Heavy Quarks and Quarkonium
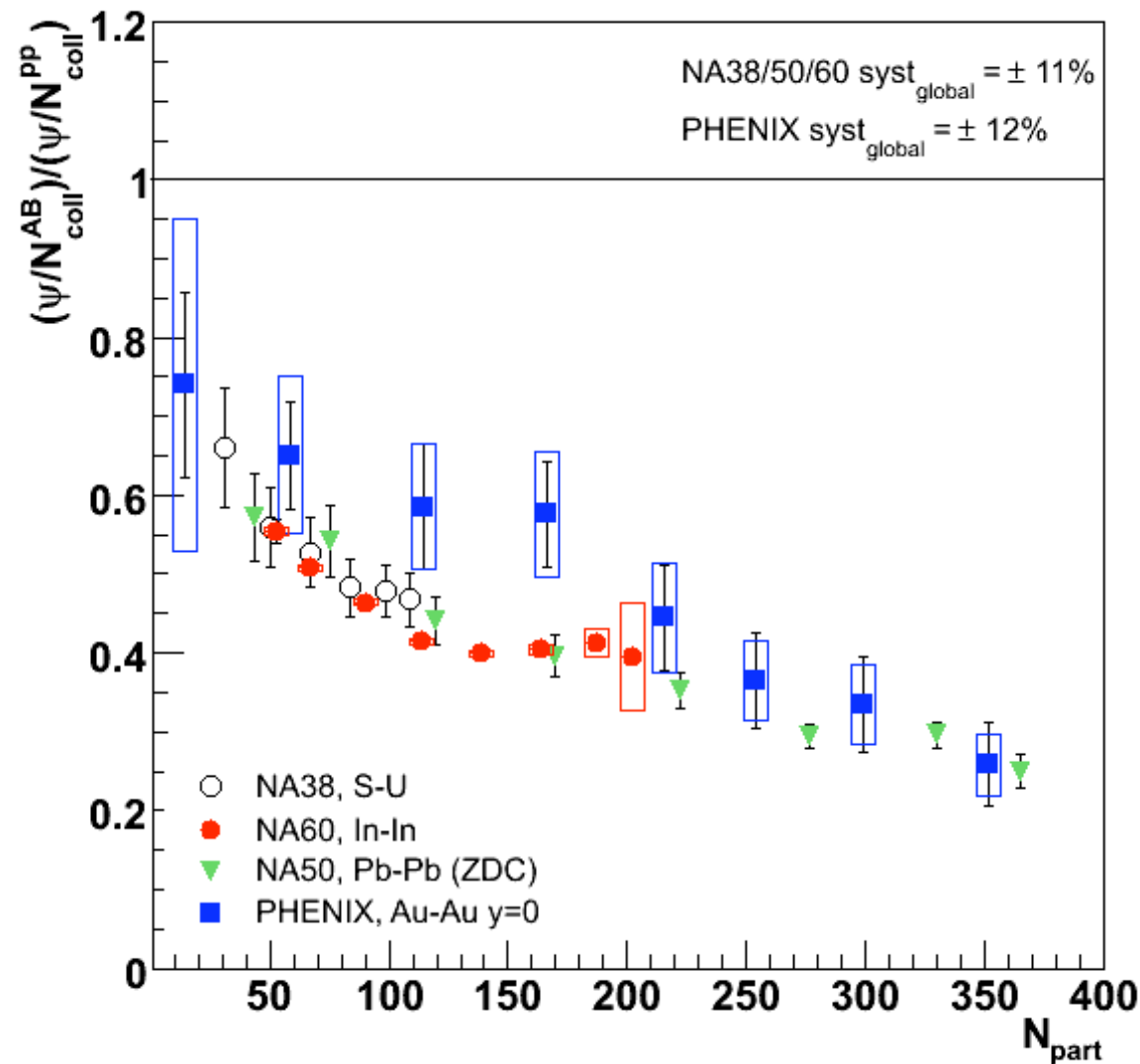
Ágnes Mócsy

Pratt Institute, Brooklyn, New York

Pratt

QUARK MATTER
ANNECY 2011

BROOKHAVEN
NATIONAL LABORATORY

The J/ψ story: Two decades worth of data

Modest theory advancement

Lots of ad-hoc phenomenological modeling

It is difficult to unambiguously interpret - we are still not there
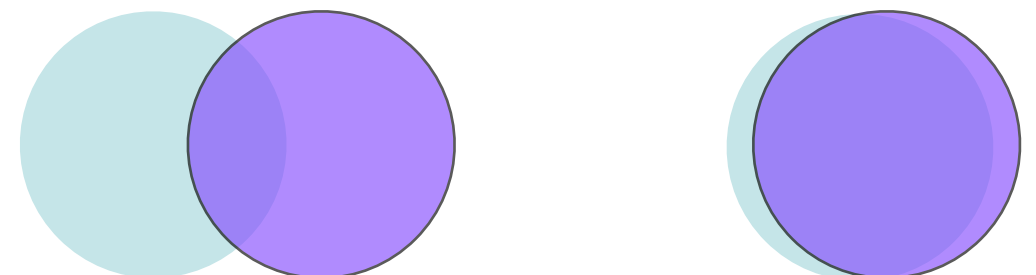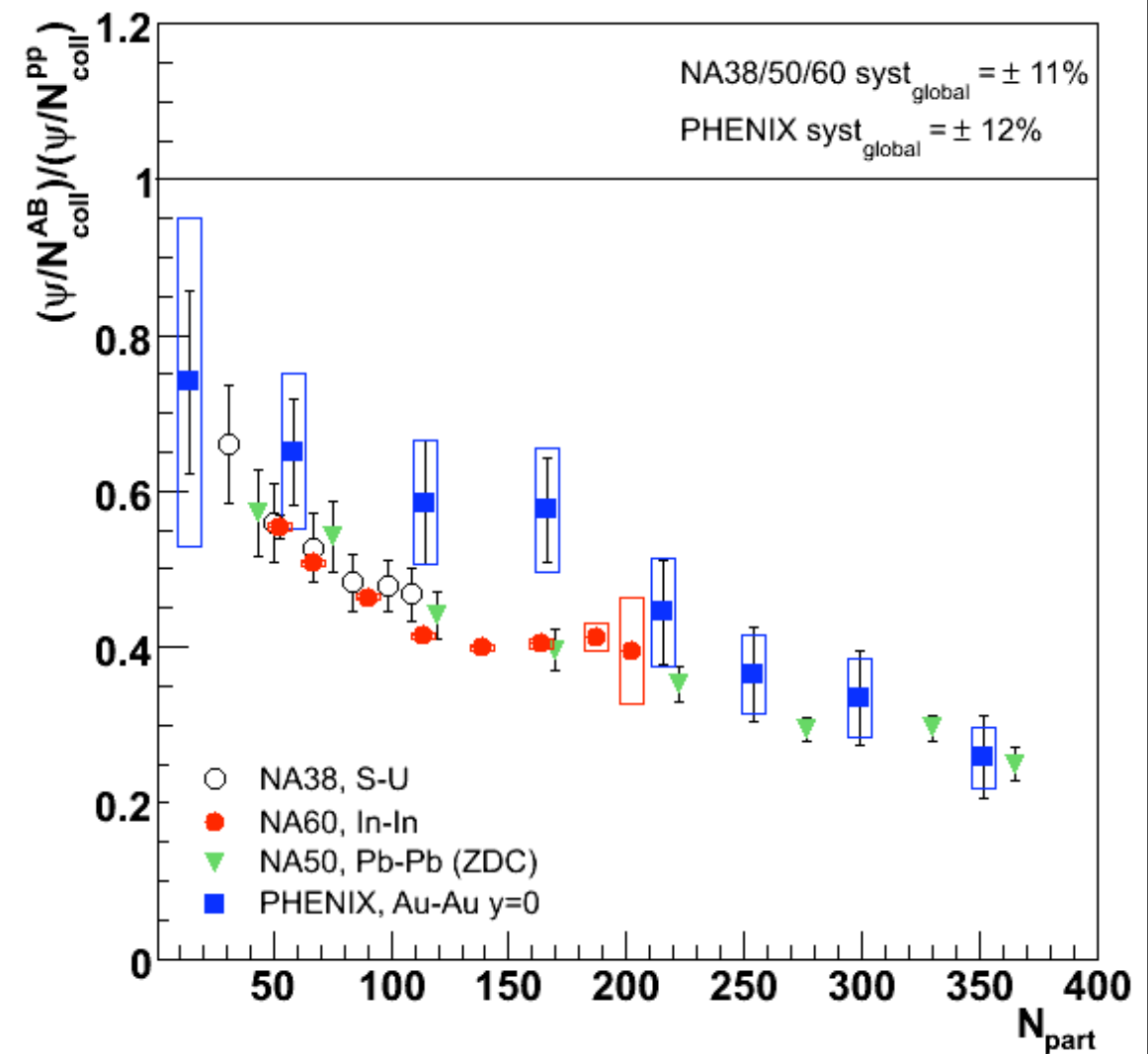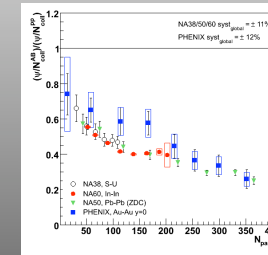
Famous Plot

What is plotted?

- J/ψ nuclear modification factor:
  yield in AA collisions relative to yield in pp
  (where no QGP formation expected) scaled with
  number of binary NN collisions

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- If AA is superposition of pp then $R_{AA}=1$
- Deviation from 1 indicates medium effects
- If no J/ψ measured then $R_{AA}=0$

- The J/ψ-suppression pattern observed at
  SPS and RHIC

NA38/50/60 syst$_{global}$ = ± 11%

PHENIX syst$_{global}$ = ± 12%

○ NA38, S-U
● NA60, In-In
▼ NA50, Pb-Pb (ZDC)
■ PHENIX, Au-Au y=0

$(\psi/N_{coll}^{AB})/(\psi/N_{coll}^{pp})$

N_{part}

Famous Plot

Why is it important?

- QCD predicts: quarkonium states disappear in the deconfined medium due to temperature effects present: *screening, Landau damping, ...*

- In-medium properties of quarkonium encoded in spectral functions

Dissolution ("melting") seen as progressive broadening and disappearance of bound-state peaks

$$\sigma(\omega, p, T) = \frac{1}{2\pi} \, \text{Im} \int_{-\infty}^{\infty} dt \, e^{i\omega t} \int d^3x \, e^{ipx} \langle [J(x,t), J(x,0)] \rangle_T$$
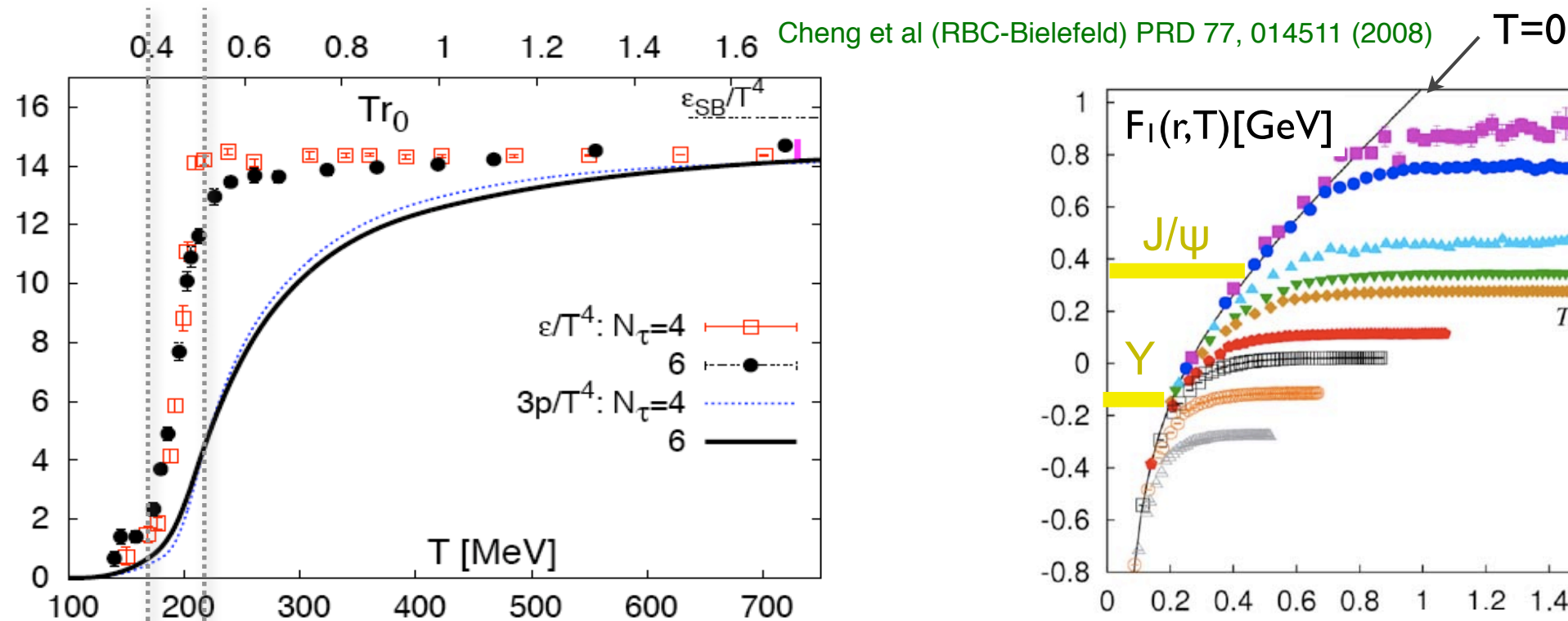
T=0   T>0   T>T$_d$
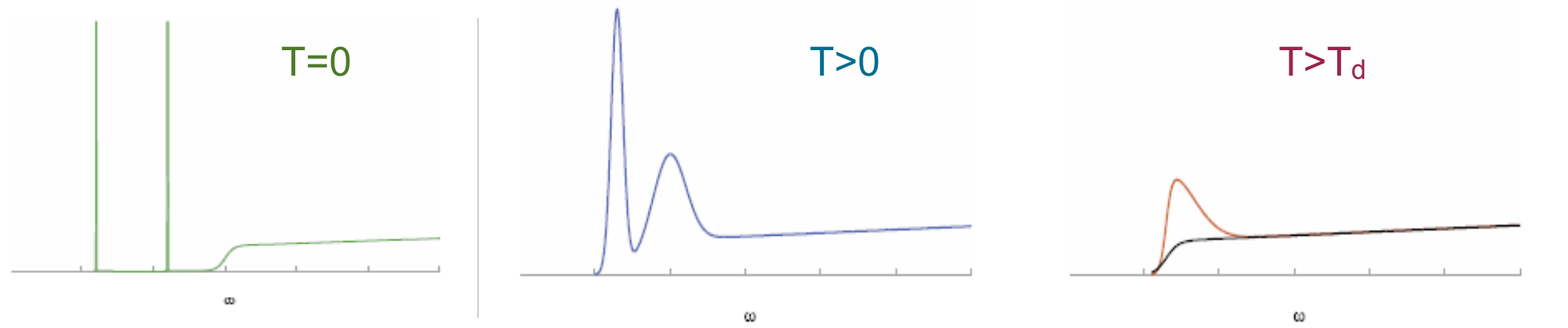
- Theory predicts the J/ψ disappears in the plasma ⟶ J/ψ suppression proposed signal of deconfined QGP
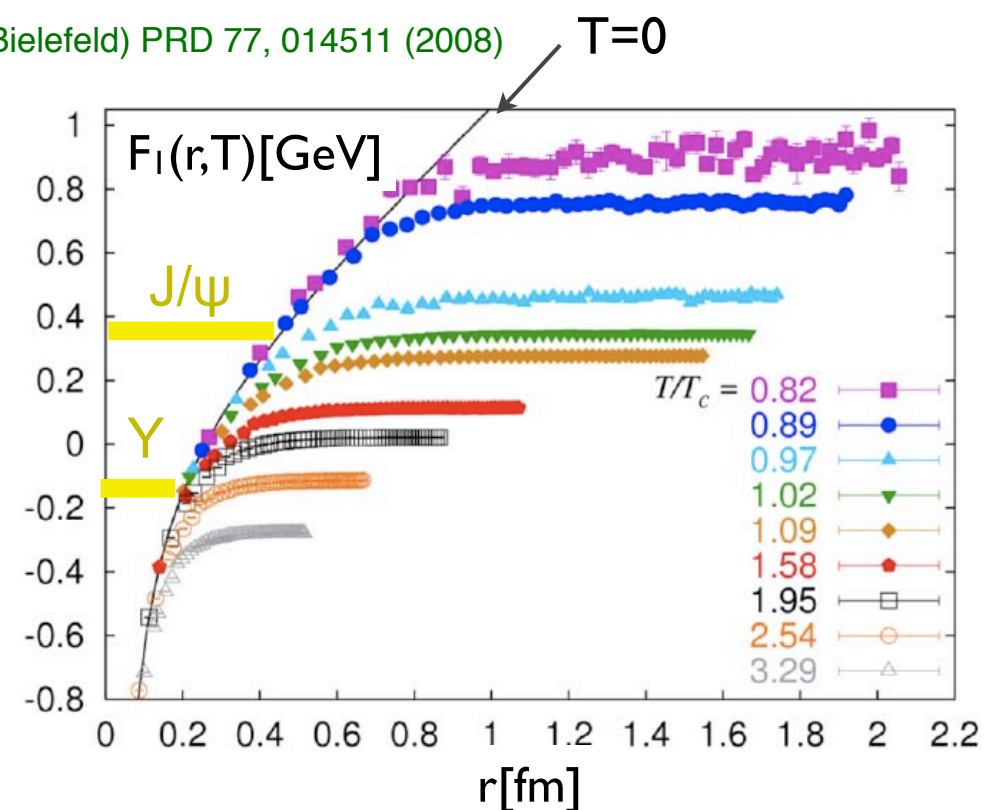
Famous Plot

Why is it important?

Deconfinement

Color screening

Cheng et al (RBC-Bielefeld) PRD 77, 014511 (2008)
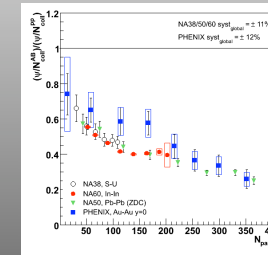

- Rapid rise of the energy density:
  liberation of new degrees of freedom
- Deconfinement seen on lattice

- Strong screening of static Q-Qbar
  free energy - sets in at shorter
  distances with increasing T

$r_{scr} < r_{J/\psi}$ "melting" of the J/ψ

Famous Plot

Why is it important?

Deconfinement

Color screening

Cheng et al (RBC-Bielefeld) PRD 77, 014511 (2008)

T=0

$F_1(r,T)$[GeV]

J/ψ

Υ

T/T_c =
0.82
0.89
0.97
1.02
1.09
1.58
1.95
2.54
3.29

r[fm]
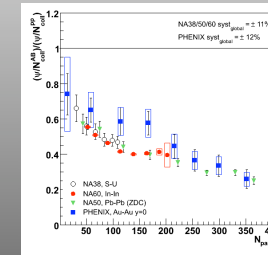
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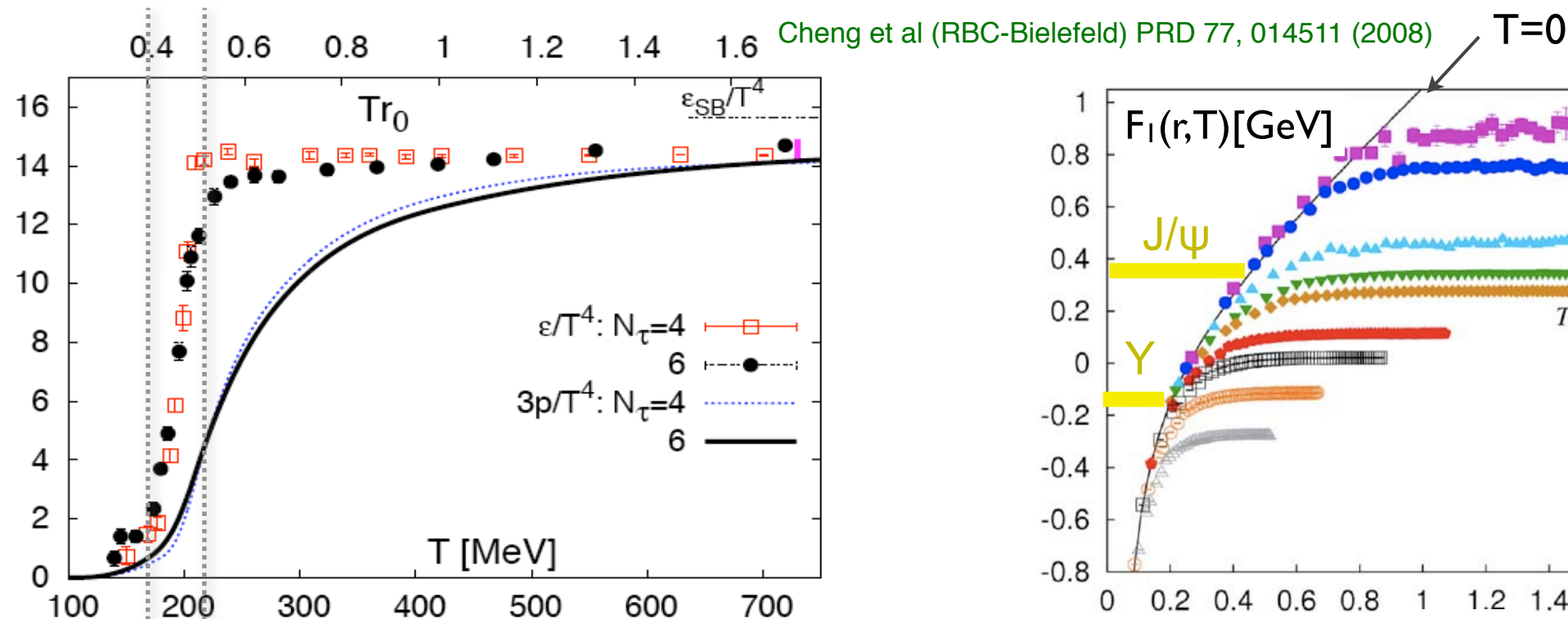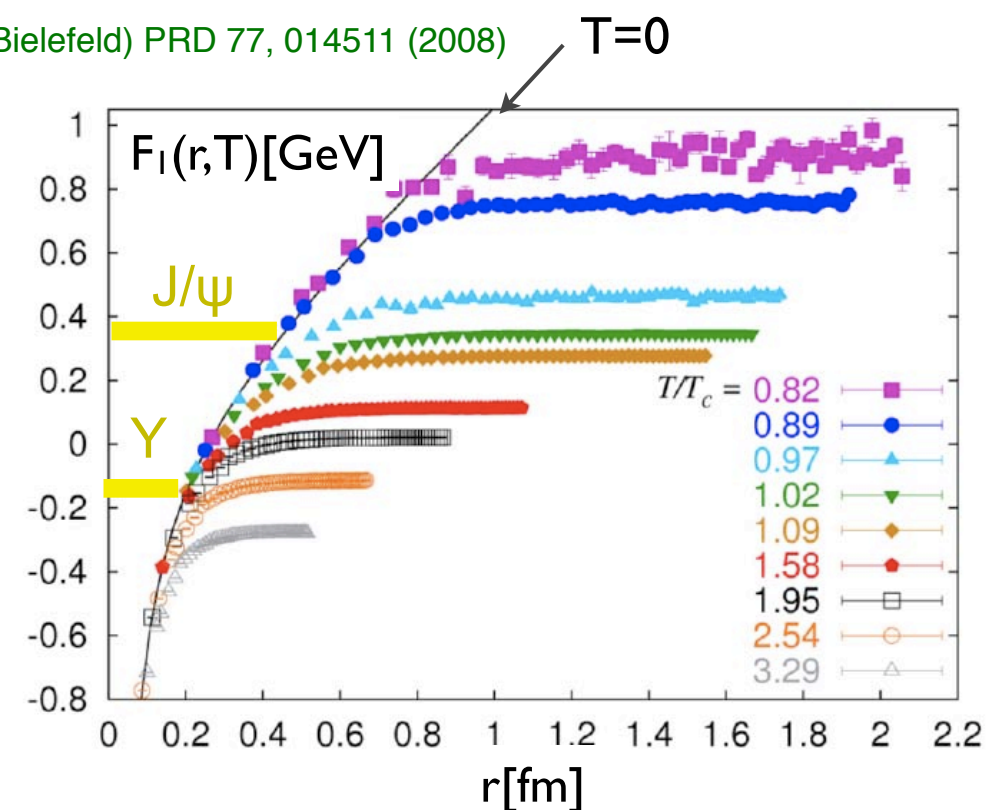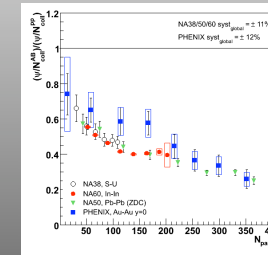
$r_{scr} < r_{J/\psi}$ "melting" of the J/ψ

But is the Jpsi RAA a signal for deconfinement and screening (?)

Famous Plot

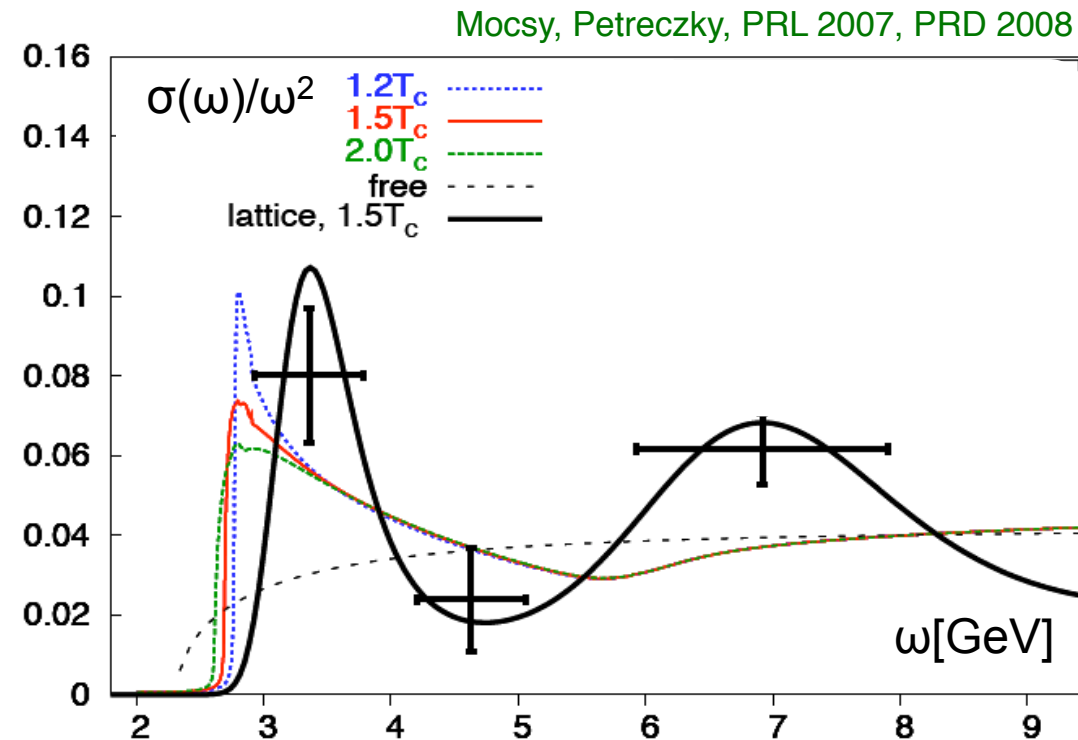## What is the physics behind it?

But is the Jpsi RAA a signal for deconfinement and screening (?)

To answer this question we need to know:

- How the properties of J/ψ change in a deconfined medium
  determine the spectral function

- Relate an equilibrium spectral function to R_{AA}
  through real-time dynamics

- Identify what physics might contribute to R_{AA}
  for example: suppression is seen in pA, dA data as well
          (where no QGP formation expected)
          Cold nuclear matter effects - could be relevant to AA
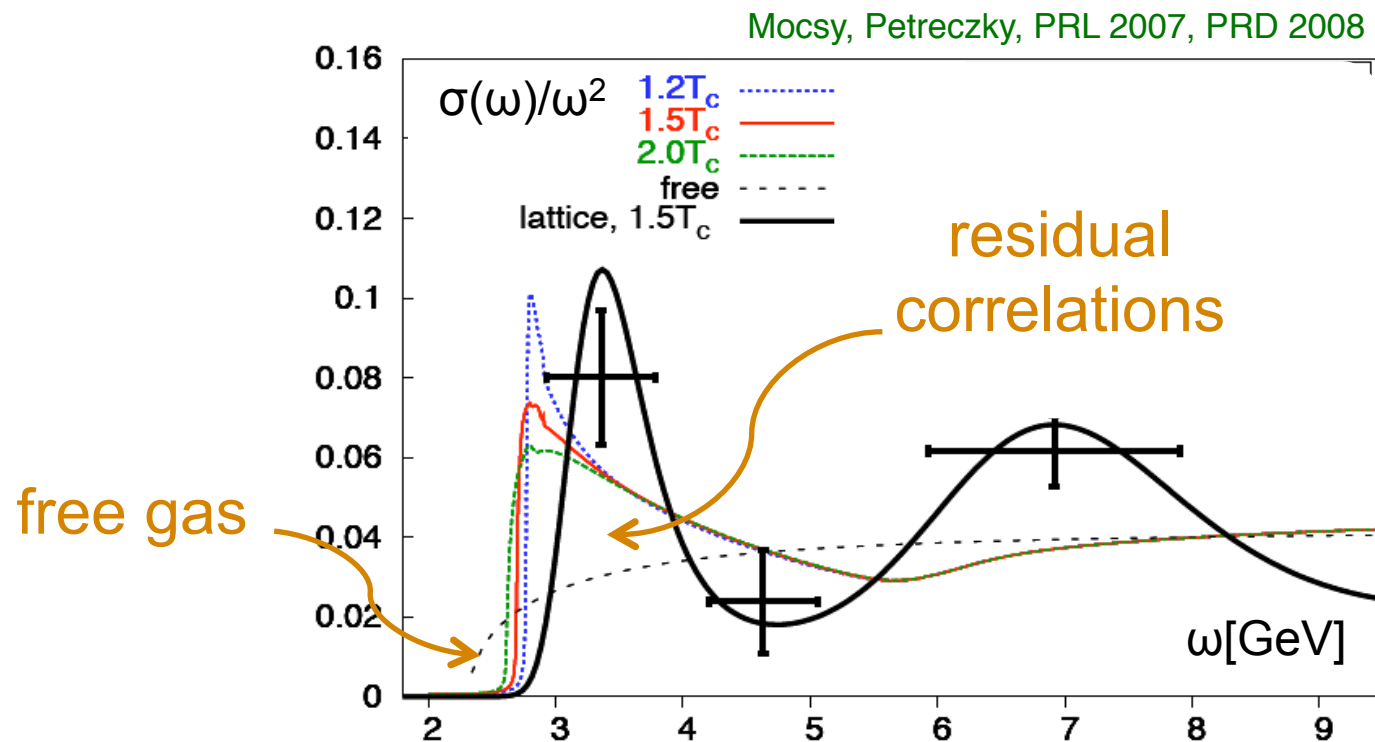
Quarkonium in Deconfined Medium

- Modest theory progress: Lattice QCD, potential models, effective field theories

- Spectral functions are calculated

Mocsy, Petreczky, PRL 2007, PRD 2008

- What we have learned:
  - binding energies of all quarkonium states reduced
  - no charmonium bound-states above $T_c=T_{deconfinement}$
  - c-cbar residual correlations persist - threshold enhancement
  - quantitative estimates of peak disappearance - T_{diss}

    upper limits

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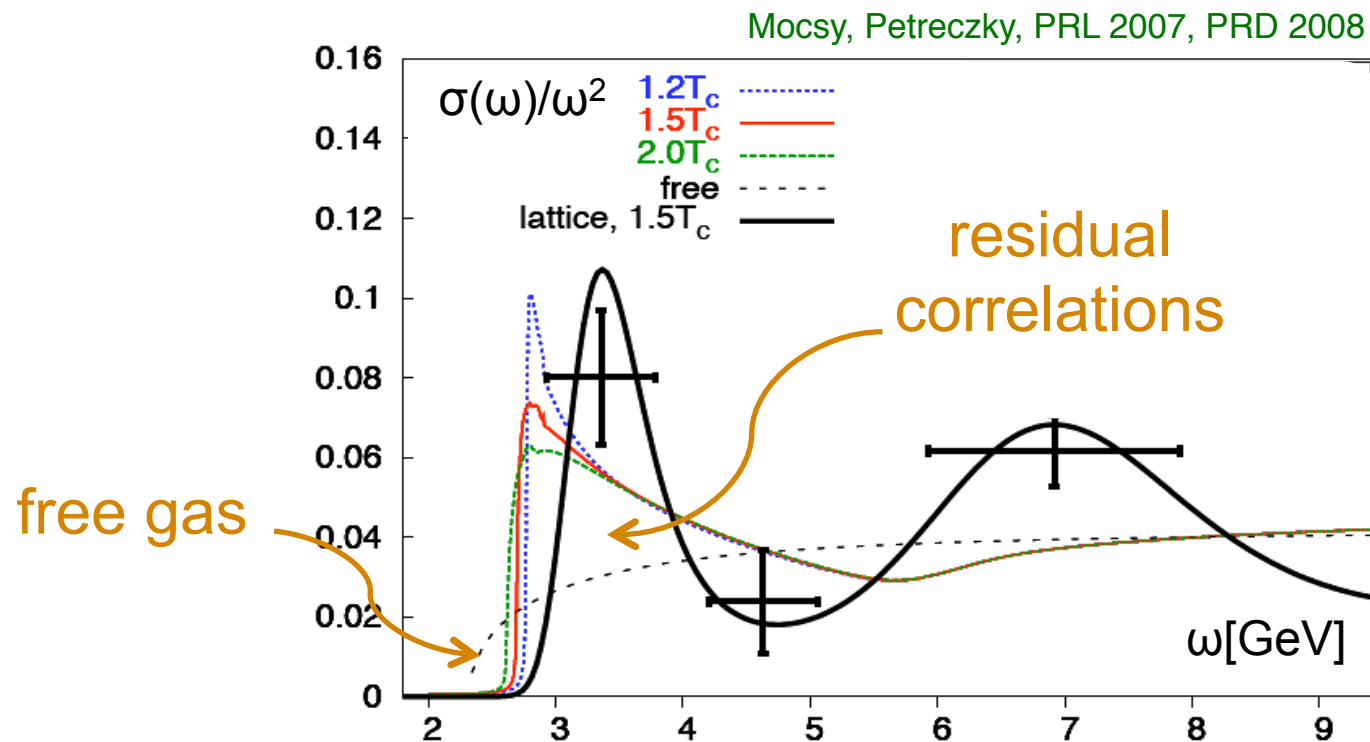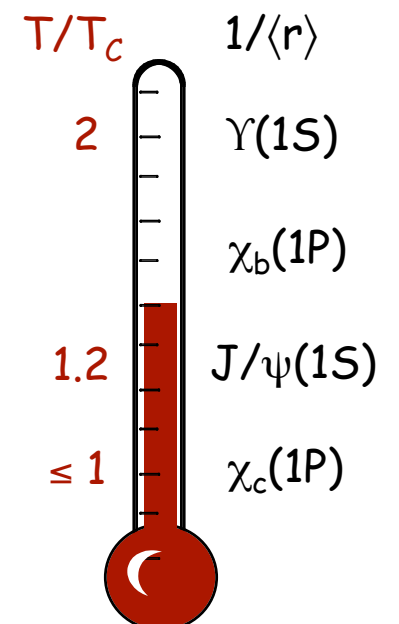   upper limits

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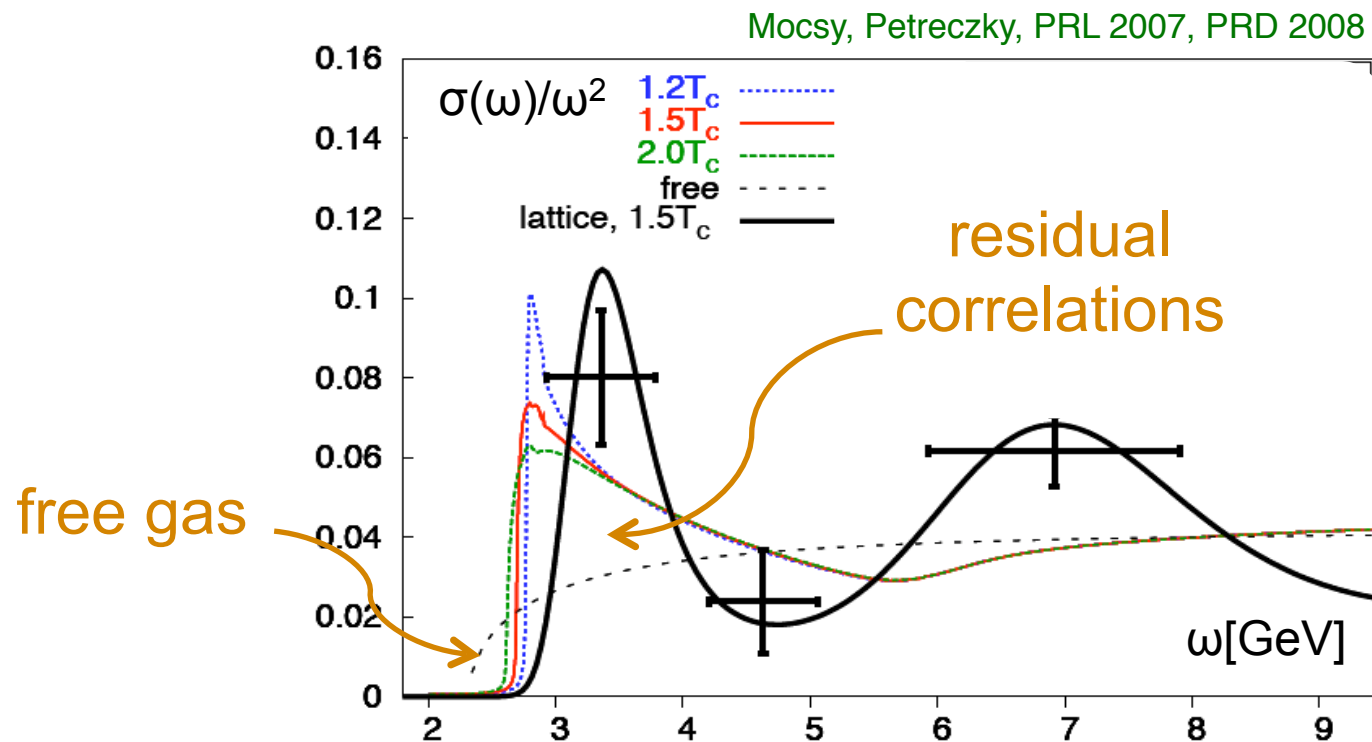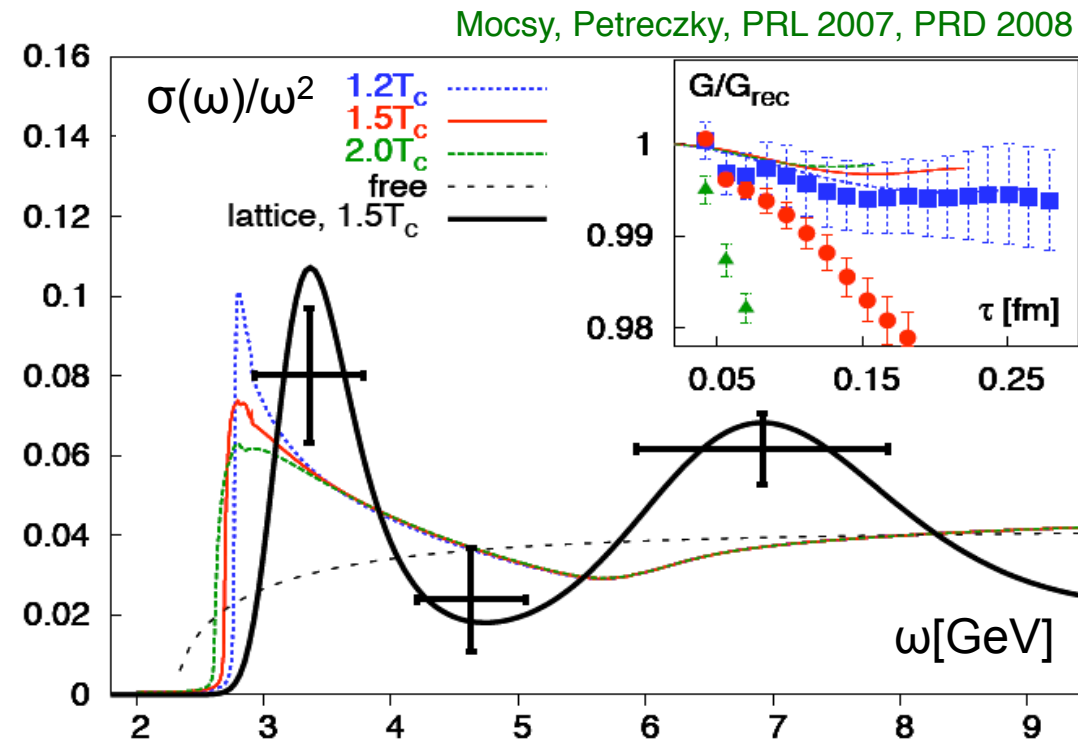
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Mocsy, Petreczky, PRL 2007, PRD 2008

residual correlations

free gas

$\sigma(\omega)/\omega^2$

1.2T_c
1.5T_c
2.0T_c
free
lattice, 1.5T_c

ω[GeV]

- *Ugly rumor : "Lattice tells J/ψ survives to 2T_c"*

  - We can calculate the Euclidean correlator $\quad G(\tau,T) = \int \sigma(\omega,T)K(\tau,\omega,T)d\omega$

  - Correlators do not change - just as lattice says so!

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

  - Unchanging correlators not sensitive to spectral function changes

  From correlators consistent with one cannot conclude J/ψ survival !

€

Quarkonium in Deconfined Medium

- Modest theory progress: Lattice QCD, potential models, effective field theories
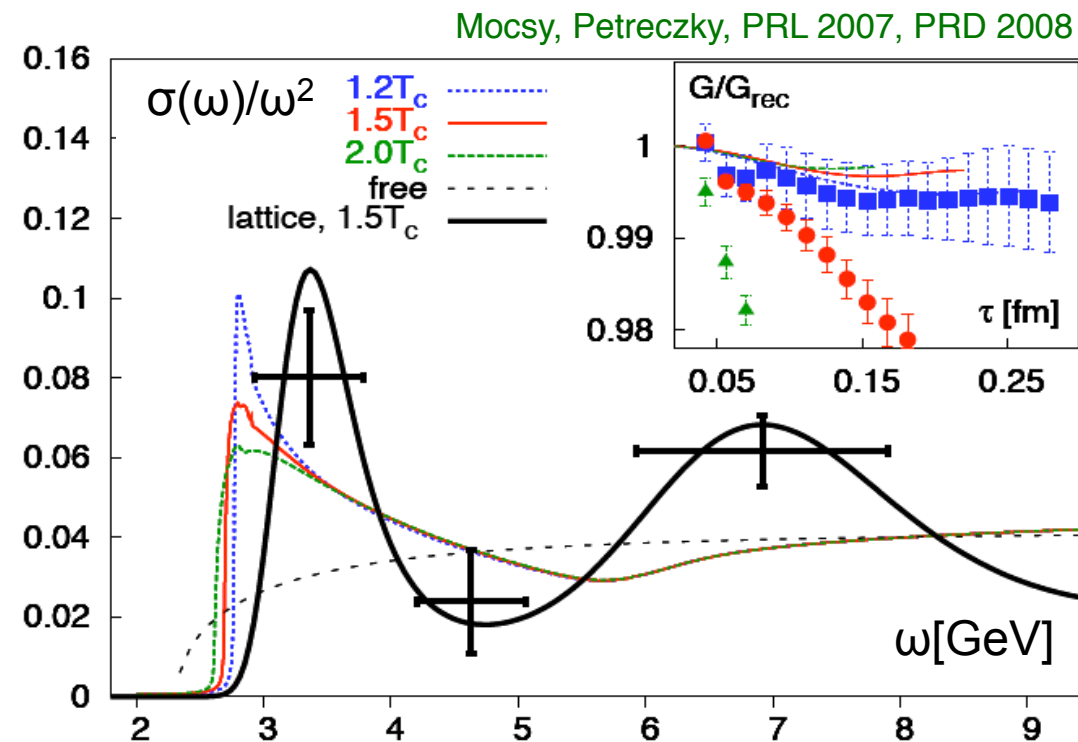
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  - One more thing: lattice spectral functions do not suggest J/ψ survival either

Quarkonium in Deconfined Medium

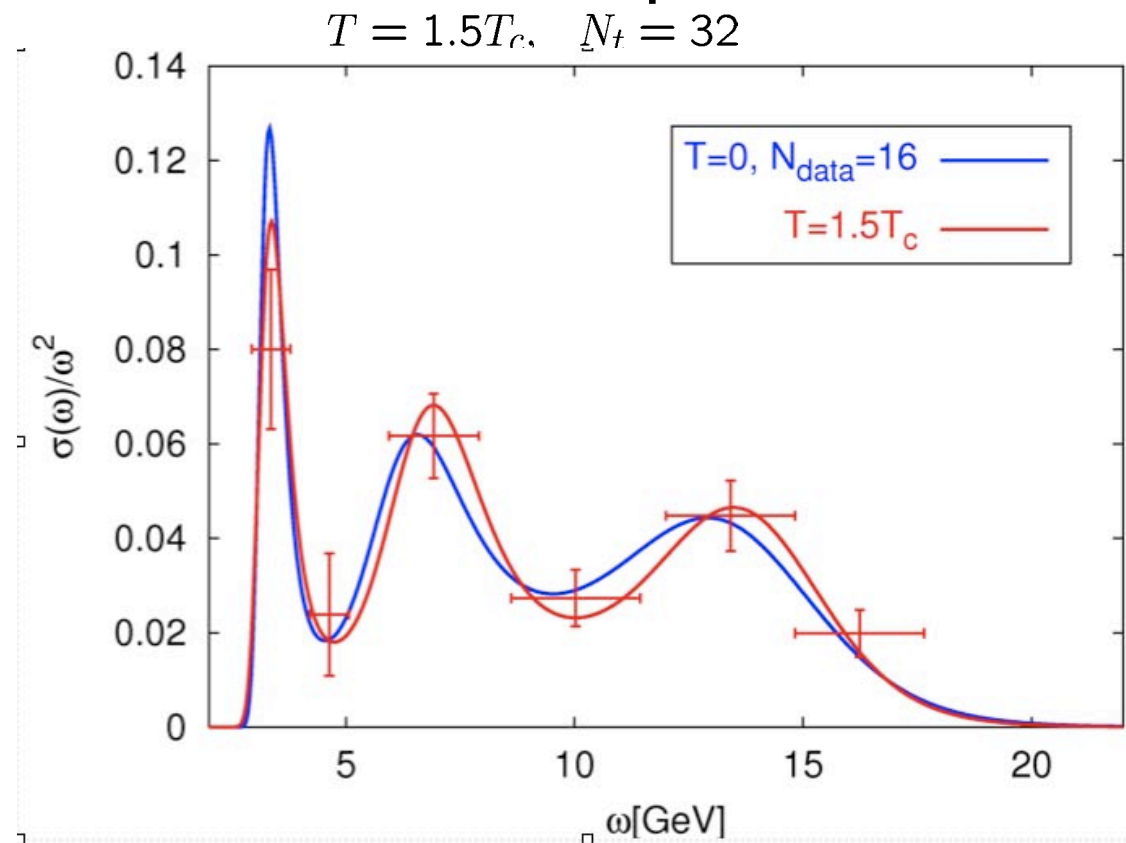- Extracted, not calculated, lattice spectral functions

$T = 1.5T_c, \quad N_t = 32$
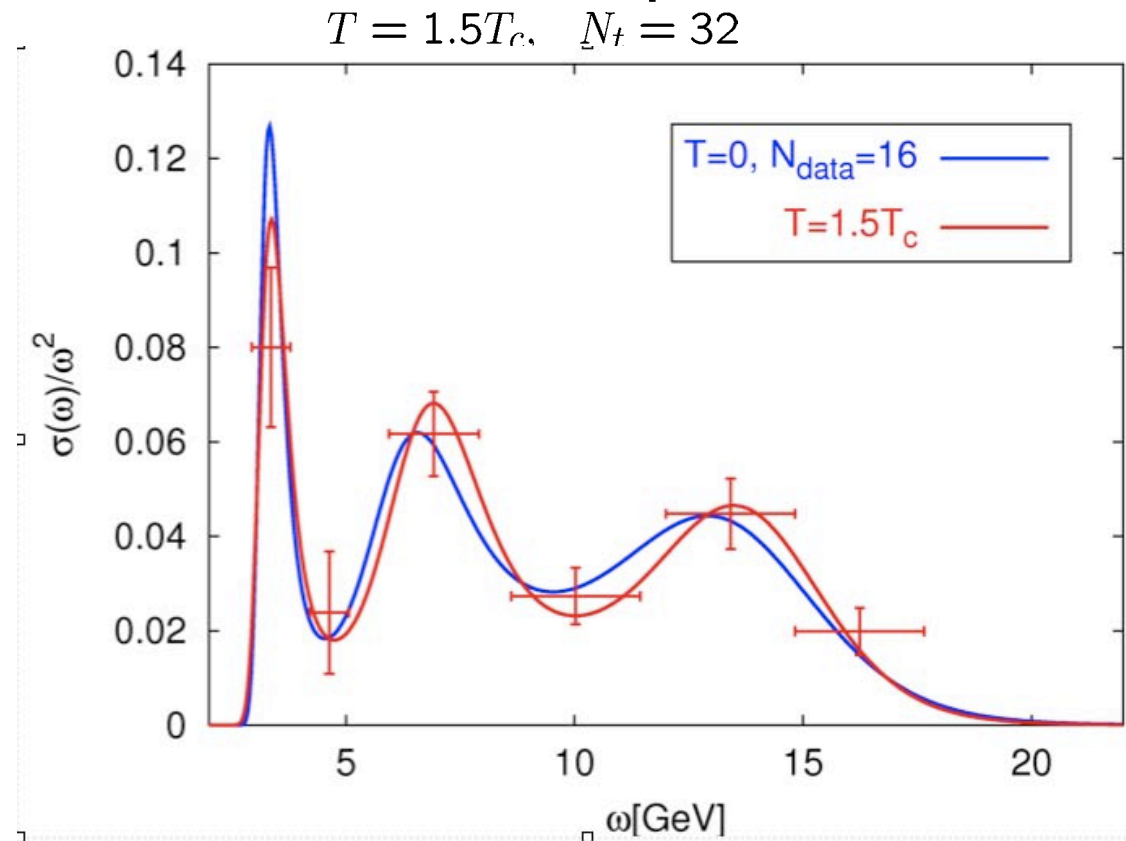
Umeda et al, EPJ C39S1 (05) 9, Asakawa, Hatsuda,PRL 92 (2004) 01200, Datta et al,PRD 69 (04) 094507, ...

$$T = 1/(N_t a)$$
$$\tau_{max} = 1/(2T)$$

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Quarkonium in Deconfined Medium

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$$T = 1/(N_t a)$$
$$\tau_{max} = 1/(2T)$$

Comparing low resolution confined phase (blue) to low resolution deconfined phase (red) and getting an agreement does **not** imply the agreement will hold at high resolution
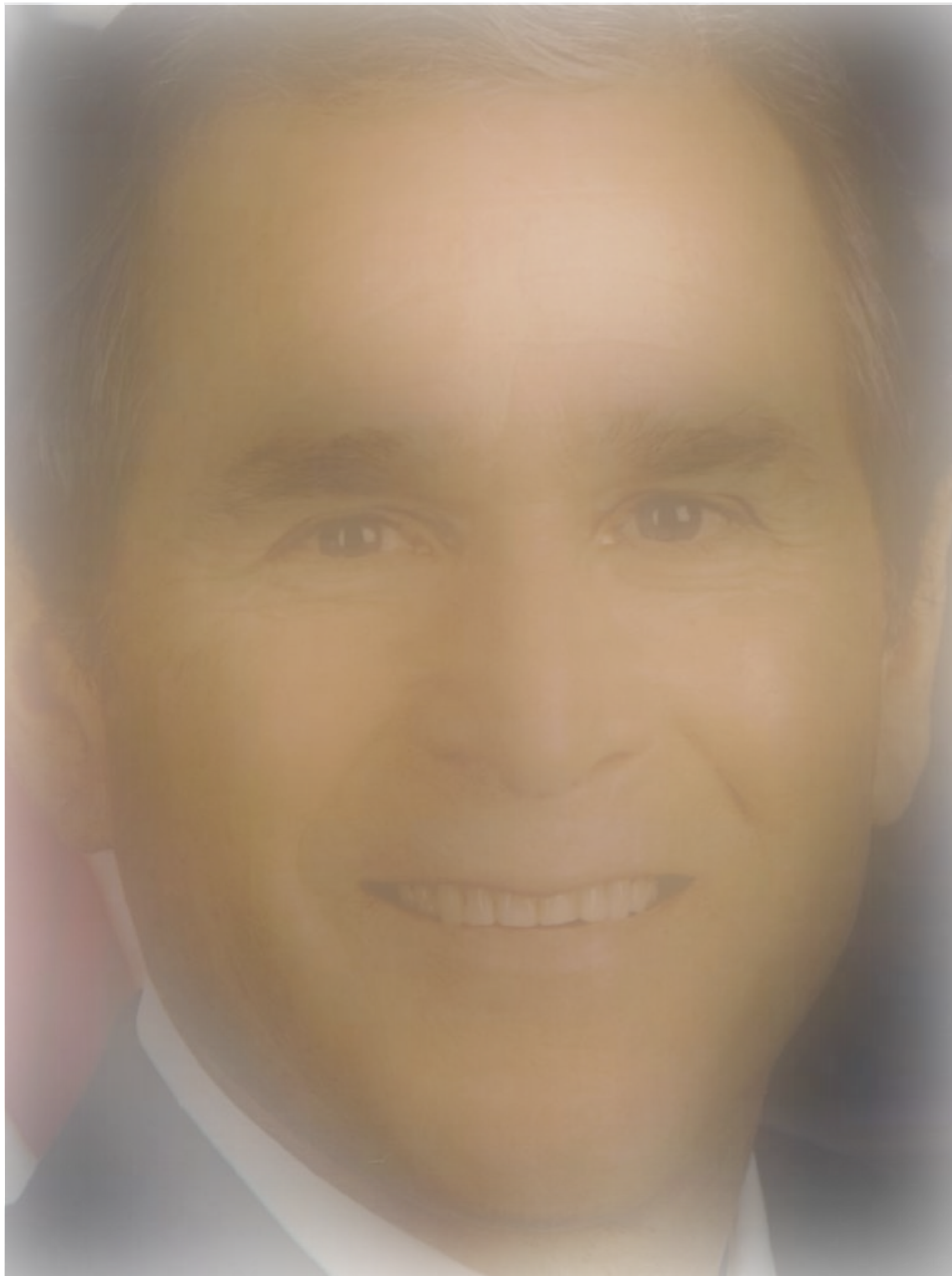
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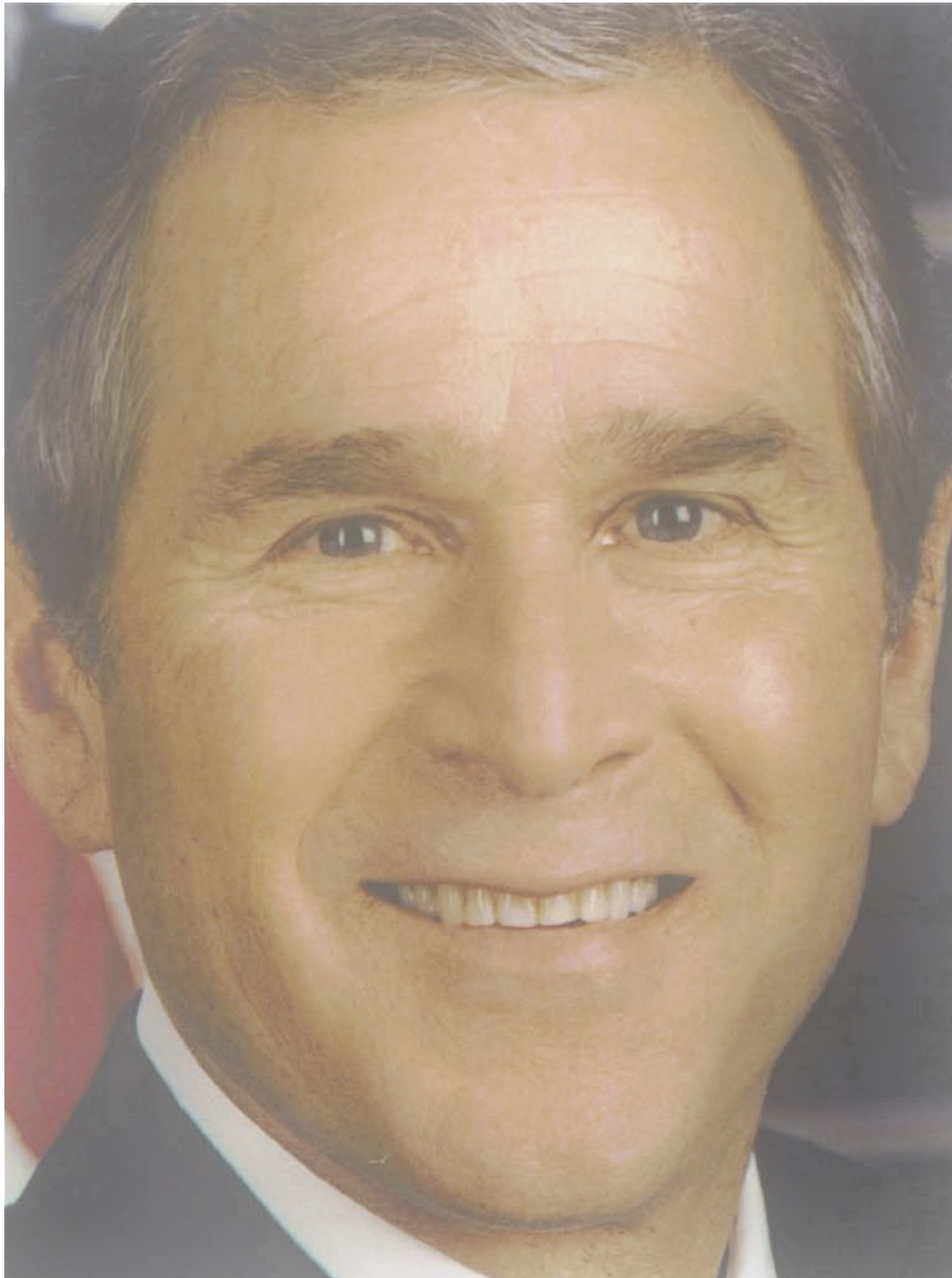
agreement in low resolution does
not imply agreement at high resolution
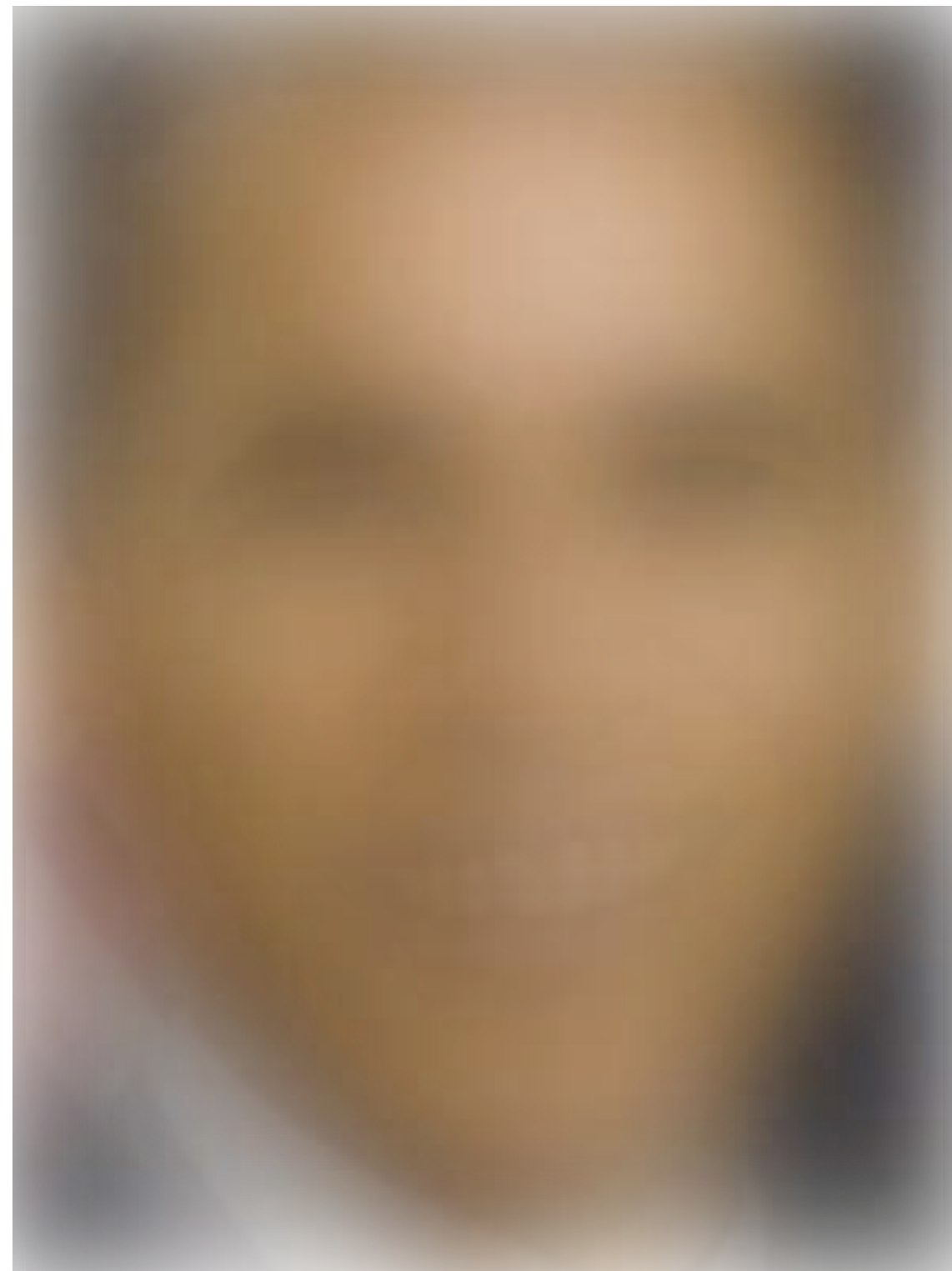
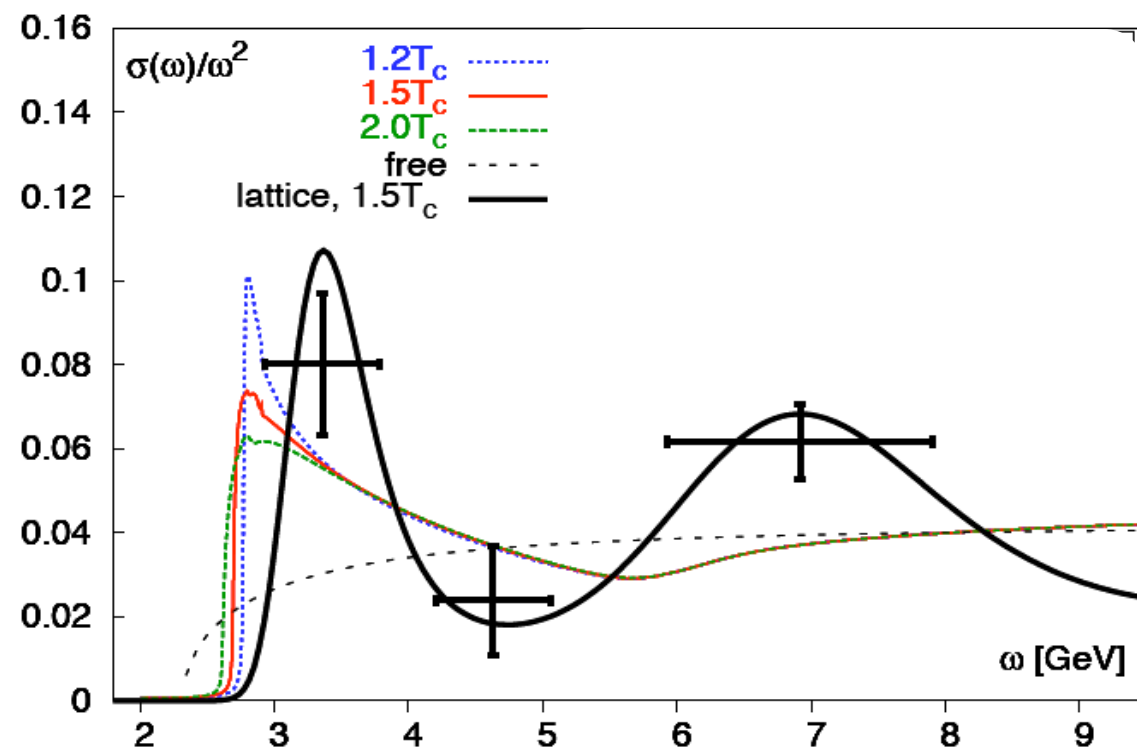agreement in low resolution does
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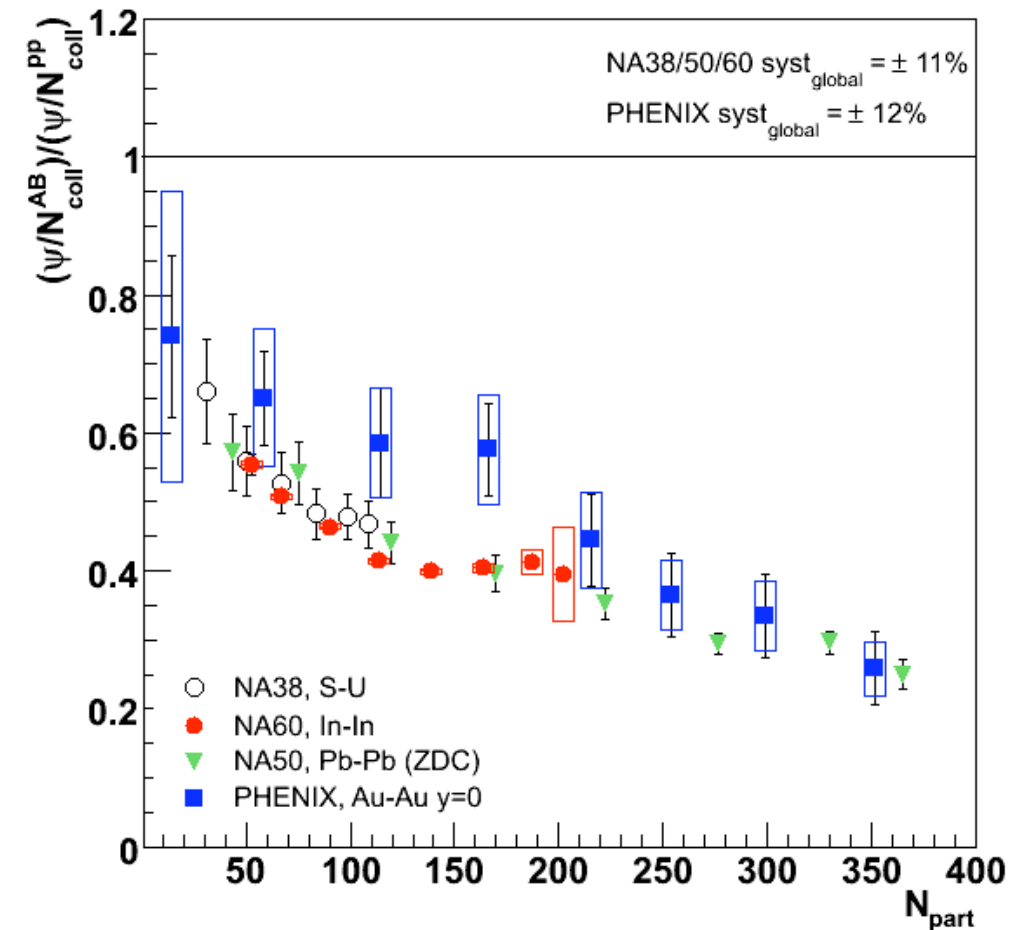not imply agreement at high resolution

agreement in low resolution does
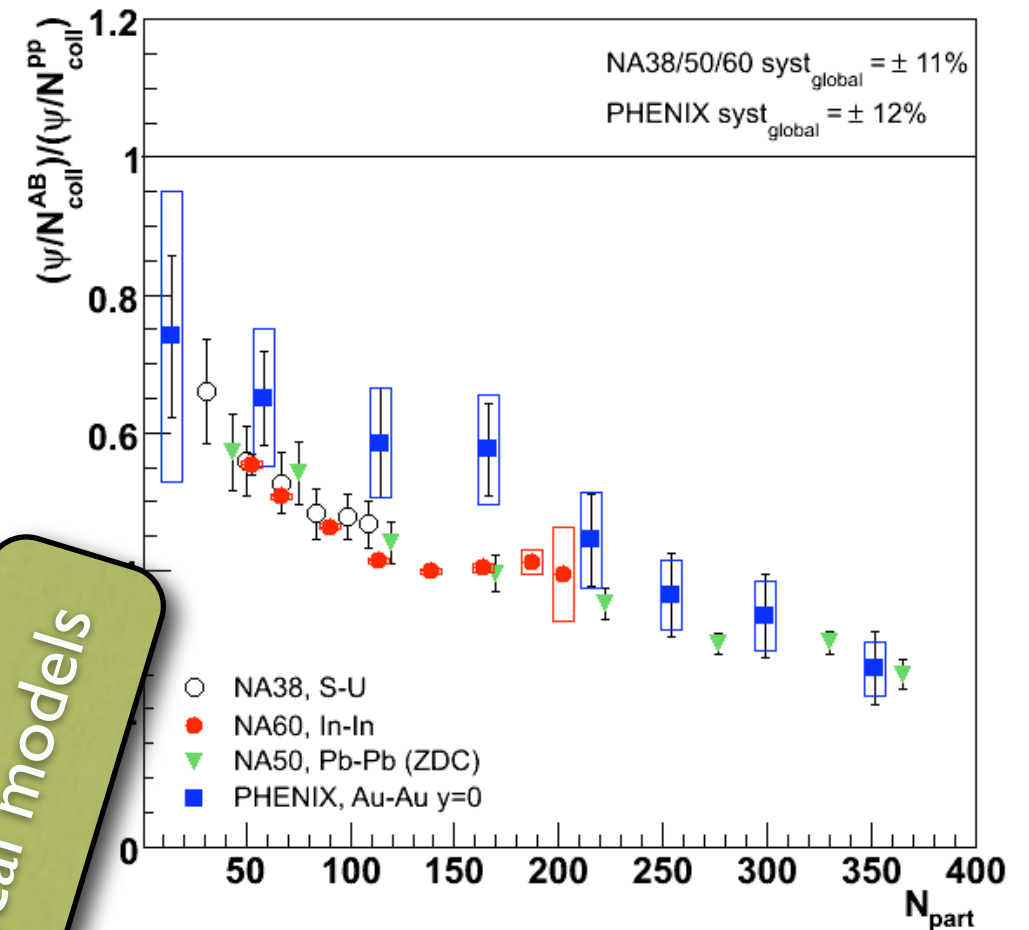not imply agreement at high resolution
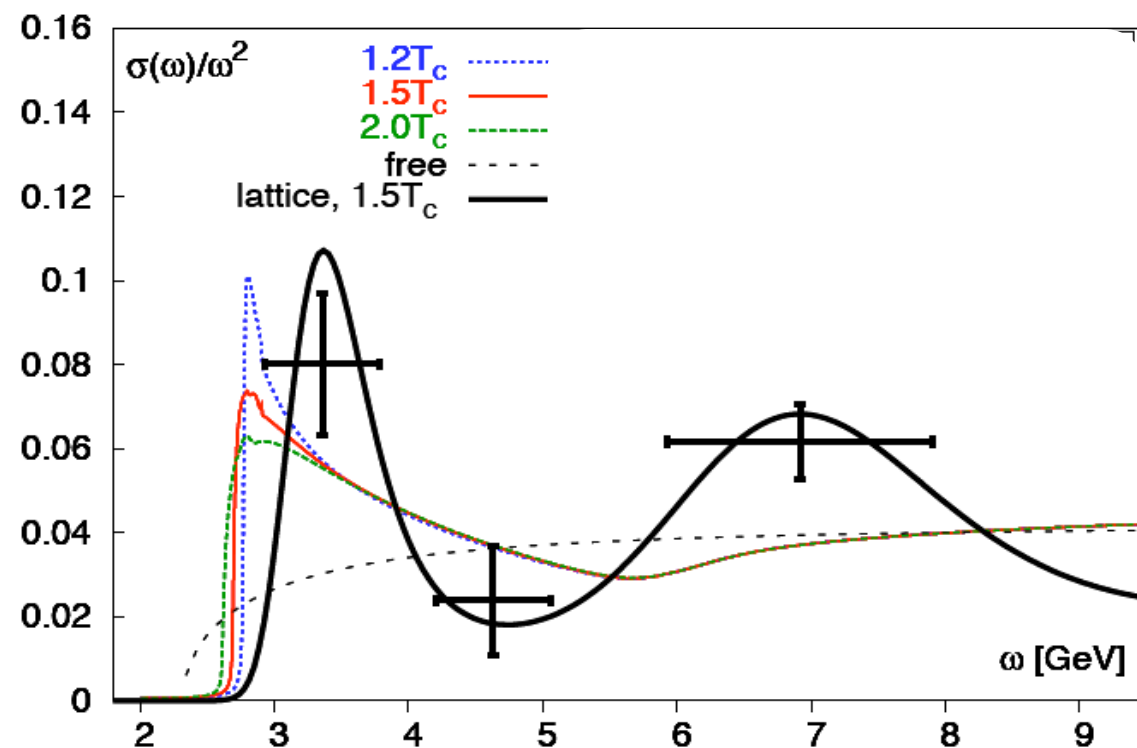
Famous Plot

How can we relate these?

Quarkonium spectral functions in equilibrated plasma

Experimental data

Famous Plot

How can we relate these?

Dynamical models

Quarkonium spectral functions in equilibrated plasma

Experimental data

The Connection

- Spectral function calculation → no bound states
  only correlated c-cbar pairs

- What is the probability that c-cbar
find themselves in proximity at the
hadronization time?

illustration by Alex Doig

- Modeling the motion of c-cbar in the
evolving fireball
  according to Langevin dynamics
   - stochastic force from the heat bath
   - attractive interaction between c-cbar

- Input: charm diffusion constant $D_c(2\pi T)$ = 1.5-3
  Best current guess Teaney and Moore,
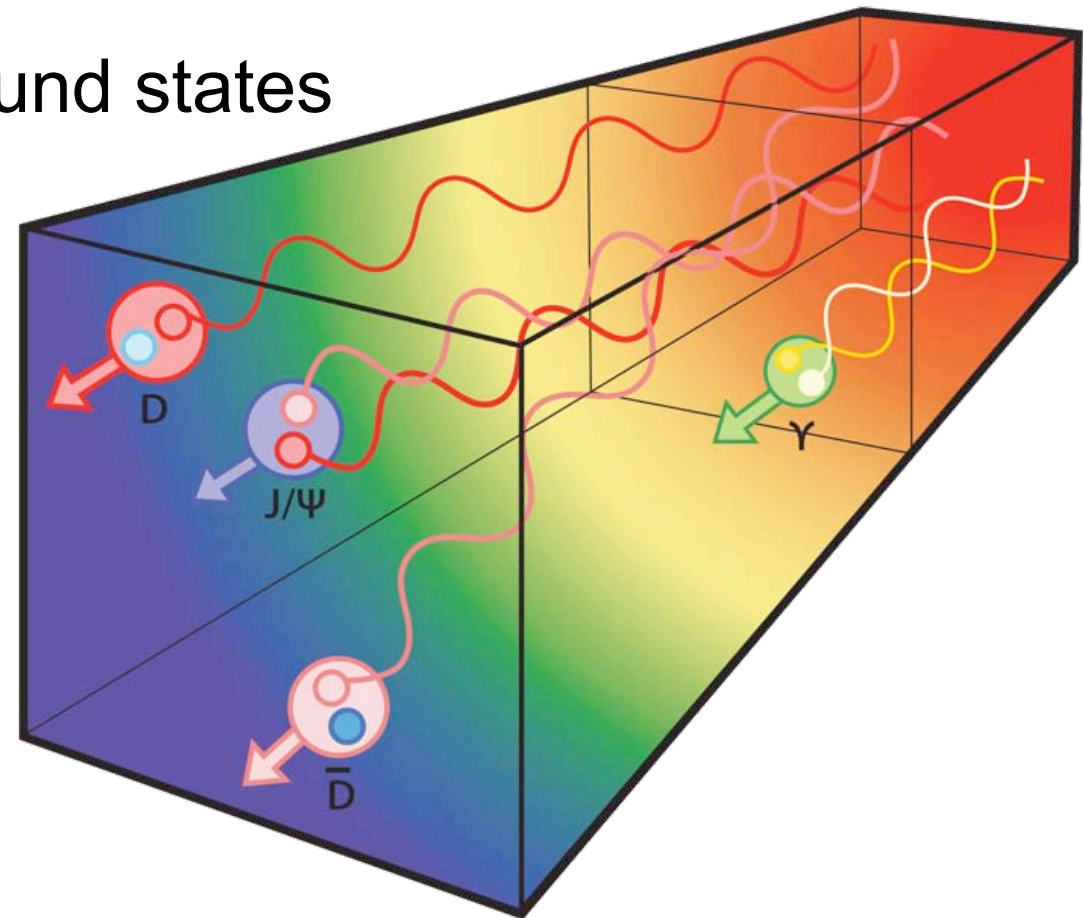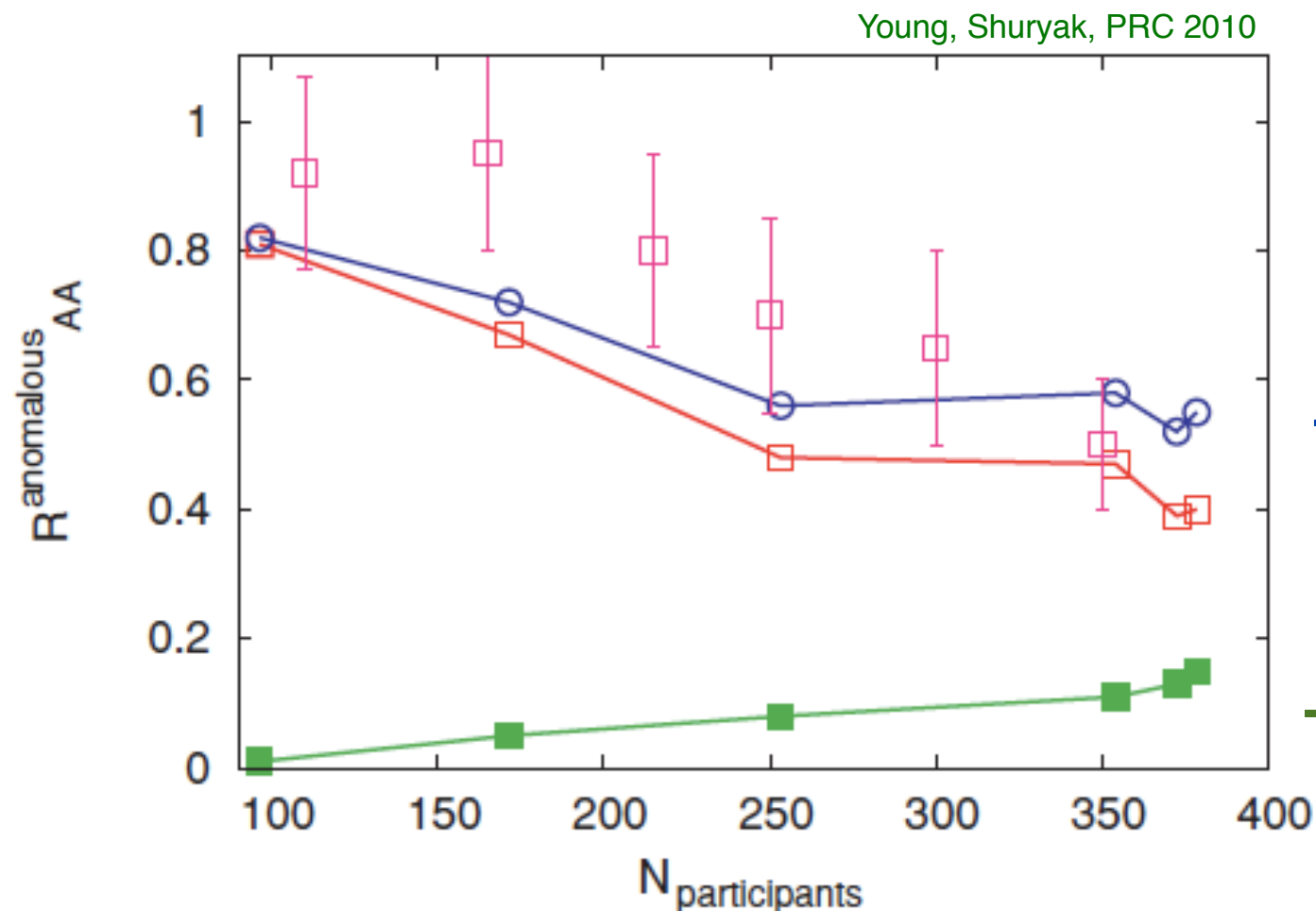 small enough that attraction between c and cbar may survive

The Connection

- Comparison to PHENIX data

Young, Shuryak, PRC 2010
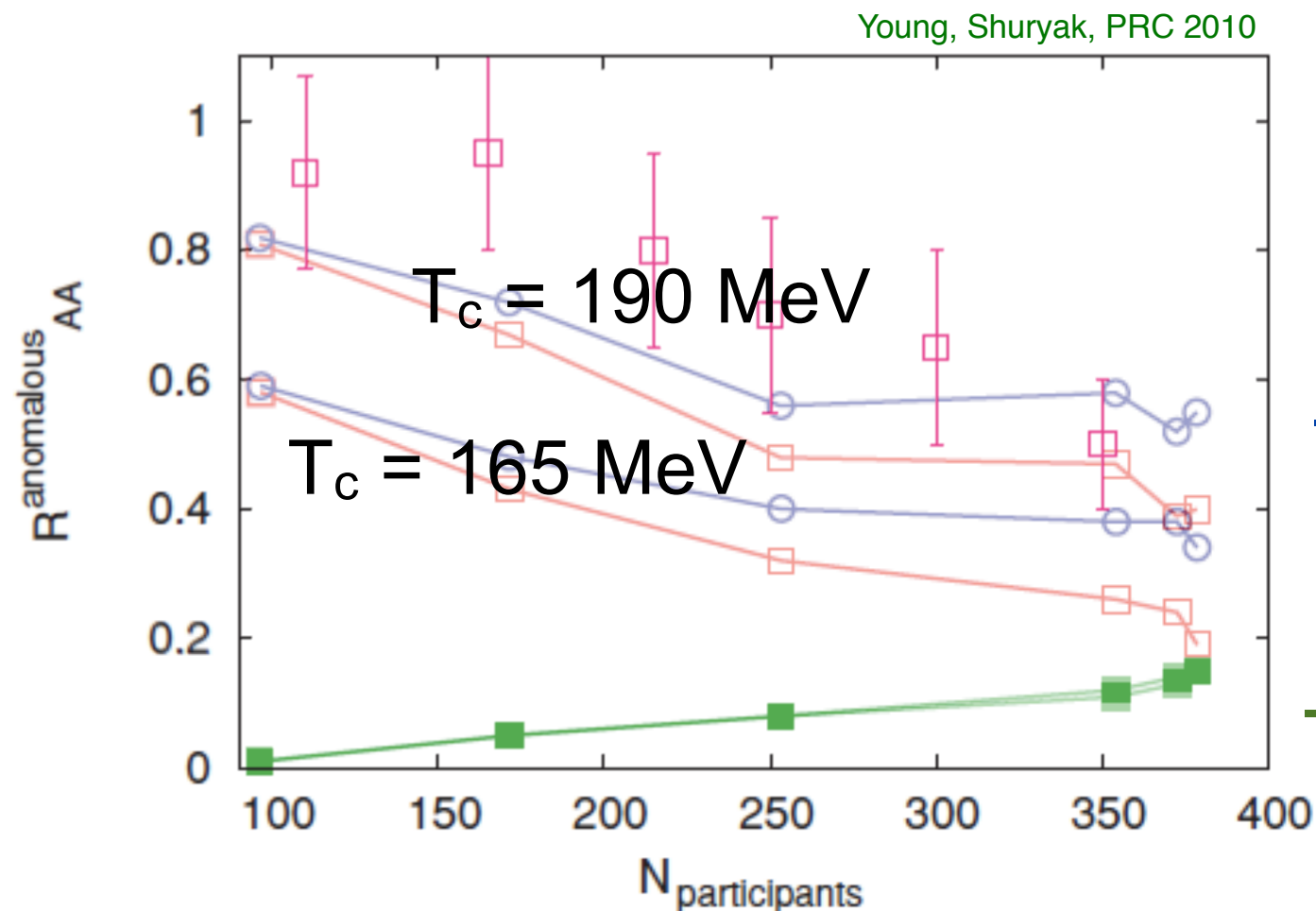
- total yield

- suppression + correlated regeneration

- statistical recombination
  c and cbar originate from different hard processes

- Direct J/ψ suppressed, but ~ 50% of correlated c-cbar recombine
- Coalescence gives relative small contribution
- Quite good agreement with data for small charm diffusion and T_c=190 MeV

Note: $T_c = T_{deconfinement}$

The Connection

- Comparison to PHENIX data

Young, Shuryak, PRC 2010

T_c = 190 MeV

T_c = 165 MeV

- total yield

- suppression +
  correlated regeneration

- statistical recombination
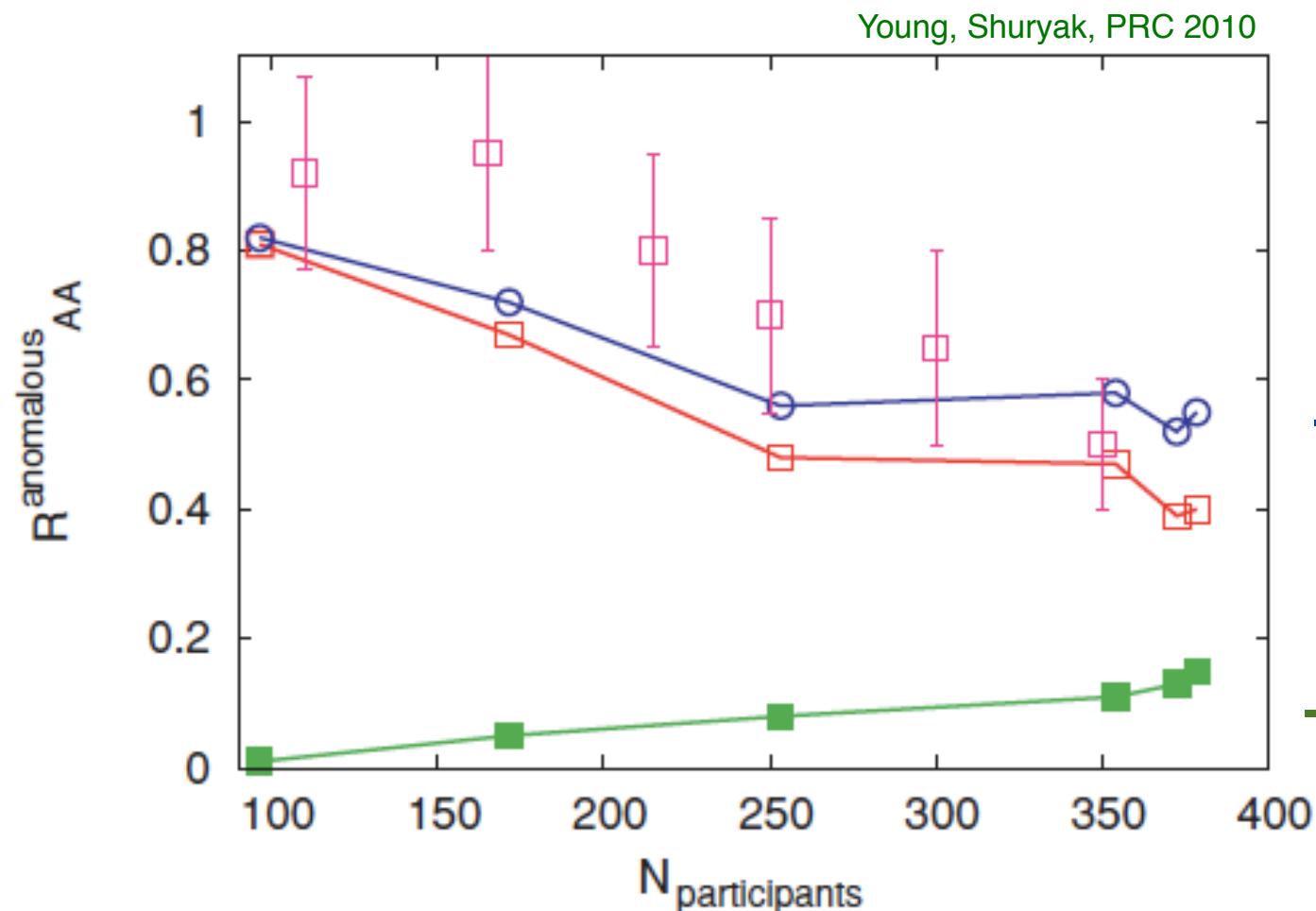 c and cbar originate from
  different hard processes

- Agreement is better with the higher deconfinement temperature,
  i.e. with a shorter QGP lifetime

The finiteness of R_{AA} can lead us to determine the plasma lifetime ?!

Note: $T_c = T_{deconfinement}$

The Connection

- Comparison to PHENIX data

Young, Shuryak, PRC 2010

- total yield

- suppression + correlated regeneration

- statistical recombination
  c and cbar originate from different hard processes

- Note

There are effects not included in this model: initial state effects and absorption in the crossover-hadronic region (CNM effects)
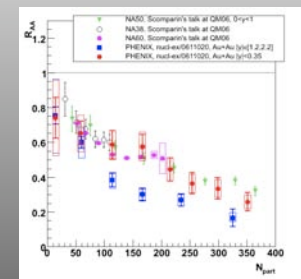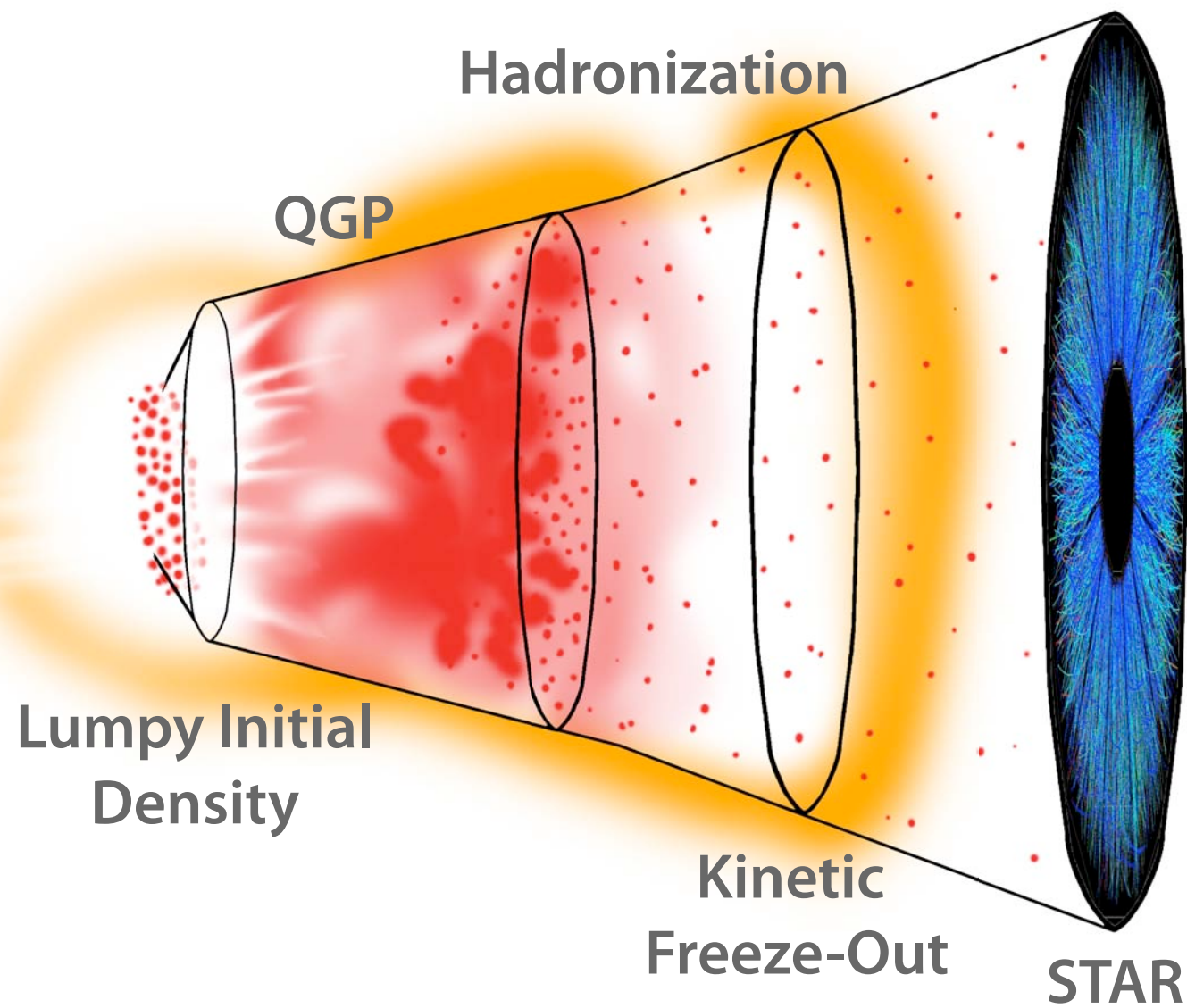
- A quantitative comparison with data is difficult

illustration by Alex Doig

Hadronization

QGP

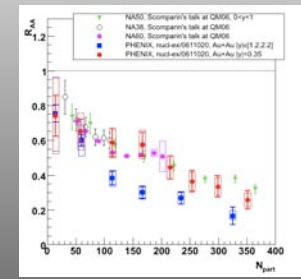**Lumpy Initial Density**

Kinetic Freeze-Out

STAR

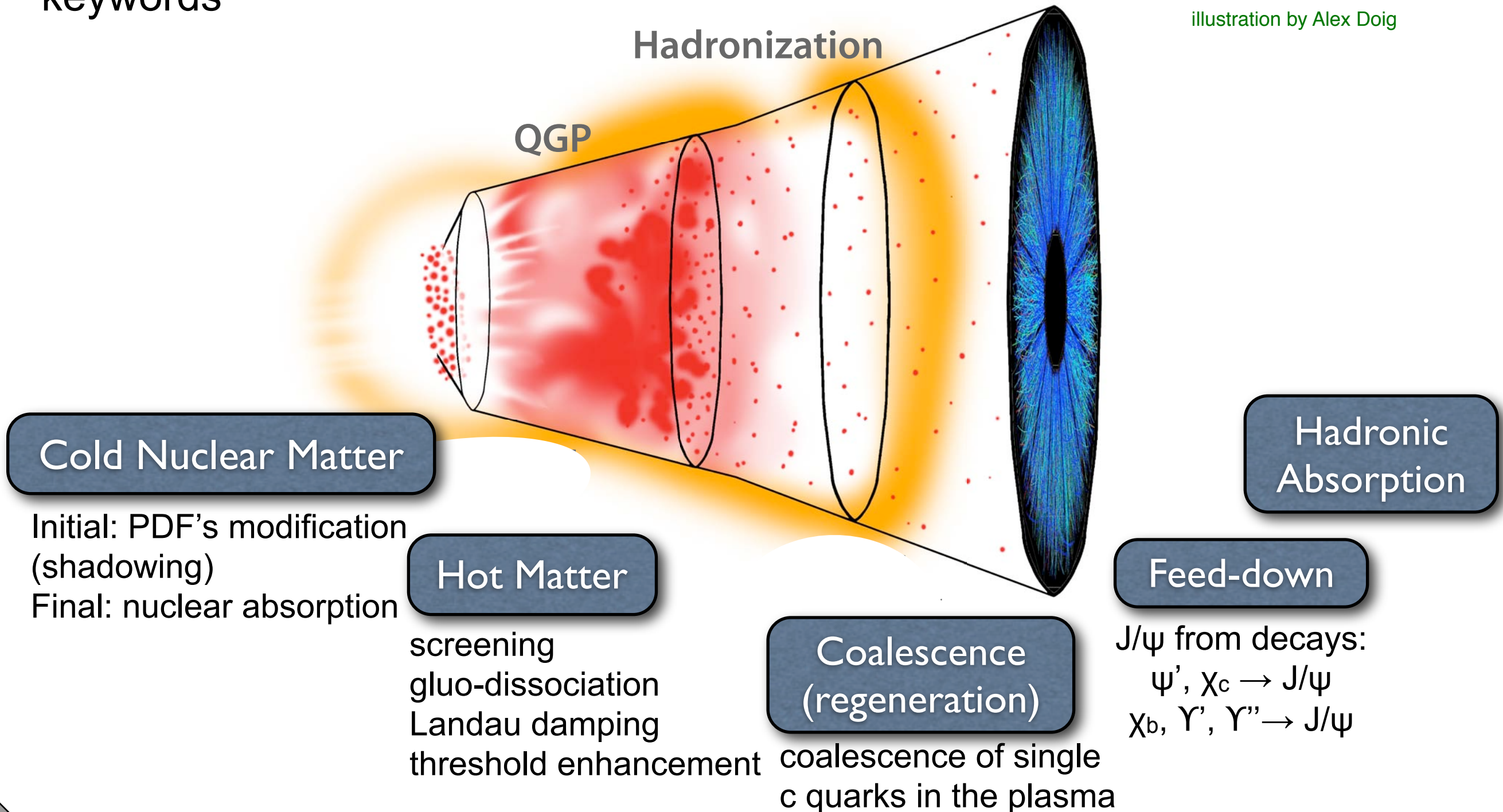c and cbar are produced at early times ...

... go through the entire evolution ...

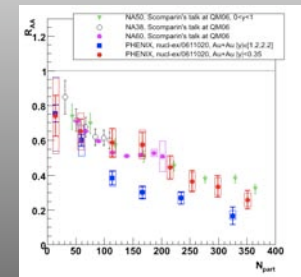... end up in hidden (J/ψ) or in open (D) charm

Famous Plot

keywords

illustration by Alex Doig

Hadronization

QGP

Cold Nuclear Matter

Initial: PDF's modification
(shadowing)
Final: nuclear absorption

Hot Matter

screening
gluo-dissociation
Landau damping
threshold enhancement

Coalescence (regeneration)

coalescence of single
c quarks in the plasma

Hadronic Absorption

Feed-down

J/ψ from decays:
ψ', χc → J/ψ
χb, Υ', Υ''→ J/ψ

Famous Plot

new way of organizing

illustration by Alex Doig

Hadronization

QGP

Initial State

Deconfined Matter

Crossover/Hadronic Region
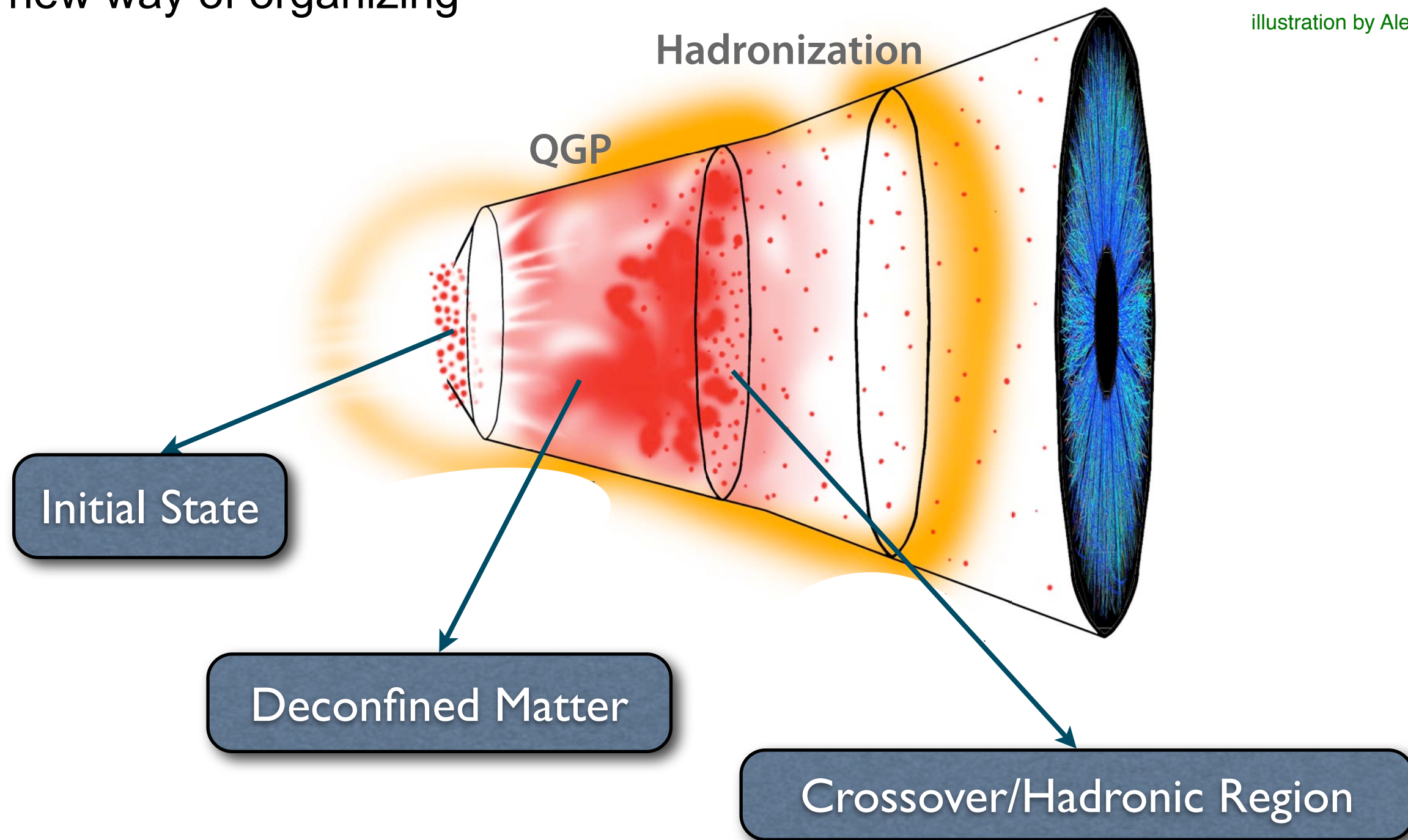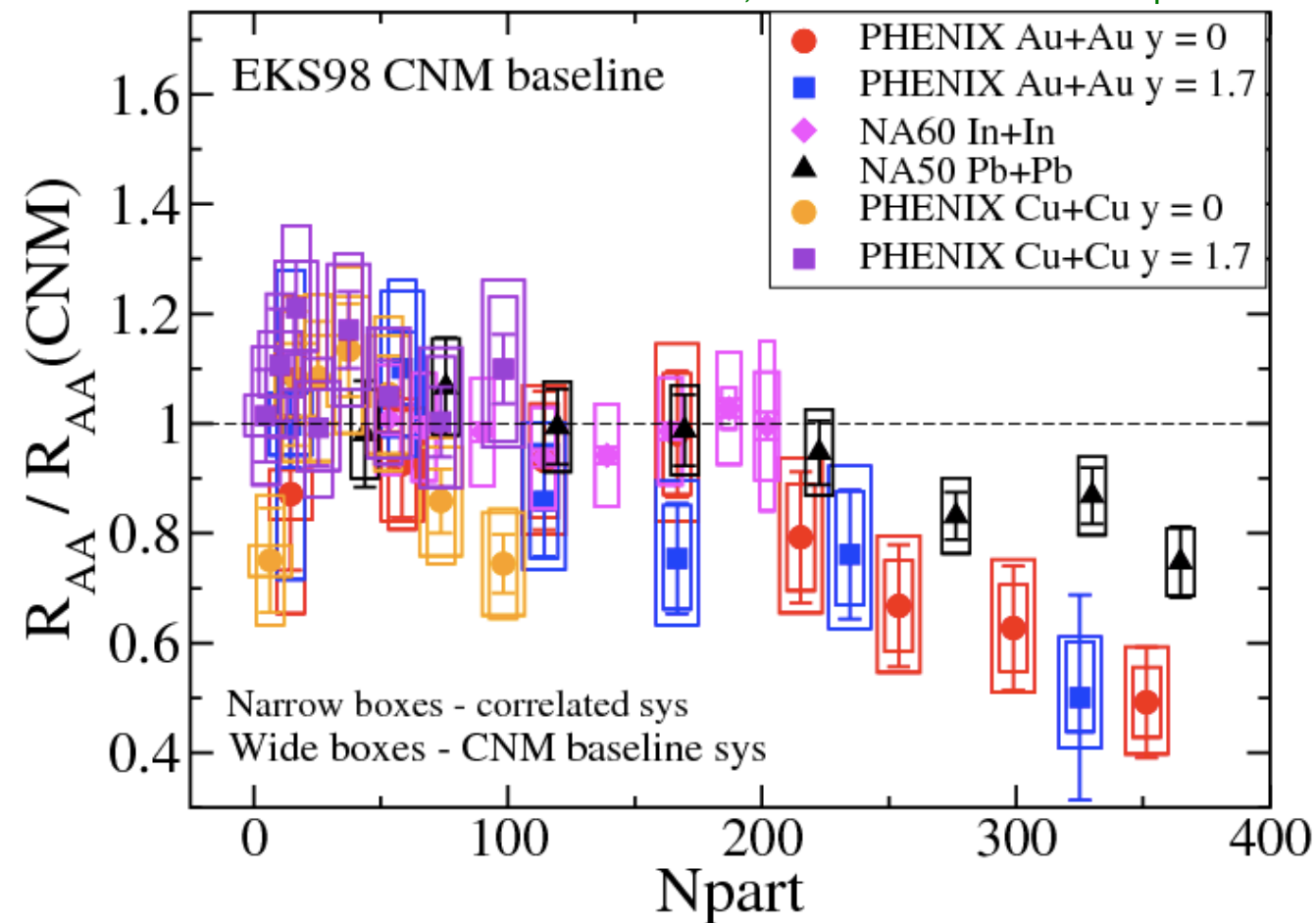
Famous Plot
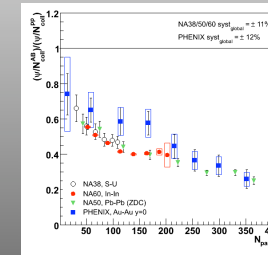
With CNM effects divided out
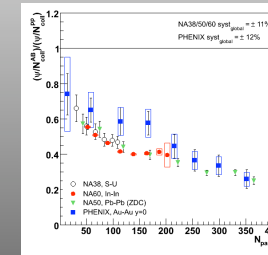
"Anomalous suppression"

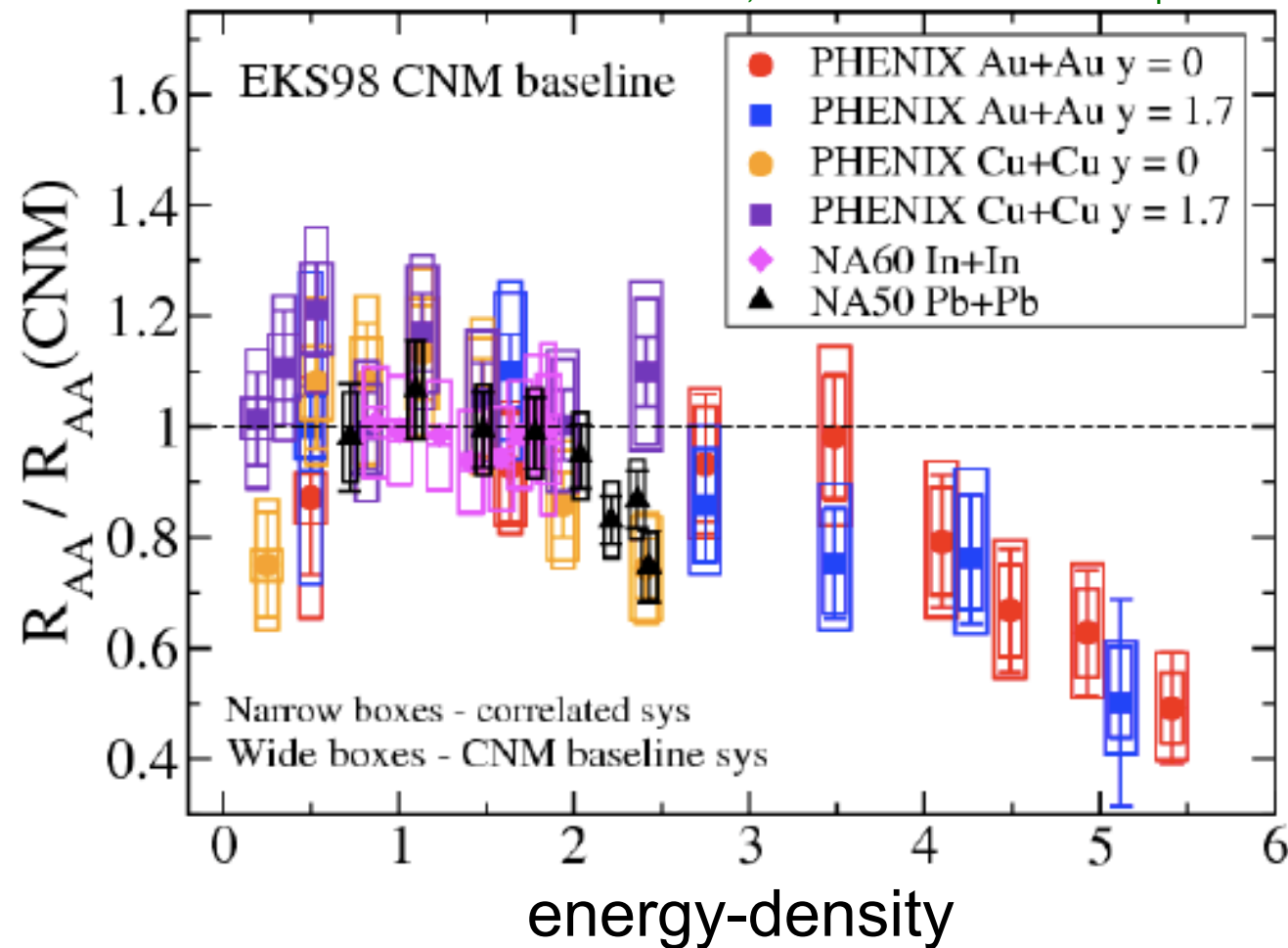M. Leitch, INT Quarkonium Workshop 2008

This makes sense if
- all CNM effects are initial state (shadowing), or
- absorption in the crossover region ("mixed phase") is similar to absorption in nuclear matter

Famous Plot

With CNM effects divided out

"Anomalous suppression"

- SPS described well with hadronic - reaches into crossover region
- RHIC reaches into deconfined region

    onset of deconfinement (onset of screening) ~ 3.5 GeV/fm^3 ~200 MeV

Other Controls

to disentangle the famous plot

$$R_{AA} \text{ versus } p_T$$

- Great for separating the different contributions
- At high p_T
  - CNM effects are not important
  - Recombination has little effect

  - A suppression at hight p_T would indicate suppression of direct J/ψ by the hot medium

  - If no suppression then J/ψ forms outside of the plasma

- At this conference: high pT R_{AA} in AU-AU by STAR RHIC

Talk by Zebo Tang

Other Controls

to disentangle the famous plot

Υpsilon

- Υ (theoretically) is a much cleaner signal

  - Initial state effects not very relevant ($m_b \gg Q^2$)

  - Absorption is small in the crossover/hadronic region

  - No recombination number of b and bbar is negligible

  - Easy to calculate spectral function, but dynamical modeling harder

  - Ground state can survive at RHIC and be suppressed at LHC

- At this conference: Υ R_{AA} at RHIC   Poster by Rosi Reed
  will provide a crucial consistency check of quarkonium suppression as deconfinement signal

Other Controls

to disentangle the famous plot

R_{AA} versus Root s

- Could help in weeding out and/or constraining some models

  Helps isolate the different effects

- Testing the crossover region

- At this conference: Low energy run results by PHENIX RHIC

Talk by Abhisek Sen

The End