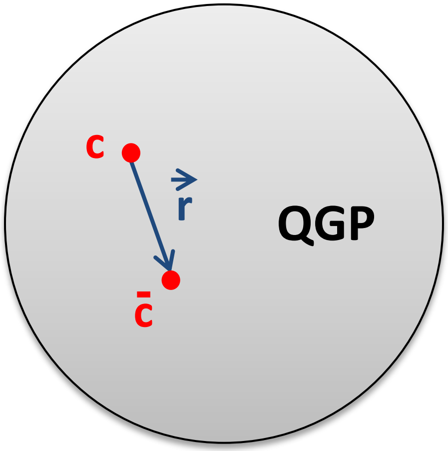
* arXiv:nucl-th/0305084v2

Quantum formalism

- **Schrödinger equation for the $c\bar{c}$ pair evolution**

$$\Psi(\mathbf{r}, t+\Delta t) = e^{-i\frac{\widehat{H}}{\hbar}\Delta t}\,\Psi(\mathbf{r}, t)$$

then expanded to the 1st degree in Δt .



Where:

$$\widehat{H} = 2m_q - \frac{(\hbar c)^2}{m_q}\nabla^2 + V(r)$$

$$\Psi(\mathbf{r}, t) = \boxed{R(r,t)} \times \cancel{Y(\theta,\phi)}$$

$$R(r,t) = u_{c\bar{c}}(r,t)/r$$

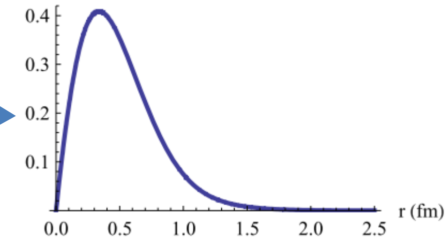
reduced radial wave-function

$$R(r, t=0) = \left(\frac{1}{\pi a^2}\right)^{3/4} e^{-\frac{r^2}{2a^2}}$$

with $a = 0.165\ \mathrm{fm}$

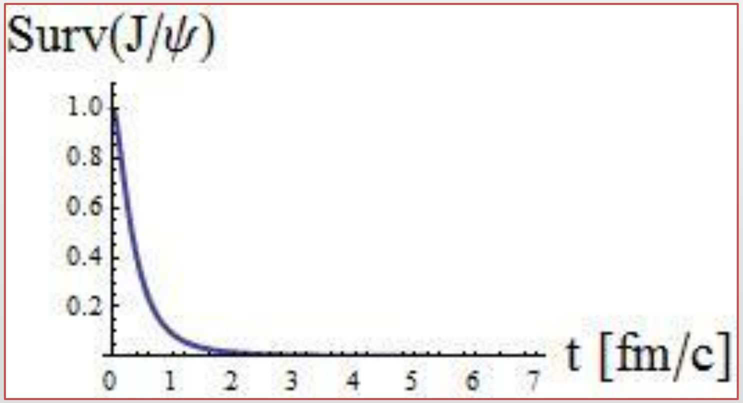
- **Projection onto the J/ψ state**

$$W_{J/\psi}(t) = \left(4\pi \,\mathrm{Abs}\left[\int_0^\infty u_{c\bar{c}}\,(r,t,T_{red}) \times u_{J/\psi}(r,T_{red}^{had})\; dr\right]\right)^2$$



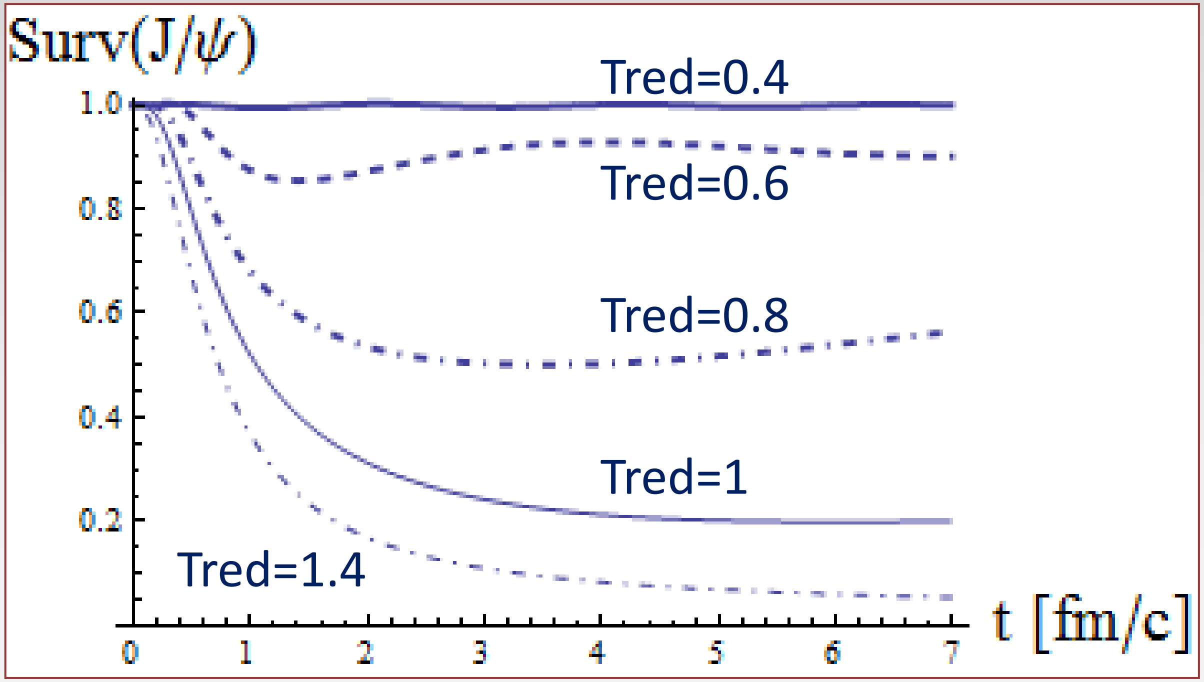
$$\mathrm{Surv}(J/\psi) = W_{J/\psi}(t)/W_{J/\psi}(0)$$

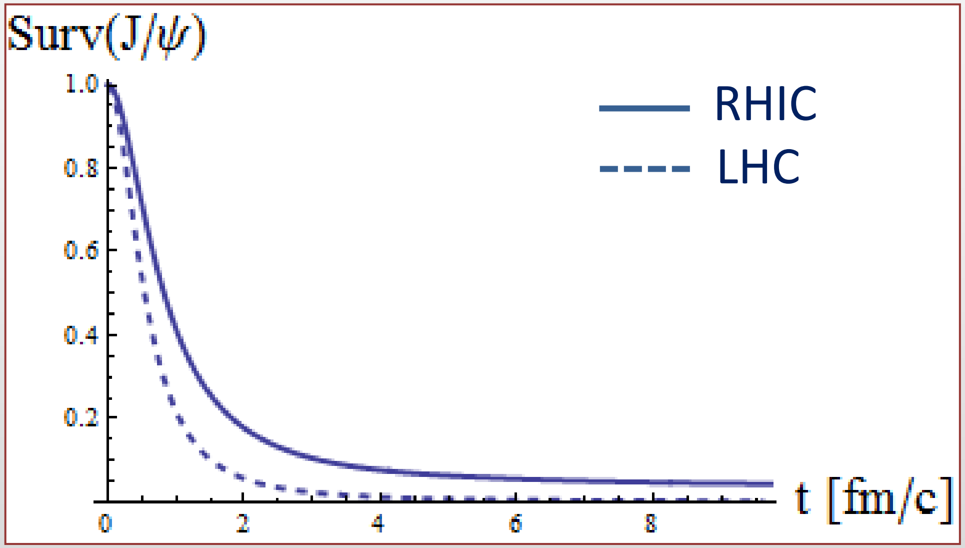
Quantum results



With **no** color potential: V=0

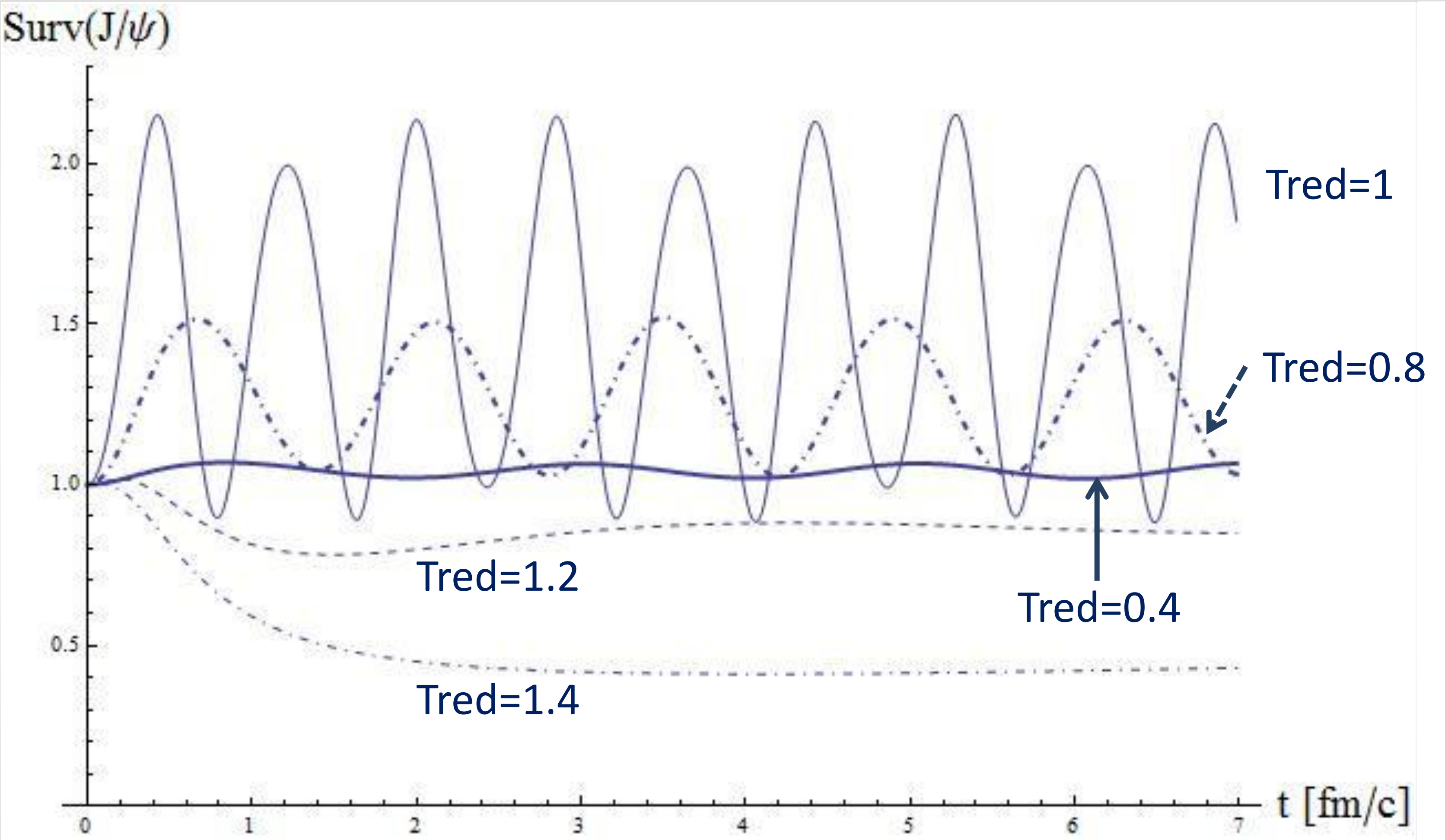
With the **weak** color potential (F<V<U) at **fixed temperatures**





With the **weak** color potential (F<V<U) and a **time-dependent temperature**

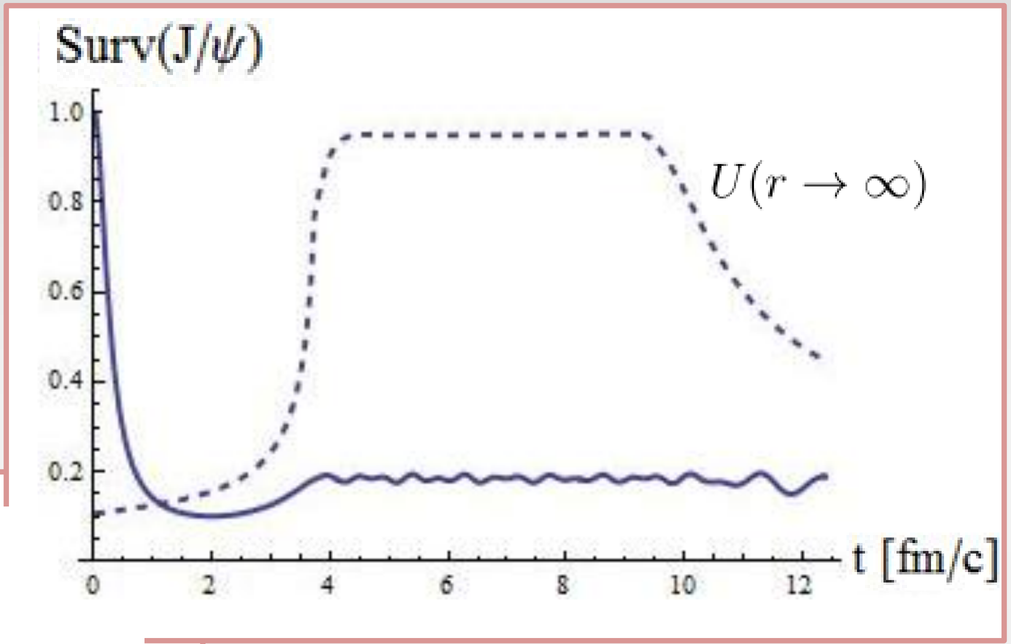
With the **strong** color potential (V=U) at **fixed temperatures**

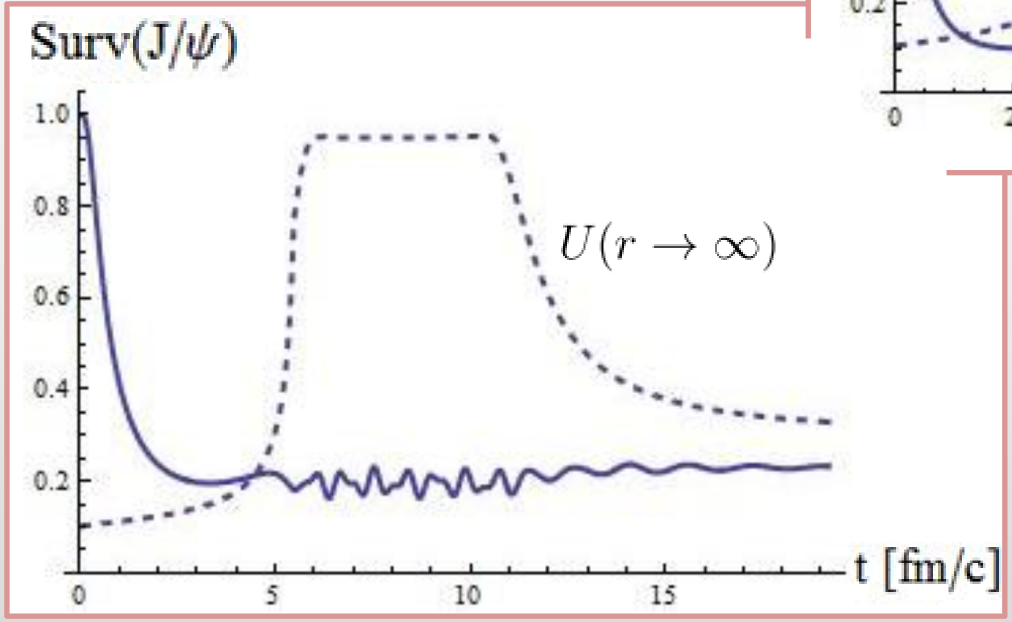


Oscillations between 2 or 3 eigenstates for U(0.4<Tred <1.2)

With the **strong** color potential (V=U) and a **time-dependent temperature**

RHIC
$\sqrt{s_{NN}} = 200\ \mathrm{GeV}$





LHC
$\sqrt{s_{NN}} = 2.76\ \mathrm{TeV}$

Semi-classical formalism

The"Quantum" **Wigner distribution of the $c\bar{c}$ pair**:

$$F\left(\vec{x},\vec{p},t\right)=\int e^{\frac{i\vec{p}\vec{y}}{\hbar}}\Psi^{*}\left(\vec{x}+\frac{\vec{y}}{2}\right)\Psi\left(\vec{x}-\frac{\vec{y}}{2}\right)d\vec{y}$$

… is **evolved** with the "classical", 1st order in ħ, Wigner-Moyal equation:

$$\left[\left(\frac{\partial}{\partial t}+\frac{\vec{p}}{m}\frac{\partial}{\partial\vec{x}}\right)-\frac{\partial}{\partial\vec{p}}\frac{\partial}{\partial\vec{x}}V\left(\vec{x}\right)\right]F\left(\vec{x},\vec{p},t\right)=0$$

Finally the **projection** onto the J/ψ state is given by:

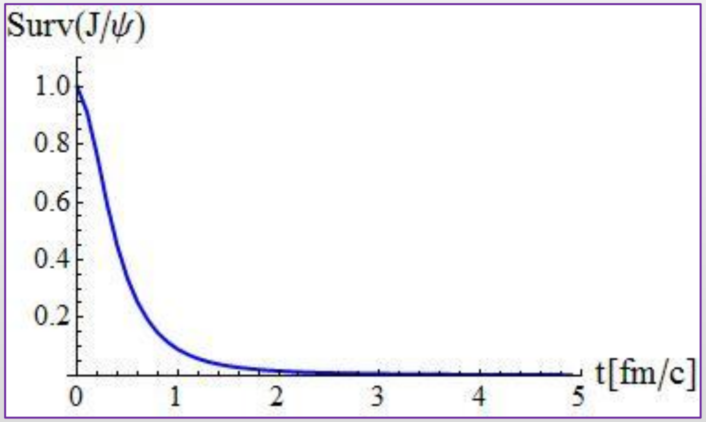
$$P_{J/\Psi}(t)=\int F\left(\vec{r},\vec{p},t\right)F_{J/\Psi}\left(\vec{r},\vec{p}\right)\frac{d^{3}\vec{p}d^{3}\vec{r}}{(\hbar c)^{3}}$$

But in practice: N test particles (initially distributed with the same gaussian distribution in (r, p) as in the quantum case), that evolve with Newton's laws, and give the J/ψ weight at t with:

$$P_{J/\Psi}(t) = \frac{1}{N}\sum_{i=1}^{N} F_{J/\Psi}\left(r_i(t), p_i(t)\right)$$

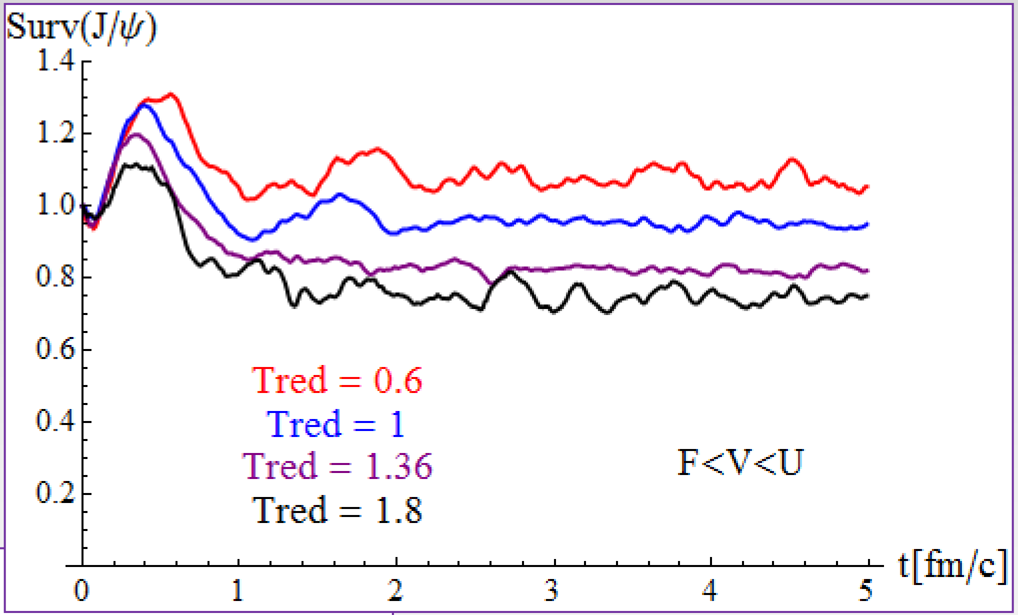
$$\mathrm{Surv}(J/\Psi) = P_{J/\Psi}(t)/P_{J/\Psi}(0)$$

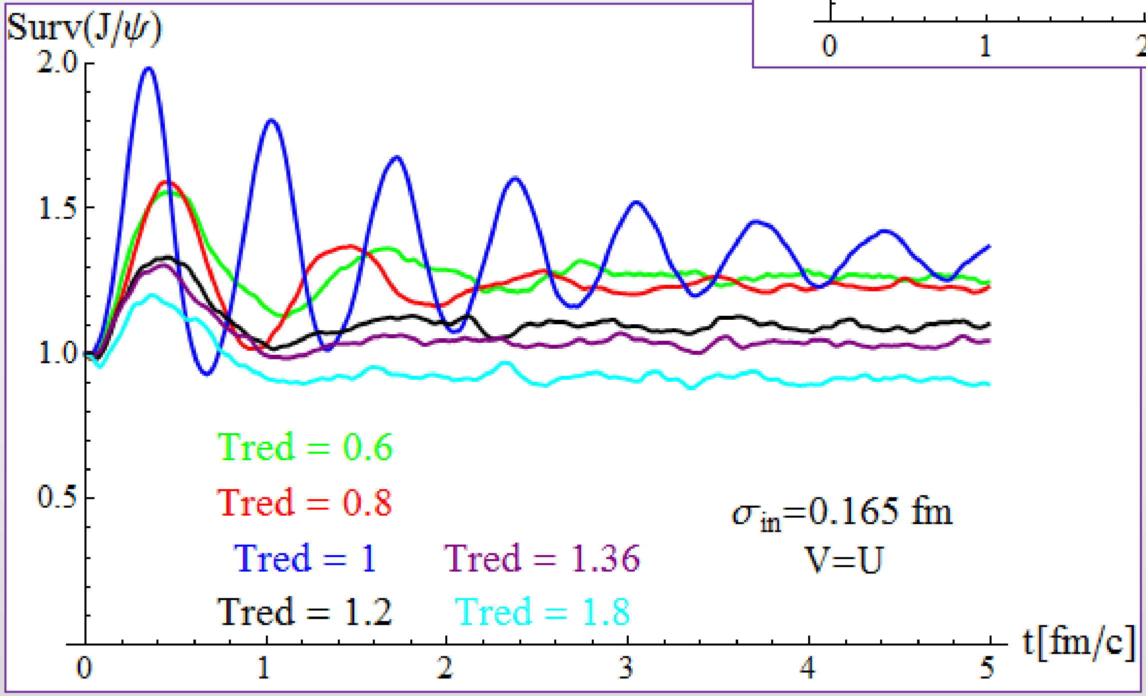
Semi-classical results



With **no** color potential: V=0

With the **weak** color potential (F<V<U) at **fixed temperatures**





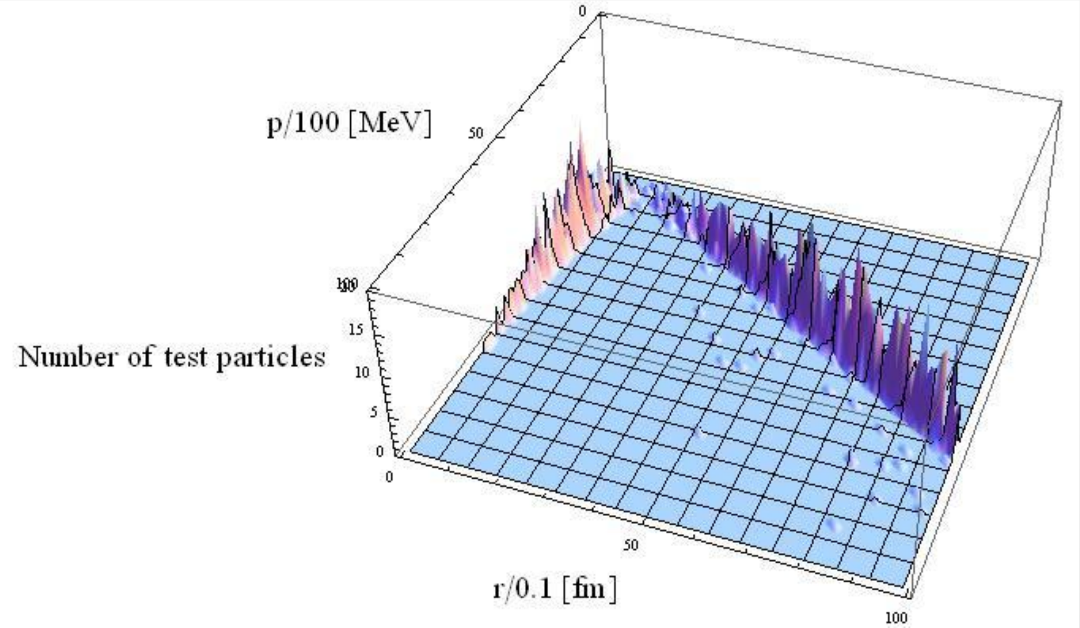
With the **strong** color potential (V=U) at **fixed temperatures**

From observing the distribution of test particles in the phase space over time:

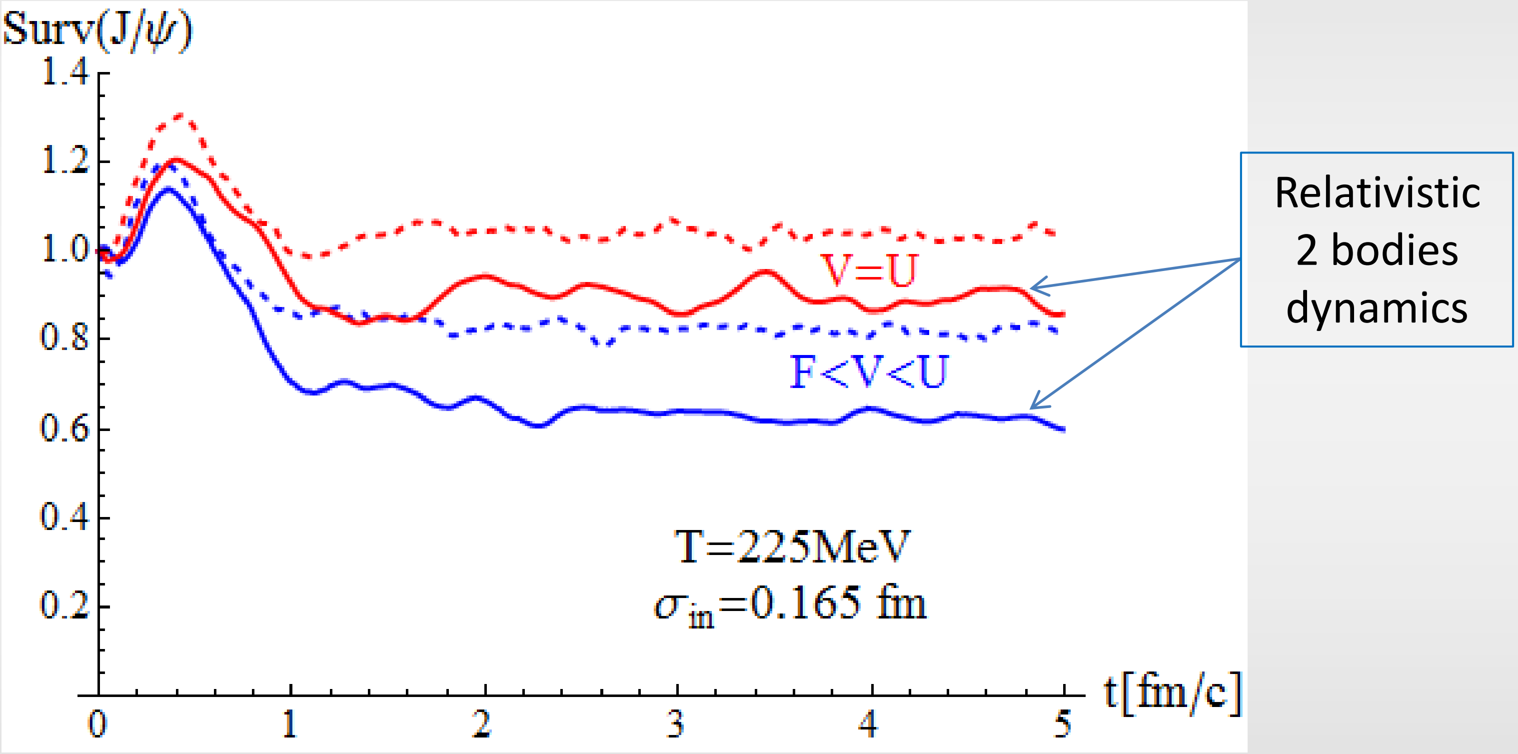
✓ *The increase of Surv(J/ψ)* for t < 0.5 fm/c **<=** some particles loose momentum while climbing the potential

✓ *And decrease of Surv(J/ψ)* for t < 1 fm/c **<=** the particles with sufficient momentum go out the « J/ψ zone » by climbing the potential

✓ *Finally Surv(J/ψ) remains constant* for t > 1 fm/c **<=** the latter particles reach the continuum



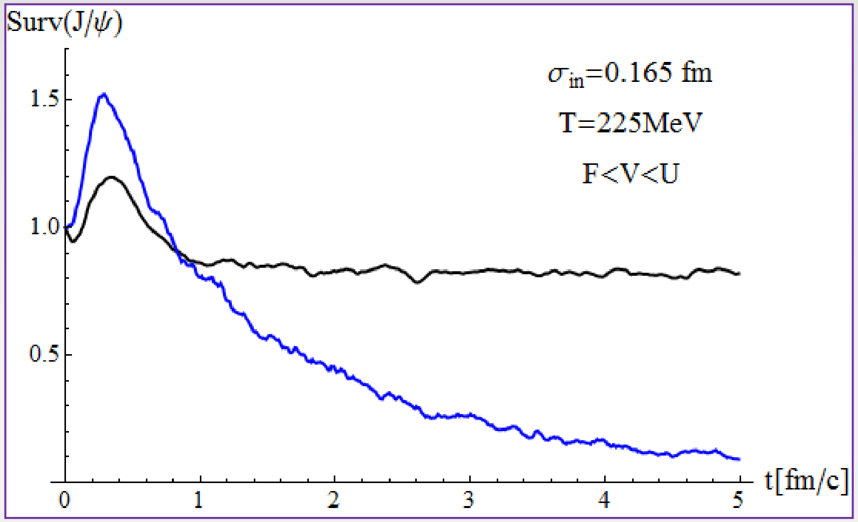
Relativistic 2 bodies dynamics
instead of the previous non-relativistic relative one

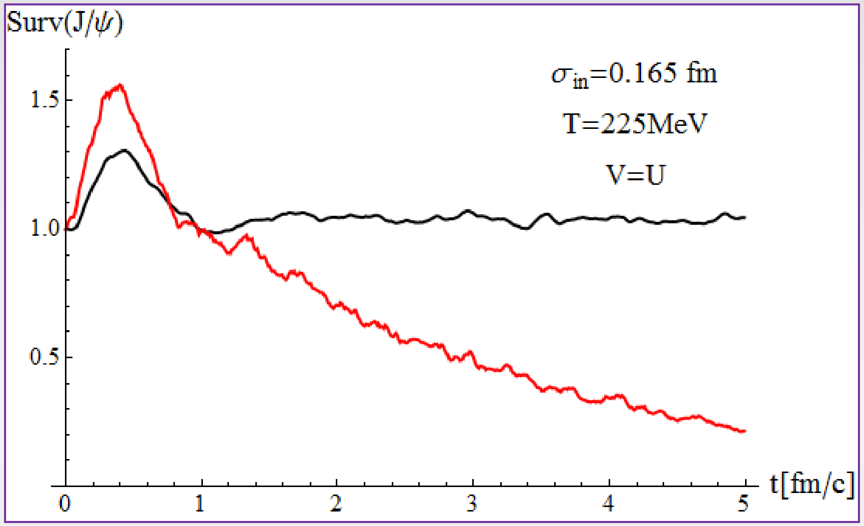


Gives around 20 % lower J/ψ survival than the previous dynamics

With additional stochastic and drag forces

The Langevin forces are added in Newton's laws.



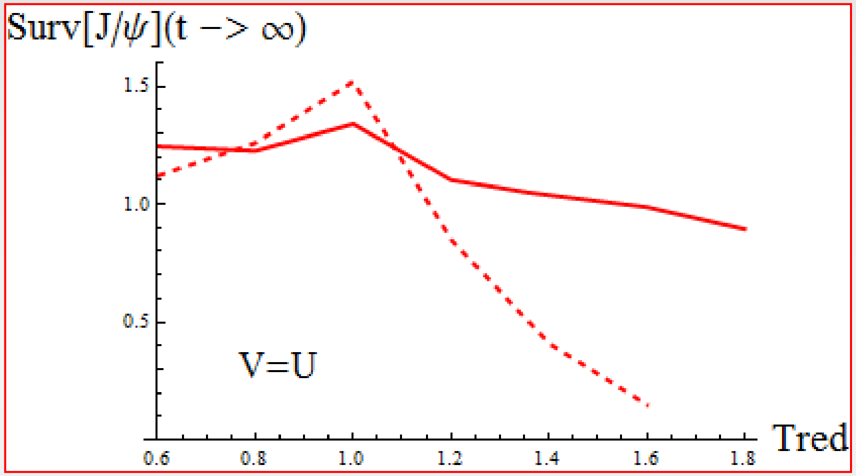


From observing the distribution of test particles in the phase space over time:

- ✓ *The increase of Surv(J/ψ)* for t < … fm/c **<=** usual effect + <u>an increased rate due to the drag force</u> that keeps the particles to quit the "J/ψ zone"
- ✓ *And decrease of Surv(J/ψ)* for t > … fm/c **<=** usual effects + <u>with an increased rate, and during a longer time, effect due to the stochastic forces</u> that continuously push the particles out of the "J/ψ zone"

Comparison

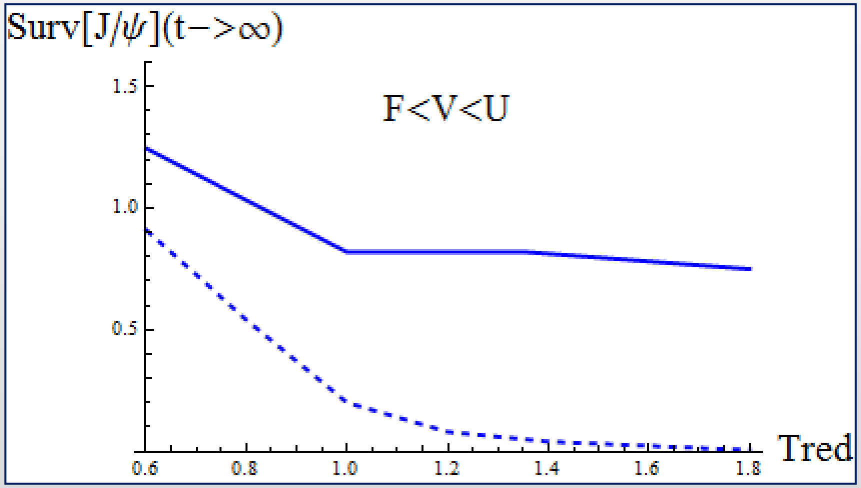
Comparison of Surv[J/ψ](t->∞) average values function of Tred



------ Quantum approach

—— Semi-classical approach

(no stochastic forces, relative dynamics)



<table>
<tr><th></th><th>Quantum</th><th>Semi-classical</th></tr>
<tr><td>V=0</td><td colspan="2">Same fast damping of the J/ψ state</td></tr>
<tr><td rowspan="2">F<V<U</td><td colspan="2">The mean values of Surv[J/ψ](t->∞) are quite different especially at large Tred</td></tr>
<tr><td></td><td>Has troubles to quit the interval around 1 of Surv[J/ψ]</td></tr>
<tr><td rowspan="3">V=U</td><td colspan="2">Same remarks than for F<V<U</td></tr>
<tr><td colspan="2">Oscillations between 2 or 3 eigenstates for U(0.4<Tred <1.2)</td></tr>
<tr><td>No damping of the oscillations</td><td>The oscillations are damped</td></tr>
<tr><td>Additionnal stochastic and drag forces</td><td>Future work</td><td>Close result for both potentials</td></tr>
</table>

Conclusion

This project

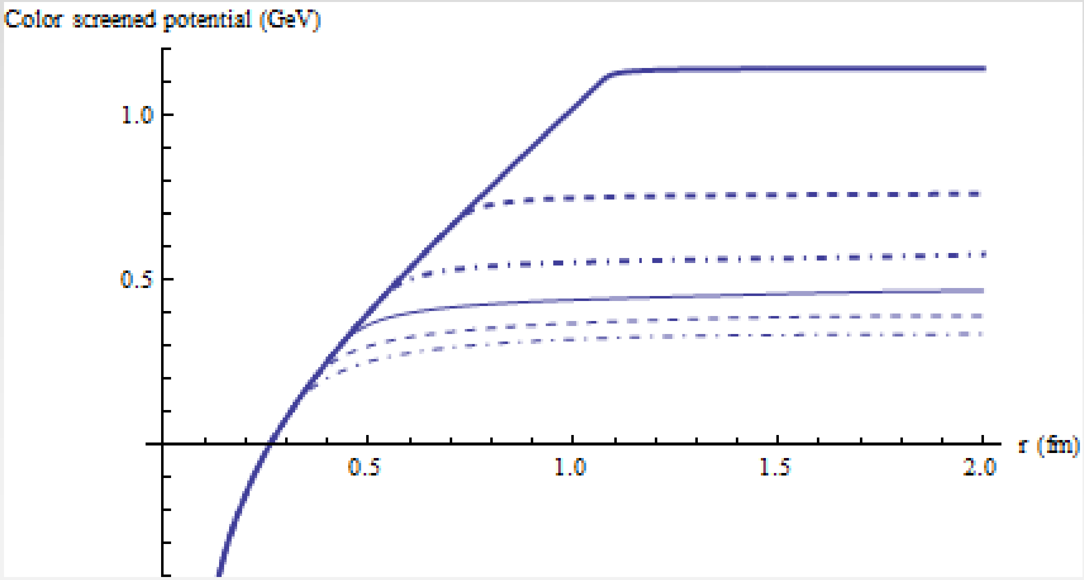
- The J/ψ survival in a screening medium -> studied with two different temperature dependent potentials and with two different approaches.

- Strong discrepancies between the two approaches => the semi-classic approach proposed by Young and Shuryak may not be relevant when quarkonia are studied in a color screened medium.

Future work

- The quantum approach should then be pursued ->
  - Bottomonia
  - Different additional stochastic and drag forces (<=> taking into account the direct interactions with the medium particles)

Backup



With weak potential F<V<U with Tred from 0.4 to 1.4

With strong potential V=U with Tred from 0.4 to 1.4