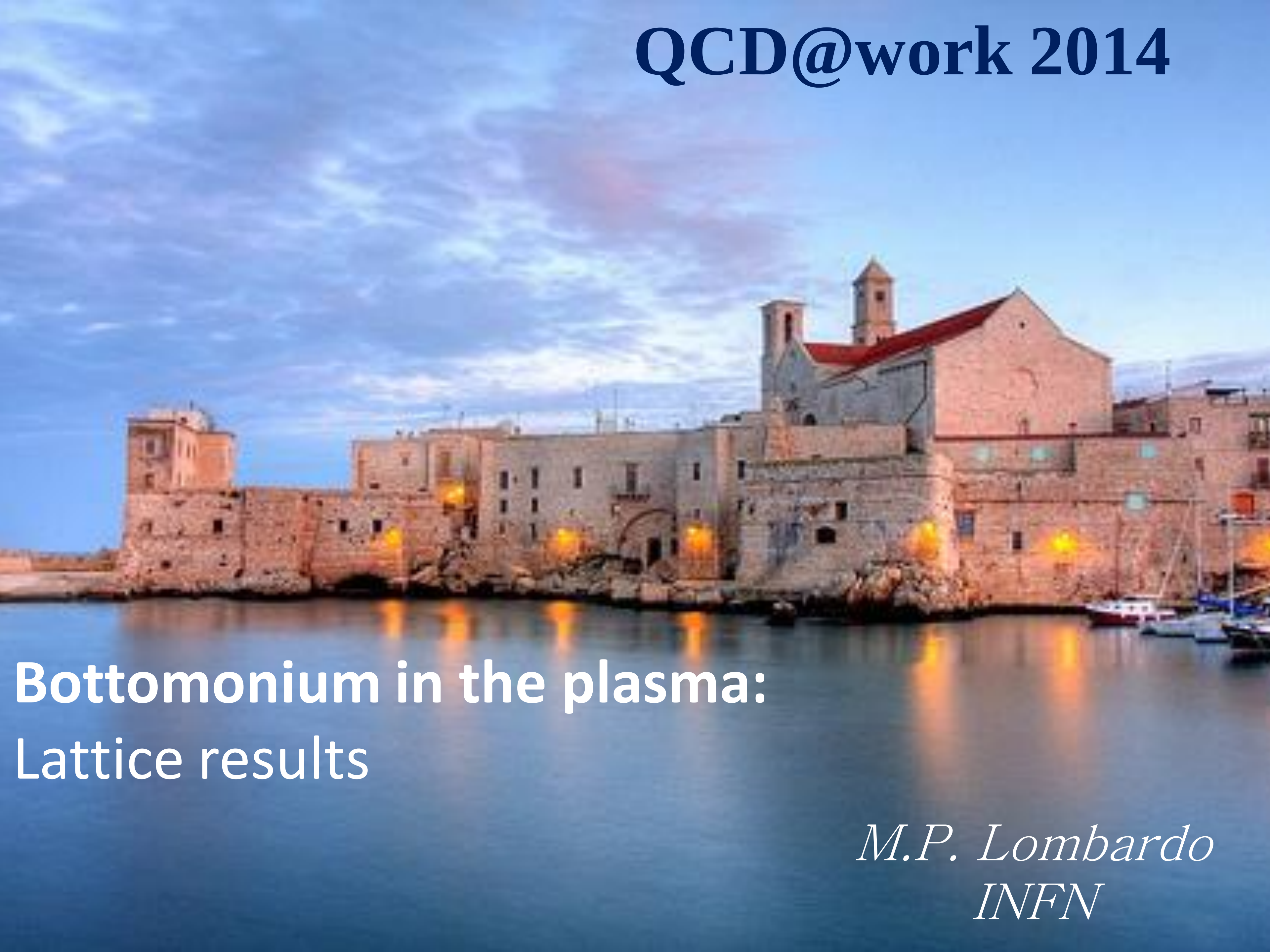
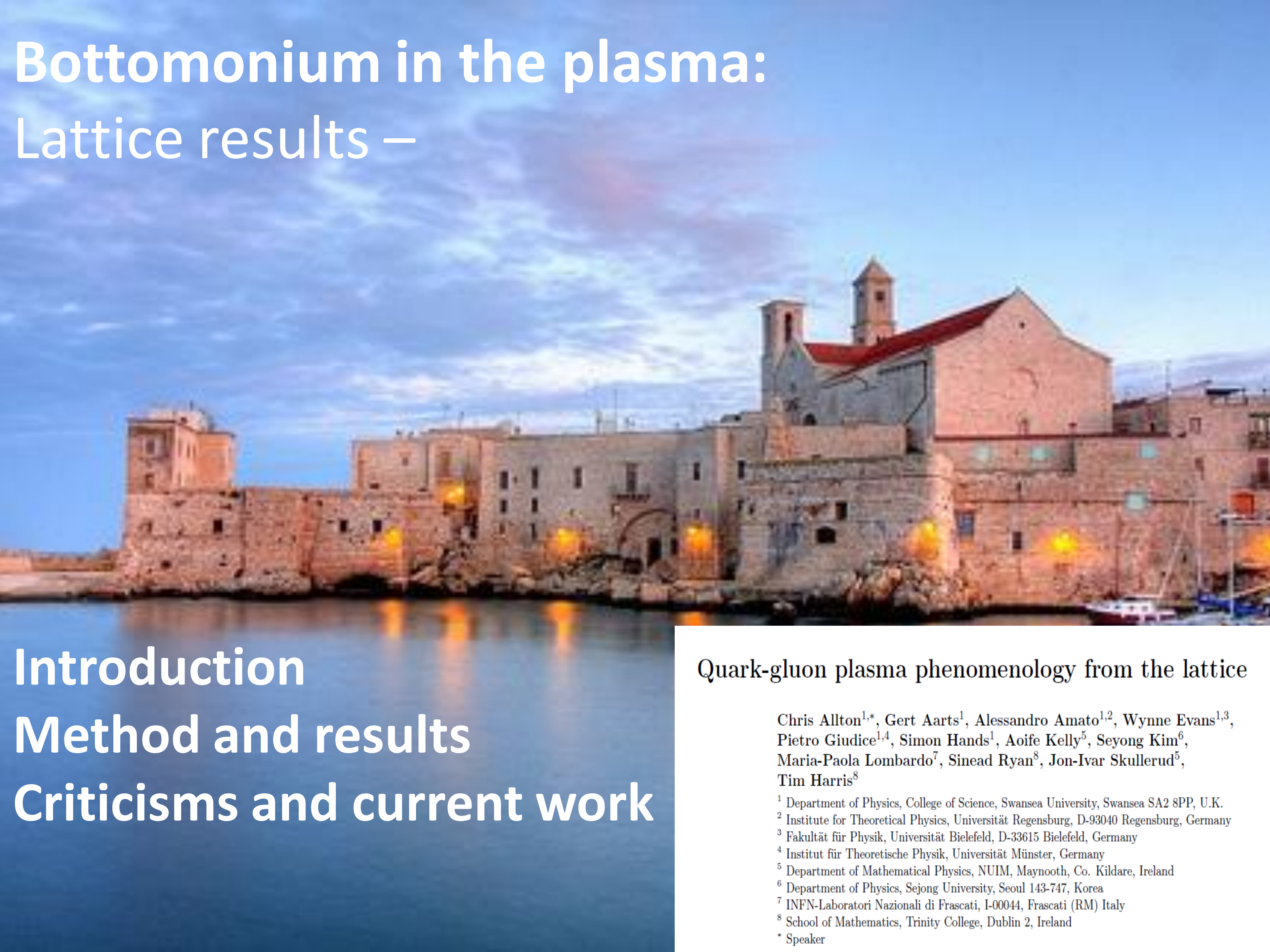


QCD@work 2014

Bottomonium in the plasma:
Lattice results

M.P. Lombardo
INFN



Bottomonium in the plasma:

Lattice results –

Introduction

Method and results

Criticisms and current work

Quark-gluon plasma phenomenology from the lattice

Chris Allton[1,*], Gert Aarts[1], Alessandro Amato[1,2], Wynne Evans[1,3], Pietro Giudice[1,4], Simon Hands[1], Aoife Kelly[5], Seyong Kim[6], Maria-Paola Lombardo[7], Sinead Ryan[8], Jon-Ivar Skullerud[5], Tim Harris[8]

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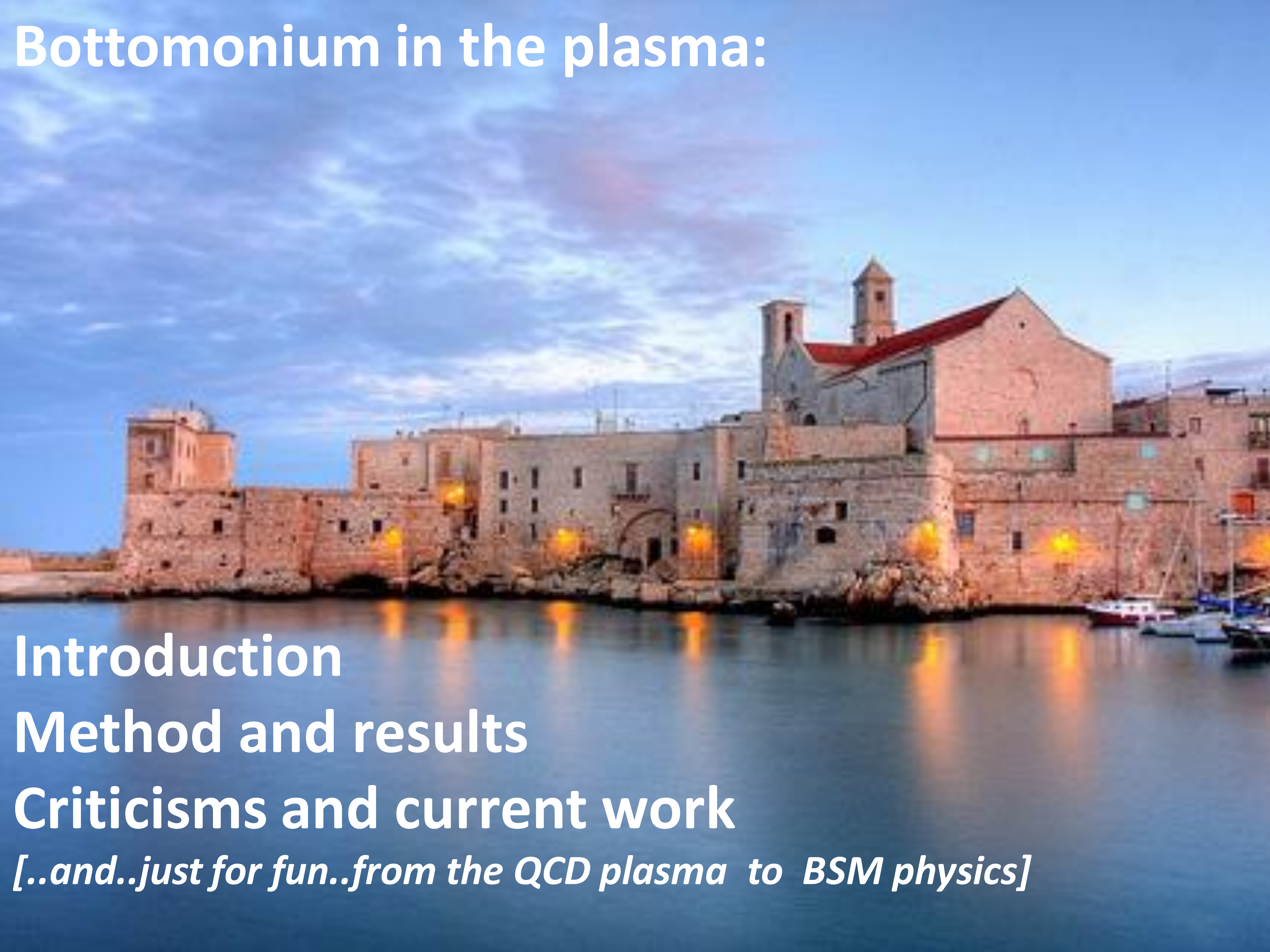
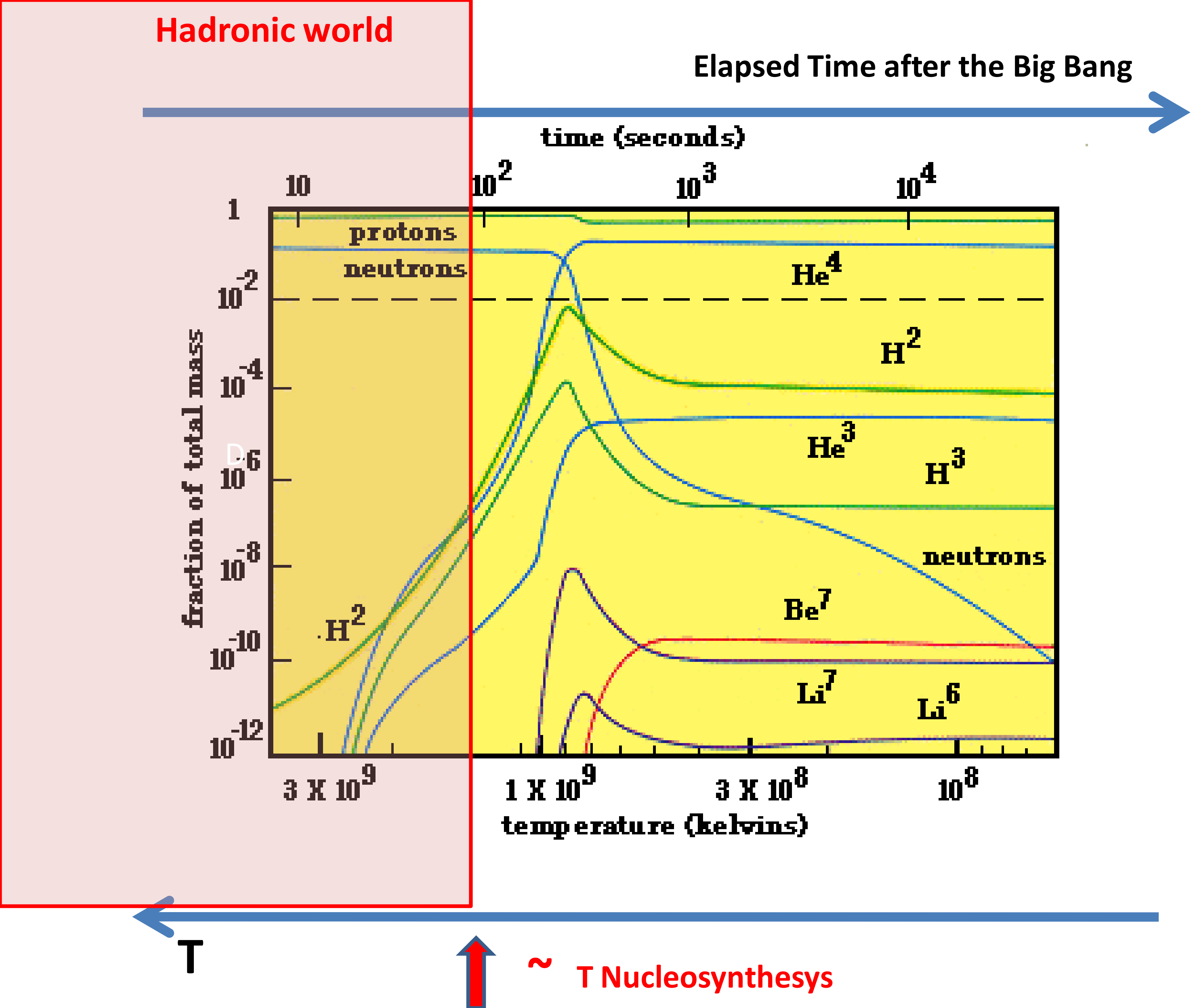
[8] School of Mathematics, Trinity College, Dublin 2, Ireland
[*] Speaker



Bottomonium in the plasma:

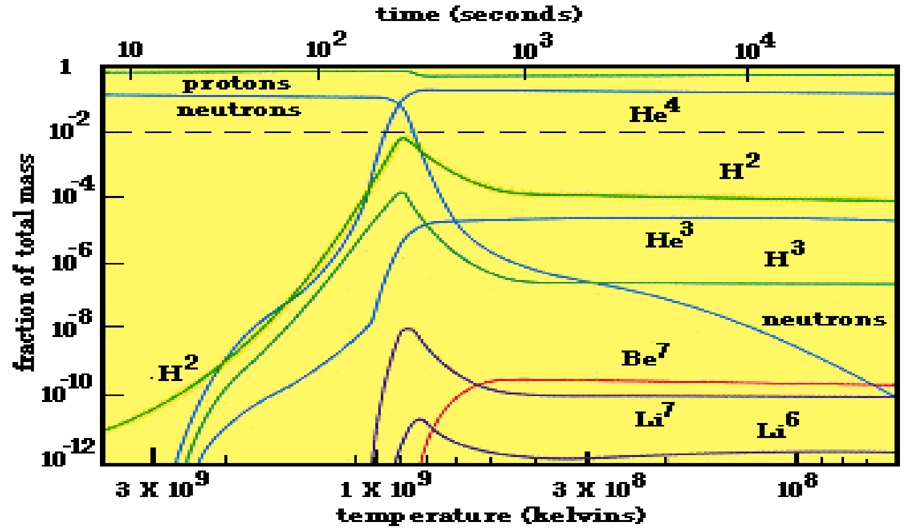
Introduction
Method and results
Criticisms and current work

[..and..just for fun..from the QCD plasma to BSM physics]



Hadronic world
Elapsed Time after the Big Bang
time (seconds)
10
10^{2}
10^{3}
10^{4}
1
protons
neutrons
He^{4}
10^{-2}
H^{2}
10^{-4}
He^{3}
H^{3}
10^{-6}
10^{-8}
neutrons
Be^{7}
H^{2}
10^{-10}
Li^{7}
Li^{6}
10^{-12}
fraction of total mass
$3 X 10^{9}$
$1 X 10^{9}$
$3 X 10^{8}$
10^{8}
temperature (kelvins)
T
~ T Nucleosynthesys

The hadronic world and Hagedorn's limiting temperature.



$\rho(m) \sim \exp(m/T_h)$

T_h= 170 MeV (10^13 K.)

hence

$Z(T) \sim \int dm\, \rho(m) \exp(-m/T)$

Diverges at T_h

T_h is the *extreme temperature* for the hadronic world

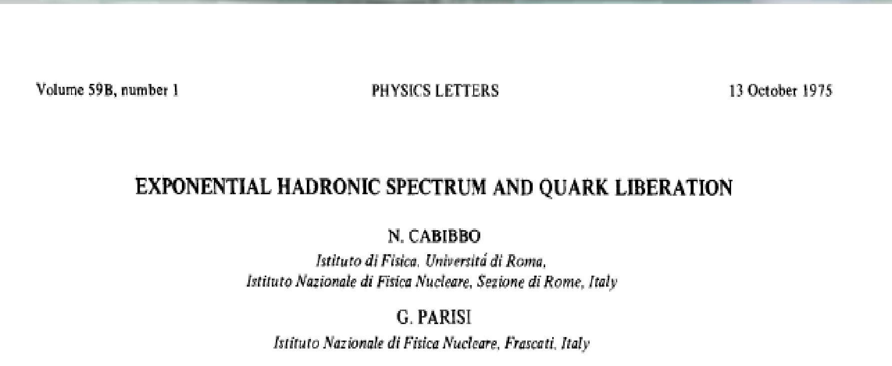

Finisterrae Hadronic World: T= 10^13 Kelvin

Quark Gluon Plasma

beyond finisterrae ..

Strongly interactive quark gluon plasma

Hadronic Matter



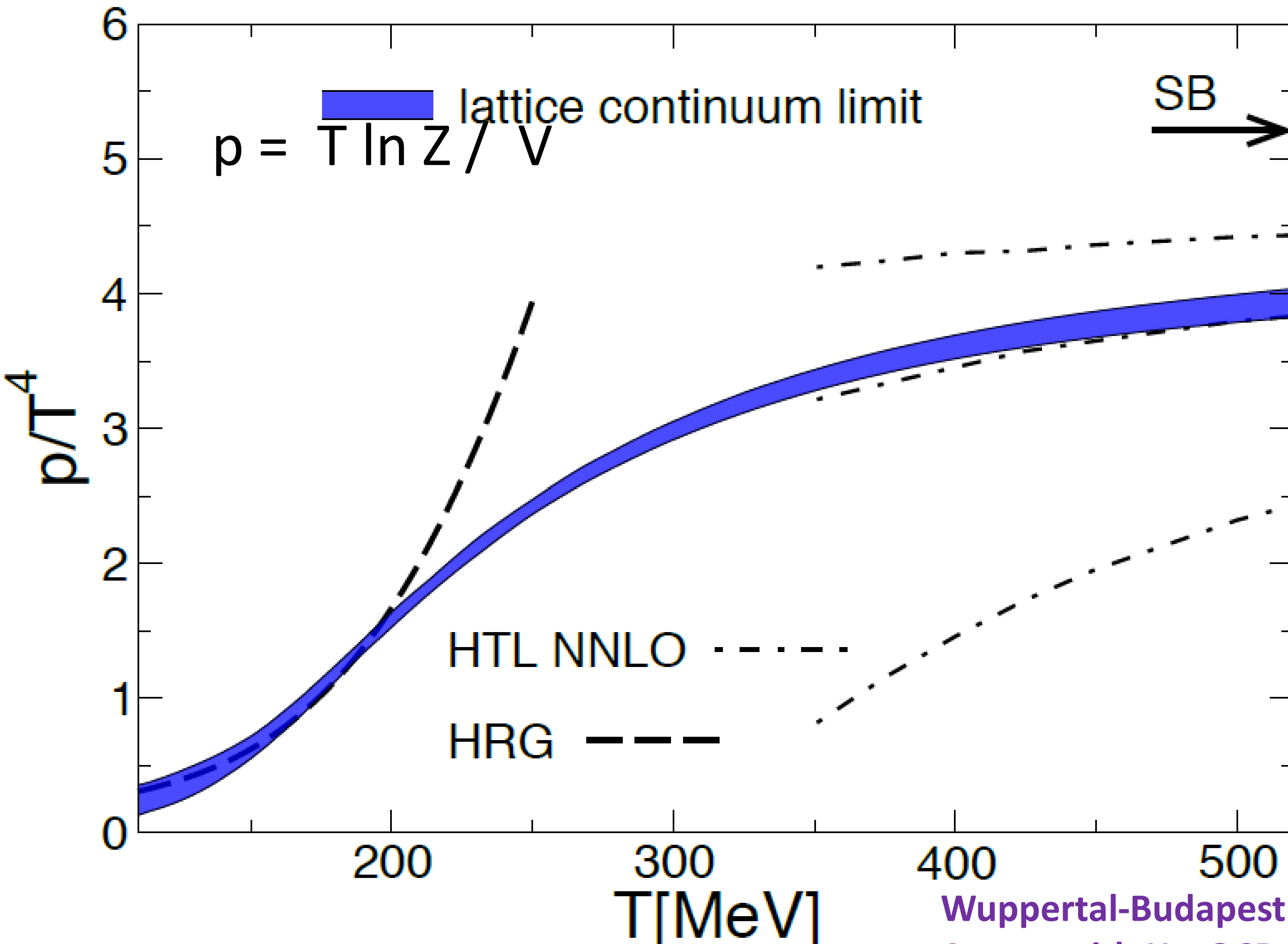
Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

2014 Status



Wuppertal-Budapest 2014
Agrees with HotQCD
(Ding and Bazavov at QM2014)

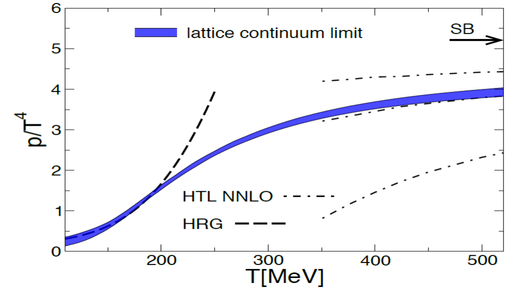
Pressure : counting degrees of freedom

From low temperature gas of light pions to
free quarks and gluons (SB limit):

Gluons Quarks

$$\frac{p}{T^4} = \left(2(N^2 - 1) + 4NN_f\frac{7}{8} \right) \frac{\pi^2}{90}.$$

We are proceeding towards free quarks,
but we are not really there yet..



Nature of the transition?

Nature of the medium, relevant degrees of freedom, interactions?

Pressure : counting degrees of freedom

From low temperature gas of light pions to free quarks and gluons (SB limit):

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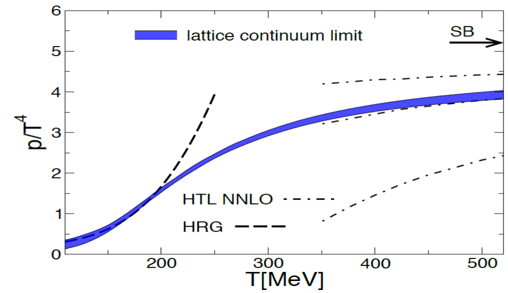


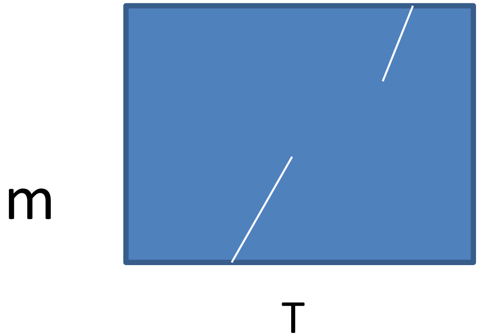
Nature of the transition?

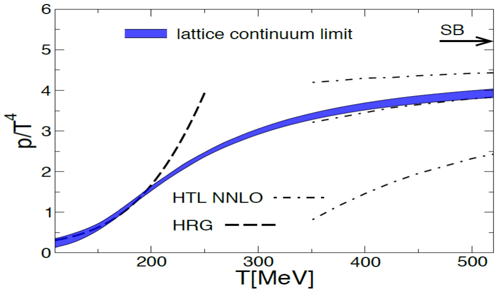
Nature of the medium, relevant degrees of freedom, interactions?

Phases of QCD

Deconfinement – Confinement : m =∞

Exact order parameter for infinite quark mass





Chirally broken – Chirally symmetric :m = 0

Exact order parameter for massless quark

QCD Symmetries, lattice and the real world

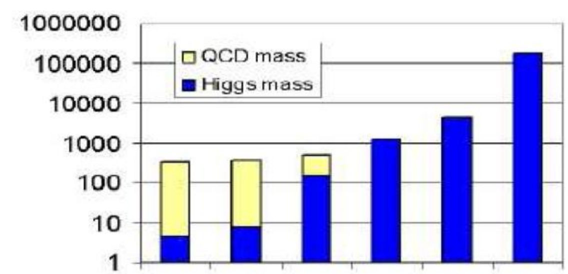
High T

$SU(N_f)_R \times SU(N_f)_L \times U_A(1)$

$SU(N_f)_V$

Low T

c,b,t do not participate in the chiral dynamics around the critical temperature. Lattice simulations around Tc are then performed with up,down,strange quarks – Nf = 2+1



	SU(N)XSU(N)	$U_A(1)$
Staggered	Remnant U(1)	Broken
Wilson	Broken	Broken
Domain Wall	Exact (for $L \to \infty$)	Exact (for $L \to \infty$)
Overlap	Exact	Exact

Quarkonia:
bottomonia (and charmonia)

Ideal probe of gauge dynamics at high T

Tc	340 –380 MeV RHIC AuAu 200 GeV	420-480 MeV LHC 2.76 TeV	500- 600MeV LHC hot spots 2.76 TeV	→	**1 GeV** **LHC** **7 TeV**
≈200MeV					[Expected]

Quark Gluon Plasma @ Colliders

Milestones to Bottomonium as QGP 'thermometer'

Charmonium suppression predicted

Matsui-Satz 1986

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

Surprise I: Not really...previous theoretical analysis too crude. Cold nuclear matter effects – unrelated to QGP – might well reduce the primordial charmonum rate. Further competing effects between thermalization rate and formation time of charmonium.

- Sequential suppression,

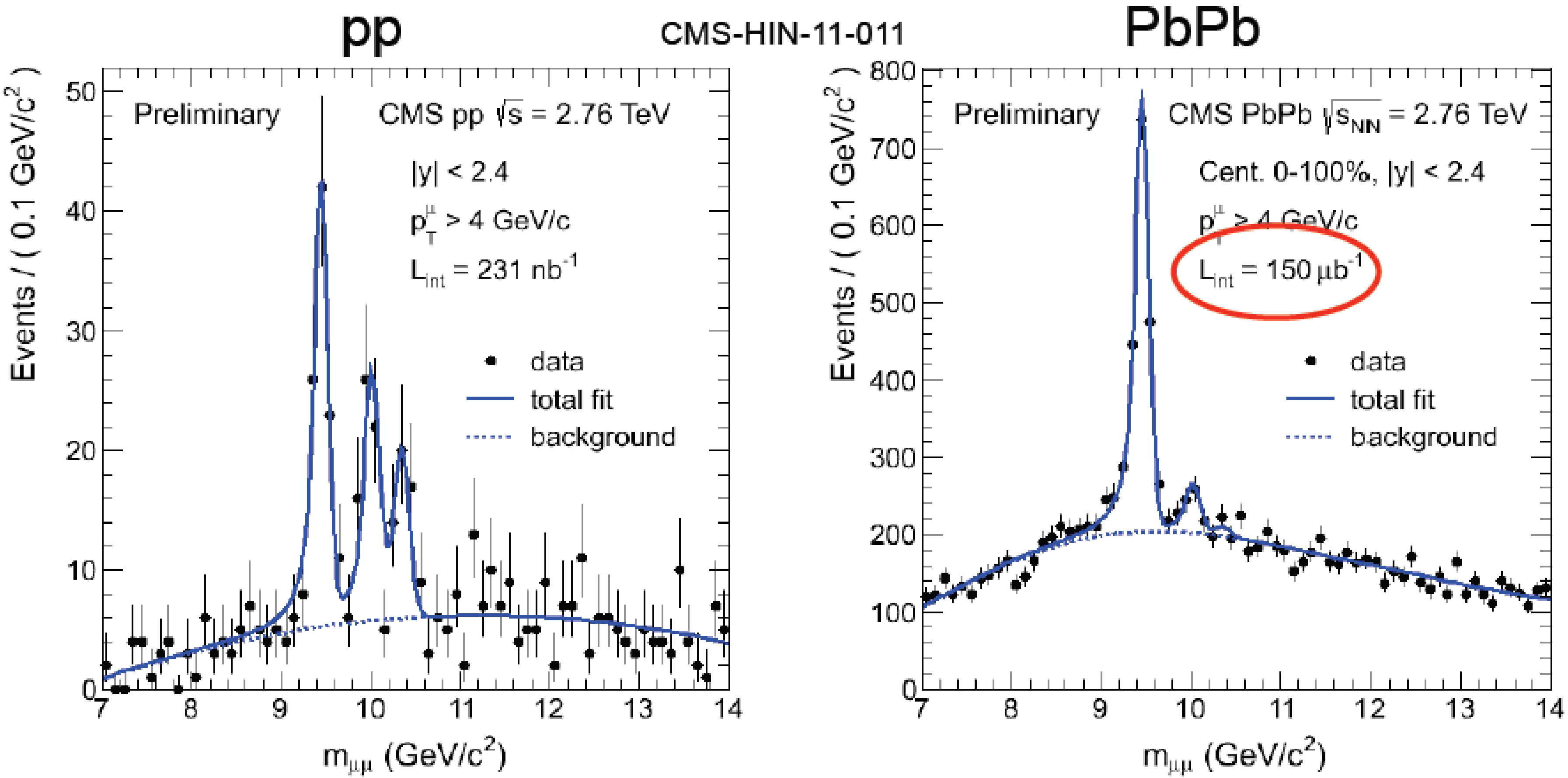
RHIC and LHC era

Surprise II ! Charmonia production and suppression rates at RHIC and LHC quite similar – regeneration effects compensating higher suppression.

Intepretation – Bottomonium less subjected to regeneration. Cleanest probe for the Quark Gluon Plasma.

High precision Charmonium AND Bottomonium physics – calling for accurate theoretical predictions .

Bottomonia: T Ca. 420 MeV



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

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

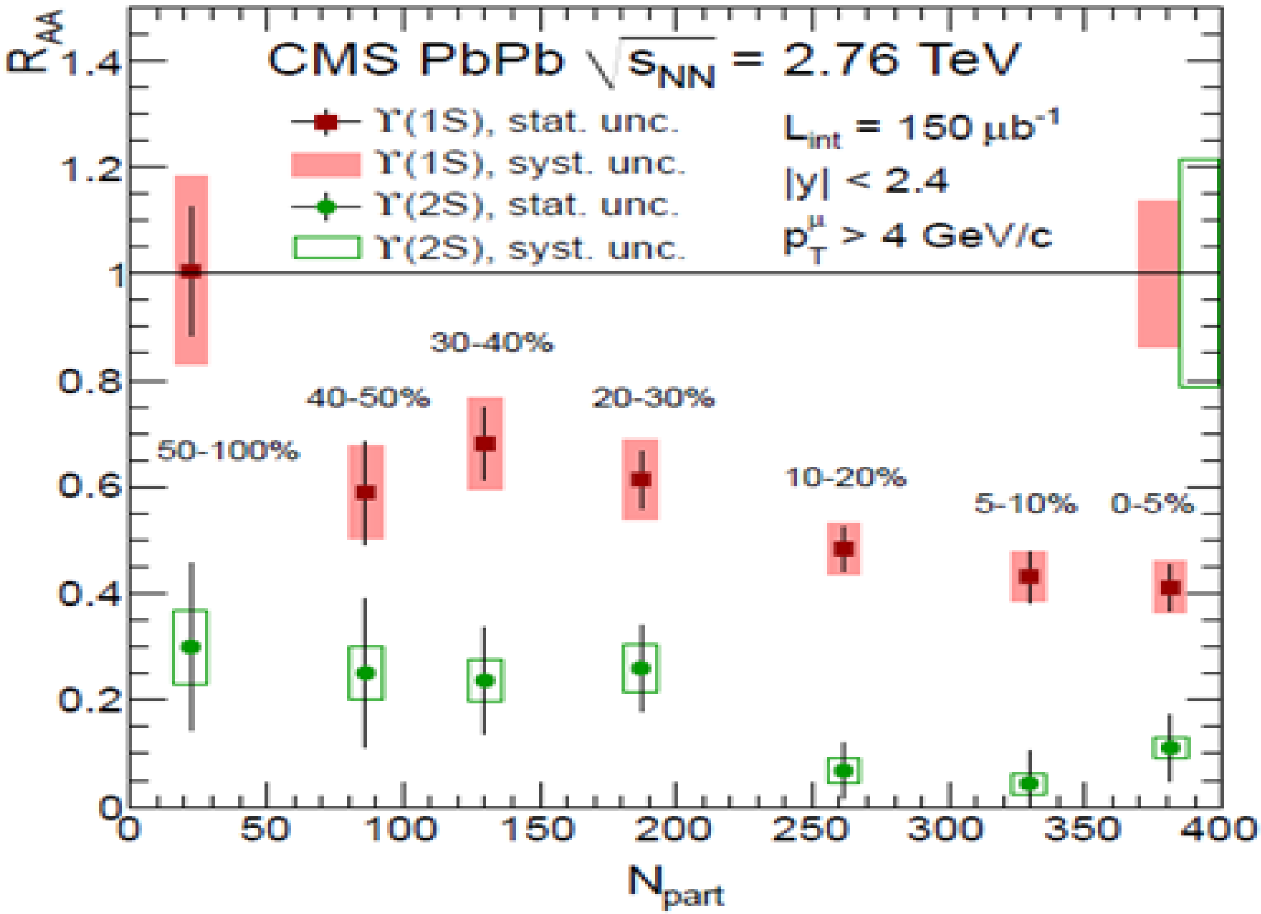
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

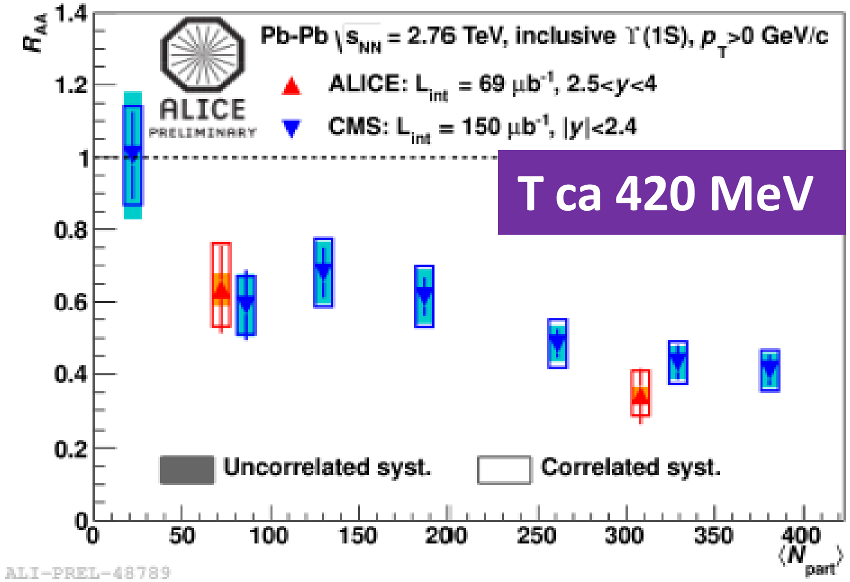
Ratios not corrected for acceptance and efficiency

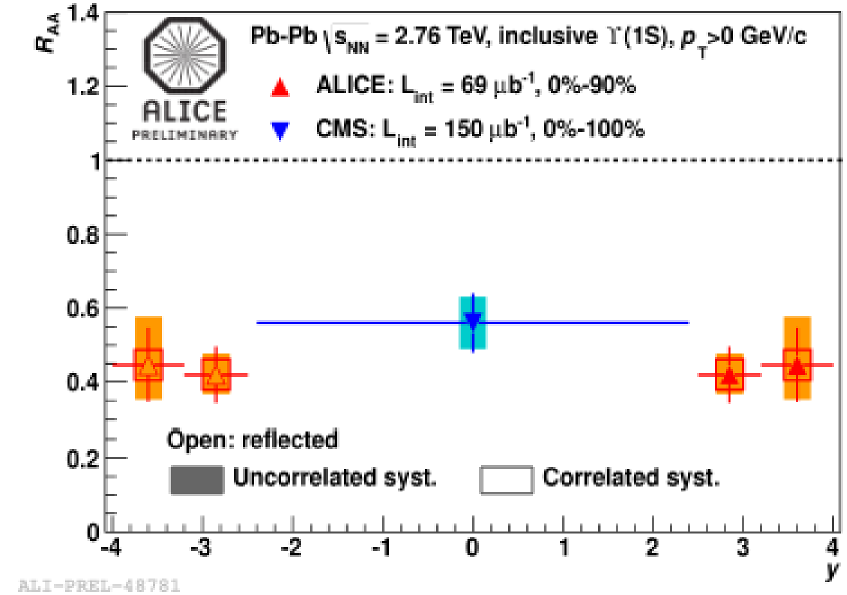
T Ca. 420 MeV : Dissociation of excited states

A. Andronic QM2014



Comparison of ALICE forward-rapidity results with CMS mid-rapidity



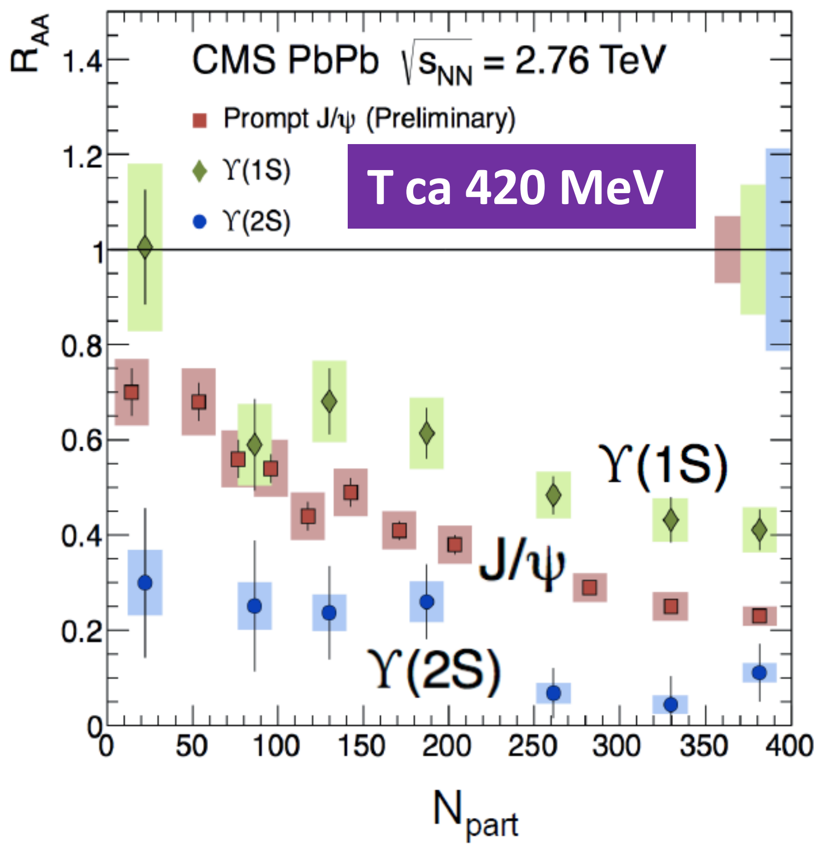


→ The suppression at forward rapidity in ALICE is similar to that at mid-rapidity measured by CMS for both central and semi-peripheral collisions

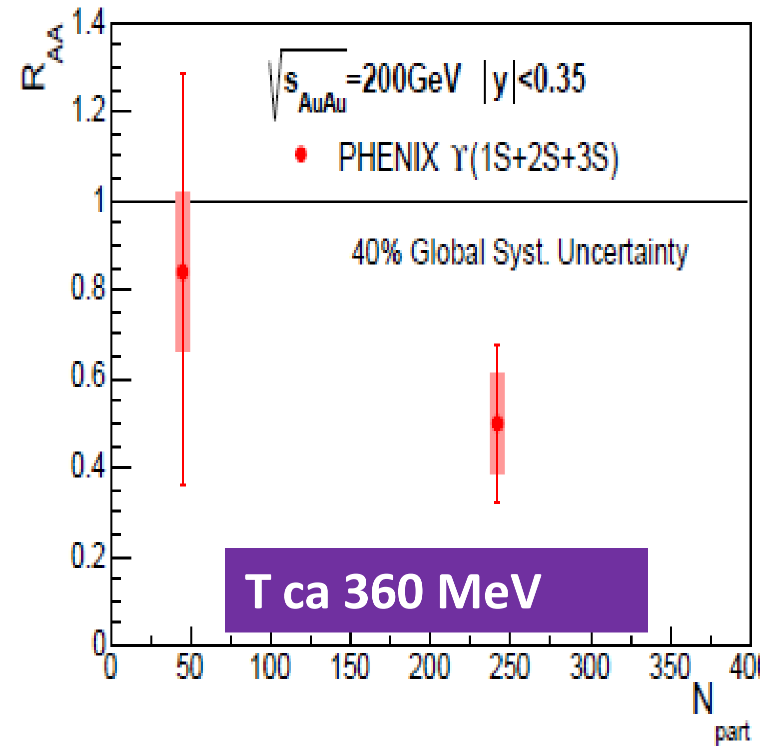
→ No strong rapidity dependence of R_{AA} within the large range probed by ALICE and CMS

Reference for CMS Data points: PRL 109, 222301, (2012)

Comparison of CMS (LHC) with Phenix (RHIC)

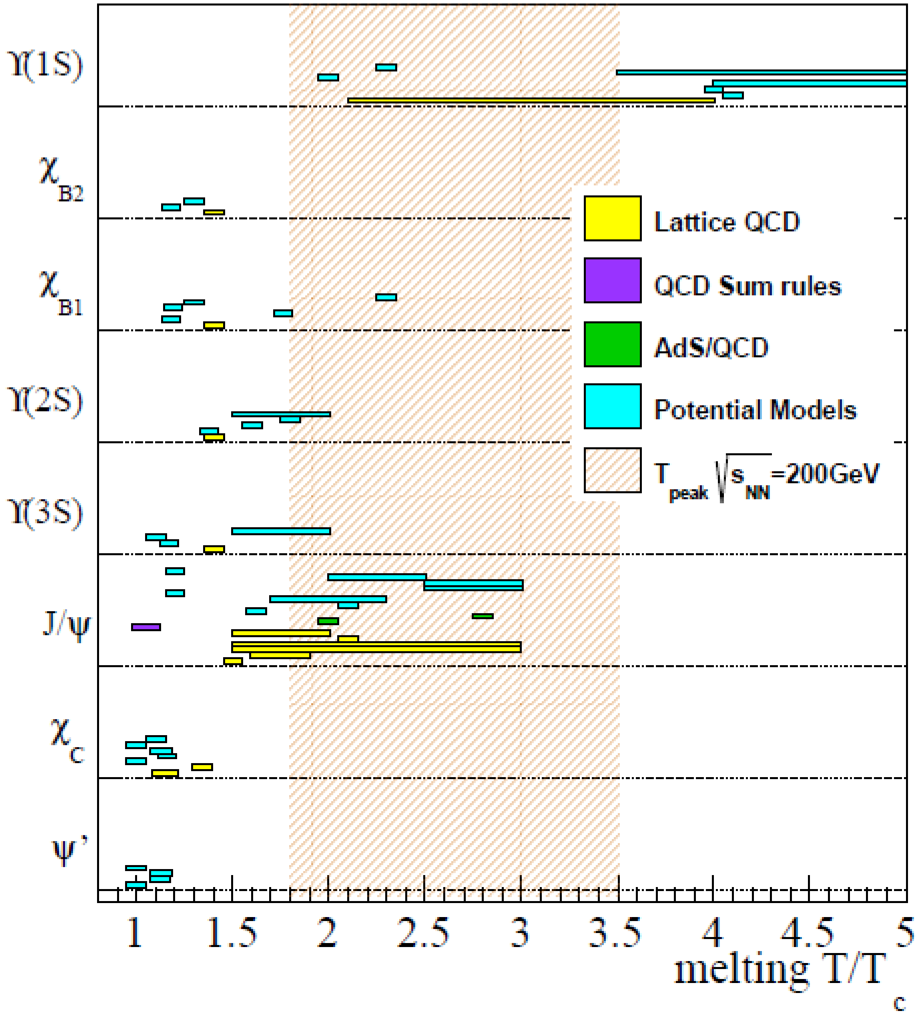


Phenix 2014



Quarkonium suppression as a thermometer of the QGP:

Melting temperatures from different approaches

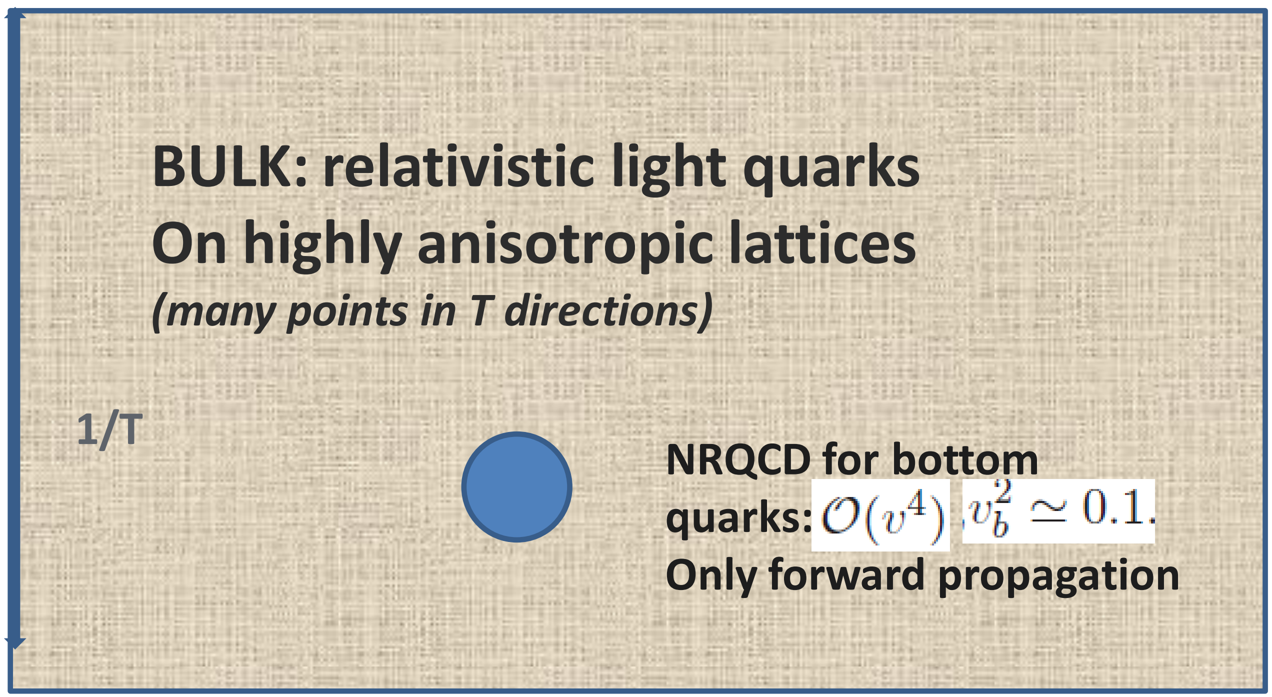


Compilation from PHENIX 2014

Method and Results

A controlled lattice approach to Bottomonium

$$m_u, m_d \ll m_s \simeq T_c \simeq \Lambda_{QCD} \ll \quad m_c, m_b$$

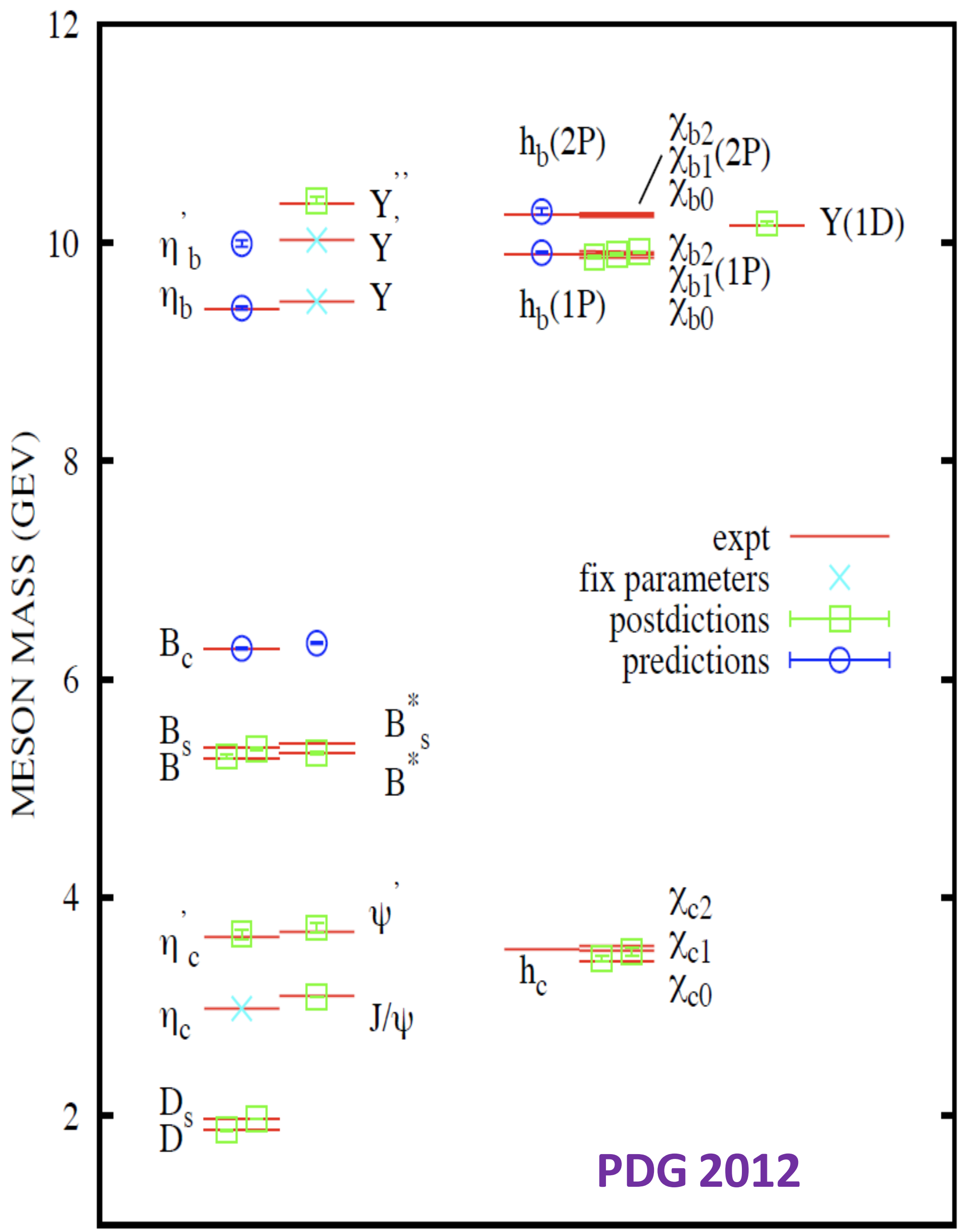


$$G(n + a_\tau e_\tau) = \left(1 - \frac{a_\tau H_0|_{n_\tau + a_\tau}}{2k}\right)^k U_\tau^\dagger(n) \left(1 - \frac{a_\tau H_0|_{n_\tau}}{2k}\right)^k (1 - a_\tau \delta H)\, G(n).$$

Bottomonium states from lattice NRQCD

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)

Fastsum 2012



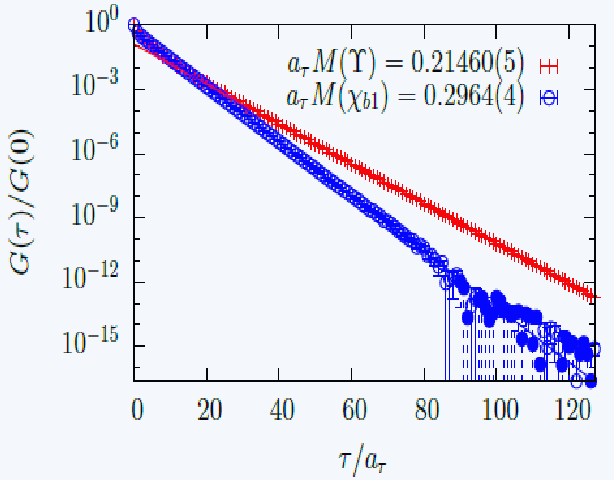
PDG 2012

On the lattice : correlators in Euclidean time

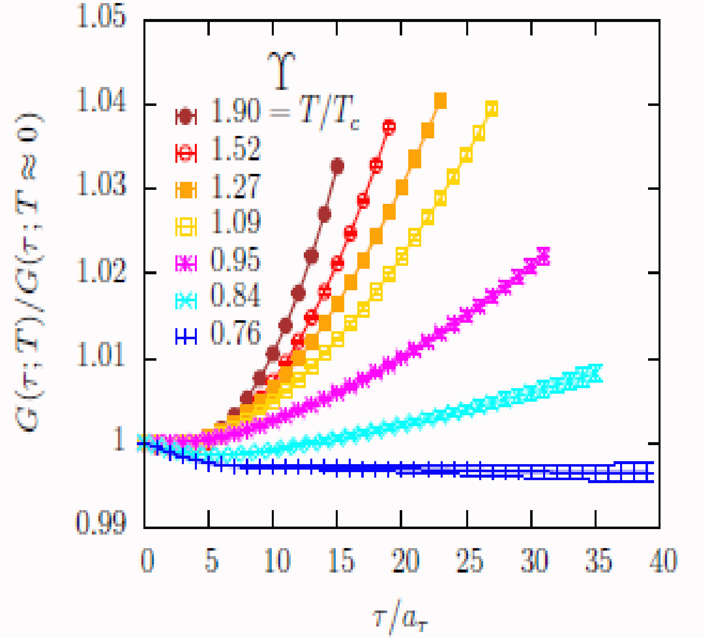
T=0

G(t) = A exp(-mt)

t →∞

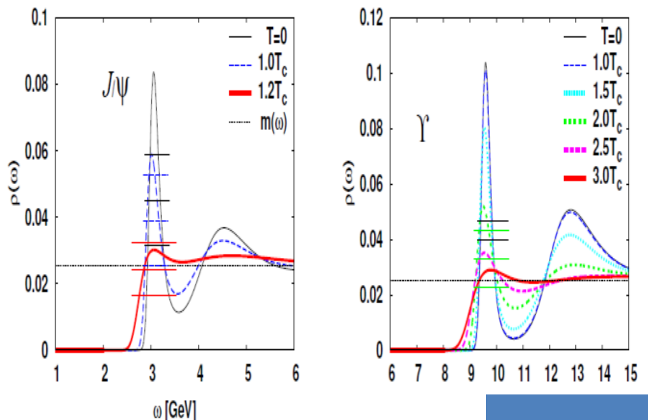


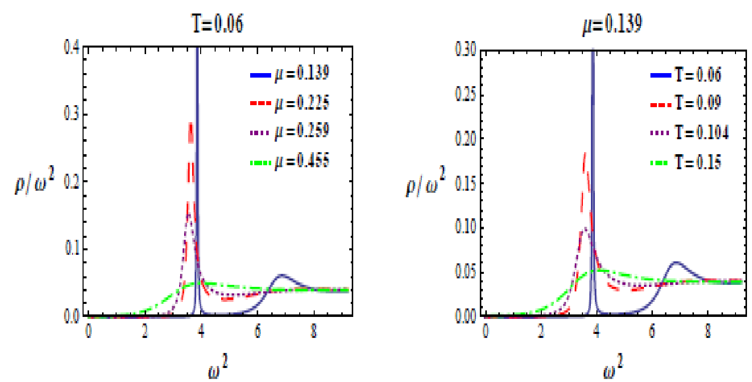
- Thermal modifications



What we need : Spectral functions

- Full physical information
- Directly related to transport coefficients
- **Computable in model theories and in HTL**





P. Colangelo, F. Giannuzzi and S. Nicotri 2012

K.Morita 2012

QCD sum rules

Holographic QCD

Spectral analysis of correlators

In general

$$G(\tau) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K(\tau,\omega)\rho(\omega),$$

$$K(\tau,\omega) = \frac{\cosh\left[\omega(\tau - 1/2T)\right]}{\sinh\left(\omega/2T\right)} \longrightarrow \exp(-\omega'\tau)$$

For NRQCD

$$\rho_{\text{free}}(\omega) \propto (\omega-\omega_0)^{\alpha}\,\Theta(\omega-\omega_0), \quad \text{where} \quad \alpha = \begin{cases} 1/2, & \text{S wave.} \\ 3/2, & \text{P wave.} \end{cases}$$

$$G_{\text{free}}(\tau) \propto \int d\omega\, e^{-\omega\tau}\rho(\omega) \propto \frac{e^{-\omega_0\tau}}{\tau^{\alpha+1}}.$$

Free limit

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

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

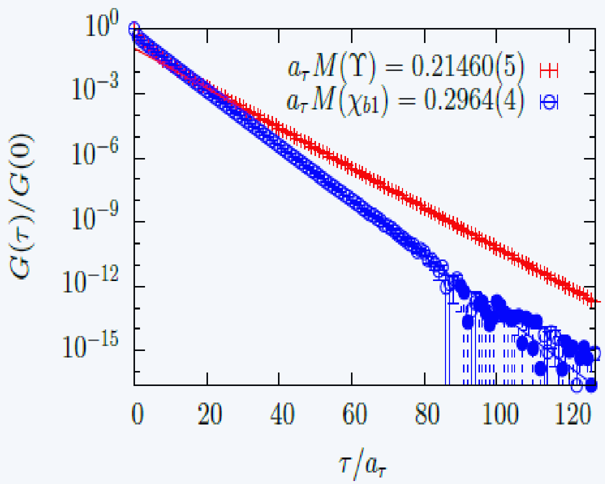
Diagnostic tool

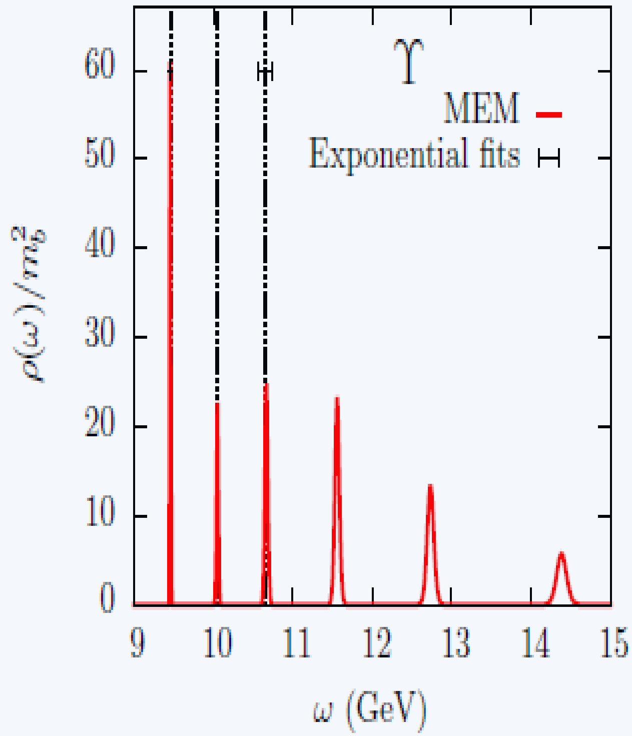
Spectral analysis of correlators

T=0

$G(t) = \Sigma A_i \exp(-m_i t)$

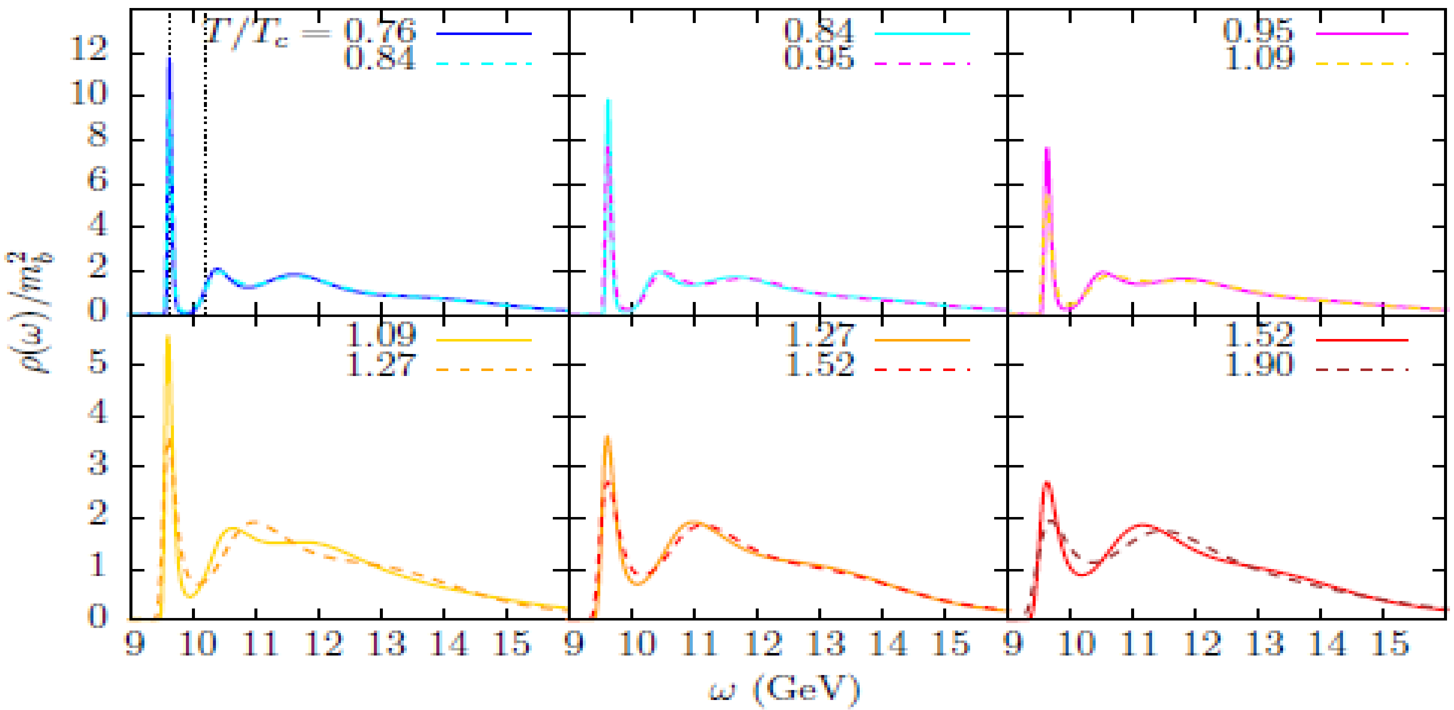
$\rho(\omega) = \Sigma A_i \, \delta(\omega - m_i)$





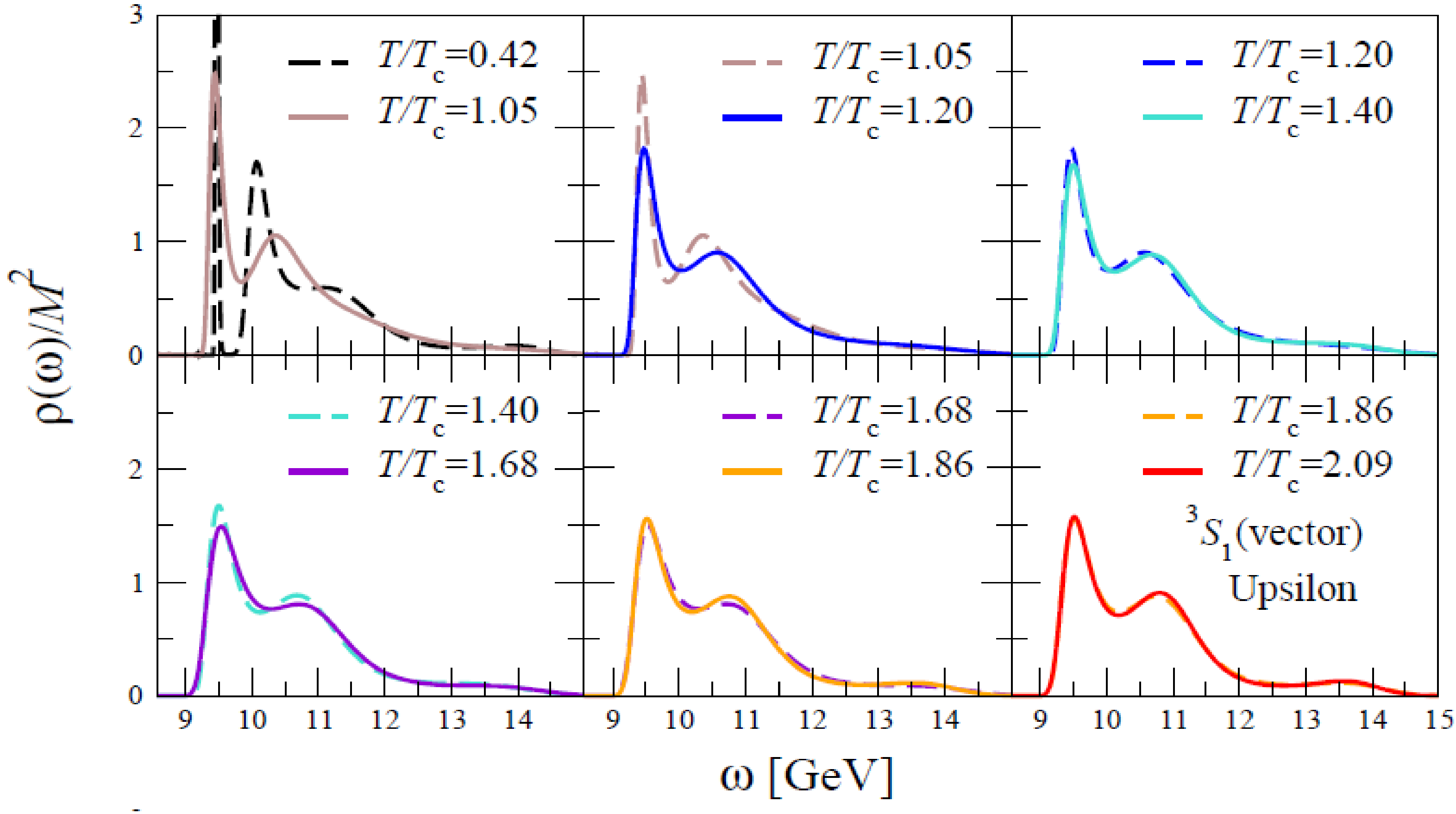
S waves : Upsilon; Nf = 2+1

Melting of the excited states



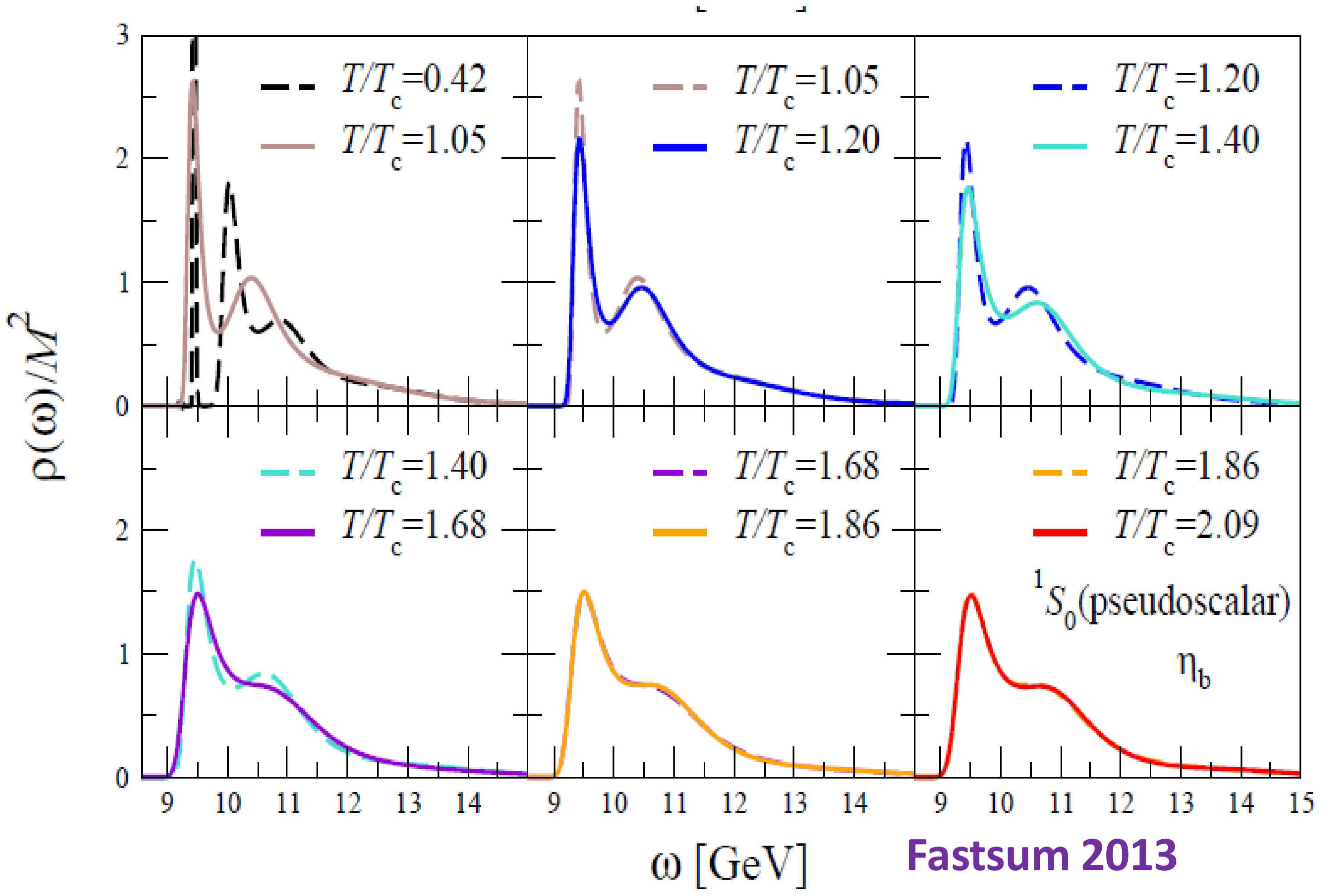
Fastsum 2014

S waves : Upsilon; Nf = 2



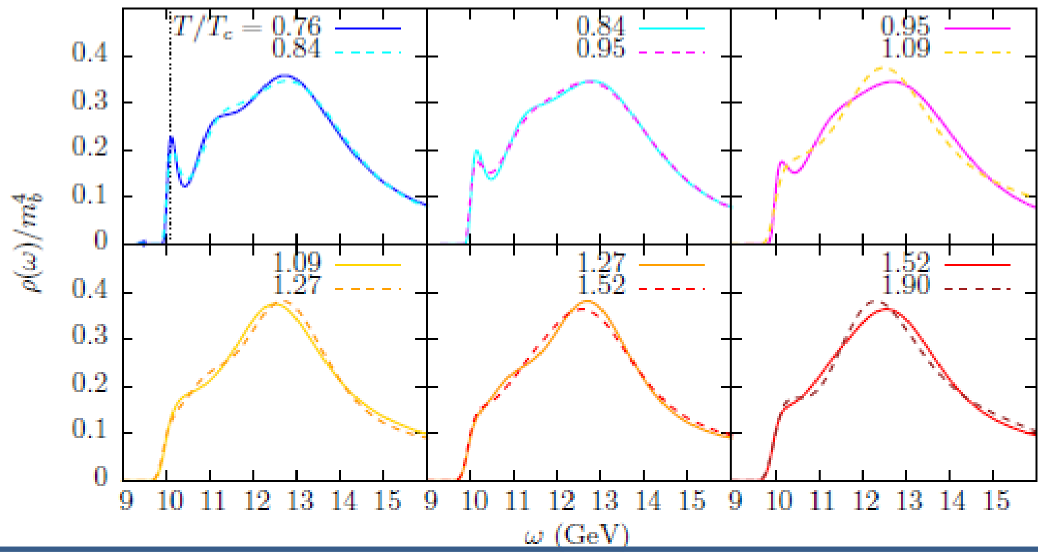
Fastsum 2013

S waves : ηb



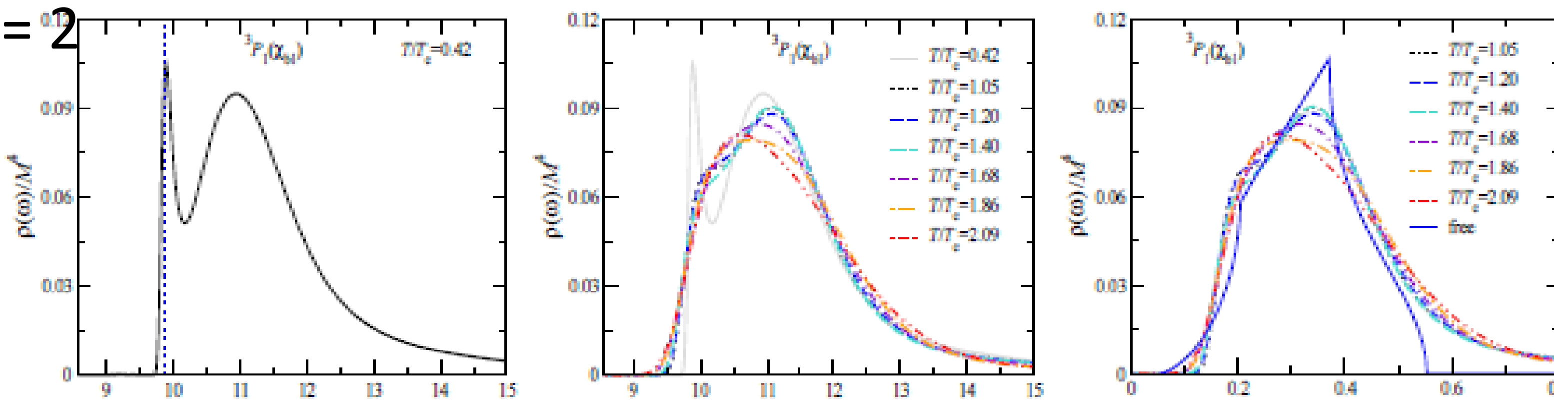
T/Tc=0.42
T/Tc=1.05
T/Tc=1.05
T/Tc=1.20
T/Tc=1.20
T/Tc=1.40
T/Tc=1.40
T/Tc=1.68
T/Tc=1.68
T/Tc=1.86
T/Tc=1.86
T/Tc=2.09
1S0(pseudoscalar)
ηb
ρ(ω)/M²
ω [GeV]
Fastsum 2013

P waves: χ

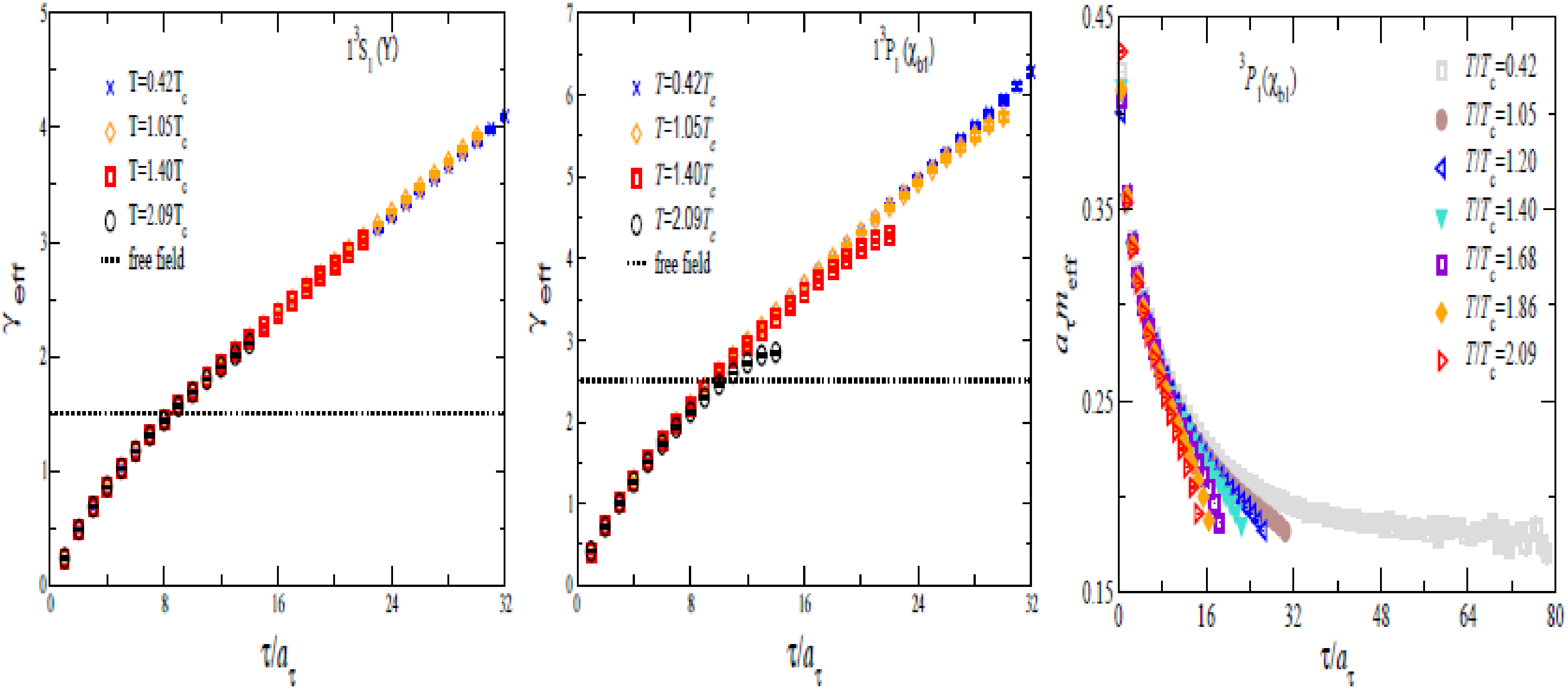


Nf = 2 +1

Nf = 2

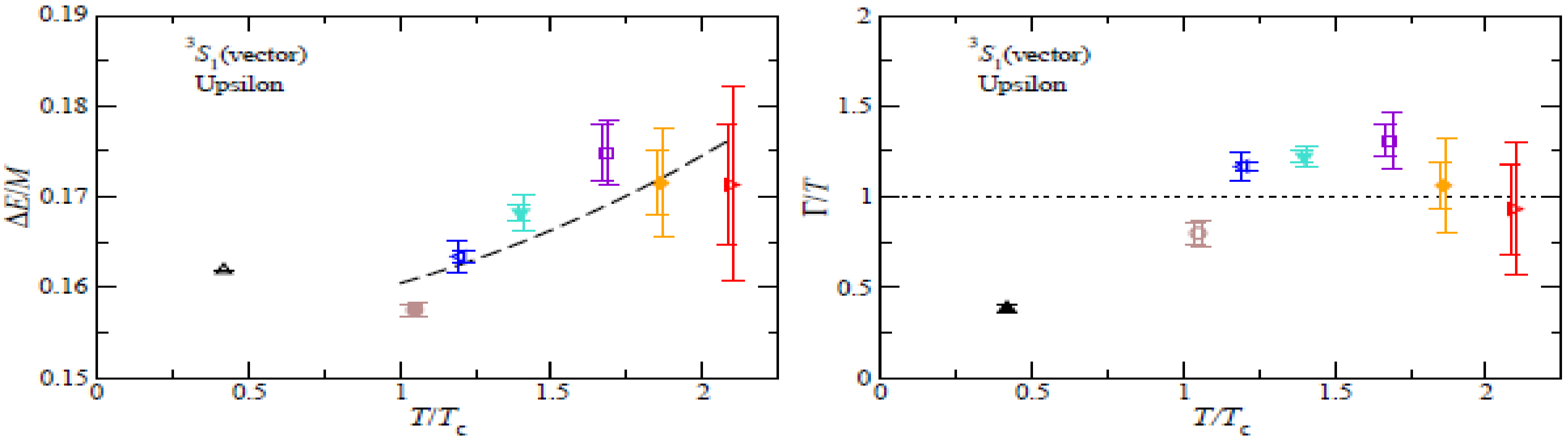


A simple minded cross check using correlators



Fastsum 2012

..and a comparison with effective models



$$\frac{\Gamma}{T} = \frac{1156}{81}\alpha_s^3 \simeq 14.27\alpha_s^3, \qquad \alpha_s \sim 0.4$$

Fastsum 2013

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

Brambilla et al 2009

Moving NRQCD

Lattice dispersion relations:

$$a_s^2 \mathrm{p}^2 = 4\sum_{i=1}^{3} \sin^2 \frac{p_i}{2}, \qquad p_i = \frac{2\pi n_i}{N_s}, \qquad -\frac{N_s}{2} < n_i \le \frac{N_s}{2}.$$

Used in this study:

n	(1,0,0)	(1,1,0)	(1,1,1)	(2,0,0)	(2,1,0)	(2,1,1)	(2,2,0)
$\lvert\mathbf{p}\rvert$ (GeV)	0.634	0.900	1.10	1.23	1.38	1.52	1.73
v/c (Υ)	0.0670	0.0951	0.116	0.130	0.146	0.161	0.183
v/c (η_b)	0.0672	0.0954	0.117	0.130	0.146	0.161	0.183

At the largest momentum (2,2,0):

$$\lvert\mathbf{p}\rvert \lesssim 1.73\,\mathrm{GeV}, \qquad v = \frac{\lvert\mathbf{p}\rvert}{M_S} \lesssim 0.2,$$

Still non relativistic

Temperature and momentum dependence for the Υ

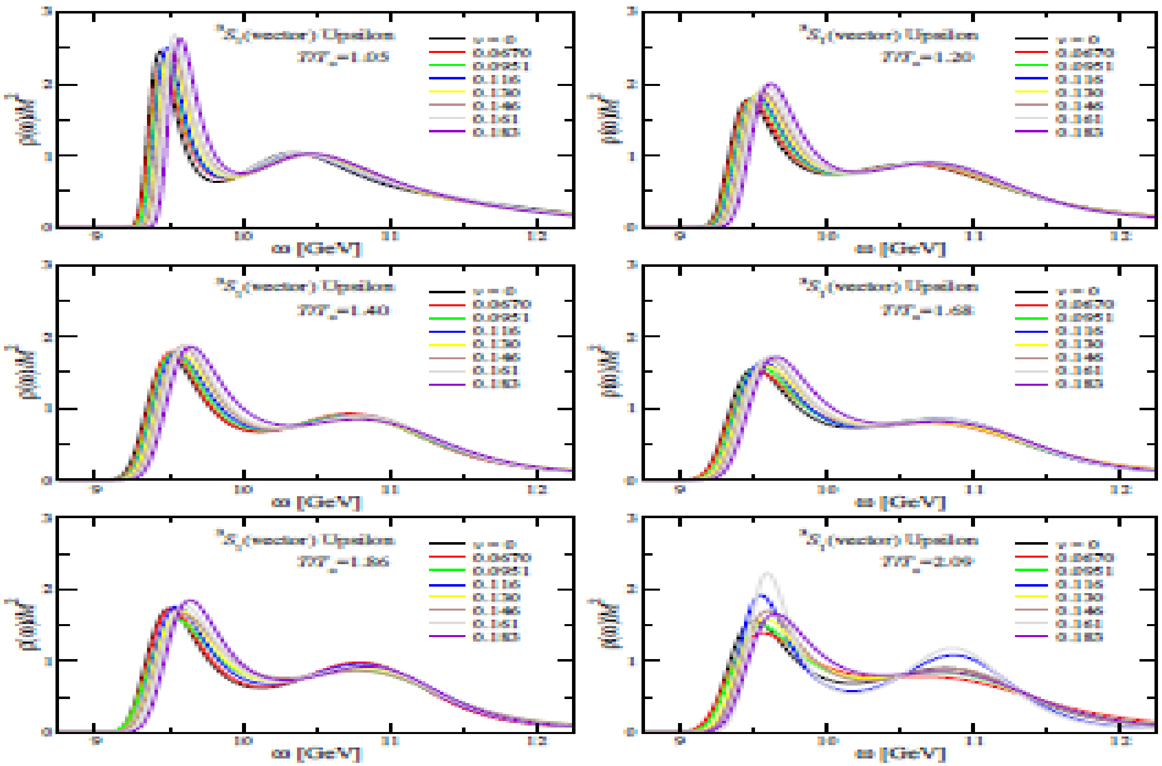
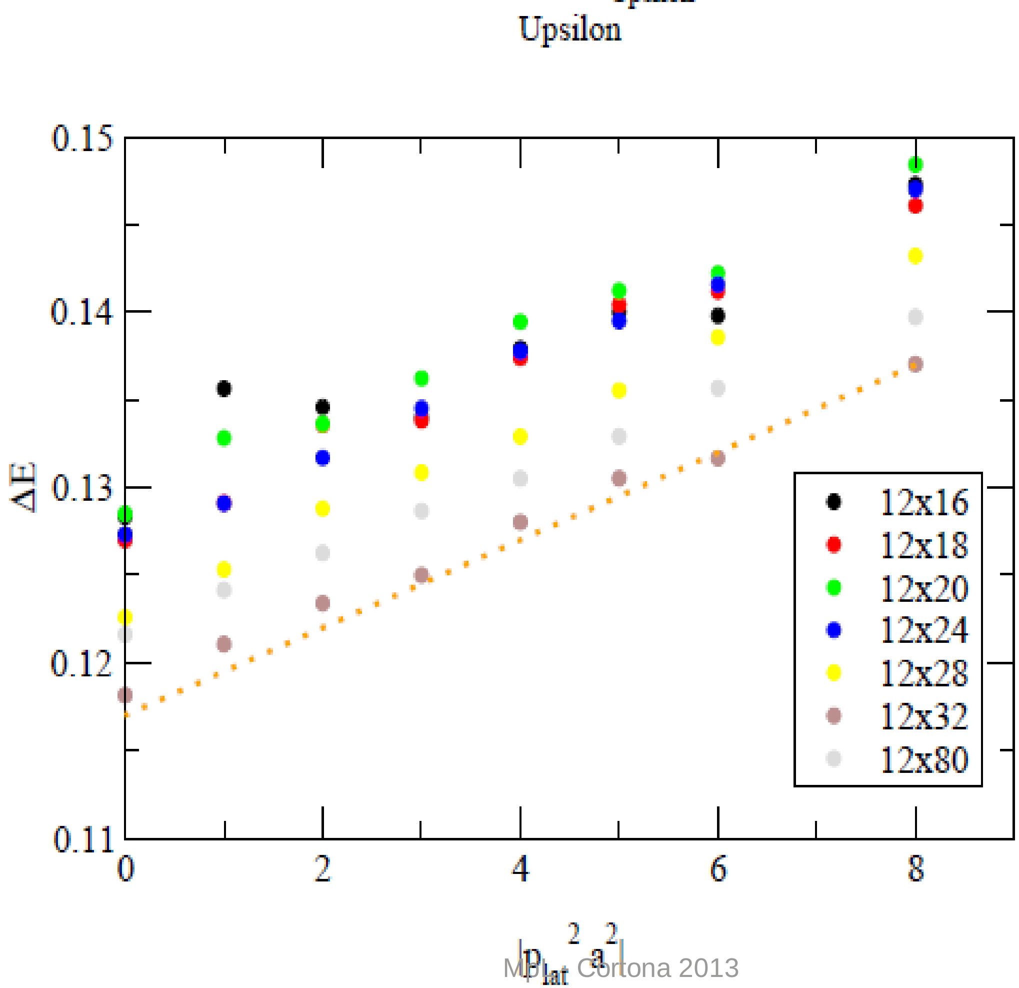


Figure 5: High-temperature results in the vector (Υ) channel. Spectral functions $\rho(\omega, \mathbf{p})$, normalized with the heavy quark mass, as a function of energy, at the six different temperatures above T_c, for several velocities $v = |\mathbf{p}|/M_\Upsilon$. fig:rho-

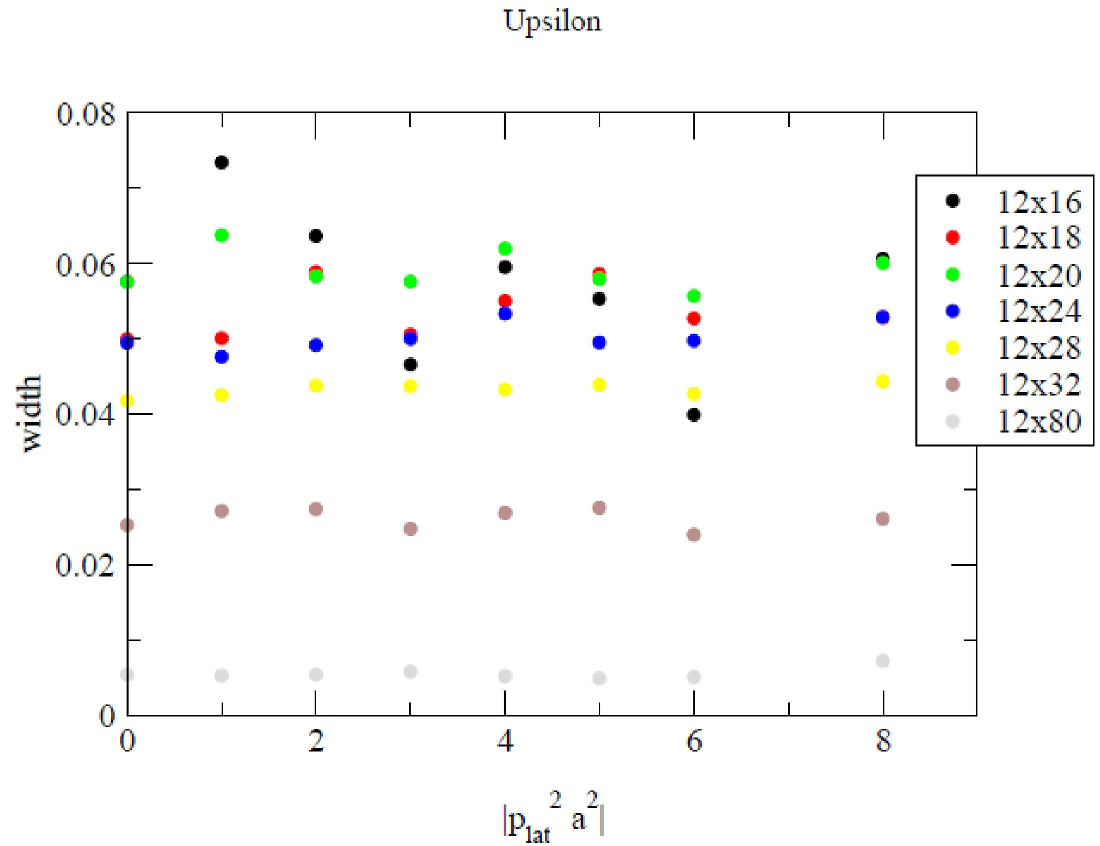
Moving Upsilon in a thermal bath: I

- observable heavy quarkonium velocity ($\frac{v_{\text{Upsilon}}}{c^2} \sim 0.03$) effect on the S-wave state mass (NR dispersion $\sim \frac{\vec{p}^2}{2M_{\text{Upsilon}}}$)



Moving Upsilon in a thermal bath: II

- no observable v^2_{Upsilon} effect on the S-wave state "width" (Escobedo et al., PRD84 (2011) 016008, $\Gamma_v/\Gamma_0 \sim 1 - \frac{2}{3}v^2_{\mathrm{Upsilon}}$)



Slide from
S Kim
@Lat2012

..all in all..

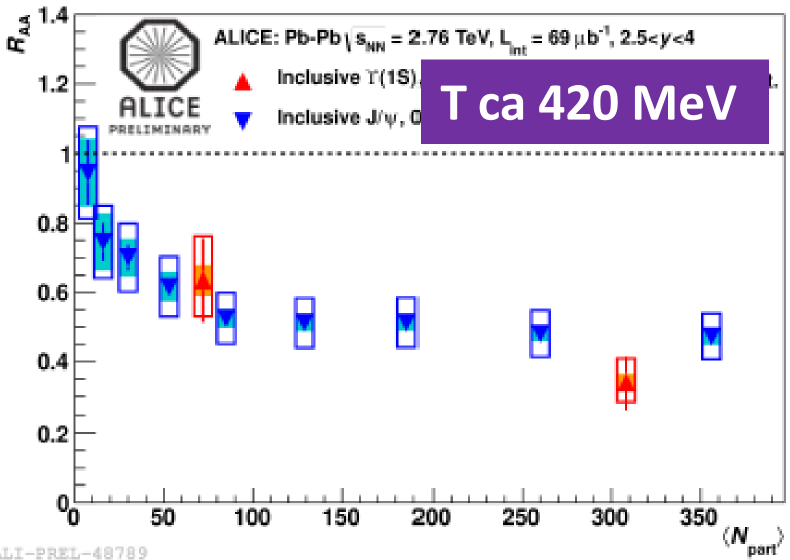
We have a coherent scenario for the Upsilon: the fundamental state survives up to about 2 Tc, while the excited states dissolve. This is consistent with the observations of CMS, ALICE and Phenix. The fundamental state has some modifications whose basic features are consistent with the predictions of effective field theories.

However......

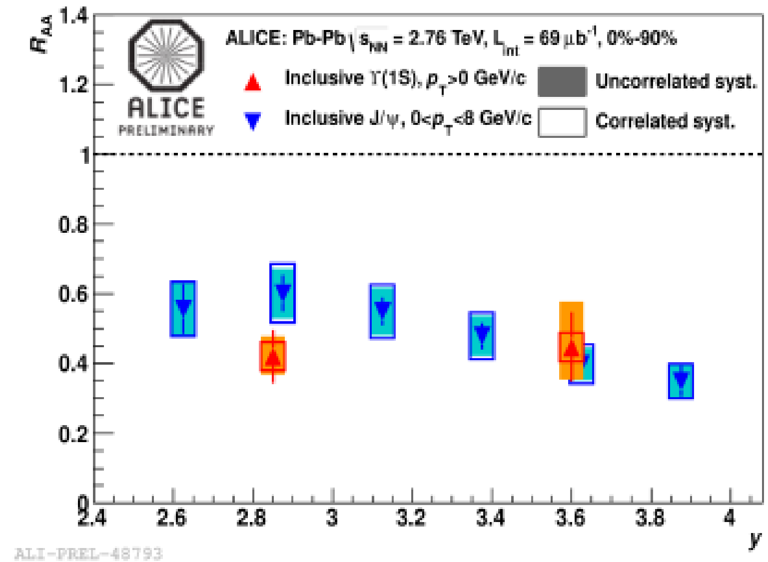
SQM 2013 BIRMINGHAM

Comparison of J/ψ and ϒ(1S)

ALICE



T ca 420 MeV



→ Suppression of ϒ and J/ψ is comparable within the present uncertainties

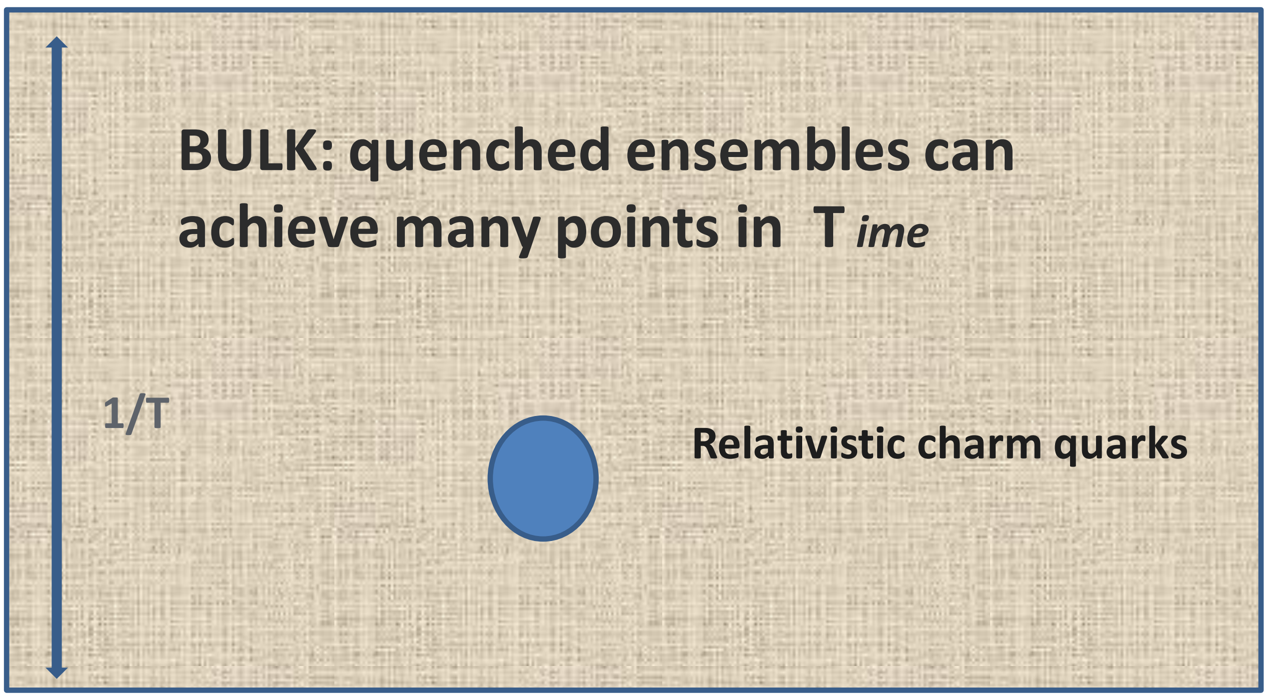
→ ϒ is expected to be less sensitive to regeneration than J/ψ

→ Feed down from higher excited states ϒ(2S), ϒ(3S), χ_b, χ_b' ~ 50 %

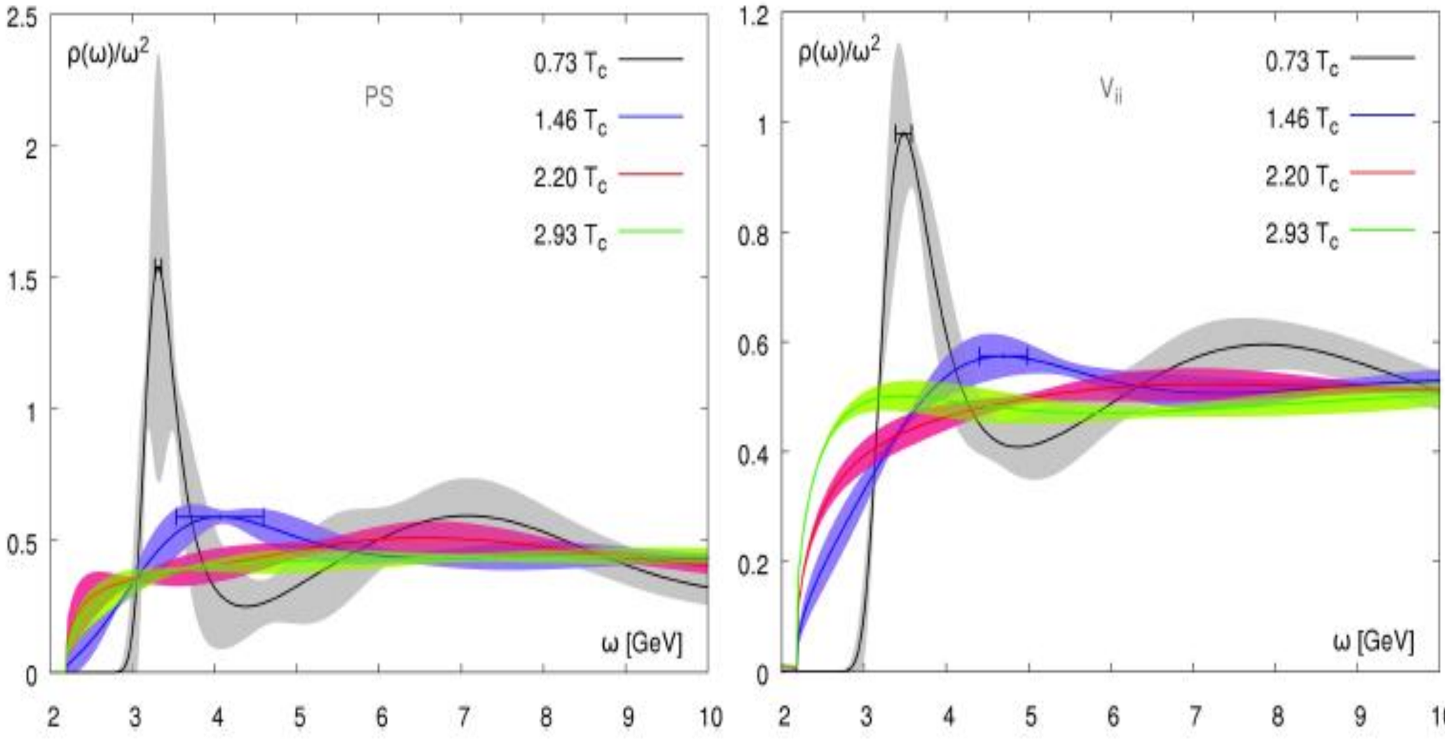
→ Weak rapidity dependence of R_{AA} for both J/ψ and ϒ(1S)

* for J/ψ in Pb-Pb see the talk of Lizardo Valencia Palomo

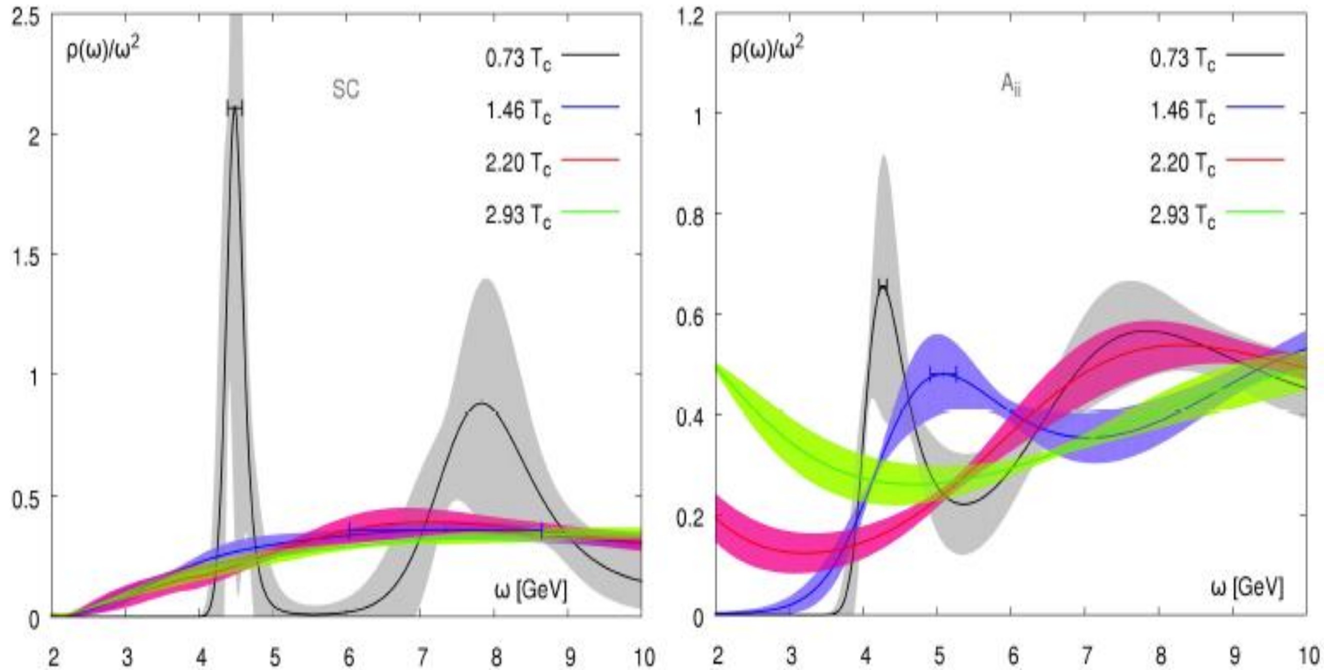
Quenched approach to Charmonium



Charmonium **Ding et al.2012**



Charmonium Ding et al 2012



Transport peak

$$D = \frac{1}{6\chi^{00}} \lim_{\omega\to 0} \sum_{i=1}^{3} \frac{\rho_{ii}^{V}(\omega, \vec{p}=0, T)}{\omega}$$

Ding et al.2012

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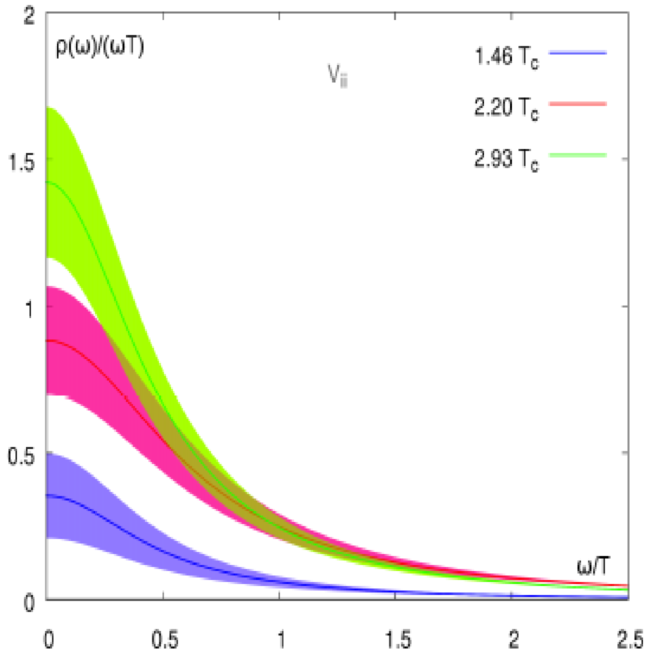
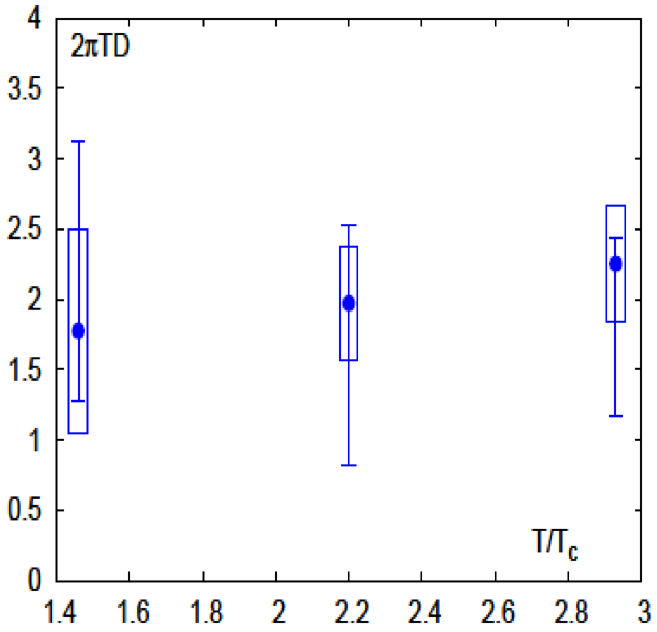
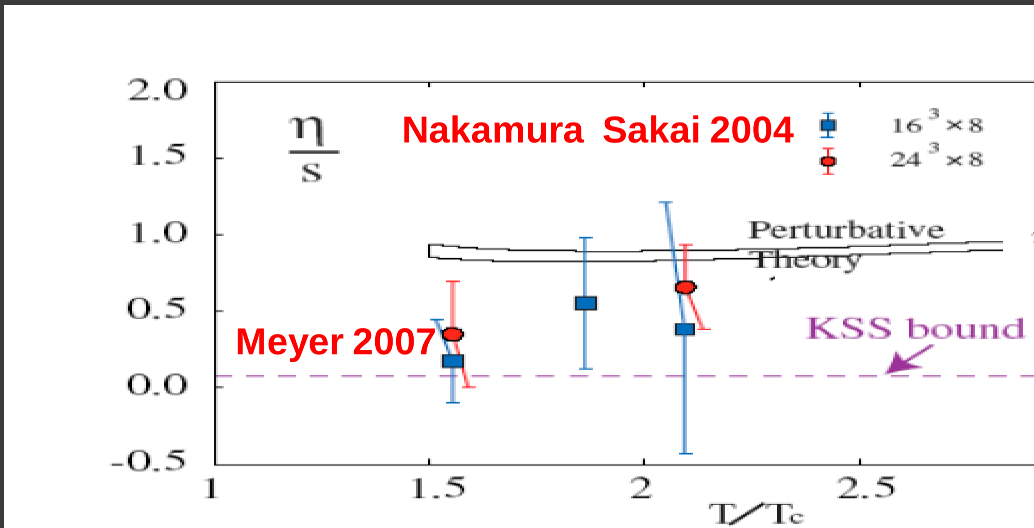




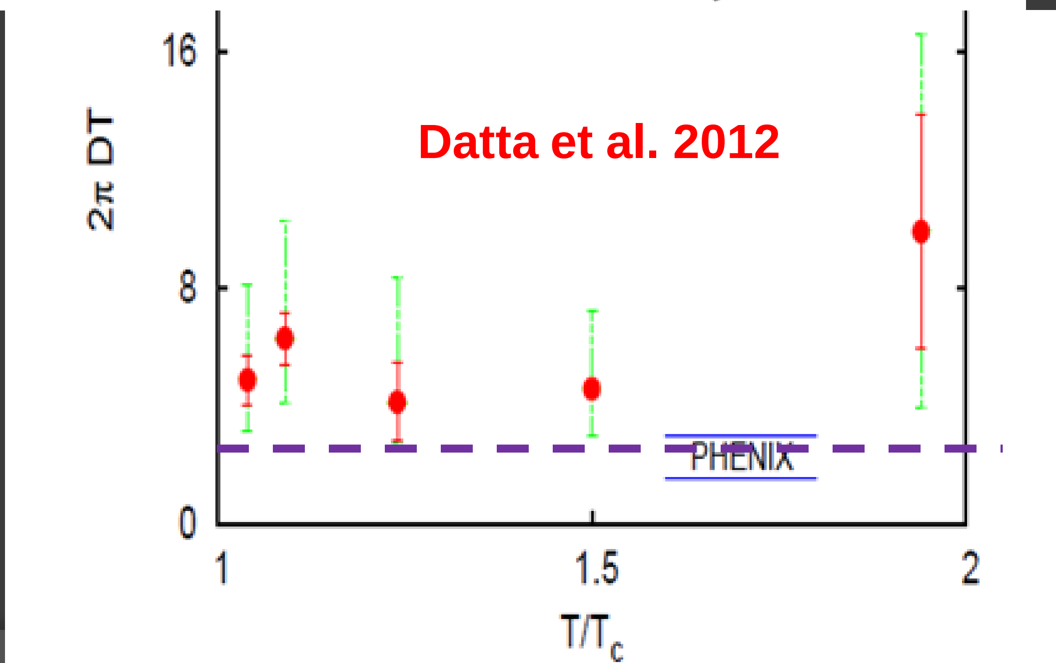
sQGP and trasport

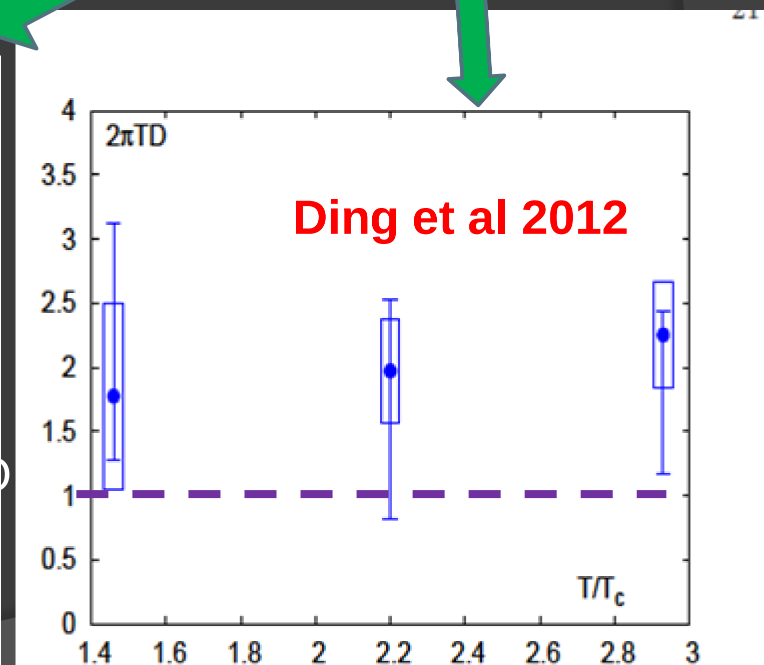
$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$



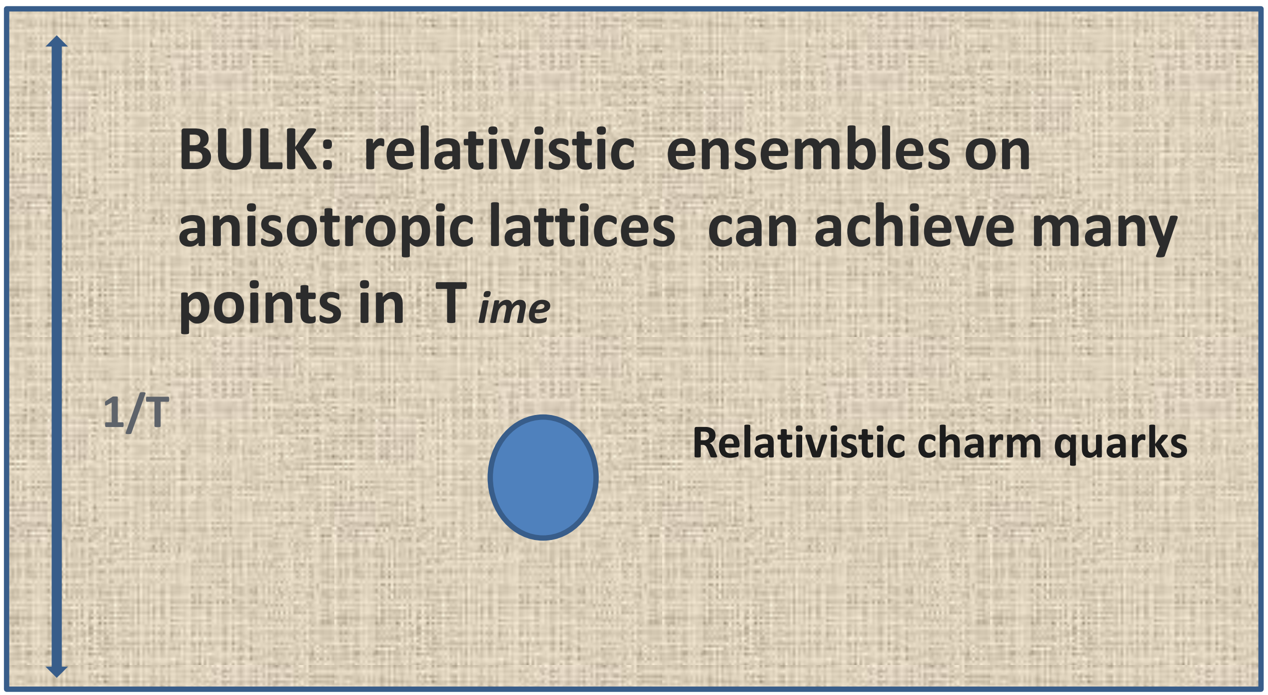
Early evidence for sQGP (from D. Kharzeev)

Recent results for the HQ diffusion coeff.



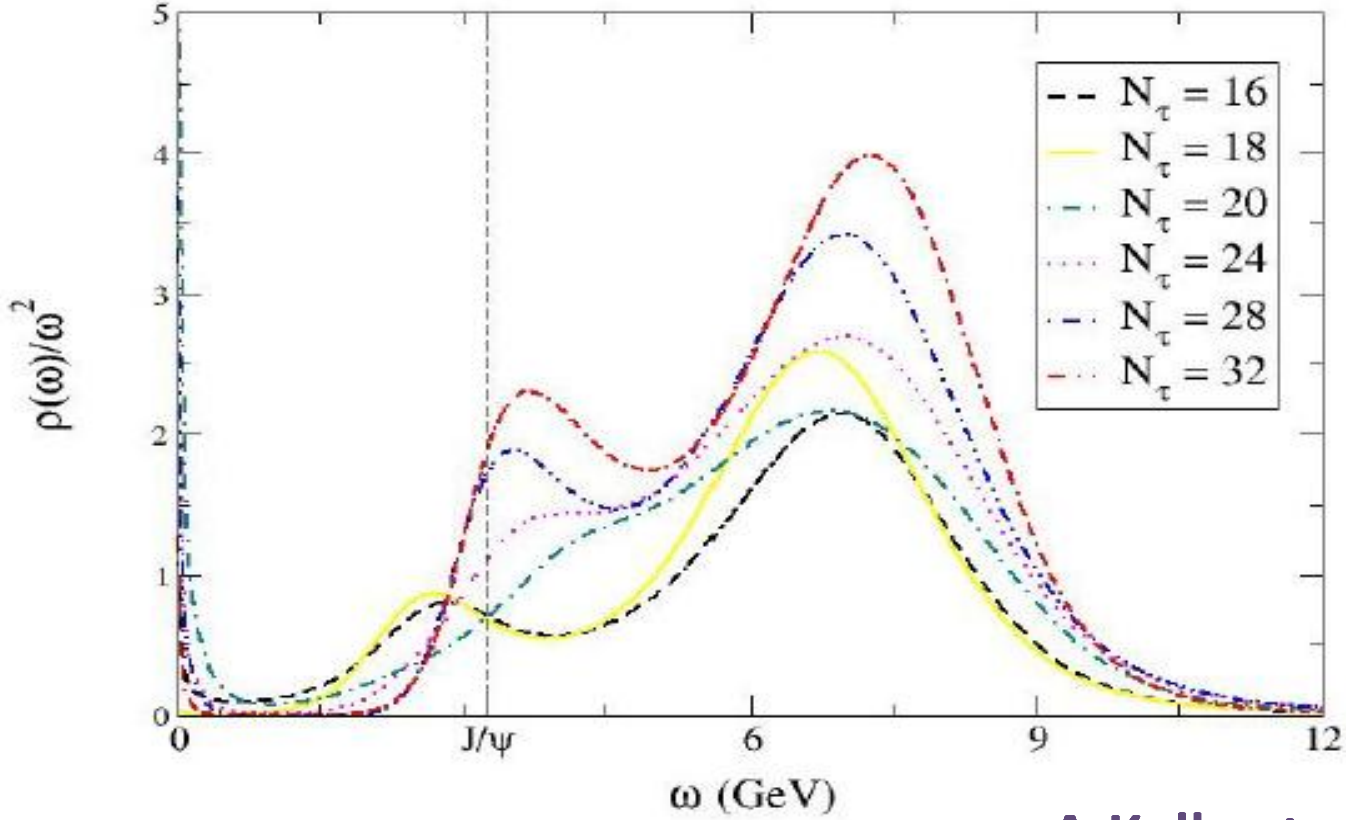


Relativistic approach to Charmonium



Charmonium and dynamical light quarks

(first serious attempts)



A.Kelly et al (FASTSUM) 2014

Open issues and ongoing work

Matter content of the gauge configurations

So far : m_π/m_ρ 0.4; m_s ∞ or almost physical; m_c ∞

Aim : physical mu,d,s for T < 350 MeV ; physical mu,d,s,c for T > 400 MeV

Lattice systematic

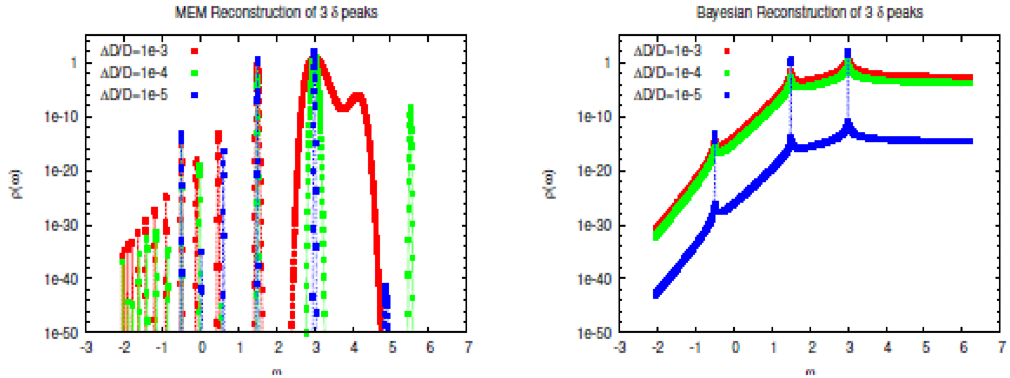
Need to study of the sensitivity to the lattice spacing – NB : similar to T=0 as UV issue

Reconstruction of spectral functions from lattice correlators

Alternative Bayesian method

Direct calculation of Laplace Inverse transform

In either cases,
use spectral functions from model studies as testbeds.



Burnier, Rothkops 2013

Quarkonium Summary

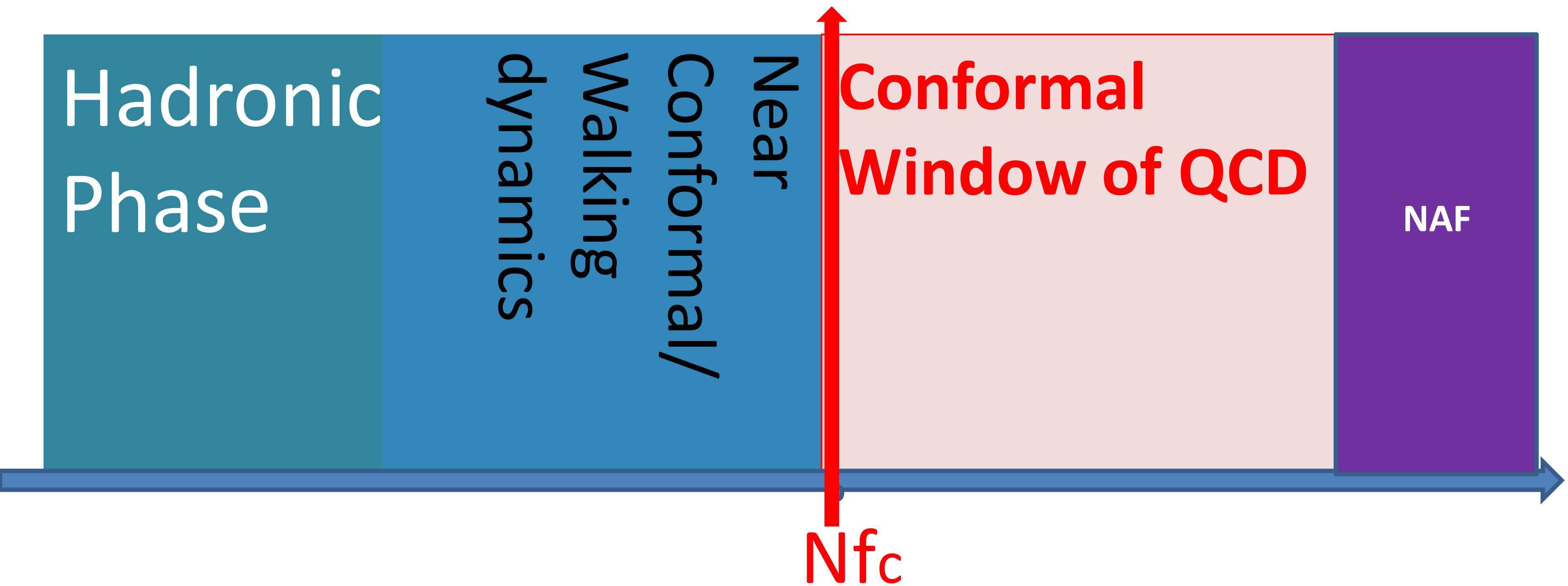
- High quality results for ***charmonium*** from relativistic spectral functions with quenched gauge fields.
- Possible to extract trasport coefficient
- No signs of bound states at temperatures above **1.46 Tc**
- The temperature dependence of ***bottomonium*** for 0.4 Tc < T < T 2.1 Tc has been investigated with nonrelativistic dynamics for the bottom quark and full relativistic QCD for up, down and strange quarks
- Various systematic errors still needs to be quantified and possibly reduced
- Correlators and spectral functions indicate that the Upsilon and ηb 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 ηb) excited states are no longer visible at temperatures above **1.4 Tc** , **in agreement with experimental observations at RHIC and LHC**

..a glimpse beyond QCD

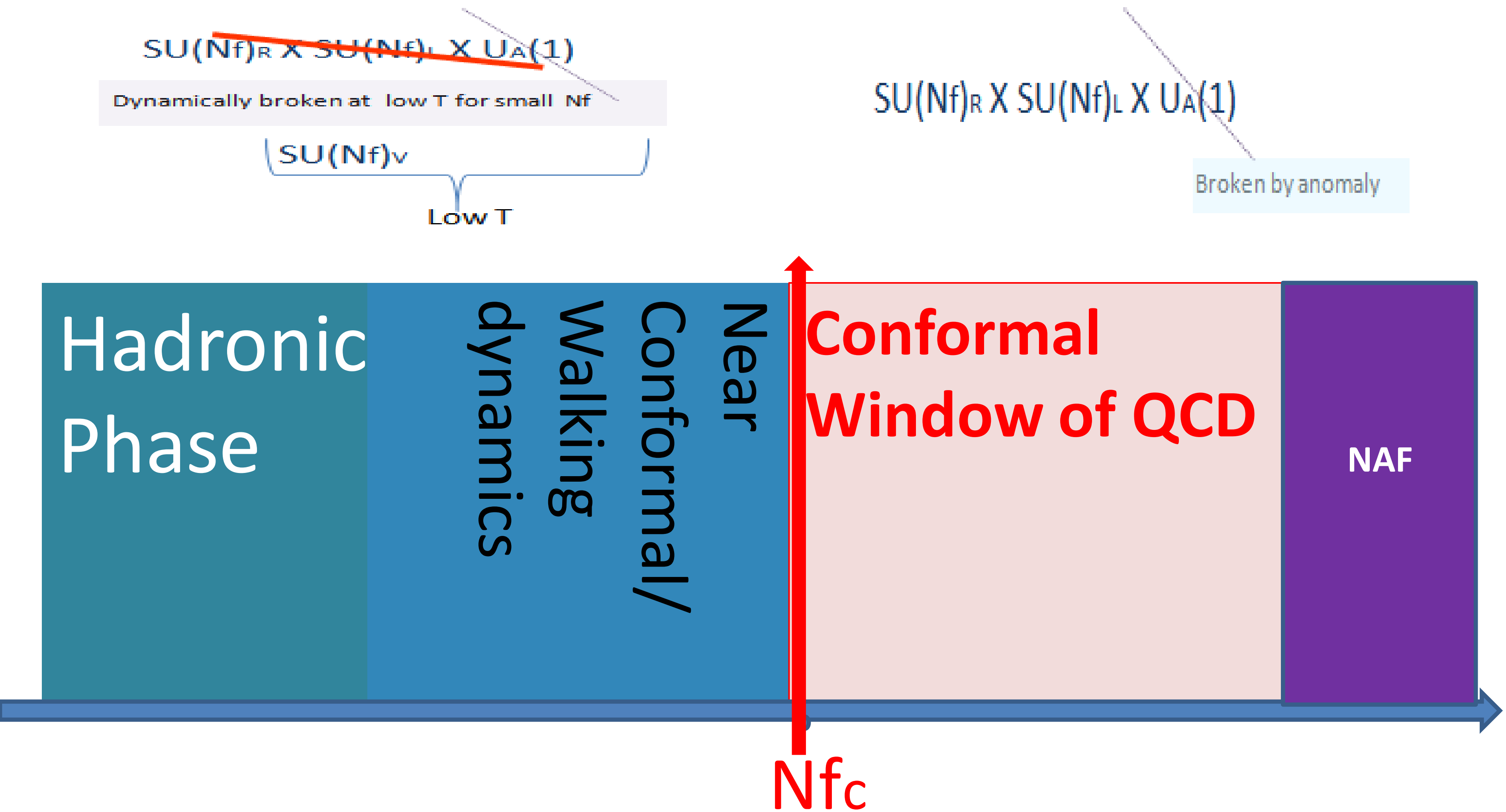
A dynamical charm is needed when T exceeds 400 MeV....

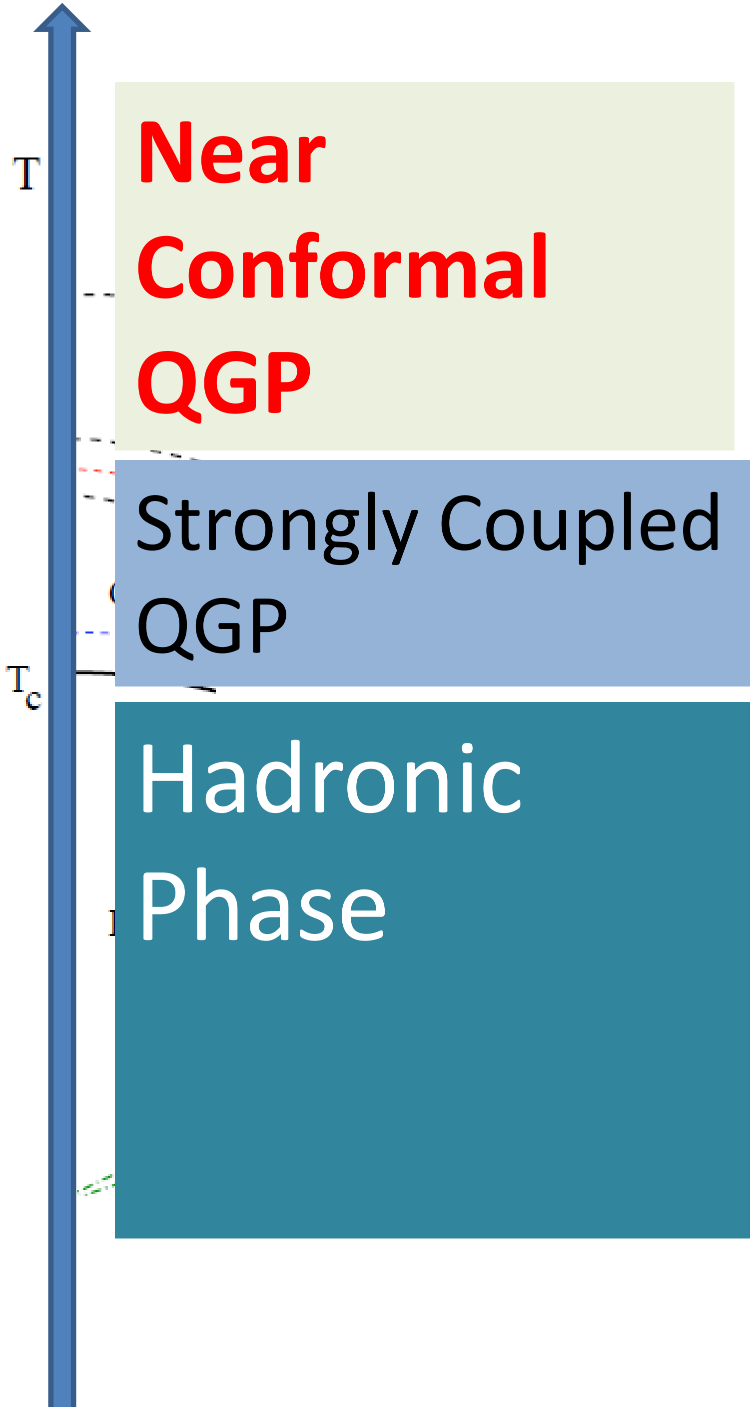
......suppose we add more massless flavors..

Adding flavor: phases of QCD at T=0

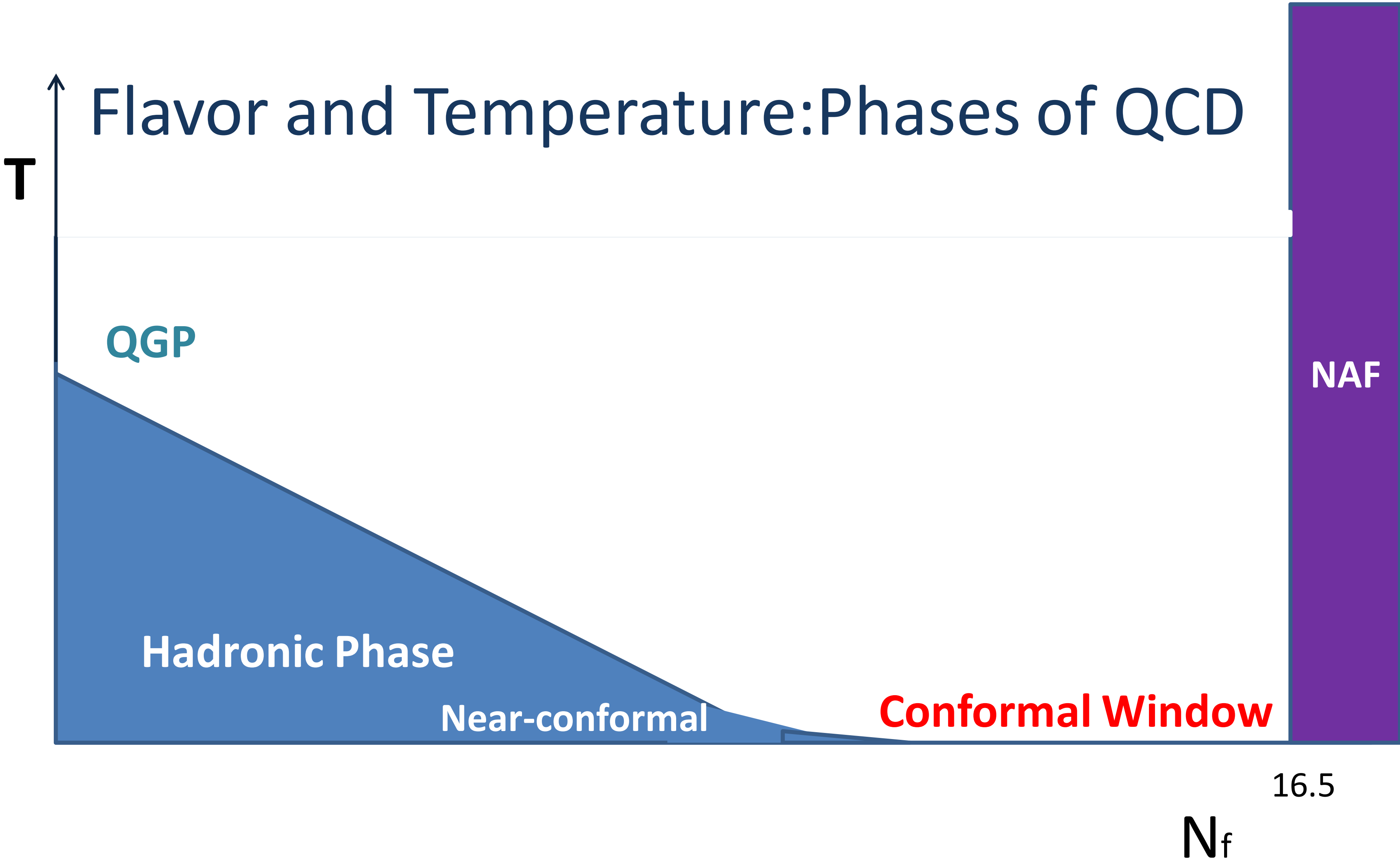


Adding flavor: phases of QCD at T=0



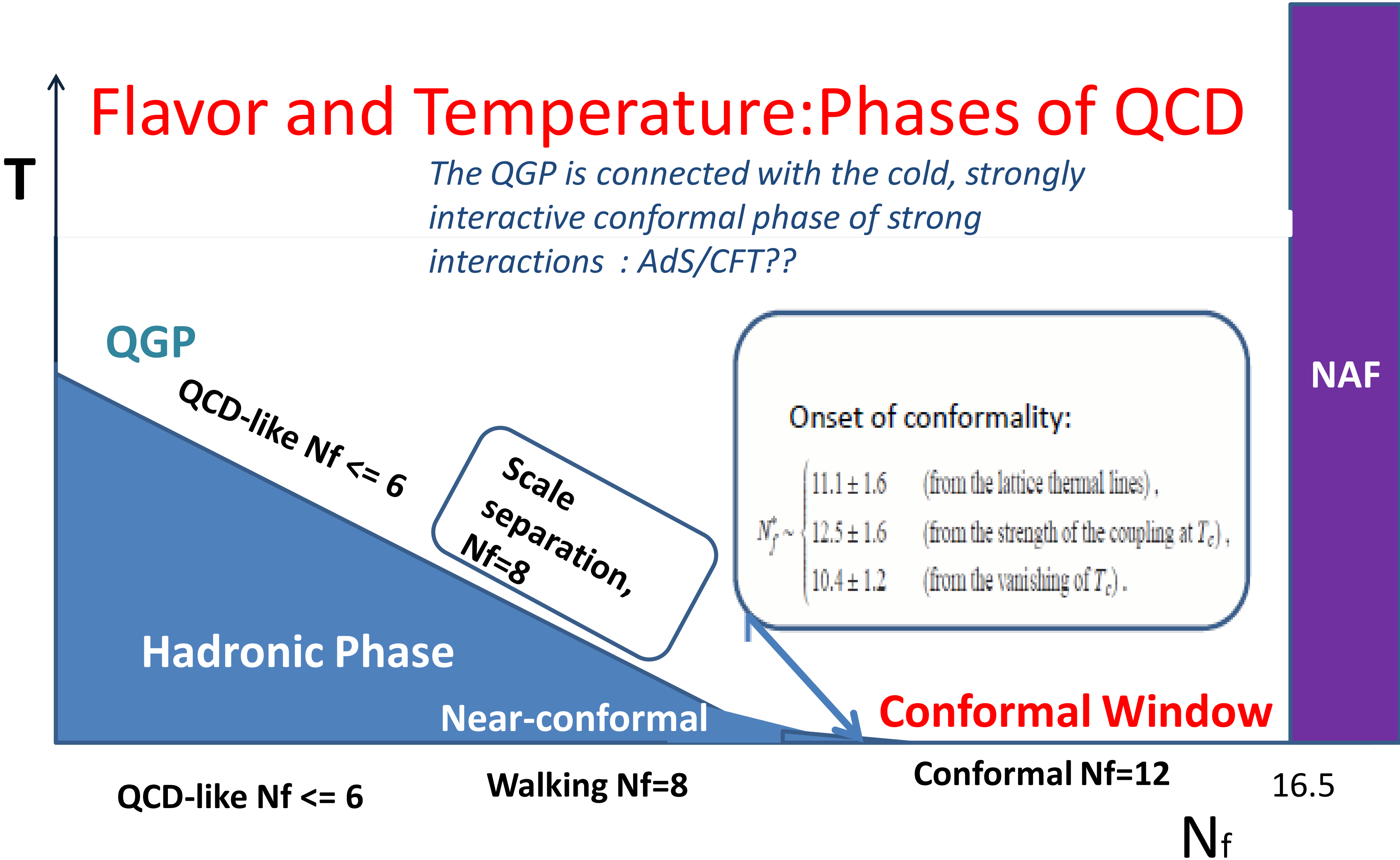

T
Near Conformal QGP
Strongly Coupled QGP
Tc
Hadronic Phase

Flavor and Temperature:Phases of QCD

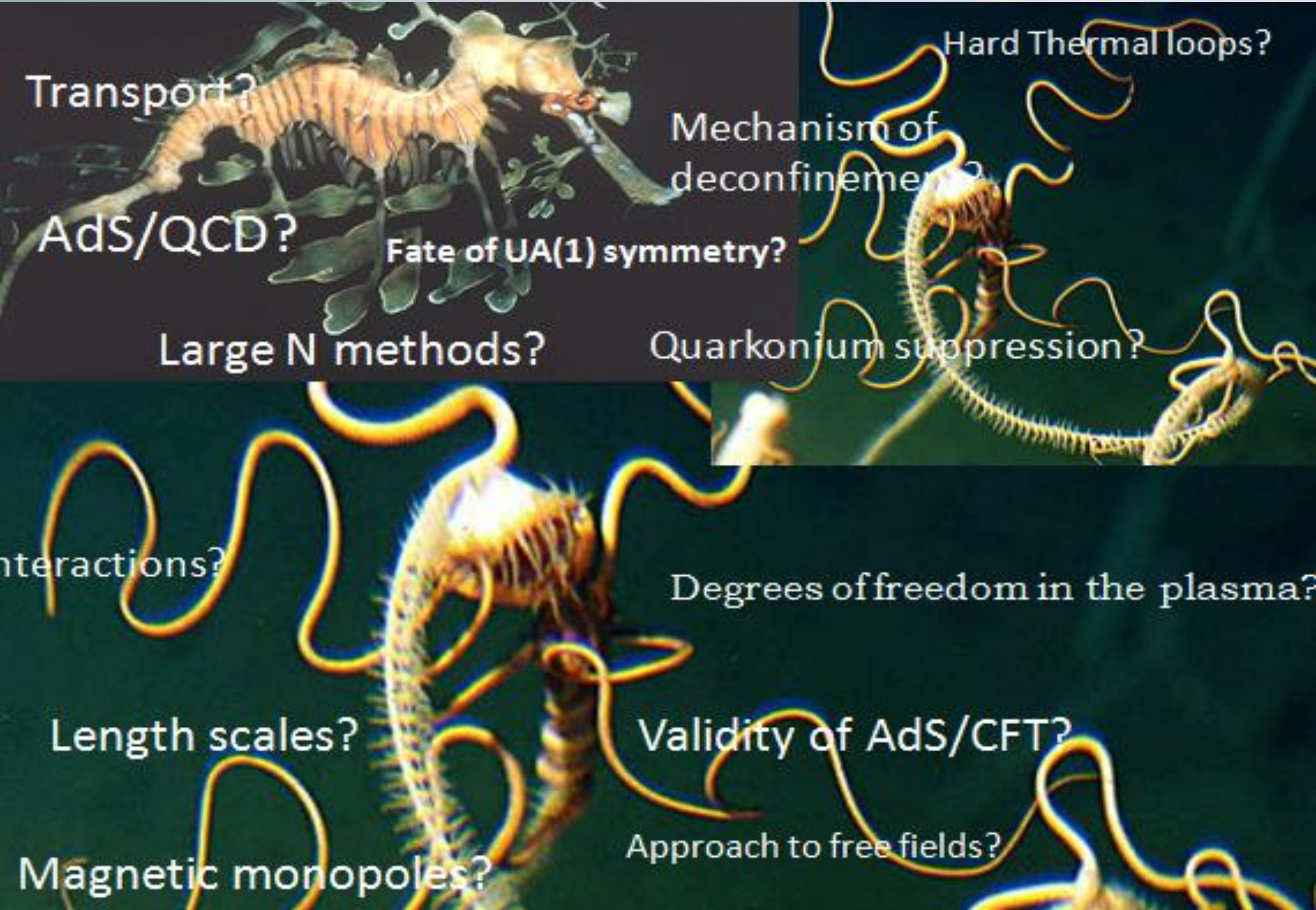


Flavor and Temperature:Phases of QCD

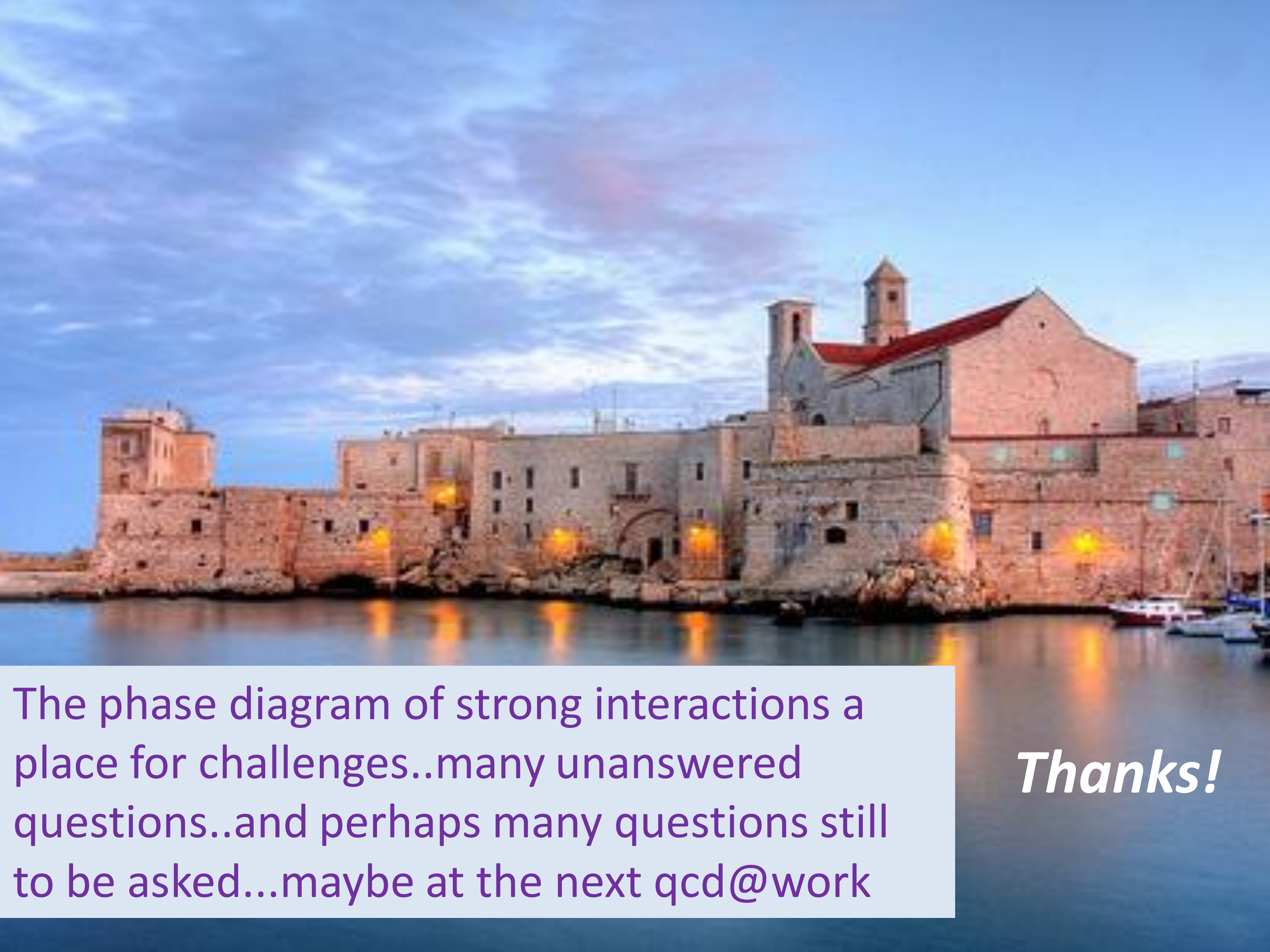
The QGP is connected with the cold, strongly interactive conformal phase of strong interactions : AdS/CFT??



Many untouched related issues...



The phase diagram of strong interactions a place for challenges..many unanswered questions..and perhaps many questions still to be asked...maybe at the next qcd@work



The phase diagram of strong interactions a place for challenges..many unanswered questions..and perhaps many questions still to be asked...maybe at the next qcd@work

Thanks!