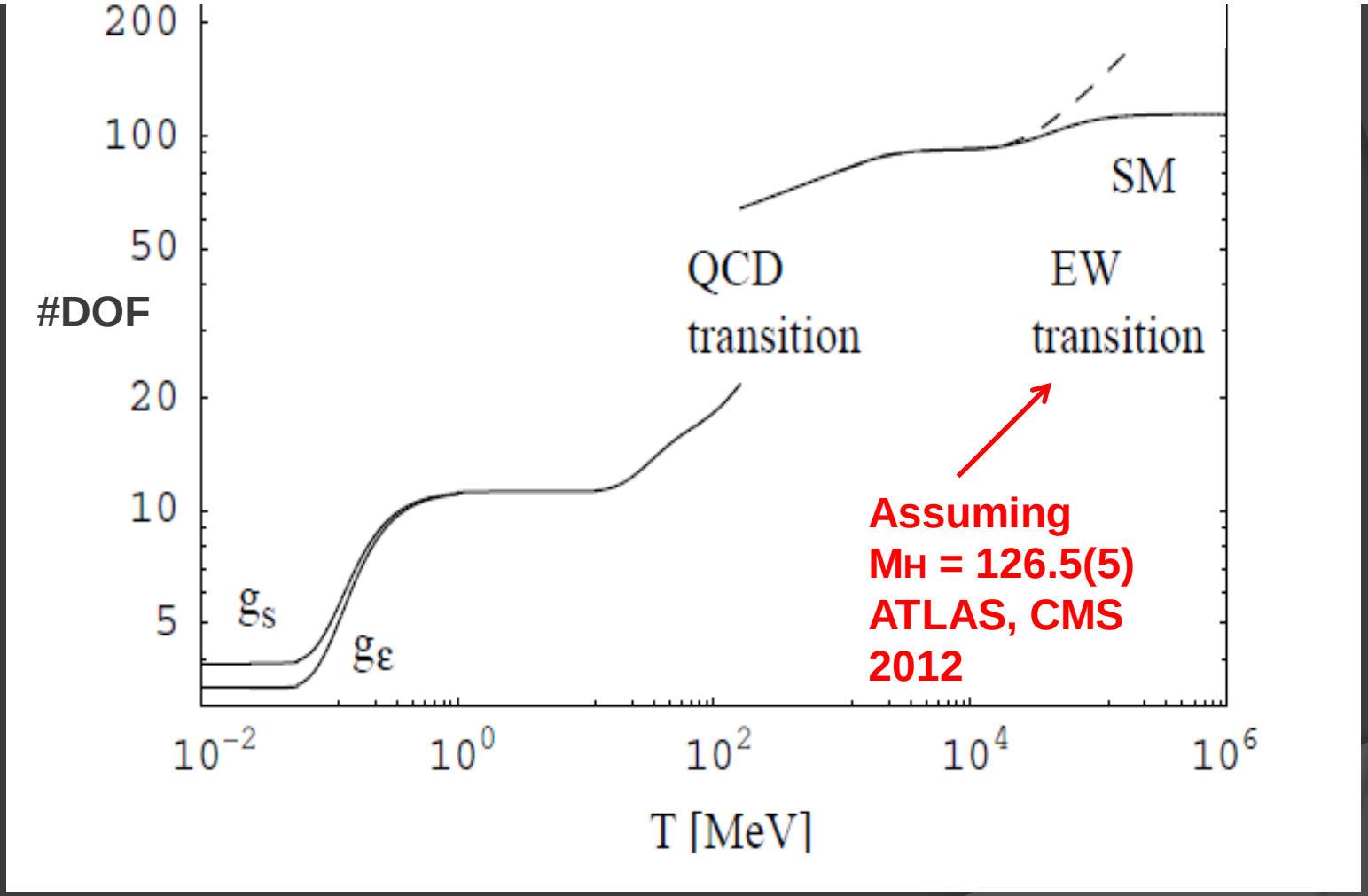
Maria Paola Lombardo
Istituto Nazionale di Fisica Nucleare – Italy

Quarkonia in the Quark Gluon Plasma

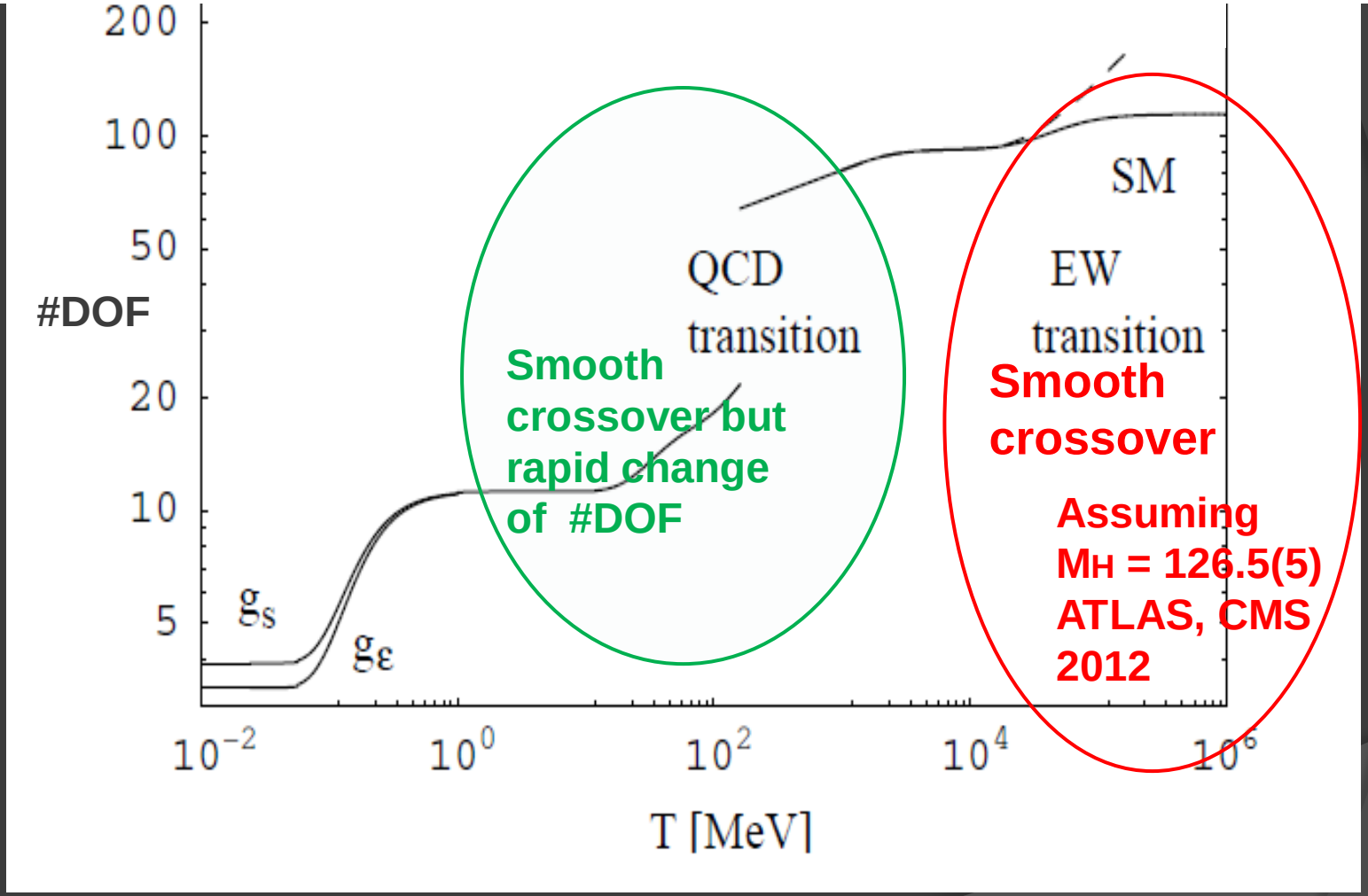
STRONG & ELECTROWEAK MATTER
SWANSEA UNIVERSITY
10 –13 JULY 2012

QGP and Particle Cosmology



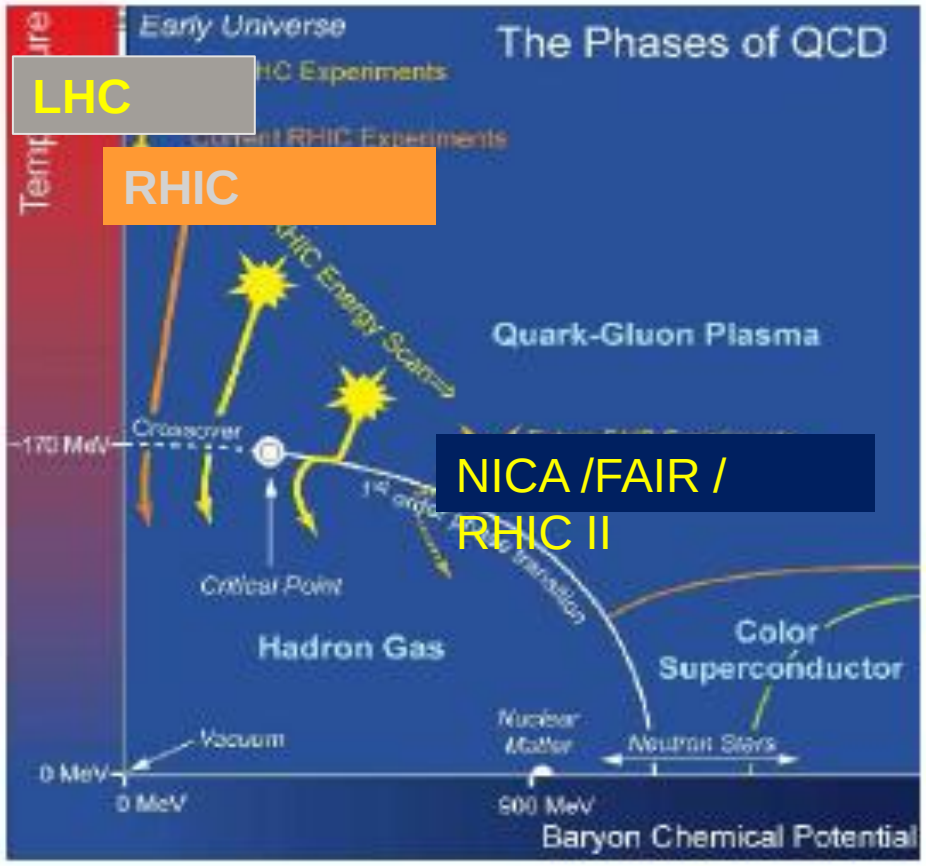
Adapted from D. Schwartz

QGP and Particle Cosmology

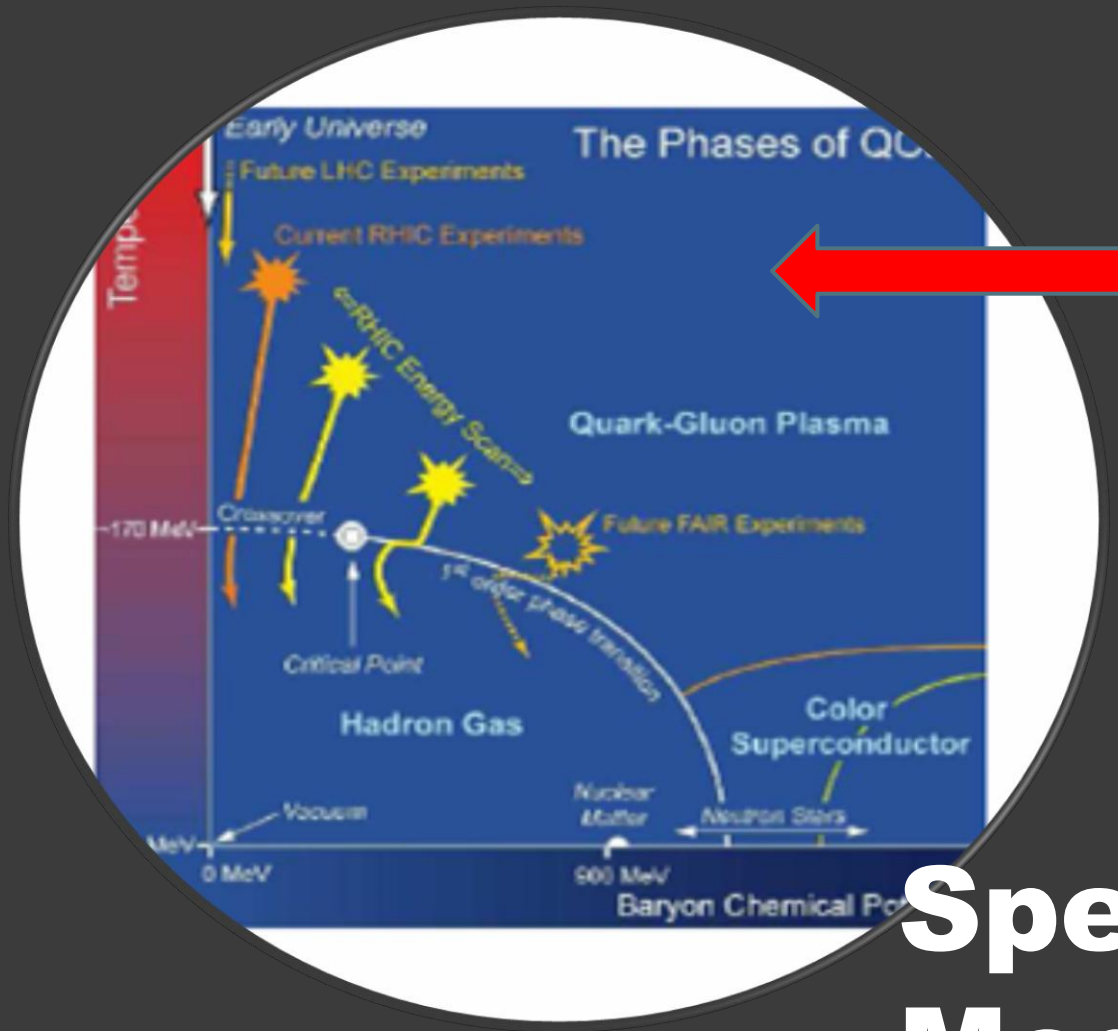


Adapted from D. Schwartz

QGP in the QCD Phase Diagram



US NSAC Long RangePlan (adapted)



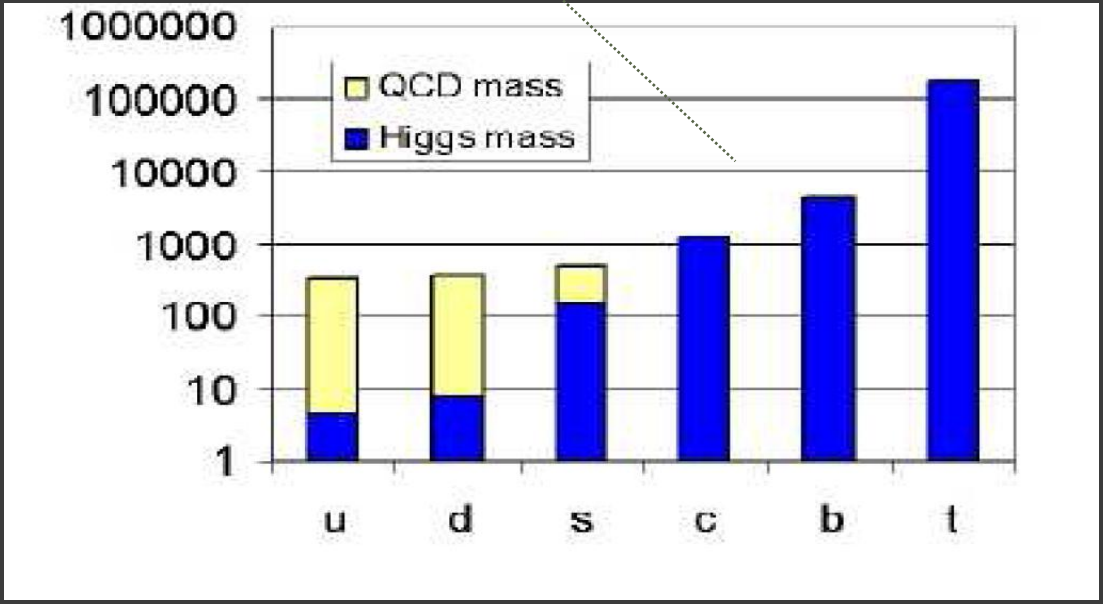
Quark Gluon Plasma

Deconfinement

Chiral Symmetry Restoration

Spectrum Modifications

Charm and Bottom:



Picture from B. Muller

‘Blind’ to QCD chiral symmetry
Probes of gauge dynamics in the QGP

A short History

The Theory: Charmonium suppression predicted
Matsui-Satz 1986

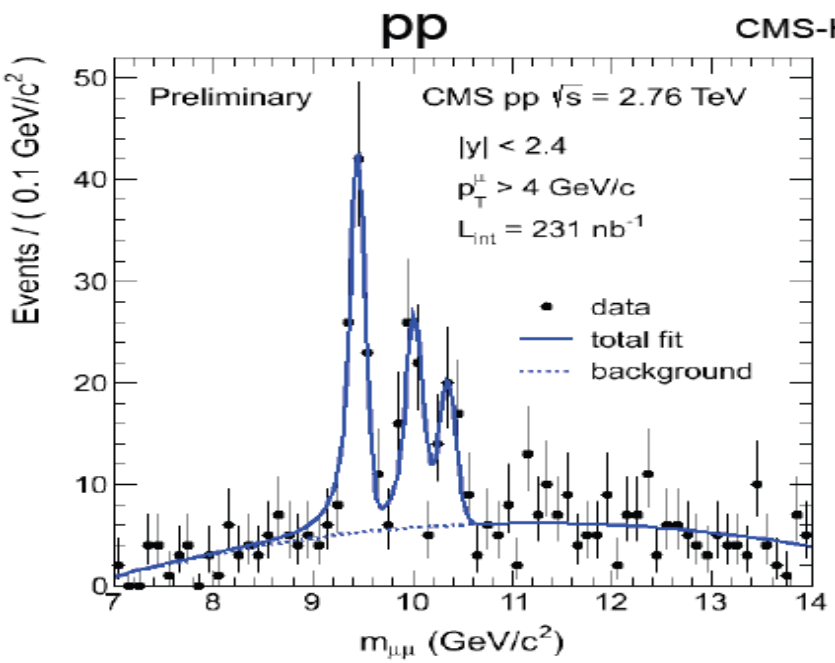
SPS: Charmonium suppression observed –
, Quark Gluon Plasma discovered!!

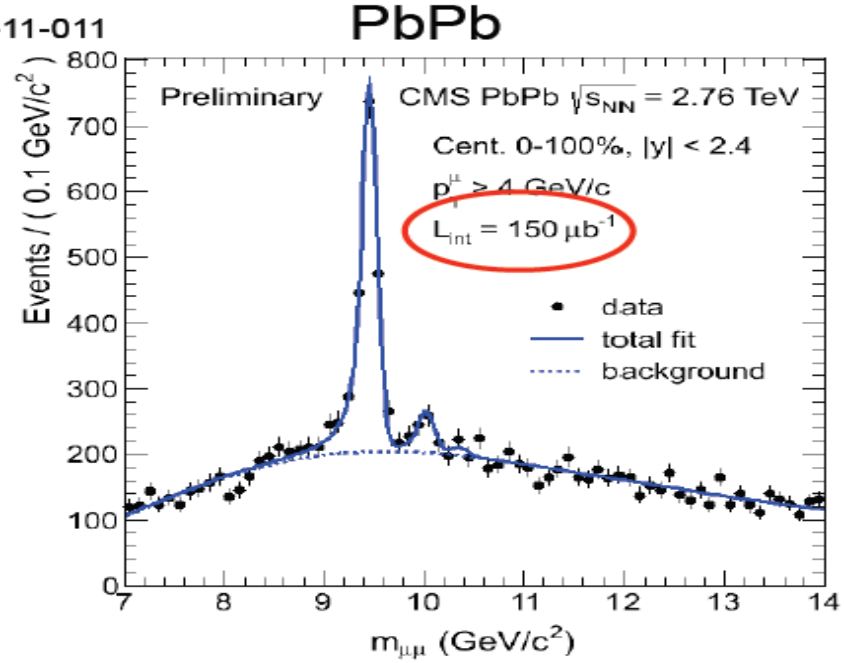
RHIC: Not really…previous theoretical analysis too crude..
Charmonium suppression is not enough .. Competing effects

LHC + RHIC: High precision Charmonium AND Bottomonium physics – calling for a better theoretical understanding

QGP and Bottomonium

Bottomonia: with 2011 data





$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Ratios not corrected for acceptance and efficiency

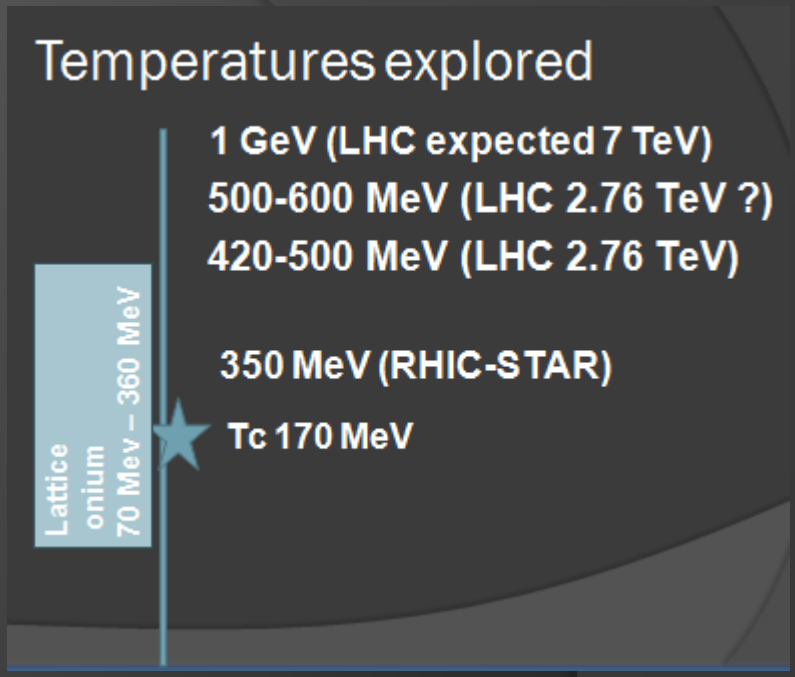
T. Dahms CMS Hard Probes 2012

Outline

- QCD thermodynamics at RHIC-LHC energies
- Quarkonia and heavy quark potential
- Quarkonia from first principles

  Charmonium

  Bottomonium
- Summary, and a few open questions



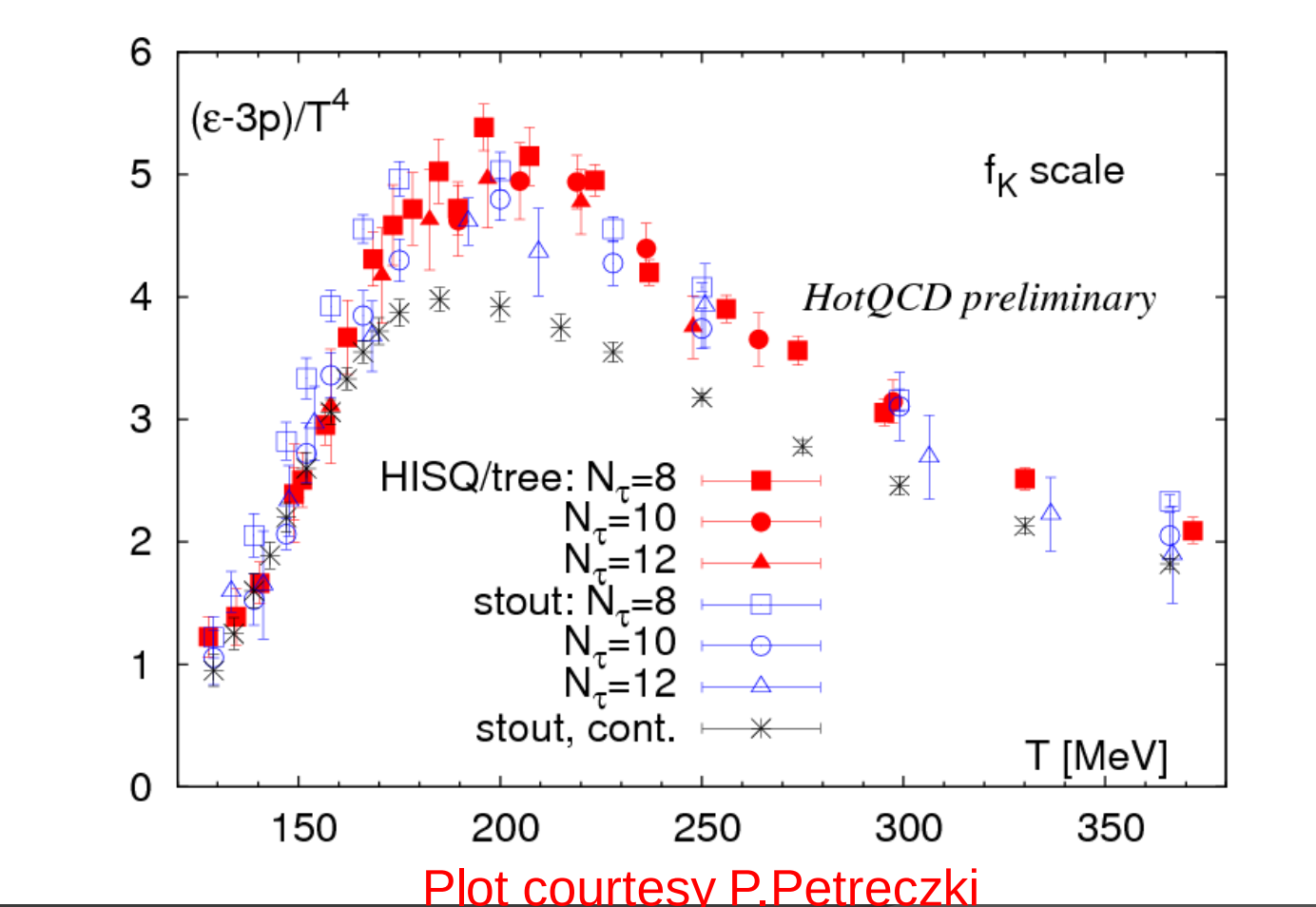
Recent lattice results

EoS, potential, quarkonium

Status of QCD thermodynamics in the RHIC-LHC range

sQGP and EoS

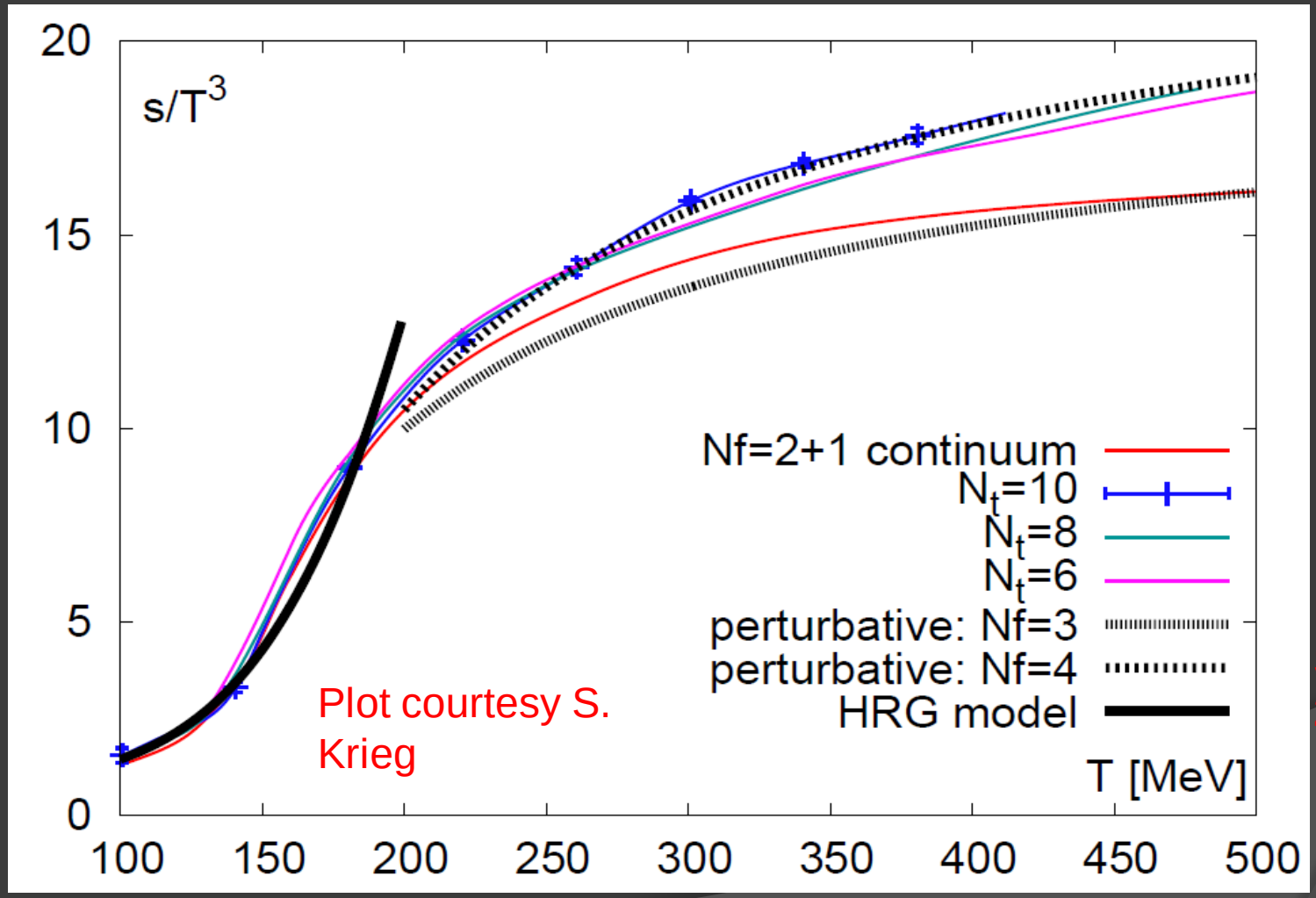
P. Petreczki (HotQCD) Lattice2012



Plot courtesy P.Petreczki

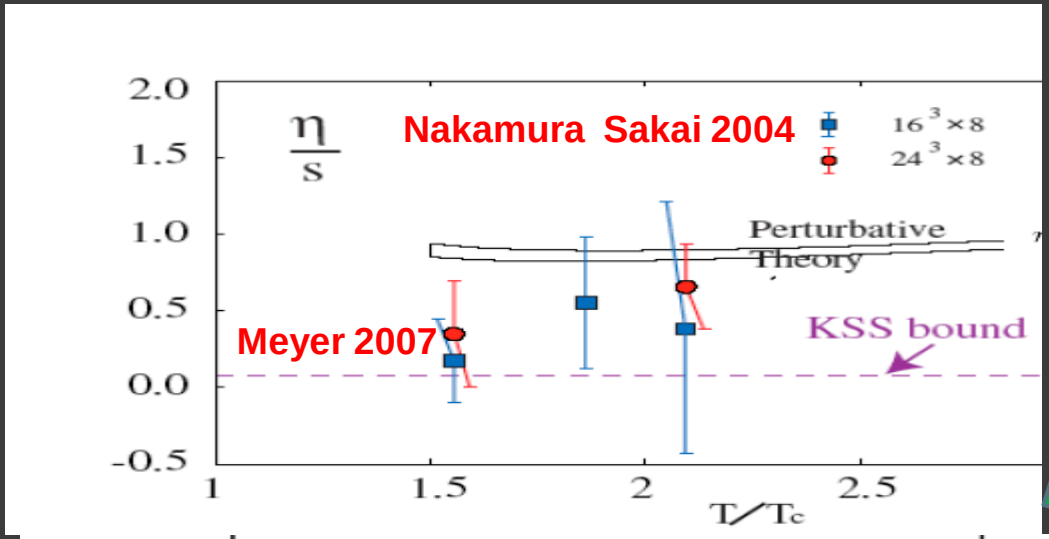
sQGP and EoS

Krieg - Wuppertal Budapest Lat2012



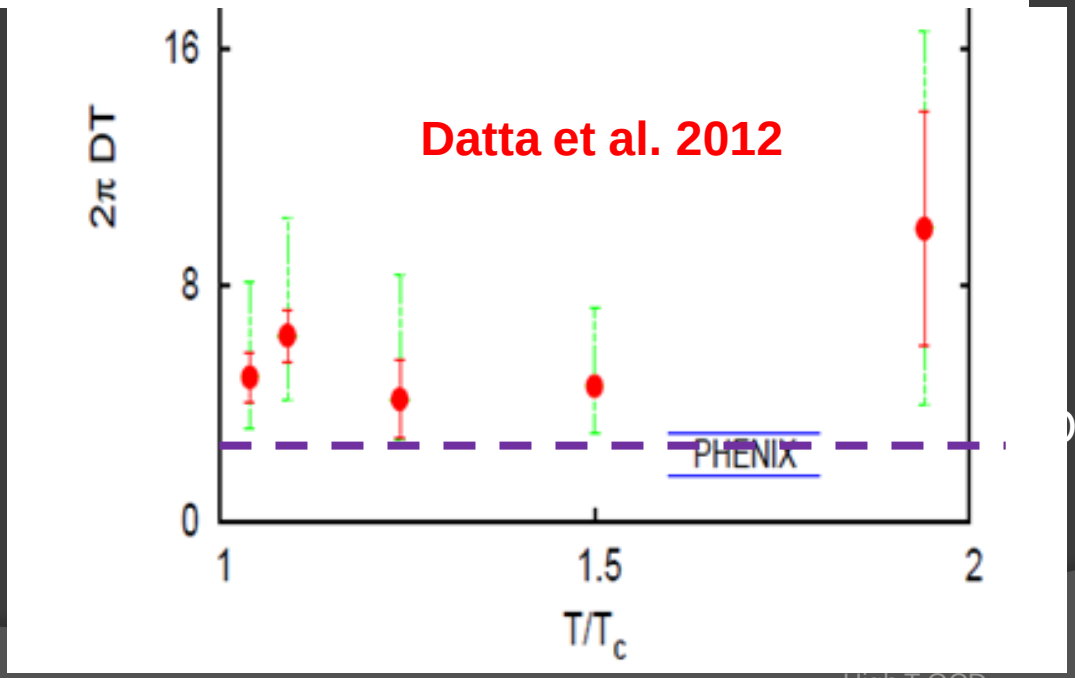
Laine Schroeder 2006

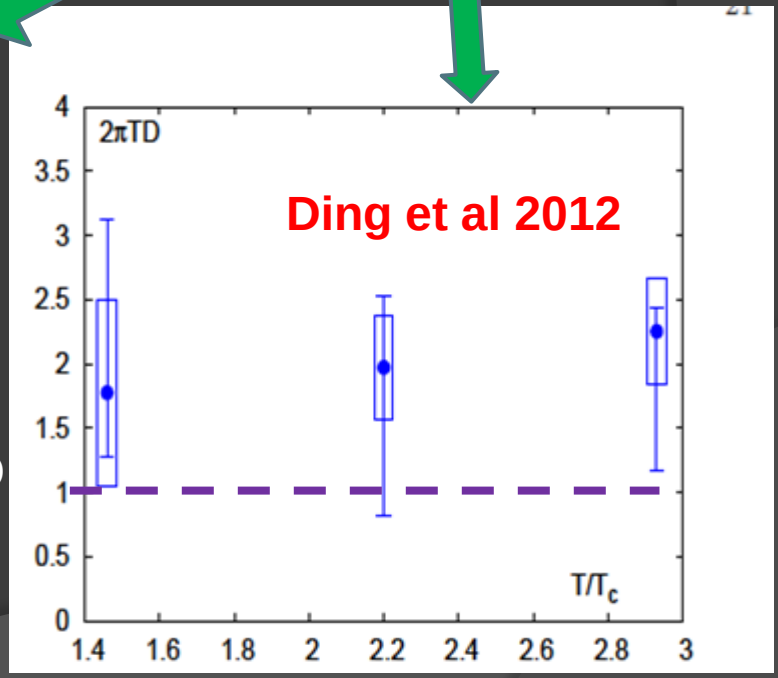
sQGP and trasport



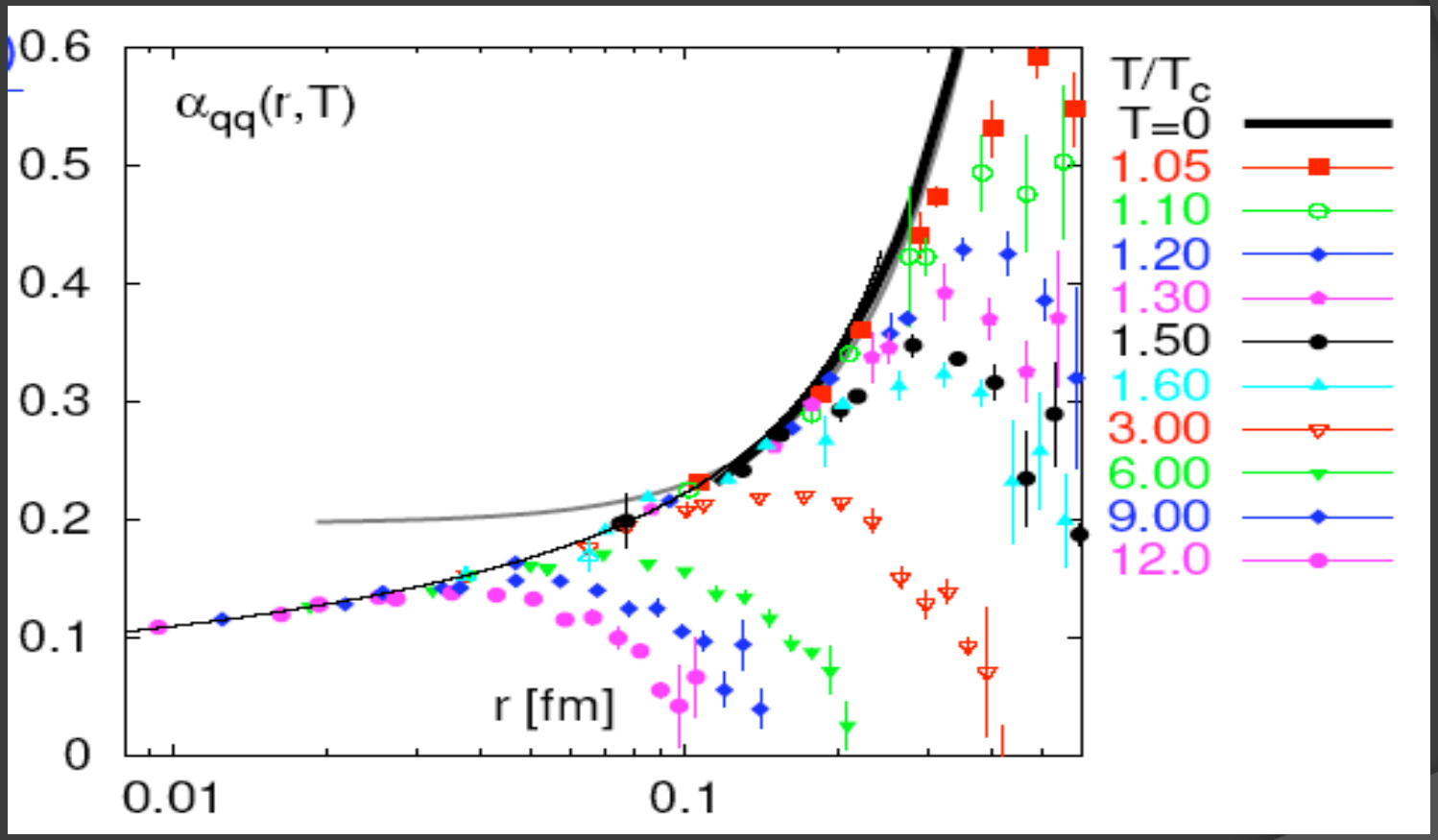
Early evidence for sQGP (from D. Kharzeev)

Recent results for the HQ diffusion coeff.



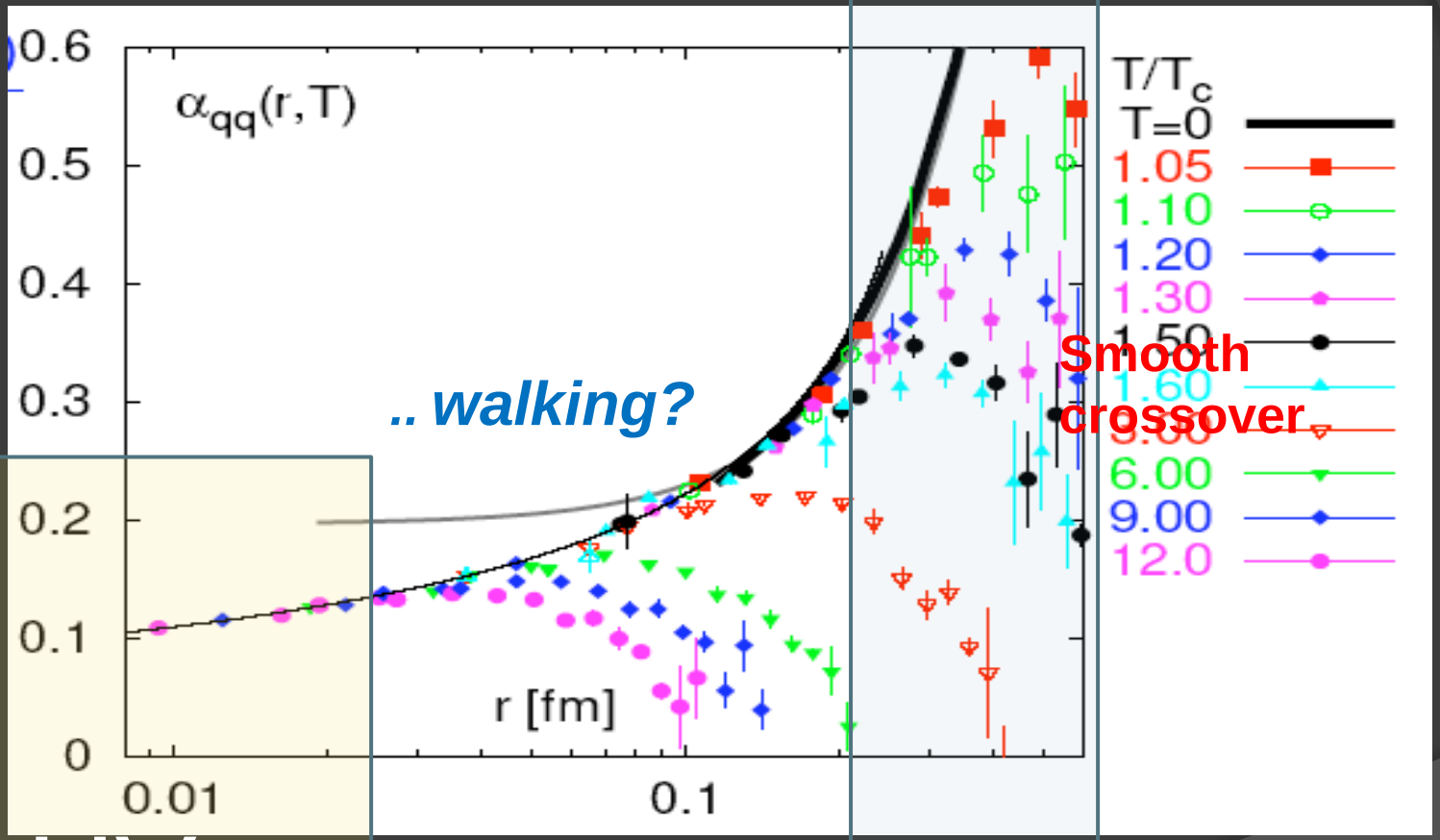


sQGP and heavy quarks potential

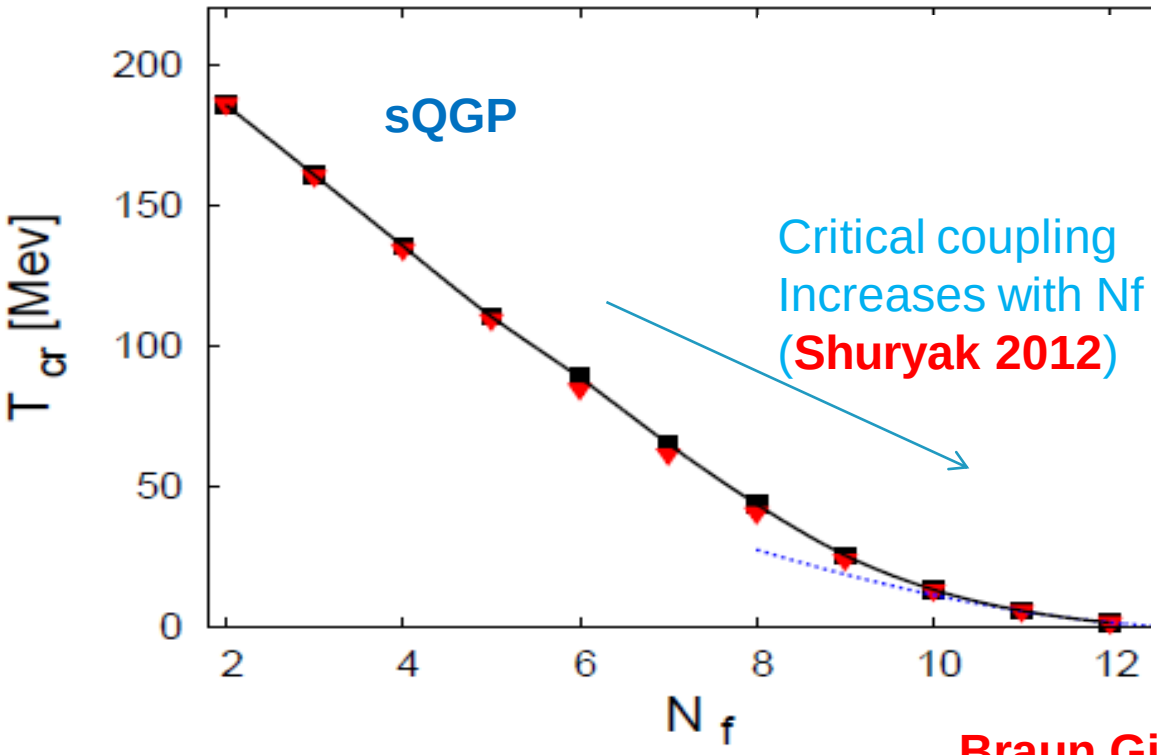


Karsch et al. 2007

sQGP and heavy quark potential



sQGP and QCD conformal window

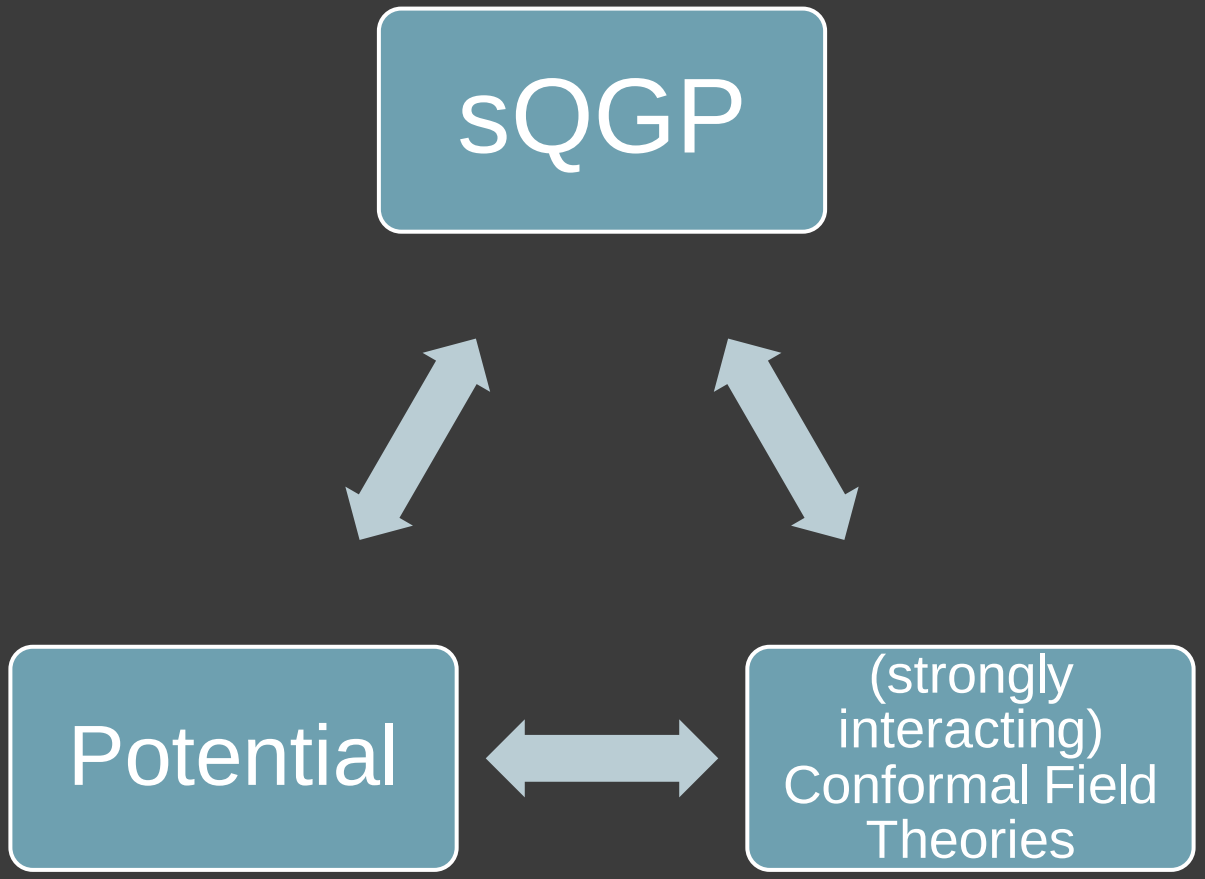


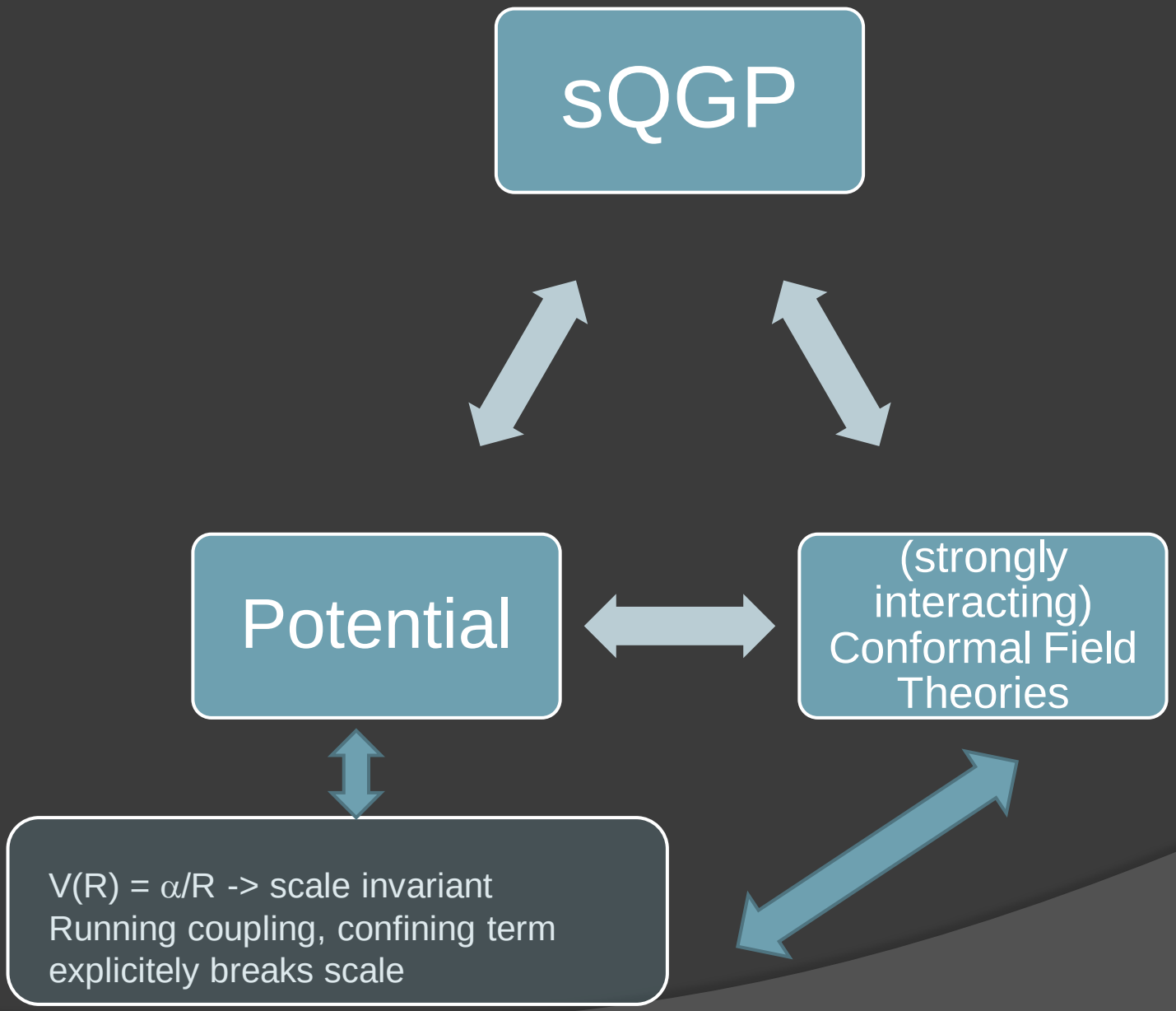
Conformal Window at SEWM2012:

F. Sannino
K. Rummukkainen
A. Rago
Ph.de Forcrand
K. Miura
T. Nunes da Silva

Conformal window: Strongly interactive CFT

Braun Gies 2006-2010

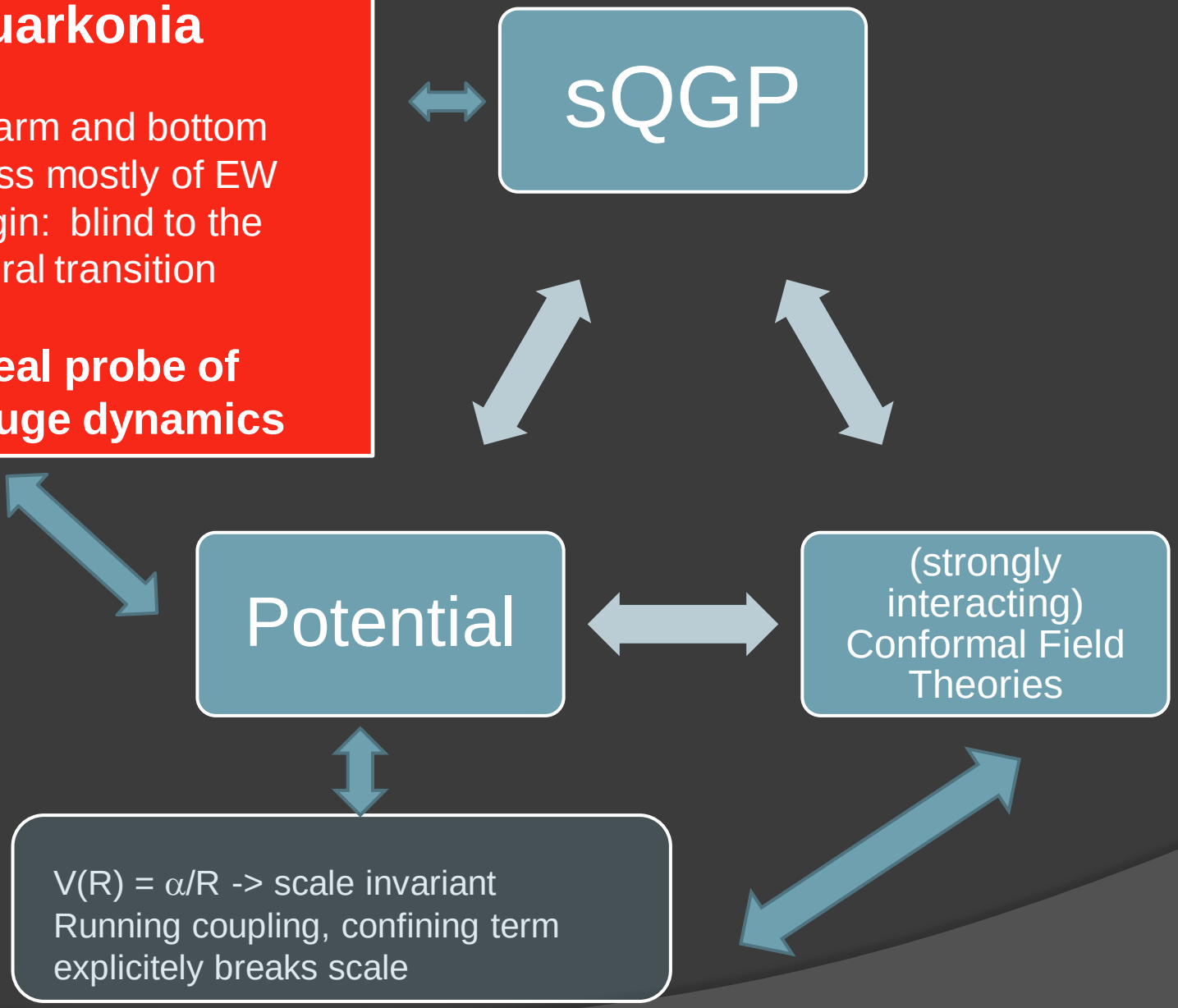

sQGP
Potential
(strongly interacting) Conformal Field Theories


sQGP
Potential
(strongly interacting) Conformal Field Theories
V(R) = α/R -> scale invariant
Running coupling, confining term explicitely breaks scale

Quarkonia

Charm and bottom mass mostly of EW origin: blind to the Chiral transition

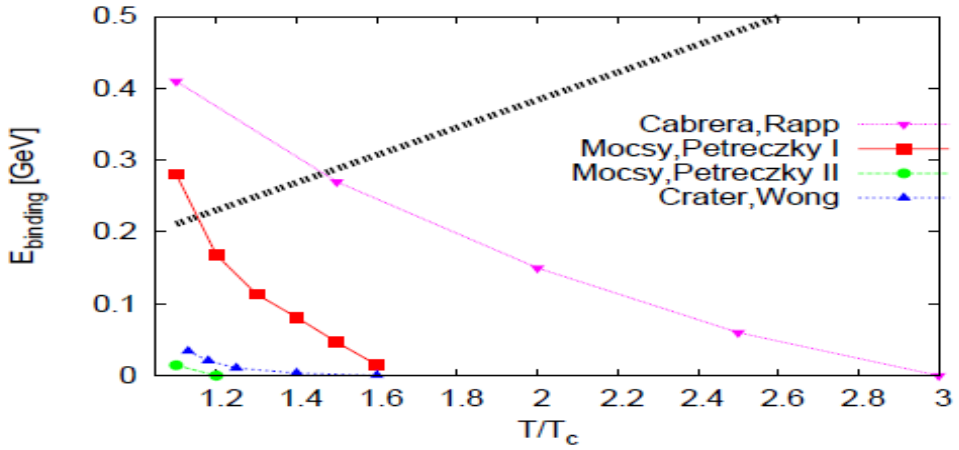
Ideal probe of gauge dynamics



$$\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$$

Quarkonia in the QGP and Heavy Quark Potential

Dissociation criterium from early studies : $E_{binding} < T$



state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
$V(r,T) = U(r,T)$	2.1	1.2	1.1
$V(r,T) = F(r,T)$	1.2	1.0	1.0

J/ψ results

From A. Mocsy

Dissociation temperatures In unit of Tc

From H. Satz

Modern era of potential studies: thermal width expressed by an imaginary component

M.Laine et al. 2006 2007

Same as before

From perturbation theory

$$V_A = \mathrm{U} + i\Im[V] - \frac{0.8\,\sigma}{m_Q^2 r}$$

$$V_B = \mathrm{F} + i\Im[V] - \frac{0.8\,\sigma}{m_Q^2 r}$$

+ anisotropy of the medium taken into account

M. Strickland 2012

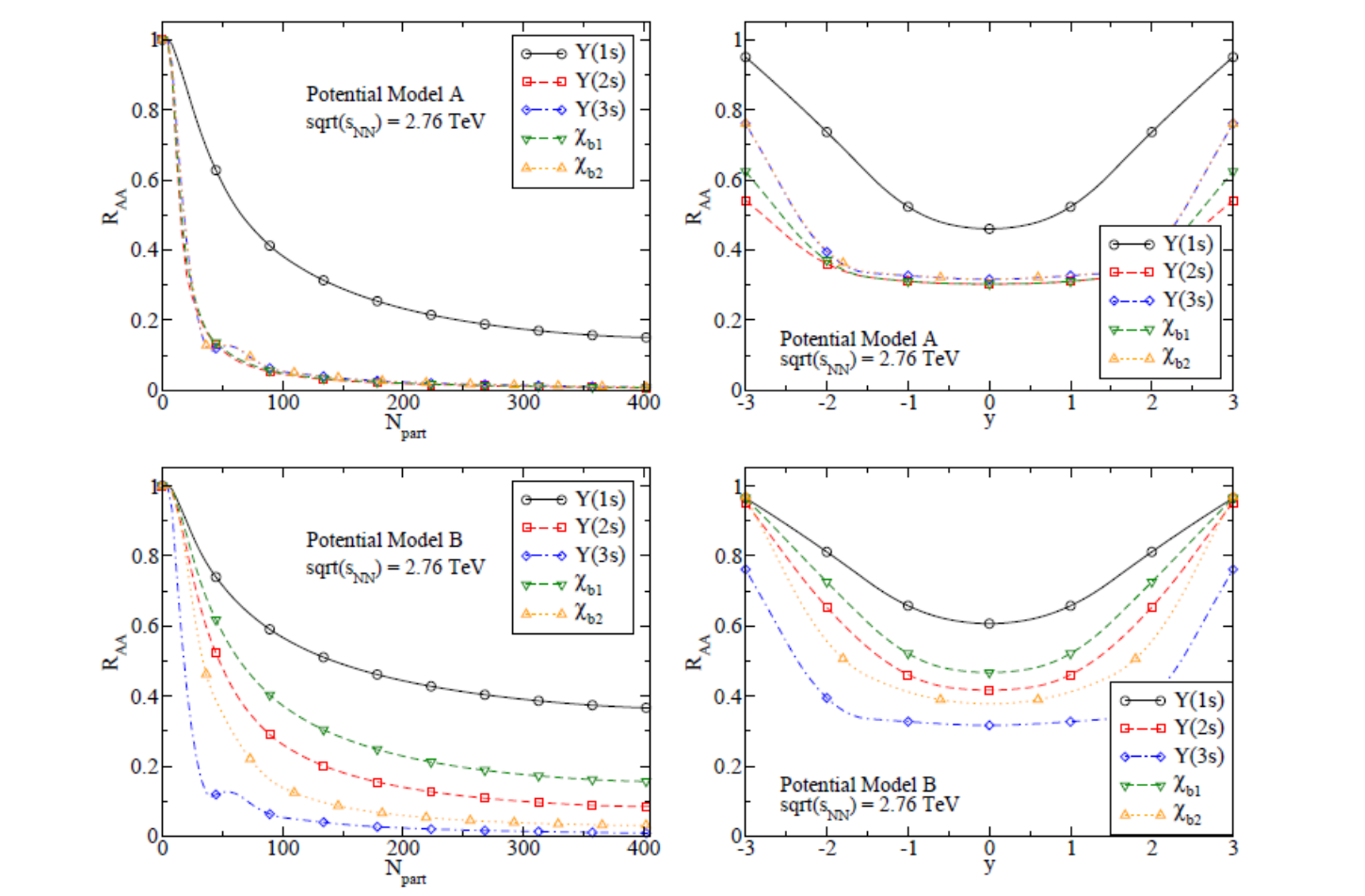
More sound criterium for dissociation

	Isotropic		Anisotropic	
State	Potential A	Potential B	Potential A	Potential B
$\Upsilon(1s)$	298 MeV	593 MeV	373 MeV	735 MeV
$\Upsilon(2s)$	$<$ 192 MeV	228 MeV	$<$ 192 MeV	290 MeV
$\Upsilon(3s)$	$<$ 192 MeV	$<$ 192 MeV	$<$ 192 MeV	$<$ 192 MeV
χ_{b1}	$<$ 192 MeV	265 MeV	$<$ 192 MeV	351 MeV
χ_{b2}	$<$ 192 MeV	$<$ 192 MeV	$<$ 192 MeV	213 MeV

Still Sensitive to the choice of potential

Possible to use analytic results to model RAA

Strickland 2012



$$G_i(\tau,T) = \int d\omega\ \sigma_i(\omega,T)\ K(\omega,\tau,T)$$

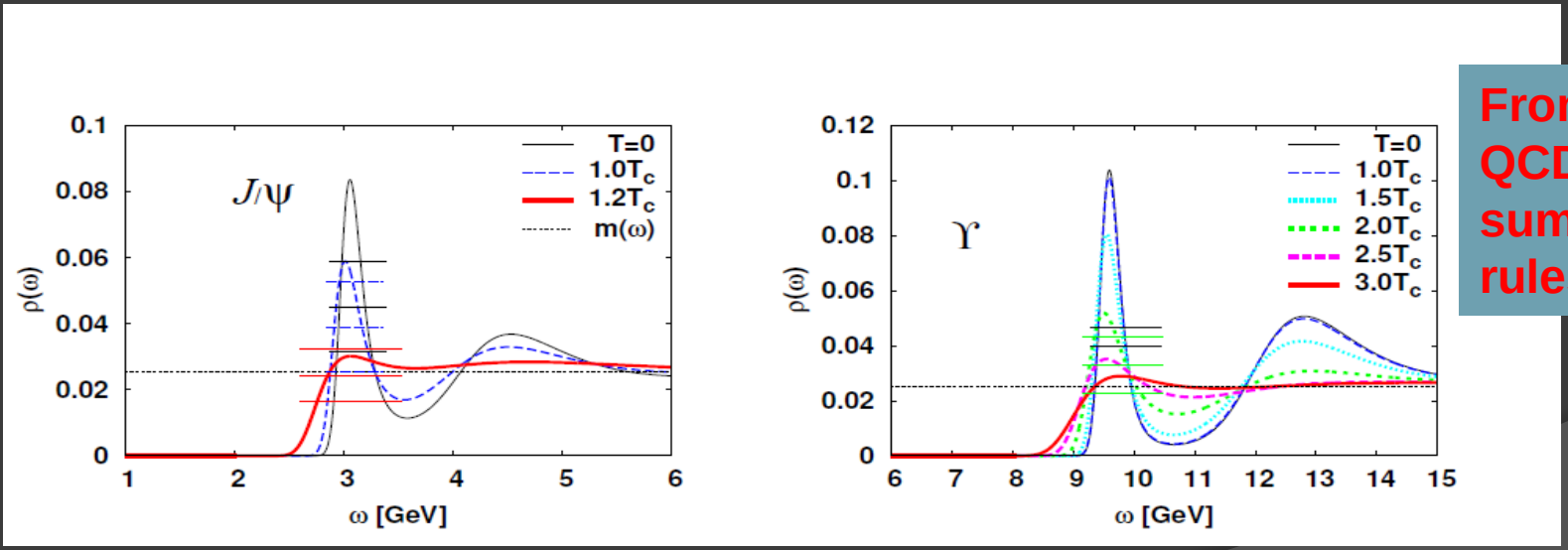
Charmonium

Bottomonium

Quarkonia in the QGP from first principles

Spectral functions

- Full physical information
- Directly related to transport coefficients
- Difficult to compute: needs many time slices

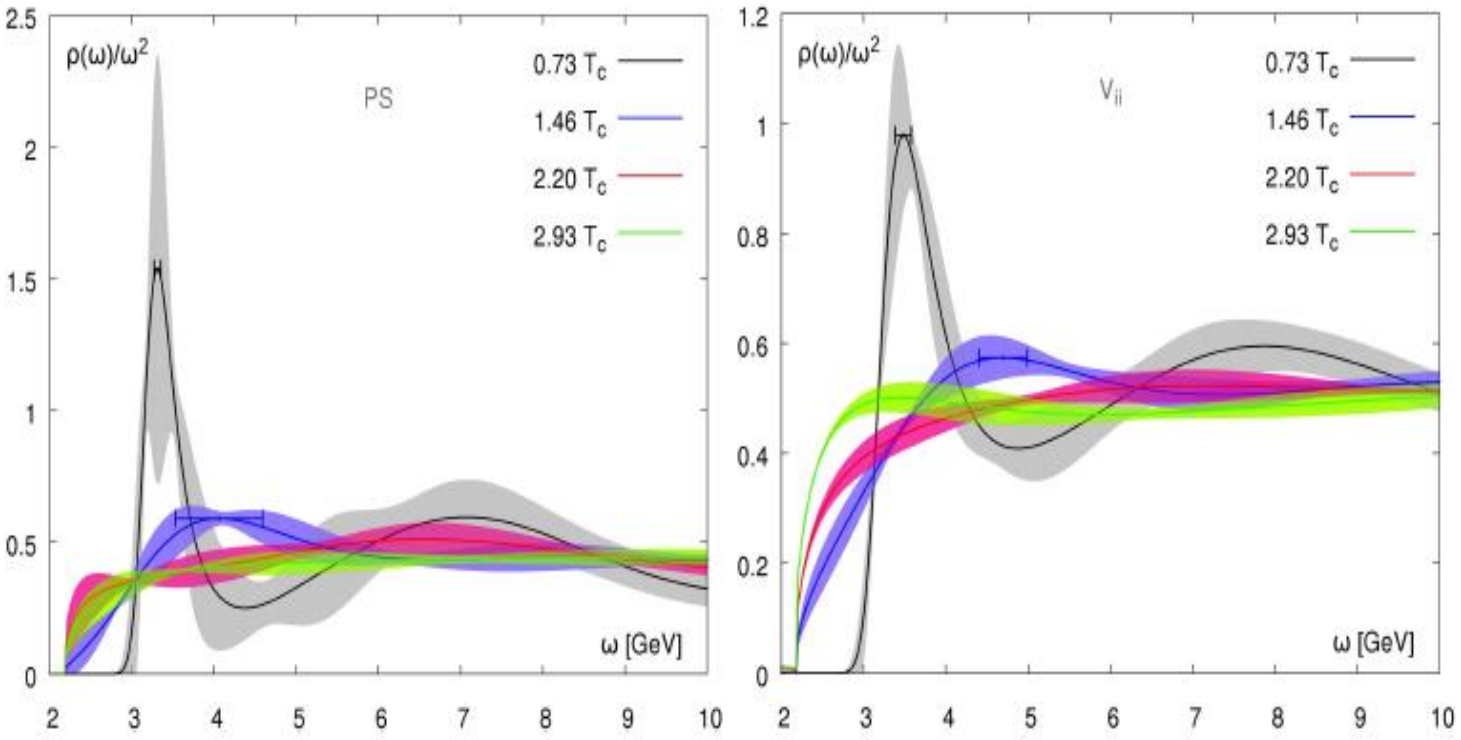


From QCD sum rules

K.Morita 2012

Charmonium

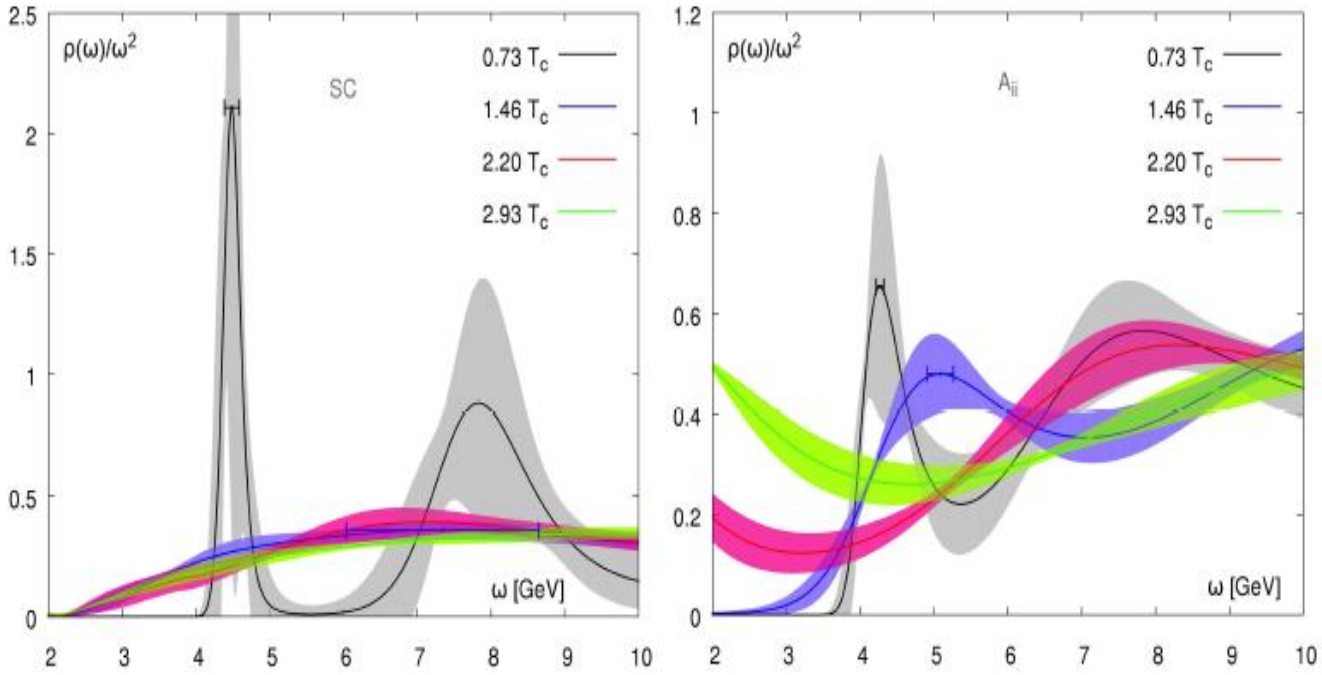
Ding et al.2012



Quenched calculation

Charmonium

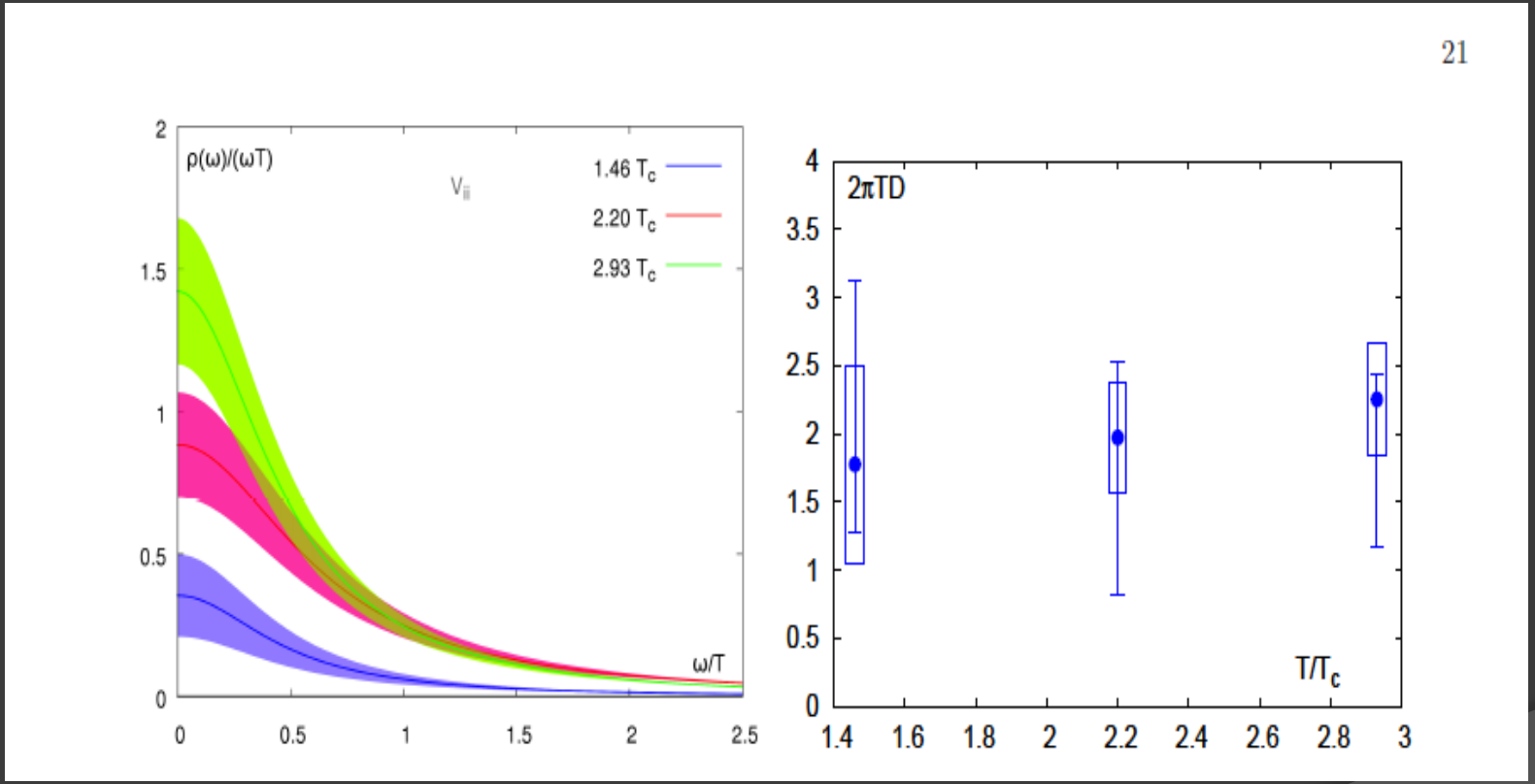
Ding et al 2012



Quenched calculation

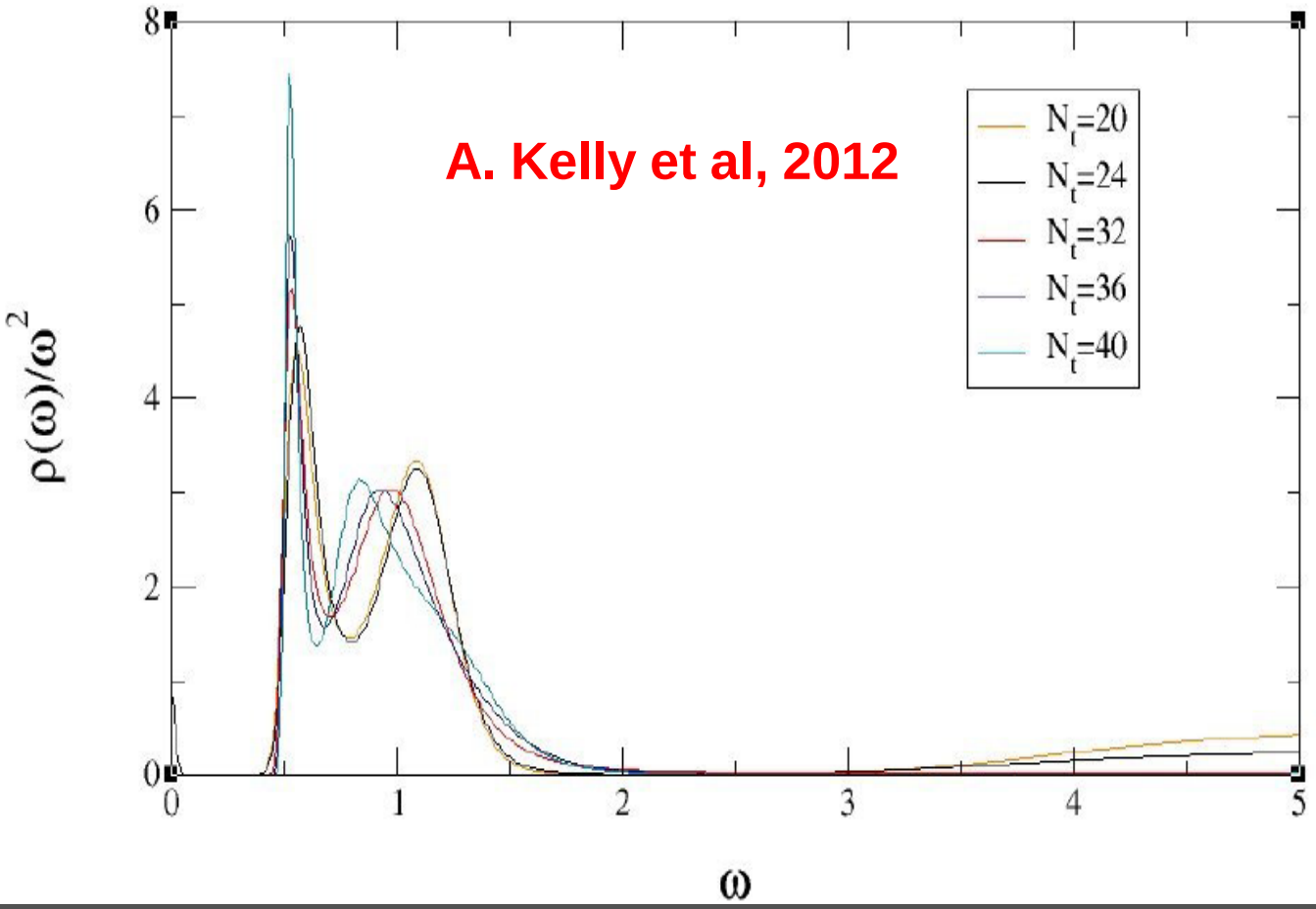
Charmonium Transport Peak

Ding et al.2012

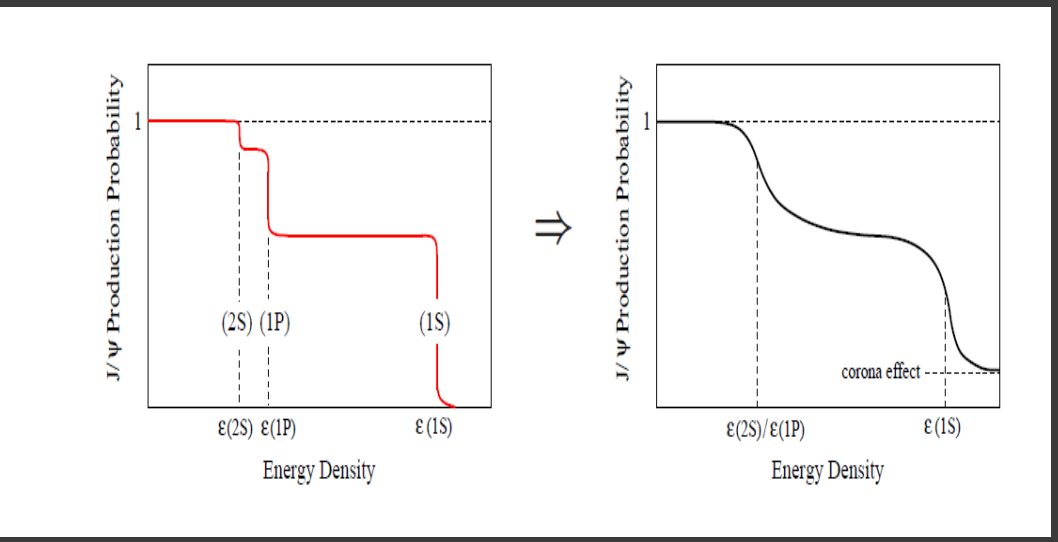


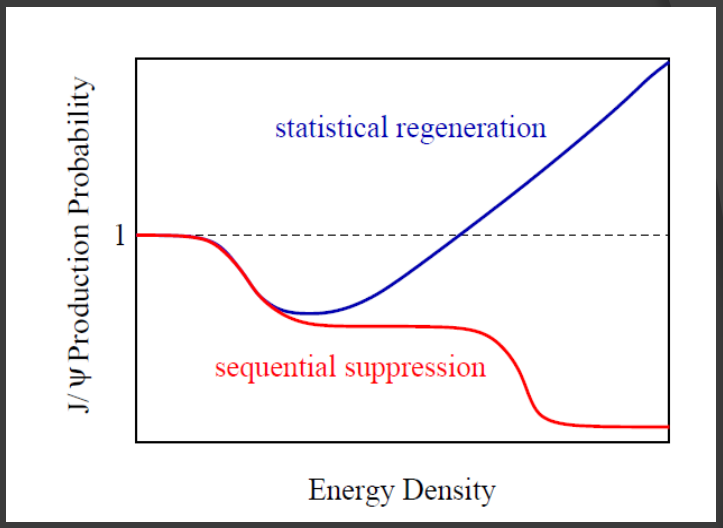
Quenched calculation

Charmonium and dynamical light quarks



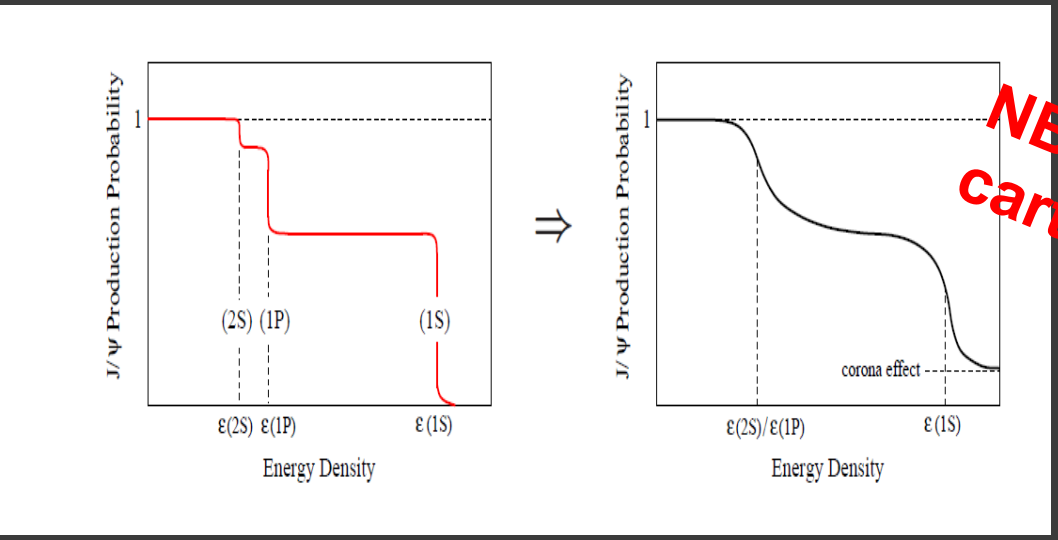
From spectral functions to sequential suppression: charmonium





From H. Satz

From spectral functions to sequential suppression: bottomonium



NB : just a cartoon!!

Bottomonium less affected by statistical regeneration !

Bottomonium

Aarts et al (FASTSUM) 2010-2012

- 1. Use full relativistic dynamics for up and down quarks (strange in progress)
- 2. Treat bottom with NRQCD
- 3. Make the most of correlators in Euclidean space.
- 4. MEM analysis → Spectral functions
- 5. Masses, Width and Effective models
- 6. Momentum and mass dependence

Step 1:

Full Relativistic Lattice QCD for light quarks with asymmetric gauge couplings to increase number of points in t-direction

N_s	N_τ	$T(\mathrm{MeV})$	T/T_c	N_{cfg}
12	80	90	0.42	250
12	32	230	1.05	1000
12	28	263	1.20	1000
12	24	306	1.40	500
12	20	368	1.68	1000
12	18	408	1.86	1000
12	16	458	2.09	1000

Step 2 : NRQCD for bottom quarks

Check: Zero Temperature Results

state	$a_\tau \Delta E$	Mass (MeV)	Exp. (MeV) [34]
$1^1S_0(\eta_b)$	0.118(1)	9438(7)	9390.9(2.8)
$2^1S_0(\eta_b(2S))$	0.197(2)	10009(14)	-
$1^3S_1(\Upsilon)$	0.121(1)	9460*	9460.30(26)
$2^3S_1(\Upsilon')$	0.198(2)	10017(14)	10023.26(31)
$1^1P_1(h_b)$	0.178(2)	9872(14)	-
$1^3P_0(\chi_{b0})$	0.175(4)	9850(28)	9859.44(42)(31)
$1^3P_1(\chi_{b1})$	0.176(3)	9858(21)	9892.78(26)(31)
$1^3P_2(\chi_{b2})$	0.182(3)	9901(21)	9912.21(26)(31)

NRQCD for bottom quarks:

NB Propagators initial value problem

$$G(\mathbf{x}, \tau = 0) = S(\mathbf{x}),$$

$$G(\mathbf{x}, \tau = a_\tau) = \left(1 - \frac{H_0}{2n}\right)^n U_4^\dagger(\mathbf{x}, 0) \left(1 - \frac{H_0}{2n}\right)^n G(\mathbf{x}, 0),$$

Temperature (= boundary condition) dependence is only due to the thermal medium!

NRQCD is still valid in our T range

$$\omega = 2M + \omega'$$

$$M \gg T$$

STEP 3 : Analysis of propagators in Euclidean time

Bound states for S and P waves

$$G(\tau) \sim \exp(-\Delta E \tau)$$

Free behaviour for S and P waves

$$G_S(\tau) \sim \int \frac{d^3p}{(2\pi)^3} \exp(-2E_{\mathbf{p}}\tau) \sim \tau^{-3/2},$$

$$G_P(\tau) \sim \int \frac{d^3p}{(2\pi)^3} \mathbf{p}^2 \exp(-2E_{\mathbf{p}}\tau) \sim \tau^{-5/2},$$

Laine et al 2010

$$E_{\mathrm{p}} = \mathrm{p}^2/2M$$

Υ and χ_b in the plasma :RESULTS

Bound states

$$G(\tau) \sim \exp(-\Delta E \tau),$$

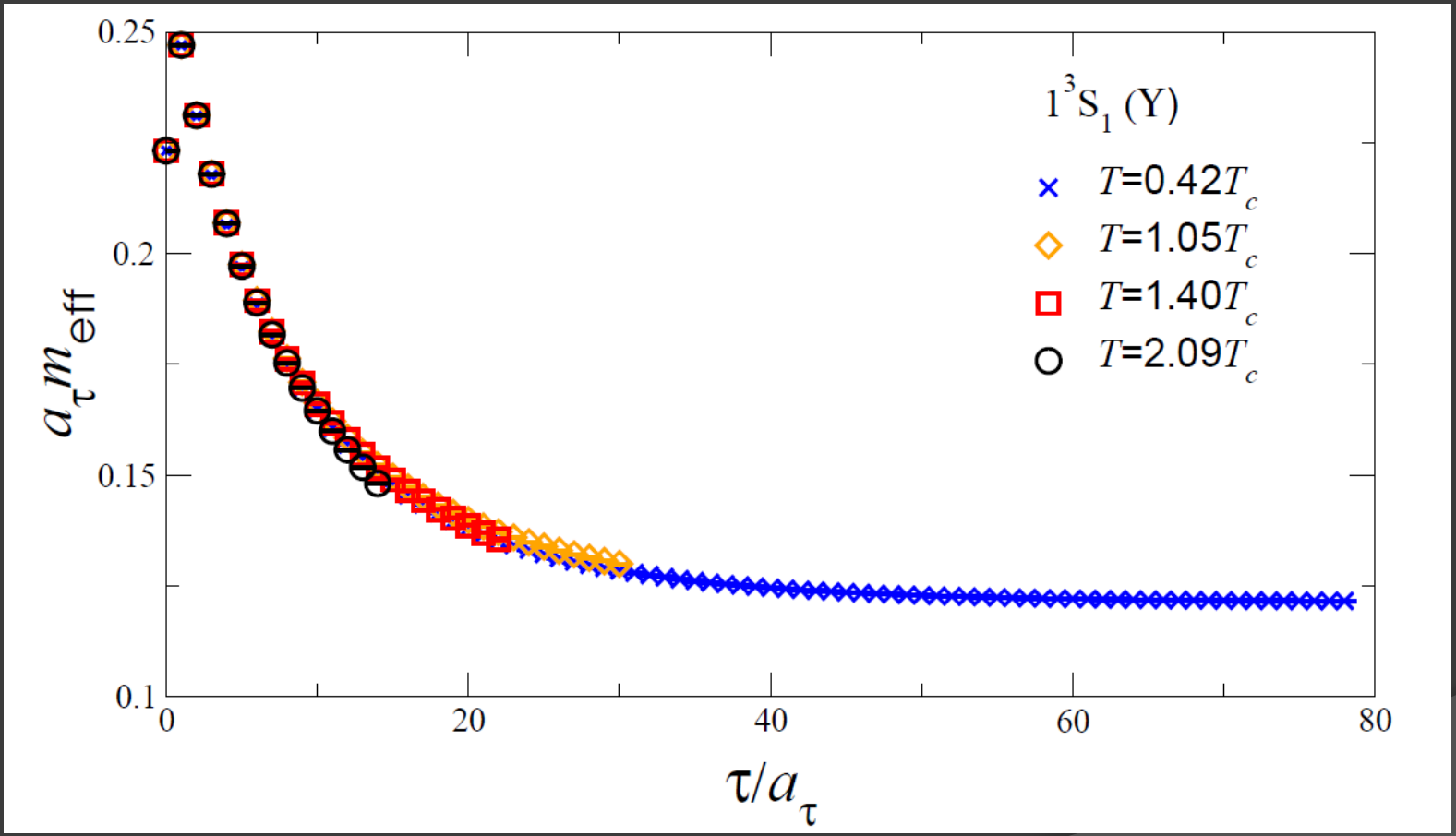
$$m_{\rm eff}(\tau) = -\log[G(\tau)/G(\tau - a_\tau)],$$

Free quarks

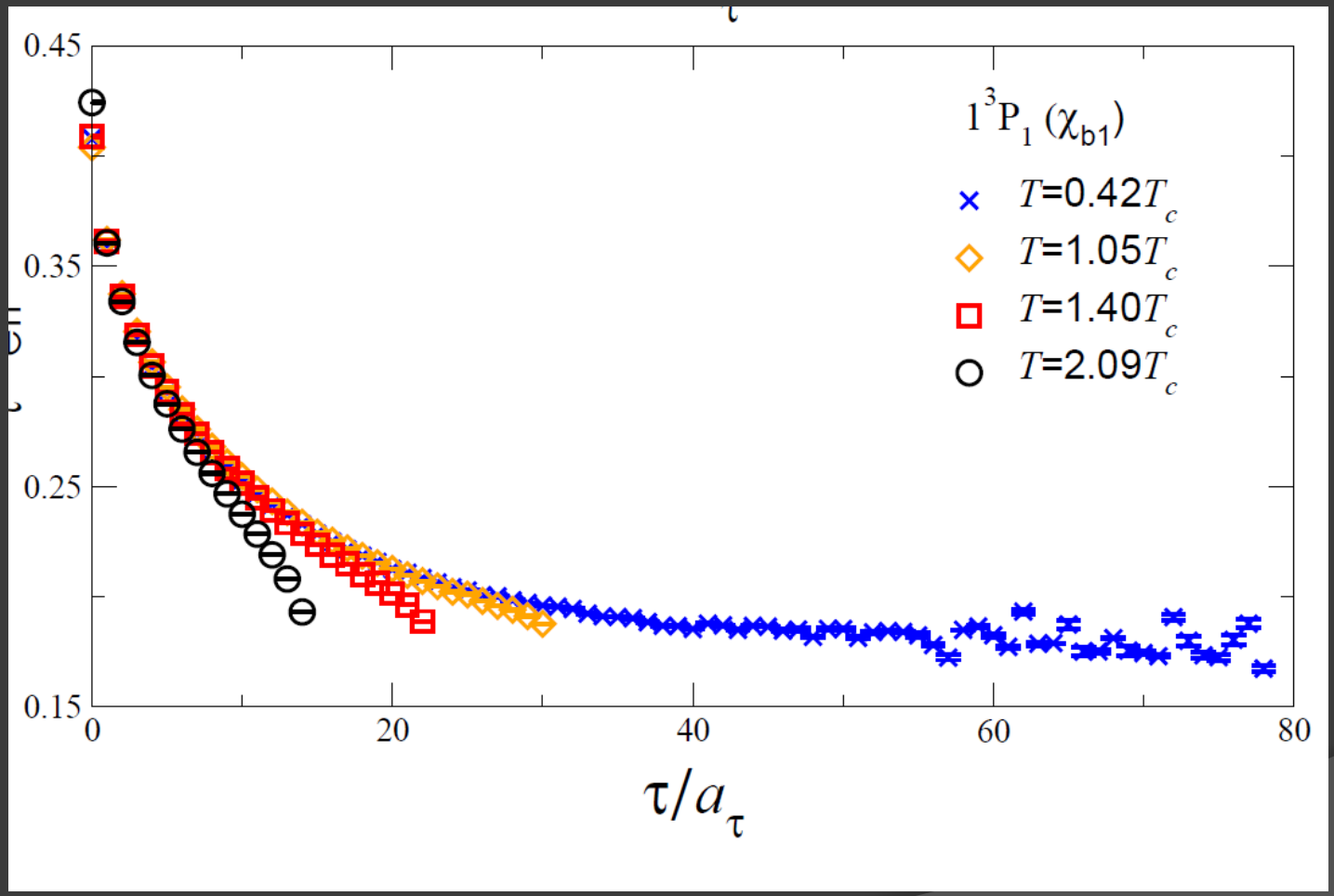
$$G(\tau) \sim \tau^{-\gamma}$$

$$\gamma_{\rm eff}(\tau) = -\tau \frac{G'(\tau)}{G(\tau)} = -\tau \frac{G(\tau + a_\tau) - G(\tau - a_\tau)}{2 a_\tau G(\tau)},$$

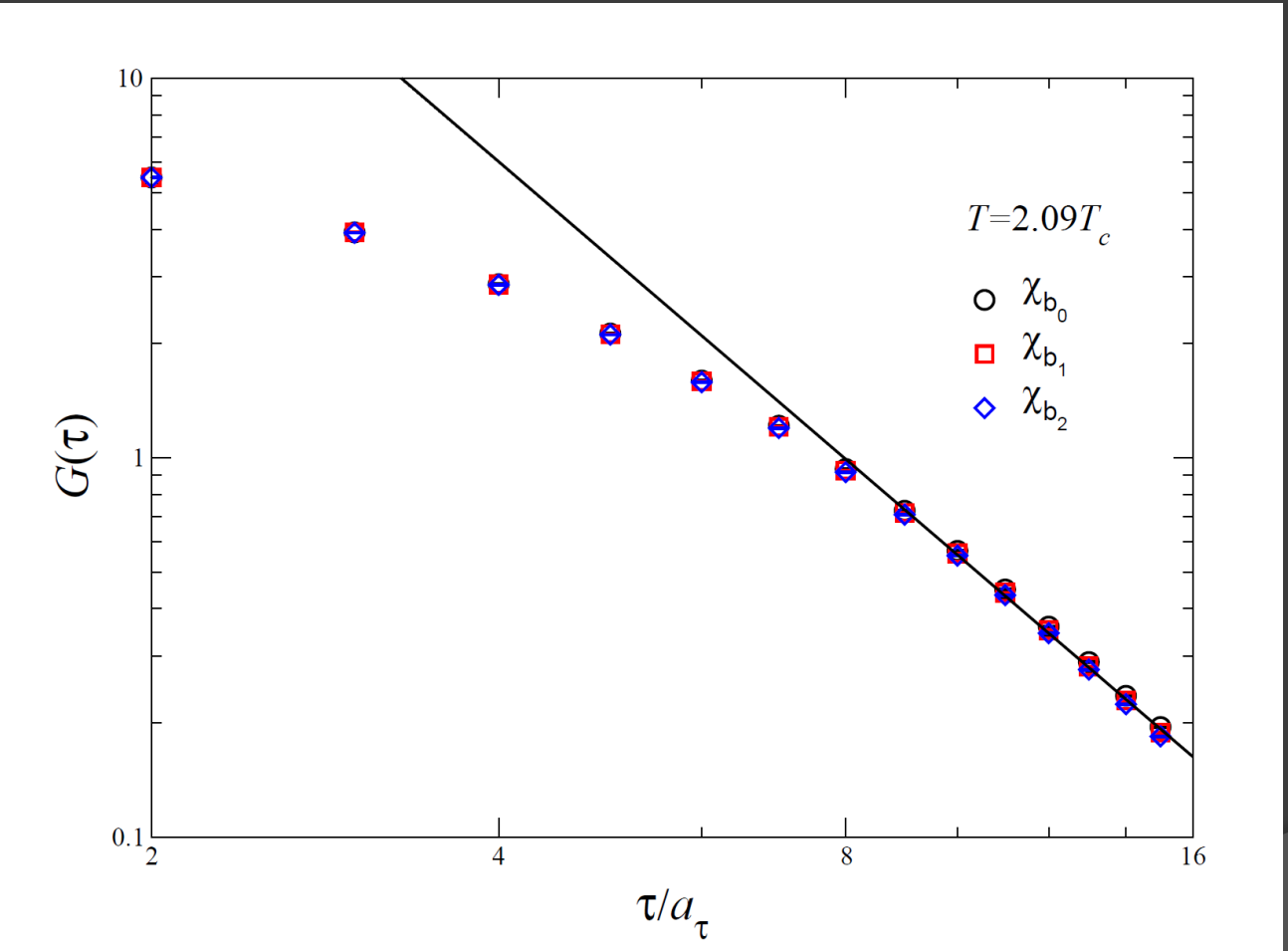
Effective mass for the Y



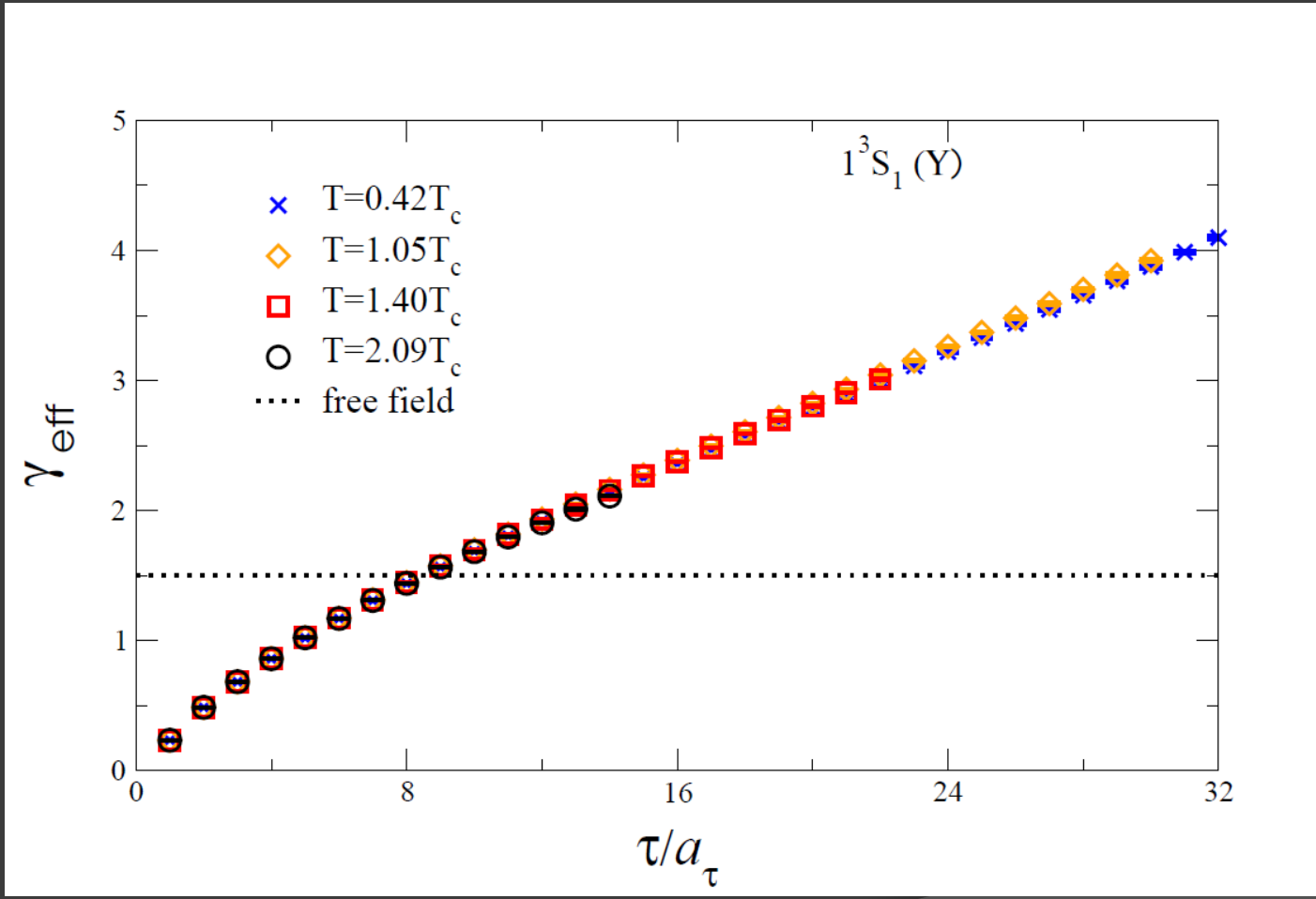
Effective mass for the χ



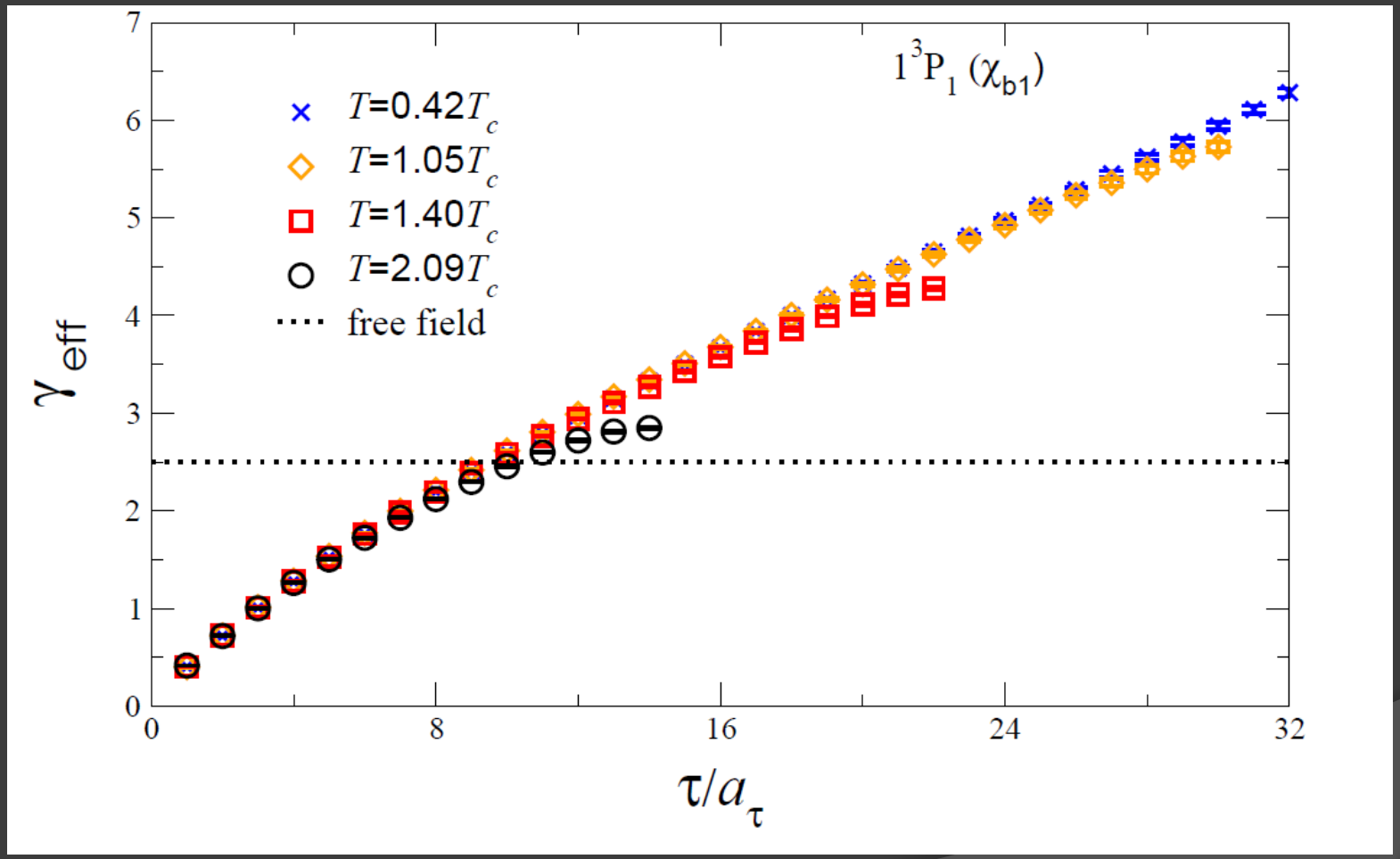
χ propagators and power law at T = 2.09 Tc : consistent with a free behaviour!



Y and (NO) free behaviour



χ free behaviour at T = 2.09Tc



Step 4: Spectral Functions

$$G(\tau) = \int_0^\infty \frac{d\omega}{\pi} \frac{\cosh\left[\omega(\tau - 1/2T)\right]}{\sinh\left(\omega/2T\right)} \rho(\omega).$$

Nontrivial spectral weight at small ω yields a constant τ-independent contribution to the correlator, which must be treated with care

Laine, Petreckzy et al.

Step 4: Spectral Functions

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Nontrivial spectral weight at small ω yields a constant τ-independent contribution to the correlator, which must be treated with care

Laine, Petreckzy et al.

$$G(\tau) = \int_{-2M}^\infty \frac{d\omega'}{\pi} \exp(-\omega'\tau)\rho(\omega') \qquad \text{(NRQCD)}$$

Spectral Functions

NRQCD PLUS'es:

No Temperature dependence in the kernel

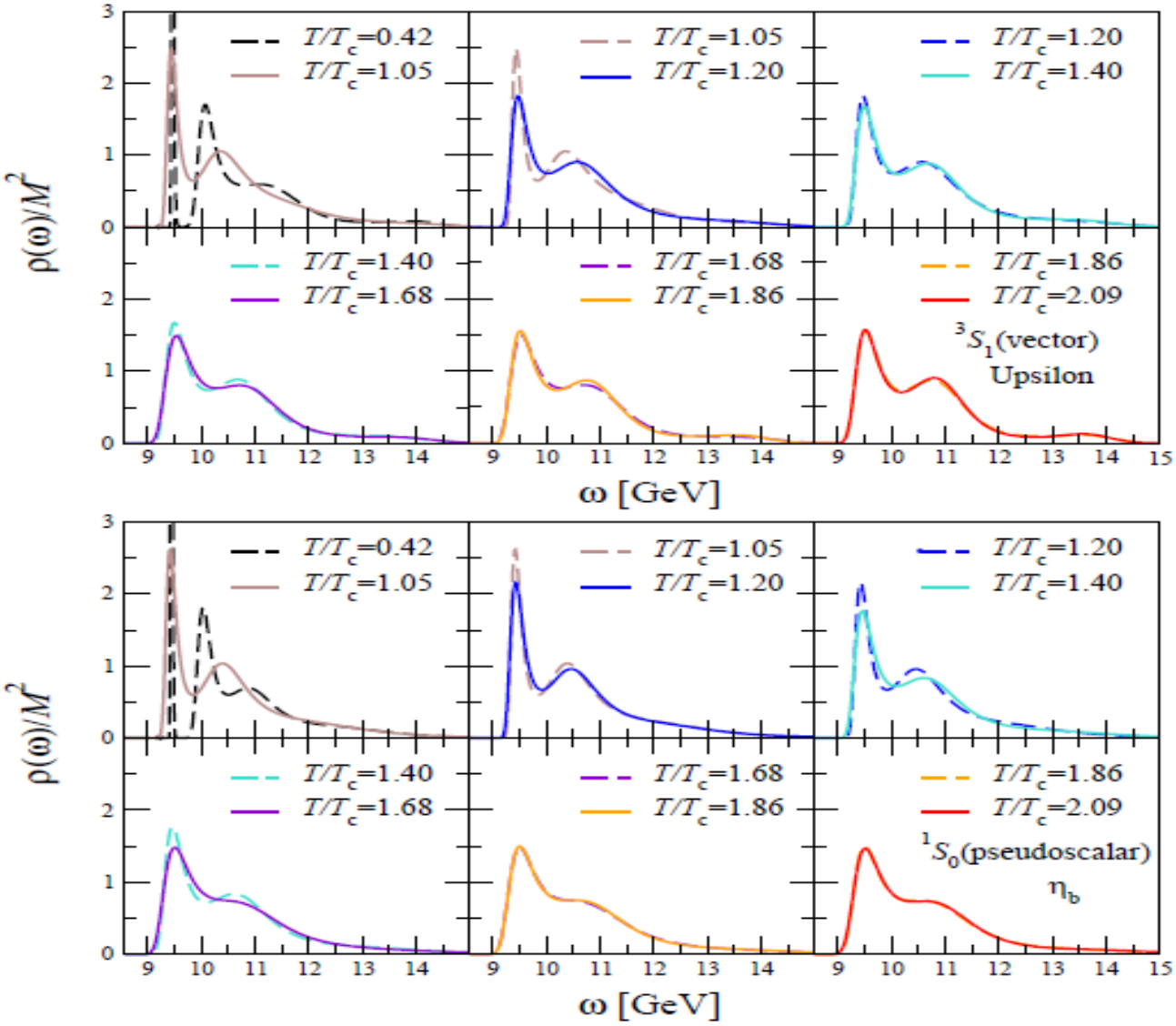
No problem with zero modes

Easier MEM analysis

Temperature dependence of the Euclidean correlators entirely dynamical

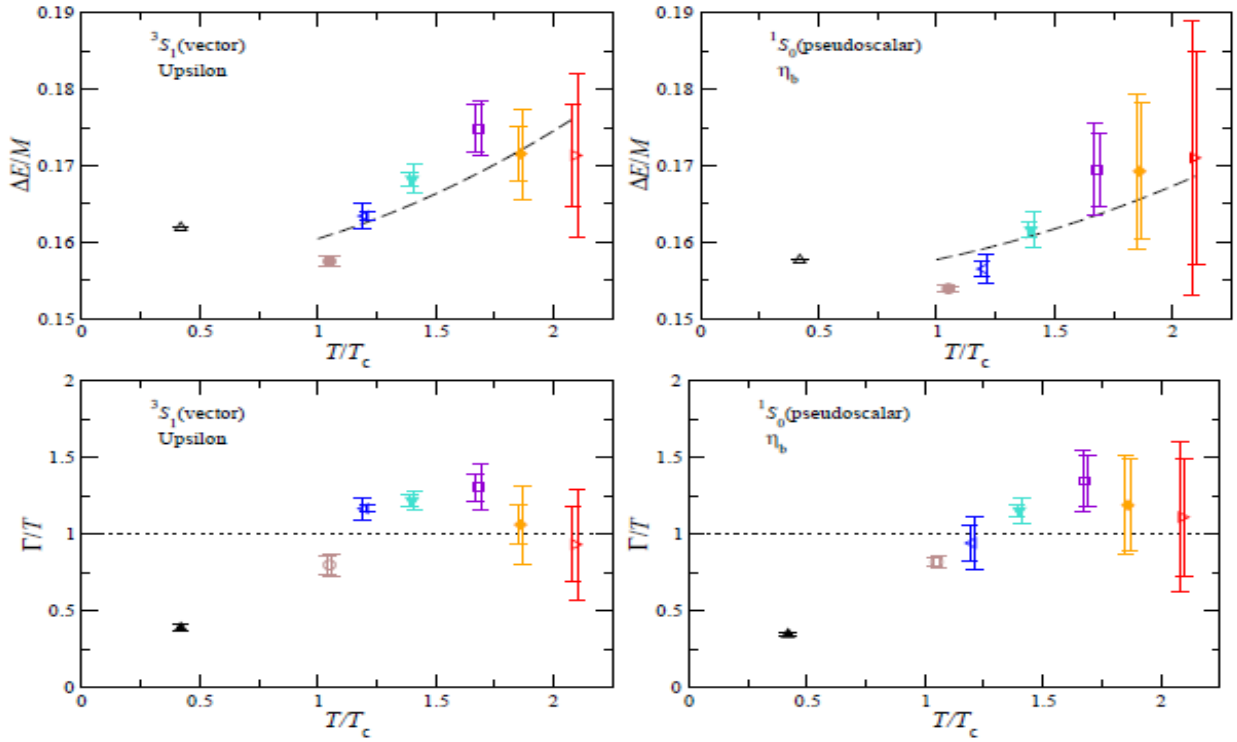
$$G(\tau) = \int_{-2M}^{\infty} \frac{d\omega'}{\pi} \exp(-\omega'\tau)\rho(\omega') \qquad \text{(NRQCD)}$$

NRQCD spectral functions – S waves



Step 5 : Results for Masses and Widths

S-Waves



Dashed line :
fit motivated by

Brambilla et al 2010

Comparision with weak coupling expansion [Brambilla et al.2010]

$$\frac{\Gamma}{T} = \frac{1156}{81}\alpha_s^3 \simeq 14.27\alpha_s^3,$$



$$\alpha_s \sim 0.4,$$

Should be applicable when
Eb < T < $1/R_B$

$$\frac{\delta E_{\text{thermal}}}{M} = 5.93\alpha_s \left(\frac{T_c}{M}\right)^2 \left(\frac{T}{T_c}\right)^2 \sim 0.0046 \left(\frac{T}{T_c}\right)^2.$$

Fit to:

$$\frac{\Delta E}{M} = c + 0.0046 \left(\frac{T}{T_c}\right)^2$$

Momentum dependence

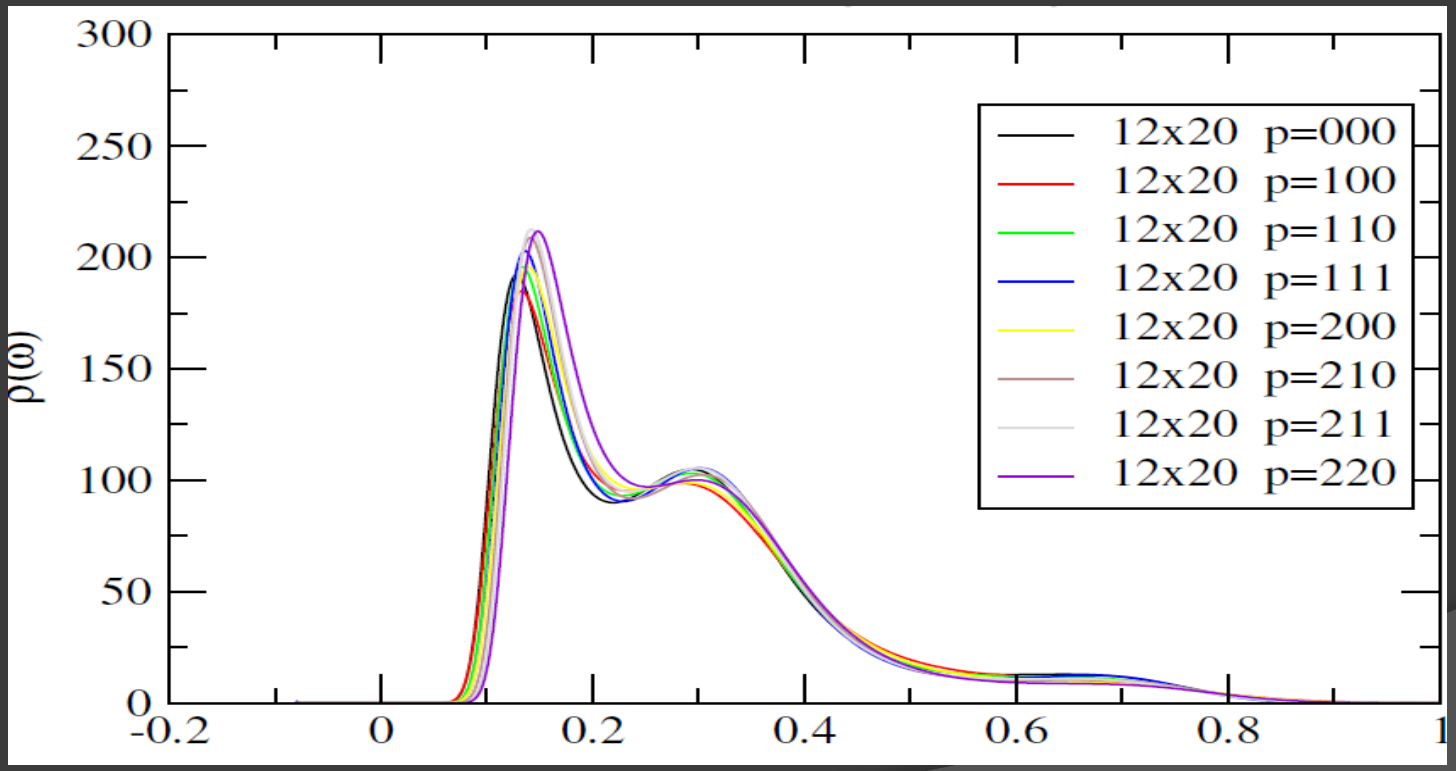
Aarts et al (FASTSUM) 2012

NRQCD for bottom

Two light flavors

Momentum dependence : v^2 sim 0.3. Visible in spectral function

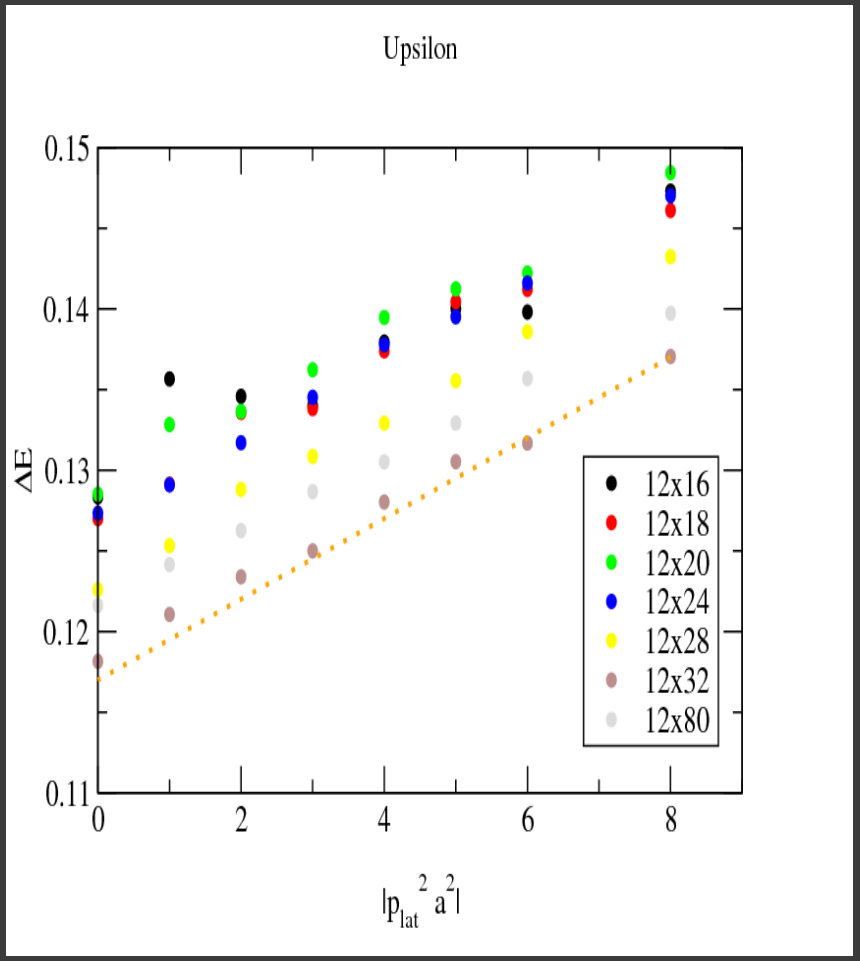
Heavy mass dependence consistent with potential models

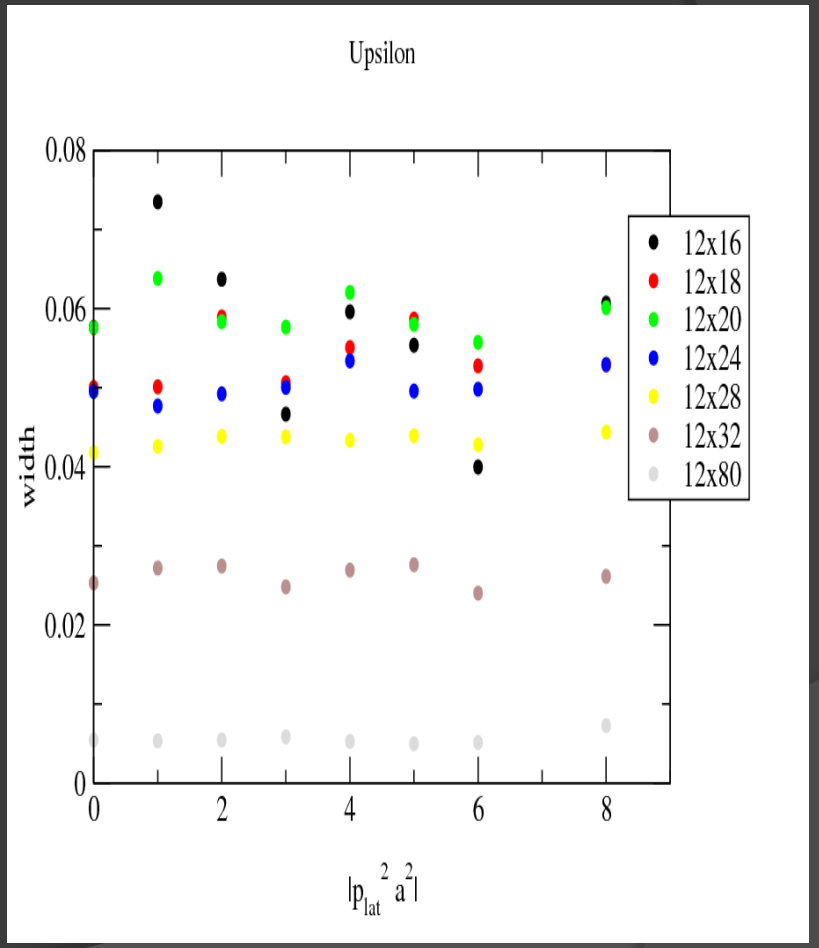


S. Kim at Lattice2012

Momentum dependence of poles and widths

observations consistent with Soto et al 2010





Summary

- *Potential* studies of quarkonia steadily developing. Uncertainties on the choice of the potential still affecting the results
- High quality results for ***charmonium*** from relativistic spectral functions with quenched gauge fields.
- Possible to extract trasport coefficient
- No signs of bound states at temperatures above **1.46 Tc**
- The temperature dependence of ***bottomonium*** for 0.4 Tc < T < T 2.1 Tc has been investigated with nonrelativistic dynamics for the bottom quark and full relativistic QCD for up and down quarks
- Correlators and spectral functions indicate that the Upsilon and η_b fundamental states are insensitive to the temperature in this range
- The χ show a crossover from an exponential decay characterizing the hadronic phase to a power-law behaviour consistent with nearly-free dynamics at 2Tc
- The Upsilon and η_b excited states are no longer visible at temperatures above **1.4 Tc** , in agreement with experimental observations at RHIC and LHC

Three open questions (among others..):

- Effects of the sea quark masses (quenched vs two flavors vs two plus one flavor?)
- Control over MEM analysis: alternative techniques, and/or direct numerical inversion of the Laplace transform?
- Analytic models for intepreting the correlators in Euclidean time?

When answered, it will perhaps be possible to use lattice results to indentify the correct heavy quark potential