Heavy Quarks & Quarkonia

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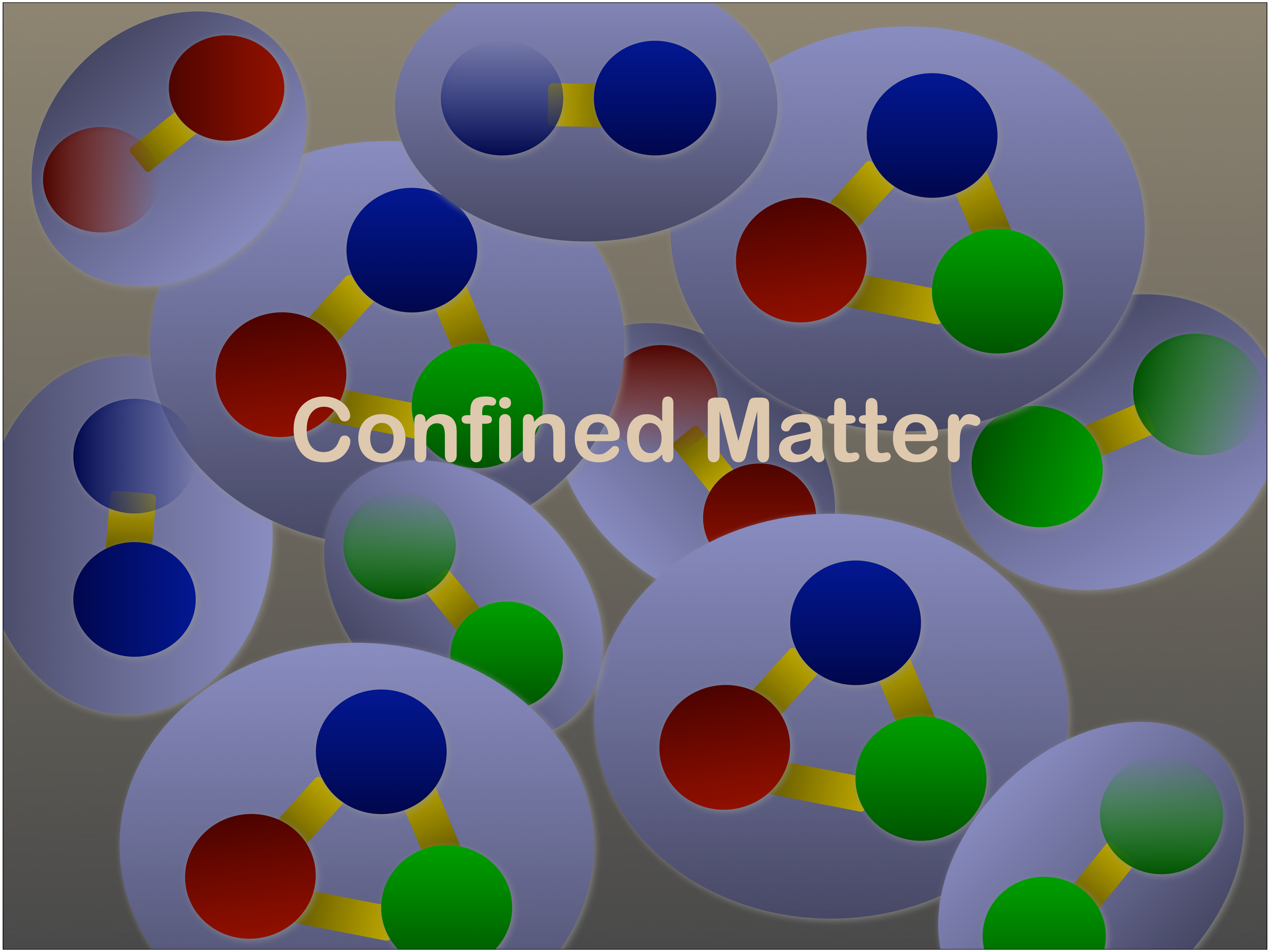
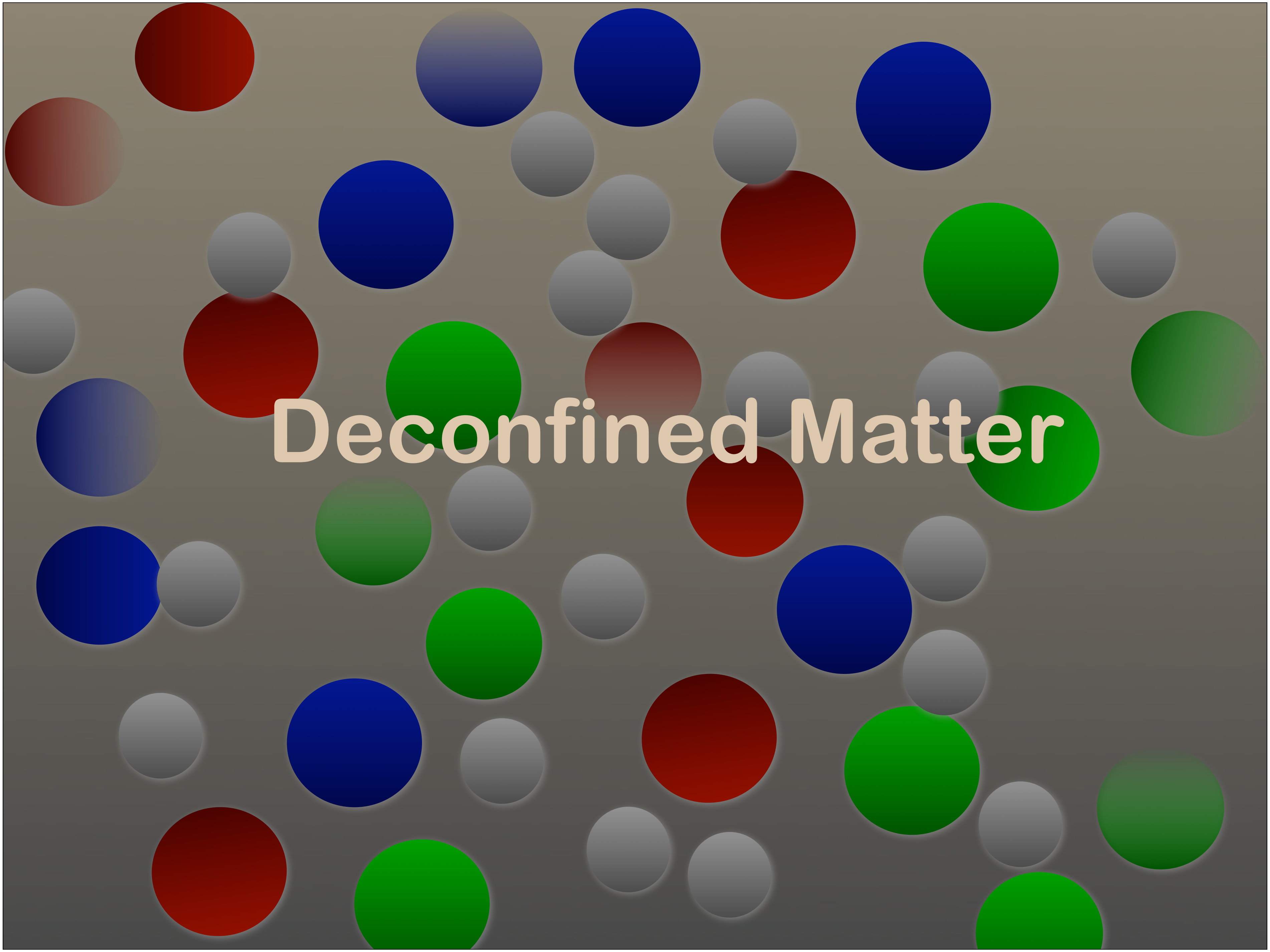
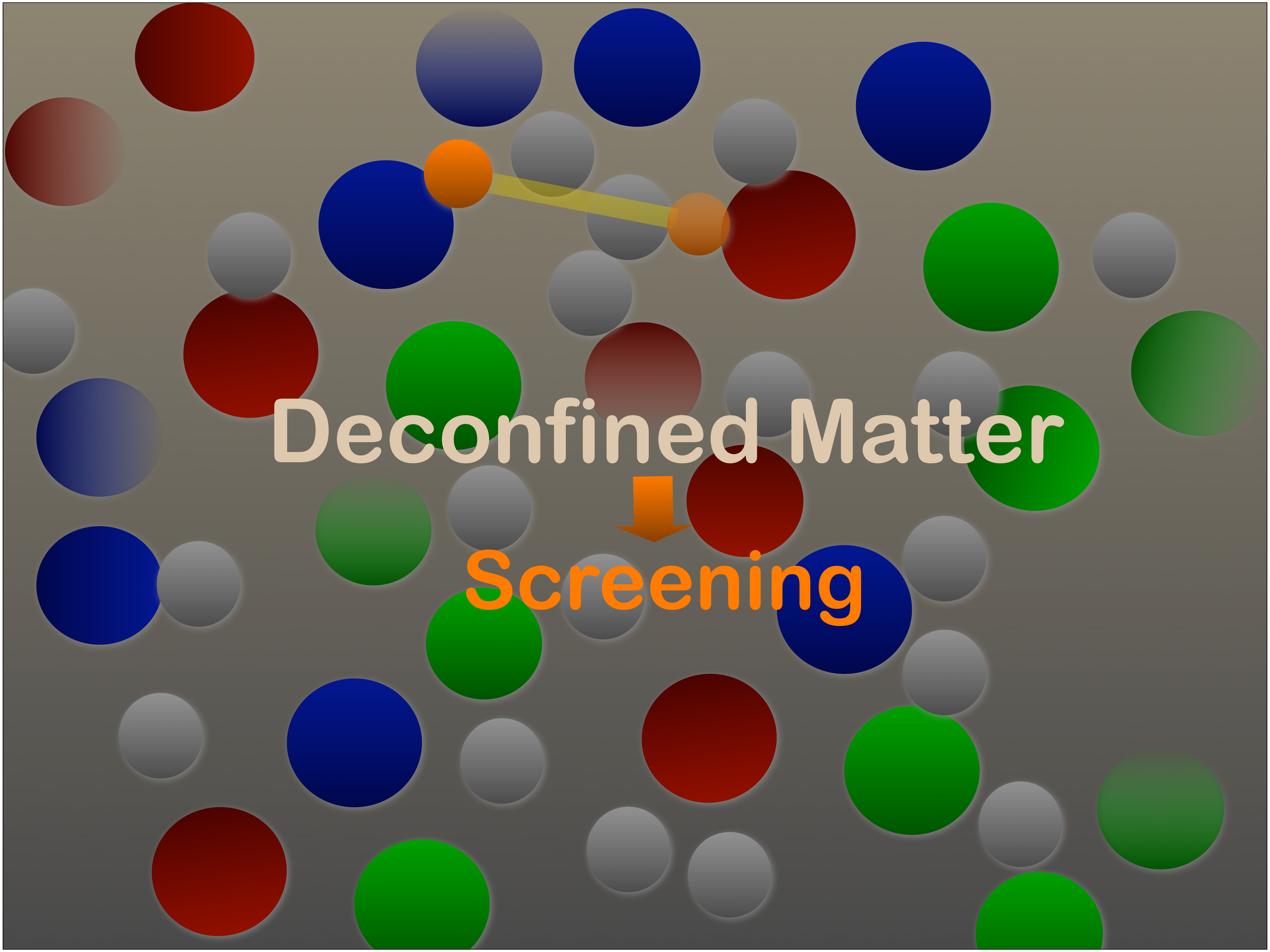
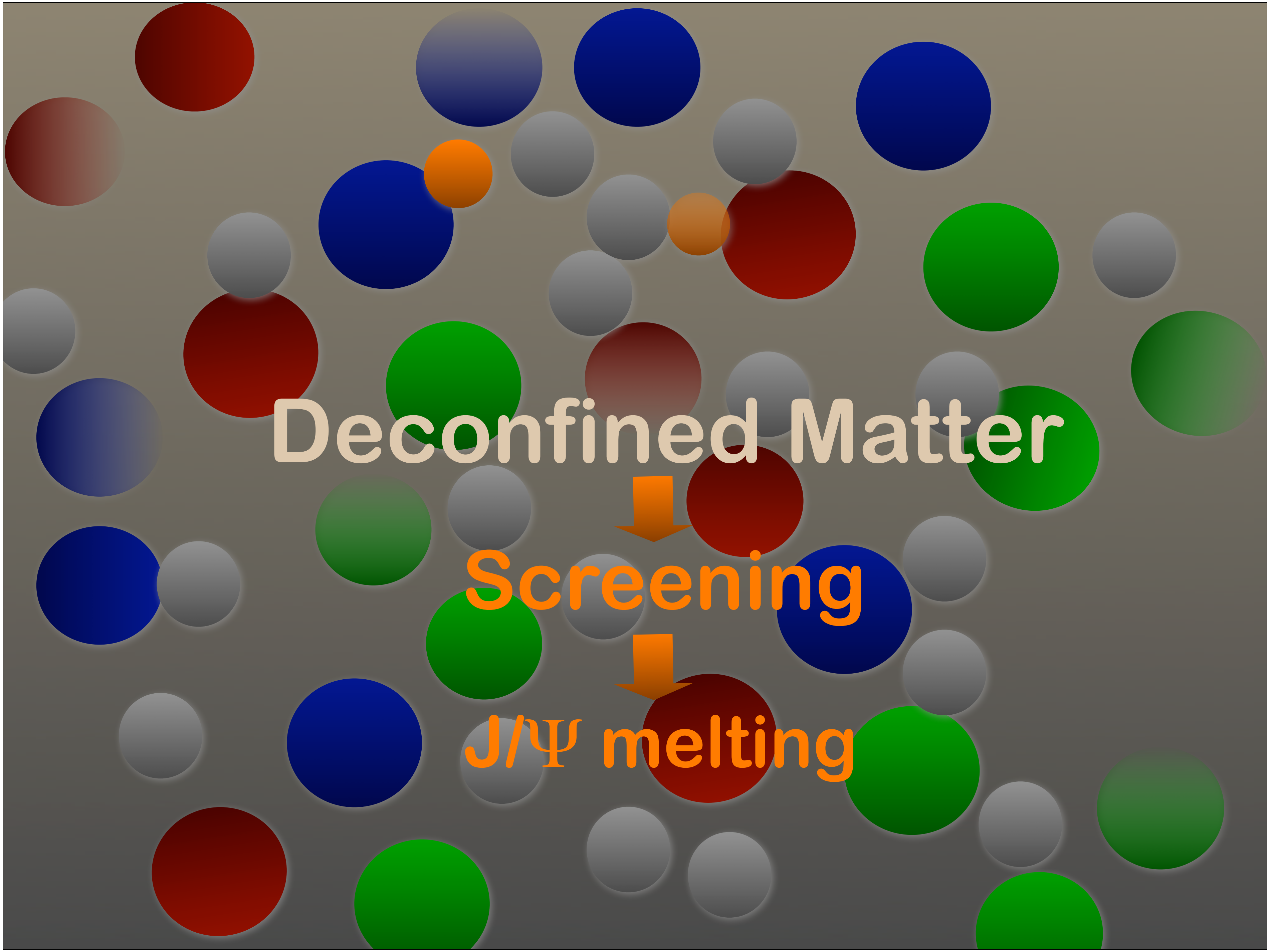
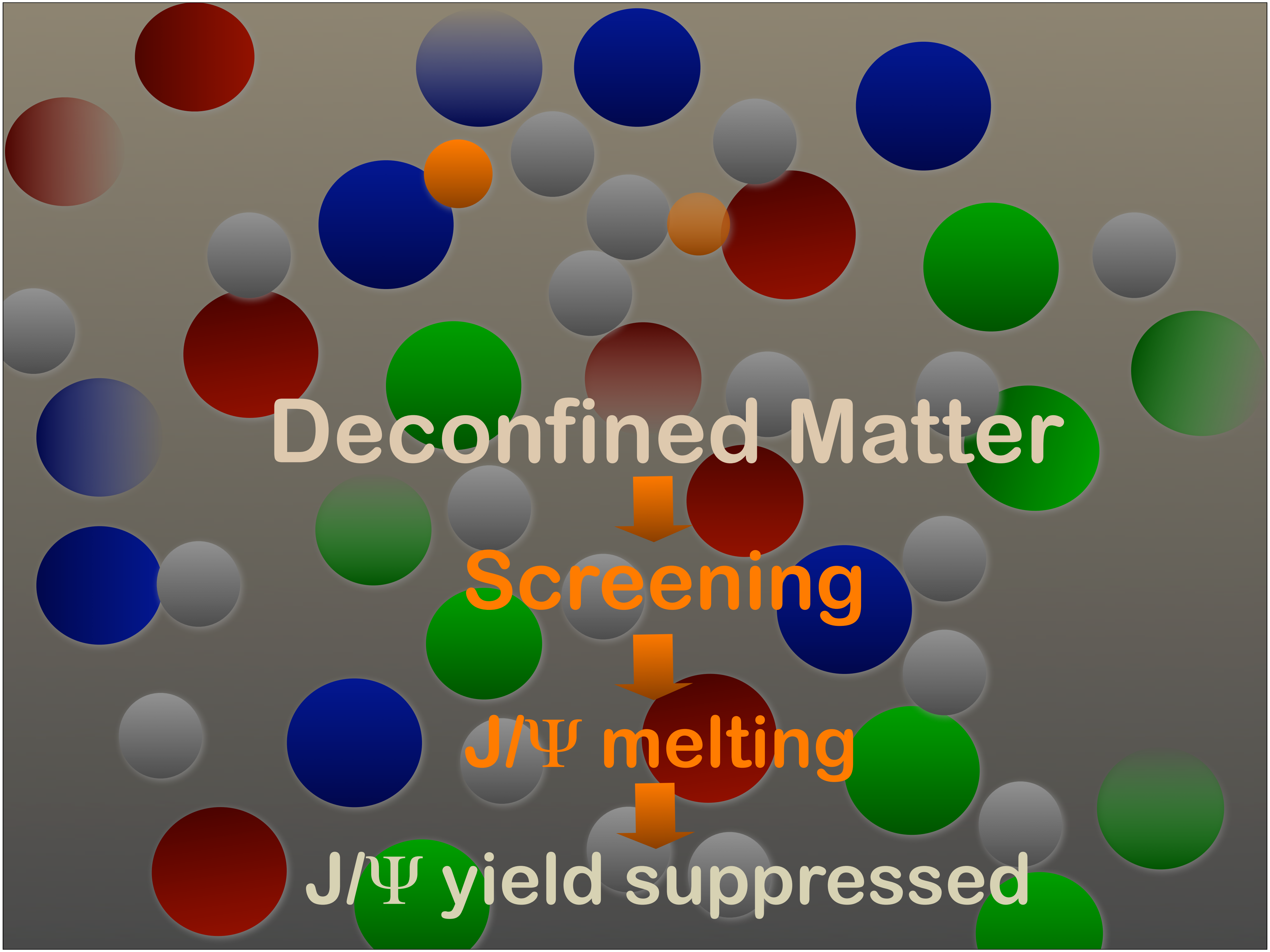
International School on
Quark Gluon Plasma and Heavy Ion Collisions
December 8-14, 2008, Torino, Italy


Confined Matter


Deconfined Matter


Deconfined Matter
Screening


Deconfined Matter
Screening
J/Ψ melting


Deconfined Matter
Screening
J/Ψ melting
J/Ψ yield suppressed

Menu

- Lecture 1: Antipasto

  Basics of quarkonium and screening

- Lecture 2: Primi piatti

  Heavy quark potentials and quarkonium

- Lecture 3: Secondi piatti

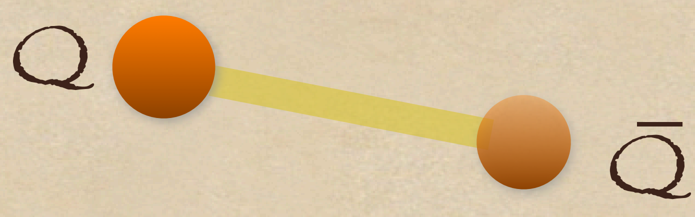
  Where do we stand now

Lecture 1:

Basics of quarkonium and screening

- Introducing quarkonium: eeet the J/psi
- Set the stage: quarkonium at T=0
- Debye color screening
- Melting of quarkonium

What is quarkonium ?



bound state of a heavy quark and its antiquark

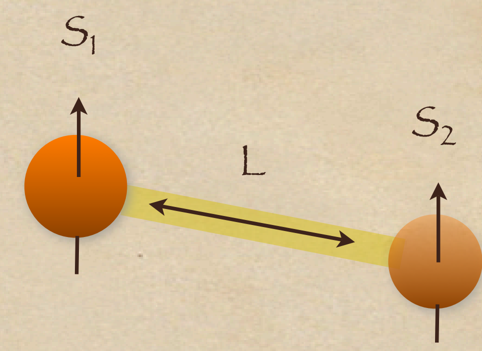
u	d	s	c	b	t
2.4 MeV	4.8 MeV	104 MeV	1.27 GeV	4.2 GeV	171.2 GeV

$m_Q >> \Lambda_{QCD} \approx 0.2\,\text{GeV}$

Quarkonium states

Different quantum numbers

S(L=0) and P(L=1) states



$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

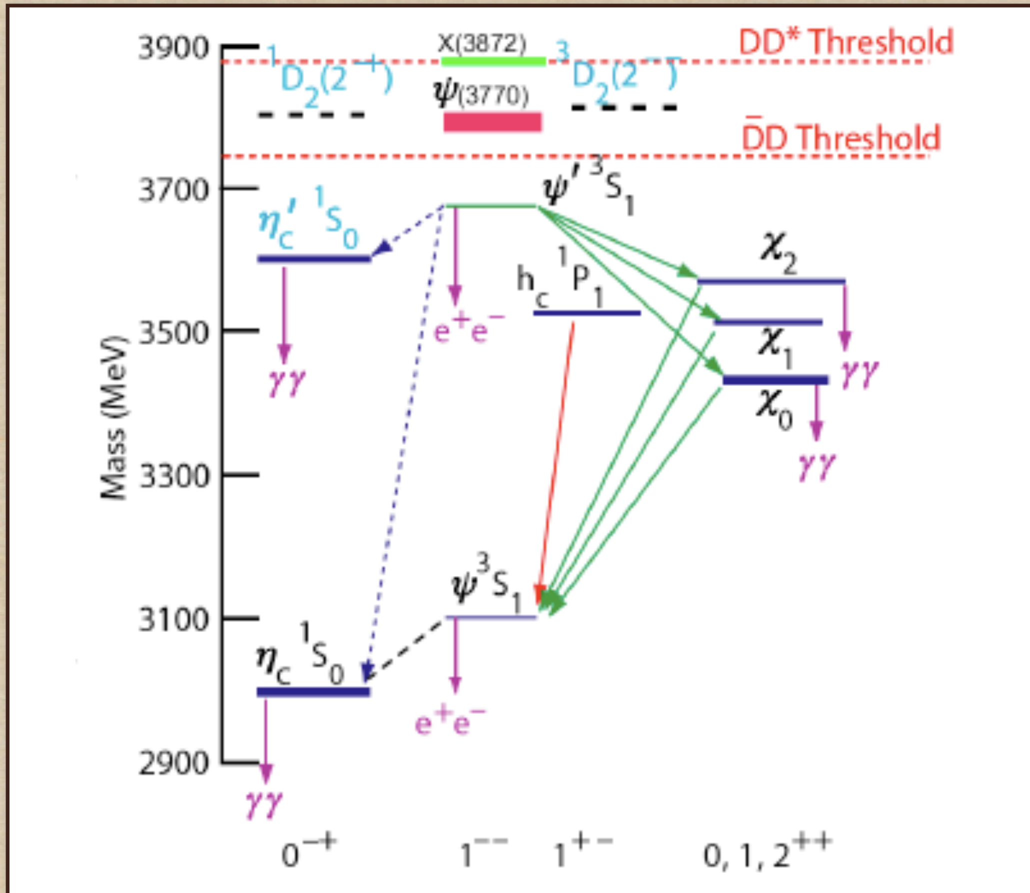
Notation

$$\Psi(1S) \equiv J/\Psi$$

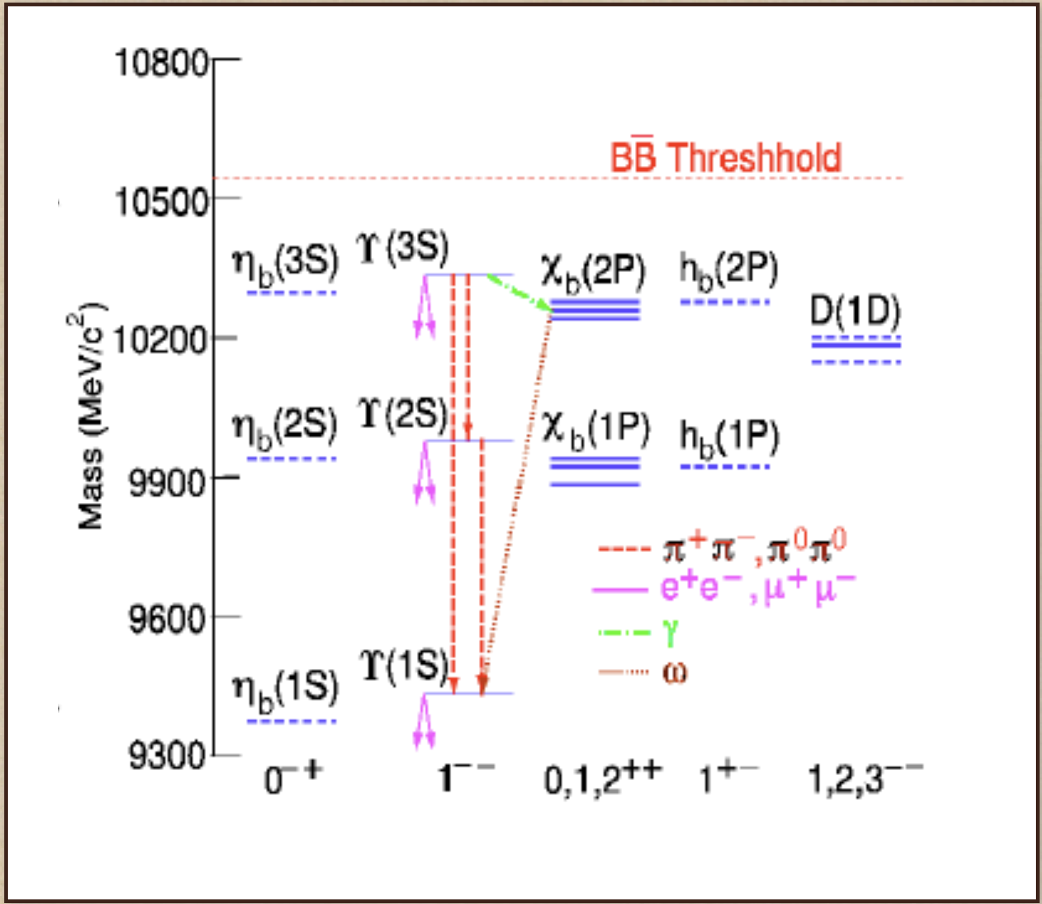
$$\Psi(2S) \equiv \Psi'$$

$$\Psi(1P) \equiv \chi_c$$

Charmonium family



Bottomonium family



J/Ψ discovery

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

BNL

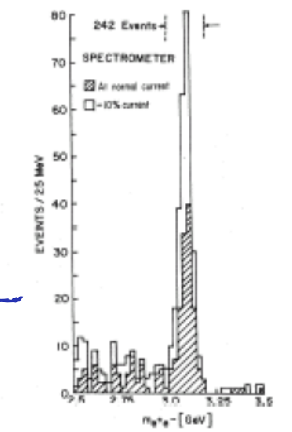


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

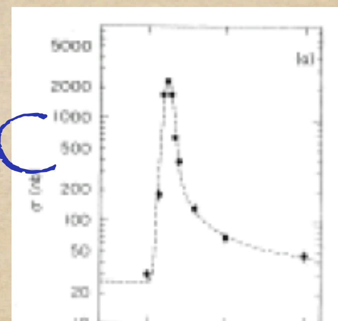
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

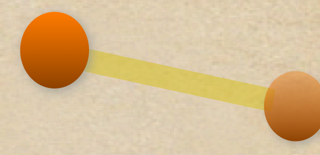
We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

SLAC



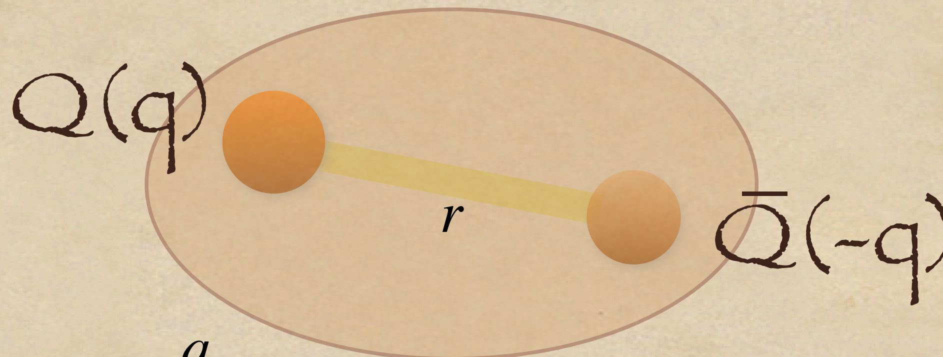
narrow width = long lifetime

Quarkonium at T=0



- quark mass $m_Q \gg \Lambda_{QCD}$ and quark velocity $v \ll 1$ allows non-relativistic treatment
- $Q\bar{Q}$ properties obtained solving Schrödinger equation
$$\left[-\frac{1}{m}\nabla_r^2 + V(r)\right]\psi(r) = E\psi(r)$$
- potential $V(r)$ describes the interaction between Q and $\bar{Q}$

Potential at T=0



Color potential from
Q as seen by $\bar{Q}$ $\quad V_{color} = \frac{q}{4\pi r}$

It's QCD, so confining $\quad V_{confinement} = \sigma r \quad$ string tension ($F=kx^2/2$)

The potential energy of the $Q\bar{Q}$ system

$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r$$

effective coupling $\alpha_{eff} = \frac{q^2}{4\pi}$

short distance + long distance

Potential at T=0

- known as Cornell potential

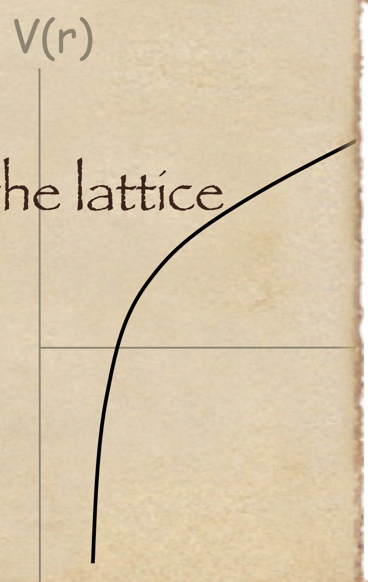
$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r$$

PHYSICAL REVIEW D VOLUME 21, NUMBER 1 1 JANUARY 1980

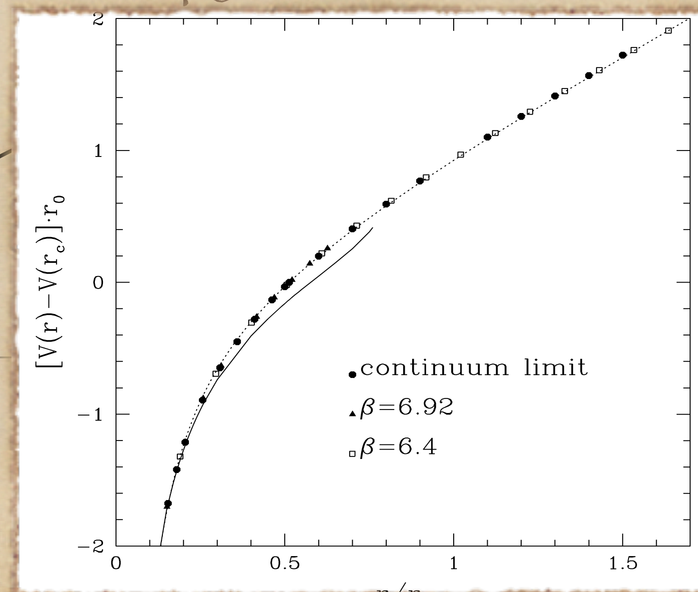
Charmonium: Comparison with experiment

E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T. M. Yan
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 25 June 1979)

- describes well the observed spectroscopy



verified on the lattice



Potential at T=0

- In perturbative QCD the $Q\bar{Q}$ potential can be related to the scattering amplitude corresponding to the 1-gluon exchange

$$V(r) = \int \frac{d^3k}{(2\pi)^3} T^{Born}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r}} = -\frac{4}{3} g^2 \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{r}} D_{00}(\mathbf{k})$$

$$D_{00}(\mathbf{k}) = \frac{1}{\mathbf{k}^2}$$

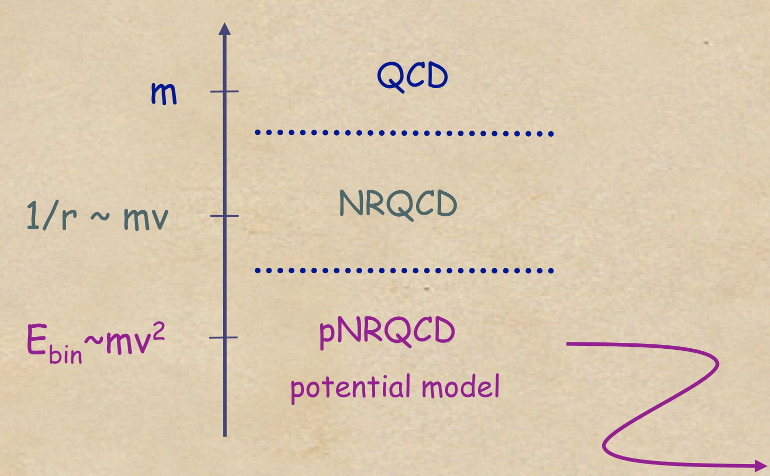
Homework: Derive the heavy quark potential in pQCD.

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

- relates the color charge q and QCD coupling constant g $\quad q^2 = \frac{4}{3} g^2 = \frac{4}{3} 4\pi\alpha_s$

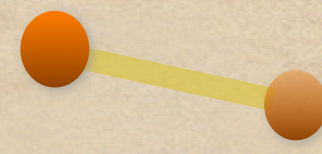
Potential at T≈0

- can be derived from QCD



$$V(r) = -\frac{a}{r} + \sigma r$$

T=0 spectroscopy



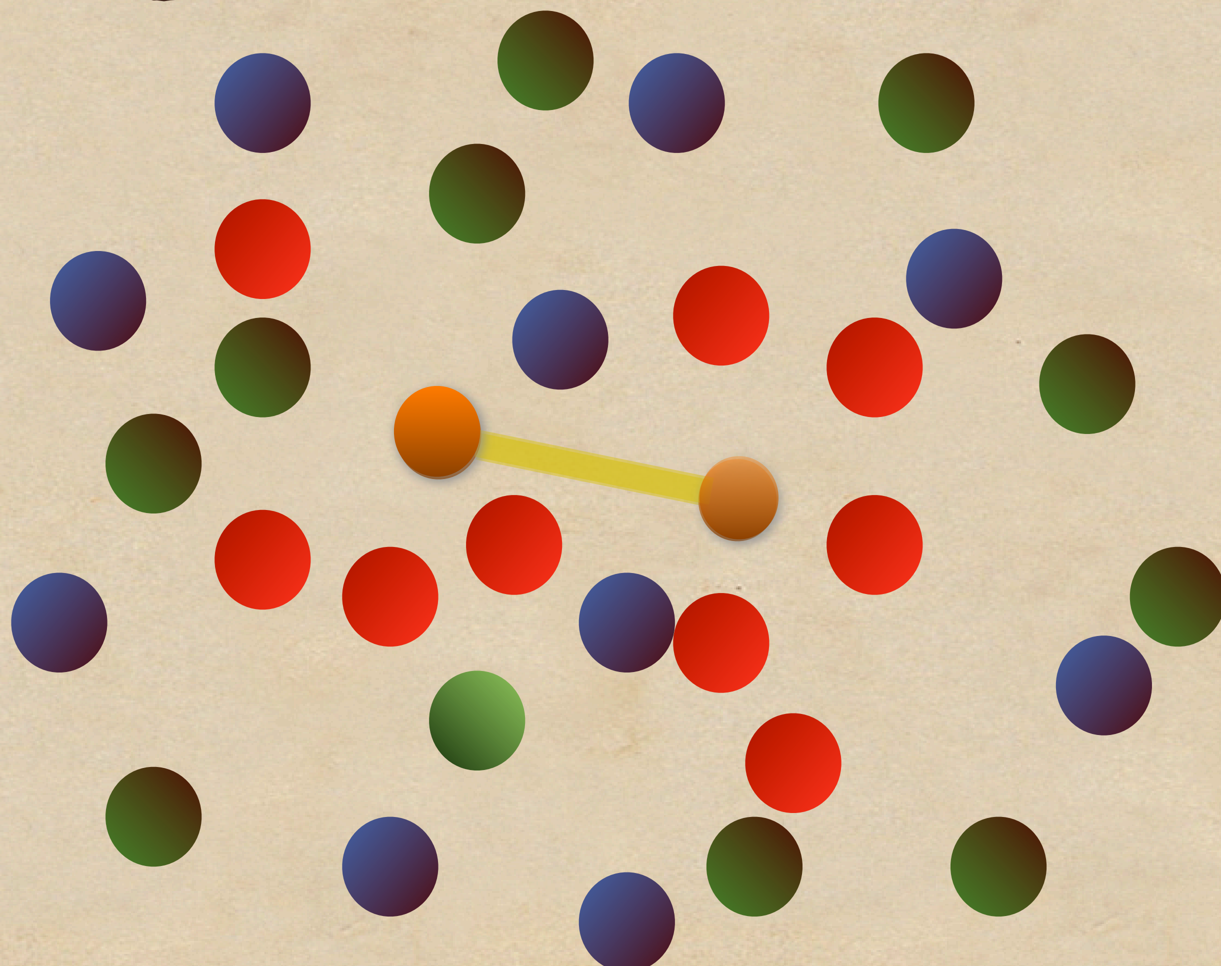
- the Hamiltonian $H_{Q\bar{Q}} = 2m_Q + \dfrac{p^2}{m_Q r} + V(r)$ $\quad H_{Q\bar{Q}}\psi = E\psi$
- in semi-classical approximation: $pr = 1$

  energy of the Q-$\bar{\text{Q}}$ system $E_{Q\bar{Q}}(r) = 2m_Q + \dfrac{1}{m_Q r^2} - \dfrac{\alpha_{eff}(r)}{r} + \sigma r$
- bound state radius obtained by minimizing the energy $\dfrac{dE_{Q\bar{Q}}}{dr} = 0$
- set of parameters m_Q, α_{eff}, σ

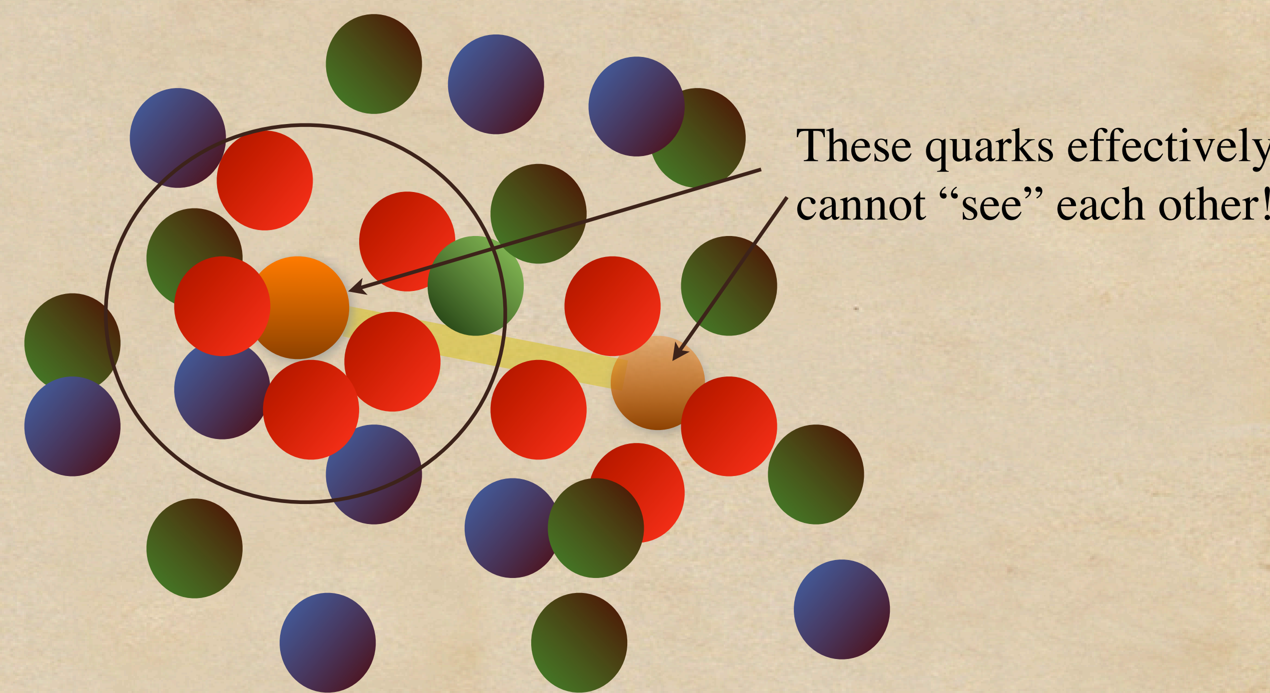
$r_{J/\psi} \approx 0.4$ fm and $r_{\Upsilon} \approx 0.2$ fm $\quad << 1$ fm

$M_{J/\psi} \approx 3.1$ GeV and $M_{\Upsilon} \approx 9.4$ GeV

Quarkonium at T≠0



Quarkonium at T≠0



- rearrangement of color around Q
- effective charge of Q reduced (screened)
- assume potential interaction at finite T

Debye screening

pQCD: modification of gluon propagator $D_{00}(\mathbf{k}) = \frac{1}{\mathbf{k}^2} \to \frac{1}{\mathbf{k}^2 + \Pi_{00}(k_0 = 0, \mathbf{k}, T)}$

Debye mass $m_D(T) \sim gT$

$-\frac{\alpha_{eff}}{r}$	$\longrightarrow$	$-\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$
T=0		$T>T_c$
long range Coulomb		short range Yukawa

Homework:
Derive the Yukawa potential at finite T in pQCD.

Debye radius $r_D(T)$ - the distance at which the effective charge is reduced 1/e and $m_D \approx 1/r_D$

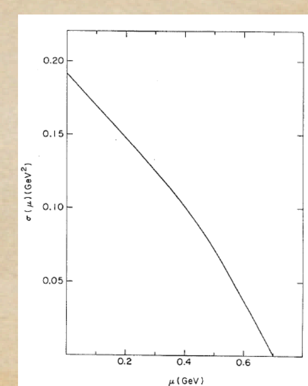
What happens to the confining term?

- Matsui, Satz: above deconfinement $\sigma(T_c) = 0$
- Karsch, Mehr, Satz (KMS)

T=0		T>T$_c$
σr	$\longrightarrow$	$\sigma r_D(T)\left(1 - e^{-r/r_D(T)}\right)$

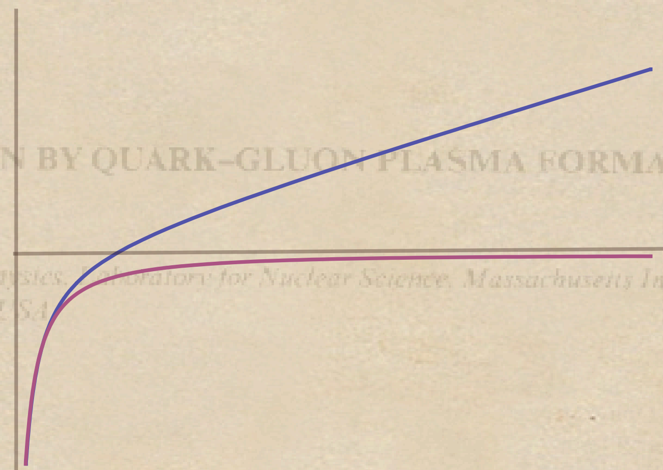
T-dependent string tension

$$\sigma(T) = \sigma\left(\frac{1 - e^{-\mu(T)r}}{\mu(T)r}\right) \rightarrow \sigma \qquad \mu = 1/r_D \rightarrow 0$$



Matsui-Satz argument

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986



$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r$$

$$V(r,T) = -\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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and

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and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

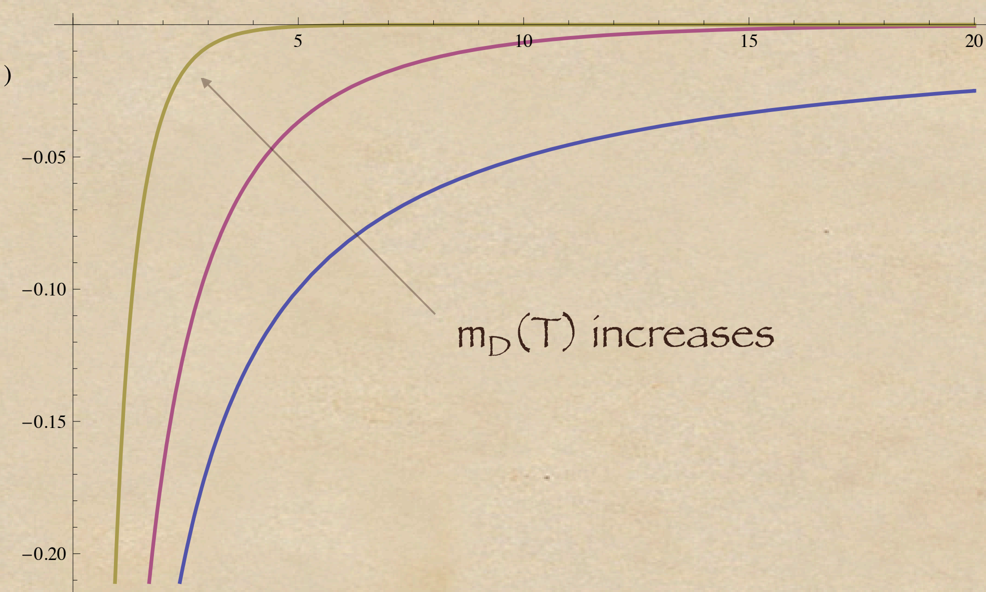
Received 17 July 1986

Yukawa potential can still hold bound states

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.

Matsui-Satz argument

$$V(r,T) = -\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$



T-dependence of the potential is completely in $r_D(T)$

Matsui-Satz argument

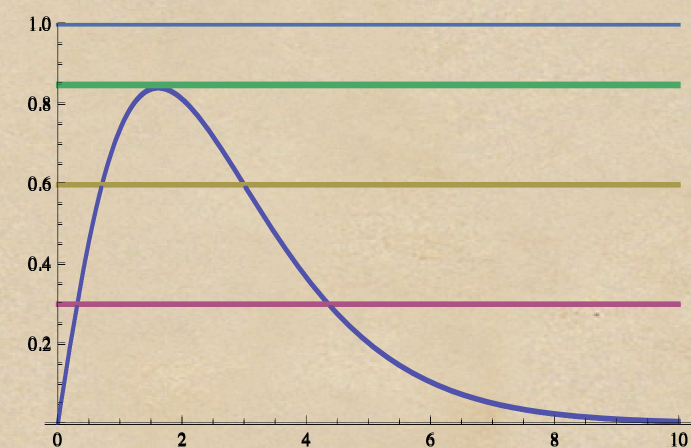
back to semi-classical approximation

$$\frac{dE_{Q\bar{Q}}(r, r_D(T))}{dr} = 0$$

$$x(1+x)e^{-x} = \frac{1}{m_Q \alpha_{eff} r_D(T)}$$

$$x = r / r_D$$

$x(1+x)e^{-x}$



$$\frac{1}{m_Q \alpha_{eff} r_D(T)}$$

at some $r_D(T)$ no solution exists, i.e. no bound state

$r_D < r_{Bohr} \approx 1/m\alpha_{eff}$

Matsui-Satz argument

quarkonium dissociates when the screening radius becomes smaller than the size of the state $r_D < r_{Bohr}$

	T=0	T=200 MeV
α_{eff}	0.52	0.2
$r_{Bohr}(J/\psi) = \frac{1}{m\ \alpha_{eff}}$	0.41 fm	1.07 fm
$r_{Debye}(pQCD) = \sqrt{\frac{2}{9\pi\alpha_{eff}}}\frac{1}{T}$	∞	0.59
From Introduction to High-Energy Heavy-Ion Collisions: C.Y. Wong 1994		

J/ψ melts at T_c

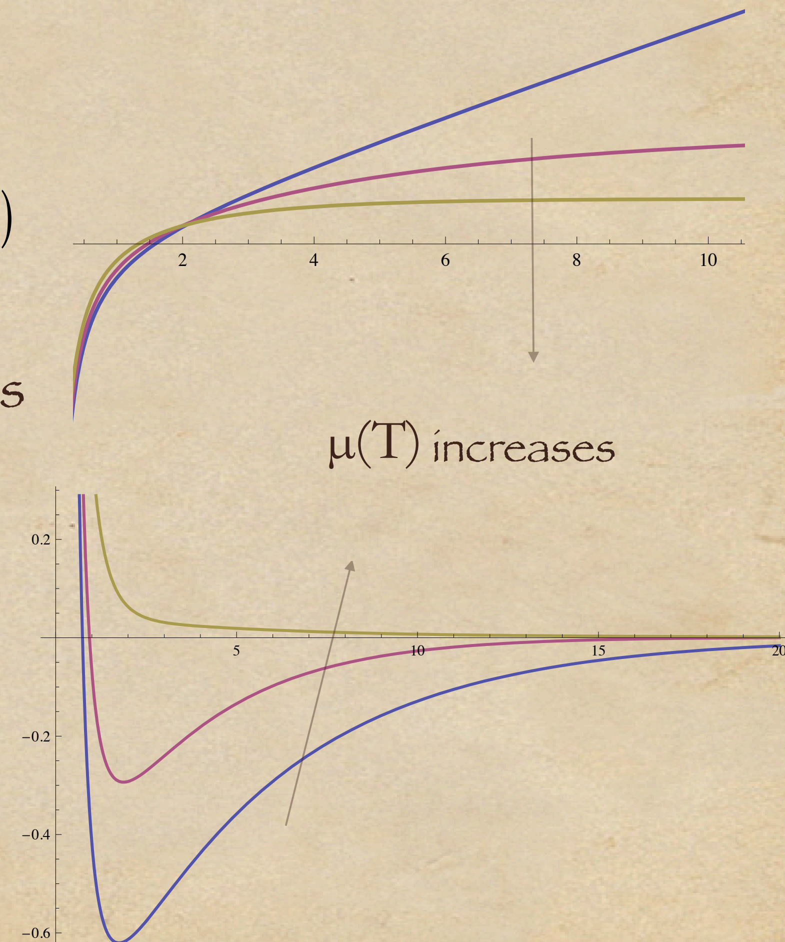
KMS potential

- Screened Cornell potential

$$V(r,T) = -\frac{\alpha_{eff}}{r} e^{-\mu(T)r} + \frac{\sigma}{\mu(T)}\left(1 - e^{-\mu(T)r}\right)$$

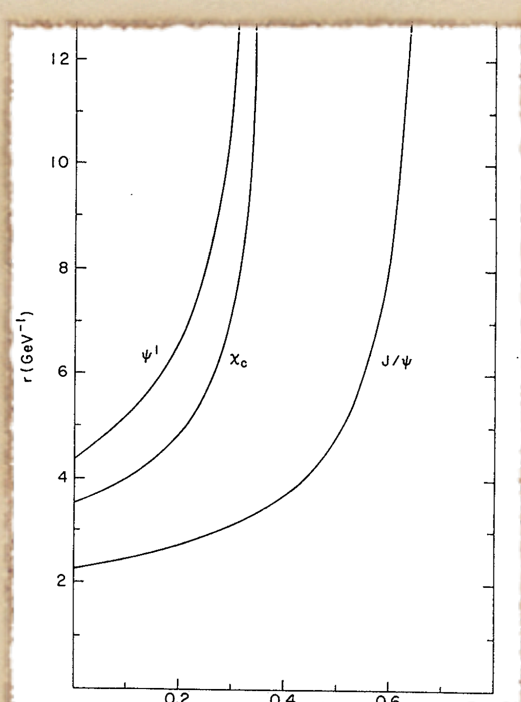
- As the screening μ(T) increases with T the potential becomes less effective

- Effective binding potential
  Large μ(T) no bound state



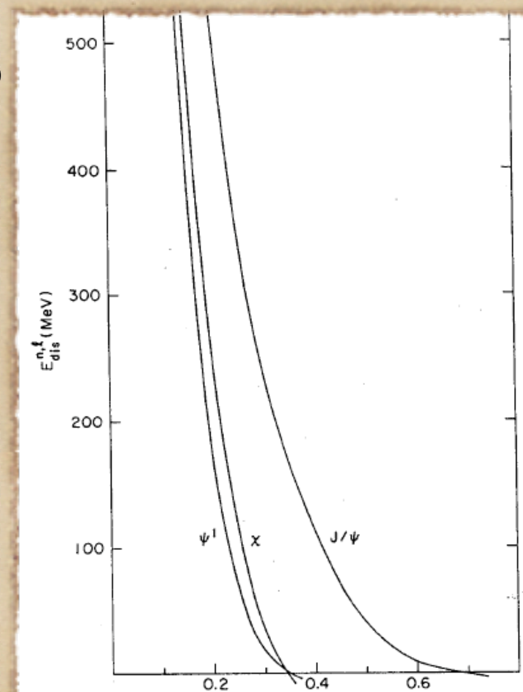
Quarkonium properties

Radii $\langle r^2 \rangle = \int d^3 r r^2 |\psi(r)|^2$

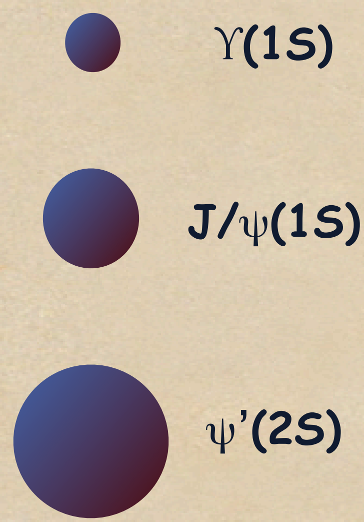


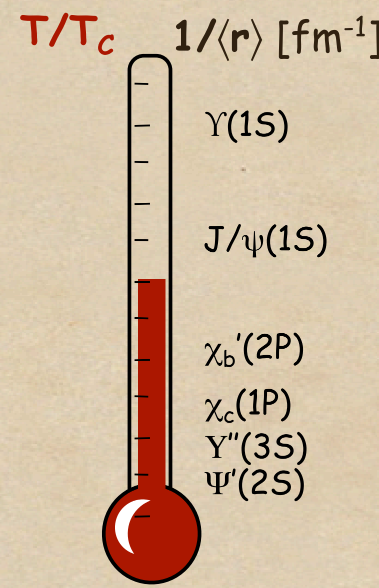
Vanishing of the states has been looked at in terms of dissociation energy

$$E_{diss}(\mu) = 2m_Q + \frac{\sigma}{\mu} - E_{Q\bar{Q}}(\mu)$$



Sequential dissociation





QGP thermometer

Observing in experiment

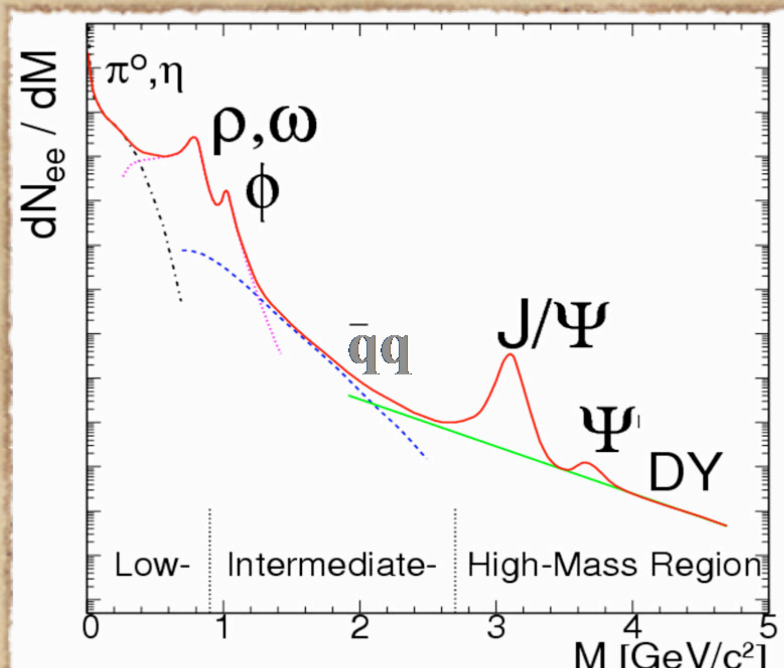
Differential dilepton rate

J/psi spectral function

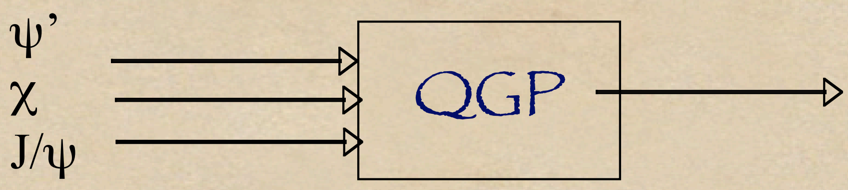
$$\frac{dW}{d\omega d^3p} = \frac{5\alpha_{em}^2}{27\pi^2}\frac{1}{\omega^2(e^{\omega/T}-1)}\sigma(\omega,\vec{p},T)$$

The presence or absence of a bound state in the spectral function shows up in the dilepton yield

$$J/\psi \rightarrow \ell^+\ell^-$$



shine 3 beams onto a black box



1) If ψ' is absorbed and χ, J/ψ get through
   => strongly interacting matter < T_c, i.e. hadrons
2) If ψ', χ are absorbed, J/ψ gets through
   => matter near T_c
3) If nothing gets through
   => QGP above T_c

but we don't have a box full of QGP or quarkonium beams

Experiments compare the number seen in A+A

to p+p or p+A

Summary of Lecture 1

- Quarkonium is small and tightly bound, but at high temperatures it can dissociate if color screening is strong enough. Suggested QGP thermometer
- - in the next lecture: heavy quark free energy and quarkonium from lattice QCD

Some relevant literature

- Eichten et al, PRD 21, 203 (1980), PRD 17, 3090 (1978)
- Necco, Sommer, Nucl Phys B622, 328 (2002)
- Matsui, Satz, Phys Lett B178, 416 (1986)
- Karsch, Mehr, Satz, Z Phys C 37, 617 (1988)
- Brambilla et al, Quarkonium Working Group report 2006
- Le Bellac "Thermal Field Theory", Cambridge Monographs,
- Ramona Vogt "Ultrarelativistic Heavy-Ion Collisions", Elsevier, 2007
- C.Y.Wong "Introduction to High-Energy Heavy-Ion Collisions", World Scientific, 1994