pNRQCD for the study of nonequilibrium evolution of quarkonium in a medium

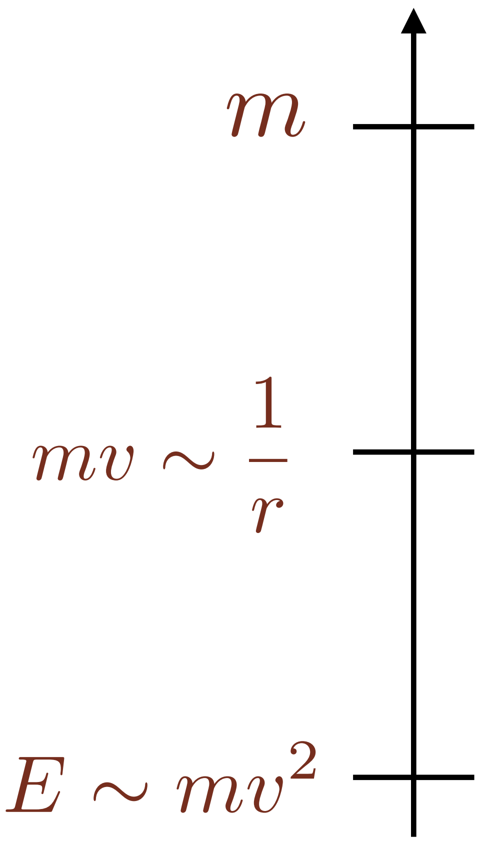
N. Brambilla, M. Escobedo

We will present results for inelastic rates, potentials and evolution density master equations in this same framework based on pNRQCD +open quantum system+ lattice

Results obtained in collaboration with :
M. Escobedo, A. Vairo, J. Soto (van der Griend) N.B. (master equations);
A. Vairo, M. Escobedo, J. Ghiglieri, P. Petreczky, M. Berwein, J. Soto, N. B. (equilibrium properties) ;
J. Weber , P. Petreczky, V. Leino, A. Vairo, N.B. (lattice inside theTUMQCD collaboration created to work at the interface between lattice and EFTs)

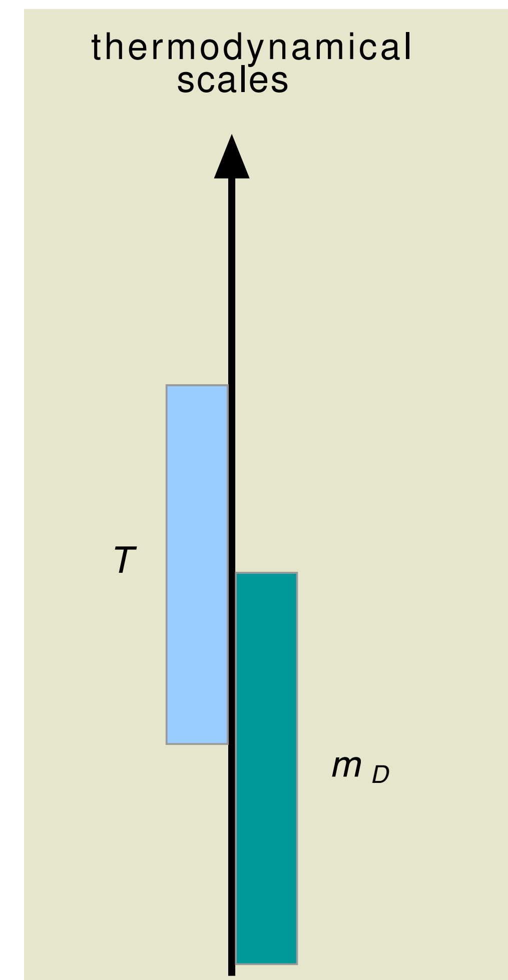
Framework: take advantage of the scales of the physical problem using non relativistic effective field theories (pNRQCD) and hard thermal loop (HTL)—> allows us to integrate out scales and expand in small parameters that are ratio of scales

Quarkonium non relativistic scales in QCD



$$m \gg \Lambda_{QCD}$$

Medium



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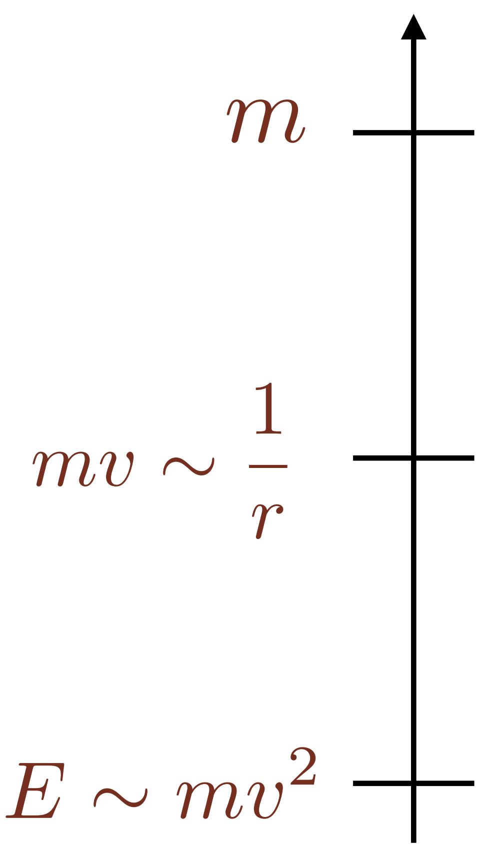

integrating out m gives NRQCD

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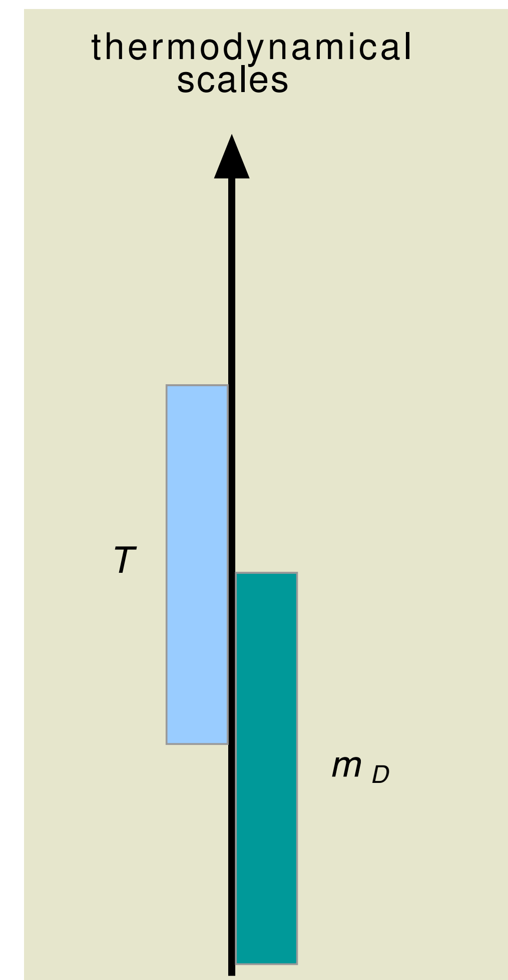

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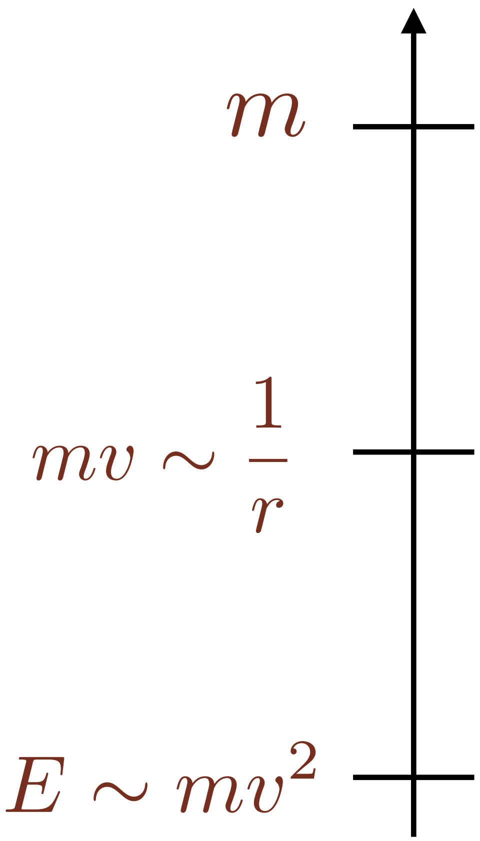
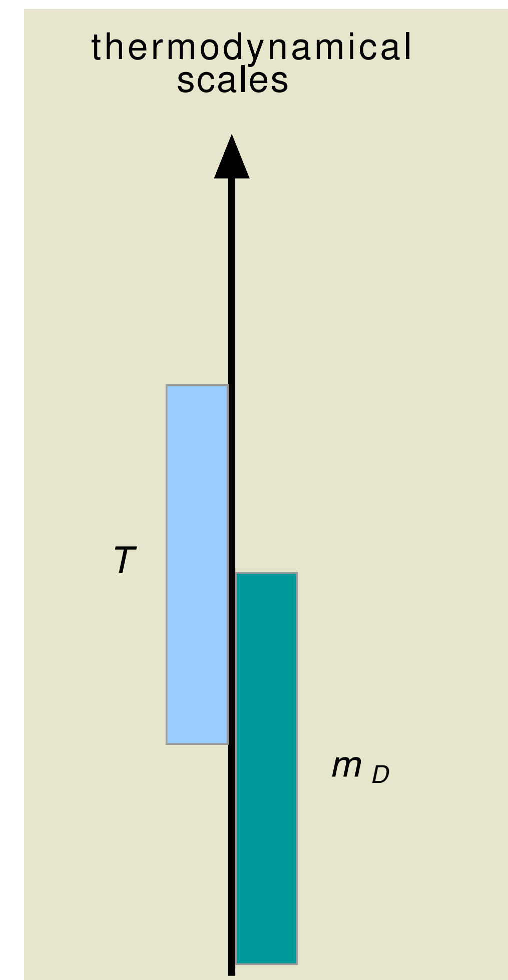


integrating out m gives NRQCD

integrating out m gives pNRQCD and the potentials that can be perturbative if $r^{-1} \gg \Lambda_{QCD}$ or nonperturbative $r^{-1} \sim \Lambda_{QCD}$

$m \gg \Lambda_{QCD}$

Medium



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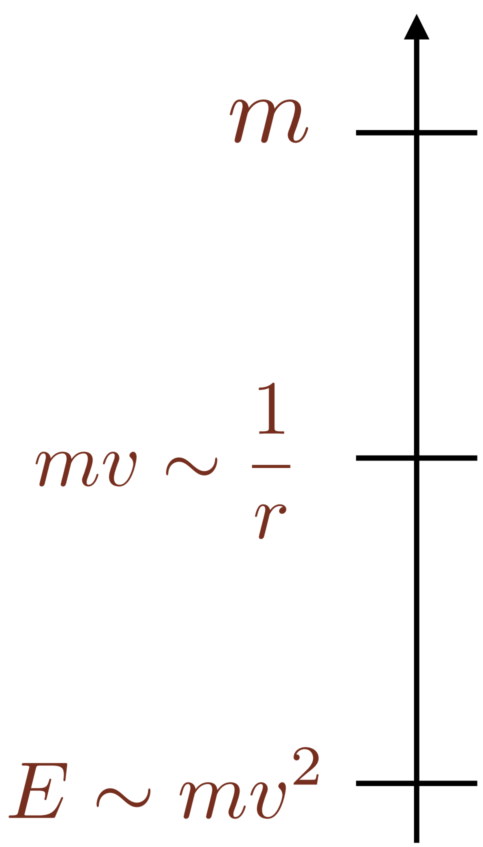

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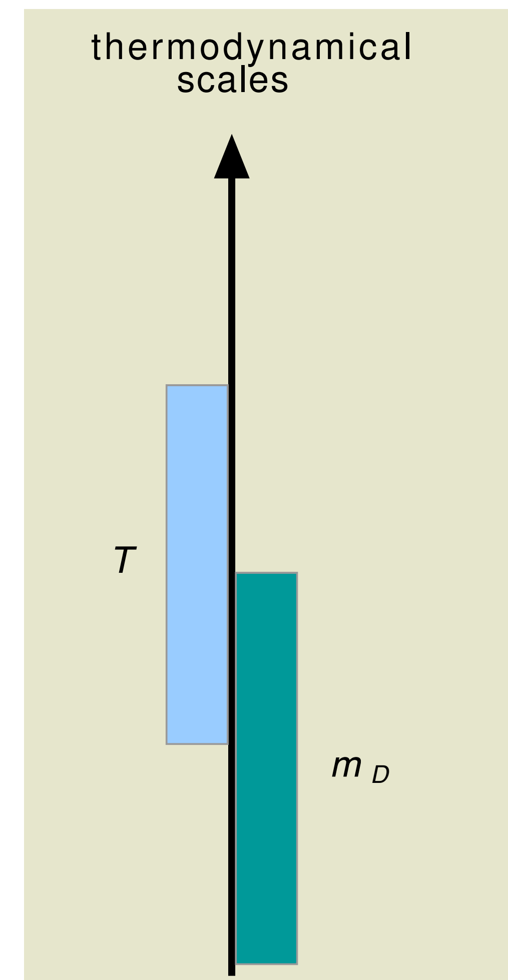

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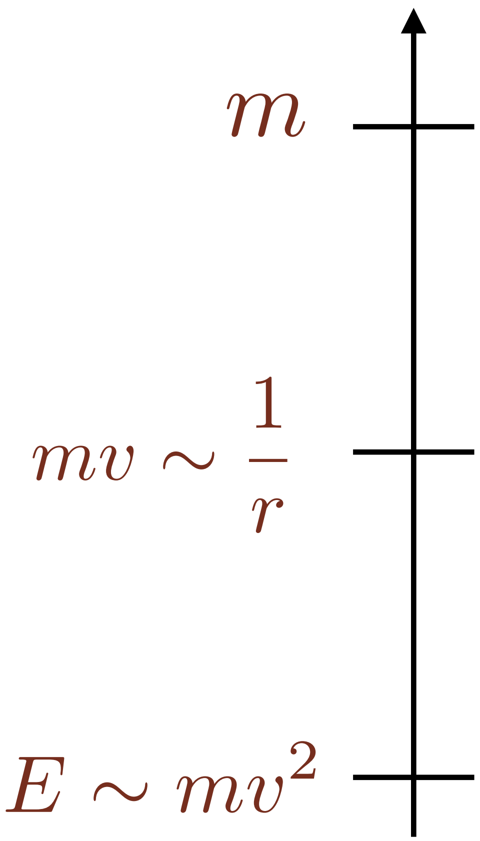

$$m \gg \Lambda_{QCD}$$

depending on the relation between T and mv, integrating out can give T contributions to the potential or to the energy

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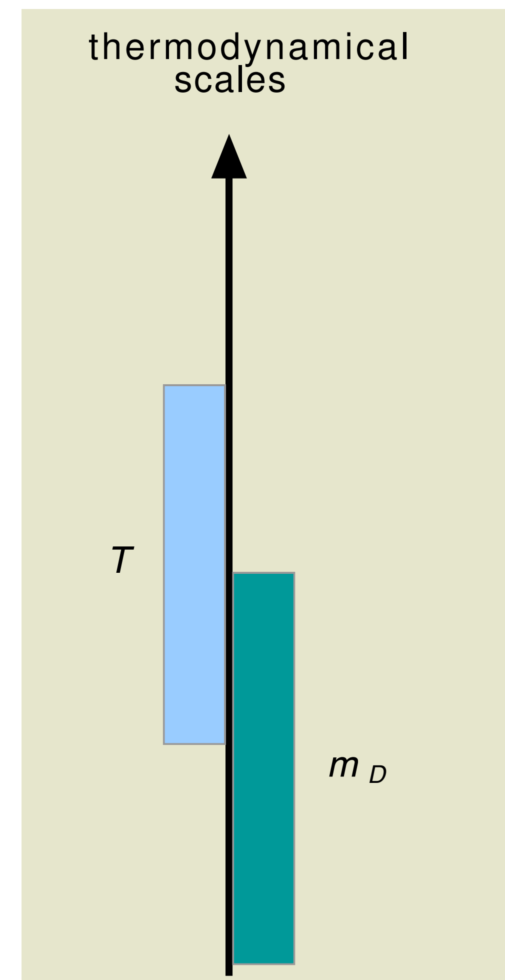

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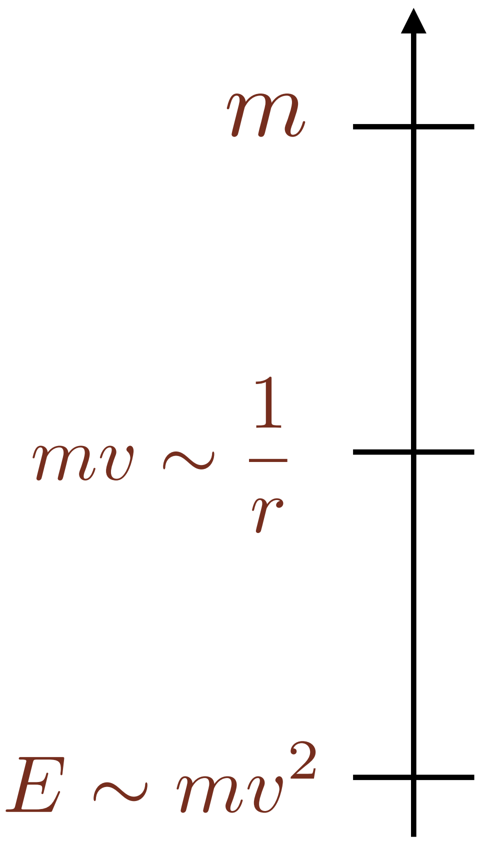

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imaginary parts in T are related to the inelastic rates of singlet to octet transitions

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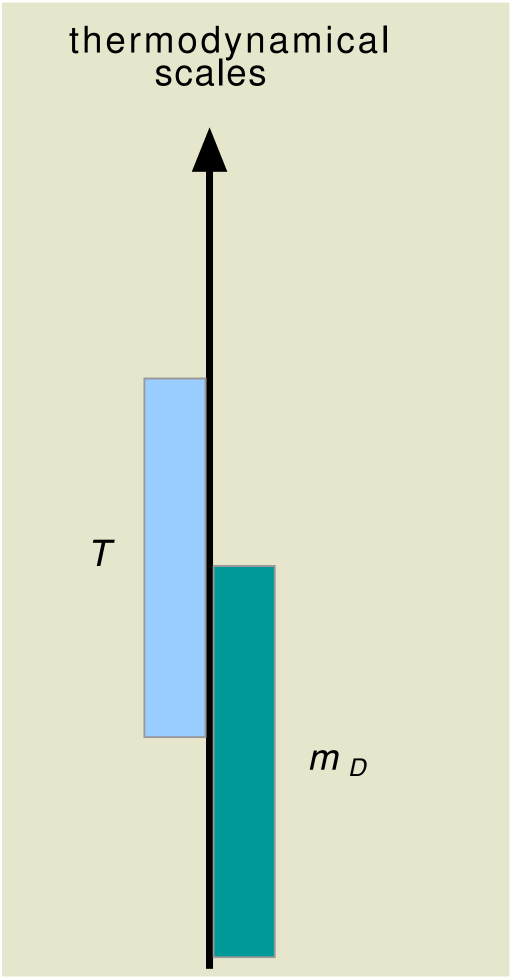

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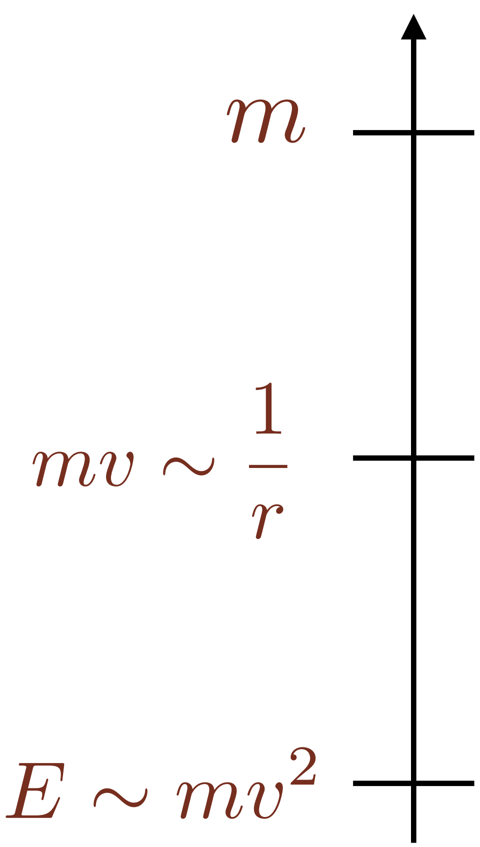

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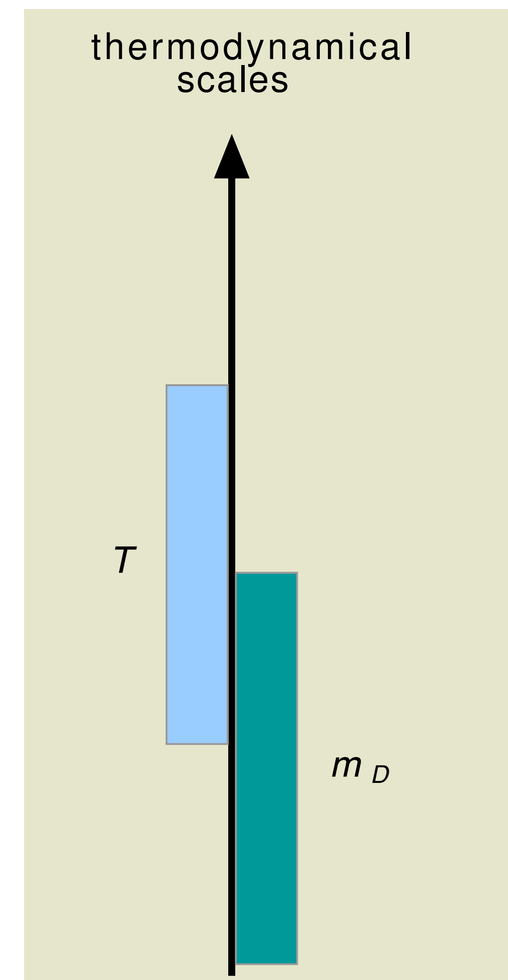
imaginary parts in T are related to the inelastic rates of singlet to octet transitions

large imaginary part call for a density matrix evolution treatment

Medium



$m \gg \Lambda_{QCD}$

$m \gg T$

Features of the pNRQCD approach:

- It is derived from QCD
- It has color singlet and color octet
- It is fully quantum
- It conserves the number of heavy quarks
- We work in real time
- Double counting is avoided
- It explores different regimes depending on the quarkonium system and the assumed scales hierarchy

- A particular interesting situation arises for $r^{-1} \gg T$ (1S or 2S bottomonium) in this case we can explore a nonperturbative QGP characterised by two transport coefficients field theoretically defined as the correlators of two chromoelectric fields the quark momentum diffusion coefficient kappa and its imaginary counterpart gamma

Inelastic rates

- In thermal equilibrium, we studied the cases from $E \sim T$ up to $m \gg T \gg \frac{1}{r} \sim m_D$.

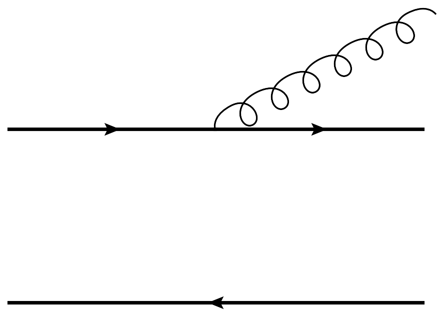
Two distinct dissociation mechanisms may be identified at leading order:

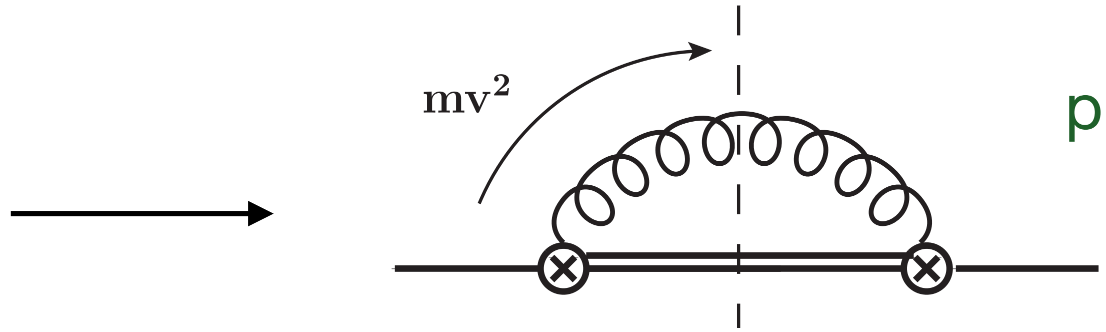
- gluodissociation,
  which is the dominant mechanism for $Mv^2 \gg m_D$;
- dissociation by inelastic parton scattering,
  which is the dominant mechanism for $Mv^2 \ll m_D$.

Beyond leading order the two mechanisms are intertwined and distinguishing between them becomes unphysical, whereas the physical quantity is the total decay width.

Gluodissociation is the dissociation of quarkonium by absorption of a gluon from the medium.

QCD





pNRQCD

- The exchanged gluon is lightlike or timelike.
- The process happens when the gluon has an energy of order Mv^2.

Gluodissociation

For a quarkonium at rest with respect to the medium, the width has the form

$$\Gamma_{nl} = \int_{q_{\min}} \frac{d^3q}{(2\pi)^3}\, n_{\rm B}(q)\, \sigma^{nl}_{\rm gluo}(q)\,.$$

- $\sigma^{nl}_{\rm gluo}$ is the in-vacuum cross section $(Q\overline{Q})_{nl} + g \to Q + \overline{Q}$.
- Gluodissociation is also known as singlet-to-octet break up.

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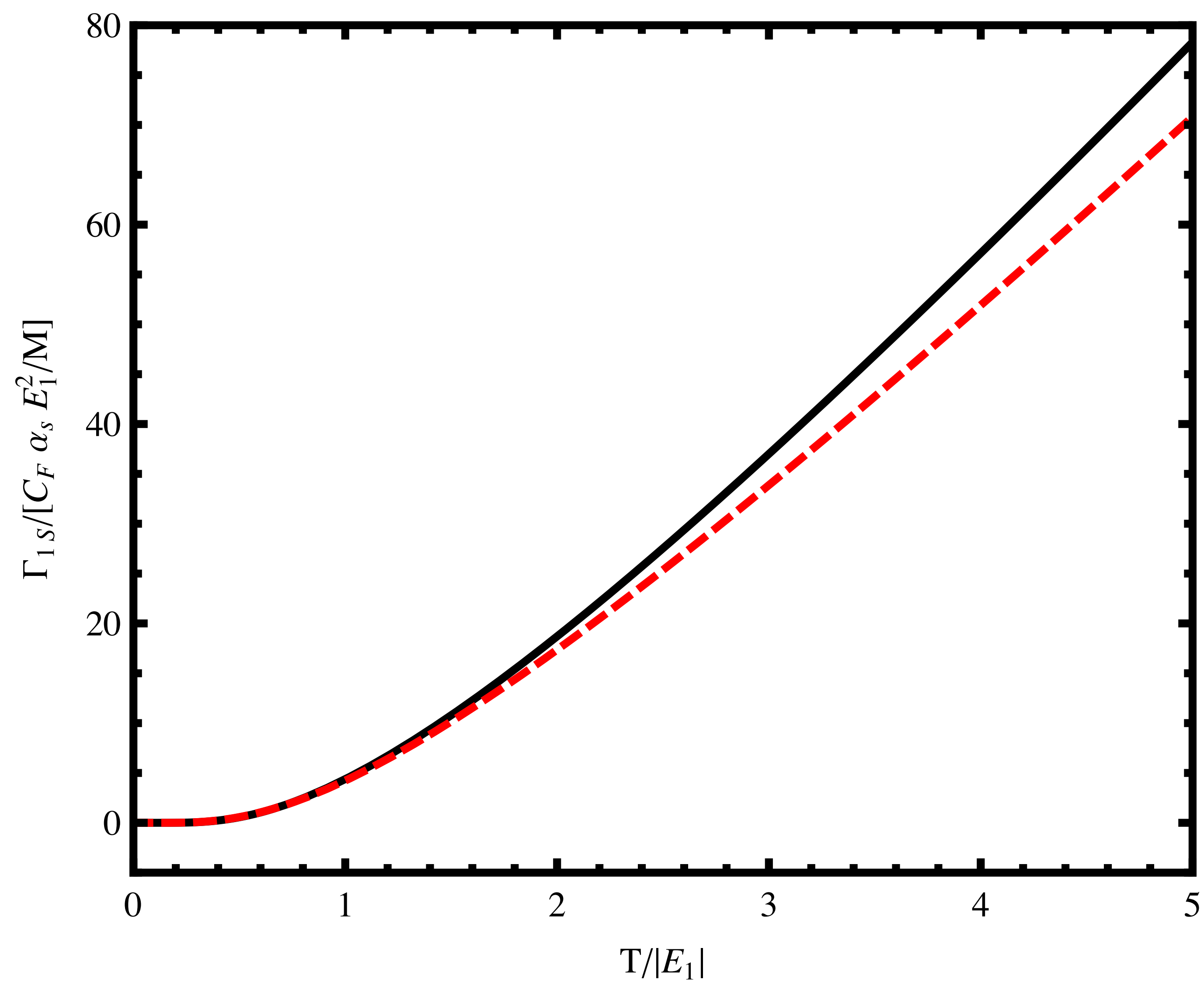
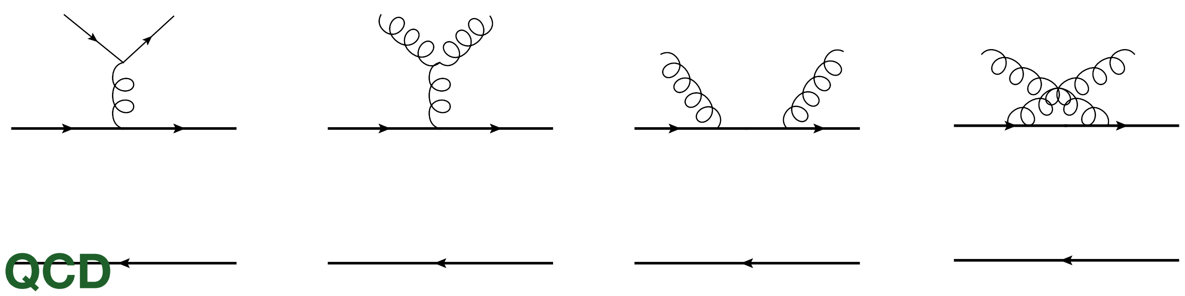
gluodissociation width
for a Coulombic 1S state
as a function of T

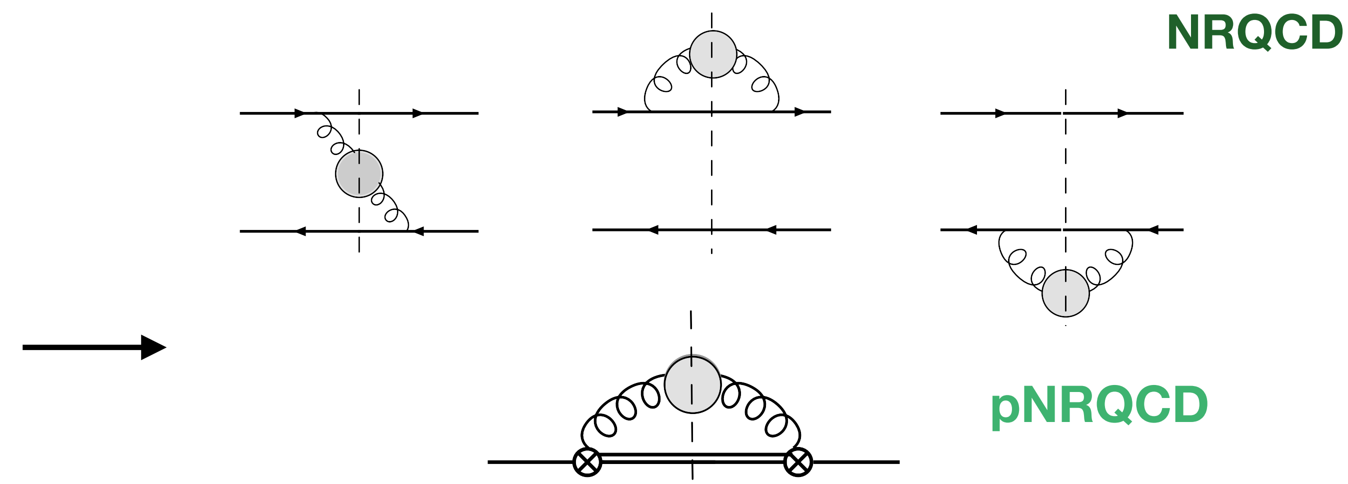
in red the Bhanot Peskin
large N_c approximation
which neglects the rescattering
of QQbar in octet configuration



Dissociation by inelastic parton scattering

Dissociation by inelastic parton scattering is the dissociation of quarkonium by scattering with gluons and light-quarks in the medium.





- The exchanged gluon is spacelike.
- External thermal gluons are transverse.
- In the NRQCD power counting, each external transverse gluon is suppressed by T/M.

- Dissociation by inelastic parton scattering is also known as Landau damping.

For a quarkonium at rest with respect to the medium, the thermal width has the form

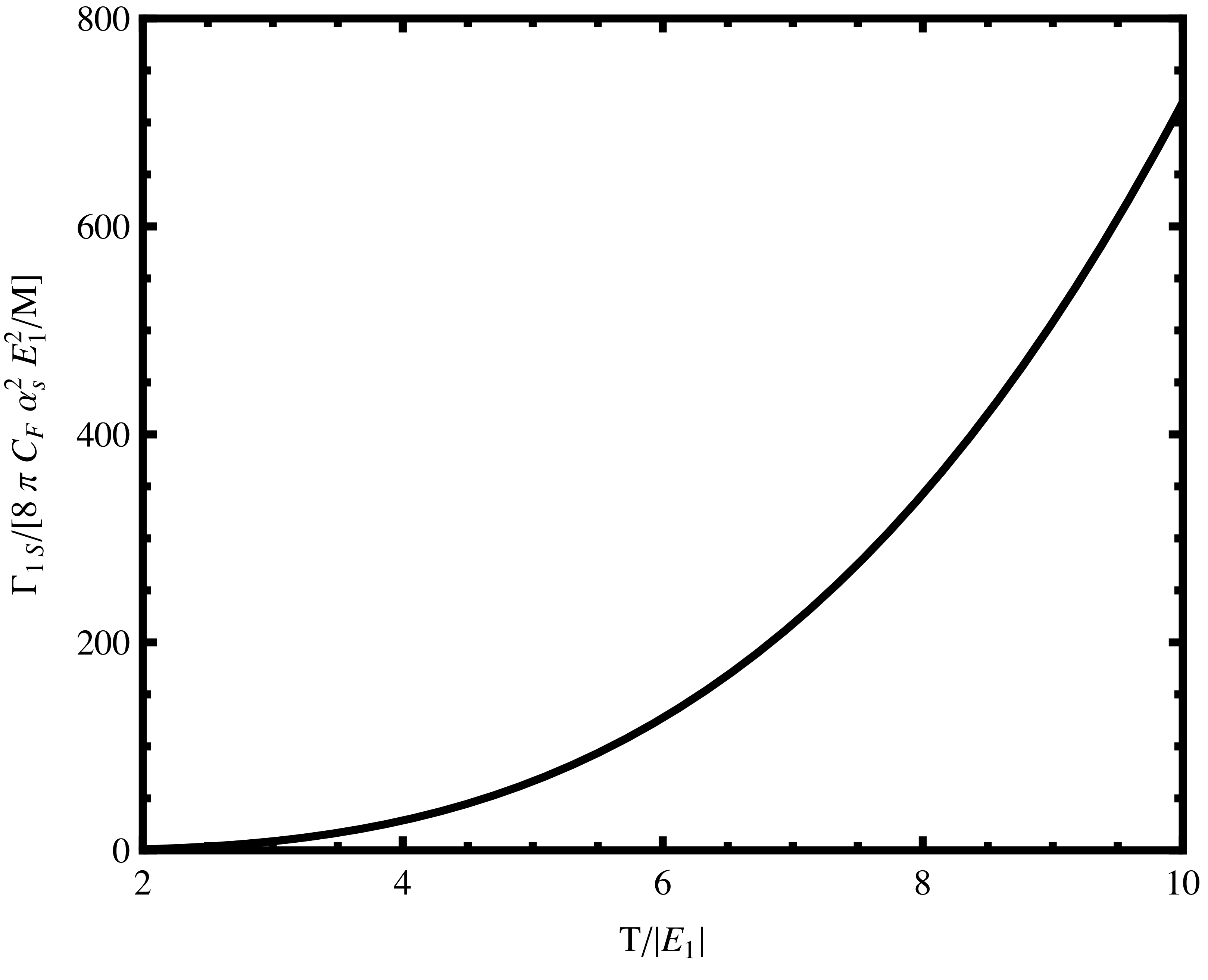
$$\Gamma_{nl} = \sum_p \int_{q_{\min}} \frac{d^3q}{(2\pi)^3}\, f_p(q)\, [1 \pm f_p(q)]\, \sigma_p^{nl}(q)$$

where the sum runs over the different incoming light partons and $f_q = n_{\rm B}$ or $f_q = n_{\rm F}$.

- σ_p^{nl} is the in-medium cross section $(Q\overline{Q})_{nl} + p \to Q + \overline{Q} + p$.
- The formula differs from the gluodissociation formula.

Dissociation by inelastic parton scattering

parton dissociation width
for a Coulombic 1S state
as a function of T



$m_D a_0 = 0.5$

$|E_1|/m_D = 0.5$

$n_f = 3$

Brambilla Escobedo Ghiglieri Vairo JHEP 05 (2013) 130 Vairo EPJ Web Conf 71 (2014) 00135

Decay rate in a quantum evolution

A master equation rules the evolution of the density matrix. In the case $\frac{1}{r} \gg T \gg E$ we obtain a master equation of the Lindblad type

$$\partial_t \rho = -i\,[H, \rho] + \sum_i \left(C_i \rho C_i^\dagger - \frac{1}{2} \left\{ C_i^\dagger C_i, \rho \right\} \right)$$

C being the collapse operators

we study the singlet and octet density matrix evolution

The rate of decay of a singlet into an octet would be

$$\Gamma(T) = \frac{Tr(\sum_i C_i^\dagger C_i \rho_s)}{Tr(\rho_s)},$$

where ρ_s is the projection of the reduced density matrix to the singlet subspace.

The $\frac{1}{r} \gg T, m_D \gg E$ regime

Brambilla, M.A.E., Soto and Vairo (2017-2018)

$$\partial_t \rho = -i[H(\gamma), \rho] + \sum_k \left(C_k(\kappa) \rho C_k^\dagger(\kappa) - \frac{1}{2}\{C_k^\dagger(\kappa) C_k(\kappa), \rho\} \right)$$

The nonperturbative QGP is characterised by two transport coefficients that have a field theoretical definition and QCD equilibrium averages

$$\kappa = \frac{g^2}{6\, N_c} \mathrm{Re} \int_{-\infty}^{+\infty} ds \, \langle \mathrm{T}\, E^{a,i}(s, \mathbf{0}) E^{a,i}(0, \mathbf{0}) \rangle$$

is the heavy quark diffusion coefficient

$$\gamma = \frac{g^2}{6\, N_c} \mathrm{Im} \int_{-\infty}^{+\infty} ds \, \langle \mathrm{T}\, E^{a,i}(s, \mathbf{0}) E^{a,i}(0, \mathbf{0}) \rangle$$

kappa is known from quenched lattice simulations, gamma is known in perturbation theory

We could extract kappa and gamma values from unquenched data on quarkonium and width in a medium —> see talk tomorrow

N.B., M. Escobedo, A. Vairo, P. Vander Griend Phys.Rev. D100 (2019) 054025

The $\frac{1}{r} \gg T, m_D \gg E$ regime

The rate in this regime is

$$\Gamma(T) = \frac{\kappa(T)\, Tr(r^2 \rho_s)}{Tr(\rho_s)}$$

it is proportional to the heavy diffusion coefficient

in cases in which the system is exactly in a 1S or 2S state we have

$$\begin{aligned} \Gamma_{1S} &= 3 a_0^2 \kappa\,, \\ \Gamma_{2S} &= 42 a_0^2 \kappa\,, \end{aligned}$$

where a_0 is the Bohr radius.

Temperature dependence of the rate

- In the case $\frac{1}{r} \gg T, m_D \gg E$, the temperature dependence of the rate is given by that of κ.
- In the lattice (also in perturbation theory) the ratio $\frac{\kappa}{T^3}$ has a mild modification with the temperature.
- Preliminary lattice results indicate that this ratio decreases when the temperature increases.

see TUMQCD results on kappa presented tomorrow by Peter