DYNAMICAL BOTTOMONIUM-SUPPRESSION (AND RECOMBINATION) IN NUCLEUS-NUCLEUS COLLISIONS

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Quantum Systems in Extreme Conditions
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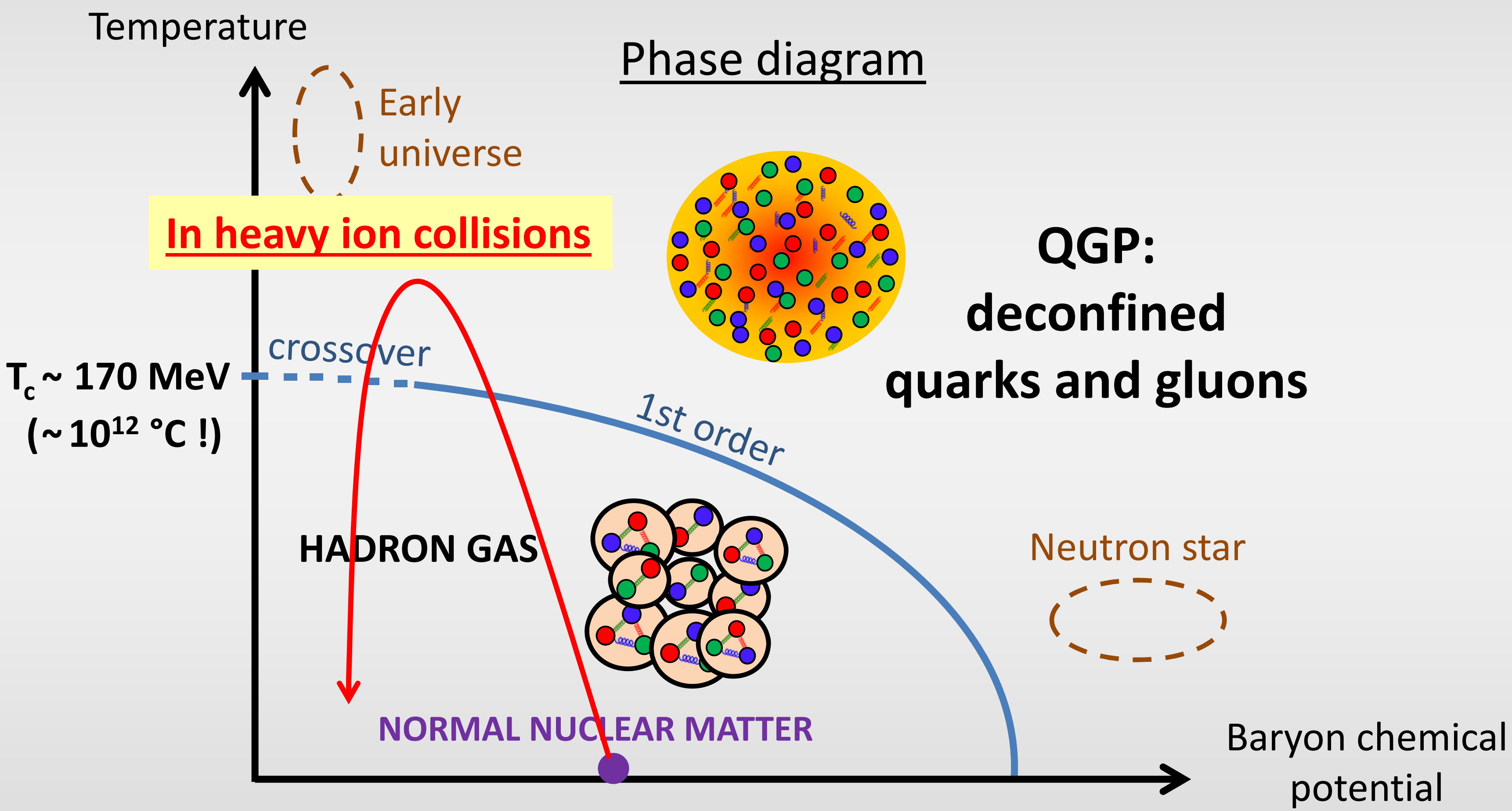
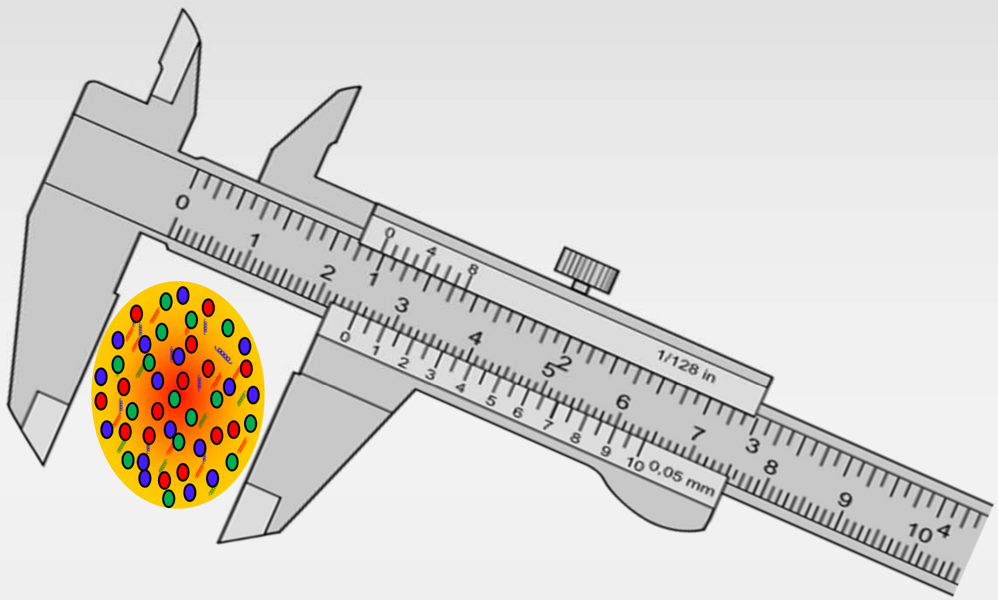
Subatech and Pays de la Loire

The Quark Gluon Plasma (QGP)



QGP in heavy ion collisions

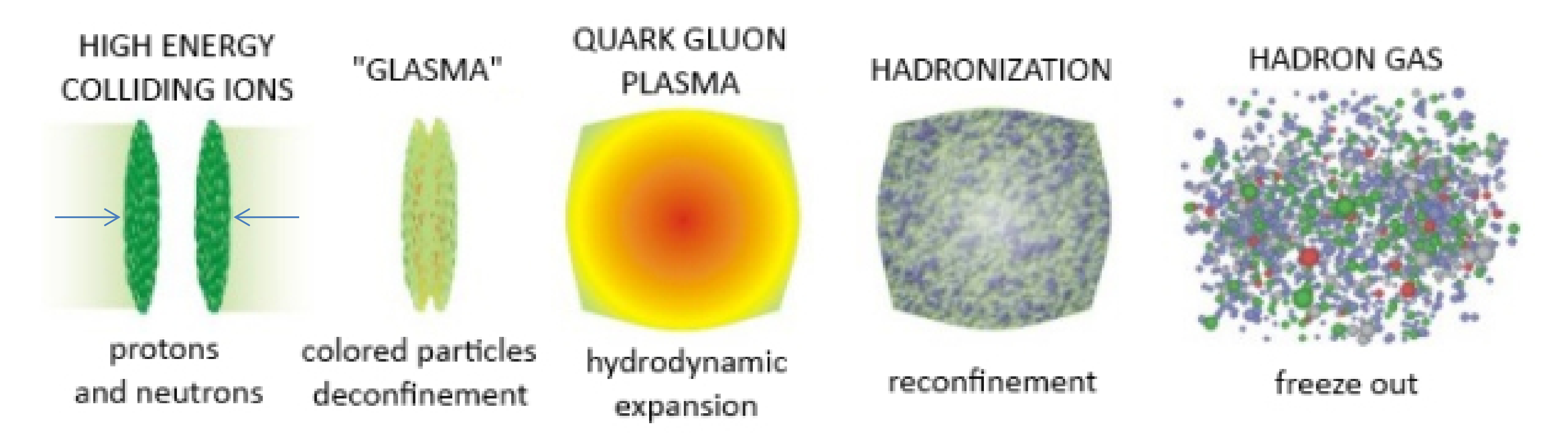


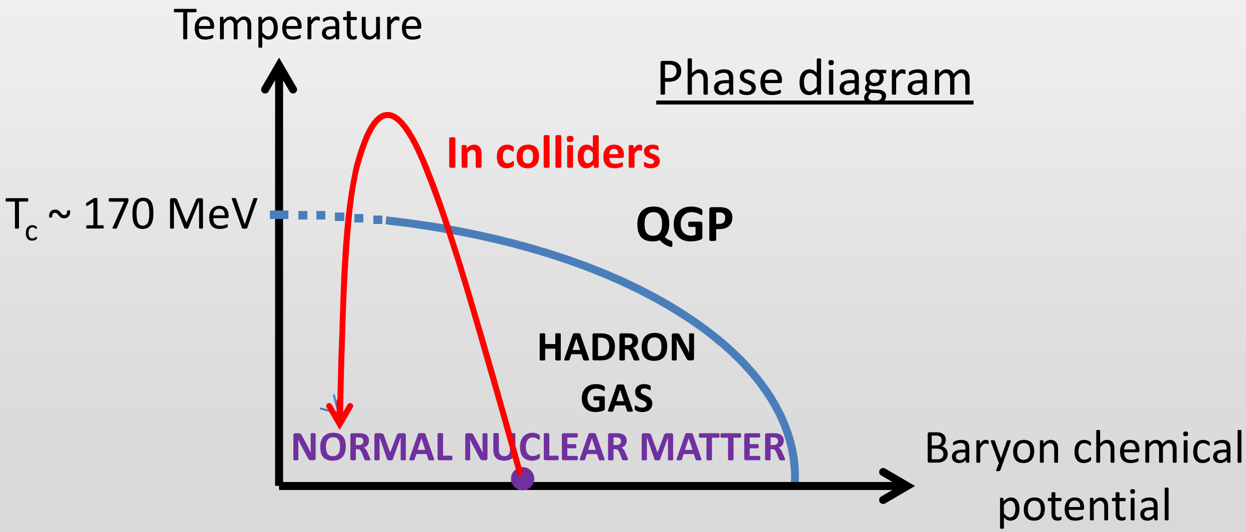
Extremely **small** (~10^{-15} m), **short-lived** (~10^{-21} s),
dynamic (relativistic), and hot (10^{12} °C) bubbles of QGP medium…

Great challenge to study !

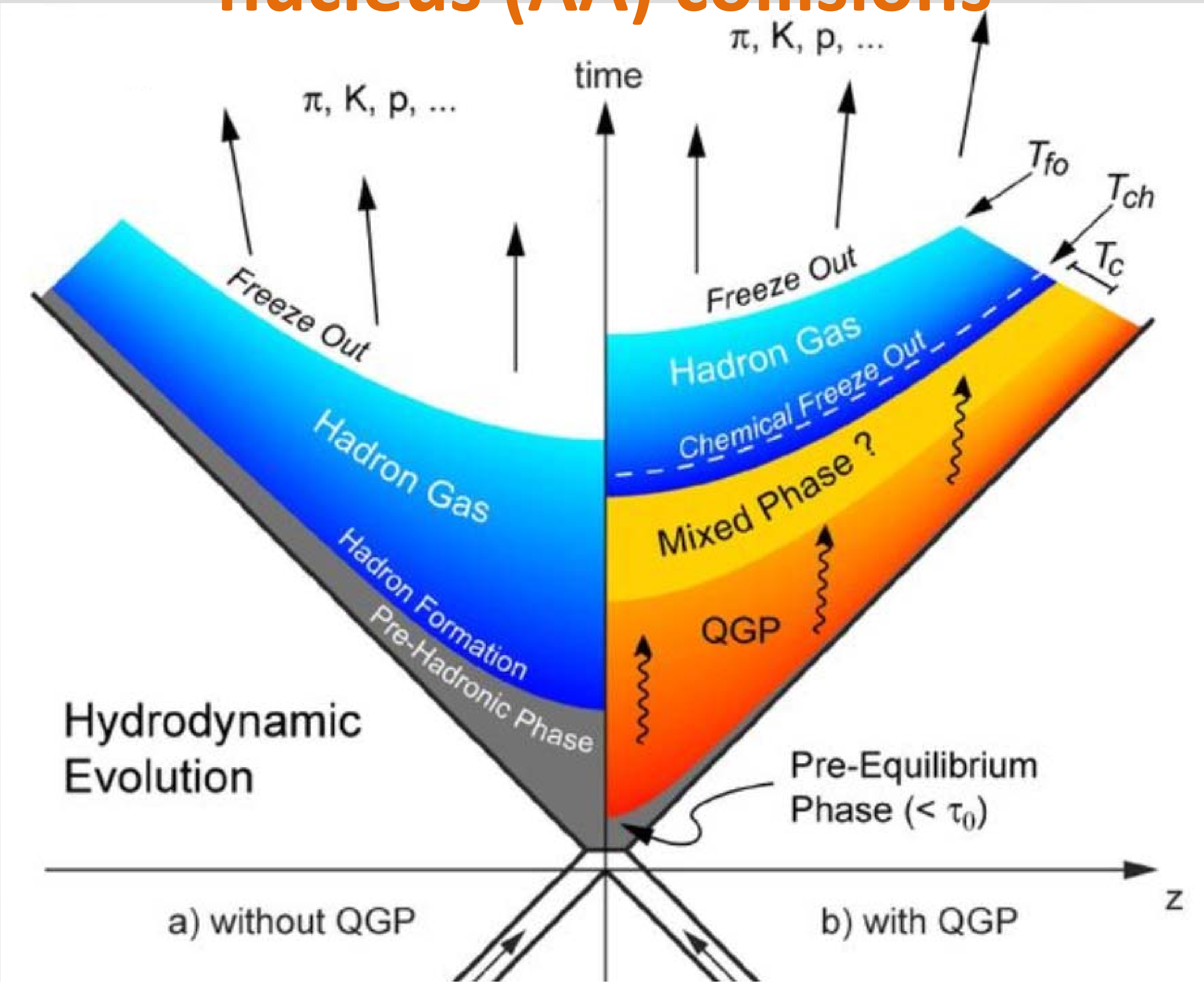
Experimental QGP

How ? => By colliding heavy ions at very high energies !





Schematic QGP evolution in nucleus-nucleus (AA) collisions



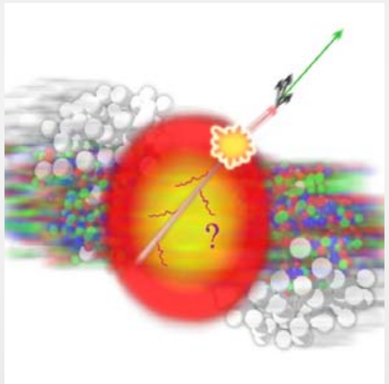
« Hard » probes

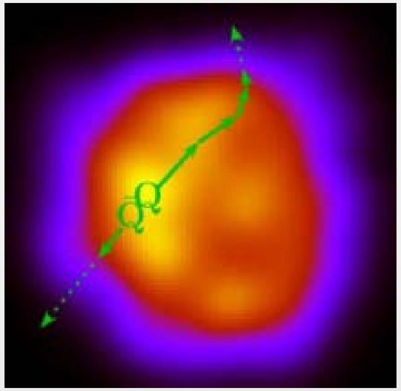
To study the medium properties before the freeze out «horizon»…

Deconfined ? Density and T ? Transport properties ? …

… one can analysed the « tomography » of the medium realised by the hard probes (⇔ incomplete thermalisation)

High p_T partons quenching





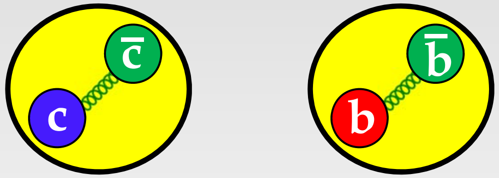
Massive quarks diffusion

Why hard probes ?

- ✓ Produced only in early pQCD processes before the GQP medium
- ✓ Do not flow hydrodynamically but propagate/interact inside the medium via other processes sensitive to its properties
- ✓ Less sensitive to hadronic stages

Quarkonia: Φ

Quarks			
	u up	*c* charm	*t* top
	d down	*s* strange	*b* bottom



CHARMONIA BOTTOMONIA

QUARKONIA

Various (more or less) tightly bound energy states

CHARMONIA

J/ψ : m = 3.096 GeV/c

χ_{cJ} : m ≈ 3.5 GeV/c

ψ' : m = 3.686 GeV/c

BOTTOMONIA

$\Upsilon(1S)$: m = 9.460 GeV/c

χ_{bJ} : m ≈ 9.9 GeV/c

$\Upsilon(2S)$: m = 10.023 GeV/c

$\Upsilon(3S)$: m = 10.355 GeV/c

Quarkonia suppression

Expected medium effects : the « Quarkonia suppression »

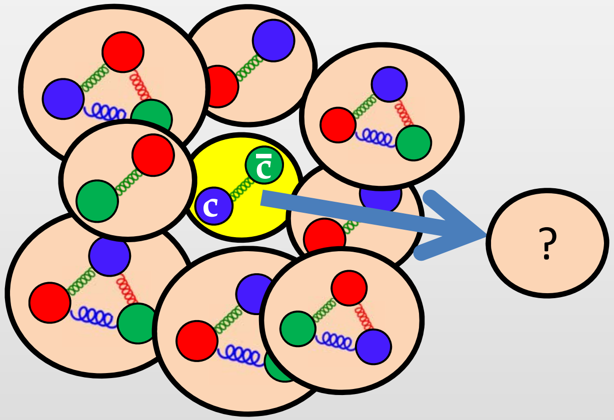
Smaller amount of quarkonia produced in heavy ion collisions per binary nucleon collision as compared to pp collisions.

Quantified with the *nuclear modfication factor:*

$$R_{\mathrm{AA}}(p_{\mathrm{T}},\eta)=\frac{dN^{\mathrm{AA}}/d^2p_{\mathrm{T}}d\eta}{\langle N_{\mathrm{coll}}\rangle\, dN^{\mathrm{pp}}/d^2p_{\mathrm{T}}d\eta}$$

Different contributions

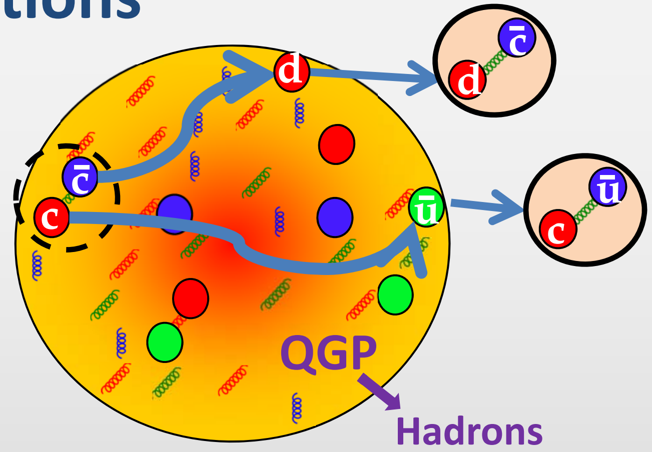
In hadronic phases:



« Normal » suppression (~ small)

From Cold Nuclear Matter effects

In QGP:



« Abnormal » suppression

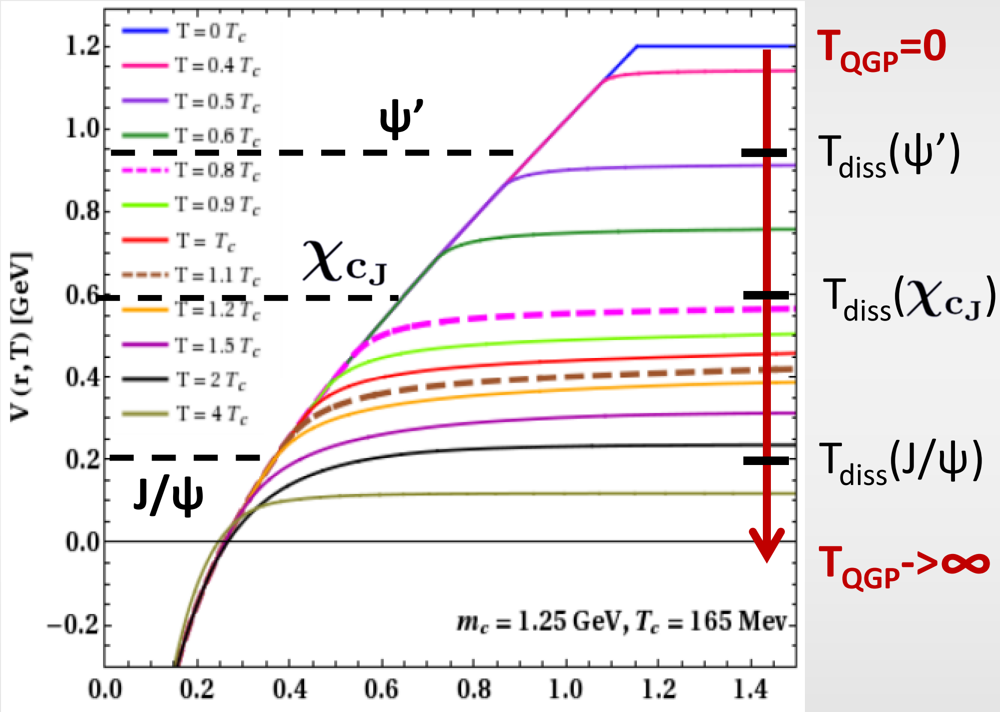
from color screening and collisions with the medium partons

+ possibility of recombination

Historical models

Sequential suppression (Matsui and Satz)

$Q\bar{Q}$ color potential



From lattice QCD

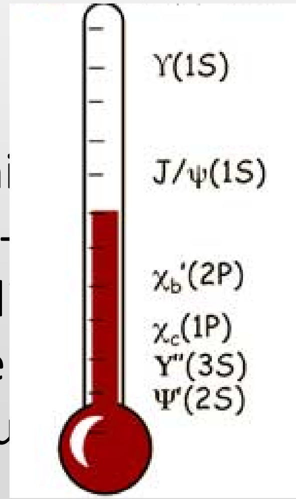
T ↗ => screening ↗ => progressive states melting

« all or nothing »:

- If $T_{\text{early QGP}} > T_{\text{diss}}$ => the state is not produced
- If $T_{\text{early QGP}} < T_{\text{diss}}$ => the state is produced like in pp

=> *Quarkonia as early QGP thermometer*

- Everythi… …INNING
in quasi-… …medium
- Ad… …ion
- No inte… …partons
- Qu… …diss

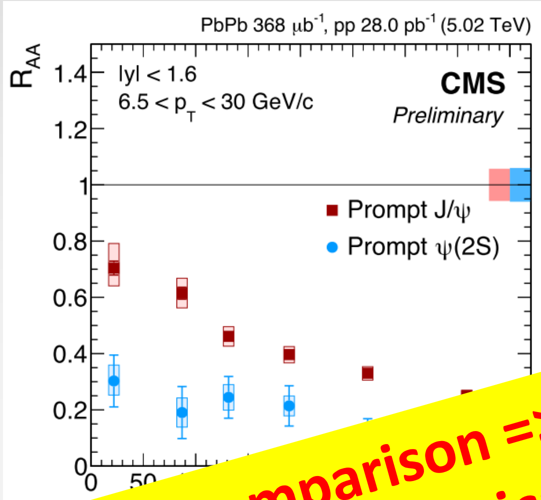


T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416

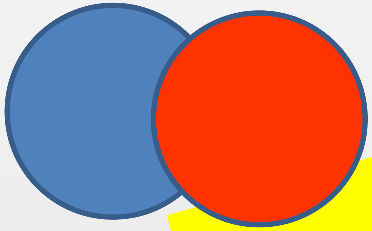
Looking at recent data

Hints for sequential-like supression of states

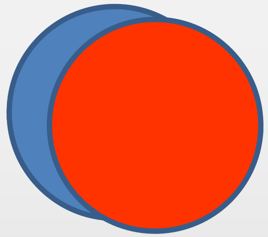
CMS arXiv:1611.01510v2



Peripheral Pb-Pb collisions

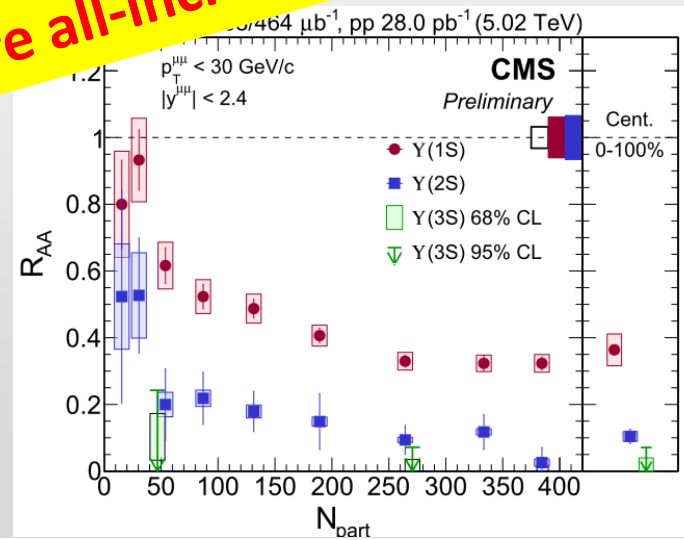


Nearly overlapping Pb-Pb collisions : hot QGP expected



Data/theory comparison =>

Need for more all-inclusive / dynamical treatments

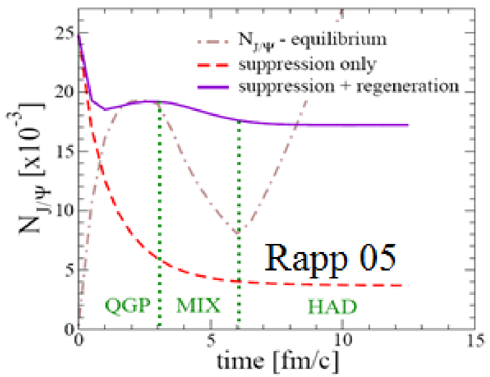


Not all equal !!!

Recombination: hierarchy of approaches…

Complexity

Statistical weights (at transition). no detailed dynamics. ☹ assumes all time scales are small vs. transition time. ☺ simple to deal with. PBM, Stachel & Andronic; Gorenstein, Kostyuk;…



Rate equations: $\frac{dN_\Psi}{dt} = -\Gamma_\Psi \left(N_\Psi - N_\Psi^{eq}\right)$

☺ Might contain the essential physics at a global level.
☹ Model of $f_c(x,p)$ needed. ☹ no possibility of studying diff. spectra. Grandchamp, rapp and Brown; (early) Thews

Transport theory assuming spatial homogeneous $f_i(p)$. ☺ diff spectra. ☹ misses surface effects, x-p correl, Q are not uniformly distributed. Thews and Mangano

Transport theory. ☺ solves the caviats of other approaches. ☹ may obscure the physics. Zhang (AMPT); Bratkovskaya (HSD); Gossiaux;…

… does not mean a hierarchy of answers (hopefully)!

A central quantity: the decay rate Γ

Several approaches

pQCD view

$$\Phi + g \to Q + \bar{Q}$$

Dissociation cross section σ

$$\Gamma_\Phi(T) = \langle \sigma n_g \rangle_T$$

QFT/Lattice QCD

Time correlator

$$\mathcal{C}_>(t, \vec{r}) \approx \langle \psi(t, \tfrac{\vec{r}}{2}) \bar{\psi}(t, -\tfrac{\vec{r}}{2}) \psi(0,0) \bar{\psi}(0,0) \rangle$$

Satisfies Schroedinger equation with imaginary potential iW

$$\Gamma_\Phi(T) = -2\langle \Phi | W | \Phi \rangle$$

Common belief in QGP community:

Quarkonia initially « formed » in QGP at time t=0 are then destroyed and suvive with a survival probability

$$S(t) = e^{-\int_0^t \Gamma(T(t'))dt'}$$

New motto: $Q\bar{Q}$ real-time dynamics

Consider:

color sreening, (non-)dissociative interactions and QGP dynamics

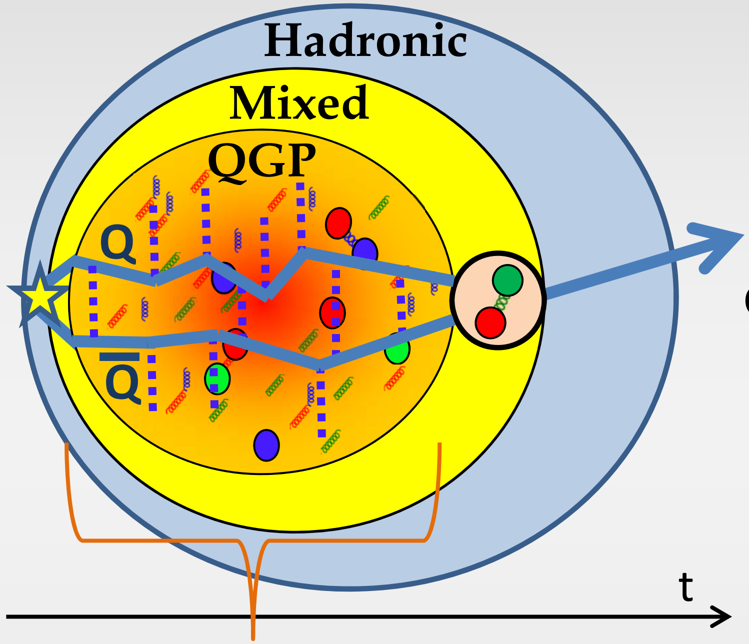
INNER DYNAMICS OF EACH $Q\bar{Q}$ PAIR
A dynamical and continuous picture of the dissociation, recombination, transitions between states, and energy exchanges with the QGP

+

$Q\bar{Q}$ PAIRS EVOLUTION IN A VERY DYNAMIC QGP
Realistic t-dependent background: Monte-Carlo event generator with initial fluctuations

=> *Quarkonia as QGP continuous thermometers*

$Q\bar{Q}$ dynamics ? -> back to concepts



Quarkonium

?

Open mesons

only resolved at the end of the evolution

Beware of quantum coherences during the whole evolution !

~~Very complicated QFT problem at finite T(t) !!!~~

How ?

Treatment within the open quantum system framework !

Dating back to Blaizot & Ollitrault, Thews, Cugnon and Gossiaux; early 90's

Open quantum systems (OQS)

In usual quantum mechanics: no irreversible/dissipative phenomena…

The quantum master equation (QME) approach

- **Idea:** density matrix of conservative {bath + subsystem of interest}
  => bath degrees of freedom integrated out
  => dissipative *quantum master equation* for the subsystem
- **But** : defining the bath & interaction is often complex,
  the calculation and application entangled

Stochastic equations

- **Idea:** *Effective equations* to unravel/mock the open quantum approach while keeping most of the quantum features
- **But** : possibly not related to a master equation or QCD

Widely applied in quantum diffusion and transport, quantum optics, low energy heavy ion scattering, quantum computers and devices...

Stochastic equations and quarkonia

Effective equations to unravel/mock the open quantum system approach while keeping most of the quantum features

Langevin-like approaches

Idea: Brownian heavy quarks (M_Q >> T) + Drag A(T) from QCD models

Young and Shuryak (2009) & R.K. and Gossiaux (2014)

Wigner description of the $Q\bar{Q}$ wavefunction + classical Langevin

But: important pitfalls (Heisenberg principle violation…)

Roland Katz and Pol-B. Gossiaux (From 2015 on)

Schrödinger-Langevin equation:

Schrödinger equation with fluctuation-dissipation terms

=> 1D analysis: most of quantum features satisfied and equilibrium ok.

Interesting suppression patterns.

But: A priori only related to a quantum master equation in phenomenological sense (see talk by A. Rothkopf for “first principle” approach)

Young and Shuryak 2009 Phys. Rev. C 79: 034907; Katz and Gossaiux J.Phys.Conf.Ser. 509 (2014) 012095; Katz and Gossaiux, Annals Phys. 368 (2016) 267-295

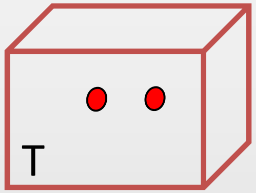
Inner dynamics: Schrödinger-Langevin (SL) equation

Derived from the Heisenberg-Langevin equation*, in Bohmian mechanics** …

$$i\hbar\frac{\partial\Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\widehat{H}_{\mathrm{MF}}(\mathbf{r}) - \mathbf{F}_{\mathbf{R}}(t).\mathbf{r} + A\big(S(\mathbf{r},t) - \langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\big)\right)\Psi_{Q\bar{Q}}(\mathbf{r},t)$$

Hamiltonian: Mean Field: T-dependent color screened potential
Generally taken from lattice-QCD

Static lQCD calculations (maximum heat exchange with the medium):



F : free energy
S : entropy

U=F+TS : internal energy
(no heat exchange)

- “Weak potential” F<Vweak<U => some heat exchange
- “Strong potential” V=U => adiabatic evolution

* Kostin The J. of Chem. Phys. 57(9):3589–3590, (1972) ** Garashchuk et al. J. of Chem. Phys. 138, 054107 (2013)
Mócsy & Petreczky Phys.Rev.D77:014501,2008 ; Kaczmarek & Zantow arXiv:hep-lat/0512031v1

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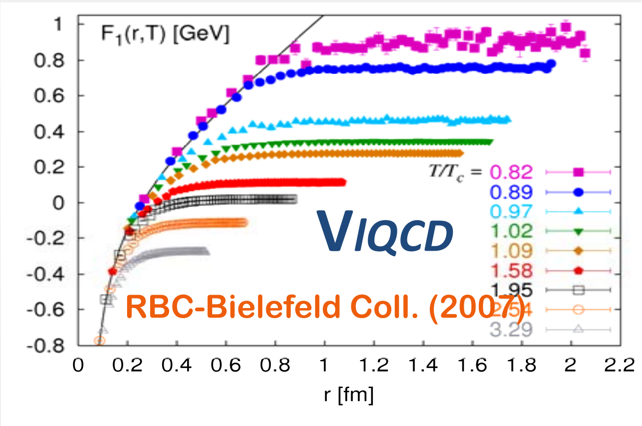
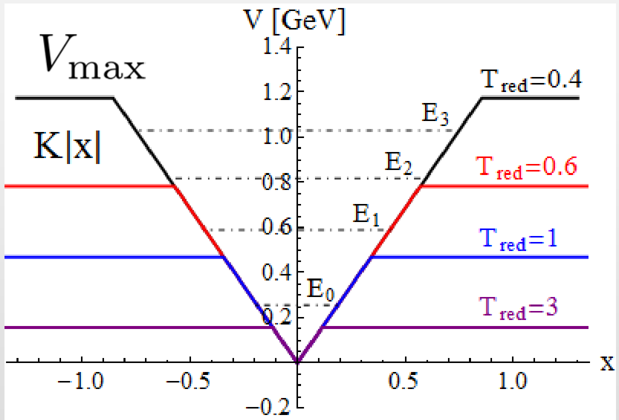
Hamiltonian: Mean Field: T-dependent color screened potential
Generally taken from lattice-QCD. Only singlet for now.

3D not easy to implement => 1D simplified model
not aim to reproduce the data but rather gives insights on the dynamics.



1D

simplification



Linear approx

Screening(T) as VlQCD

Parameters (K, Vmax) chosen to reproduce quarkonium spectrum + $B\bar{B}$ or $D\bar{D}$ threshold

Inner dynamics: SL equation

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Fluctuations: thermal excitation

Taken as a « classical » white stochastic force/noise scaled such as to obtain $T_{Q\bar{Q}} = T_{QGP}$ at equilibrium

The noise operator is assumed here to be a commutating c-number whereas it is a non-commutating q-number within the Heisenberg-Langevin framework.

I. R. Senitzky, Phys. Rev. 119, 670 (1960); 124}, 642 (1961).
G. W. Ford, M. Kac, and P. Mazur, J. Math. Phys. 6, 504 (1965).
R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

Schrödinger-Langevin (SL) equation

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Fluctuations

taken as a « classical » stochastic force

White quantum noise *

$$\langle F_R(t)F_R(t+\tau)\rangle = 2mA\,E_0\left[\coth\left(\frac{E_0}{kT_{\rm bath}}\right) - 1\right]\delta(\tau)$$

Color quantum noise **

$$\langle N[F_R(t)F_R(t+\tau)]\rangle = \frac{2mA}{\pi}\int_0^\infty \frac{\hbar\omega}{\exp(\hbar\omega/kT_{\rm bath}) - 1}\cos(\omega\tau)\,d\omega.$$

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* I. R. Senitzky, Phys. Rev. 119, 670 (1960); 124}, 642 (1961).

** G. W. Ford, M. Kac, and P. Mazur, J. Math. Phys. 6, 504 (1965).

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Dissipation: thermal de-excitation

$$S(\mathbf{r},t) = \arg\big(\Psi_{Q\bar{Q}}(\mathbf{r},t)\big)$$

✓non-linearly dependent on $\Psi_{Q\bar{Q}}$

✓ real and ohmic

✓ brings the system to the lowest state

✓with A(T) α T^2 the Drag coefficient from a microscopic model (pQCD - HTL) by Gossiaux and Aichelin

P.B. Gossiaux and J. Aichelin, Phys.Rev. C78 (2008) 014904
R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

Properties of the SL equation

- 2 parameters: A (Drag) and T (temperature)
- Unitarity and Heisenberg principle satisfied at any T
- Non linear => Violation of the superposition principle (=> decoherence)
- A priori not univoquely related to a quantum master equation: effective treatment
- Mixed state observables from statistics:

$$\Big\langle \langle\psi(t)|\hat{O}|\psi(t)\rangle \Big\rangle_{\mathrm{stat}} = \lim_{n_{\mathrm{stat}}\to\infty} \frac{1}{n_{\mathrm{stat}}} \sum_{r=1}^{n_{\mathrm{stat}}} \langle\psi^{(r)}(t)|\hat{O}|\psi^{(r)}(t)\rangle$$

- Easy to implement numerically (especially in Monte-Carlo generator)

R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

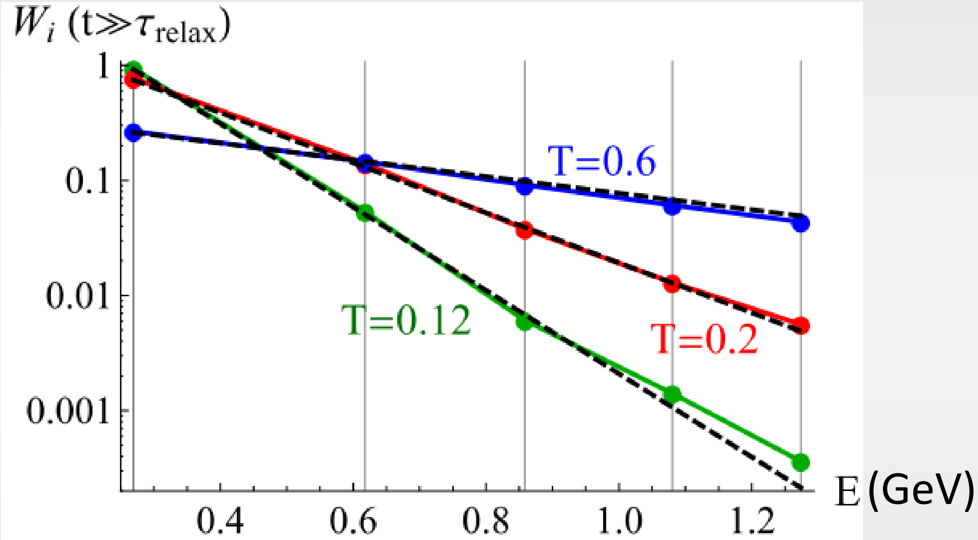
Observables

« weight » (population) W_i :

$$W_i(t) = | \langle \Psi_i(T=0) | \Psi_{Q\bar{Q}(t)} \rangle |^2$$

Properties of the SL equation

➢ Leads to local « thermal » distributions: Boltzmann behaviour for at least the low lying states



Populations $\propto \exp\left(\frac{-E_n}{k_B T}\right)$

(weak coupling limit: no shift and broadening of the energy levels assumed)

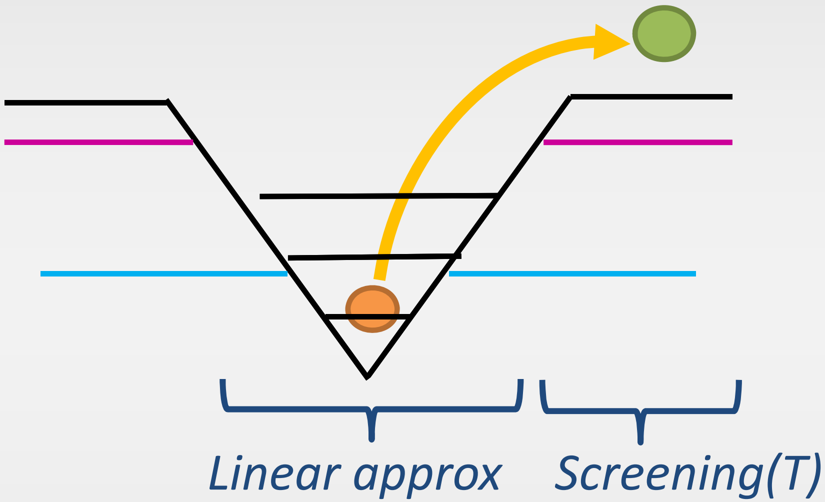
=> Fluctuation-dissipation mechanism compatible with quantum mechanics and effective !!

R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

Dynamics of $Q\bar{Q}$ with SL equation

Evolutions at constant T: understanding the model

- Simplified Potential but contains the essential physics



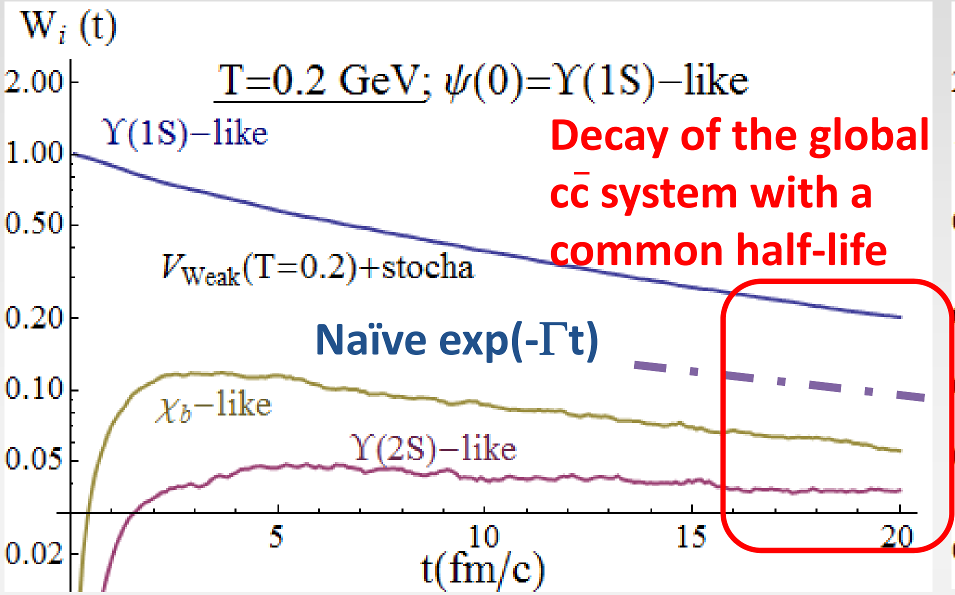
Stochastic forces =>
feed up of higher states
and continuum
=> Leakage of bound
component

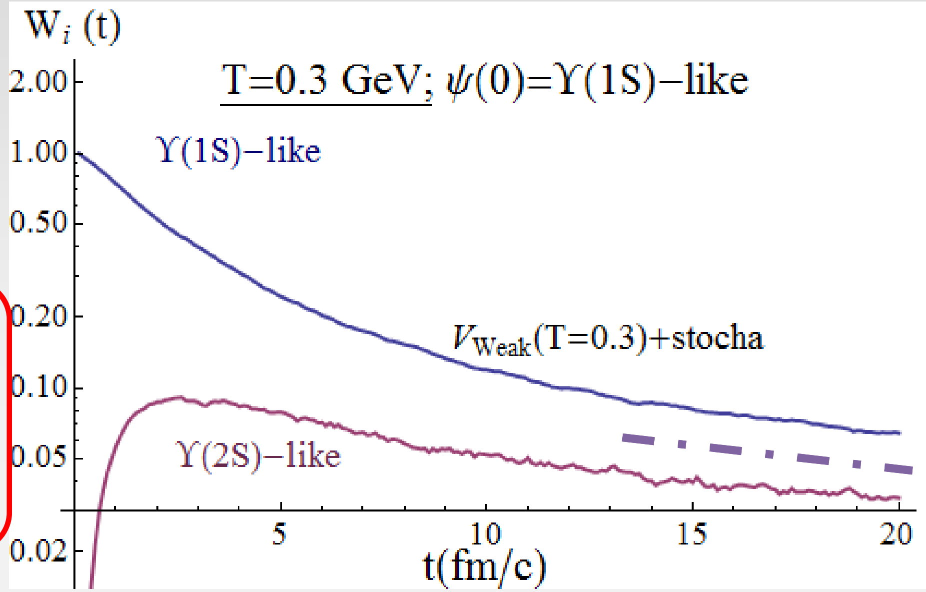
- Observables: **Weight** $W_i(t) = \left\langle \left| \langle \psi_i(T=0) | \psi_{Q\bar{Q}}(t) \rangle \right|^2 \right\rangle_{\text{stat}}$

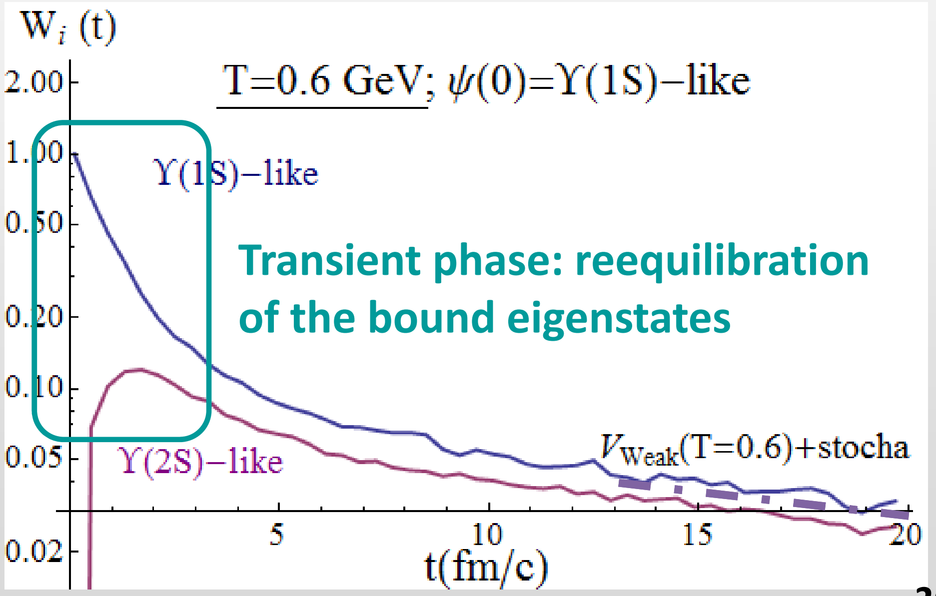
Initial $Q\bar{Q}$ wavefunction

- Produced at the very beginning : $\tau_f^{Q\bar{Q}} \sim \hbar/(2m_Q\, c^2) < 0.1\ \text{fm/c}$

Evolutions with V(T=cst) + Fstocha

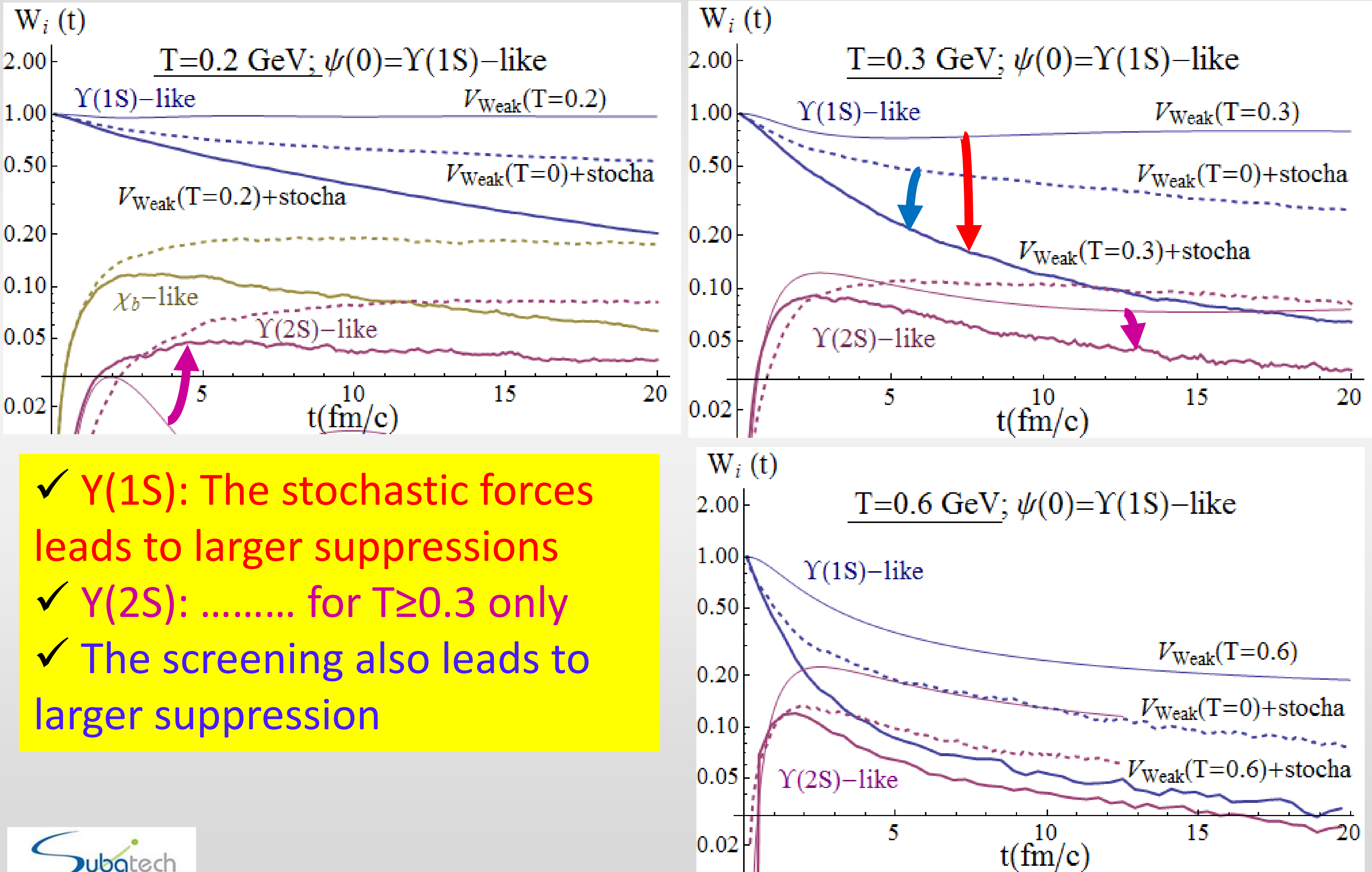






- ✓ Common decay law at large t (leakage+internal equilibration)
- ✓ Γ increases with T
- ✓ Starting from Υ(1S), higher states are asymptotically more populated at large T.

Evolutions with V(T=cst) + Fstocha



- ✓ Y(1S): The stochastic forces leads to larger suppressions
- ✓ Y(2S): ……… for T≥0.3 only
- ✓ The screening also leads to larger suppression

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Observables

« weight » (population) W_i :

$$W_i(t) = |\langle \Psi_i(T=0)|\Psi_{Q\bar{Q}(t)}\rangle|^2$$

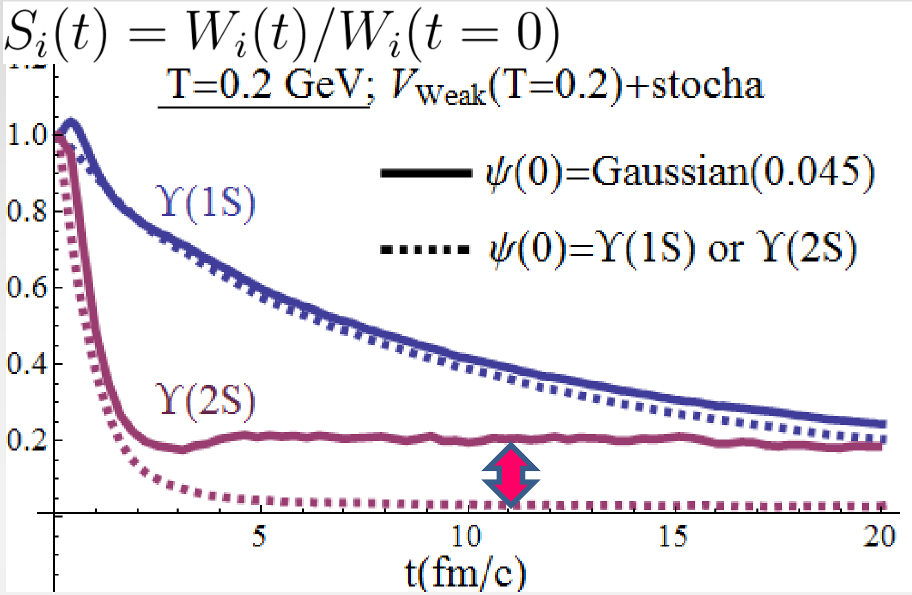
Normed weights S_i :

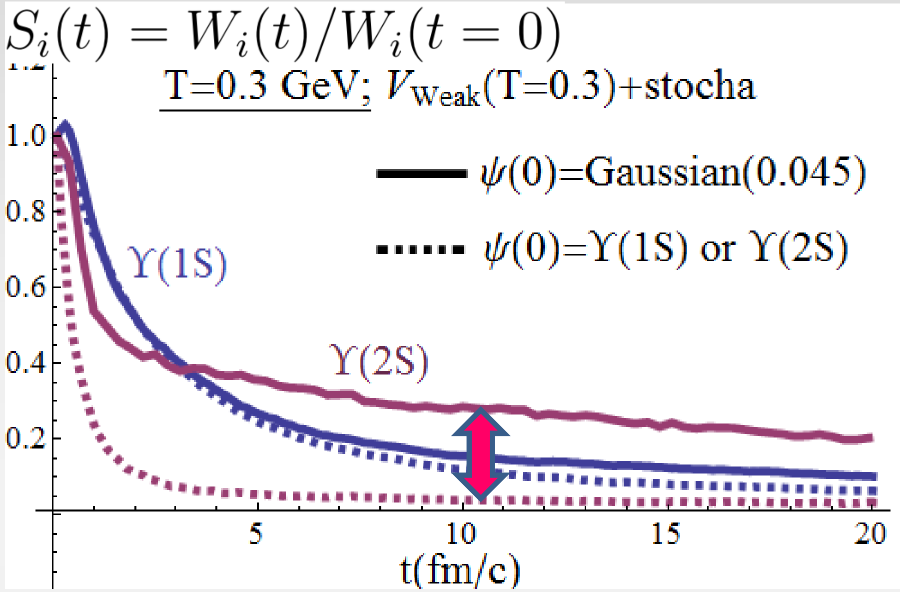
$$S_i(t) = W_i(t)/W_i(t=0)$$

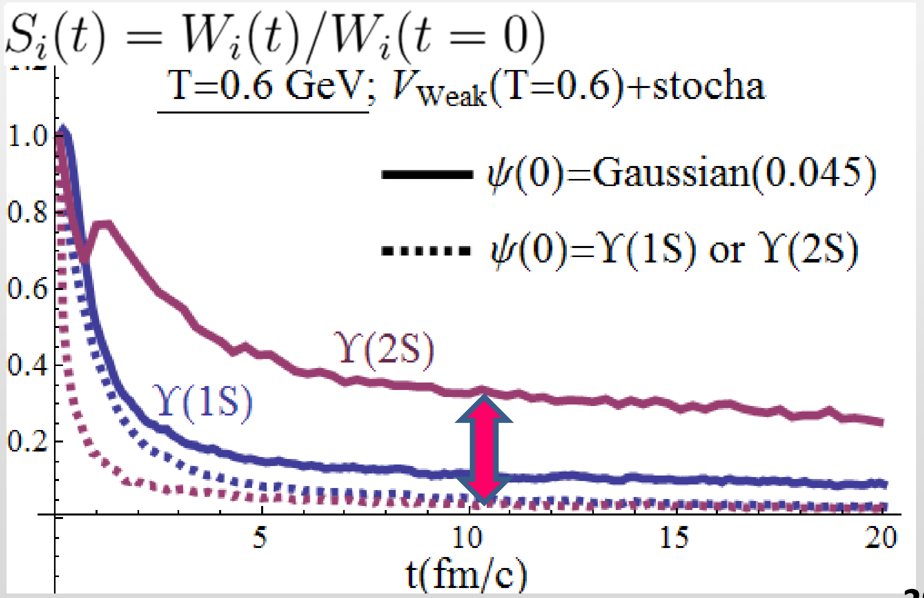
The only « physical » values are at the end of QGP evolution.

$S_i(t)$ at the end of the evolution convoluted with p_T-y spectra in pp collisions => R_{AA}

Survival probability with V(T=cst) + Fstocha







✓ S quite depends on the initial quantum state !

⇒ Kills the assumption of quantum decoherence at t=0

⇒ Need for better knowledge of this state.

Subatech

Initial $Q\bar{Q}$ pair wavefunction ?

The $Q\bar{Q}$ pairs are produced at the very beginning
BUT state formation times are subject to debate
=> we test the two extrem behaviours:

- the $Q\bar{Q}$ pair is fully decoupled into eigenstates:

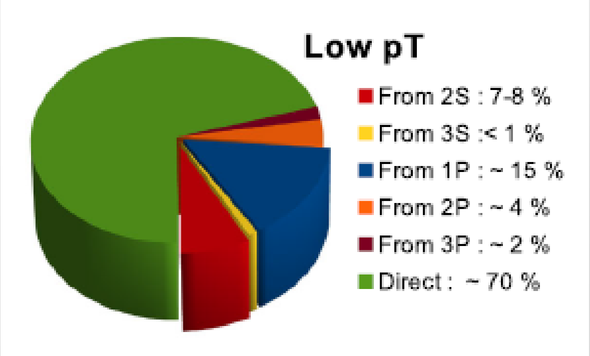
$$\psi_{Q\bar{Q}}(t=0)=\psi_i(T=0)$$

or

- the $Q\bar{Q}$ pair is not decoupled:

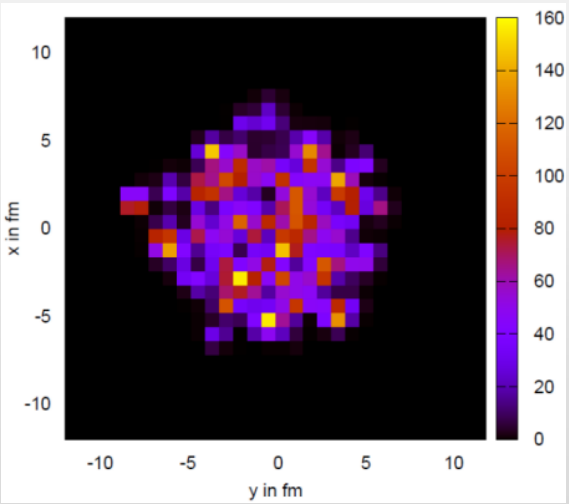
$\psi_{Q\bar{Q}}(t=0)$="a mixture of Gaussian S and P components" tuned to obtain correct feed-downs and production ratios.

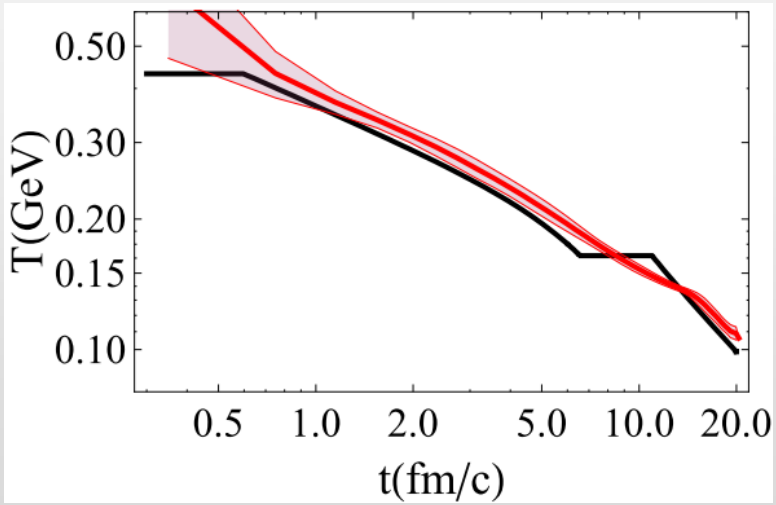
e.g.: contribution to Υ(1S) from feed downs:



Evolution of the QQ pairs on EPOS initial conditions + hydro background (EPOS2)

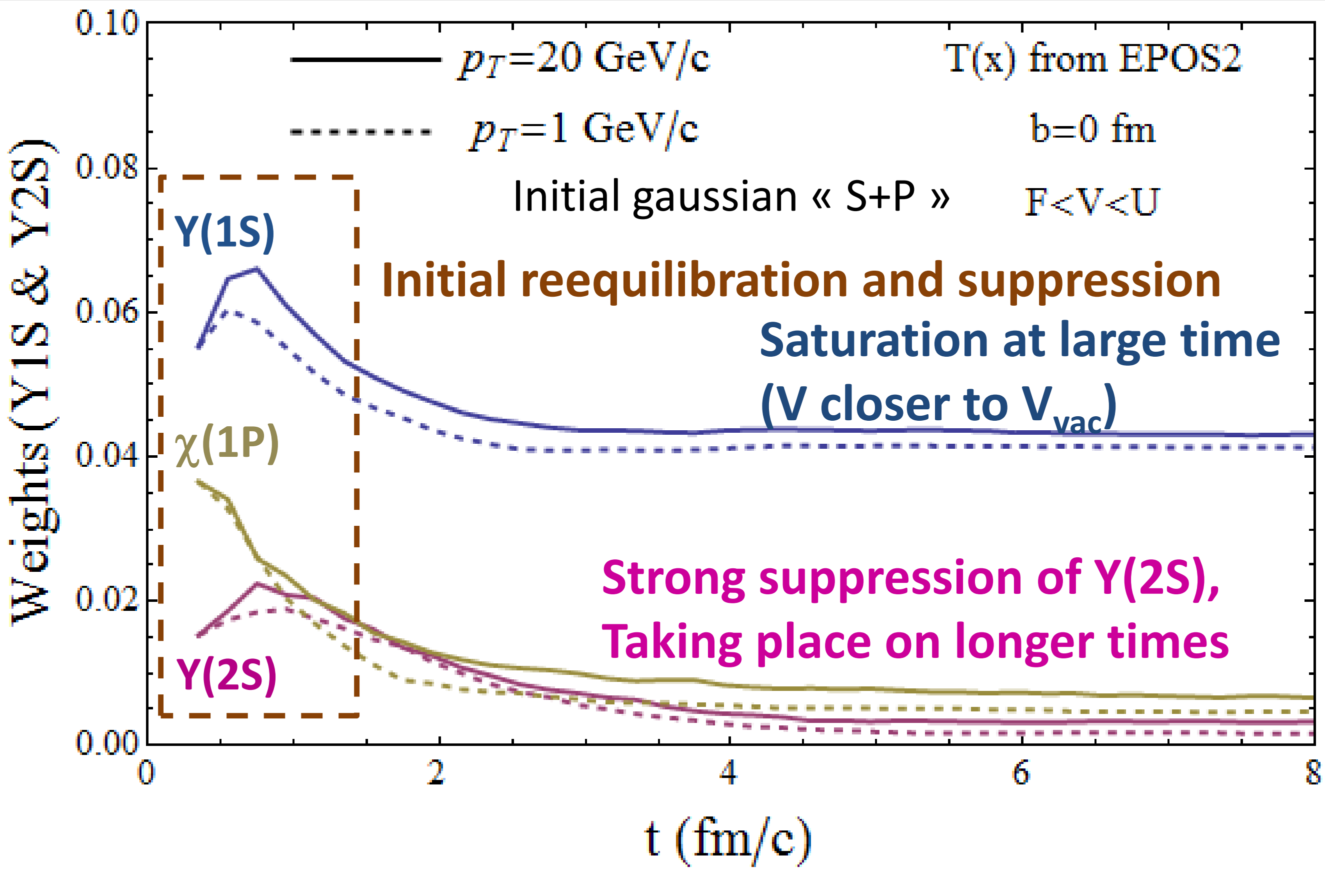
- Very good model for heavy ion collisions with initial fluctuations and ideal 3D hydrodynamics
- $Q\bar{Q}$ pairs initial positions: given by Glauber model
- No Cold Nuclear Matter effects (no shadowing and no hadronic scatterings)
- $Q\bar{Q}$ pair center-of-masse motion: along straight lines with no E_{loss} (assumed to be color singlet)
- Focus on bottomonia for now (CNM and statistical recombination small)





K. Werner, I. Karpenko, T. Pierog, M. Bleicher and K. Mikhailov, Phys. Rev. C 82 (2010) 044904. K. Werner, I. Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, Phys. Rev. C 85 (2012) 064907

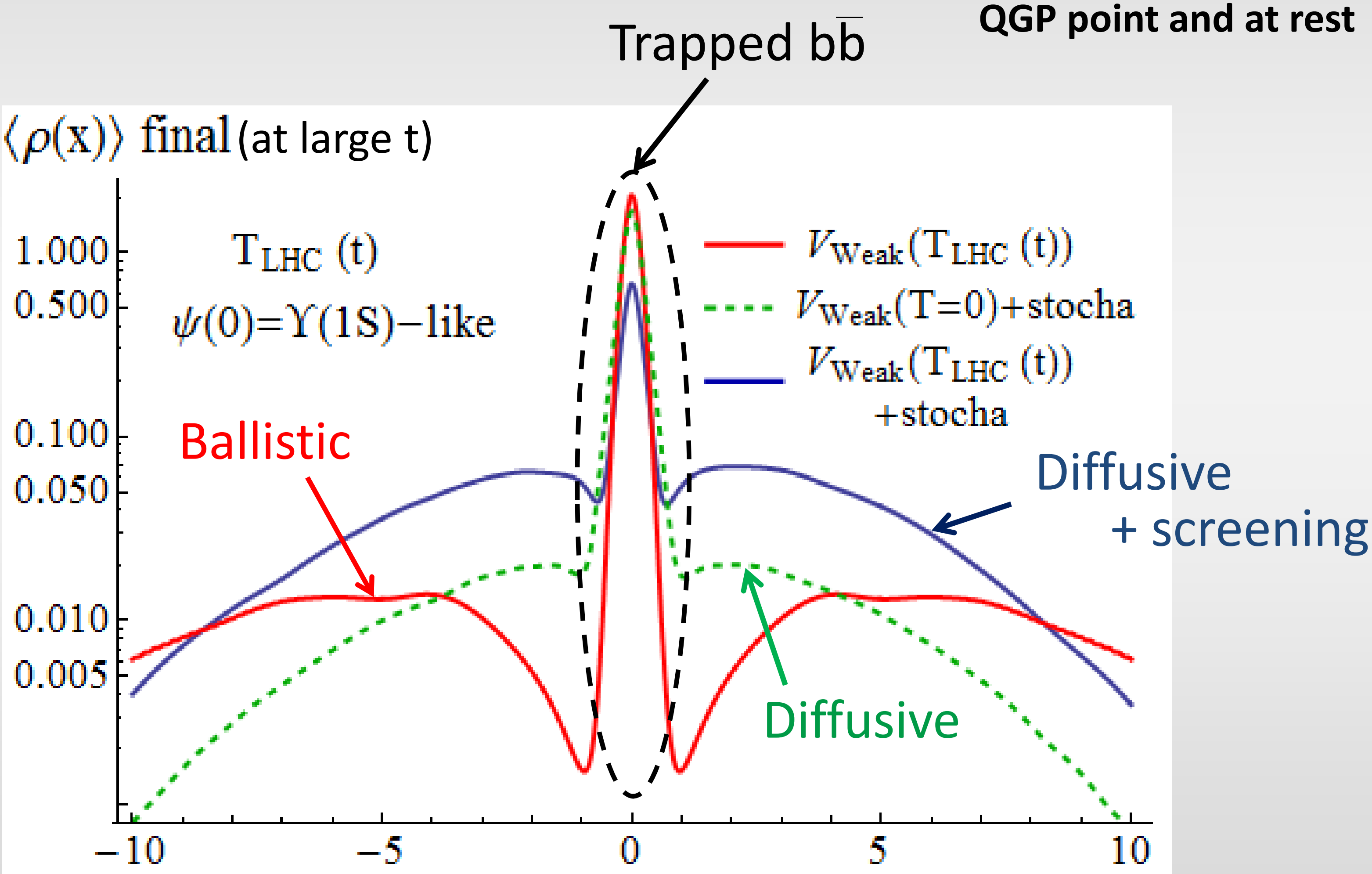
Example of evolution



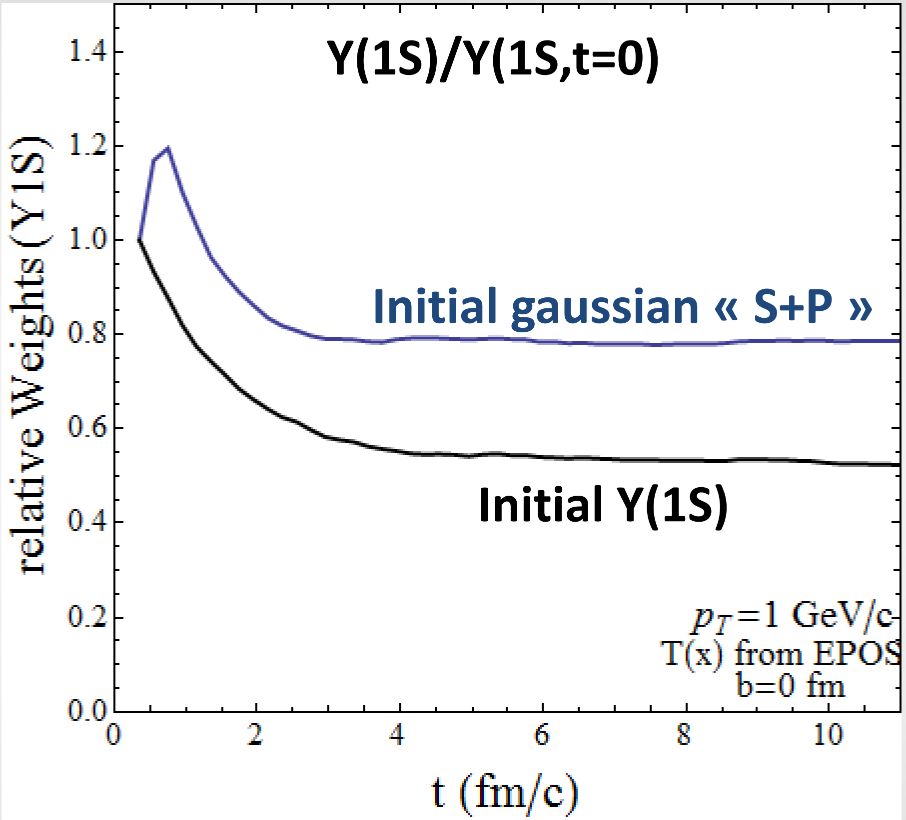
Observations
- **Smooth evolutions (especially for higher excited states)**
- **No strong p_T dependence**
- **Important transitions between bound states**
- **Not everything is about thermal decay widths**

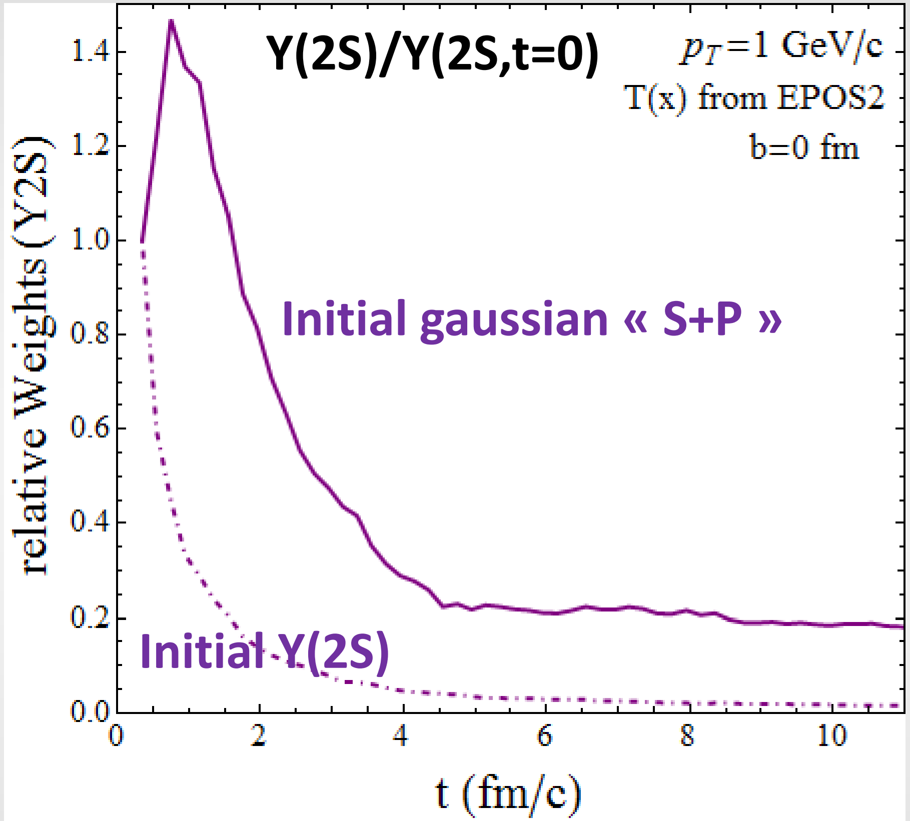
Density with V(TLHC(t,0)) and initial Υ(1S)

Case of b-bar at hottest QGP point and at rest



Influence of initial state



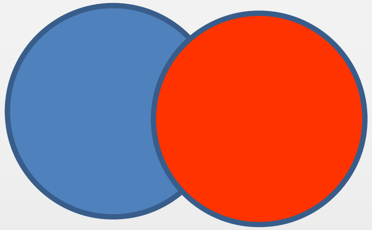


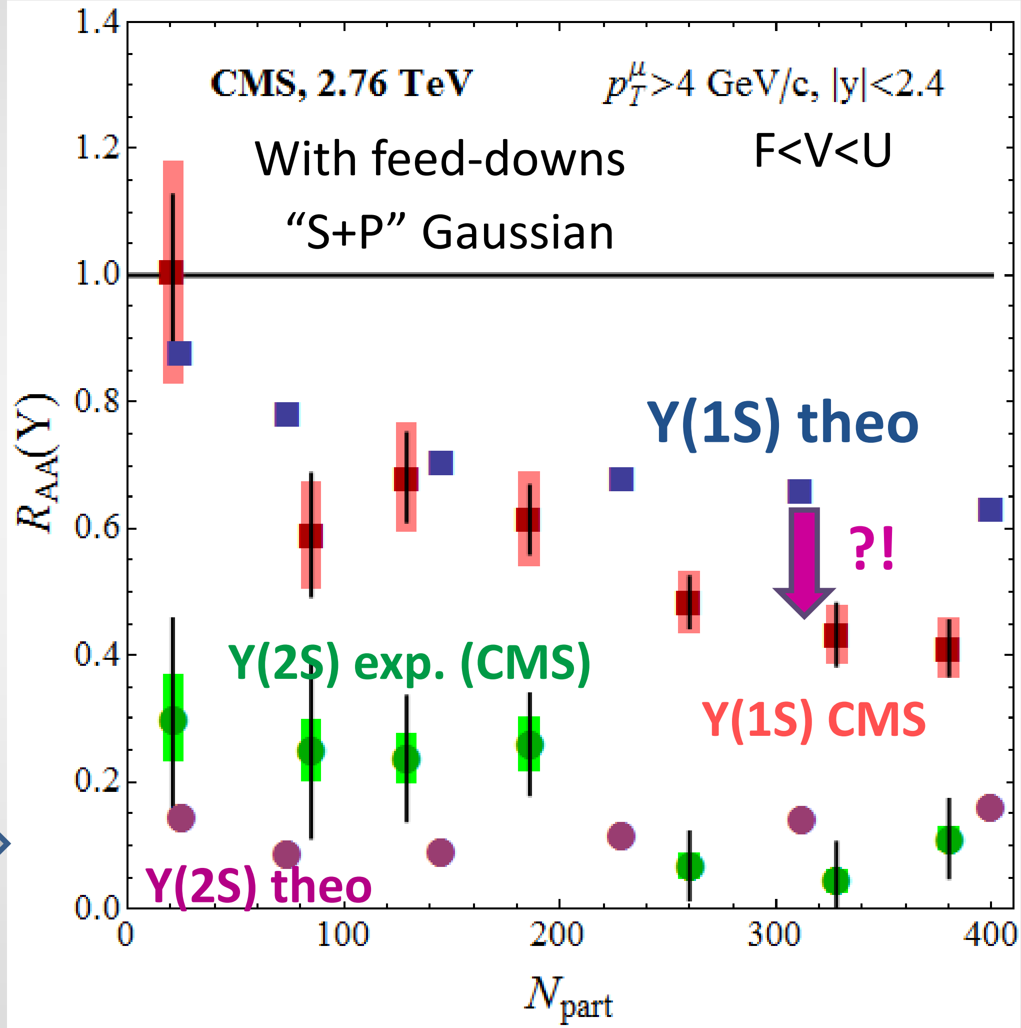
1P component feeds the Y(1S) at small times

Y(2S) found at the end of QGP evolution are mostly the ones regenerated from the 1S & 1P

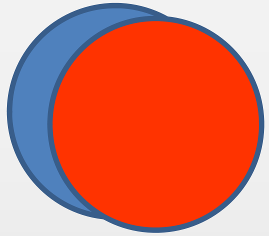
LHC (2.76 TeV): $R_{AA}(N_{part})$

Peripheral Pb-Pb collisions





Nearly overlapping Pb-Pb collisions : hot QGP expected



Y(1S) more and more suppressed for higher "centrality"

P.B. Gossiaux and R. Katz, J.Phys.Conf.Ser. 779 (2017) no.1, 012041

Historical models

Statistical hadronisation

(Braun-Munzinger, Stachel, Andronic, Thews…)

Assume that screening + multiple interactions

=>

All $Q\bar{Q}$ pairs are dissociated
+ Statistical recombination at hadronisation

=> *Quarkonia as thermometer of T_c*

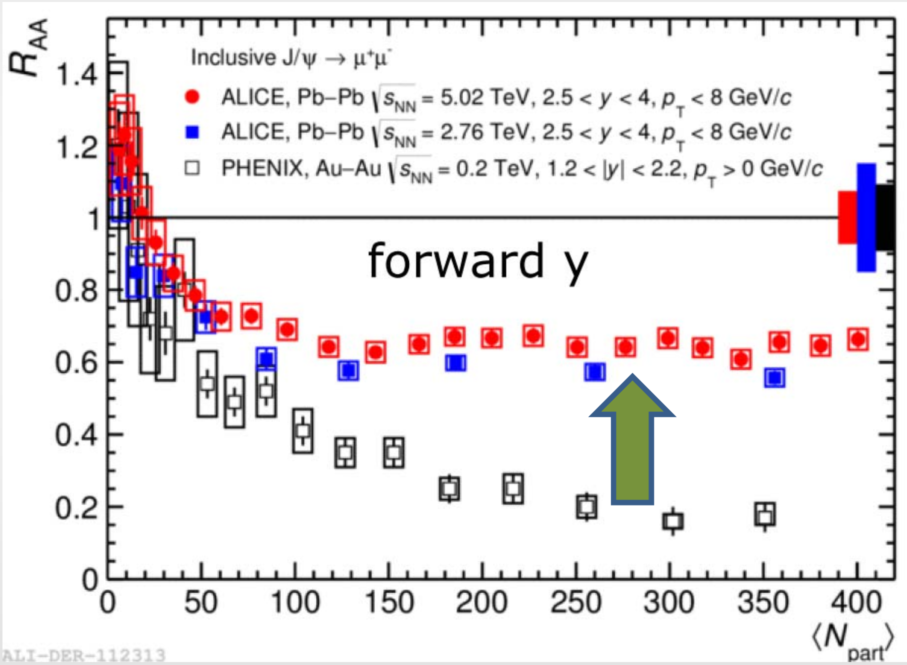
BUT:
- Everything happens at the END in a quasi-stationnary medium
- Not obvious that no tightly bound states survive

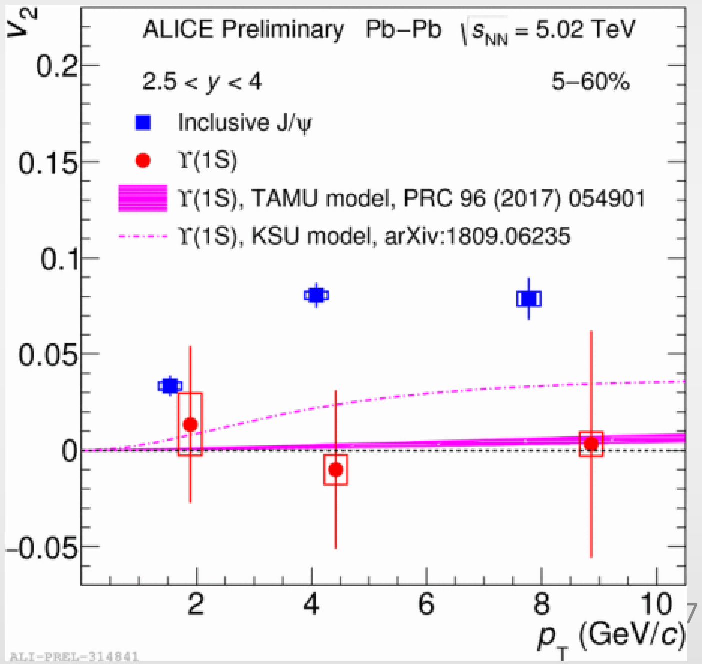
P. Braun-Munzinger and J. Stachel, Nucl. Phys. A 690 (2001) 119126

Looking at recent data

Strong Hints for some charm recombination as:

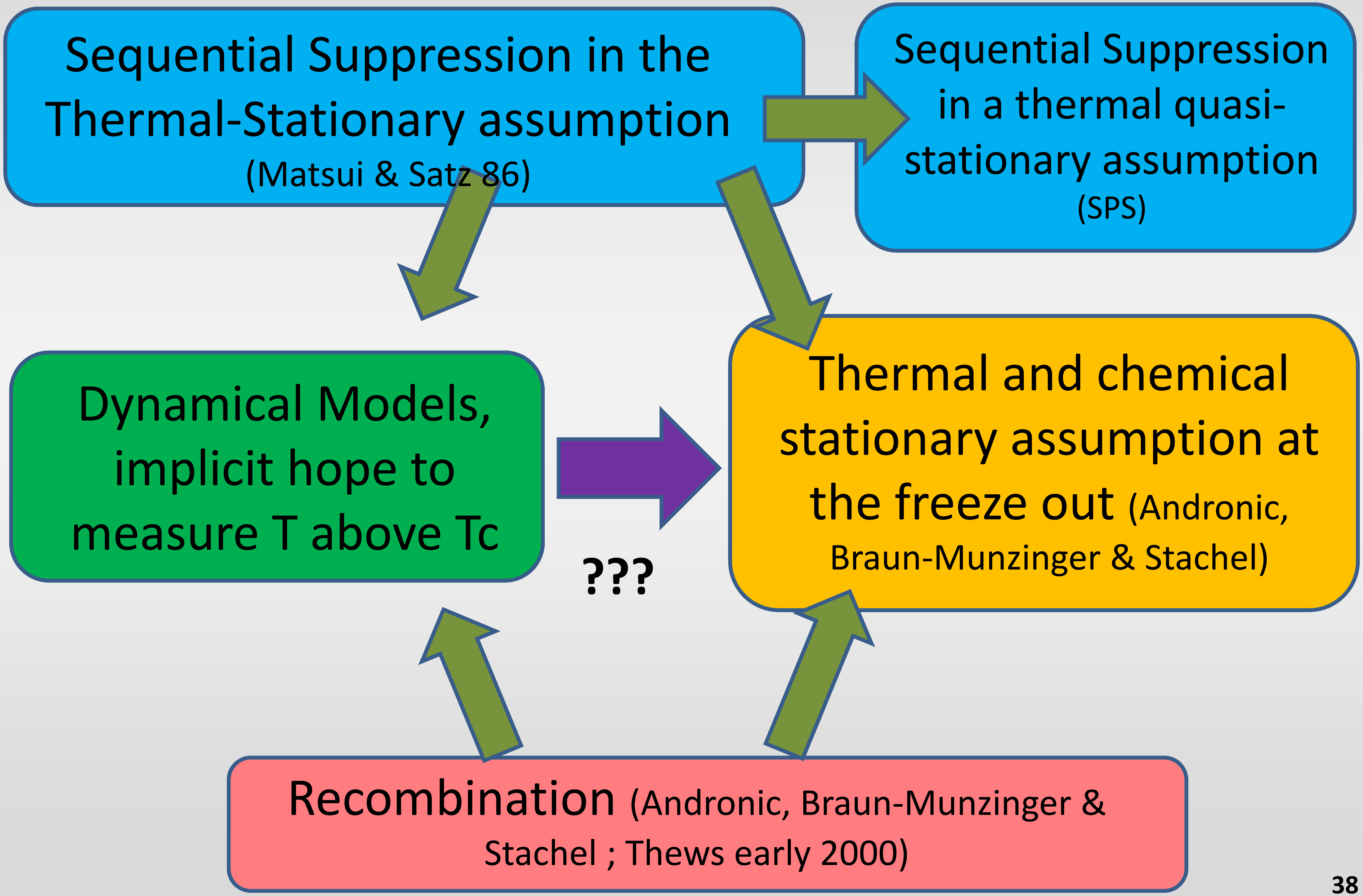
- **Less suppression passing from RHIC -> LHC collider (larger T)**
- **J/ψ benefit from medium (elliptical) flow**





…but not for bottom so far

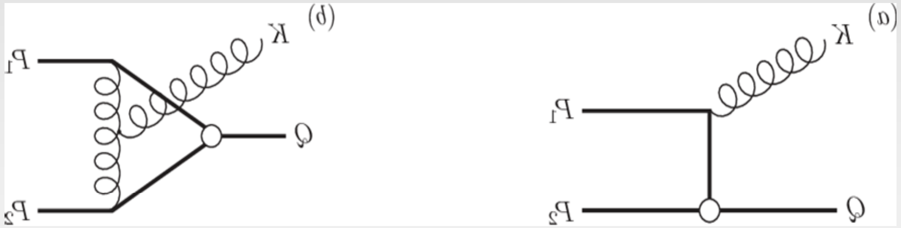
Schematic view



Dealing with « recombination »

Several approaches associated with pretty drastic assumptions

a)



$$Q + \bar{Q} \to \Phi + g$$

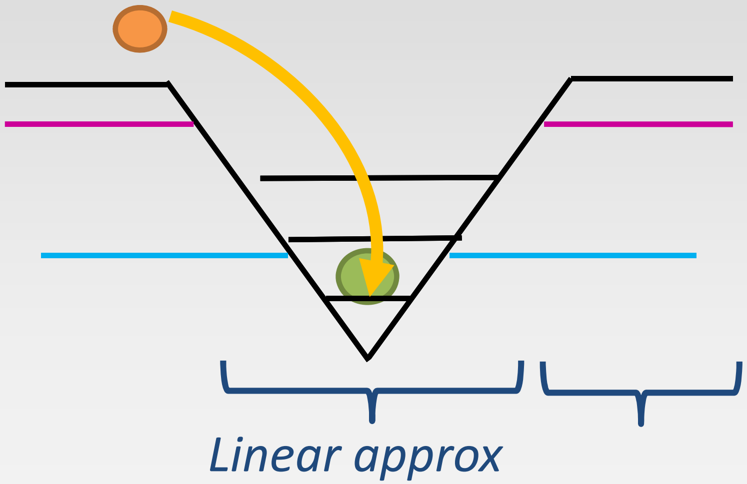
Recombination cross section σ $\quad \frac{dn_\Phi}{dt} = \langle \sigma n_Q n_{\bar{Q}} v_{\rm rel} \rangle$ (detailed balance)

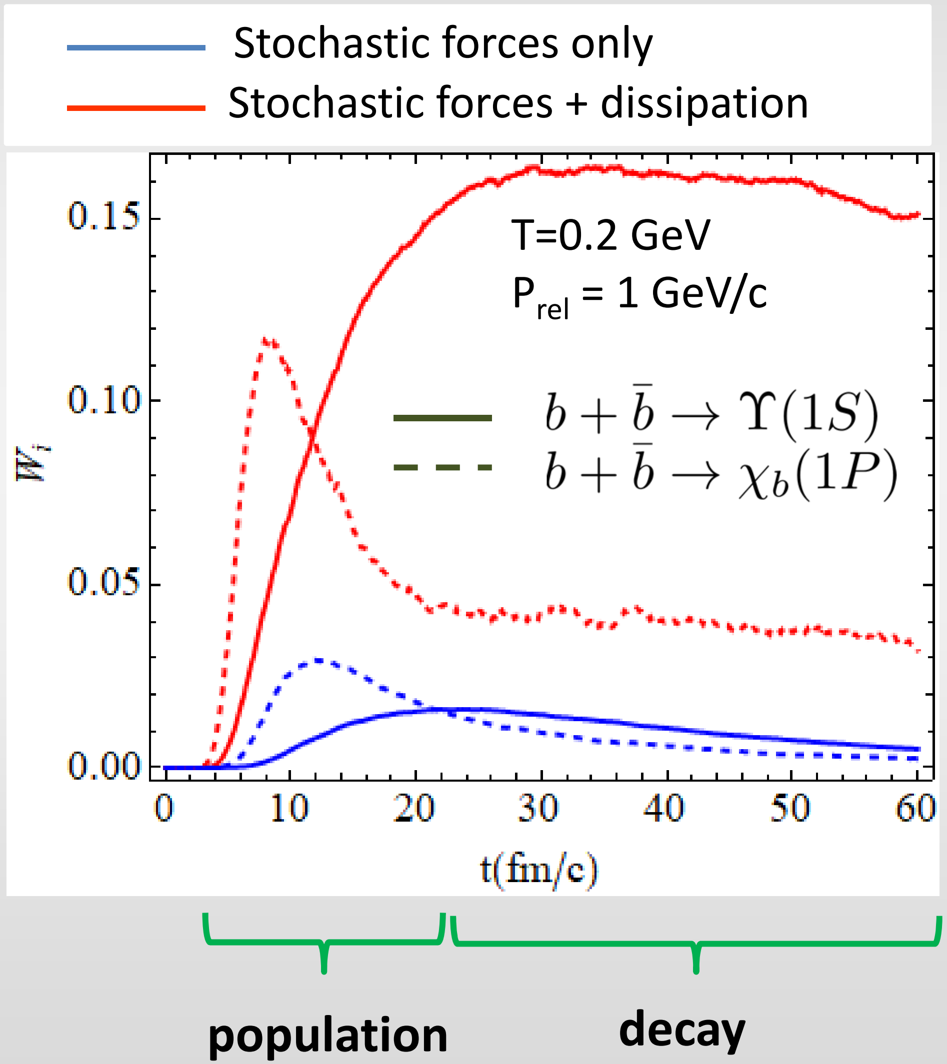
b) Instantaneous coalescence: $n_\Phi = |\langle \Phi | Q\bar{Q} \rangle|^2$ at freeze out (but no Qqbar dynamics)

$$n_\Phi = |\langle \Phi | Q\bar{Q} \rangle|^2$$

c) Thermalisation of Q and Qbar in local phase space, then quarkonia production according to statistical weights

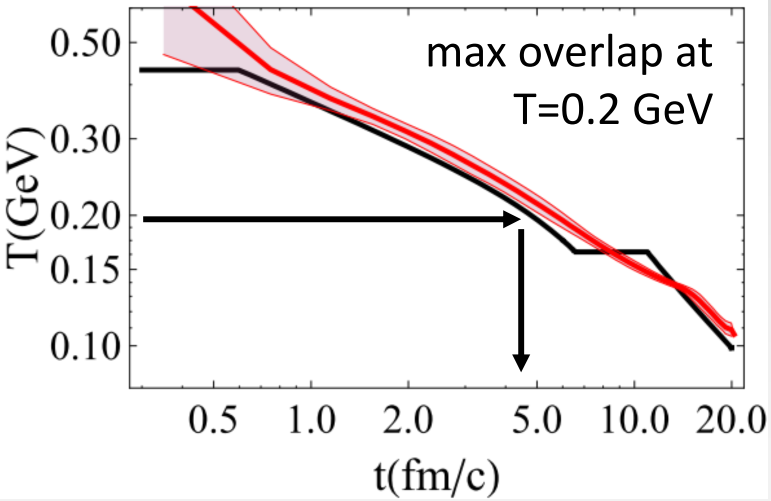
Results with SLE in a stationnary medium

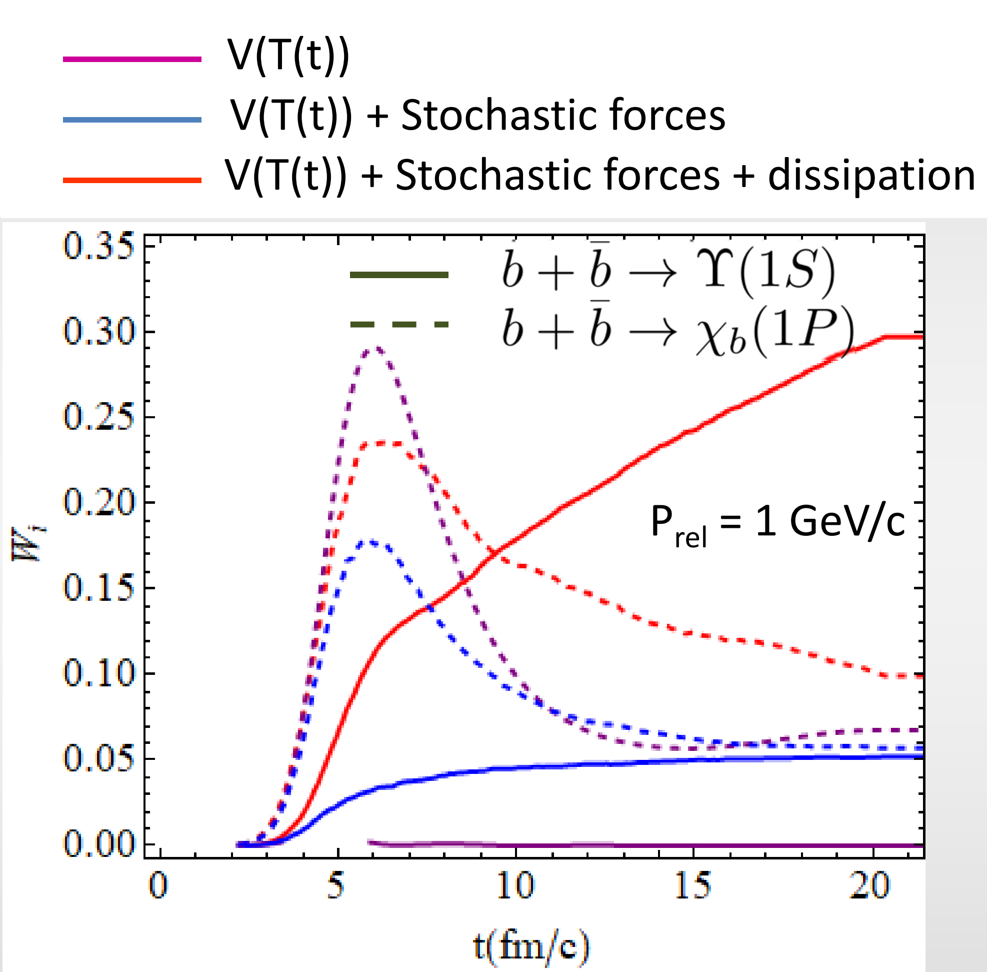




- ✓ some bound state creation through stochastic forces
- ✓ most substantial effects from dissipation
- ✓ relative weights after population compatible Boltzmann probability exp(-E_n/T)
- ✓ … but needs a long time.

Results with SLE in *evolving* medium



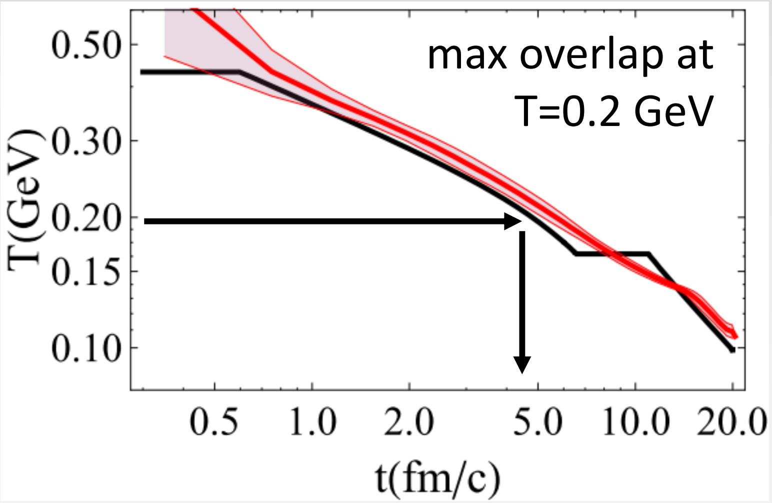


✓ Substantial recombination probability at the end of the evolution provided one includes dissipation

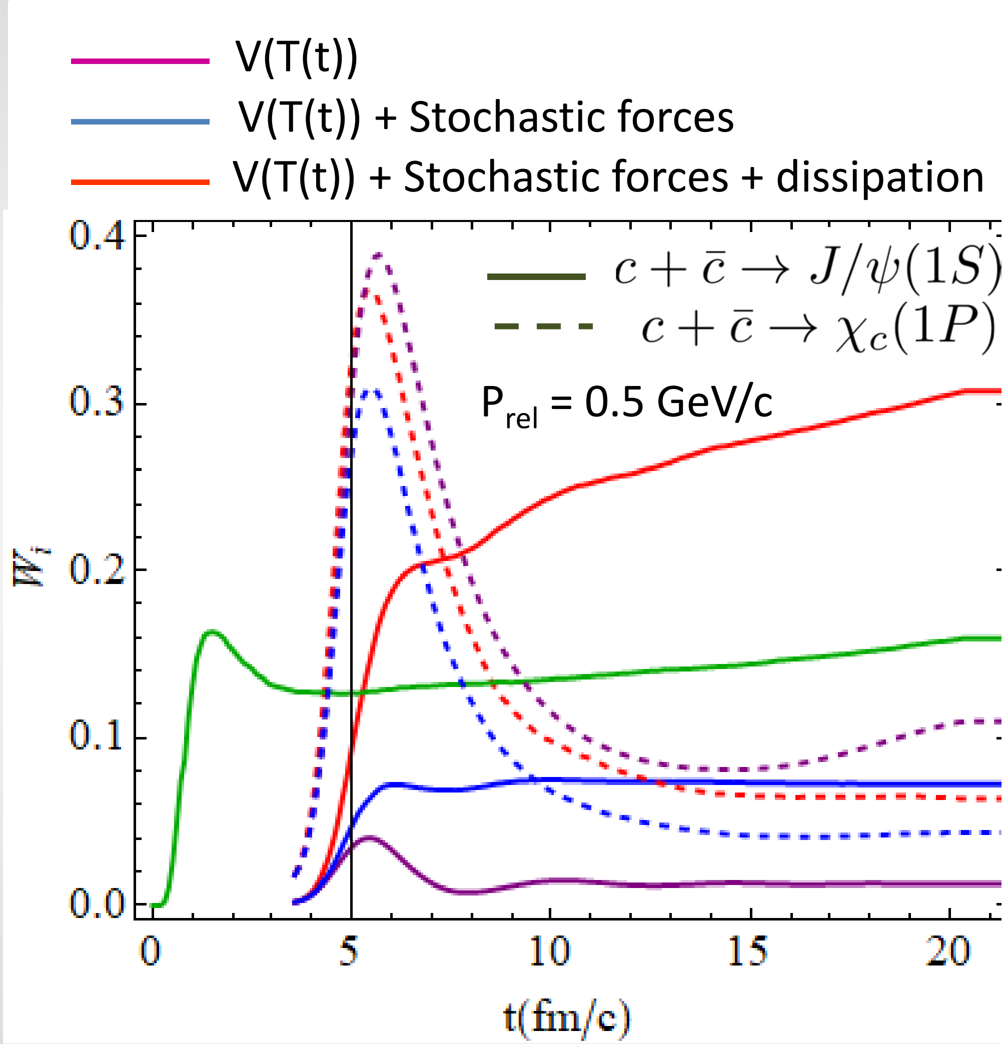
✓ Yet, no instantaneous thermalisation.

✓ Recombination probability tend to decrease for larger p_{rel}

Results with SLE in *evolving* medium



✓ Similar pattern seen for c+cbar -> charmonia family



Conclusion

These past years:
Long and tricky road to apply the Open Quantum System framework to improve the description of quarkonia physics in the QGP, with steady progress

Today:
Novelty: quantum recombination

Close future:
Good hope to rely on « event generators » based on OQS, while still a lot of unknowns (Q-QGP interaction, radiation in QGP,…)

Thank you !

Visual summary