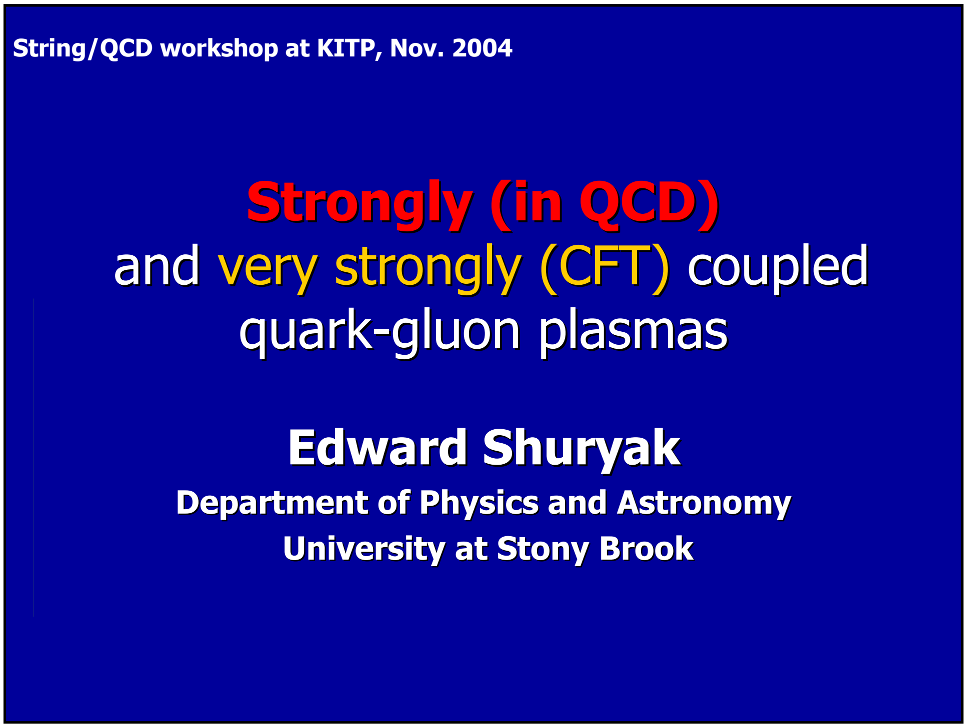

String/QCD workshop at KITP, Nov. 2004

Strongly (in QCD) and very strongly (CFT) coupled quark-gluon plasmas

Edward Shuryak

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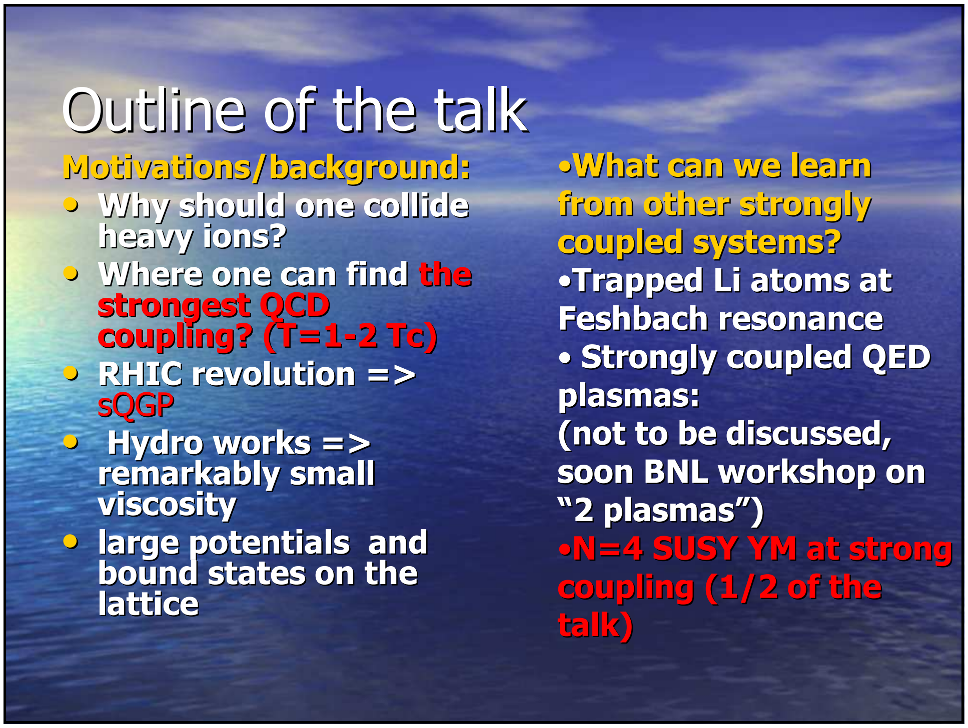
University at Stony Brook



Outline of the talk

Motivations/background:

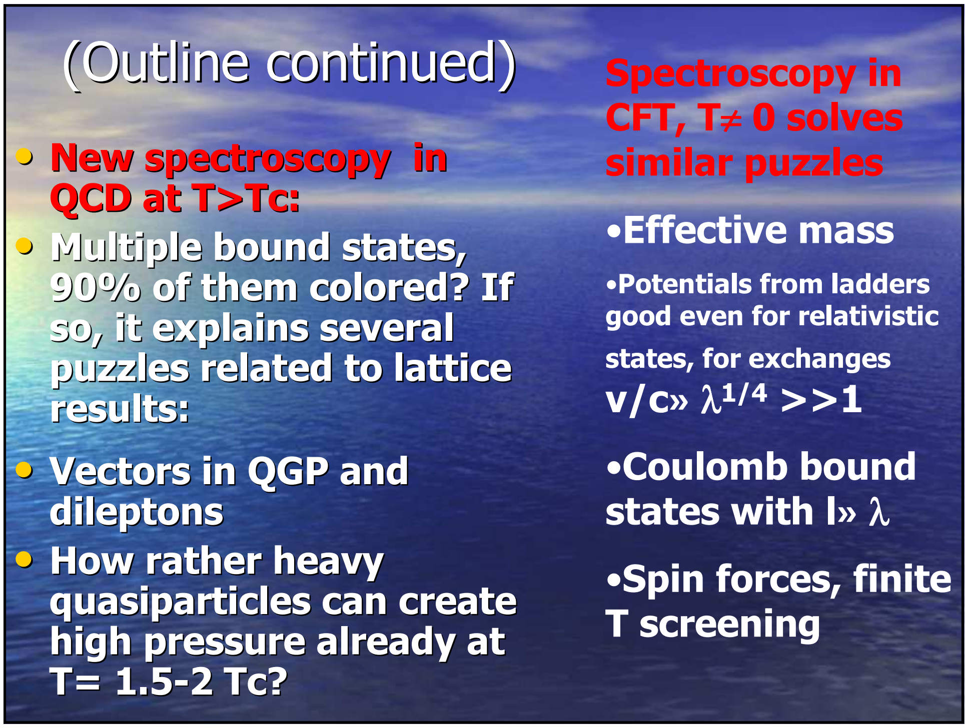
- Why should one collide heavy ions?
- Where one can find the strongest QCD coupling? (T=1-2 Tc)
- RHIC revolution => sQGP
- Hydro works => remarkably small viscosity
- large potentials and bound states on the lattice

•What can we learn from other strongly coupled systems?

•Trapped Li atoms at Feshbach resonance

• Strongly coupled QED plasmas:
(not to be discussed, soon BNL workshop on "2 plasmas")

•N=4 SUSY YM at strong coupling (1/2 of the talk)



(Outline continued)

- **New spectroscopy in QCD at T>Tc:**
- **Multiple bound states, 90% of them colored? If so, it explains several puzzles related to lattice results:**
- **Vectors in QGP and dileptons**
- **How rather heavy quasiparticles can create high pressure already at T= 1.5-2 Tc?**

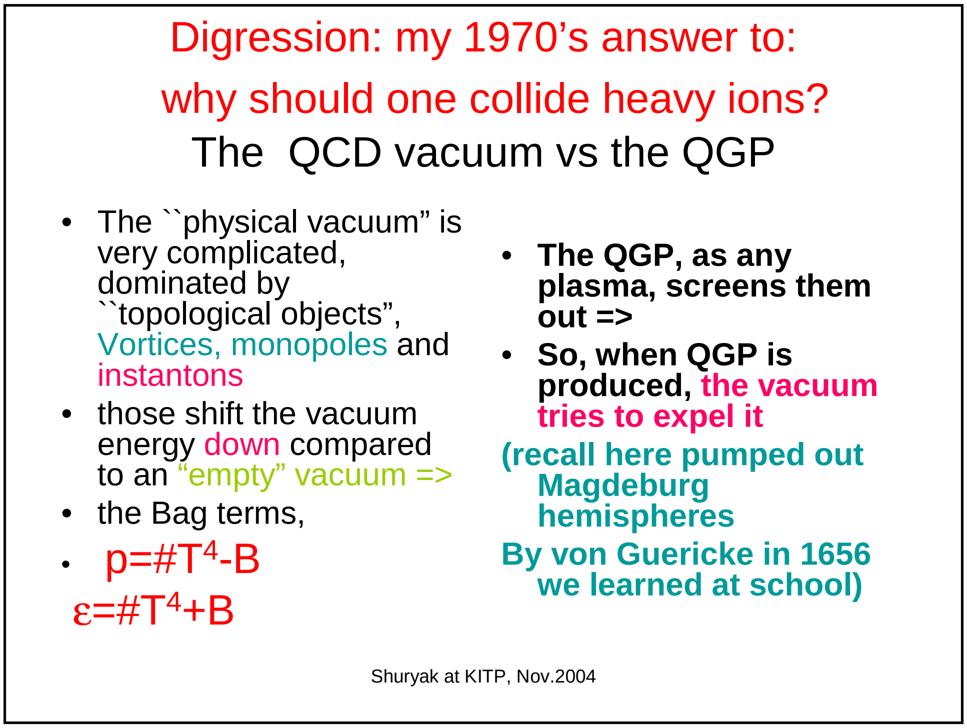
Spectroscopy in CFT, T≠ 0 solves similar puzzles

•Effective mass

•Potentials from ladders good even for relativistic states, for exchanges
v/c» $\lambda^{1/4}$ >>1

•Coulomb bound states with l» λ

•Spin forces, finite T screening



Digression: my 1970's answer to: why should one collide heavy ions?

The QCD vacuum vs the QGP

- The ``physical vacuum" is very complicated, dominated by ``topological objects", Vortices, monopoles and instantons
- those shift the vacuum energy down compared to an "empty" vacuum =>
- the Bag terms,
- $p=\#T^4-B$

$\varepsilon=\#T^4+B$

- **The QGP, as any plasma, screens them out =>**
- **So, when QGP is produced, the vacuum tries to expel it**

(recall here pumped out Magdeburg hemispheres

By von Guericke in 1656 we learned at school)

Shuryak at KITP, Nov.2004

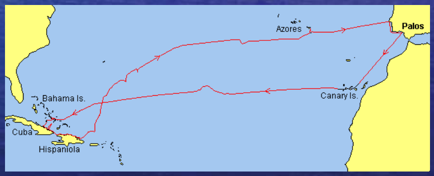
Magdeburg hemispheres 1656

- **We cannot pump the nonperturbative object out of QCD vacuum, but we can pump in something else, e.g. QGP**

- **Note: QGP was considered to be a simple q,g gas, to be described by pQCD, just a reference point. We now see it is also quite complicated matter, sQGP…**

Digression 2: One may have an absolutely correct theory and still make accidental discoveries…

Columbus believed if he goes west he should eventually come to India



But something else was on the way…

We believed if we increase the energy density, we should eventually get weakly interacting QGP. But something else was found on the way…

RHIC produced ``matter”, not a fireworks of partons !

What it means?

(the micro scale) << (the macro scale)

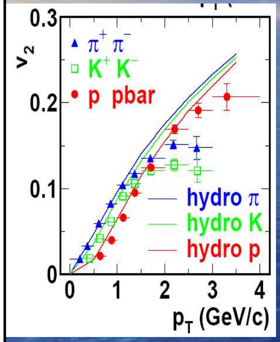
(the mean free path) << (system size)

(relaxation time) << (evolution duration)

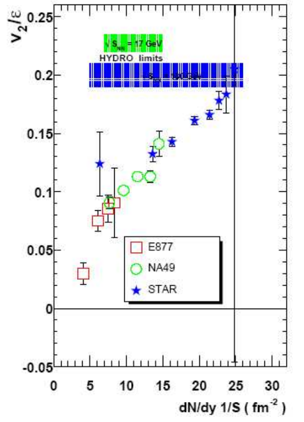
- Good equilibration (including strangeness) is seen in particle rations (as at SPS)
- **the zeroth order in l/L is called an ideal hydro with a local stress tensor.**
- **Viscosity is the first order O(l/L) effect, » velocity gradients.**
- **Note: η» m.f.p.» $1/\sigma$ is inversely proportional to σ and is thus (the oldest) strong coupling expansion tool**

Radial and Elliptic Flows for π,K,N…Ω,D …

PHENIX, PRL91(’03)182301,

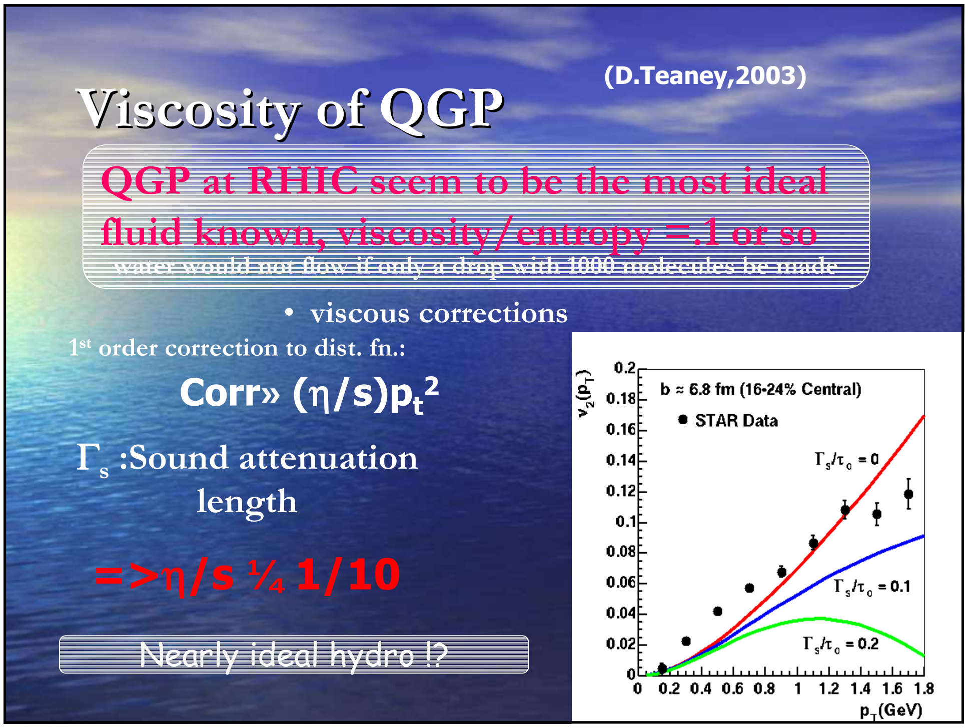


STAR, PRC66(’02)034904



Elliptic flow rapidly rises with energy Because we have surpassed ``The softest point” and Entered the QGP with high p/ε ratio!

See details in a review by P.Kolb and U.Heinz, nucl-th/0305084



Viscosity of QGP

(D.Teaney,2003)

QGP at RHIC seem to be the most ideal fluid known, viscosity/entropy =.1 or so

water would not flow if only a drop with 1000 molecules be made

- viscous corrections

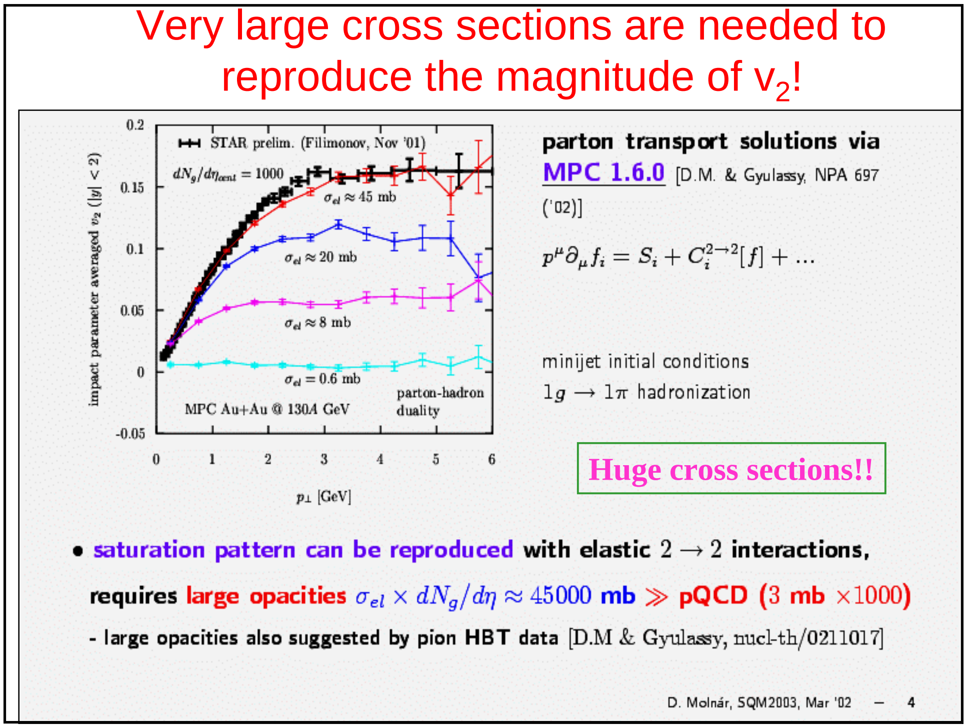
1st order correction to dist. fn.:

Corr» $(\eta/s)p_t^2$

Γ_s :Sound attenuation length

=>η/s ¼ 1/10

Nearly ideal hydro !?



Very large cross sections are needed to reproduce the magnitude of v_2!

parton transport solutions via MPC 1.6.0 [D.M. & Gyulassy, NPA 697 ('02)]

$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to 2}[f] + \ldots$$

minijet initial conditions

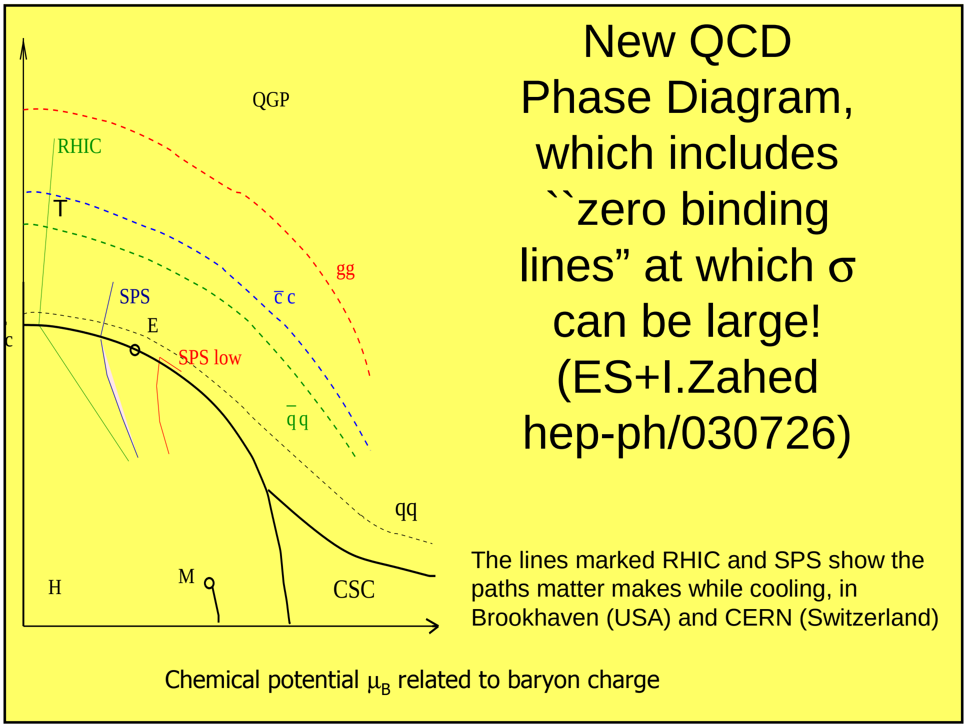
$1g \to 1\pi$ hadronization

Huge cross sections!!

- **saturation pattern can be reproduced with elastic** $2 \to 2$ **interactions,** **requires large opacities** $\sigma_{el} \times dN_g/d\eta \approx 45000$ **mb** $\gg$ **pQCD** (3 **mb** ×1000)

- large opacities also suggested by pion HBT data [D.M & Gyulassy, nucl-th/0211017]

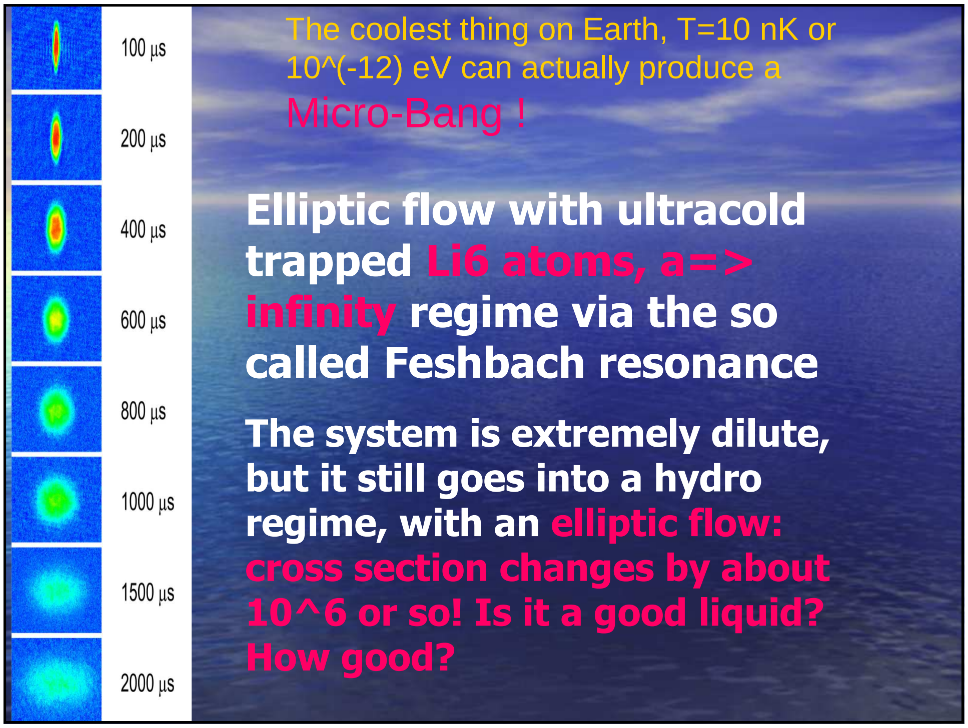
D. Molnár, SQM2003, Mar '02 — 4



New QCD Phase Diagram, which includes ``zero binding lines” at which σ can be large! (ES+I.Zahed hep-ph/030726)

The lines marked RHIC and SPS show the paths matter makes while cooling, in Brookhaven (USA) and CERN (Switzerland)

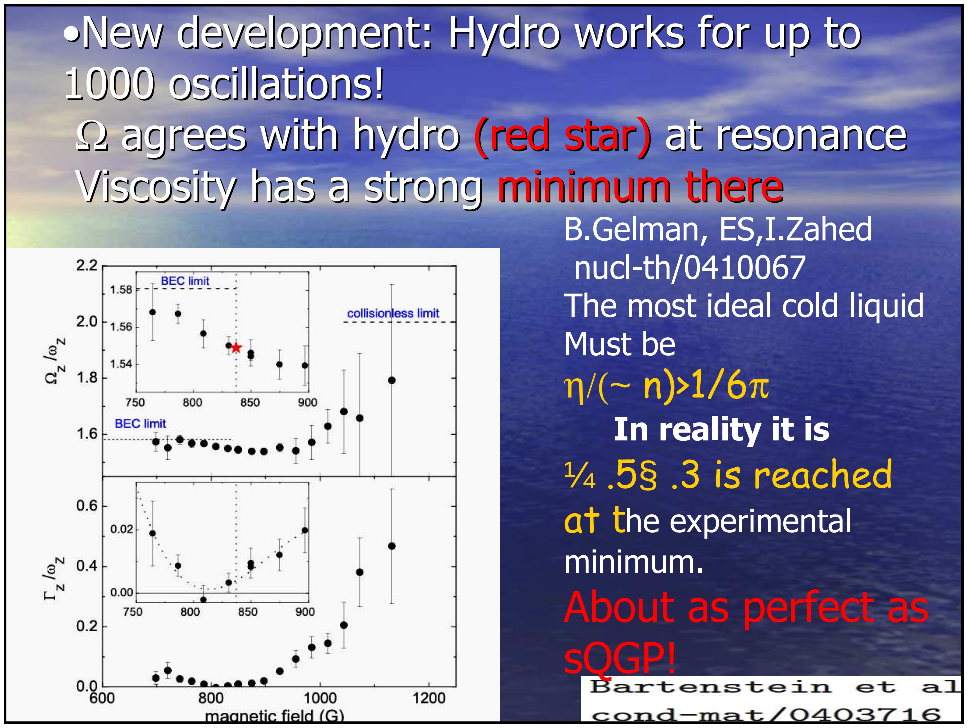
Chemical potential μ_B related to baryon charge



The coolest thing on Earth, T=10 nK or 10^(-12) eV can actually produce a Micro-Bang !

Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime via the so called Feshbach resonance

The system is extremely dilute, but it still goes into a hydro regime, with an elliptic flow: cross section changes by about 10^6 or so! Is it a good liquid? How good?



- New development: Hydro works for up to 1000 oscillations!

Ω agrees with hydro (red star) at resonance

Viscosity has a strong minimum there

B.Gelman, ES,I.Zahed
nucl-th/0410067

The most ideal cold liquid

Must be

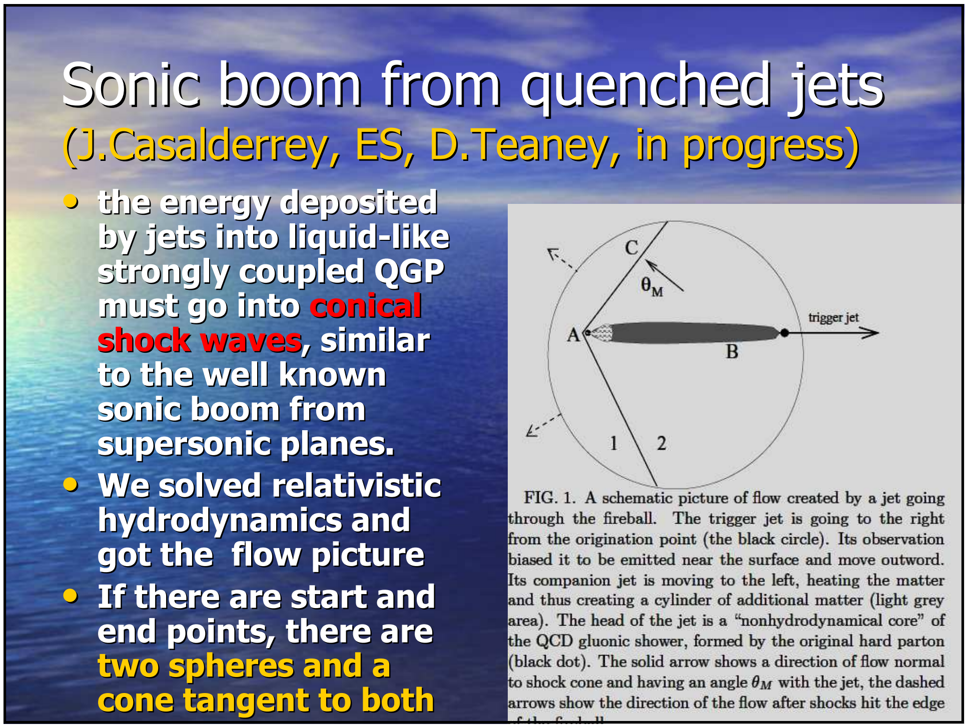
η/(~ n)>1/6π

In reality it is

¼ .5§ .3 is reached at the experimental minimum.

About as perfect as sQGP!

Bartenstein et al
cond-mat/0403716

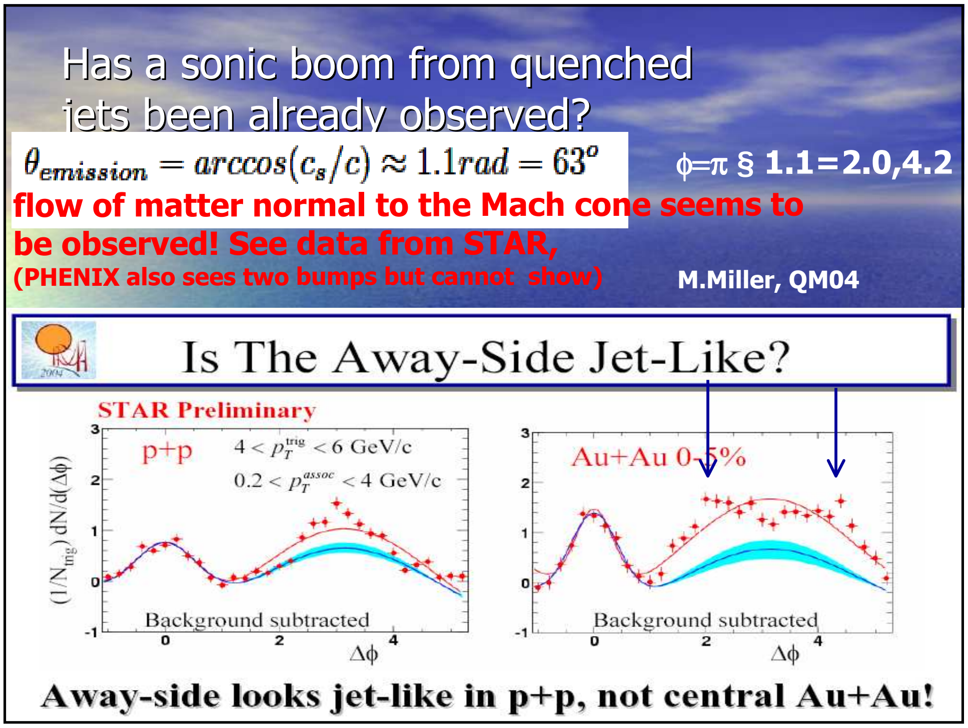


Sonic boom from quenched jets

(J.Casalderrey, ES, D.Teaney, in progress)

- **the energy deposited by jets into liquid-like strongly coupled QGP must go into conical shock waves, similar to the well known sonic boom from supersonic planes.**
- **We solved relativistic hydrodynamics and got the flow picture**
- **If there are start and end points, there are two spheres and a cone tangent to both**

FIG. 1. A schematic picture of flow created by a jet going through the fireball. The trigger jet is going to the right from the origination point (the black circle). Its observation biased it to be emitted near the surface and move outword. Its companion jet is moving to the left, heating the matter and thus creating a cylinder of additional matter (light grey area). The head of the jet is a "nonhydrodynamical core" of the QCD gluonic shower, formed by the original hard parton (black dot). The solid arrow shows a direction of flow normal to shock cone and having an angle θ_M with the jet, the dashed arrows show the direction of the flow after shocks hit the edge



Has a sonic boom from quenched jets been already observed?

$\theta_{emission} = arccos(c_s/c) \approx 1.1 rad = 63^o$

$\phi=\pi$ § 1.1=2.0,4.2

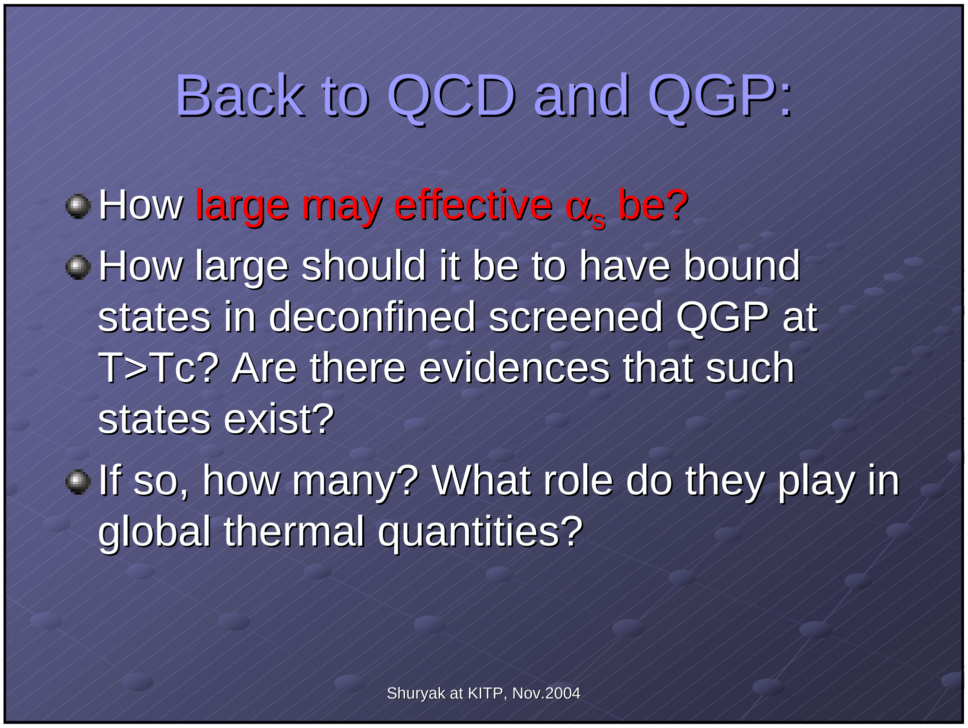
flow of matter normal to the Mach cone seems to be observed! See data from STAR,

(PHENIX also sees two bumps but cannot show)

M.Miller, QM04

Is The Away-Side Jet-Like?

Away-side looks jet-like in p+p, not central Au+Au!



Back to QCD and QGP:

- How large may effective α_s be?
- How large should it be to have bound states in deconfined screened QGP at T>Tc? Are there evidences that such states exist?
- If so, how many? What role do they play in global thermal quantities?

Shuryak at KITP, Nov.2004

For a screened Coulomb potential, a simple condition for a bound state

- (4/3)α_s (M/M$_d$) > 1.68
- M(charm) is large, M$_d$ is only about 2T
- If α(M$_d$) indeed runs to about .5-1, it is large enough to bind J/ψ till about T=2T$_c$=340 MeV

(accidentally, the highest T at RHIC)

Shuryak at KITP, Nov.2004

Fitting F to screened Coulomb

- Fit from Bielefld group hep-lat/0406036

$$\frac{F_{\rm fit}(r,T)}{T} = \frac{4\alpha(T)}{3rT}\exp\{-\sqrt{4\pi\tilde{\alpha}(T)}rT\} + c(T)$$

Note that the Debye radius corresponds to``normal" (still enhanced by factor 2) coupling, while the overall strength of the potential is much larger

Shuryak at KITP,

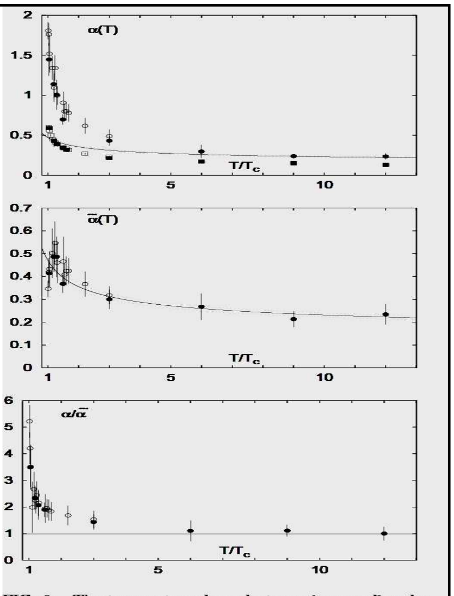
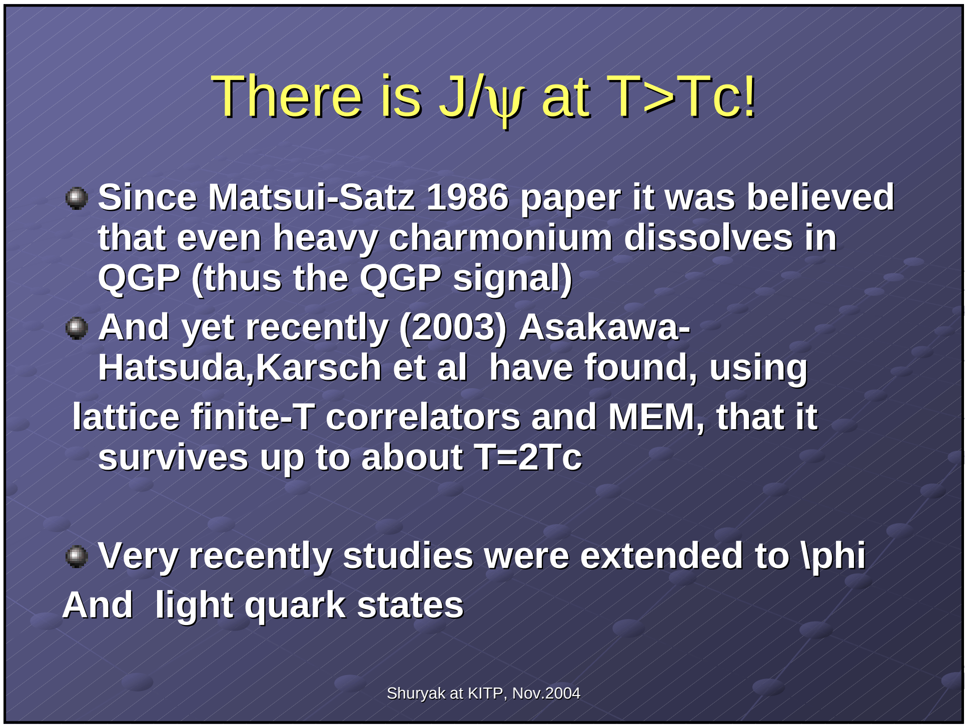


FIG. 6: The temperature dependent running coupling determined from the large distance behavior of the singlet free energy on lattices with temporal extent $N_\tau = 4$ (open symbols) and $N_\tau = 8$ (filled symbols). The upper figure shows $\alpha(T) \equiv g^2(T)/4\pi$ (dots) and the value $\alpha_{qq}(r_{\rm screen}, T)$ (squares) determined from the short distance behavior of the singlet free energy (see Fig. 3). The figure in the middle shows $\tilde{\alpha}(T) \equiv \tilde{g}^2(T)/4\pi$ and characterizes the temperature dependence of the screening mass. The lower figure gives the ratio of both fit parameters. The solid lines with the dotted error band are discussed in the text.



There is J/ψ at T>Tc!

- Since Matsui-Satz 1986 paper it was believed that even heavy charmonium dissolves in QGP (thus the QGP signal)
- And yet recently (2003) Asakawa-Hatsuda,Karsch et al have found, using lattice finite-T correlators and MEM, that it survives up to about T=2Tc

- Very recently studies were extended to \phi And light quark states

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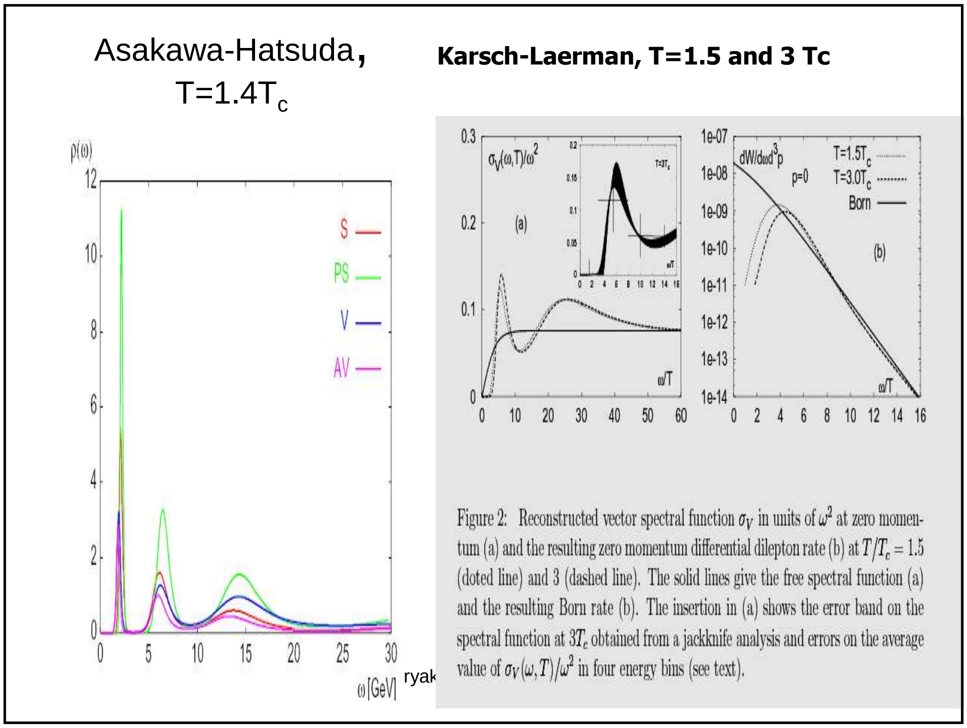
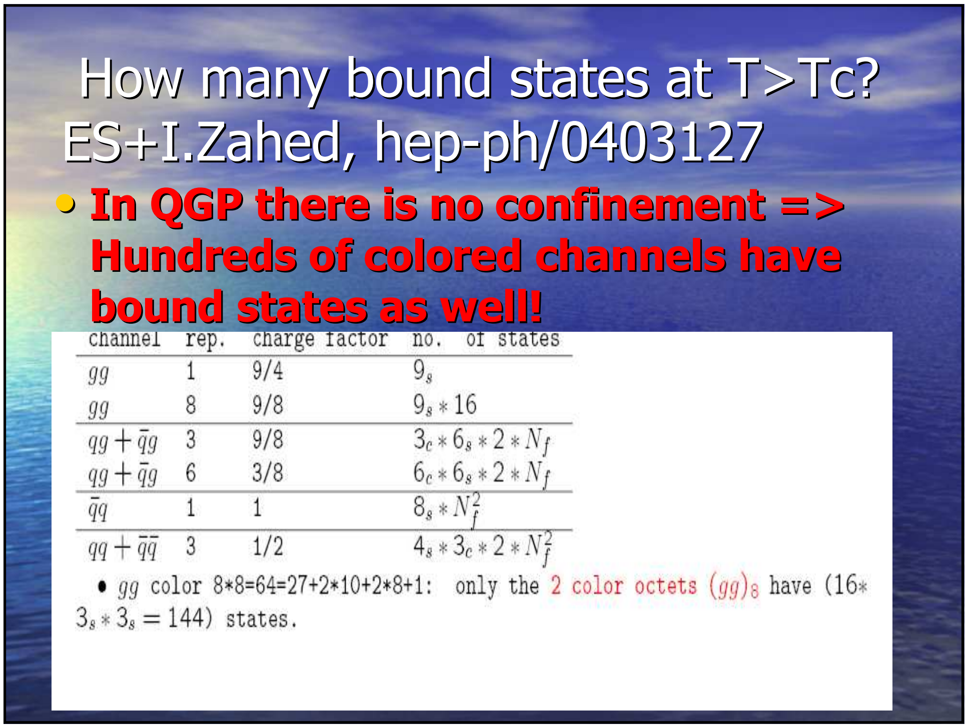


Asakawa-Hatsuda, $T=1.4T_c$

Karsch-Laerman, T=1.5 and 3 Tc

Figure 2: Reconstructed vector spectral function σ_V in units of ω^2 at zero momentum (a) and the resulting zero momentum differential dilepton rate (b) at $T/T_c = 1.5$ (doted line) and 3 (dashed line). The solid lines give the free spectral function (a) and the resulting Born rate (b). The insertion in (a) shows the error band on the spectral function at $3T_c$ obtained from a jackknife analysis and errors on the average value of $\sigma_V(\omega,T)/\omega^2$ in four energy bins (see text).

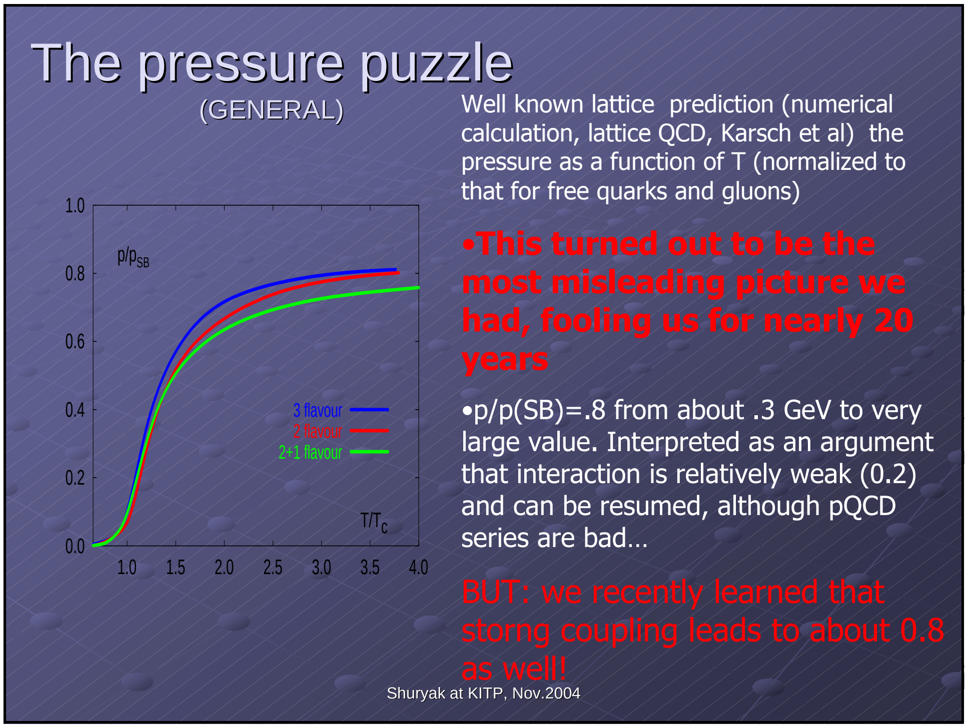


How many bound states at T>Tc? ES+I.Zahed, hep-ph/0403127

- **In QGP there is no confinement => Hundreds of colored channels have bound states as well!**

channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

- gg color 8*8=64=27+2*10+2*8+1: only the 2 color octets $(gg)_8$ have $(16 * 3_s * 3_s = 144)$ states.



The pressure puzzle

(GENERAL)

Well known lattice prediction (numerical calculation, lattice QCD, Karsch et al) the pressure as a function of T (normalized to that for free quarks and gluons)

- **This turned out to be the most misleading picture we had, fooling us for nearly 20 years**
- p/p(SB)=.8 from about .3 GeV to very large value. Interpreted as an argument that interaction is relatively weak (0.2) and can be resumed, although pQCD series are bad…

BUT: we recently learned that storng coupling leads to about 0.8 as well!

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(The pressure puzzle, cont.)

- How quasiparticles, which according to direct lattice measurements are heavy (Mq,Mg = 3T) (Karsch et al) can provide enough pressure? (exp(-3)»1/20)
- (The same problems appears in N=4 SUSY YM, where it is parametric, exp(-$\lambda^{1/2}$) for large λ´ g^{2}N$_c$À 1)

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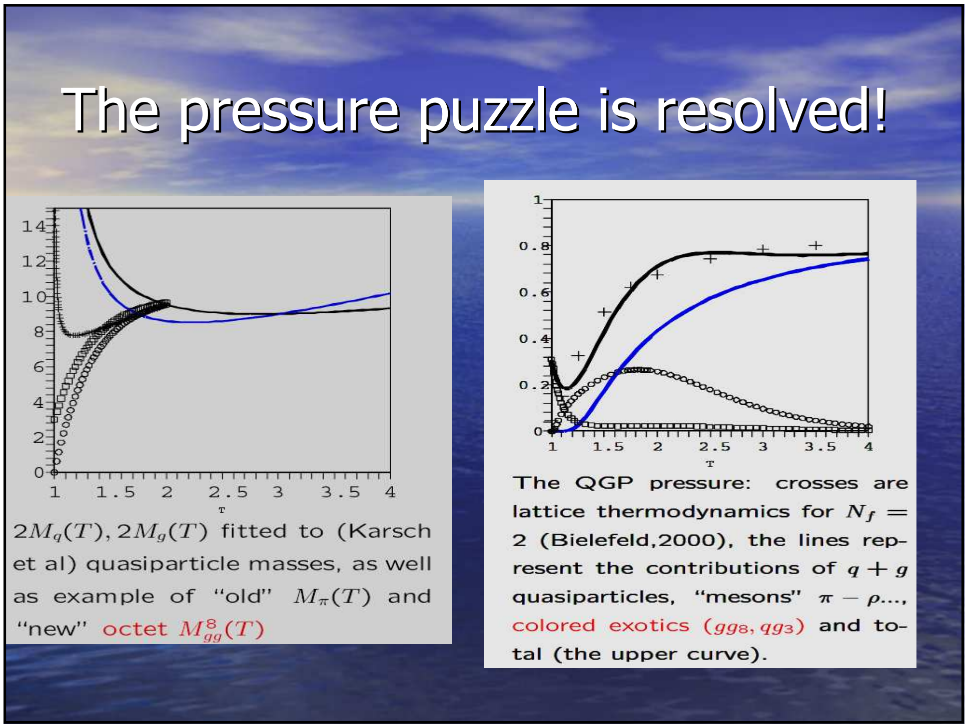


The pressure puzzle is resolved!

$2M_q(T), 2M_g(T)$ fitted to (Karsch et al) quasiparticle masses, as well as example of "old" $M_\pi(T)$ and "new" octet $M^8_{gg}(T)$

The QGP pressure: crosses are lattice thermodynamics for $N_f = 2$ (Bielefeld,2000), the lines represent the contributions of $q+g$ quasiparticles, "mesons" $\pi - \rho...$, colored exotics (gg_8, qg_3) and total (the upper curve).

Can we verify it experimentally? Dileptons from sQGP: ρ at 1.7 and ϕ at about 2 GeV? Casalderrey+ES,hep-ph

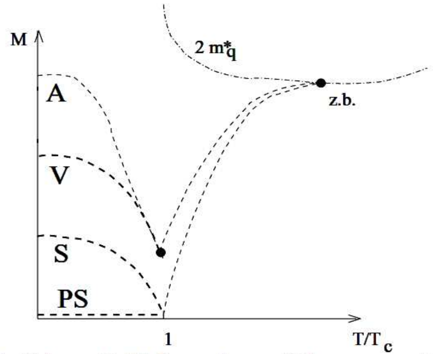
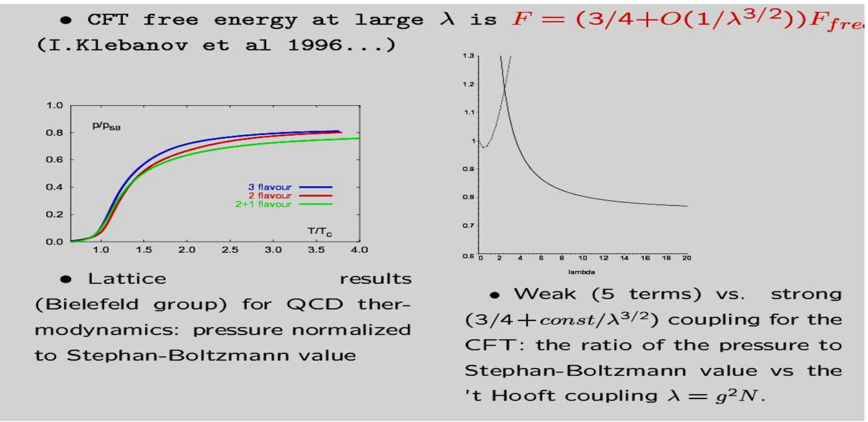


FIG. 1. Schematic T-dependence of the masses of $\bar{q}q$ states. A, V, S and PS stand for axial, vector, scalar and pseudoscalar states. The dash-dotted line shows a behavior of twice the quasiparticle mass. Two black dots indicate places where we hope the dilepton signal may be observable.

Now we are ready to move to N=4 SUSY YM at finite T

- (reminder) Weak vs strong coupling for p(T)
- (reminder) Summing ladders for a potential=> how instantaneous?
- (reminder) Falling on a center
- (reminder) M» $\lambda^{1/2}$ T
- **Yes, there are binary bound states at any coupling and M» T only**
- **Yes, p» N_c^2 T^4 due to colored ones**
- **Yes spin forces can be neglected**

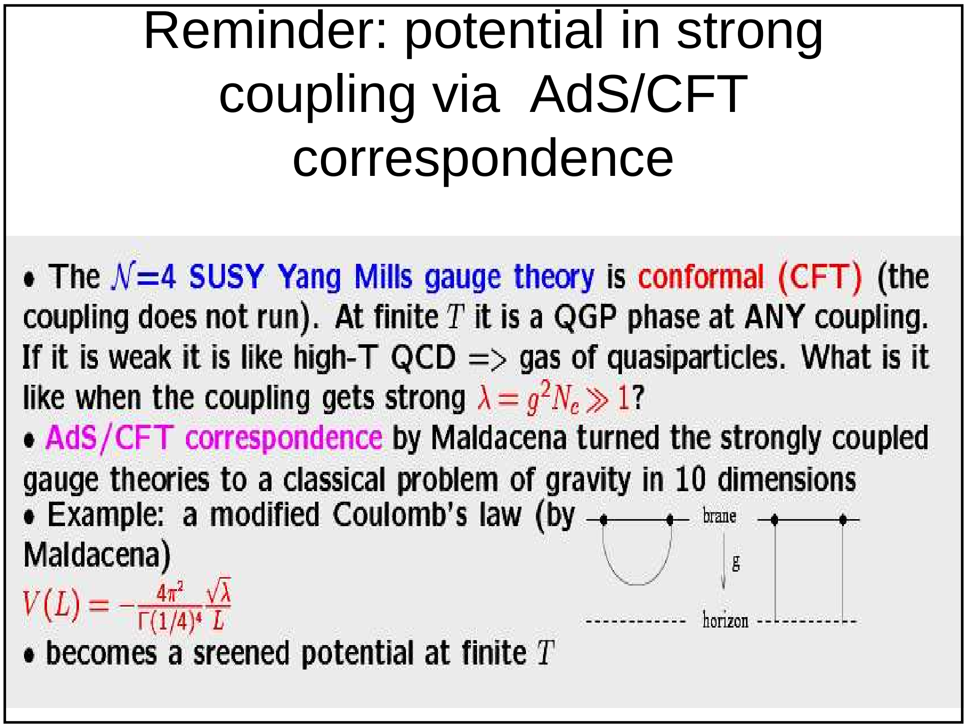
QCD vs CFT: The famous .8 again:



- CFT free energy at large λ is $F = (3/4+O(1/\lambda^{3/2}))F_{fre}$ (I.Klebanov et al 1996...)
- Lattice results (Bielefeld group) for QCD thermodynamics: pressure normalized to Stephan-Boltzmann value
- Weak (5 terms) vs. strong $(3/4+const/\lambda^{3/2})$ coupling for the CFT: the ratio of the pressure to Stephan-Boltzmann value vs the 't Hooft coupling $\lambda = g^2N$.

QCD vs CFT

- **Viscosity is η/s» .1-.3 in QCD at RHIC (Teaney)**
- **It is η/s=1/4π (Son et al) in CFT at infinite λ**

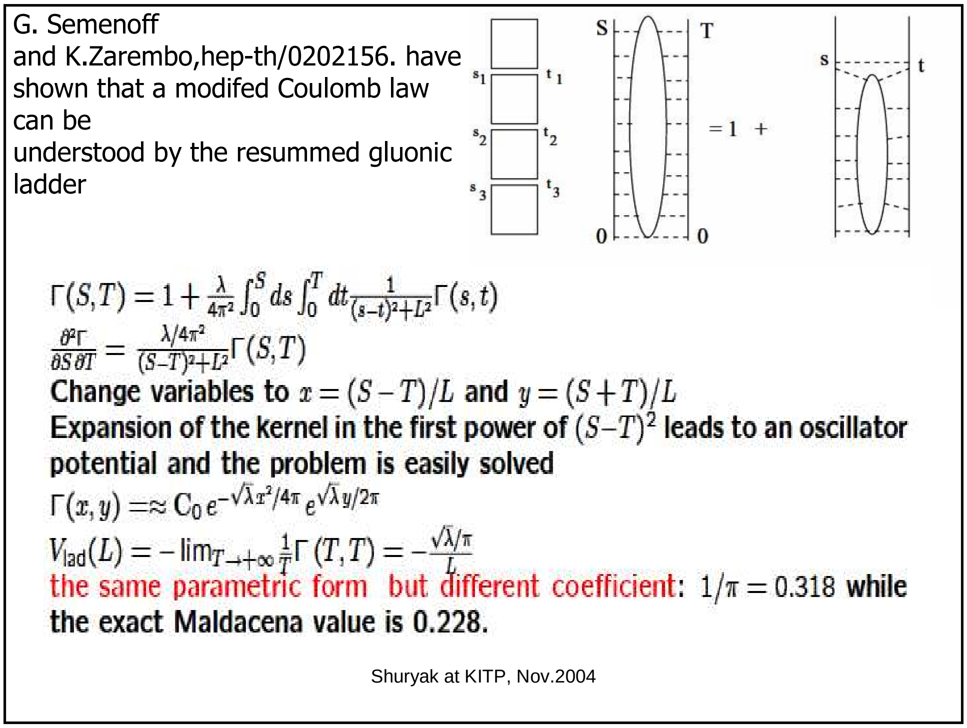


Reminder: potential in strong coupling via AdS/CFT correspondence

- The $\mathcal{N}$=4 SUSY Yang Mills gauge theory is conformal (CFT) (the coupling does not run). At finite T it is a QGP phase at ANY coupling. If it is weak it is like high-T QCD => gas of quasiparticles. What is it like when the coupling gets strong $\lambda = g^2 N_c \gg 1$?
- AdS/CFT correspondence by Maldacena turned the strongly coupled gauge theories to a classical problem of gravity in 10 dimensions
- Example: a modified Coulomb's law (by Maldacena)

$$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$$

- becomes a sreened potential at finite T



G. Semenoff
and K.Zarembo,hep-th/0202156. have shown that a modifed Coulomb law can be
understood by the resummed gluonic ladder

$$\Gamma(S,T) = 1 + \frac{\lambda}{4\pi^2}\int_0^S ds \int_0^T dt \frac{1}{(s-t)^2+L^2}\Gamma(s,t)$$

$$\frac{\partial^2\Gamma}{\partial S\,\partial T} = \frac{\lambda/4\pi^2}{(S-T)^2+L^2}\Gamma(S,T)$$

Change variables to $x = (S-T)/L$ and $y = (S+T)/L$

Expansion of the kernel in the first power of $(S-T)^2$ leads to an oscillator potential and the problem is easily solved

$$\Gamma(x,y) =\approx C_0 e^{-\sqrt{\lambda}x^2/4\pi} e^{\sqrt{\lambda}y/2\pi}$$

$$V_{\mathrm{lad}}(L) = -\lim_{T\to+\infty}\frac{1}{T}\Gamma(T,T) = -\frac{\sqrt{\lambda}/\pi}{L}$$

the same parametric form but different coefficient: $1/\pi = 0.318$ while the exact Maldacena value is 0.228.

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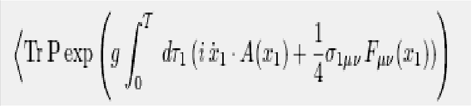
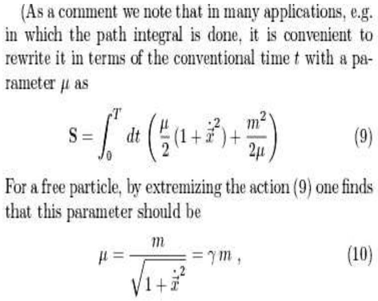
Spin-spin and spin-orbit forces at Strong coupling:

ES and I.Zahed, hep-th/0310031,plb

- Non-static Wilson lines with spin



$$\left\langle \mathrm{Tr}\,\mathrm{P}\exp\left(g\int_0^T d\tau_1\,(i\,\dot{x}_1\cdot A(x_1)+\frac{1}{4}\sigma_{1\mu\nu}F_{\mu\nu}(x_1))\right)\right.$$



(As a comment we note that in many applications, e.g. in which the path integral is done, it is convenient to rewrite it in terms of the conventional time t with a parameter μ as

$$\mathrm{S}=\int_0^T dt\left(\frac{\mu}{2}(1+\dot{\vec{x}}^2)+\frac{m^2}{2\mu}\right) \qquad (9)$$

For a free particle, by extremizing the action (9) one finds that this parameter should be

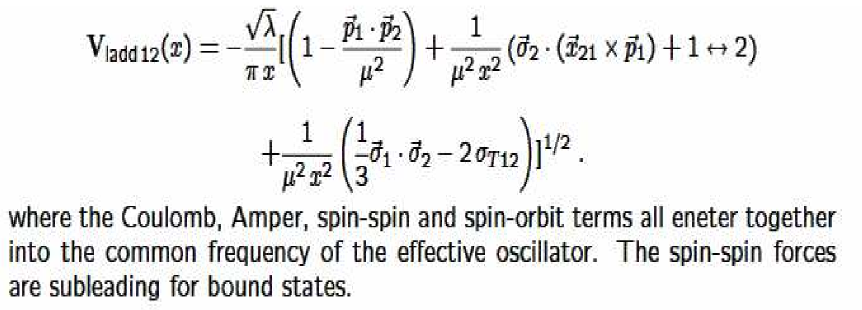
$$\mu=\frac{m}{\sqrt{1+\dot{\vec{x}}^2}}=\gamma m\,, \qquad (10)$$

•Due to strong coupling, gluon propagates instantaneously and thus there is no time delay!

Spin-spin and spin-orbit forces at Strong coupling: IZ and ES, hep-th/0310031. cont.

• Weak coupling textbook results are reproduced:

•Here is our strong coupling resummed result:



$$\mathrm{V}_{\mathrm{ladd}\,12}(x)=-\frac{\sqrt{\lambda}}{\pi x}[\left(1-\frac{\vec{p}_1\cdot\vec{p}_2}{\mu^2}\right)+\frac{1}{\mu^2x^2}(\vec{\sigma}_2\cdot(\vec{x}_{21}\times\vec{p}_1)+1\leftrightarrow 2)$$

$$+\frac{1}{\mu^2x^2}\left(\frac{1}{3}\vec{\sigma}_1\cdot\vec{\sigma}_2-2\,\sigma_{T12}\right)]^{1/2}\,.$$

where the Coulomb, Amper, spin-spin and spin-orbit terms all eneter together into the common frequency of the effective oscillator. The spin-spin forces are subleading for bound states.

All terms except velocity-velocity (Ampere) term are actually suppressed in unltrarelativistic limit by the gamma factor in μ

Is there formation of a string-like configuration in high orders, in spite of Conf.Sym.? Seems to be:

- **Some higher orde**
  diagrams have e
- **s d4x λ » O(1):**
  multibody Bethe-

Salpeter

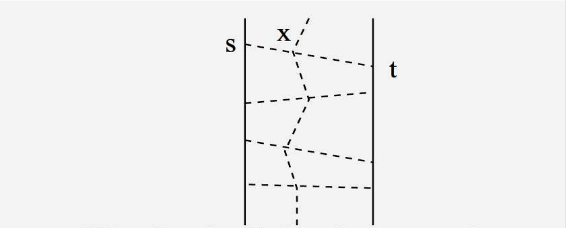
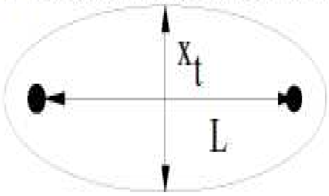


FIG. 3. Examples of higher-order diagrams with an extra scalar/gluon connecting the ladder rungs.

- vertices distributed in a quasi-string regime

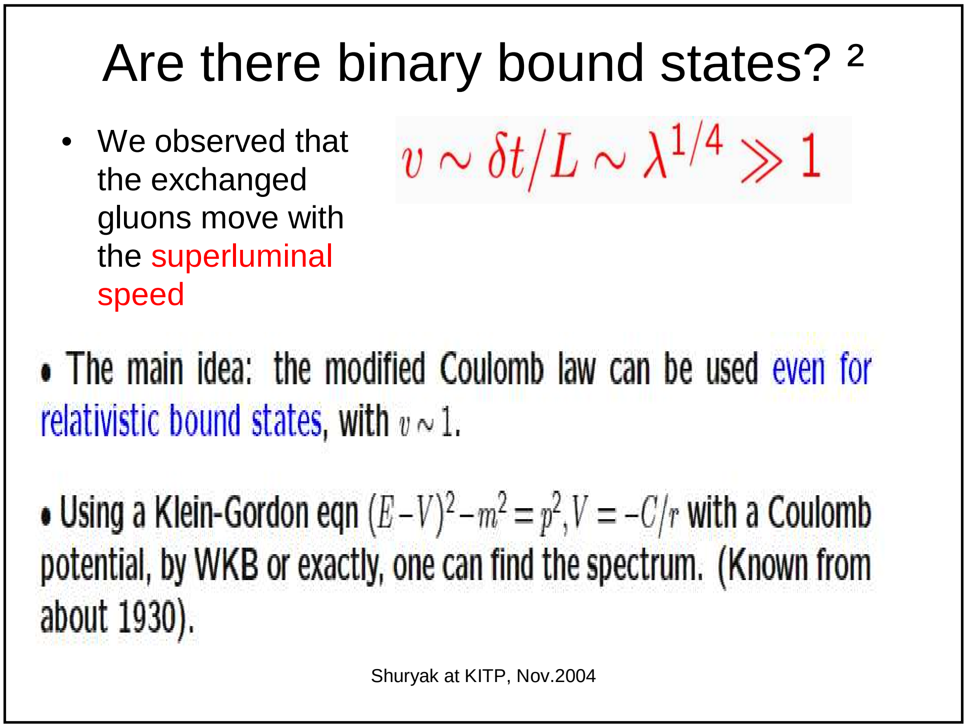


tranverse size is $L_T \sim L/\lambda^{1/4} \ll L$

What is the potential at finite T?

- Scalar, electric and magnetic gluon exchanges now become all different => different polarization operators, so it is rather involved calculations, see paper
- Approximate form
- V(L,T)» $\lambda^{1/2}$/L/sinh(π T L)
- Thus the Debye radius has no λ,

As obtained from ads/cft previously (Rey et al)



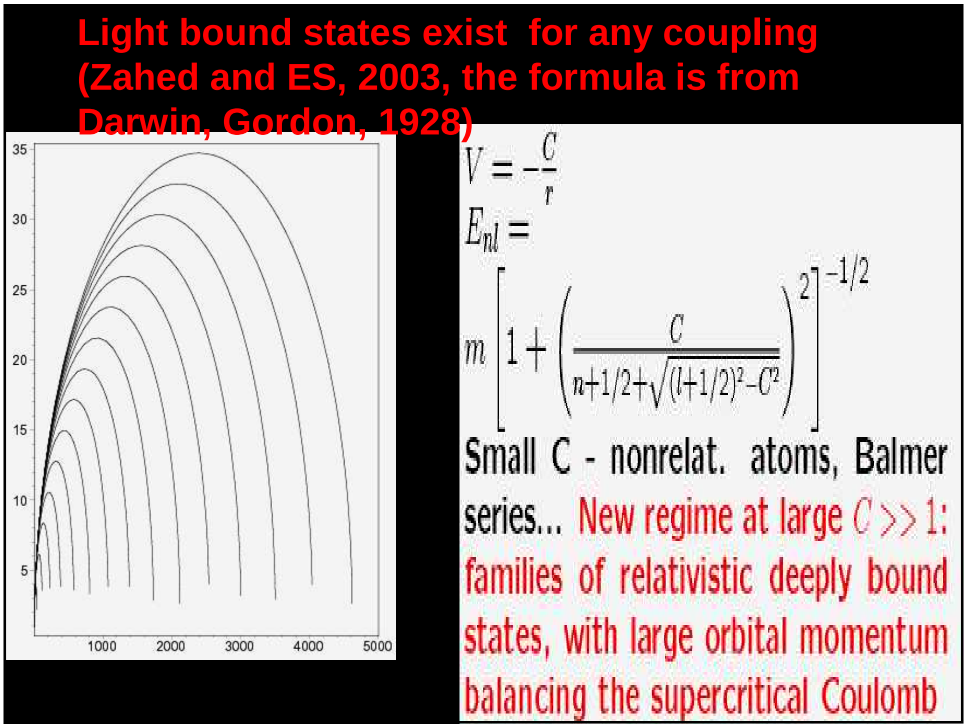
Are there binary bound states? 2

- We observed that the exchanged gluons move with the superluminal speed

$$v \sim \delta t/L \sim \lambda^{1/4} \gg 1$$

- The main idea: the modified Coulomb law can be used even for relativistic bound states, with $v \sim 1$.
- Using a Klein-Gordon eqn $(E-V)^2 - m^2 = p^2, V = -C/r$ with a Coulomb potential, by WKB or exactly, one can find the spectrum. (Known from about 1930).

Shuryak at KITP, Nov.2004

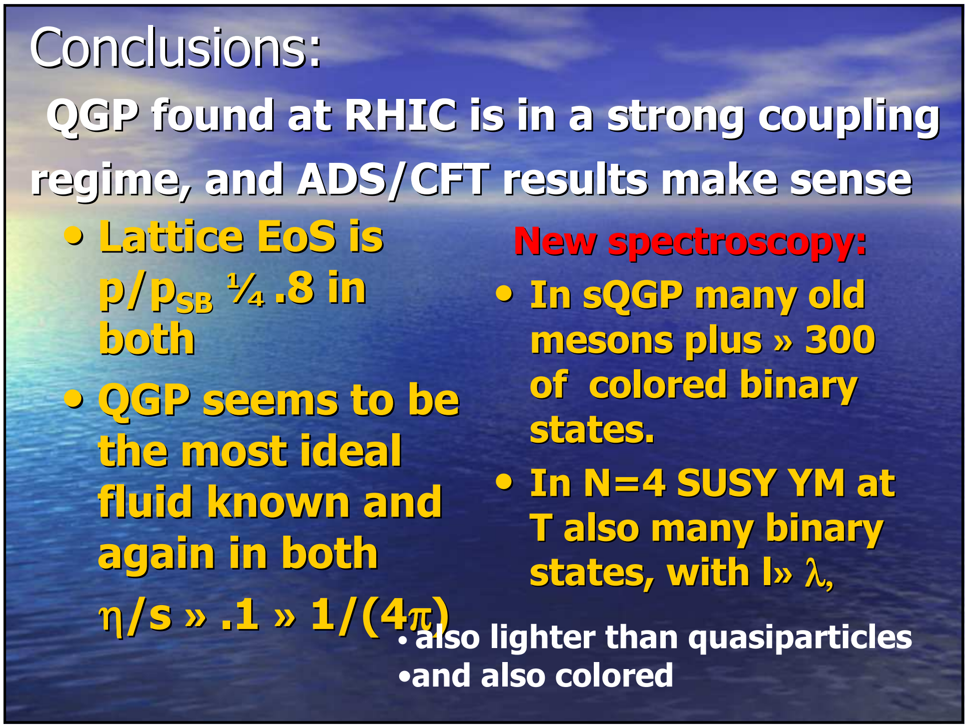


Light bound states exist for any coupling (Zahed and ES, 2003, the formula is from Darwin, Gordon, 1928)

$$V = -\frac{C}{r}$$

$$E_{nl} = m\left[1+\left(\frac{C}{n+1/2+\sqrt{(l+1/2)^2-C^2}}\right)^2\right]^{-1/2}$$

Small C - nonrelat. atoms, Balmer series... New regime at large $C >> 1$: families of relativistic deeply bound states, with large orbital momentum balancing the supercritical Coulomb



Conclusions:

QGP found at RHIC is in a strong coupling regime, and ADS/CFT results make sense

- Lattice EoS is p/p_{SB} ¼ .8 in both
- QGP seems to be the most ideal fluid known and again in both

  η/s » .1 » $1/(4\pi)$

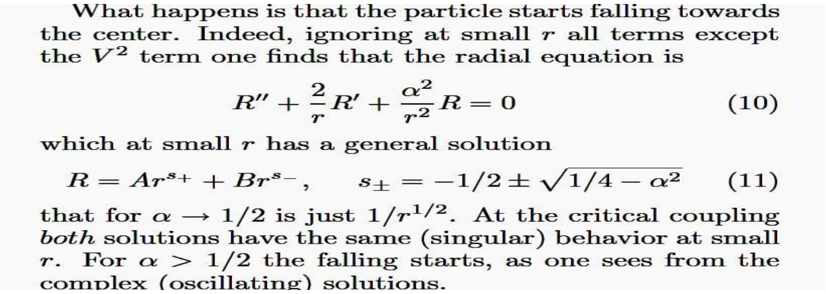
New spectroscopy:

- In sQGP many old mesons plus » 300 of colored binary states.
- In N=4 SUSY YM at T also many binary states, with l» λ,

- also lighter than quasiparticles
- and also colored

Additional slides

Relativistic eqns have a critical Coulomb coupling for falling onto the center (known since 1920's)



What happens is that the particle starts falling towards the center. Indeed, ignoring at small r all terms except the V^2 term one finds that the radial equation is

$$R'' + \frac{2}{r}R' + \frac{\alpha^2}{r^2}R = 0 \qquad (10)$$

which at small r has a general solution

$$R = Ar^{s_+} + Br^{s_-}, \qquad s_\pm = -1/2 \pm \sqrt{1/4 - \alpha^2} \qquad (11)$$

that for $\alpha \longrightarrow 1/2$ is just $1/r^{1/2}$. At the critical coupling *both* solutions have the same (singular) behavior at small r. For $\alpha > 1/2$ the falling starts, as one sees from the complex (oscillating) solutions.

- $(4/3)\alpha_s=1/2$ is a critical value for Klein-Gordon eqn, at which falling onto the center appears. (It is 1 for Dirac).

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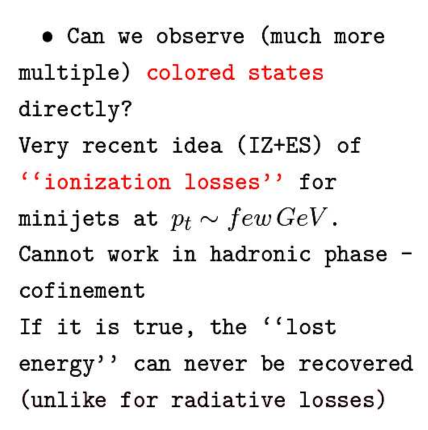
Jet quenching by ``ionization" of new bound states in QGP?

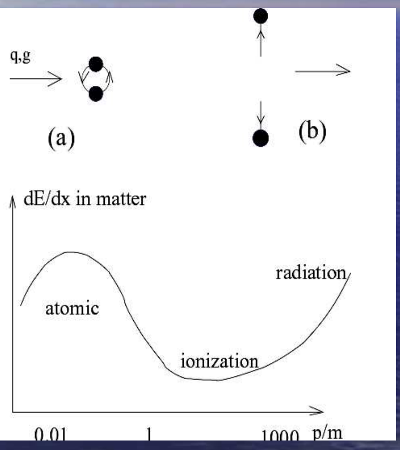


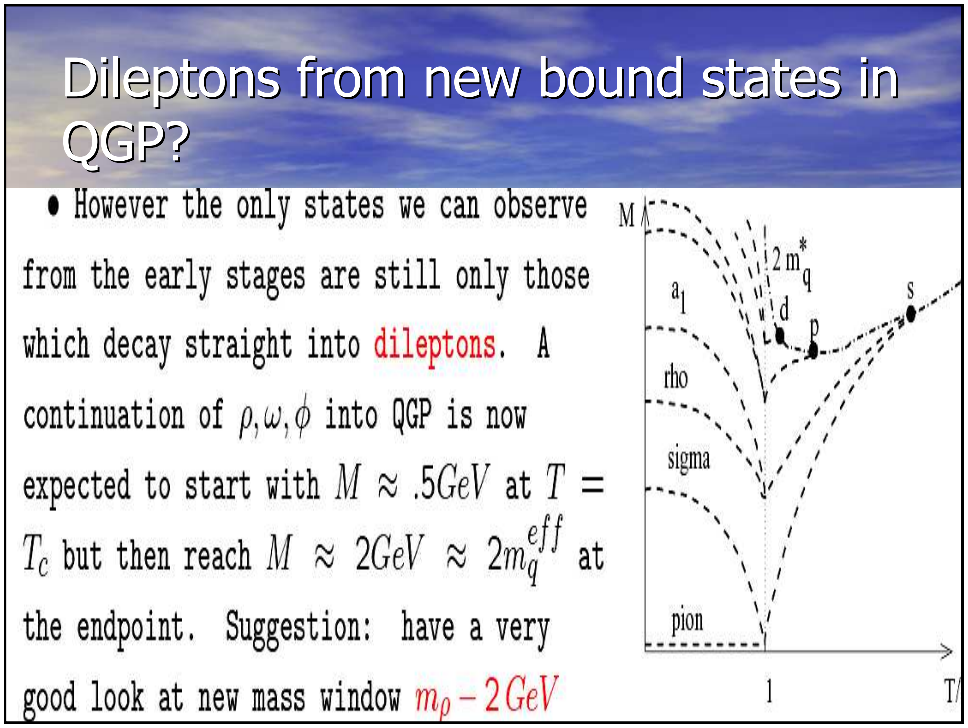
- Can we observe (much more multiple) colored states directly?

Very recent idea (IZ+ES) of ''ionization losses'' for minijets at $p_t \sim few\, GeV$.

Cannot work in hadronic phase - cofinement

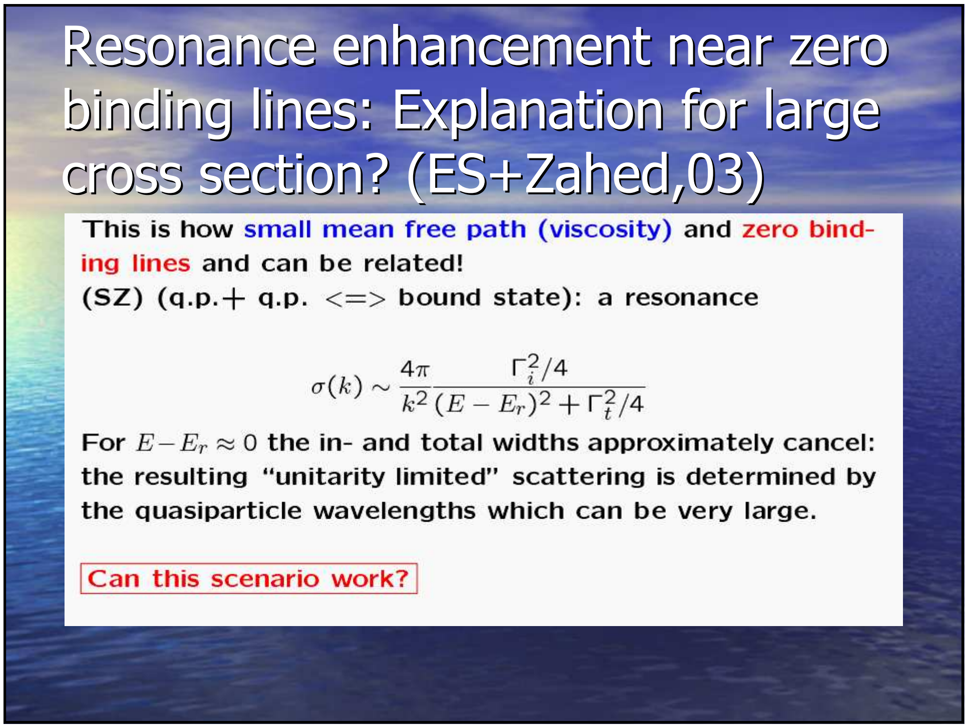
If it is true, the ''lost energy'' can never be recovered (unlike for radiative losses)





Dileptons from new bound states in QGP?

- However the only states we can observe from the early stages are still only those which decay straight into dileptons. A continuation of ρ, ω, ϕ into QGP is now expected to start with $M \approx .5 GeV$ at $T = T_c$ but then reach $M \approx 2GeV \approx 2m_q^{eff}$ at the endpoint. Suggestion: have a very good look at new mass window $m_\rho - 2\,GeV$



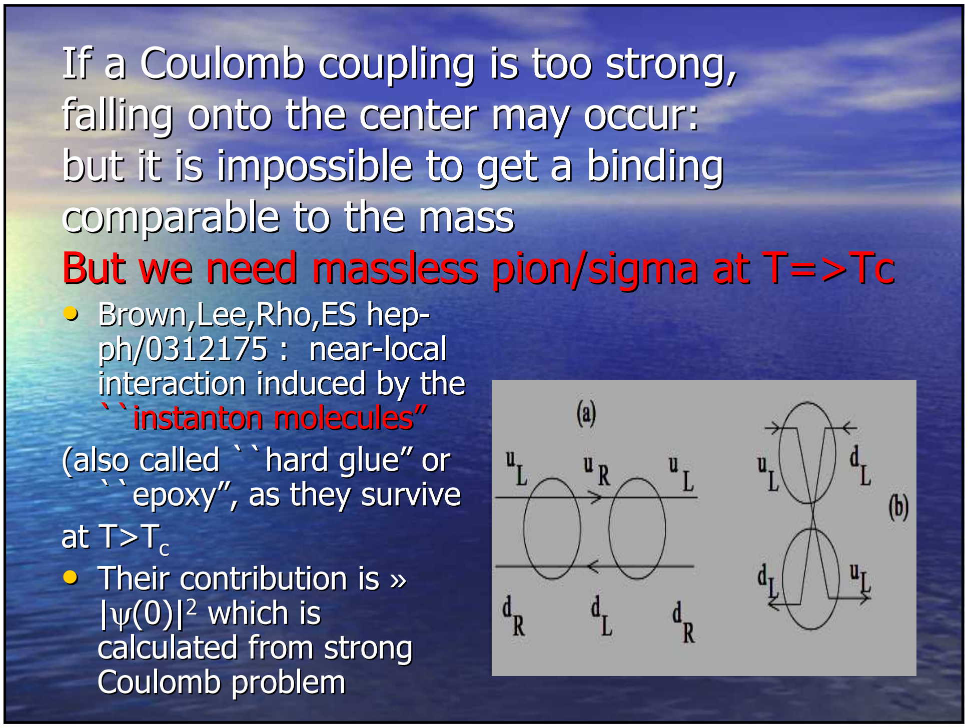
Resonance enhancement near zero binding lines: Explanation for large cross section? (ES+Zahed,03)

This is how small mean free path (viscosity) and zero binding lines and can be related!
(SZ) (q.p.+ q.p. <=> bound state): a resonance

$$\sigma(k) \sim \frac{4\pi}{k^2} \frac{\Gamma_i^2/4}{(E-E_r)^2 + \Gamma_t^2/4}$$

For $E - E_r \approx 0$ the in- and total widths approximately cancel: the resulting "unitarity limited" scattering is determined by the quasiparticle wavelengths which can be very large.

Can this scenario work?



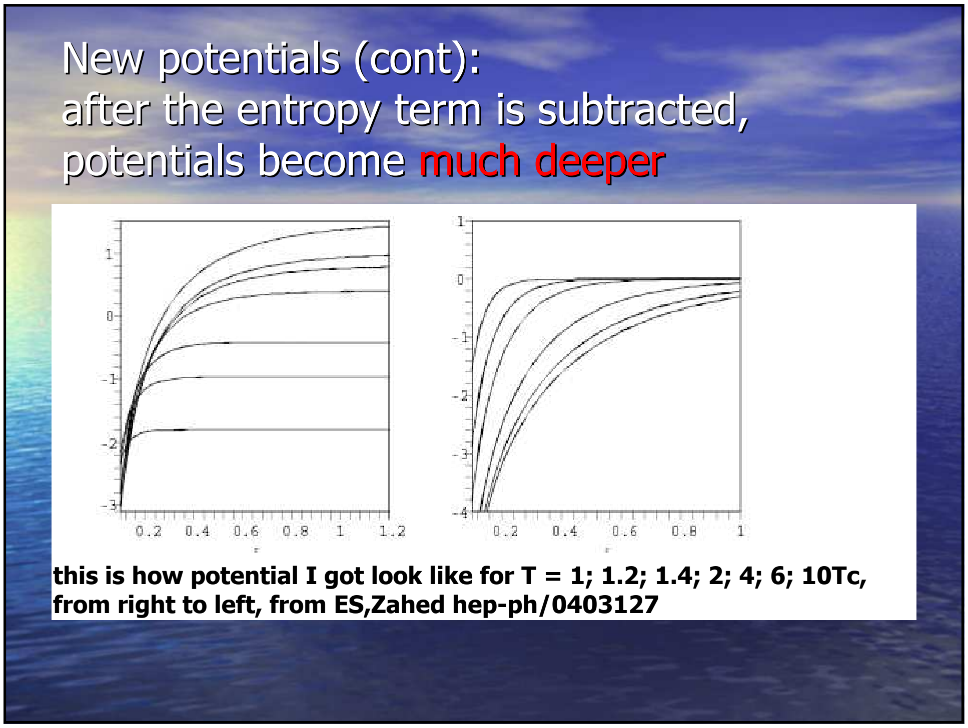
If a Coulomb coupling is too strong, falling onto the center may occur: but it is impossible to get a binding comparable to the mass

But we need massless pion/sigma at T=>Tc

- Brown,Lee,Rho,ES hep-ph/0312175 : near-local interaction induced by the ``instanton molecules”

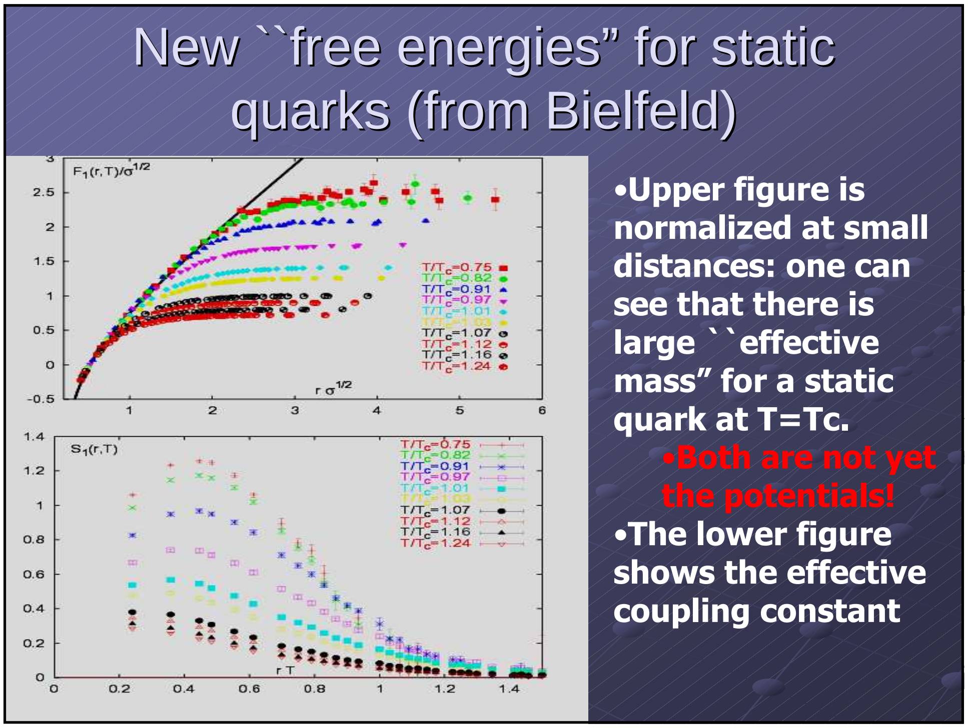
(also called ``hard glue” or ``epoxy”, as they survive at $T>T_c$

- Their contribution is » $|\psi(0)|^2$ which is calculated from strong Coulomb problem



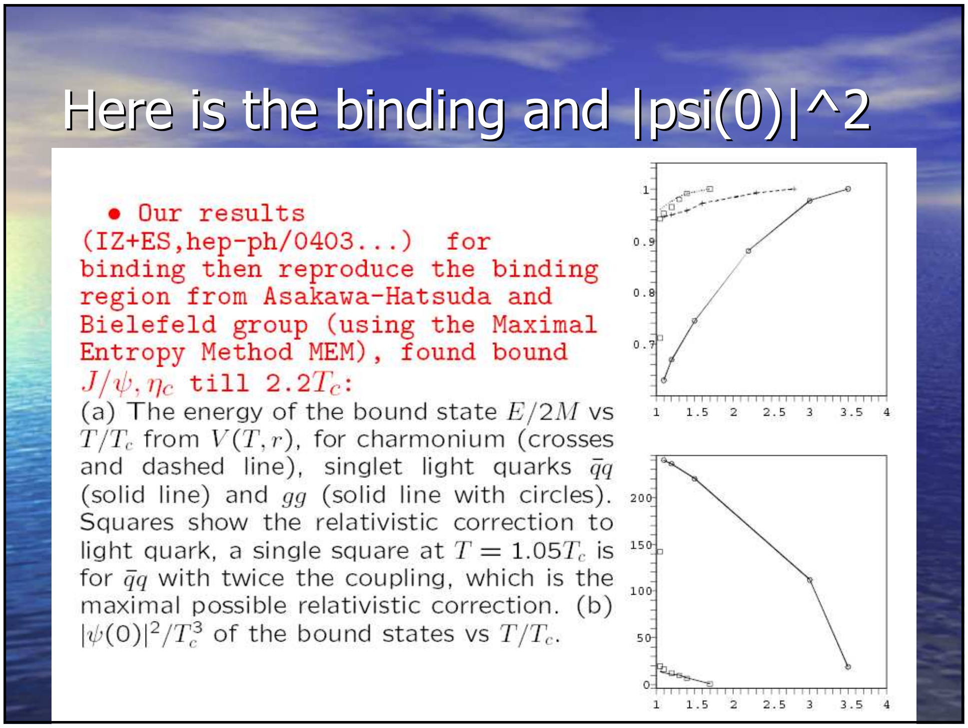
New potentials (cont): after the entropy term is subtracted, potentials become much deeper

this is how potential I got look like for T = 1; 1.2; 1.4; 2; 4; 6; 10Tc, from right to left, from ES,Zahed hep-ph/0403127



New ``free energies” for static quarks (from Bielfeld)

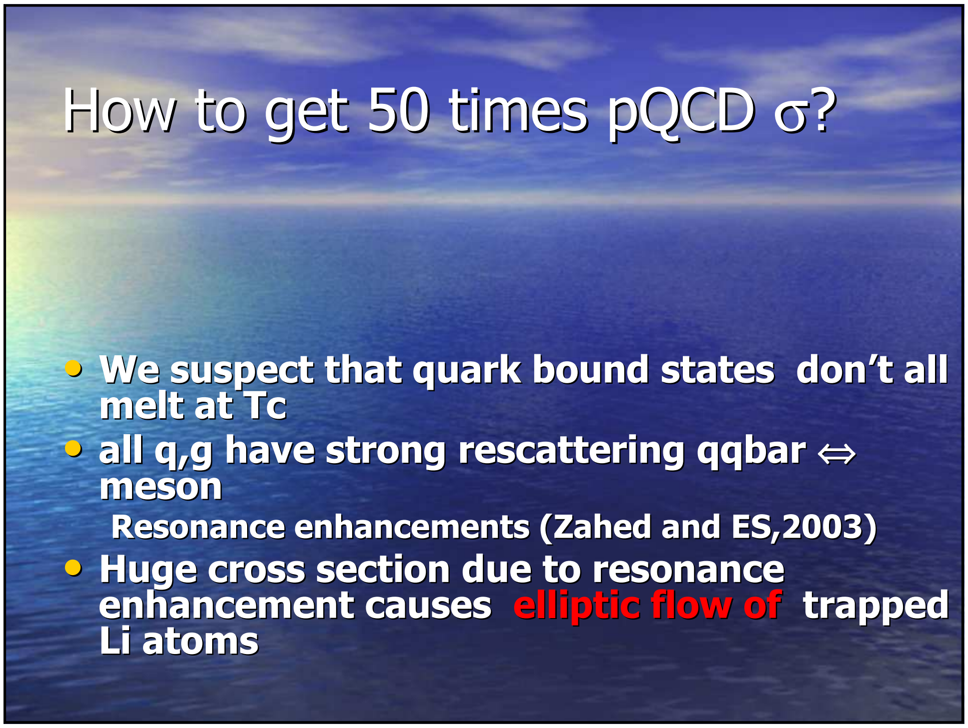
- **Upper figure is normalized at small distances: one can see that there is large ``effective mass” for a static quark at T=Tc.**
  - **Both are not yet the potentials!**
- **The lower figure shows the effective coupling constant**



Here is the binding and |psi(0)|^2

- Our results (IZ+ES,hep-ph/0403...) for binding then reproduce the binding region from Asakawa-Hatsuda and Bielfeld group (using the Maximal Entropy Method MEM), found bound $J/\psi, \eta_c$ till $2.2T_c$:

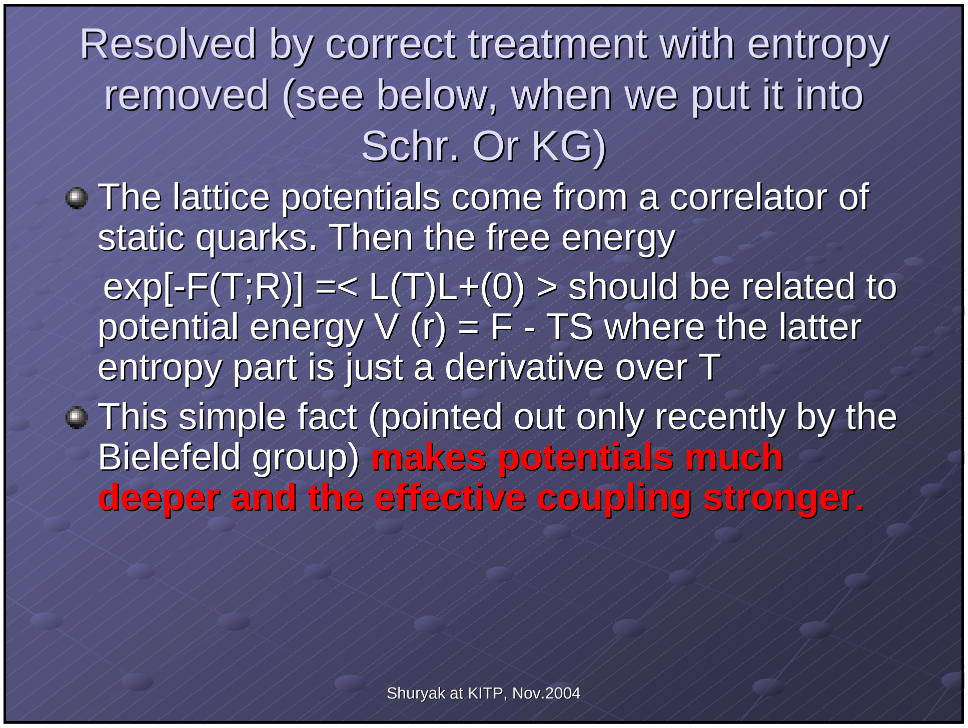
(a) The energy of the bound state $E/2M$ vs T/T_c from $V(T,r)$, for charmonium (crosses and dashed line), singlet light quarks $\bar{q}q$ (solid line) and gg (solid line with circles). Squares show the relativistic correction to light quark, a single square at $T=1.05T_c$ is for $\bar{q}q$ with twice the coupling, which is the maximal possible relativistic correction. (b) $|\psi(0)|^2/T_c^3$ of the bound states vs T/T_c.



How to get 50 times pQCD σ?

- **We suspect that quark bound states don't all melt at Tc**
- **all q,g have strong rescattering qqbar ⇔ meson**

  Resonance enhancements (Zahed and ES,2003)
- **Huge cross section due to resonance enhancement causes elliptic flow of trapped Li atoms**

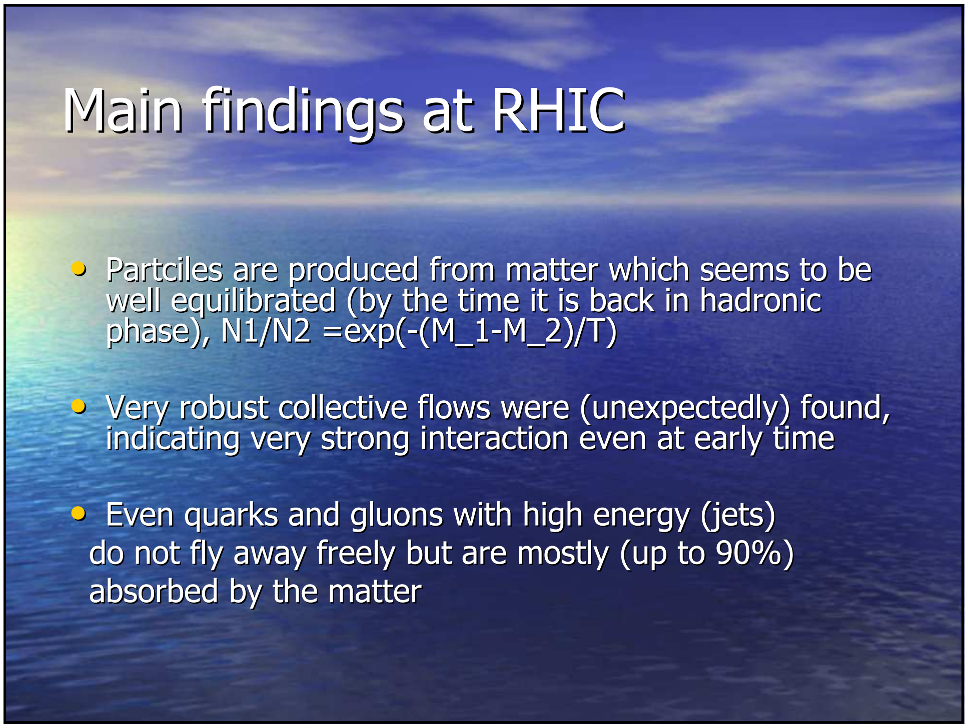


Resolved by correct treatment with entropy removed (see below, when we put it into Schr. Or KG)

- The lattice potentials come from a correlator of static quarks. Then the free energy

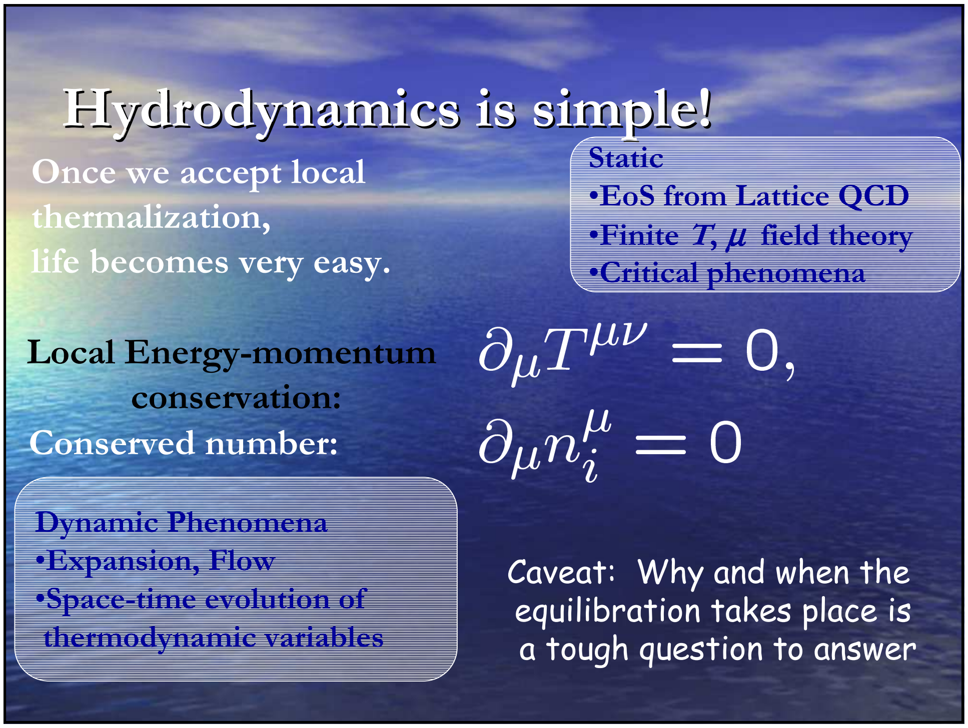
  exp[-F(T;R)] =< L(T)L+(0) > should be related to potential energy V (r) = F - TS where the latter entropy part is just a derivative over T
- This simple fact (pointed out only recently by the Bielefeld group) **makes potentials much deeper and the effective coupling stronger.**

Shuryak at KITP, Nov.2004



Main findings at RHIC

- Partciles are produced from matter which seems to be well equilibrated (by the time it is back in hadronic phase), N1/N2 =exp(-(M_1-M_2)/T)
- Very robust collective flows were (unexpectedly) found, indicating very strong interaction even at early time
- Even quarks and gluons with high energy (jets) do not fly away freely but are mostly (up to 90%) absorbed by the matter



Hydrodynamics is simple!

Once we accept local thermalization, life becomes very easy.

Static
•EoS from Lattice QCD
•Finite T, μ field theory
•Critical phenomena

Local Energy-momentum conservation:

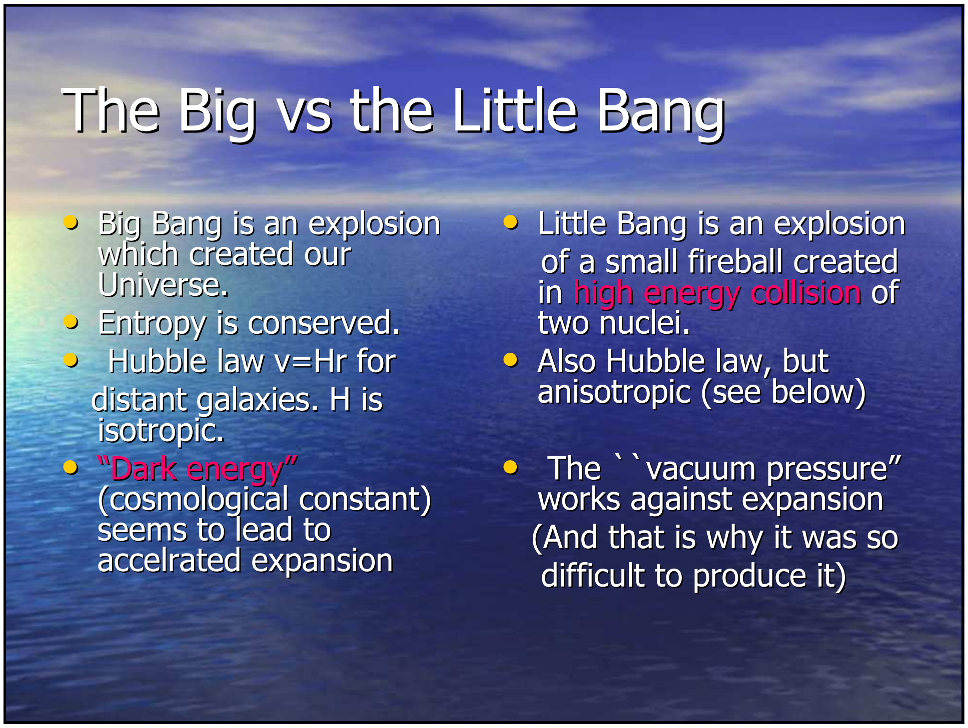
$$\partial_\mu T^{\mu\nu} = 0,$$

Conserved number:

$$\partial_\mu n_i^\mu = 0$$

Dynamic Phenomena
•Expansion, Flow
•Space-time evolution of thermodynamic variables

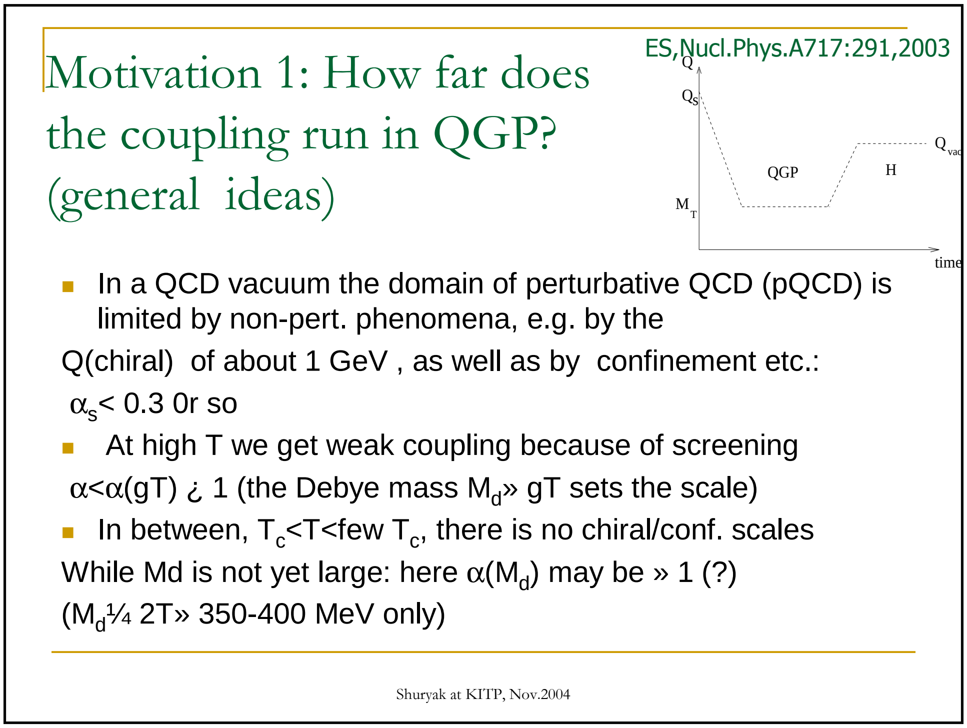
Caveat: Why and when the equilibration takes place is a tough question to answer



The Big vs the Little Bang

- Big Bang is an explosion which created our Universe.
- Entropy is conserved.
- Hubble law v=Hr for distant galaxies. H is isotropic.
- "Dark energy" (cosmological constant) seems to lead to accelrated expansion

- Little Bang is an explosion of a small fireball created in high energy collision of two nuclei.
- Also Hubble law, but anisotropic (see below)
- The ``vacuum pressure" works against expansion (And that is why it was so difficult to produce it)



Motivation 1: How far does the coupling run in QGP? (general ideas)

ES,Nucl.Phys.A717:291,2003

- In a QCD vacuum the domain of perturbative QCD (pQCD) is limited by non-pert. phenomena, e.g. by the

Q(chiral) of about 1 GeV , as well as by confinement etc.:

α_s< 0.3 0r so

- At high T we get weak coupling because of screening

α<α(gT) ¿ 1 (the Debye mass M_d» gT sets the scale)

- In between, T_c<T<few T_c, there is no chiral/conf. scales

While Md is not yet large: here α(M_d) may be » 1 (?)

(M_d¼ 2T» 350-400 MeV only)

Shuryak at KITP, Nov.2004