Quarkonia suppression in QGP

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P.B. Gossiaux (SUBATECH, UMR 6457)

With J Aichelin, H. Berrehrah, R Katz & V Marin

Outline

1. Motivation
2. Stationnary quarkonia in stationnary QGP
3. Caveats and uncertainties
4. Two-components model for quarkonia suppression
5. Stationnary quarkonia in evolving QGP
6. Dynamical quarkonia in QGP (beyond 2-components model)

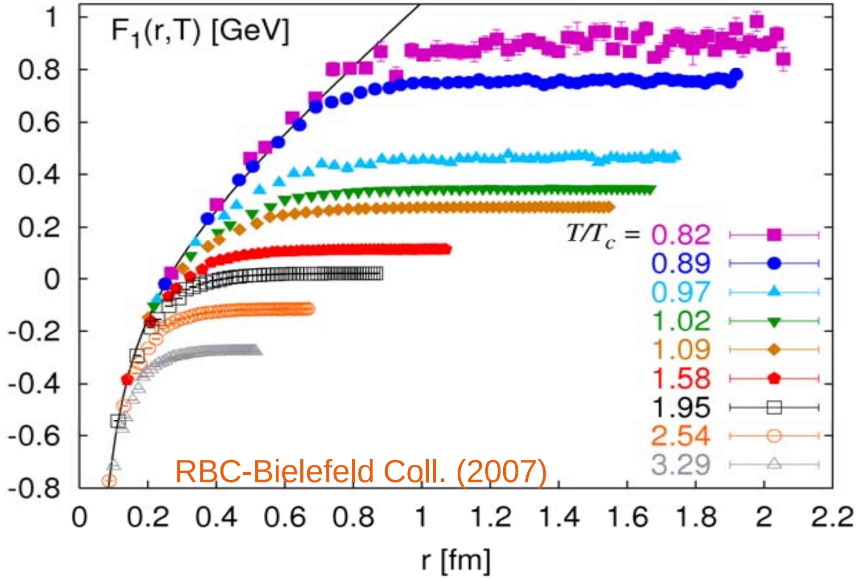
Probing deconfinement ?

How can we prove that we have really achieved a *deconfined* state of matter in ultra-relativistic heavy ions collisions ?

Challenge

"deconfinometer" ≡
- Color fluctuations
- Propagation of individual quarks over large distances

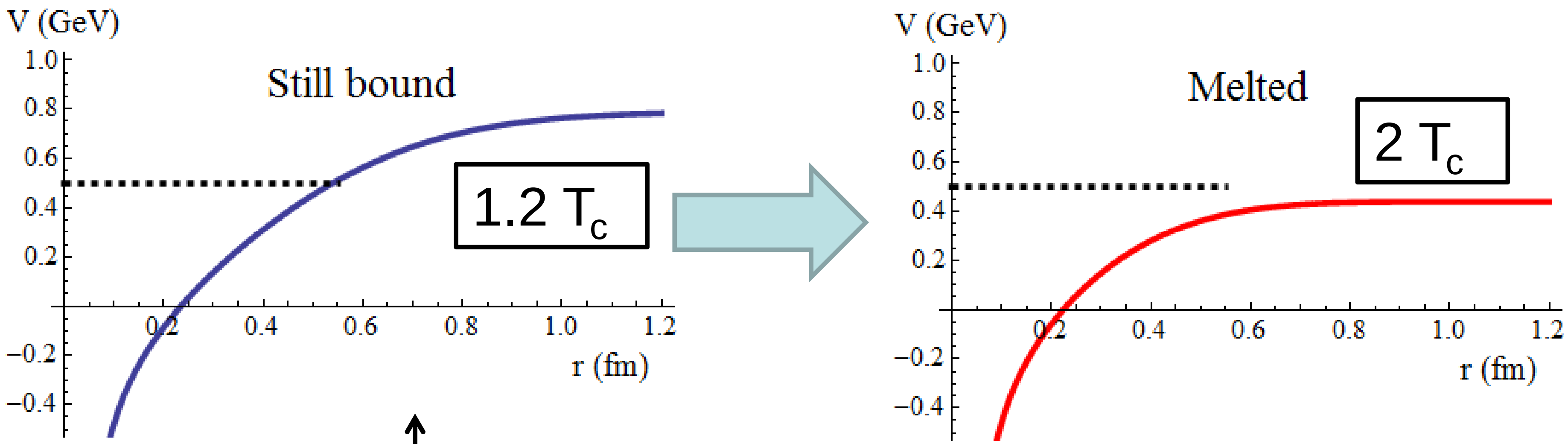
Looking at the QQbar potential on the lattice

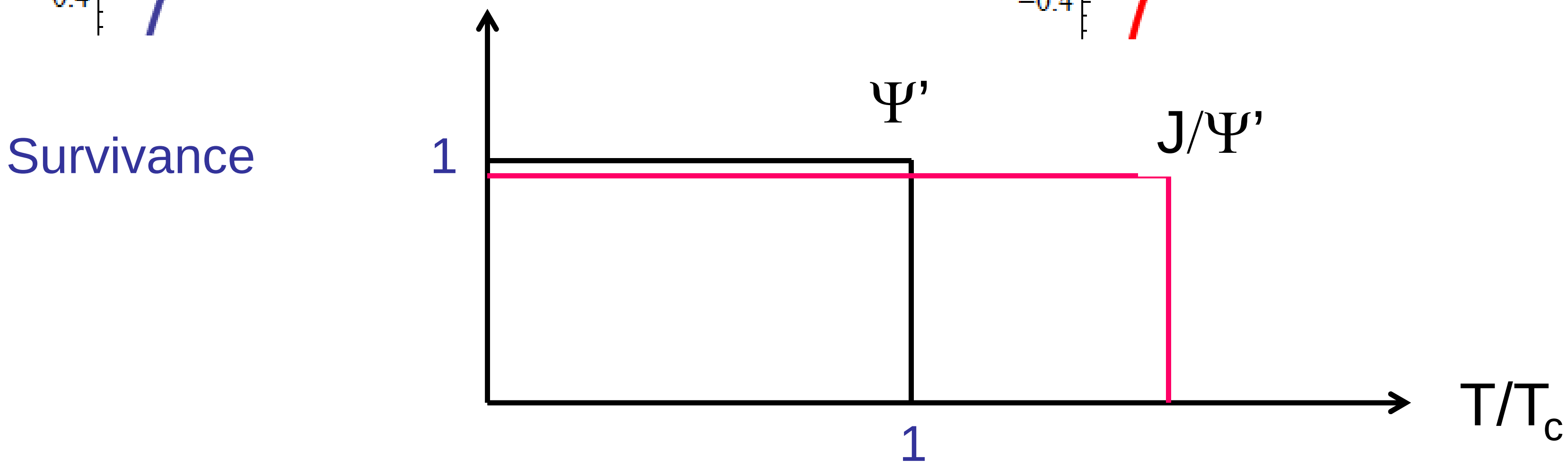


Increased screening at larger temperatures

Quarkonia in Stationary QGP

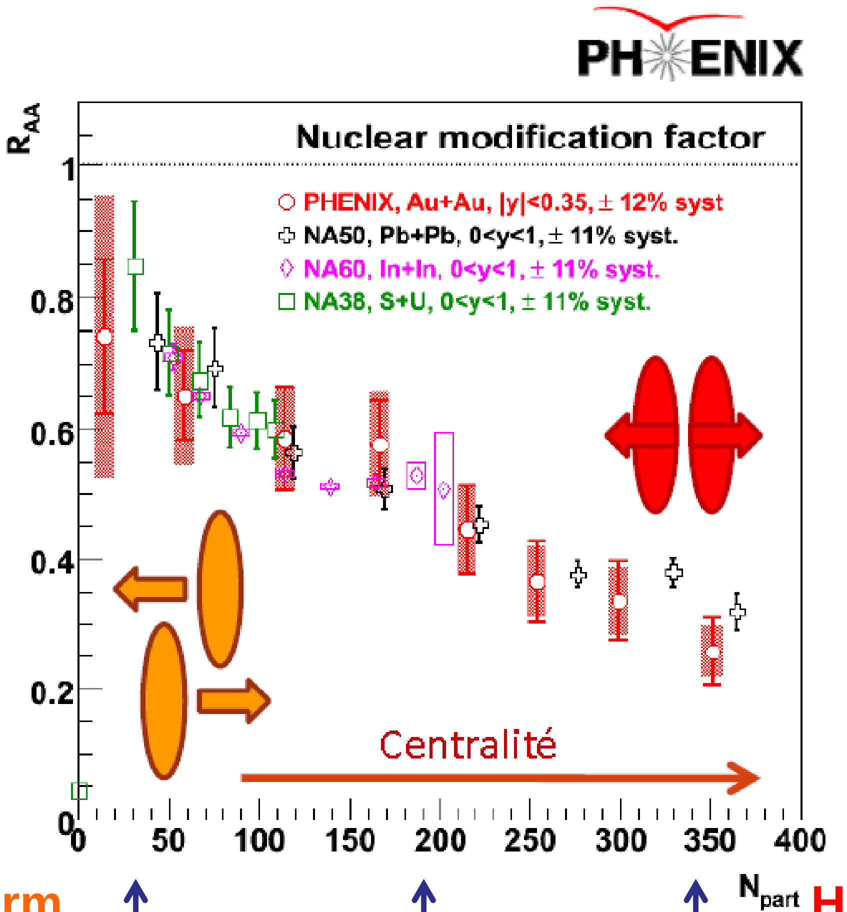
Consequence for Q-Qbar states (Q: heavy quark):





Best candidate: Quarkonia sequential "suppression", i.e. melting and/or dissociation (Matsui & Satz 86)

Quarkonia in Stationary QGP



Warm

Hot

Melted ψ'

Melted χ_c

J/ψ starts to melt

Observed J/ψ =

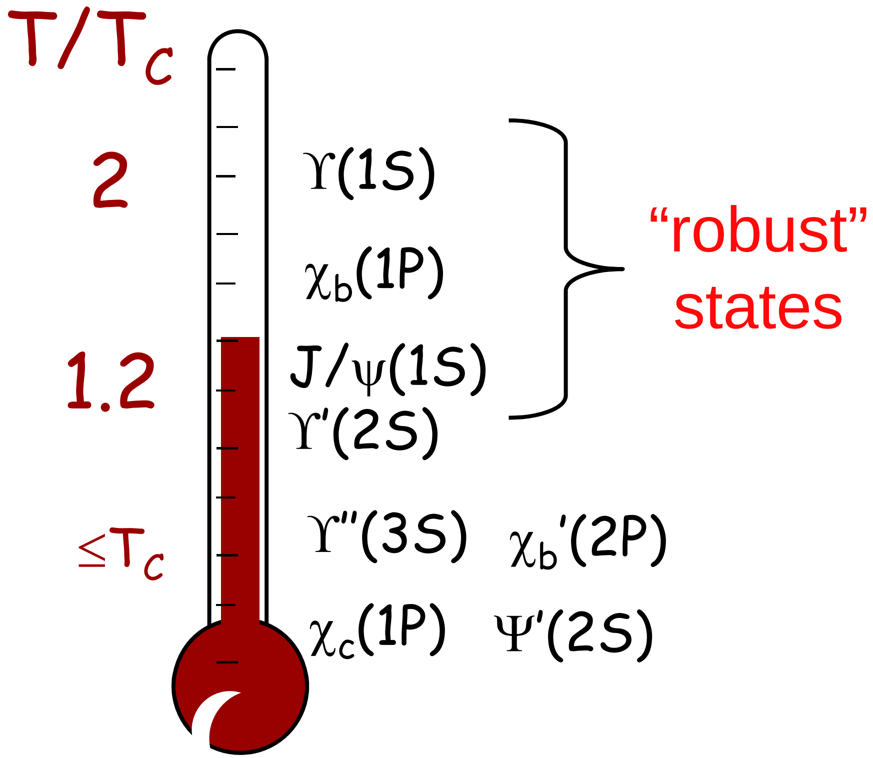
prompt J/ψ + 30% χ_c + 10 % ψ'

No further suppression at RHIC (as compared to SPS)

=> Claim that T_{diss} (J/ψ) is pretty high (strongly bound)

Quarkonia in Stationary QGP

QGP
Thermometer

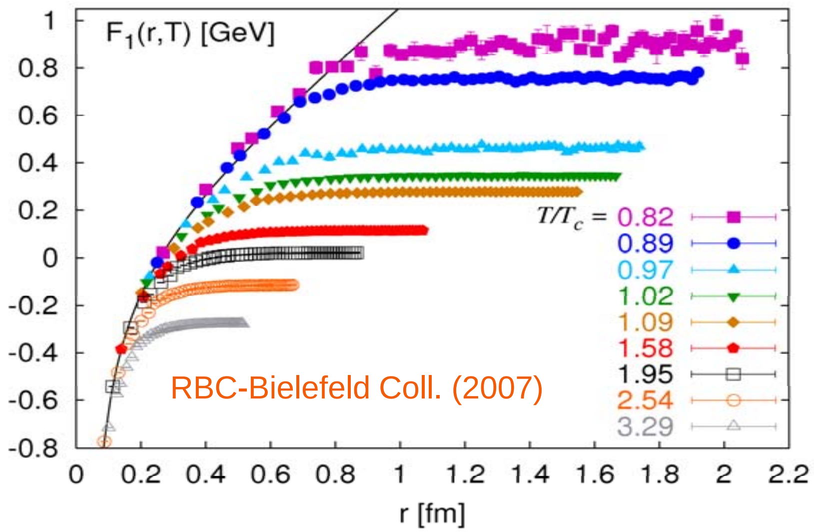


Indeed observed at SPS (CERN) and RHIC (BNL) experiments. However:

- alternative explanations, lots of unknown (also from theory side)
- less suppression at LHC

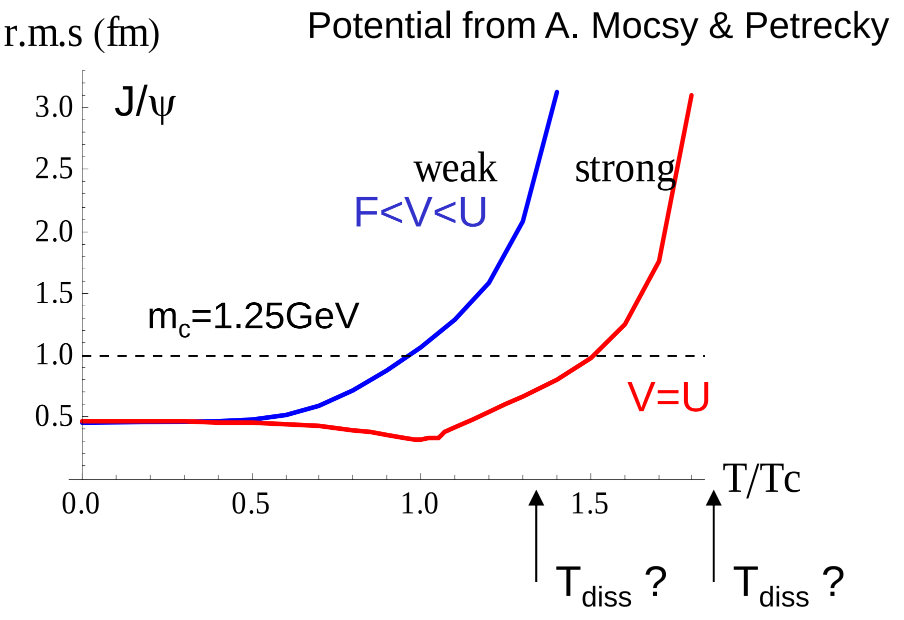
Caviats & Uncertainties

I. Quarkonia in *stationnary* medium are not well understood from the fundamental finite-T LQCD



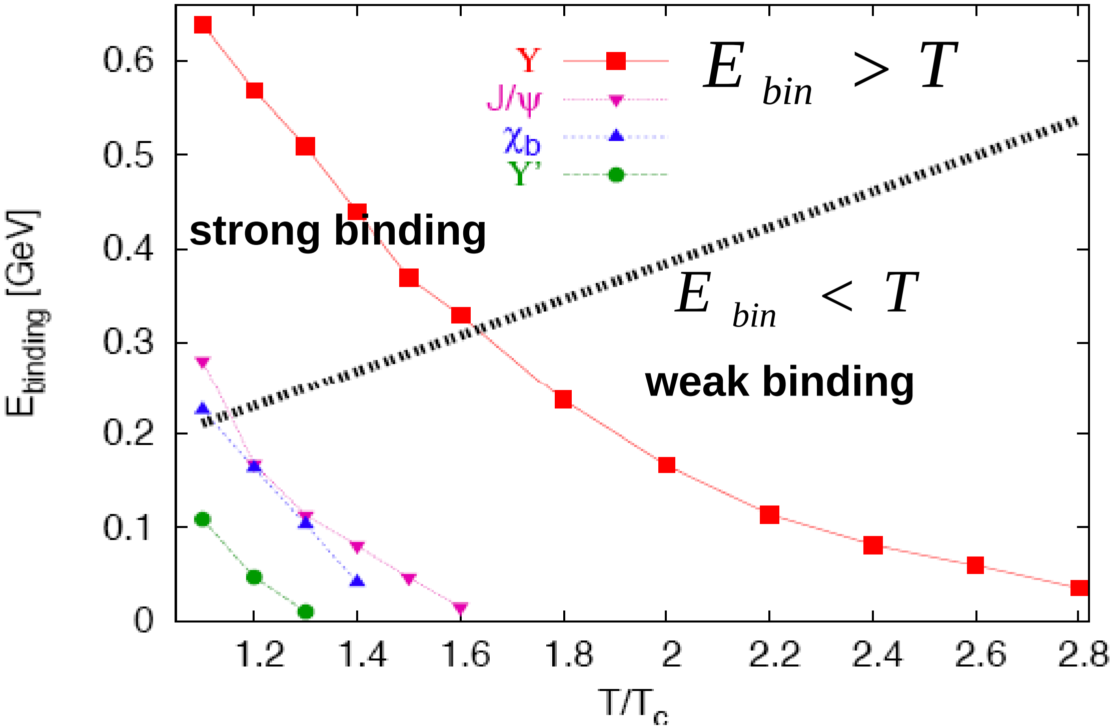
From free energy $\Rightarrow$ V(r,T) ?

Several prescriptions in litterature



Caviats & Uncertainties

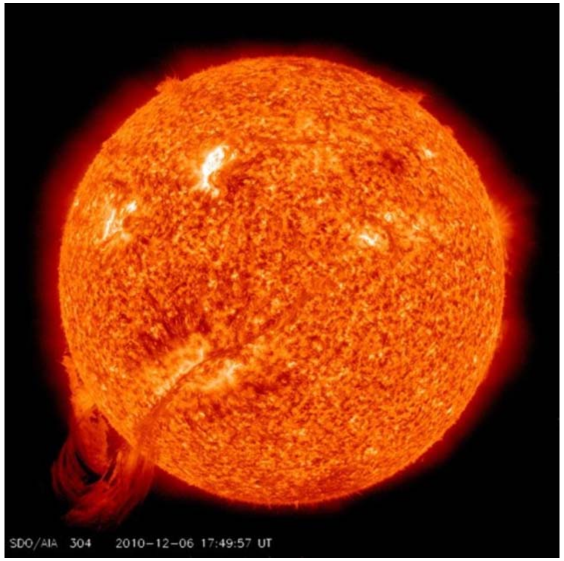
II. Criteria for quarkonia “existence” (as an effective degree of freedom) in *stationnary* medium is even less understood



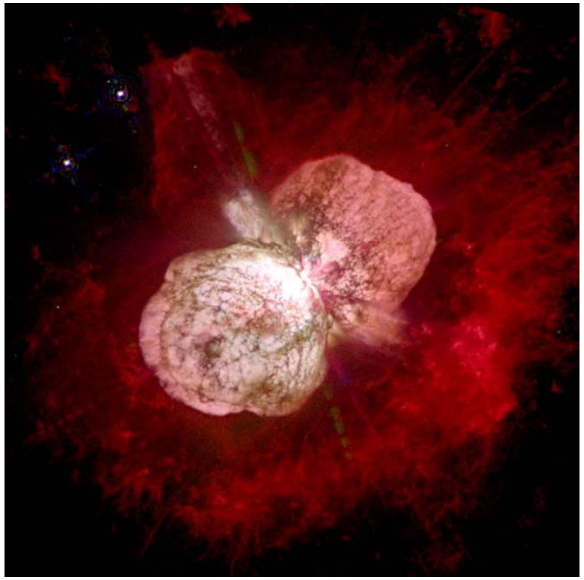
From A. Mocsy (Bad Honnef 2008)

Caviats & Uncertainties

III. What does this stationary picture has to do with reality anyhow ?



Picture



Reality

Need for a time-dependent scenario

Semi-Qualitative questions

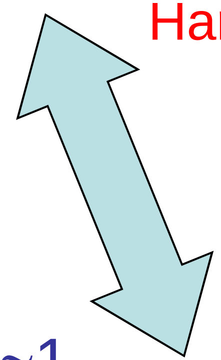
The *main* object of interest here: T_{diss}, one of the fundamental quantities of statistical QCD.

1. Can we try to *extract* the dissociation temperature from the data ?

2. Are the data compatible with the picture of a strongly bound J/ψ (sequential suppression) ?

$T_{diss}/T_c >(>)1$

Hard probe



$T_{diss}/T_c \approx 1$

Soft probe (as usual hadrons)

3. Can we challenge the picture of statistical recombination ?

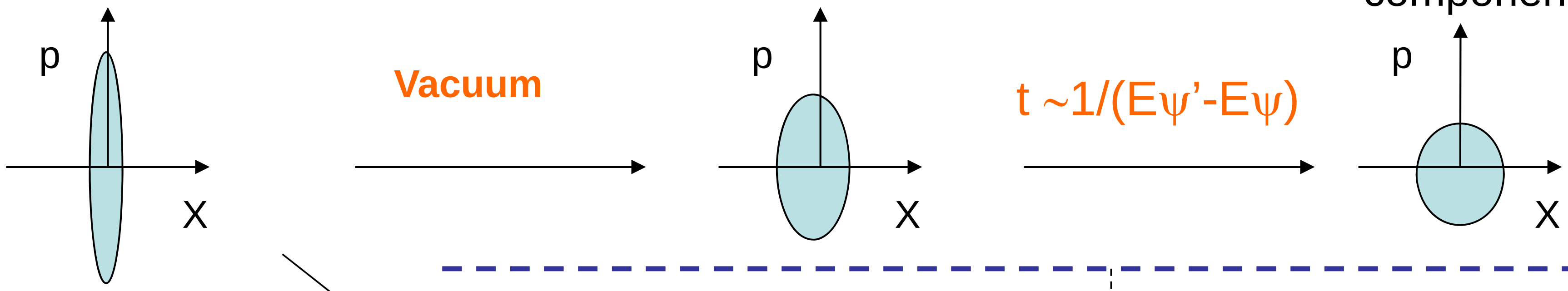
(A. Andronic, PBM, J. Stachel)

Quarkonia fate along decreasing T(t)

Initial Q-Qbar state (broad in p_{rel}, narrow in x_{rel})

State extends in x_{rel} and narrows in p_{rel} (evaporation of higher components)

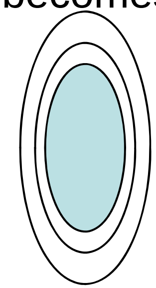
Quarkonia is “formed” (separation from other components)



In hot (but cooling) medium

Some loosely bound components are scattered while the remaining part becomes bounder

Quarkonia is “formed” (with reduced probability) in a state ~ vacuum and can only be dissociated through hard collision (q ~ M α^2)



t such that $\Gamma(T(t))<(E\psi'-E\psi)$

“Truth”

“Dual *Model*”

a) Instantaneous “melting” / thermal excitation

b) No “Q-Qbar→Quarkonia” fusion

a) Hard gluo-dissociation à la “Bhanot-Peskin”

b) “Q-Qbar → Quarkonia” fusion allowed (+g)

Quarkonia fate along decreasing T(t)

"Dual *Model*"

a) Instantaneous melting / thermal excitation

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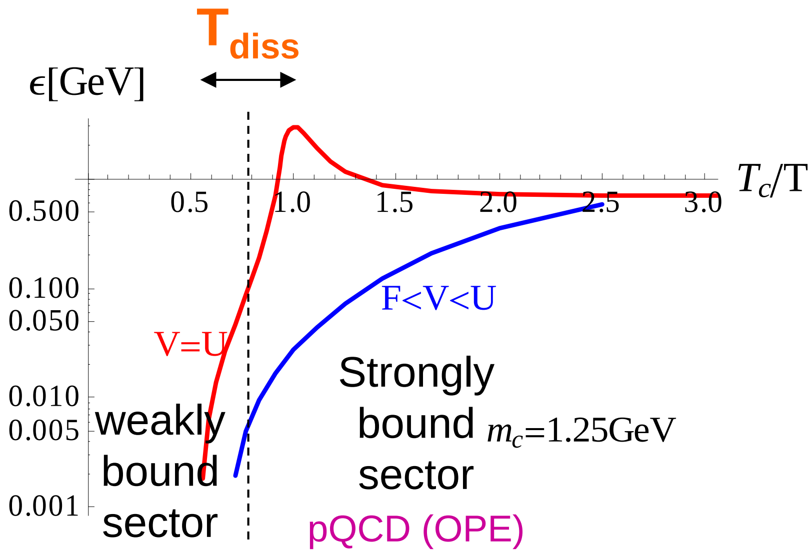
a) Hard gluo-dissociation à la "Bhanot-Peskin"

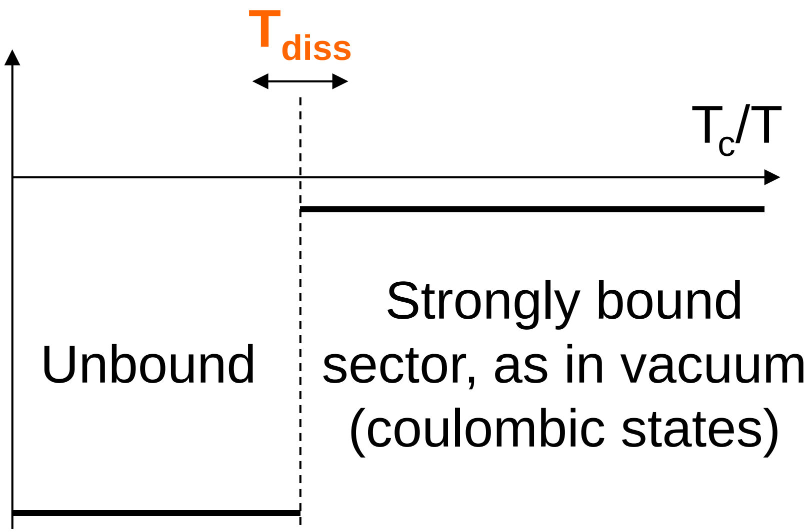
b) "Q-Qbar → Quarkonia" fusion allowed

$T>T_{diss}$



Model

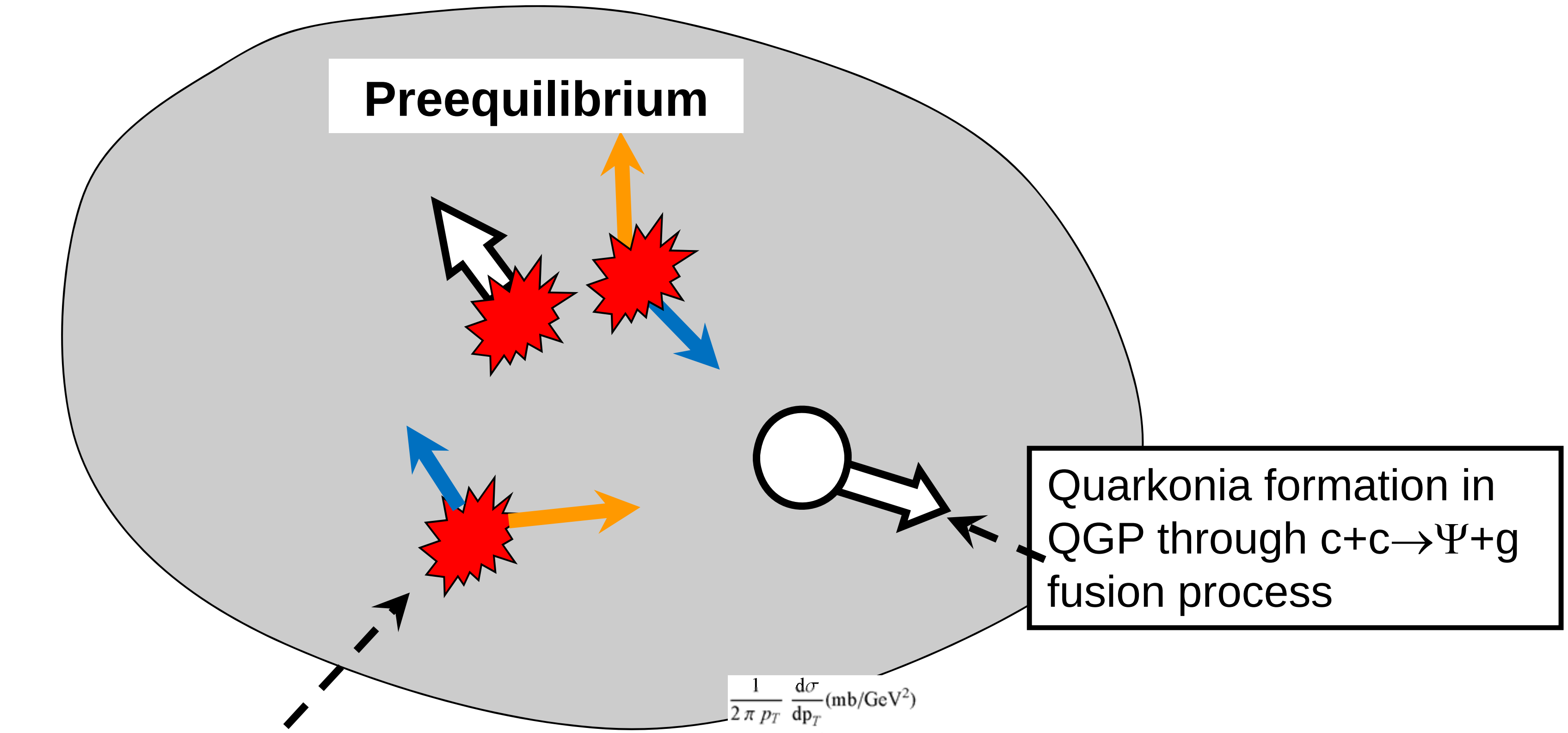
$T<T_{diss}$

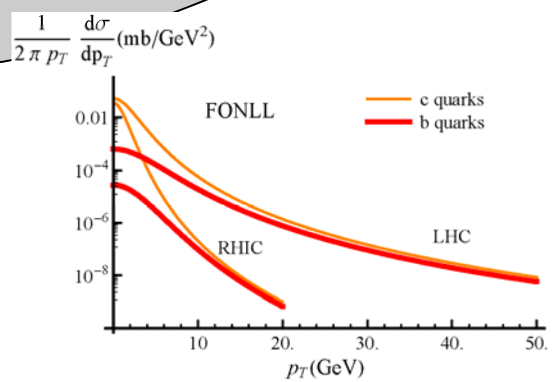


The key idea: AS THE LATTICE and POTENTIAL MODELS are inconclusive, let T_{diss} as a *free parameter* and see if this can be constrained by the data.

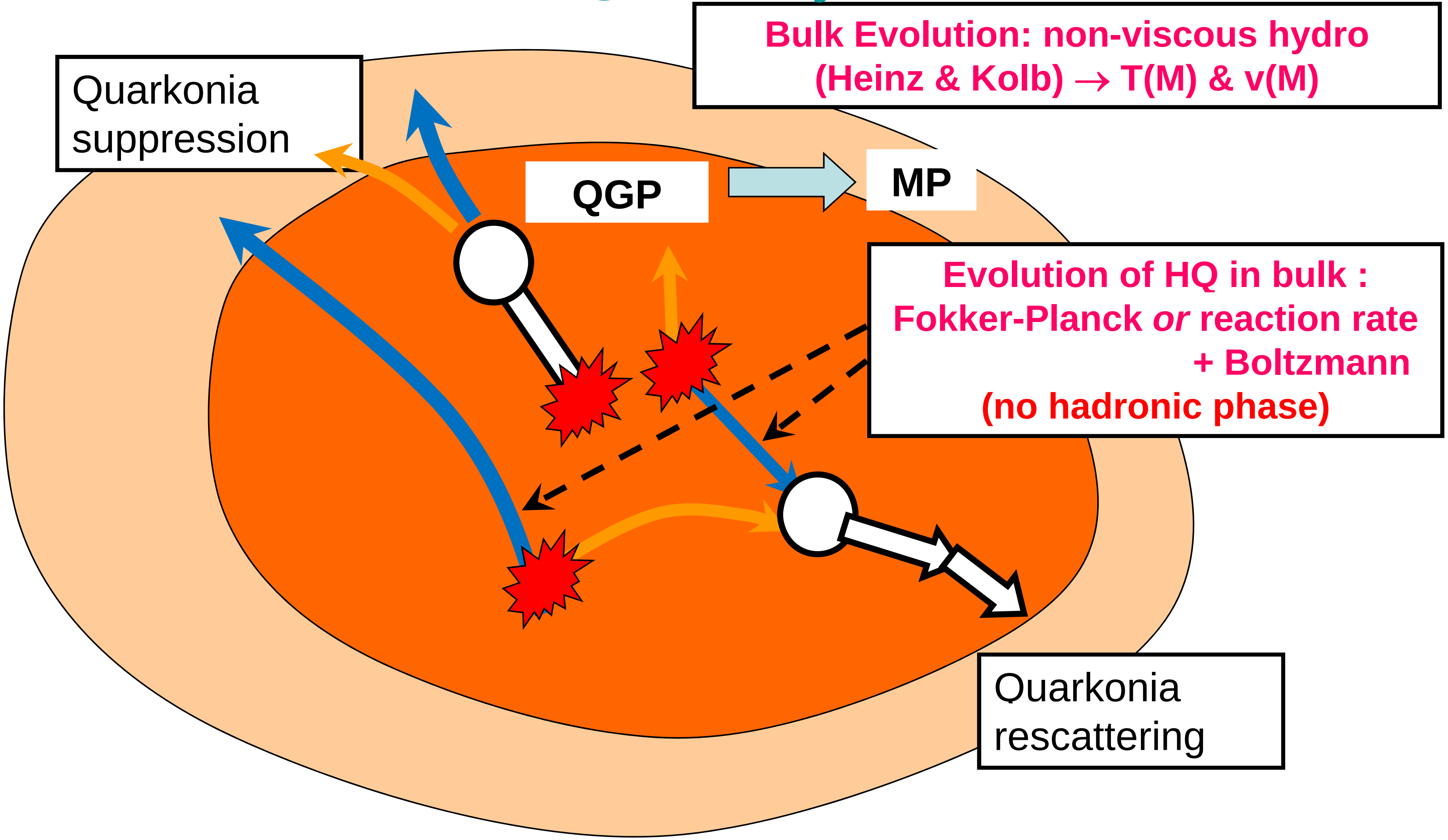
“Stationnary” quarkonia in evolving QGP

The Monte Carlo @ Heavy Quark Generator



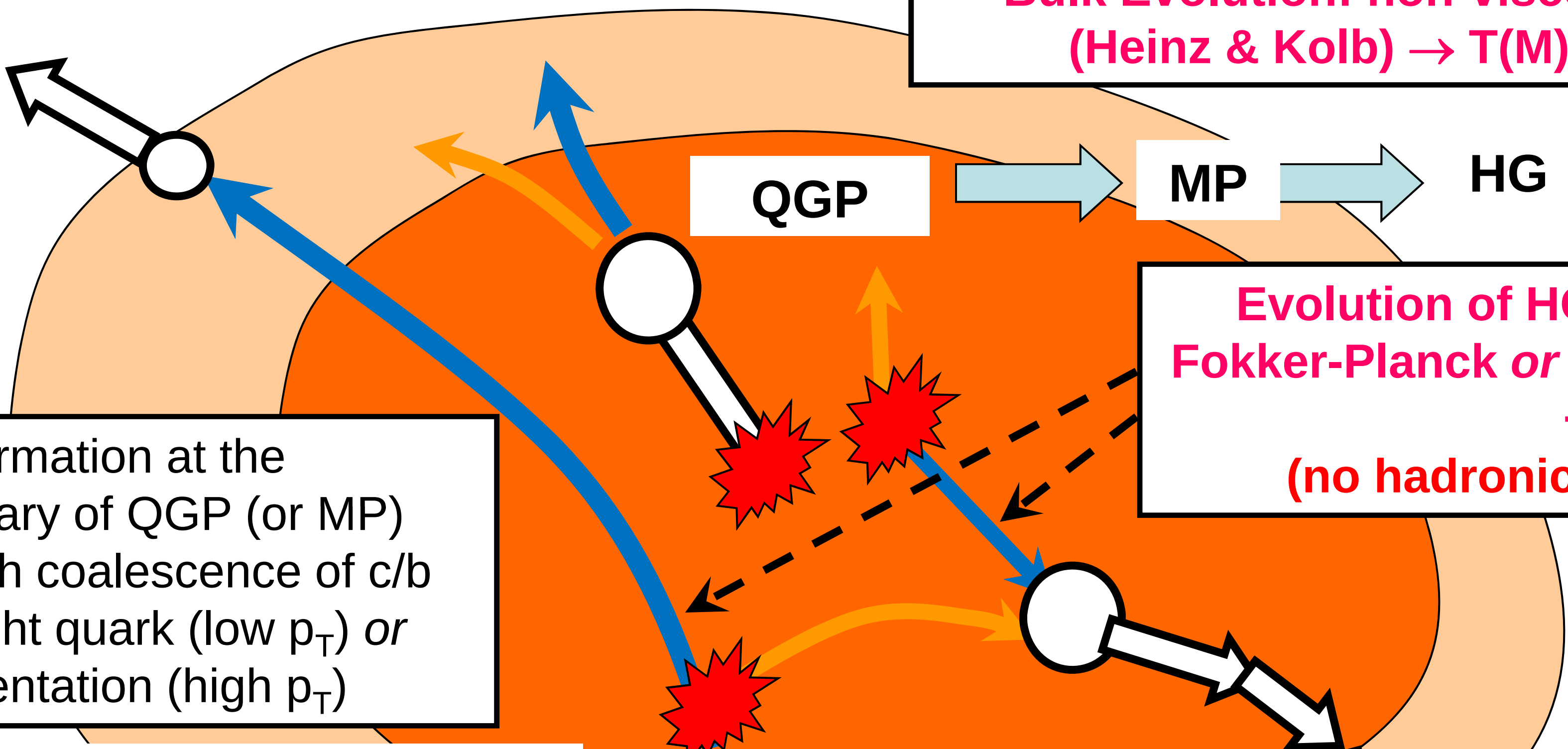


The Monte Carlo @ Heavy Quark Generator



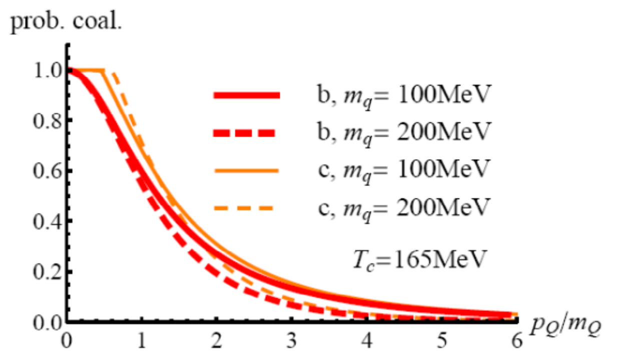
The Monte Carlo @ Heavy Quark Generator

Bulk Evolution: non-viscous hydro (Heinz & Kolb) → T(M) & v(M)



Evolution of HQ in bulk : Fokker-Planck *or* reaction rate + Boltzmann
(no hadronic phase)

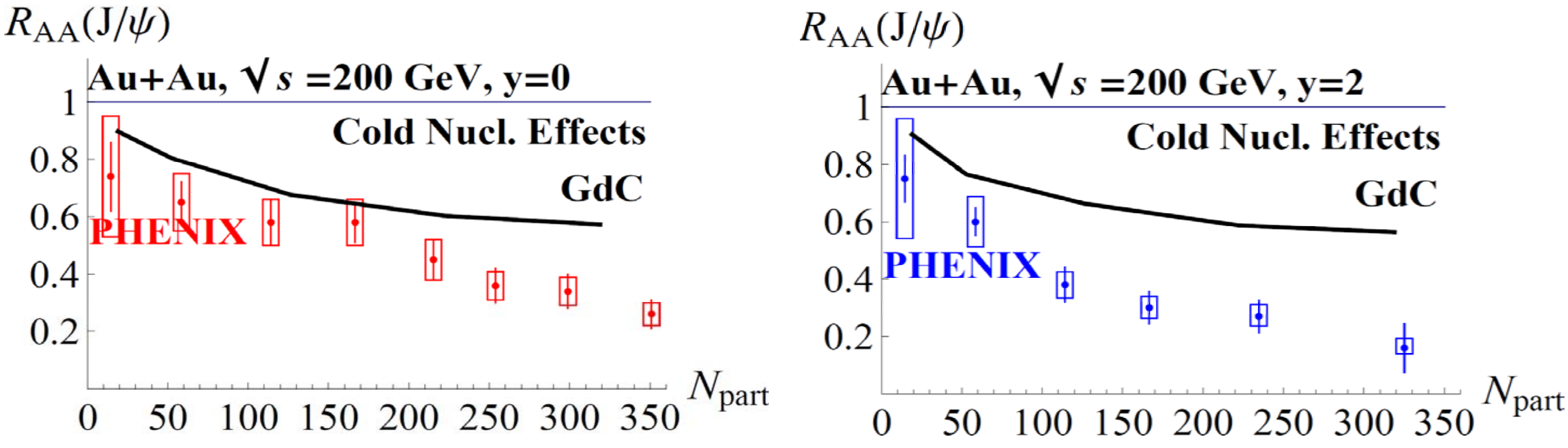
D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low p_T) *or* fragmentation (high p_T)



Nothing spectacular at freeze-out
(quarkonia are white objects already)

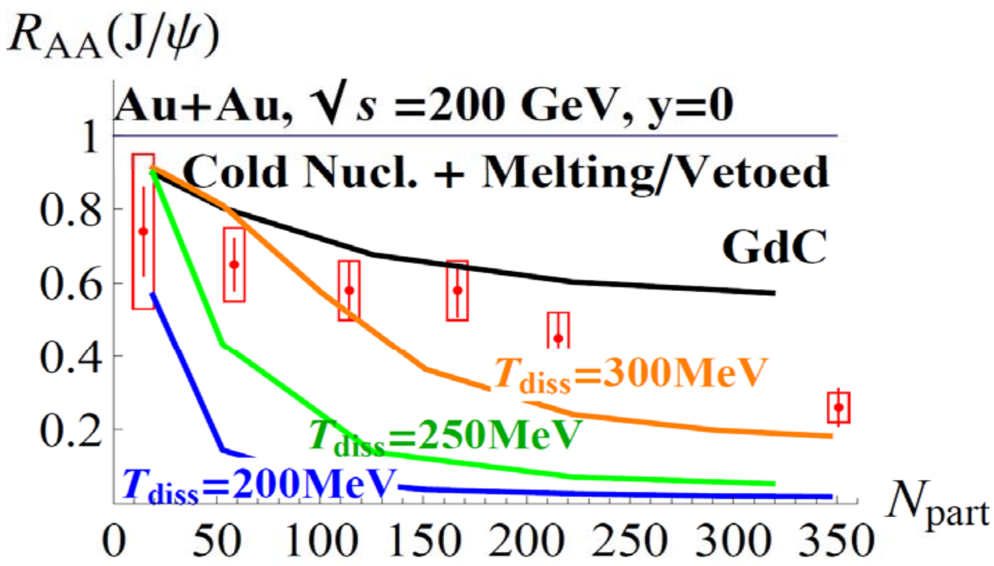
Integrated J/Ψ numbers @ RHIC

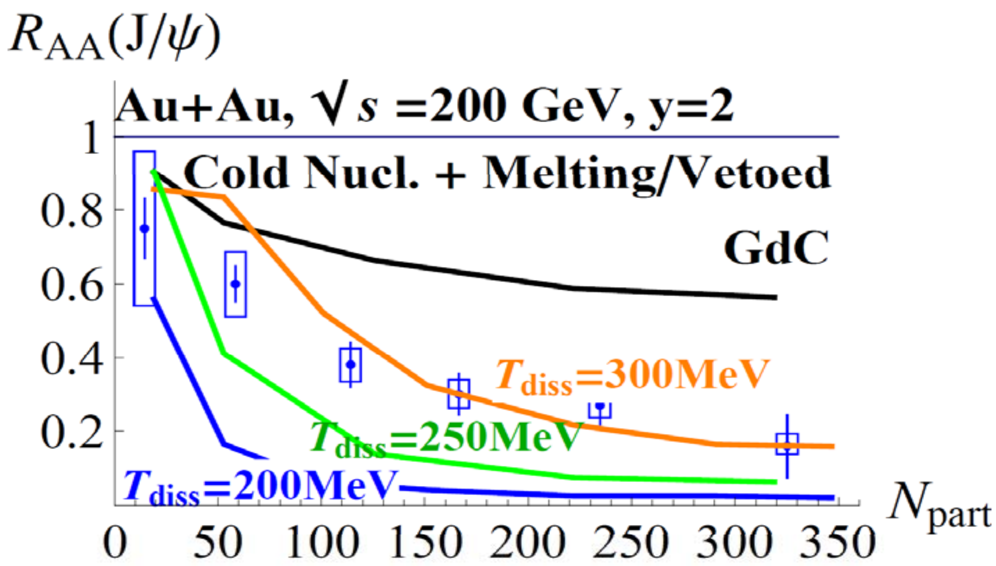
First, we need a baseline taking into account the cold nuclear matter effects (Shadowing, Cronin,..); we take the picture of R. Granier de Cassagnac (2007)



Integrated J/Ψ numbers @ RHIC

Next, the (*instantaneous*) vetoing of quarkonia formation due to melting:





Good agreement obtained with a rather large value of $T_{diss} \approx 2\ T_c$.

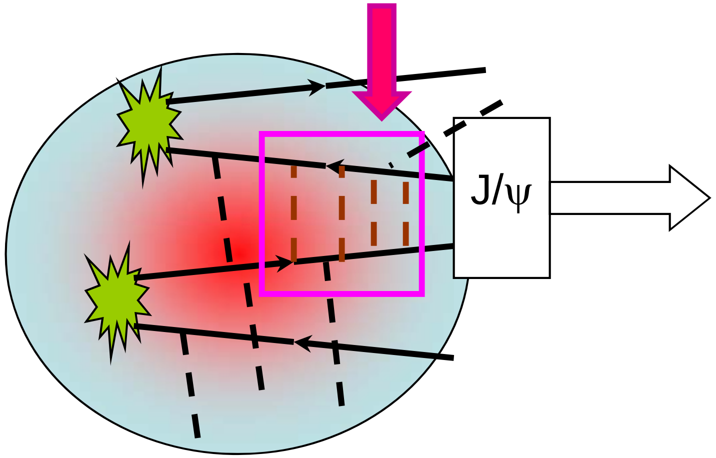
Some claims of "sequencial suppression" with a very bound J/ψ were indeed made by several physicists

``````We do not need recombination !''''''…

except that Q and Qbar may be close in phase space

Turning on (re)combination + hard dissociation

(Re)combination (could be major process at LHC):



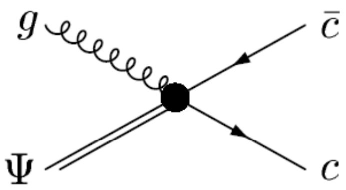
$$\underbrace{Q\bar{Q}}_{\text{Entrance channel}} \rightarrow \underbrace{J/\psi^{\star}}_{\text{Binding}} \rightarrow J/\psi$$

Often treated as a quasi-instantaneous fusion process

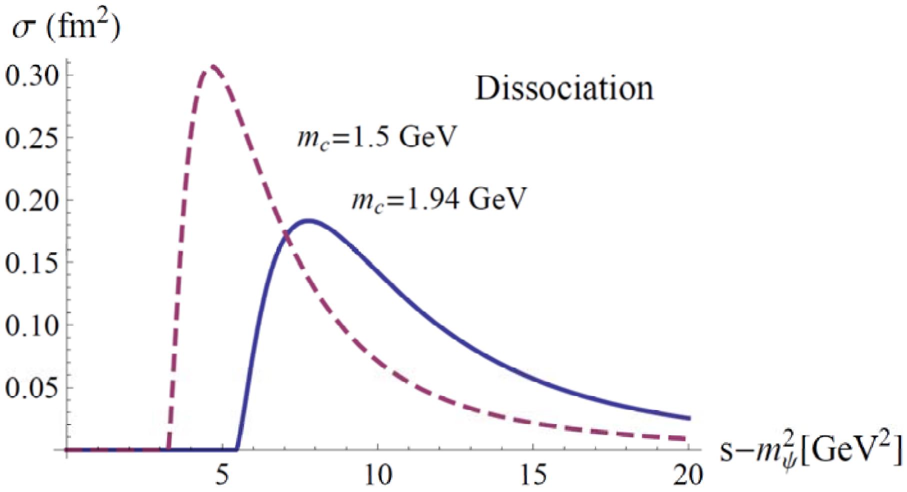
Basic Ingredients

Dissociation

hard dissociation taken according to Bhanot and Peskin + recoil correction (Arleo et al 2001)



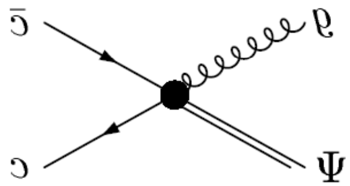
$$\sigma_{(Q\overline{Q})g}(\omega) = \frac{2^{11}}{3^4}\alpha_s \pi a_0^2 \frac{(\omega/\varepsilon(0)-1)^{3/2}}{(\omega/\varepsilon(0))^5}\Theta(\omega-\varepsilon(0))$$

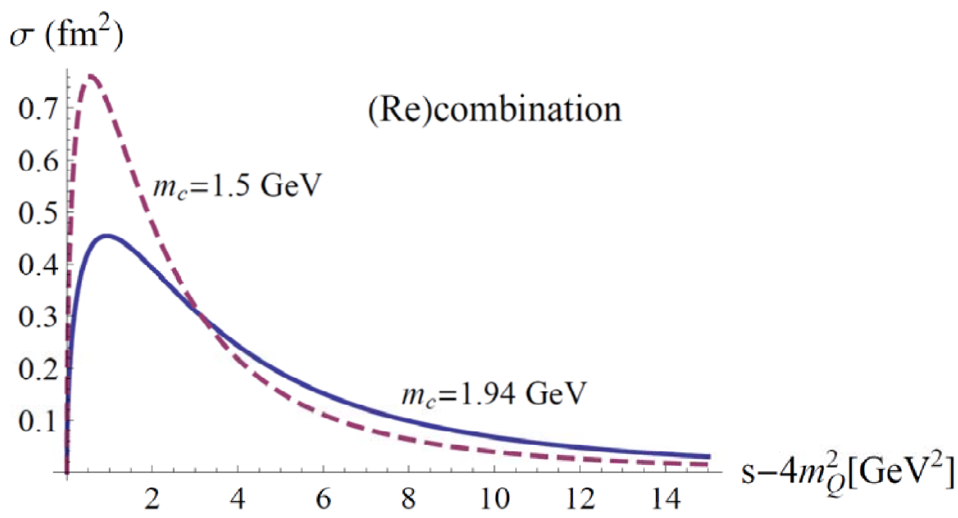


Max ≈ 2 fm^2 at ω ≈ 500 MeV

Recombination

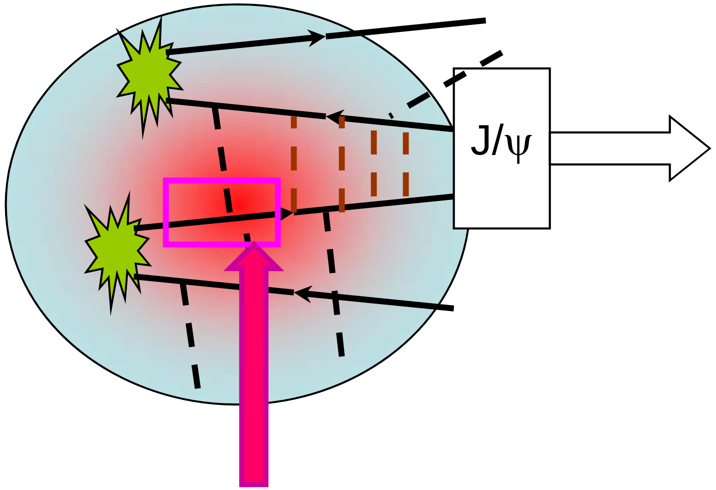
Cross section obtained from σ_{diss} via detailed balance





Turning on (re)combination + hard dissociation

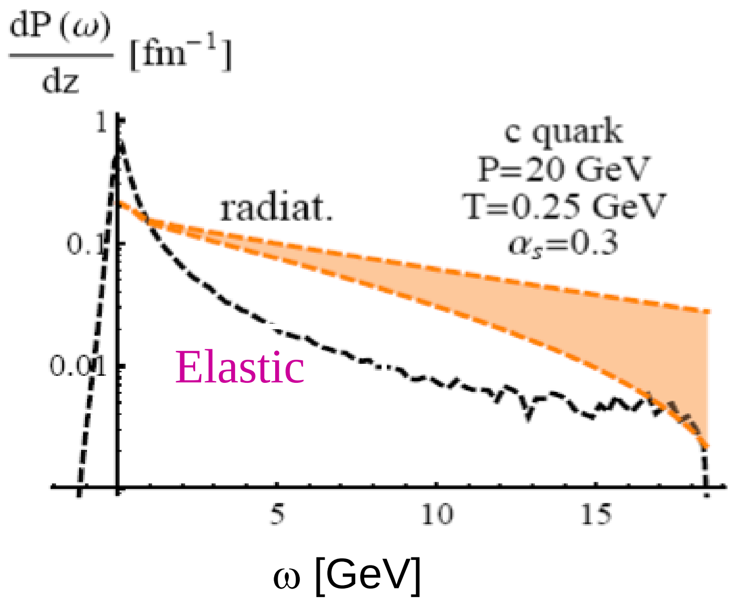
(Re)combination (could be major process at LHC):



Even if binding process is fast and medium-independent (quarkonia are small bound states), the distributions of Q and Qbar in the entrance channel depend on the past history

(transport theory)

What is the dominant E loss mechanism @ RHIC and LHC ? Does its detailed origin influences the fate of quarkonia's ?

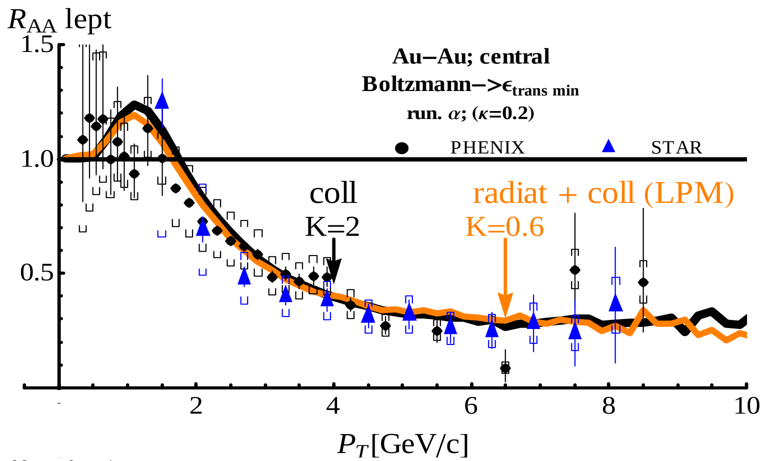


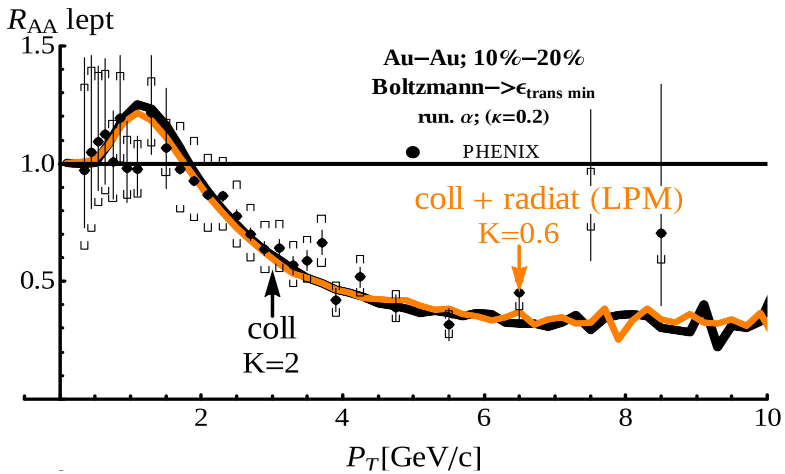
{Radiative + Elastic} vs Elastic for leptons @ RHIC

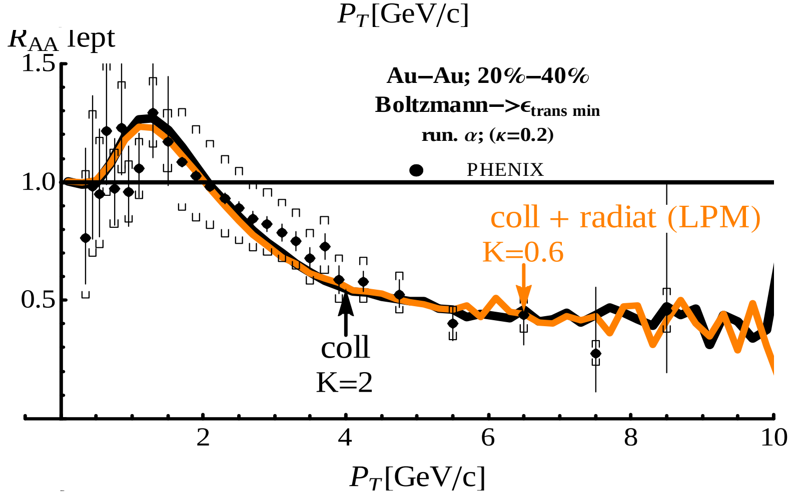
El. and rad. Eloss exhibit very different energy and mass dependences. However…

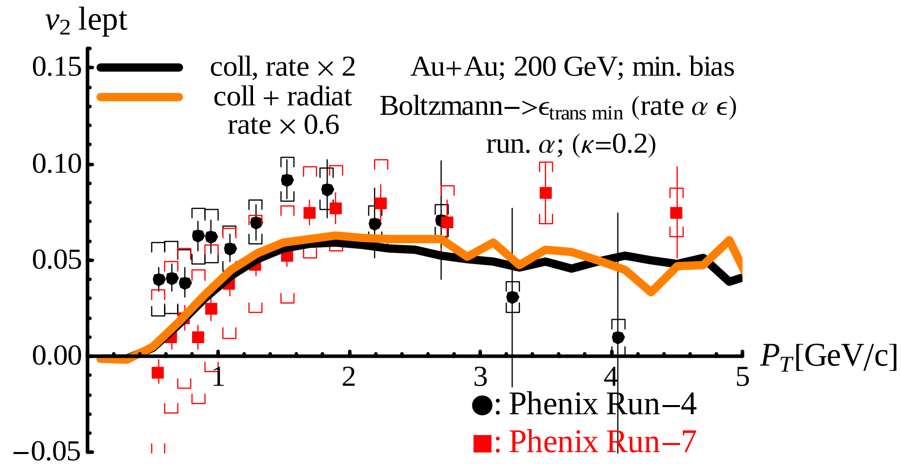
σ_{el} & σ_{rad} cocktail: rescaling by K=0.6

σ_{el} alone rescaling: K=2





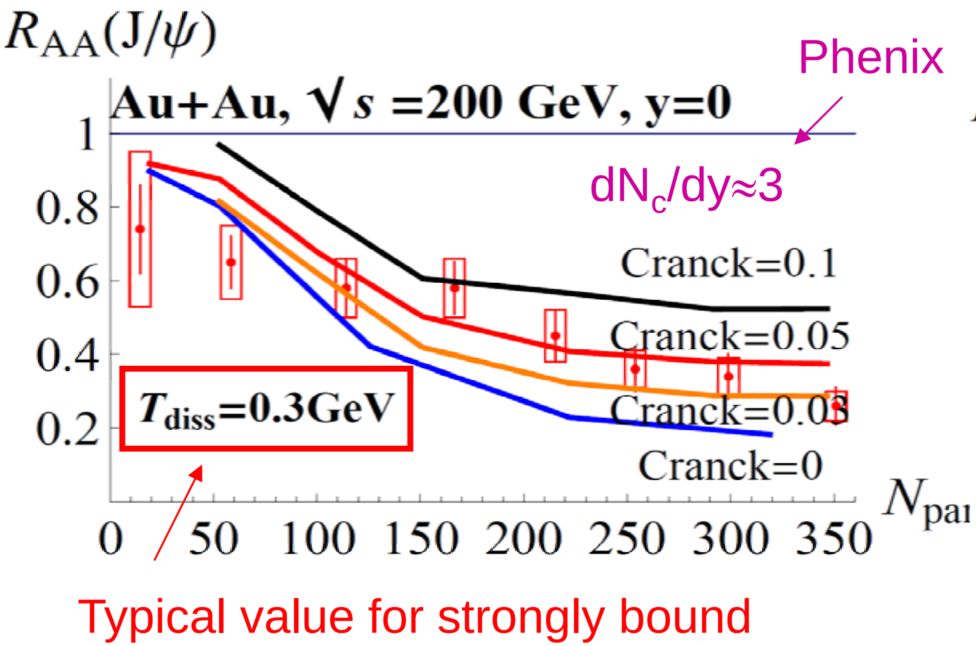


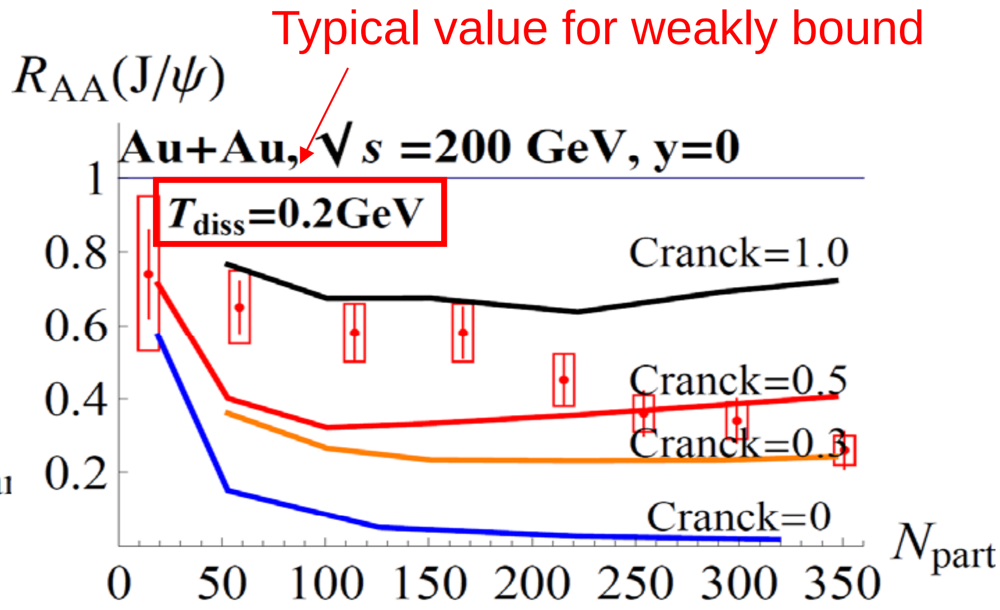


One "explains" it all with ΔE α L (for HQ)

RHIC data cannot decipher between the 2 local microscopic E-loss scenarios

Turning on (re)combination + hard dissociation





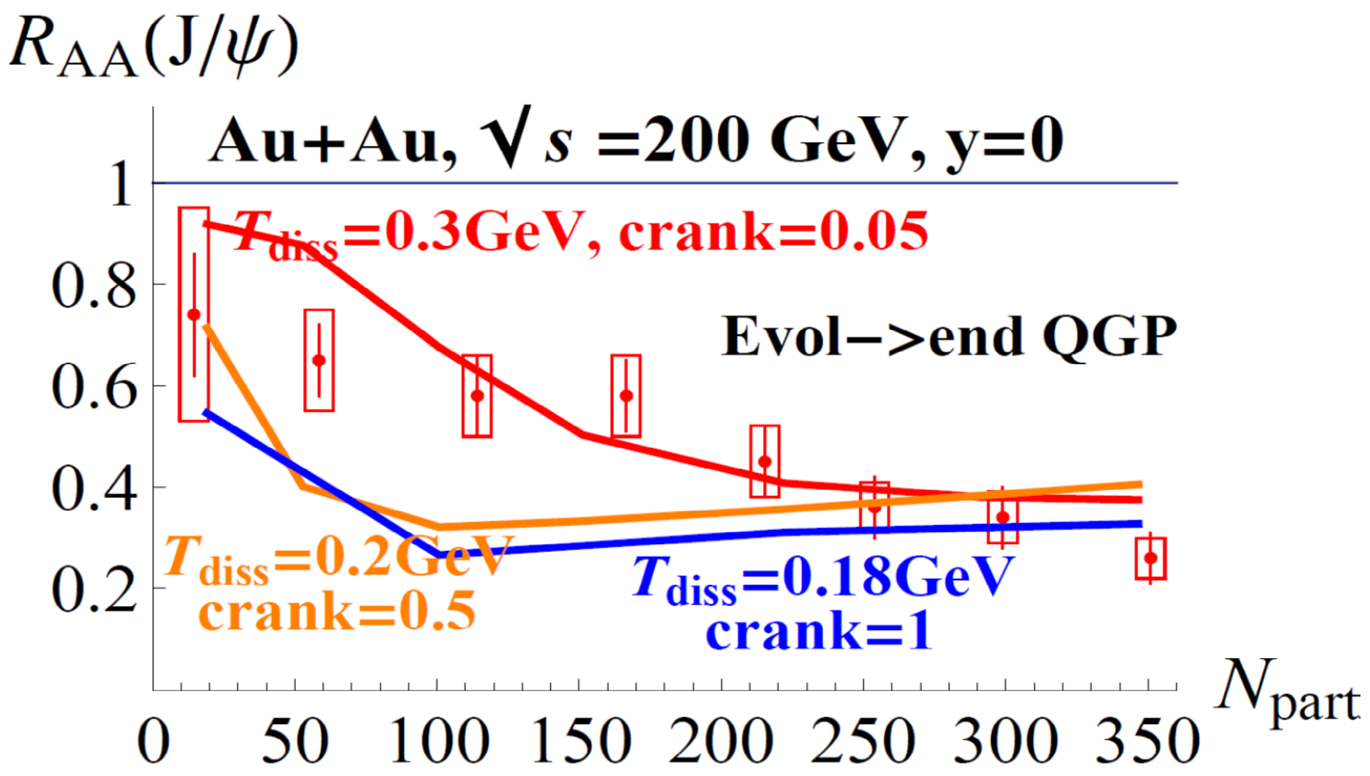
Problem: One has to reduce the fusion probability by a factor ~10 to reproduce the data (if recomb. cross section taken at face value, one arrives at R_{AA} (most central > 2 !).

Problem never comes alone:
Strongly bound quarkonia are the ones for which the Bhanot-Peskin approach should be legitimate. Φ states exist early => lot of HQ pairs present in pahse space

Absolute numbers are better reproduced (if one believes in mostly canonical – cranck=0.5-1 – recombination), although **the R_{AA} dependence on N_{part} is not as satisfying**

Best parameters from R_{AA}

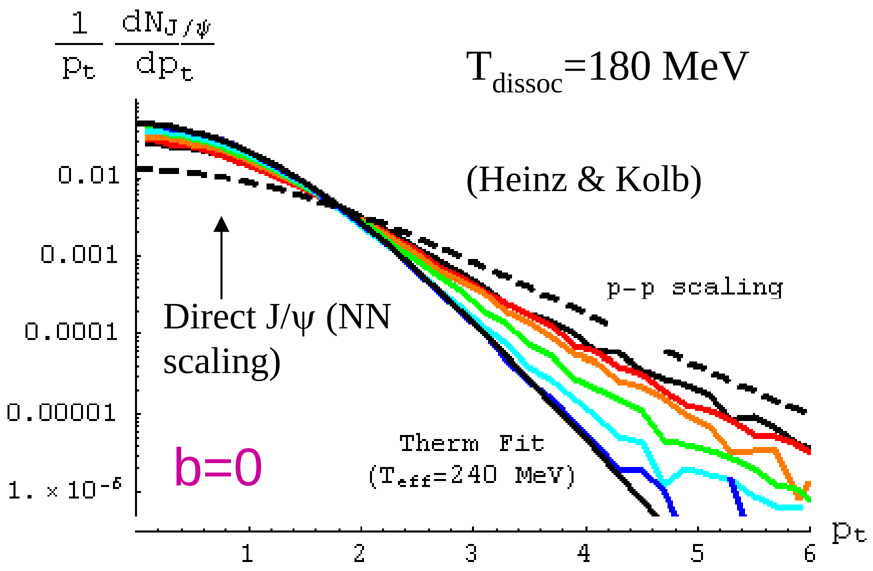
"Optimal" choices in the (T_{diss}, σ_{fus}.) parameter plane

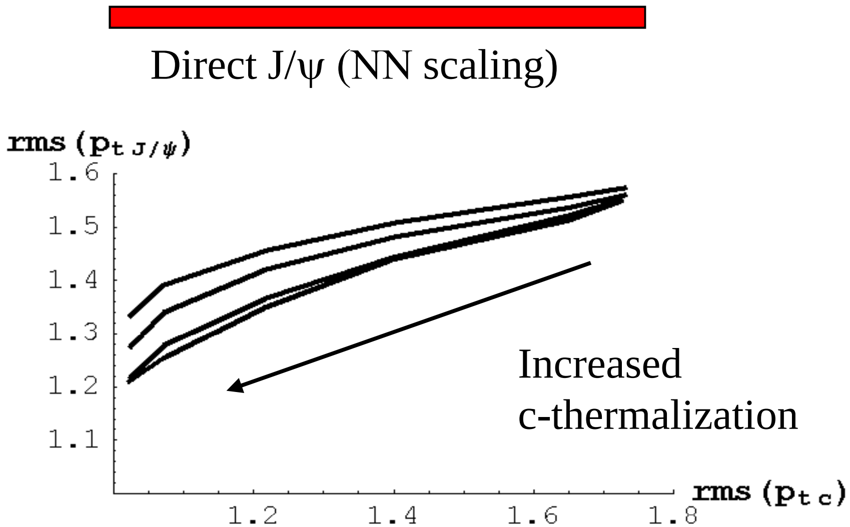


$T_{diss} \in$ [0.2 GeV,0.3 GeV]… but difficult to go beyond

The p_t world

Differential production might reveal more physics





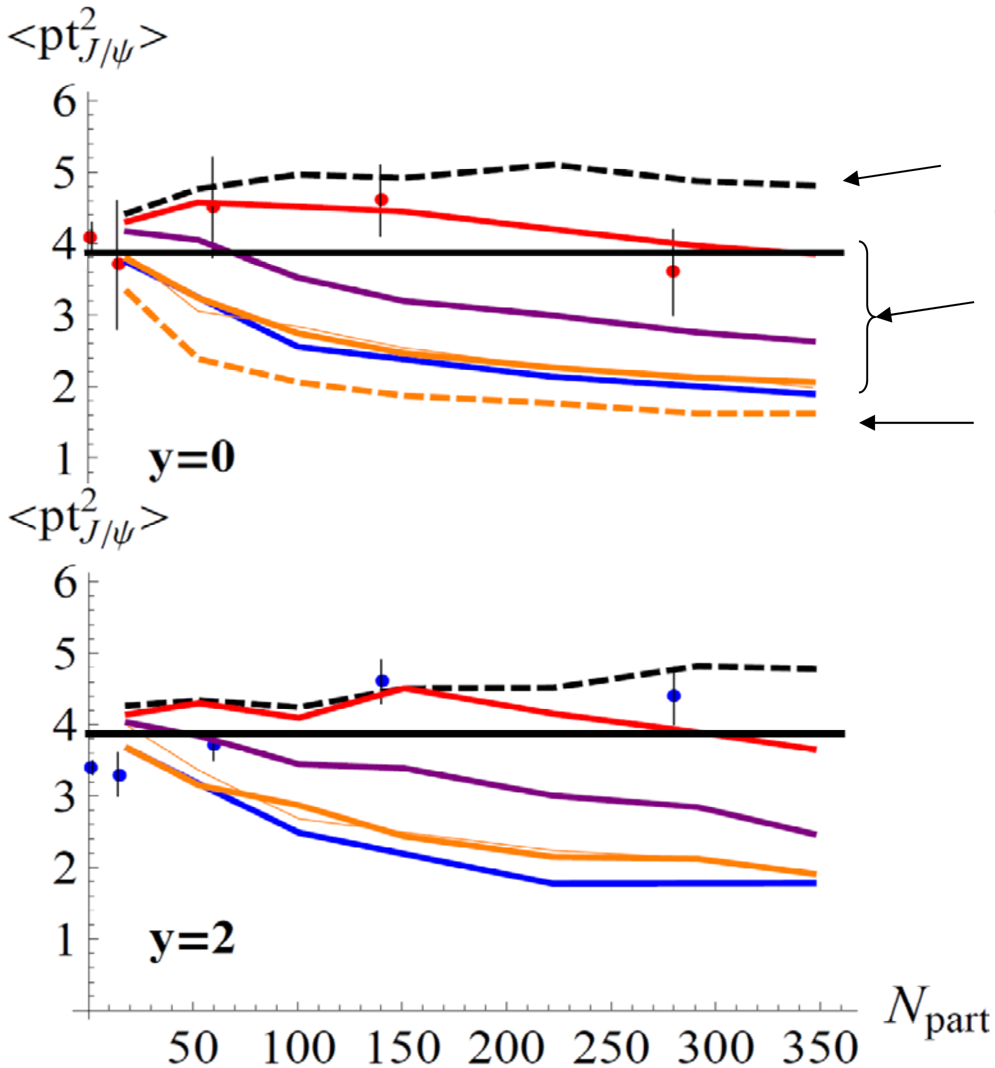
QGP "cools" the charms, even with the radial flow

Prediction for b=0 and just recombination

Softer p_t spectrum as for direct production. Possible "p_t shrinking" in A-A. But first, understand the k_t broadening in d+Au (recently observed by PHENIX)

The p_t world

… and now compared with the data:



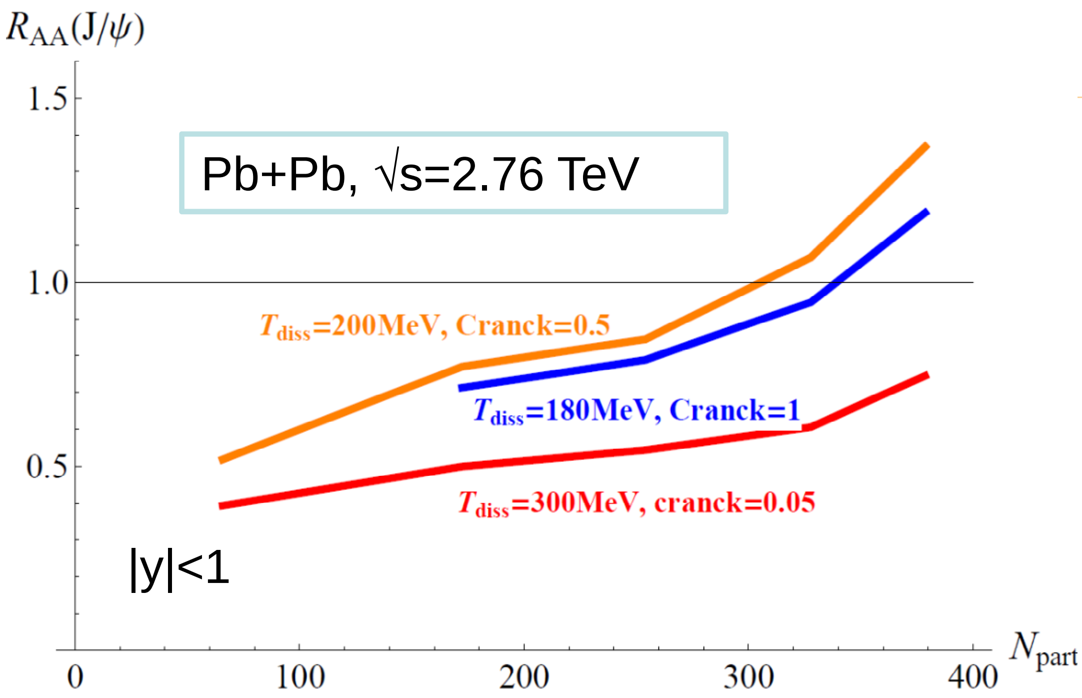
Cronin effect at initial stage (and no further effect)

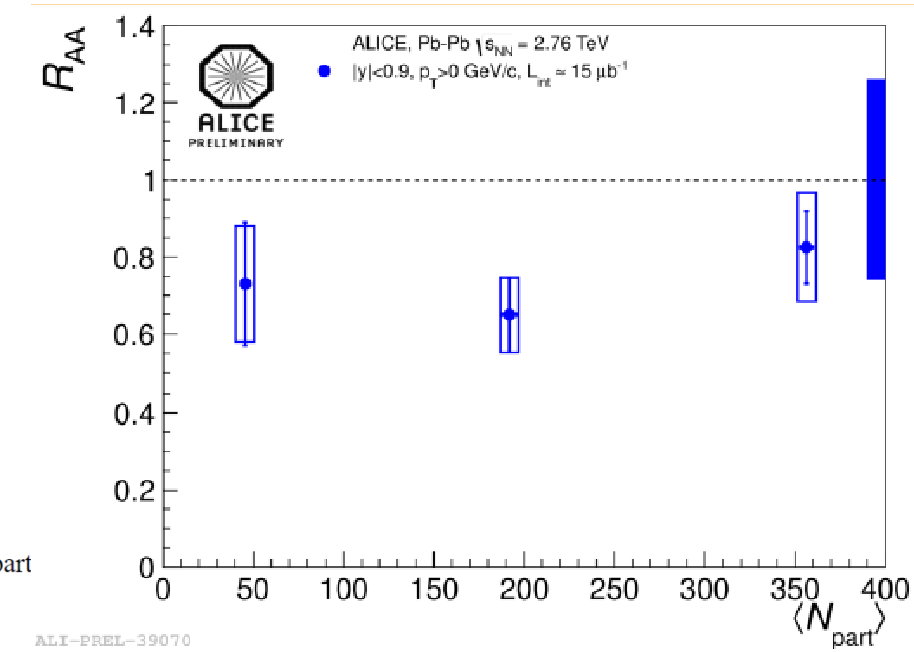
Results for T_{diss}= 0.3, 0.25, 0.2 and 0.18 (with initial Cronin effect).

T_{diss}= 0.2 and NO Cronin effect.

T_{diss}= 0.3 GeV should be favored

Prediction for LHC





<u>Hydro Parameters:</u>

s_0= 268 fm^{-3}

≡

$dN_{ch}/d\eta \approx 2300$ in PbPb, b=0

<u>HQ Parameters:</u>

$dN_c/dy \approx 30$ in PbPb

$d\sigma_\psi/dy = 2\mu b$ in pp

Fusion of c-quarks at LHC: 15-25 x more probable that at RHIC, but strong increase of the prompt J/ψ as well….

Preliminary conclusions

Reasonnable agreement with RHIC data for J/ψ, but difficulties to tame the recombination down

1. Can we try to *extract* the dissociation temperature from the data ?

A rather large effective dissociation temperature ($T_{diss} \approx 0.25$-0.3 GeV) seems to be favored by the data, provided one has a good quantitative argument to explain why the recombination of HQ should be reduced by a factor 10 w.r.t. the naive Bhanot - Peskin cross section (gluon mass ? J/ψ(T) in BP ?)

Otherwise, low dissociation ($T_{diss} \approx 0.2$ GeV) are unavoidable… supported by finite J/ψ v2 seen by ALICE

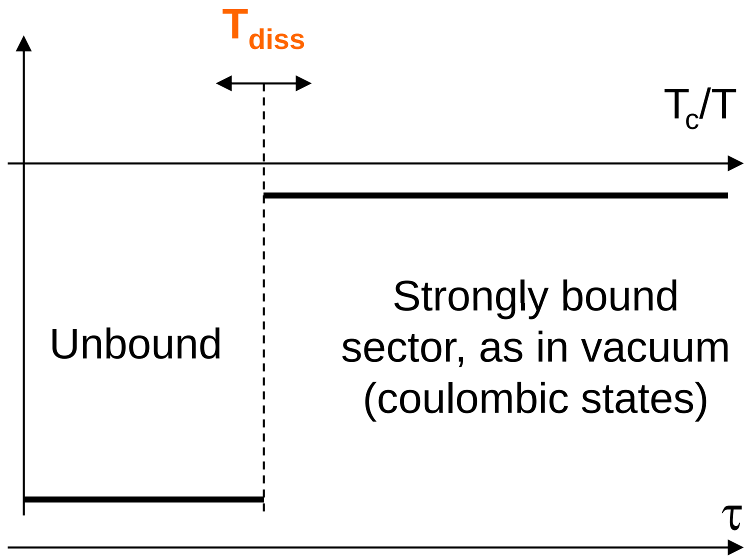
2. Are the data compatible with the picture of a strongly bound J/ψ (sequential suppression) ?

Not clear to us… questions the OPE approach

Need for a better description of Qqbar states in QGP

Dynamical quarkonia in QGP

Beyond the 2-components model



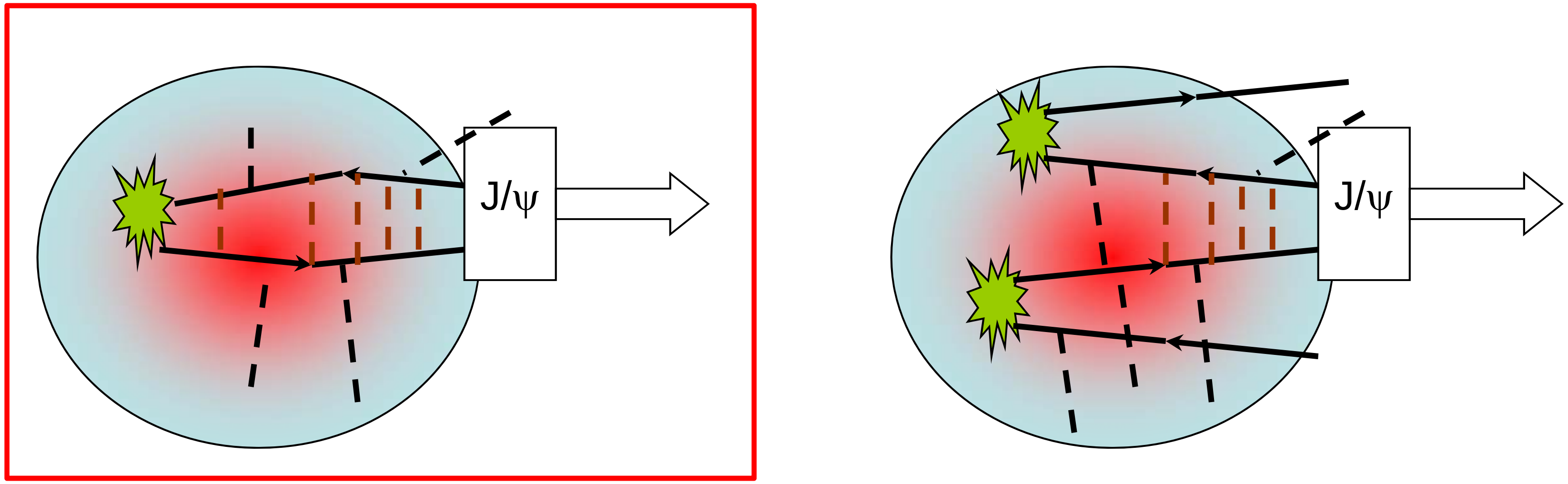
Please keep in mind:

I. Quarkonia represent only a small % of the total Q-Qbar state => should not be treated independently from one another (besides recombinations)… open quantum system

II. Use of cross sections in very dense medium is rather questionable (no asymptotic incoming or outgoing state)

Beyond the 2-components model

Need for a better theoretical understanding of QQbar binding under *continuous* perturbation both in suppression and recombination



Recently: Major steps in this direction by Beraudo & Blaizot, Akamatsu, Strickland

New concept: introduction of imaginary part to the potential

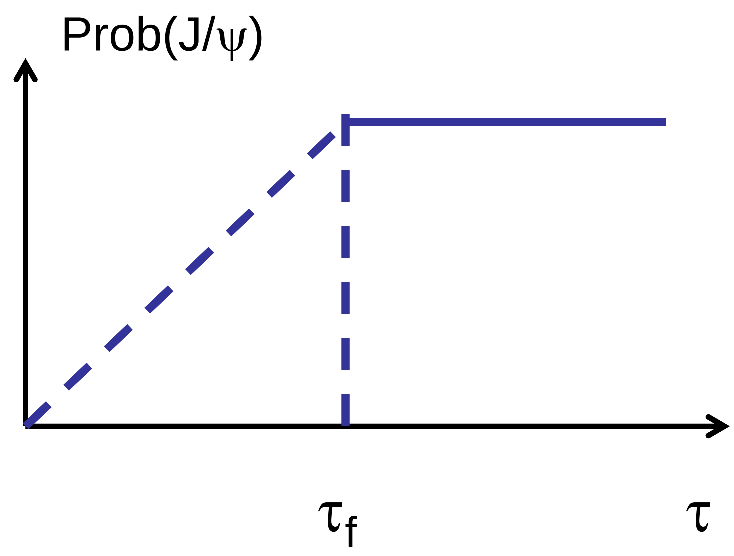
Not reviewed here

J/Ψ suppression at high temperature

Standard folklore:

a) Following sequential suppression (quasi-stationnary picture)… The quarkonia which should be formed at (t_0,x_0) is not if $T(t_0,x_0)>T_{diss}$ => Q-Qbar pair is “lost” for quarkonia formation

b) Refined version wrt a) : quarkonia need some formation time τ_f to be resolved:



First quantum-like dynamical ingredient

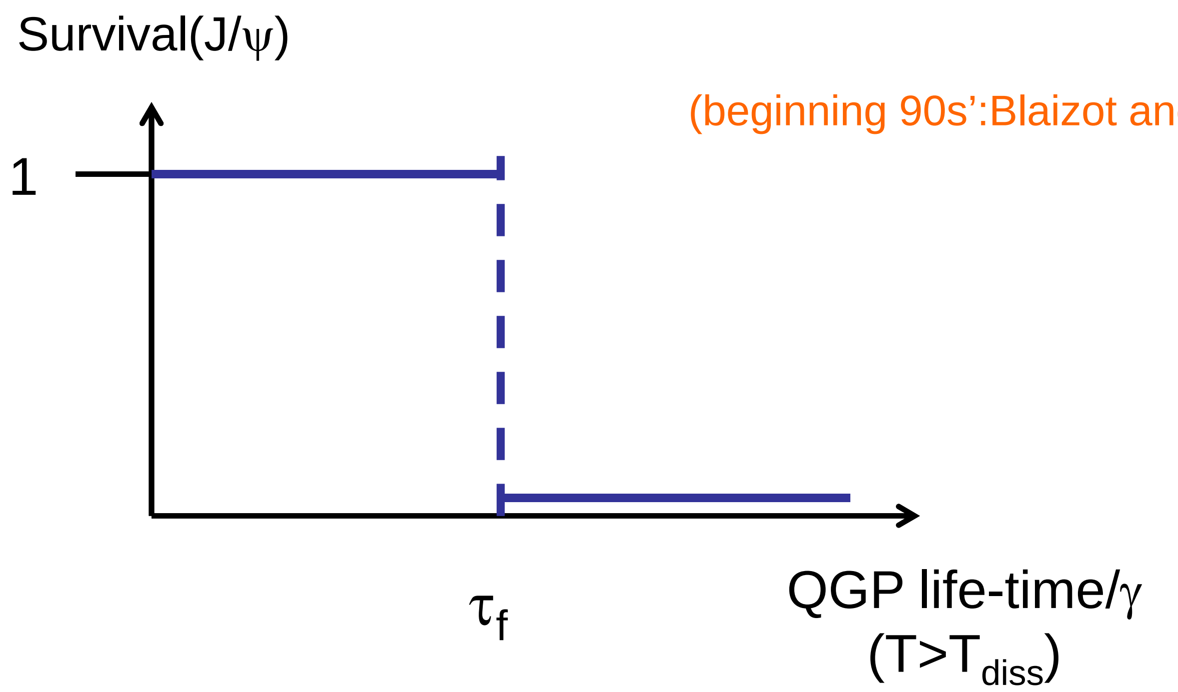
J/Ψ suppression at high temperature

We let the QQbar pair evolve until $\left(t_0 + t_f, \vec{x}_0 + \vec{v}_{Q\bar{Q}} t_f\right)$ and then look whether

$T\left(t_0 + t_f, \vec{x}_0 + \vec{v}_{Q\bar{Q}} t_f\right) > T_{\rm diss}$	$T\left(t_0 + t_f, \vec{x}_0 + \vec{v}_{Q\bar{Q}} t_f\right) < T_{\rm diss}$
Not formed	Formed as in vacuum

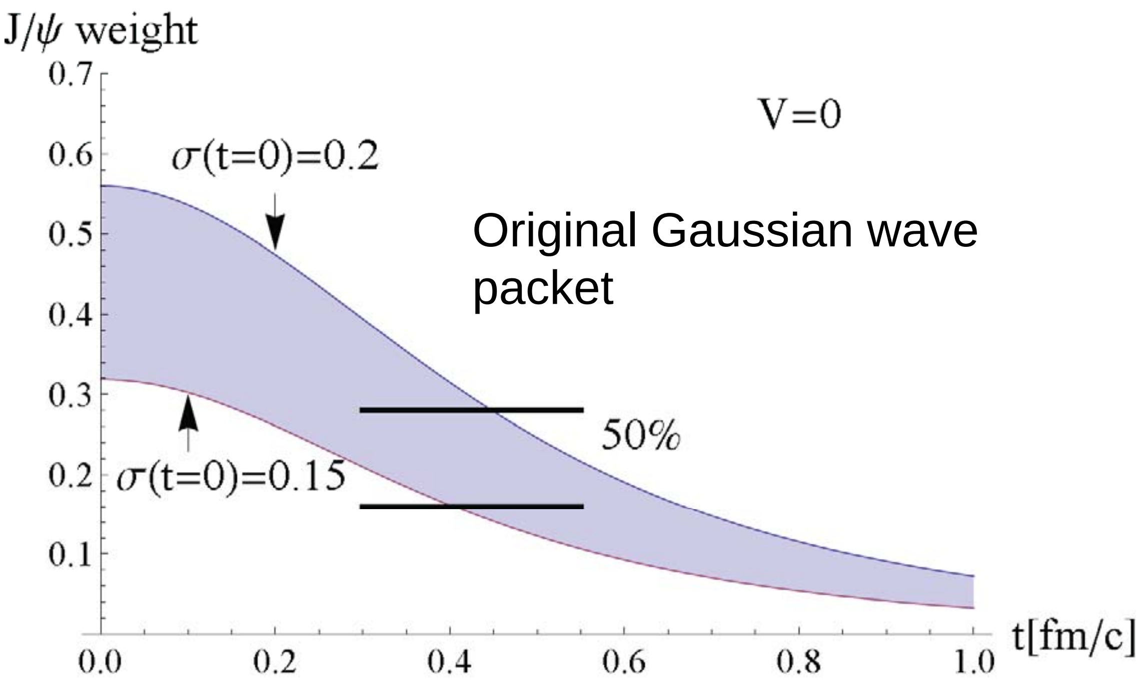
1rst crude description ("delayed" 2-components model)

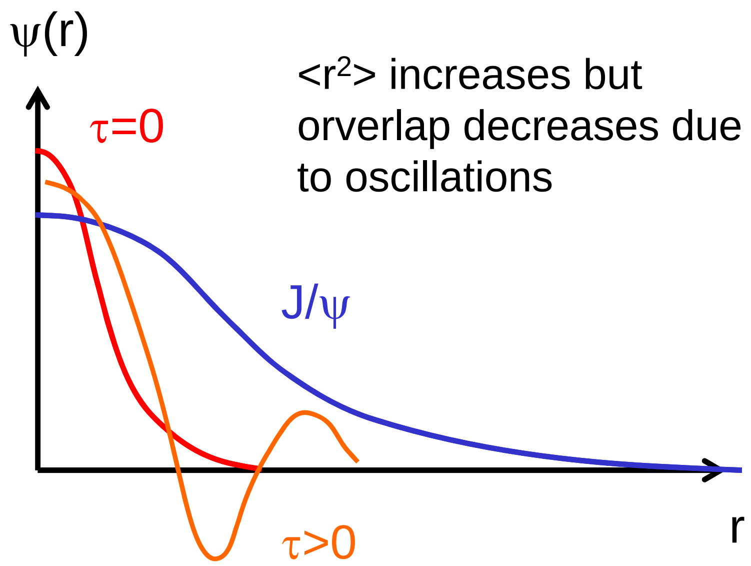
(beginning 90s':Blaizot and Ollitrault)

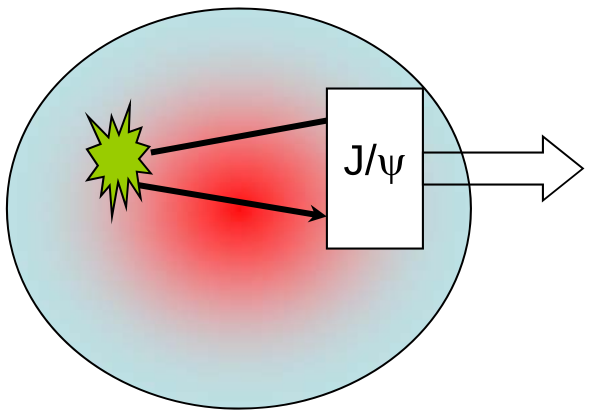


J/Ψ formation at high temperature

Alternate quantum description: Q-Qbar state described by a wave function evolving in V=0:

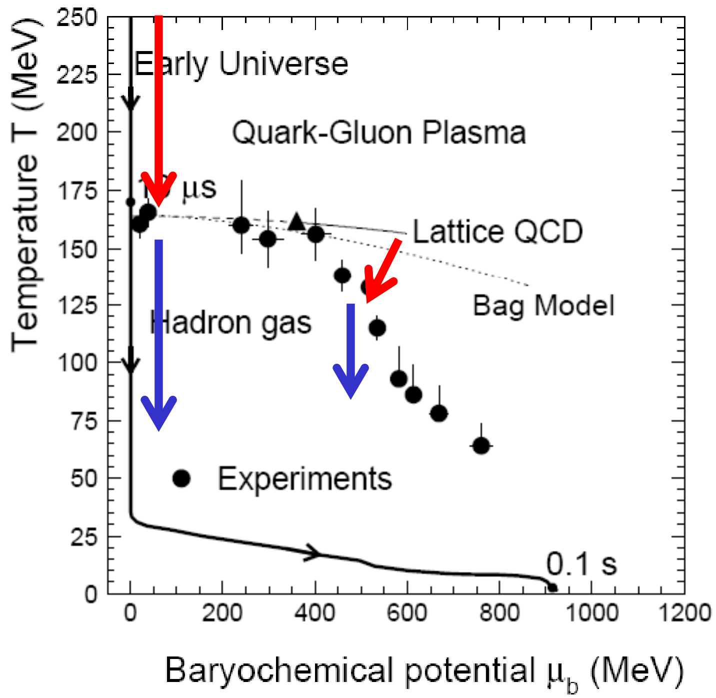


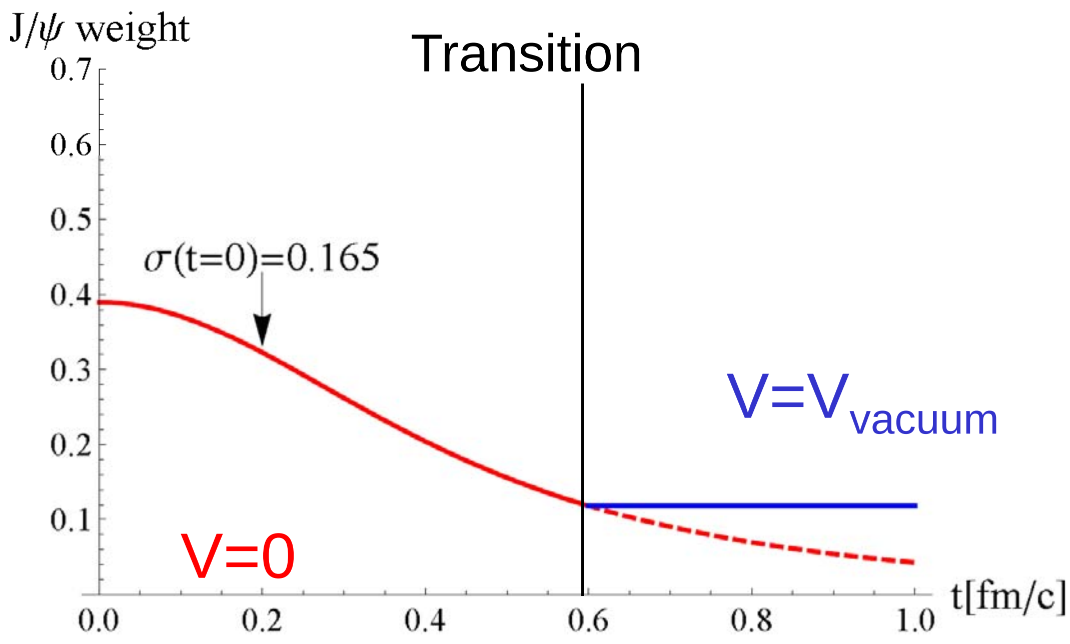




J/Ψ suppression (dynamical)

Continuous evolution





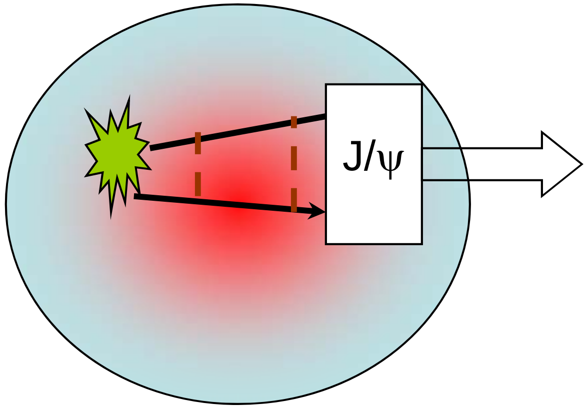
For this example: Survival ≈ 0.13/0.4 ≈ 33%

Important feature: quantum evolution leads to smooth suppression patterns

For realistic QGP lifetimes at RHIC: Survival of a few % (neglecting corona effects)

=> Should we care ?

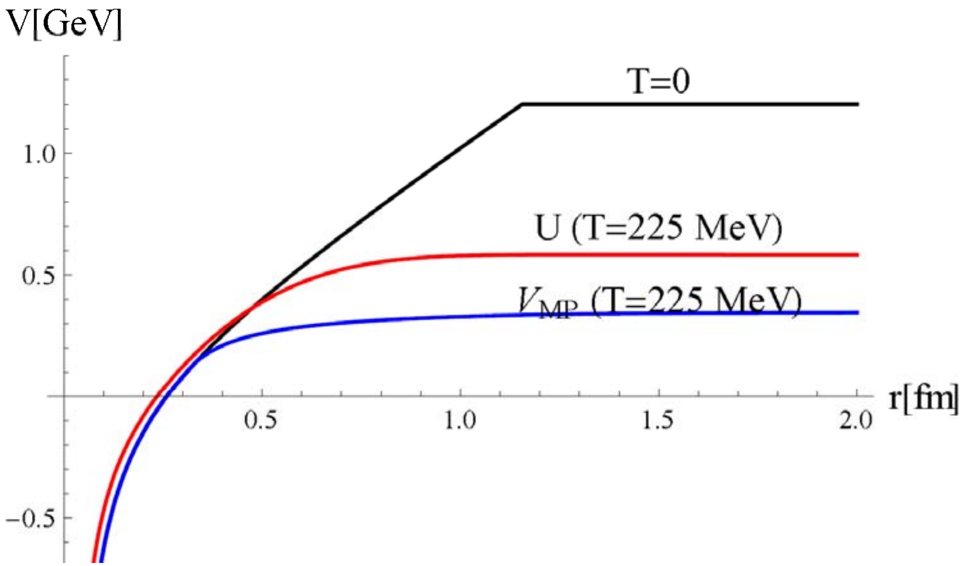
J/Ψ suppression (dynamical)

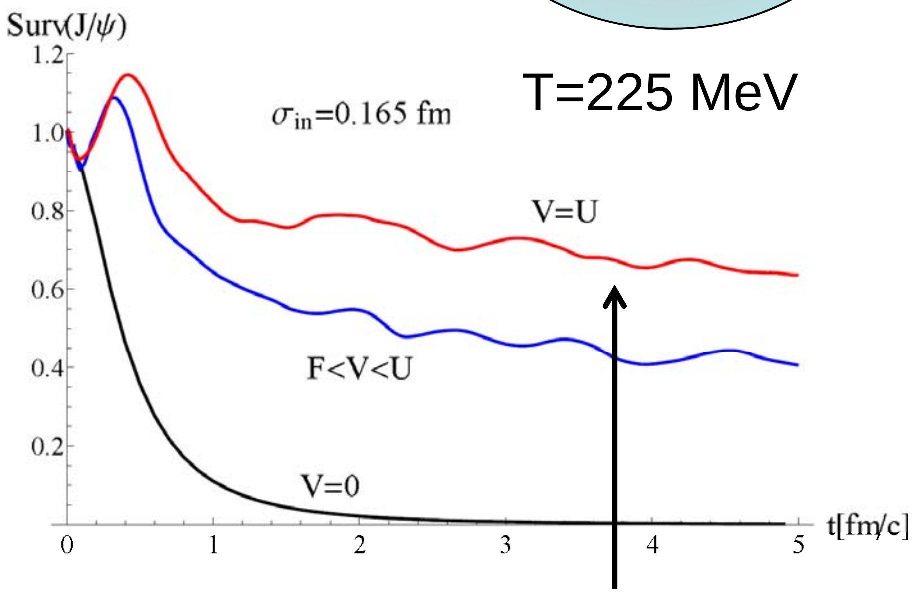


BUT: 2 missing ingredients

1. Q-Qbar forces (beginning 90s':Thews, Gossiaux and Cugnon,…) :

permits to preserve some Q and Qbar at close distance





Indeed, the "residual" potential permits to slow down the suppression along time ! We converge towards asymptotic survival probabilities ∈ [0,1]

J/Ψ suppression (dynamical)

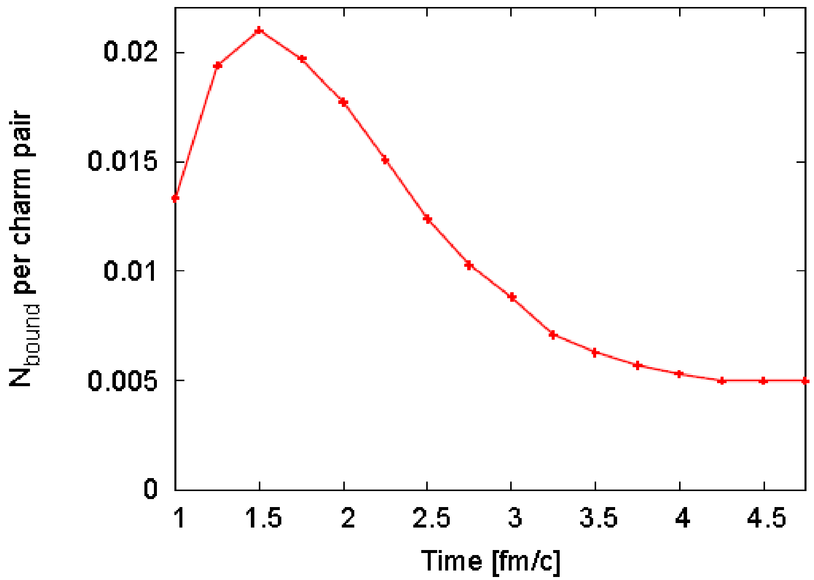
BUT: 2 missing ingredients

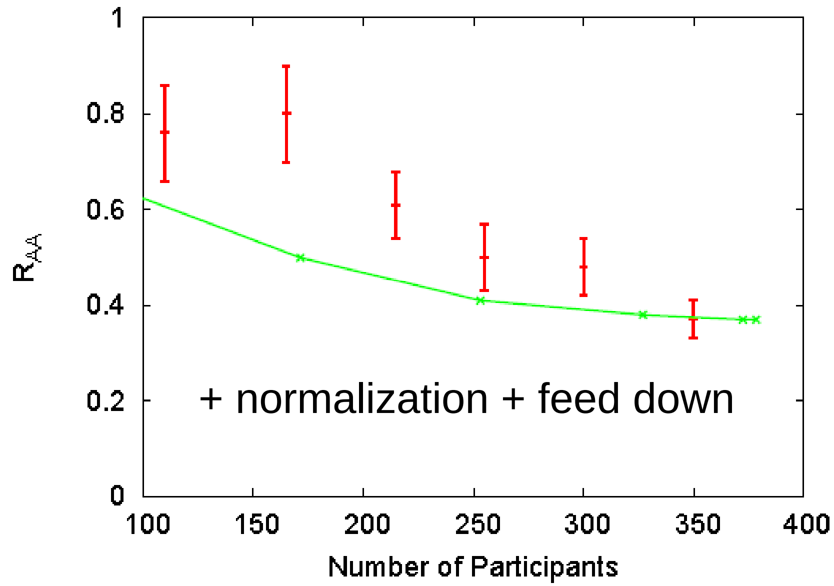
2. Stochastic q-Q, g-Q forces

For a long while: interactions with QGP/hot medium constituents only thought as the source for quarkonia dissociation (Bhanot – Peskin) and treated through inelastic cross-sections… True for dilute media

Shuryak & Young (08):

In strong QGP, diffusion of HQ slow down their separation ($<r^2> \alpha D_s t$) and helps in reducing the suppression !!!

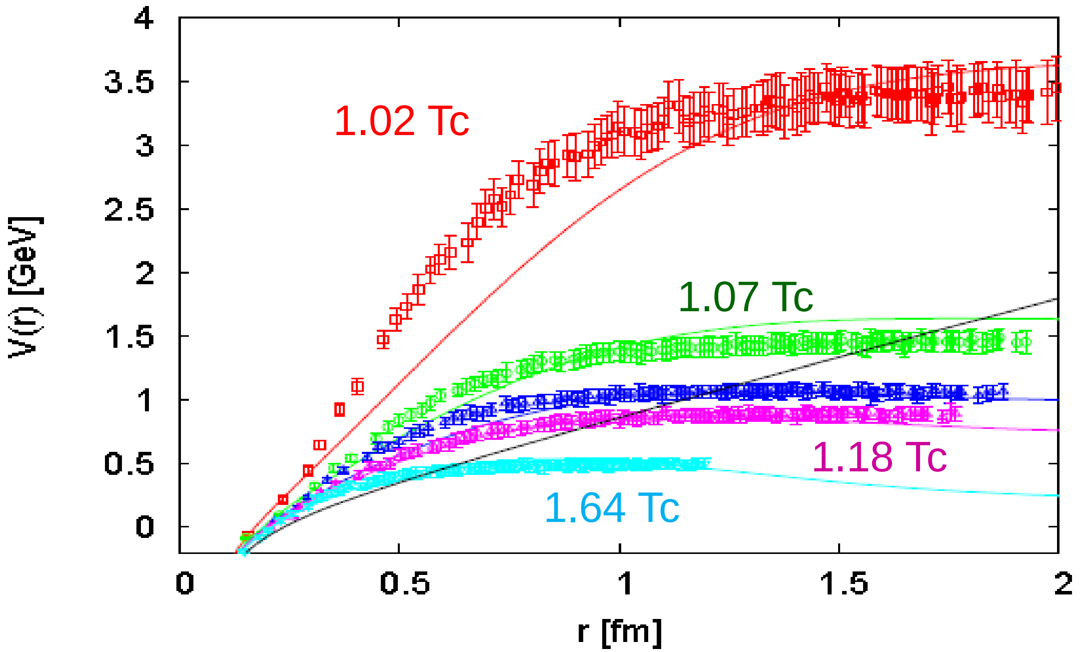




Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ U as a potential



The most “binding” choice; Around T_c: String tension up to 3 times string tension in vacuum !!!

Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ Dealing both with quantum evolution and stochastic forces:

Wigner Moyal distribution (density operator):

$$F(\mathbf{x}^N, \mathbf{p}^N, t) = \left(\frac{1}{\pi\hbar}\right)^{3N} \int e^{2i\mathbf{p}^N\cdot\mathbf{y}^N/\hbar} \rho(\mathbf{x}_-^N, \mathbf{x}_+^N, t)\, d\mathbf{y}^N$$

Right concept for non pure quantum system (statistical average), but also to make contact with semi-classical interpretations

Wigner-Moyal equation in relative coordinates:

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\mu}\cdot\frac{\partial}{\partial \vec{x}}\right) f(\vec{x},\vec{p};t) = \frac{2}{\hbar}\sin\left(\frac{\hbar}{2}\frac{\partial}{\partial \vec{p}}\cdot\frac{\partial}{\partial \vec{x}}\right) V(\vec{x}) f(\vec{x},\vec{p};t) + I_{\mathrm{col}}$$

with $\vec{x} = \vec{x}_Q - \vec{x}_{\bar{Q}}$ and $\vec{p} = \frac{\vec{p}_Q - \vec{p}_{\bar{Q}}}{2}$

Exact equation, but difficult to solve due to sign problem

Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ Dealing both with quantum evolution and stochastic forces:

Semi-classical expansion => 1 body Liouville equation:

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\mu}\cdot\frac{\partial}{\partial \vec{x}} - \frac{\partial V}{\partial \vec{x}}\cdot\frac{\partial}{\partial \vec{p}}\right) f(\vec{x},\vec{p};t) = I_{\rm col}$$

Test particles method, submitted to the QQbar force + stochastic external forces

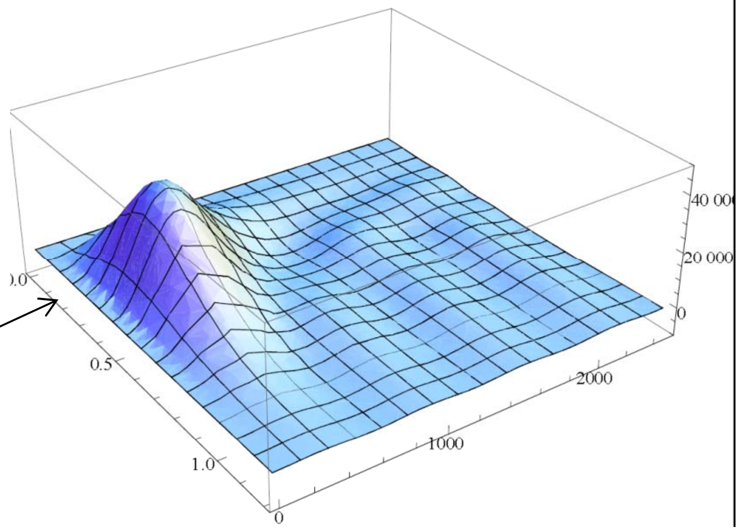
Langevin evolution with binding force (♥ fast !!! ♥)

Prob J/ψ(t): $P_{J/\psi}(t) = \frac{1}{N}\sum_{i=1}^{N} f_{J/\psi}(\vec{x}_i(t),\vec{p}_i(t))$

Caviat: f is not a density (not defined positive)
semi-classical approx justified ?

Notice however that $f_{J/\psi}$ is mostly positive
(but not a full justification)

$$x^2 p^2 f_{J/\psi}(x,p,\theta(\vec{x},\vec{p})=0)$$



Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

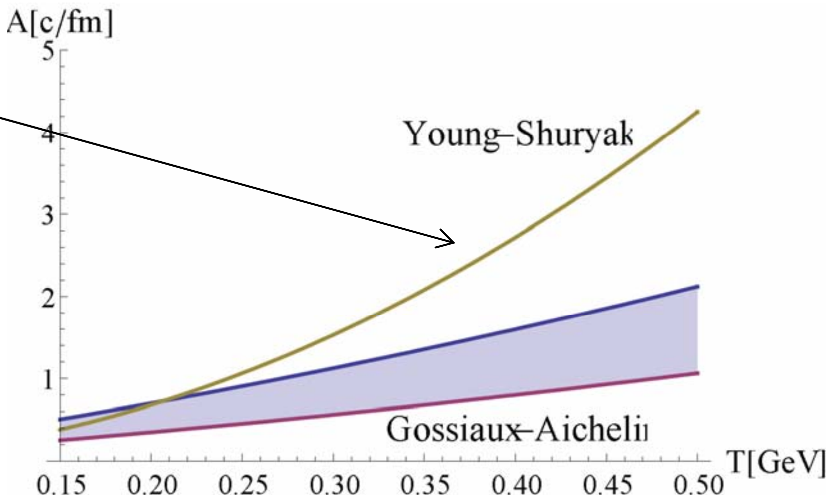
✓ Stochastic force on Q and Qbar are uncorrelated

… although QQbar is seen as a dipole at short distances

…but most of Q-Qbar pairs are not at close distance already after short time
=> probably ok !

✓ Hydro evolution and HQ dynamics from Moore and Teaney (2005). In particular $D_c \times 2\pi T$=1.5-3 =>

$$A_c = \frac{T}{MD_c} = \frac{2\pi T^2}{1.5M}$$



Our model + detailed comparison to RHIC:

$$A_c[\mathrm{c/fm}] = K\left(1.5T[\mathrm{GeV}] + 1.25T^2\right)$$

Effective linear rise: $\alpha_s(T)$

Test of robustness

Goal of our contribution:

- ✓ Get acquainted with the impact of stochastic forces on quarkonia suppression
- ✓ Test the robustness of the results obtained by Young and Shuryak, modifying

  a) the V(T)

  b) the drag coefficient A(T)

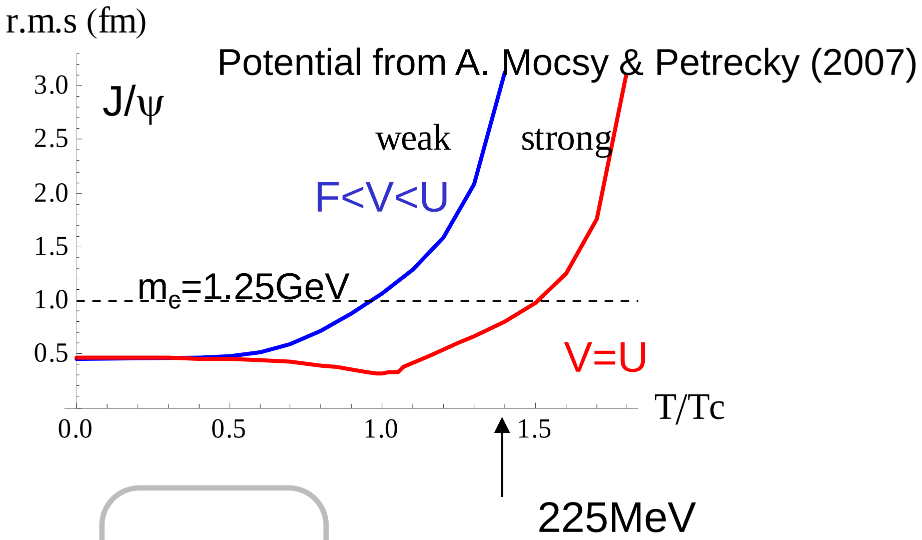
  c) the semi-classical treatment of the c-cbar evolution (tougher, not today)

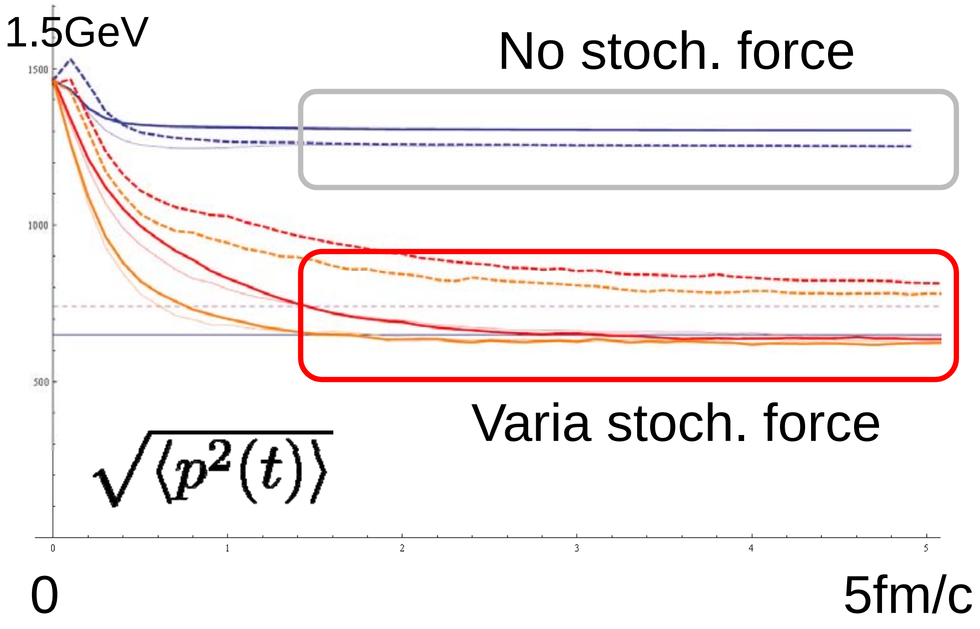
Test of robustness for stationnary QGP

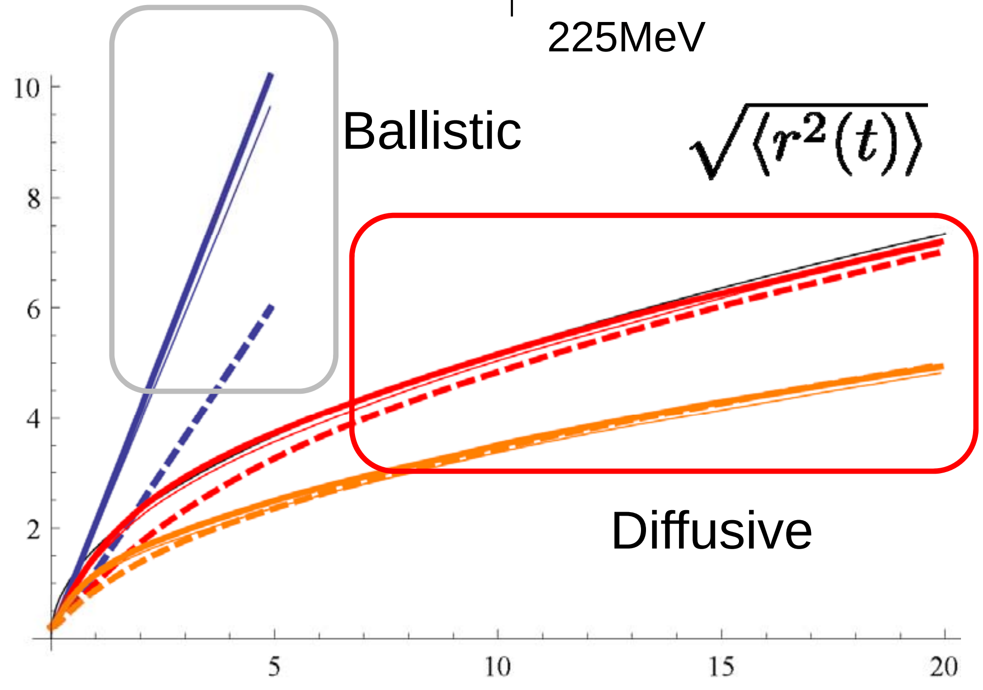
T=225 MeV (T/Tc ≈ 1.4):

Nearly unbound if one takes $V=V_{PM}$,
still strongly bound if one takes V=U

$$\sqrt{\langle r^2(t=0)\rangle} = 0.2 \text{ fm}$$





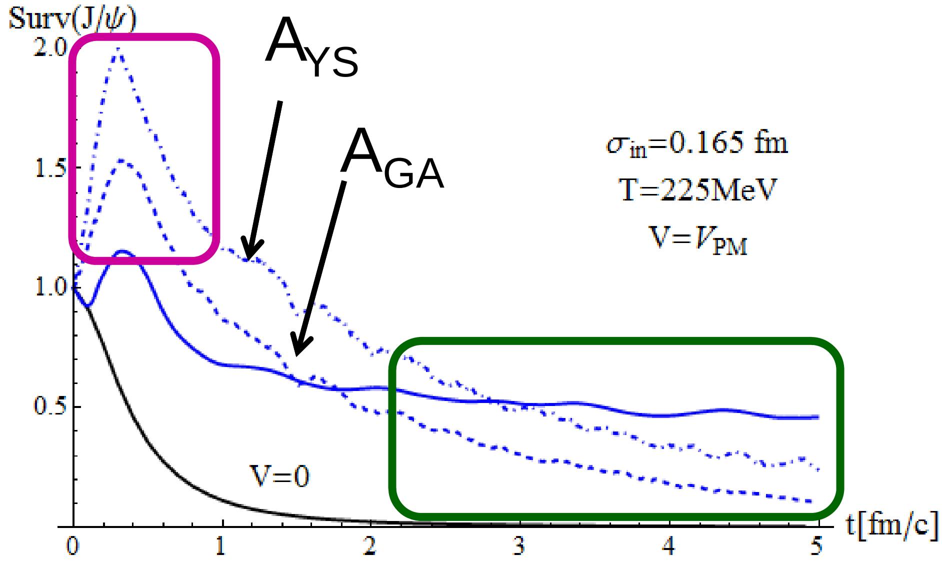


Stochastic cooling of c-cbar state

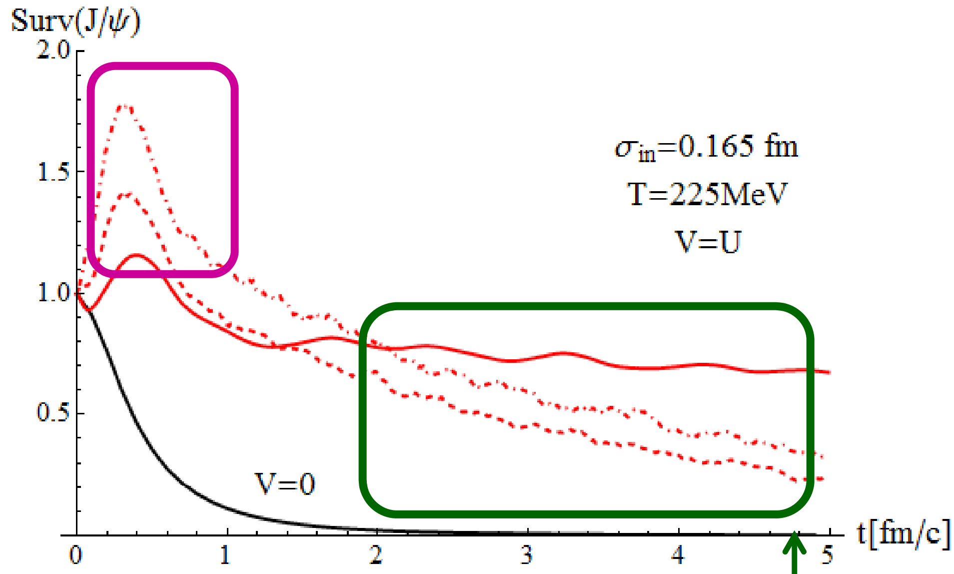
Test of robustness for stationnary QGP

T=225 MeV (T/Tc ≈ 1.4):

$V=V_{PM}$ (weakly bound)



V=U (strongly bound)

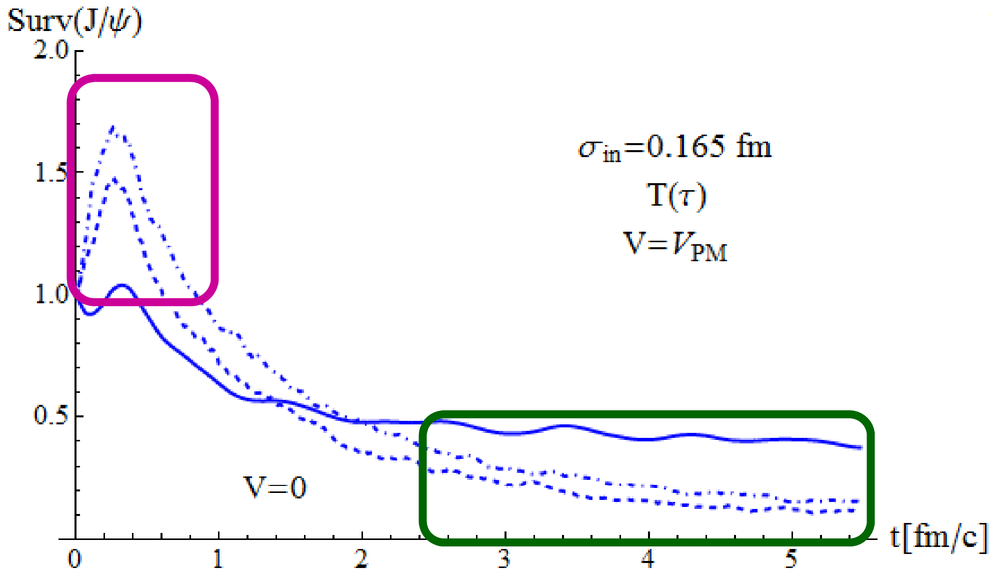


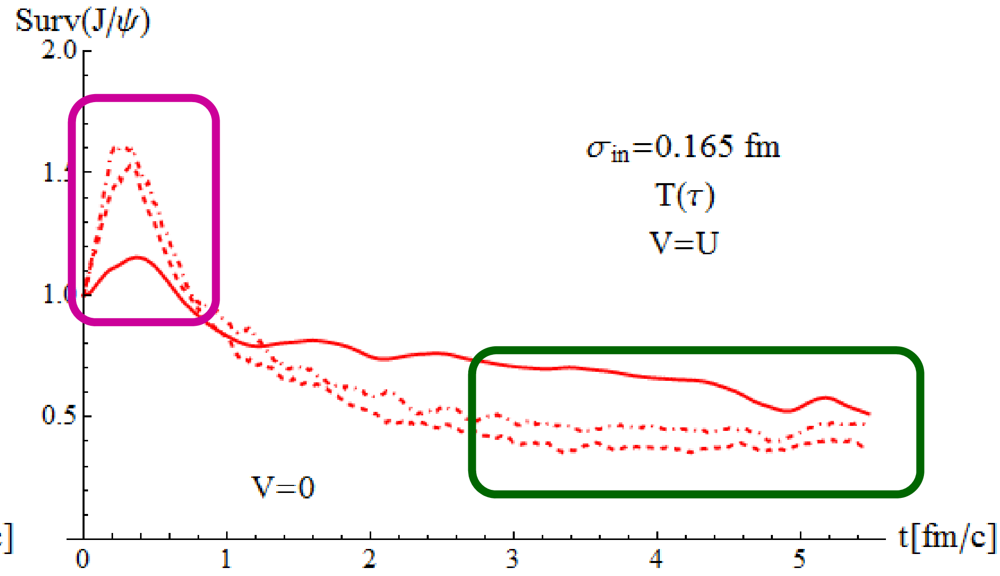
- Around initial time, cooling down by stochastic forces increase the J/ψ content of the quantum QQbar state
- At later times, the stochastic sources act as a source of dissociation of the remaining state

Test of robustness for evolving QGP

T(τ), central Au-Au @ RHIC, $\vec{x}_\perp = \vec{0}$

V=V_{PM} (weakly bound) V=U (strongly bound)



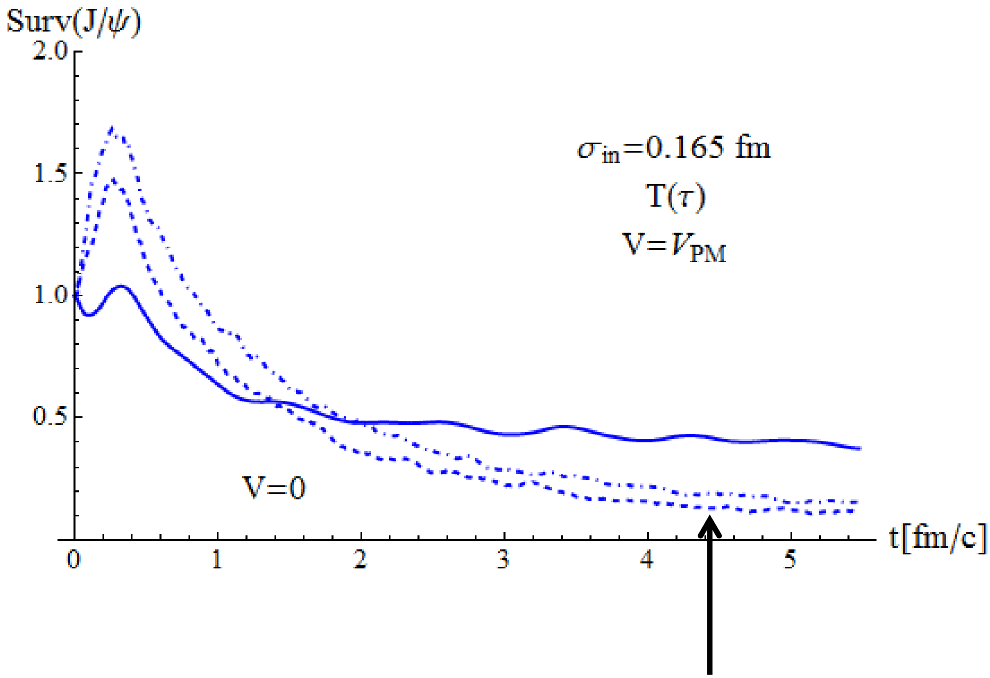


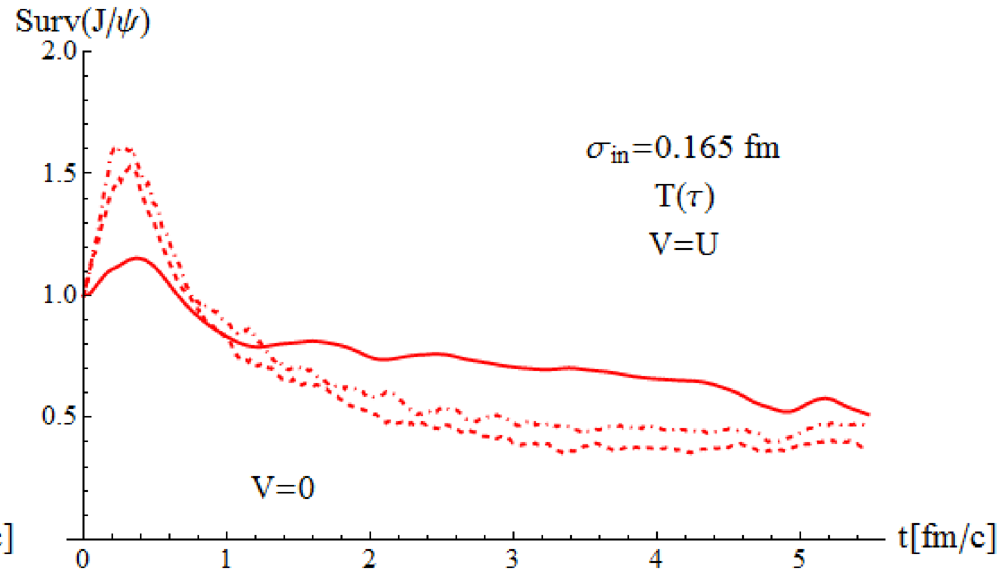
- Similar features as for T=225: rapid thermalization in p-space (-> quasi equilibrium), followed by induced leakage in r space
- For potential chosen as V=U, survival compatible to 0.5, as claimed by Young and Shuryak

Test of robustness for evolving QGP

T(τ), central Au-Au @ RHIC, $\vec{x}_\perp = \vec{0}$

V=V_{PM} (weakly bound) V=U (strongly bound)



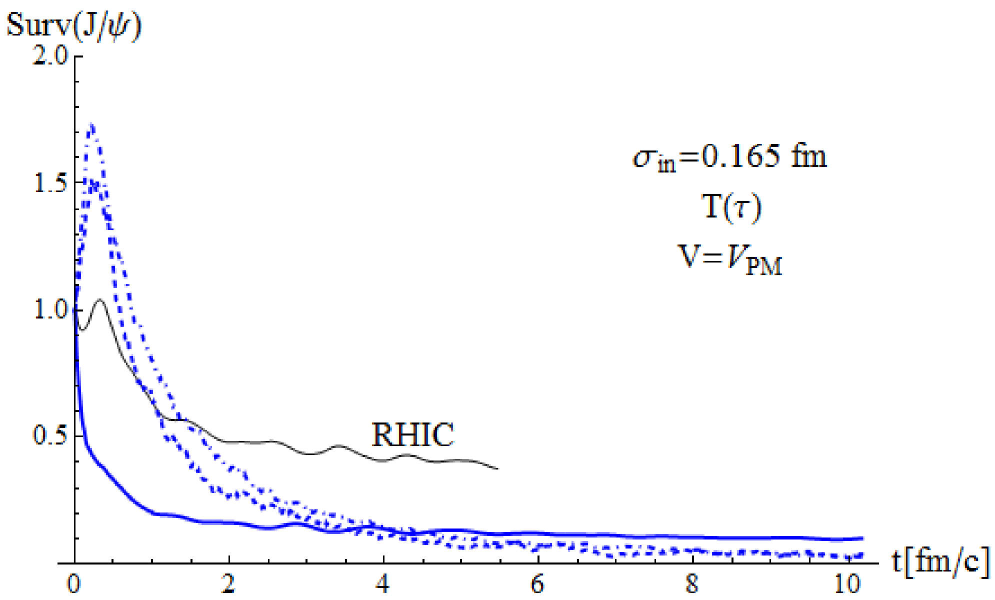


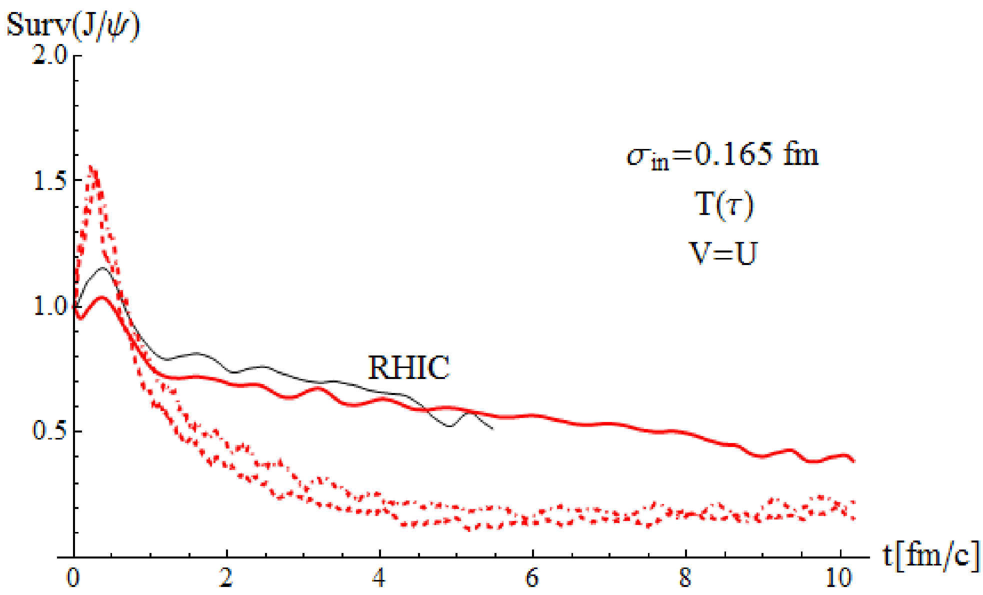
- No large dependence vs precise choice for drag coefficient…
- But large dependence vs choice of potential, especially if one includes the stochastic forces (can dissociate weakly bound states, but rather inefficient to dissociate strongly bound states).

Survival @ LHC

T(τ), central Pb-Pb @ LHC, $\vec{x}_\perp = \vec{0}$

Preliminary





Even at LHC, up to 25% survival if V=U;

should not be neglected

Conclusion & Prospects

1. Important to include a time-dependent microscopic description of Q-Qbar states in the transport codes… to be pursued

2. We confirm the claim of Shuryak and Young of large J/ψ survival… for V chosen to be the total energy U…

3. However, their choice of parameters probably correspond to the most favorable case !

Possible way to make progress on this point: evaluate $\Gamma_{J/\psi}$(T) for both types of potentials and compare with lattice

4. I am very excited(QCD) about all of this