Quarkonium at Finite Temperature

Phenomenology & Lattice

Ágnes Mócsy
Pratt Institute, Brooklyn, NY
Pratt

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In this talk

- Motivation for finite T quarkonium studies
- Quarkonium properties in a hot dense medium - equilibrated plasma
    - Potential models
    - Lattice calculations
- First studies of anisotropy effects
- Effective field theories

based on work in collaboration with

Péter Petreczky (BNL)
Adrian Dumitru (Baruch)
Yun Guo (Frankfurt)
Mike Strickland (Gettysburg)

Mócsy, Petreczky, Eur. Phys. J C 43, 77-80 (2005)
Mócsy, Petreczky, PRD 73, 074007 (2006)
Mócsy, Petreczky, PRL 99, 211602 (2007)
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Mócsy, Eur. Phys. J C (2008)
Dumitru, Guo, Mócsy, Strickland PRD (2009)

23 years ago …

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J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

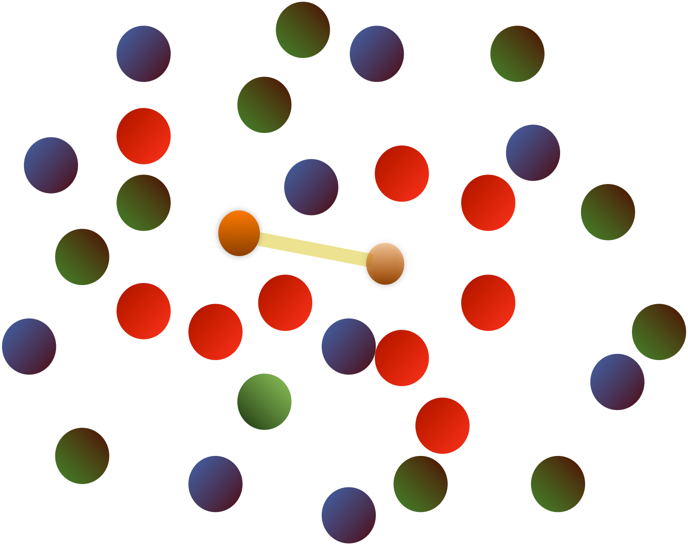
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

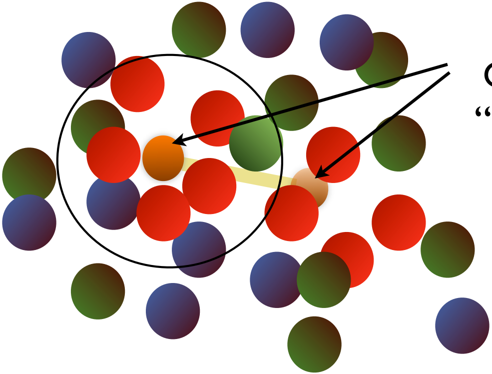
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

… the story of quarkonium at finite temperature began

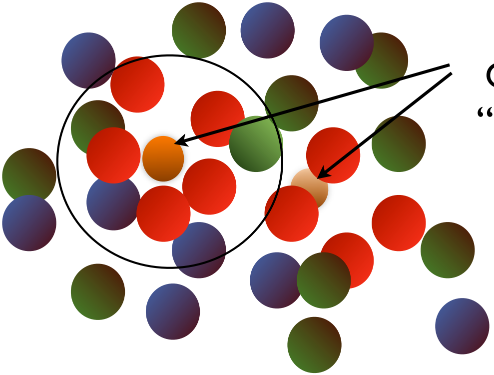
Screening in a Deconfined Medium



Screening in a Deconfined Medium



Screening in a Deconfined Medium



for $r_D < r_{Q\bar{Q}}$
Q and $\bar{Q}$ cannot
“see” each other

quarkonium states not form

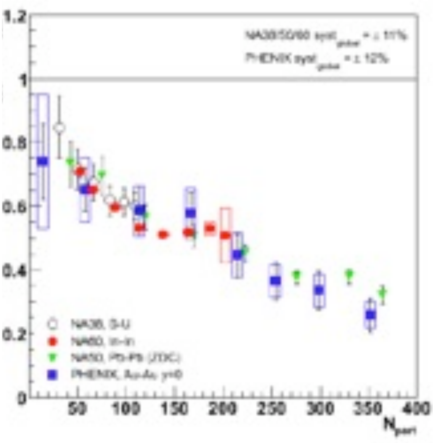
--

yield suppressed

Experimental observation

J/ψ nuclear modification factor R_{AA}

$$R_{AA}^{J\psi} = \frac{1}{N_{coll}} \frac{\dfrac{dN^{A+A\to J\psi+X}}{d^2k\,dy}}{\dfrac{dN^{p+p\to J\psi+X}}{d^2k\,dy}}$$



centrality

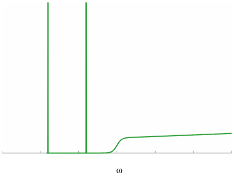
J/ψ suppression experimentally observed

But to understand the data we must know how quarkonium behaves at high T

Quarkonium Spectral Function

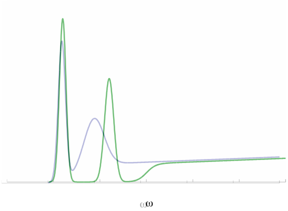
provides unified treatment of bound states, continuum and threshold

T = 0 narrow states



non-zero E_{bin}

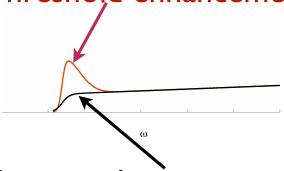
T > 0 broadening resonances - spectral function σ(ω,T)



No peak no bound state

E_{bin} = 0 condition is an overkill

Threshold enhancement



Free quark propagation

Calculating T>0 Spectral Functions

from Potential models

+ easy to handle
+ easily accommodate non-perturbative info (lattice)
- ad hoc

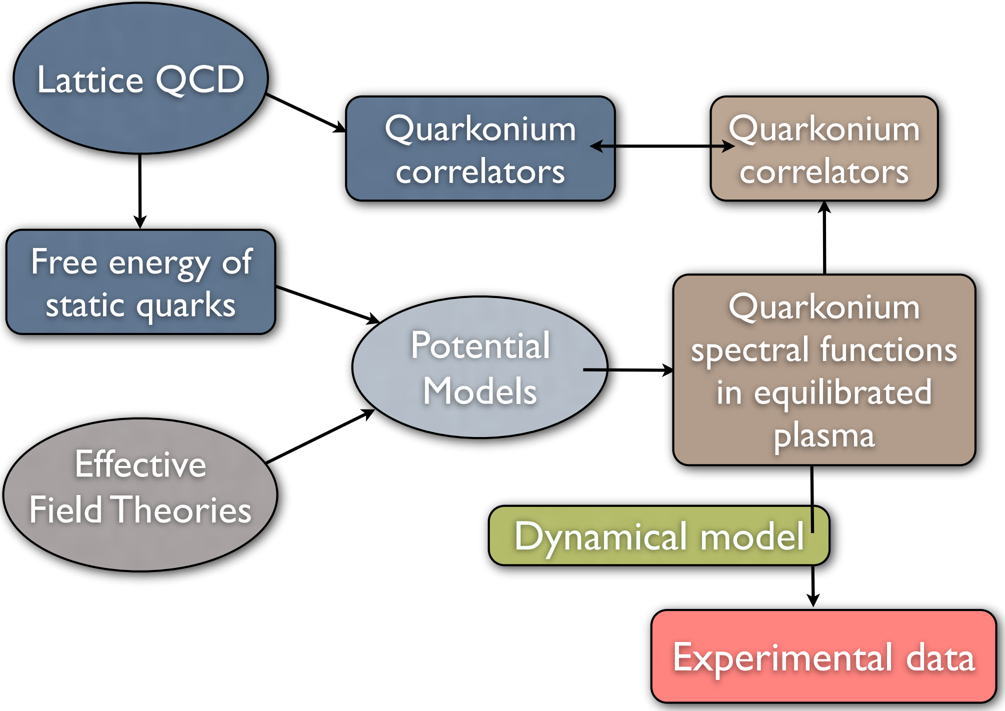
from Lattice QCD

+ exact (includes everything)
- difficult to get anything quantitative

from Effective Field Theories

+ directly from QCD
+ clarifies the applicability domain of potential model approach
- assumes scale separation
- utilizes weak coupling techniques

] near T_c problematic


Lattice QCD
Quarkonium correlators
Quarkonium correlators
Free energy of static quarks
Potential Models
Quarkonium spectral functions in equilibrated plasma
Effective Field Theories
Dynamical model
Experimental data

Potential Models

- Assume that ALL medium effects are given by a temperature-dependent potential

phenomenological potentials

lattice-based potentials

potentials from effective field theories: life is not so simple

- Non-perturbative effects can be accommodated utilizing lattice data on heavy quark singlet free energy *“lattice-based potentials”*

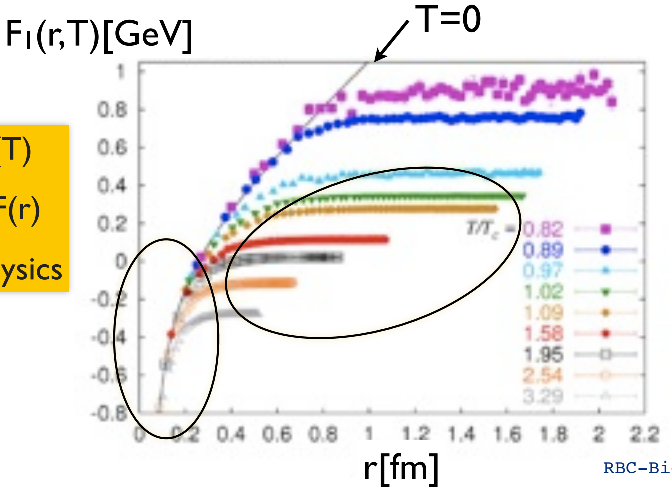
Heavy quark singlet free energy

from lattice QCD

$r < r_{med}(T)$

$F(r,T) = F(r)$

vacuum physics



RBC-Bielefeld 2008

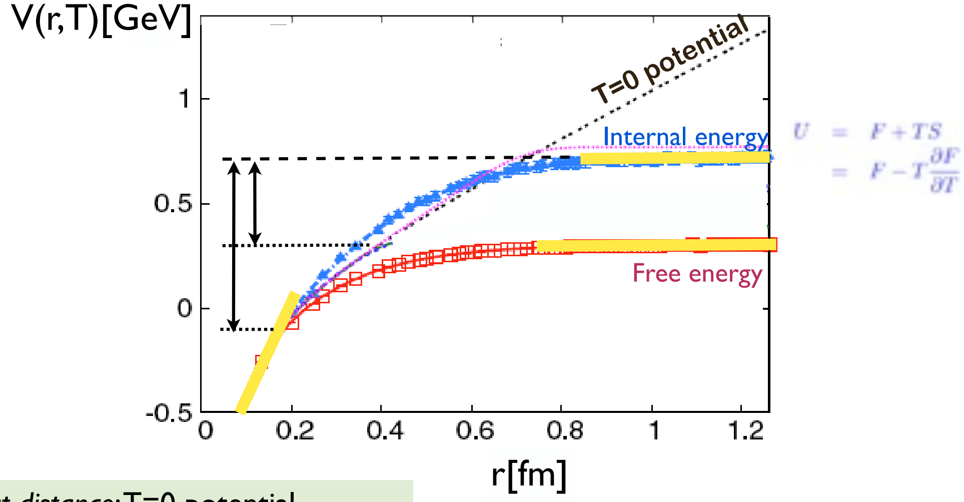
$r > r_{scr}(T)$

$F(r,T) = F(T)$

screening

Strong screening modification of static Q and $\bar{Q}$ interaction **is seen**

Lattice-based "potentials"

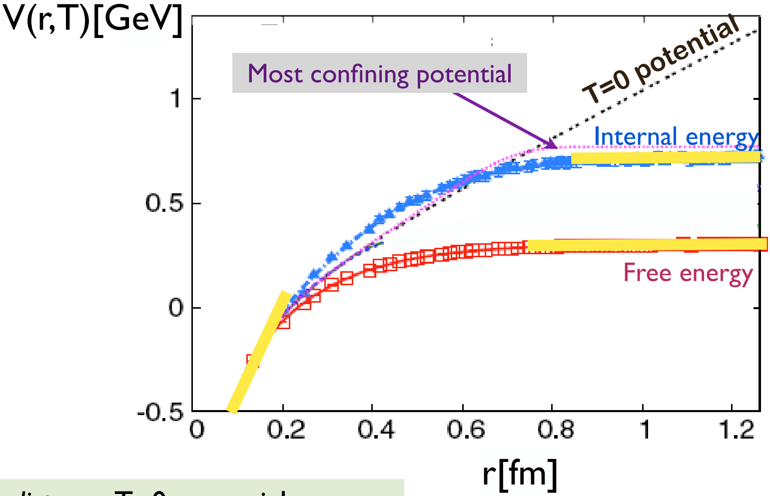


Short distance: T=0 potential
Large distance: constrained domain
Intermediate distance: we don't know

$F_{\infty Latt}(T) \lesssim V_{\infty}(T) \lesssim U_{\infty Latt}(T)$

Shortcoming: ad hoc

Lattice-based "potentials"



$$U = F + TS = F - T\frac{\partial F}{\partial T}$$

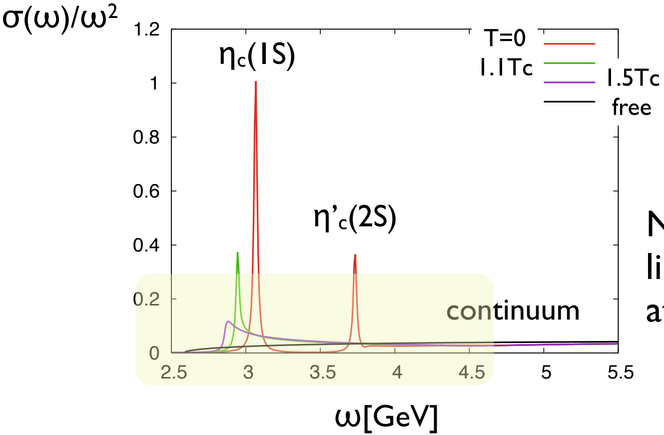
Short distance: T=0 potential
Large distance: constrained domain
Intermediate distance: we don't know

$F_{\infty Latt}(T) \lesssim V_\infty(T) \lesssim U_{\infty Latt}(T)$

Shortcoming: ad hoc

Spectral Functions

from potential models



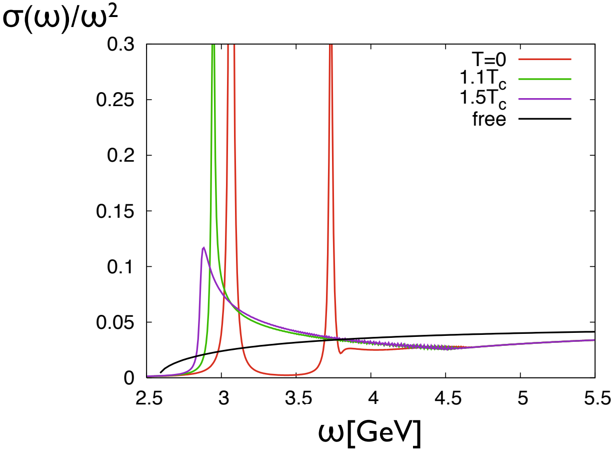
charmonium

No resonance-like structure at $1.2T_c$

Mocsy,Petreczky PRL2007, PRD2008

Spectral Functions

from potential models



charmonium

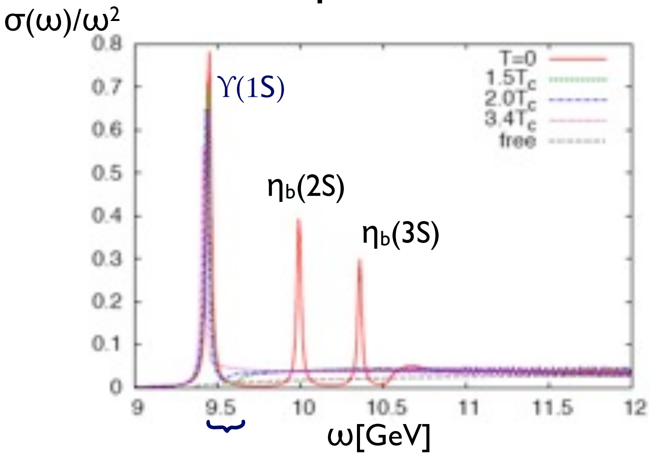
No resonance-like structure at $1.2T_c$

- Threshold enhancement up to high T - indicating correlation between c and cbar
- Binding energy decreases

Common to all models

Spectral Functions

from potential models



bottomonium

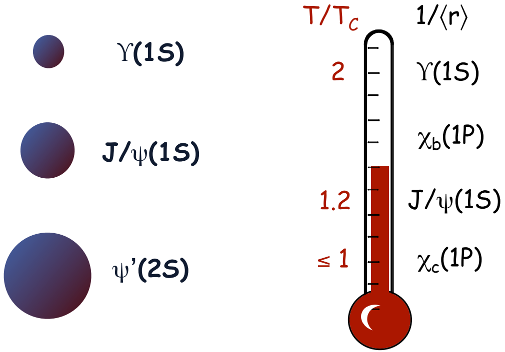
May see peak structure at high T
BUT
binding energy reduced

$E_{bin} = 2m_q + V_\infty(T) - M$ energy gap between peak position and threshold

Important note: states broaden with T
There is no bound state even before reaching $E_{bin} = 0$

Plasma Thermometer - upper limits

from potential models in agreement with lattice data



Upper limits of T above which bound states can not form in the plasma

"decays before bounds"

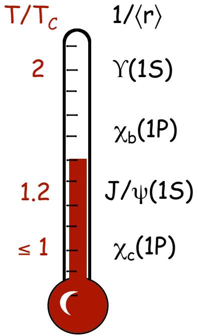
width ≥ 2 x binding energy

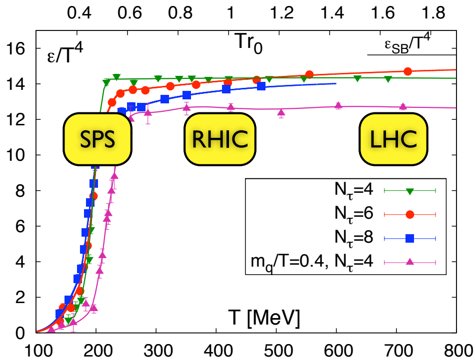
estimated by thermal excitation rate
Kharzeev,McLerran,Satz

conservative!

from potential models
Mocsy,Petreczky 2008

Relevance for experiments





Bazavov et al 2009

At RHIC no peak in the J/Ψ spectral function: J/Ψ not formed, only c & cbar some of which will be correlated

- if not diffused away they can bind - 50% will bind Young, Shuryak 2008

How does this compare to lattice?

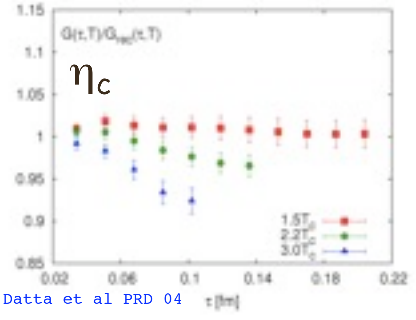
Correlation function of mesonic currents in Euclidean time

$$G(\tau,\vec{p},T) = \int d^3x e^{i\vec{p}\vec{x}} \left\langle j_H(\tau,\vec{x}) j_H^{+}(0,\vec{0}) \right\rangle = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega$$

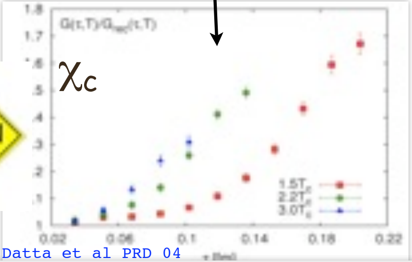
$$K(\tau,\omega,T) = \frac{\cosh(\omega(\tau - 1/(2T)))}{\sinh(\omega/(2T))}$$

this is calculated on the lattice — spectral function

$$\frac{G(\tau,T) = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega}{G_{rec}(\tau,T) = \int \sigma(\omega,T=0) K(\tau,\omega,T) d\omega}$$



Datta et al PRD 04



Datta et al PRD 04

Initial interpretation: J/ψ (η_c) survives up to 1.5-2T_c and χ_c gone by 1.1 T_c

How does this compare to lattice?

Correlation function of mesonic currents in Euclidean time

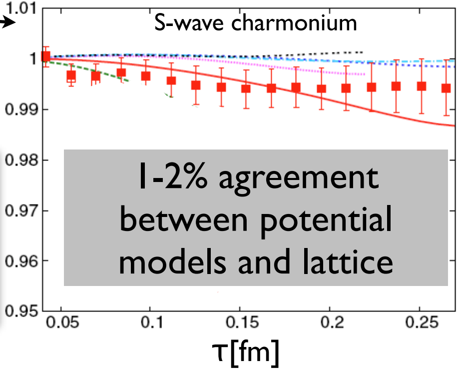
$$G(\tau,\vec{p},T) = \int d^3x e^{i\vec{p}\vec{x}} \left\langle j_H(\tau,\vec{x}) j_H^+(0,\vec{0}) \right\rangle = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega$$

$$K(\tau,\omega,T) = \frac{\cosh(\omega(\tau - 1/(2T)))}{\sinh(\omega/(2T))}$$

this is calculated on the lattice — $G(\tau,\vec{p},T)$

spectral function — $\sigma(\omega,T)$

$$\frac{G(\tau,T) = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega}{G_{rec}(\tau,T) = \int \sigma(\omega,T=0) K(\tau,\omega,T) d\omega}$$

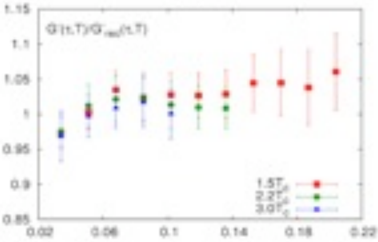


1-2% agreement between potential models and lattice

Changes in the spectral function do not show up in G/G_{rec}

Threshold enhancement compensates for lack of bound states

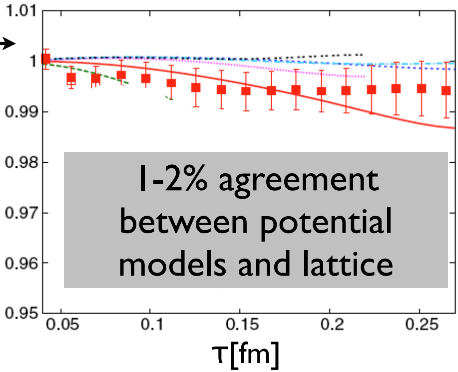
How does this compare to lattice?



Datta,Petreczky 2008

$$\frac{G(\tau,T) = \int \sigma(\omega,T) K(\tau,\omega,T) d\omega}{G_{rec}(\tau,T) = \int \sigma(\omega,T=0) K(\tau,\omega,T) d\omega}$$

Note: G/G_{rec} flat up to high T also in P-channels



1-2% agreement between potential models and lattice

Changes in the spectral function do not show up in G/G_{rec}

Threshold enhancement compensates for lack of peak

Quarkonium Spectral Functions

from lattice QCD

"Lattice indicates J/Ψ survival up to 2T_c"

Not true. This was a premature conclusion.

$$G(\tau,T) = \int \sigma(\omega,T)K(\tau,\omega,T)d\omega$$

correlator
directly calculated

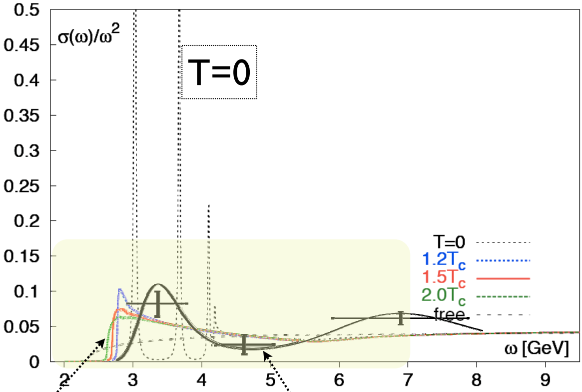
spectral function extracted
not directly calculated

$G(\tau,T)$ → MEM → $\sigma(\omega,T)$

Shortcomings:
limited # of data points
limited extent in tau
prior (default model) dependence

Matsufuru, Umeda, Asakawa, Hatsuda, Datta, Karsch, Petreczky, Jakovac, Aarts ..

Lattice vs Potential model



$1.5T_c$
Potential model

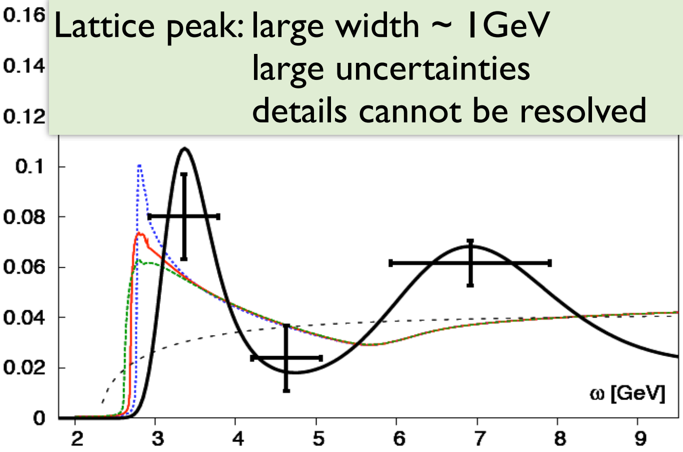
$1.5T_c$
Lattice data

Mocsy,Petreczky 2007

Jakovac et al 2007

Lattice vs Potential model

Lattice peak: large width ~ 1GeV
large uncertainties
details cannot be resolved



Lattice data is consistent with no bound state but threshold enhancement

Q  $\bar{Q}$ in anisotropic plasma

Dumitru, Guo, Mocsy, Strickland, PRD 2009

The medium exhibits local anisotropy in momentum space; expanding viscous plasma always *slightly* away from equilibrium

Anisotropic angular-dependent screening

Dumitru,Guo,Strickland 2008

$$m_D \rightarrow \mu(\theta;\xi,T) = m_D \left(1 - \xi \frac{3+\cos 2\theta}{16}\right)$$

anisotropy parameter → ξ

$$\xi = \frac{10}{T\tau}\frac{\eta}{s}$$

Asakawa,Bass,Muller 2007

Potential depends on distance, temperature, anisotropy, and direction of anisotropy

$$F(r,T) = -\frac{\alpha}{r}\exp(-r\,m_D) + \frac{\sigma}{m_D}[1-\exp(-r\,m_D)]$$

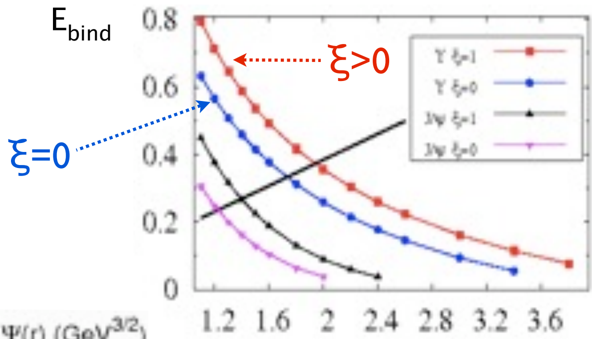
V_∞ → $\frac{\sigma}{m_D}$

inspired by
Karsch,Mehr,Satz 1988

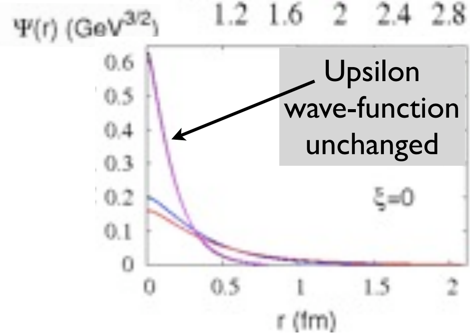
Binding energies in anisotropic plasma

with *most confining potential*

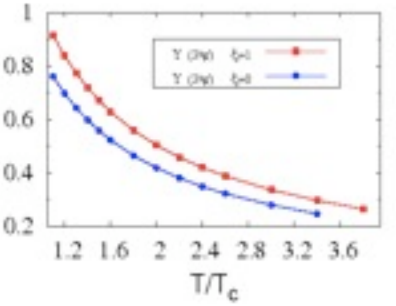
Dumitru, Guo, Mocsy, Strickland, PRD 2009



ξ>0: smaller screening mass, stronger binding



T, ξ–dependence of E_{bind} dominated by V_∞ (especially for ϒ)



Binding energies in anisotropic plasma

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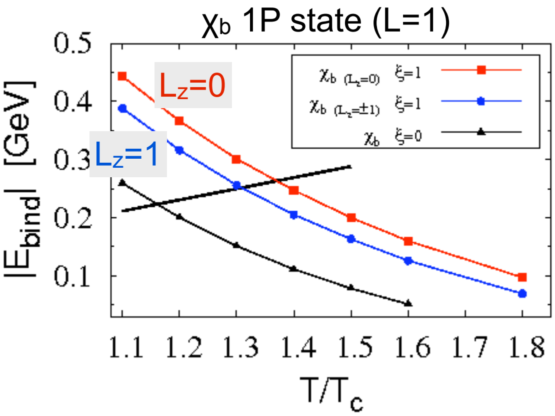
Dumitru, Guo, Mocsy, Strickland, PRD 2009



Polarization of P-state (L_z=0 is preferred) induced by the angular dependence of the potential

At T=200MeV the population of L_z=0 enhanced by ~ $\exp(-E_{bind}/T)$ = 30% compared to states along the anisotropy direction

Effective Field Theories

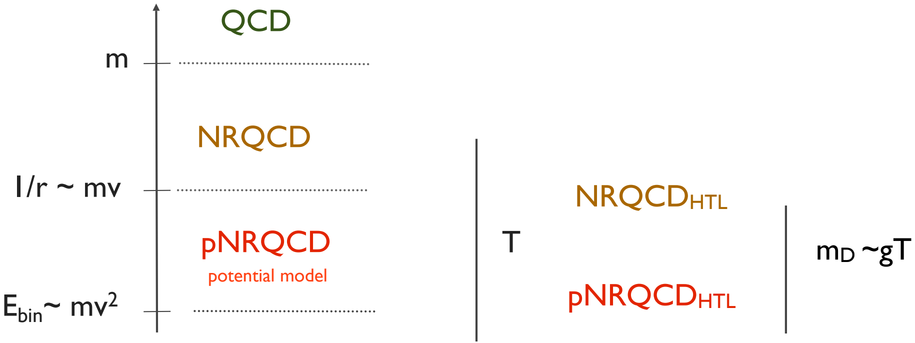
quarkonium potential derived from QCD Lagrangian

Bound state scales
m, mv, mv^2

Temperature scales
T, gT, g^2T

Quark mass $m = m_Q \gg \Lambda_{QCD}$
Size of bound state $r \ll \Lambda_{QCD}^{-1}$
Relative velocity of quarks $v \ll 1$

Assumptions: $m \gg T$
$T > gT > g^2T$ weak coupling
$r > r_D = 1/m_D$, $m_D \sim gT$ no bound states



Discovery from new EFT calculations:

1.Quarkonium potential has Real & Imaginary part

$\mathrm{ReV_s}\,(r,T)$

$\mathrm{ImV_s}\,(r,T)$

thermal width of $Q\bar{Q}$

octet transition

thermal breakup of a Q-$\bar{Q}$ color singlet into a color octet state and gluons

Brambilla, Vairo, Giglieri,Petreczky 2009

Landau damping

gluon self-energy, scattering of particles in the medium with space-like gluons

Laine 2007

Discovery from new EFT calculations:

2. Temperature effects can be other than screening

$\mathrm{Re}V_S(r,T)$ $\mathrm{Im}V_S(r,T)$

$T > 1/r$ and $1/r \sim m_D \sim gT$

exponential screening

Laine et al 2007
Blaizot et al 2008

$T > 1/r$ and $1/r > m_D \sim gT$

no exponential screening, but
power-like T-corrections

Brambilla et al 2009

$T < E_{bin}$

no corrections, but
non-potential T contributions

Discovery from new EFT calculations:

2. Temperature effects can be other than screening

$\mathrm{Re}V_S(r,T)$ $\mathrm{Im}V_S(r,T)$

$T > 1/r$ and $1/r \sim m_D \sim gT$

exponential screening

Laine et al 2007
Blaizot et al 2008

$T > 1/r$ and $1/r > m_D \sim gT$

no exponential screening, but
power-like T-corrections

Brambilla et al 2009

$T < E_{bin}$

no corrections,
non-potential T cont

Shortcomings:
near Tc weak coupling techniques areproblematic
non-perturbative effects need to be included

Lessons about quarkonium in medium

from Potential models

Binding energy decrease

Threshold enhancement leading to residual c-cbar correlations

Implications for experimental data can be investigated with dynamic models

Polarization of P states - could signal of viscosity

from Lattice QCD

Correlation between Q and Qbar above T_c

Data is consistent with J/Ψ screening just above T_c

Conclusion of "survival to $2T_c$" was premature

from Effective Field Theories

Temperature dependent widths

Temperature effects beyond what potential models account for

More theory development needed

*** The End ***