PHENIX dilepton workshop, Santa Fe, June 21st 2004

Dileptons from Strongly Coupled quark-gluon plasma (sQGP)

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Outline of the talk

Motivations:

- Reduced scale => enhanced coupling
- Hydro works and QGP seem to have remarkably small viscosity
- Lattice bound states and large potentials

New spectroscopy of sQGP

•Multiple bound states, 90% of them colored? If so, it explains several puzzles related to lattice results:

•Why resonances in correlators (MEM)?

•How rather heavy quasiparticles can create high pressure already at T= 1.5-2 Tc?

(Outline continued –new ideas)

Vectors in QGP and dileptons:

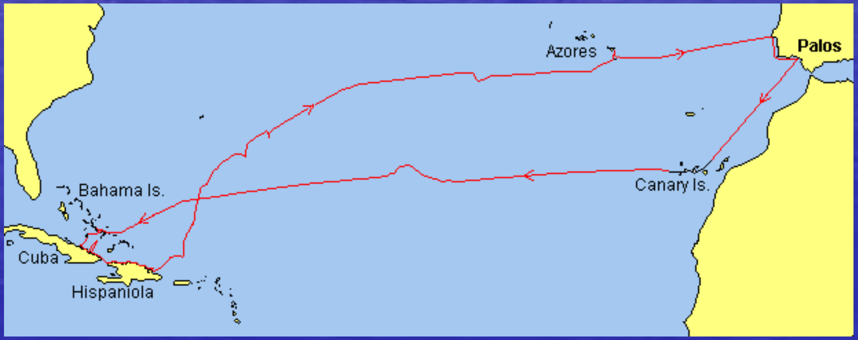
Bound states (ρ,ω,ϕ, L and R) and near-threshold bumps can tell us what are the quasiparticle masses and interaction strength in QGP

Jet quenching due to ``ionization" of new bound states

- What can we learn from other strongly coupled systems?
- Trapped Li atoms at Feshbach resonance => universal liquid
- **N=4 SUSY YM at finite T**

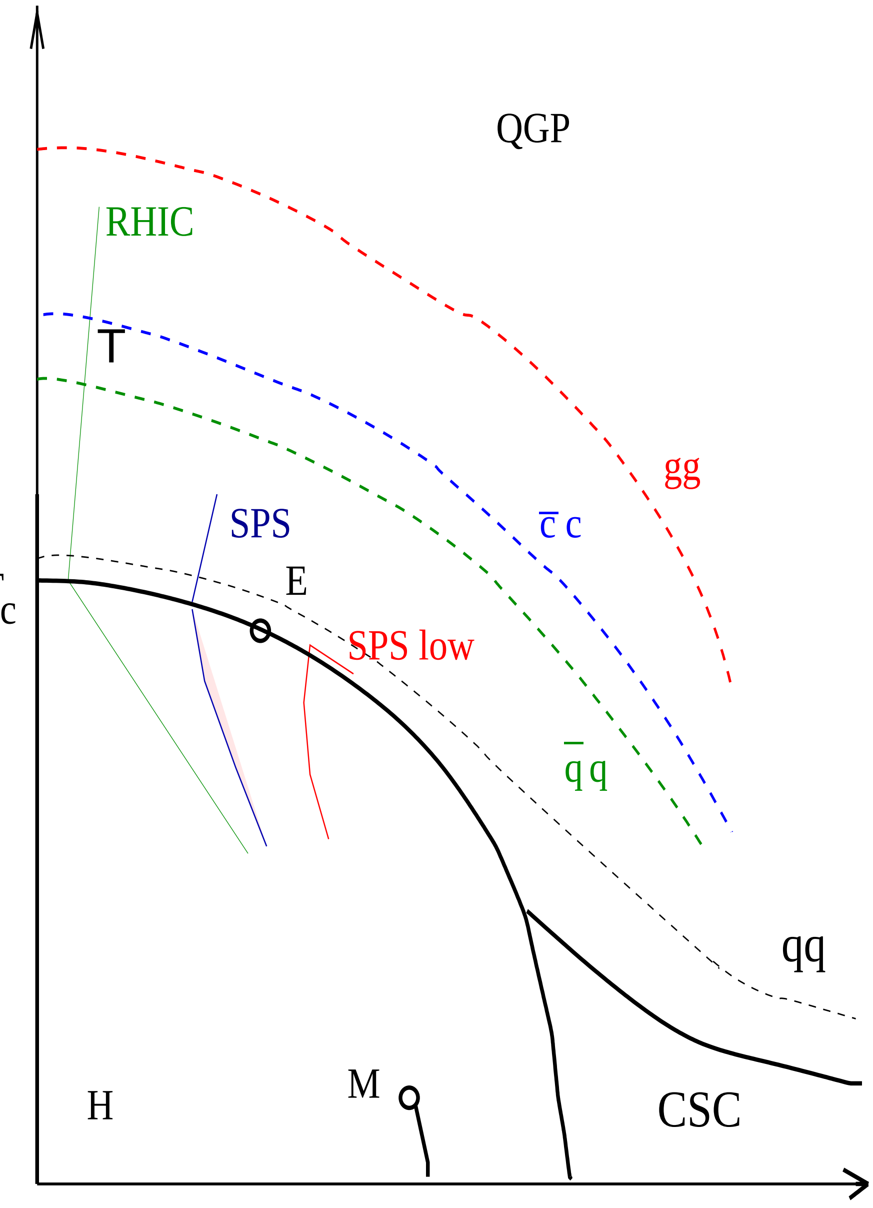
Digression: One may have an absolutely correct theory and still make accidental discoveries...

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...



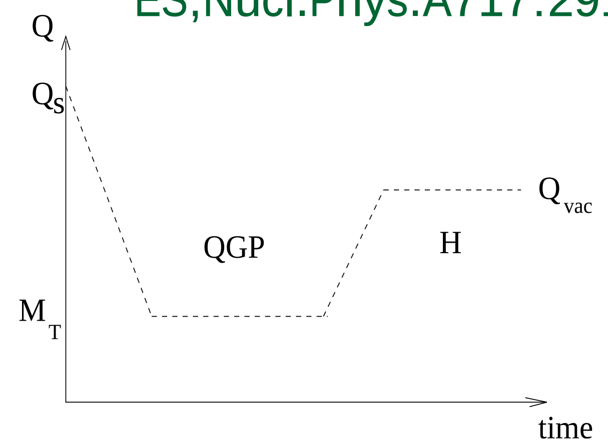
Chemical potential μ_B

New QCD Phase Diagram, which includes ``zero binding lines" (ES+I.Zahed hep-ph/030726)

The lines marked RHIC and SPS show the adiabatic cooling paths

ES,Nucl.Phys.A717:291,2003

How strong is strong interaction and where? How large can α_s become in QGP ?



- In a QCD vacuum the domain of perturbative QCD (pQCD) is limited by non-pert. phenomena, e.g. by the Q_χ» 1 GeV as well as by confinement: so α_s< 0.3
- 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 M_d¼ 2T» 350-400 MeV is not yet large: can

$\alpha_s(M_d)$ be » .5-1 (?). If so, binding appears. (ES-Zahed,03)

- Instanton-induced effects remain strong at Tc<T<2Tc, where they are present as inst-antiinst. ``molecules”

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

- $(4/3)\alpha_s\ (M/M_{Debye}) > 1.68$
- M(charm) is large, M_d is only about 2T
- If $\alpha(M_d)$ indeed runs and is about ½-1, it is large enough to bind charmonium till about $T=2T_c=340$ MeV

(accidentally, the highest T at RHIC)

- Since q and g quasiparticles are heavy,

M» 3T, they all got bound as well !

Solving for the bound states ES+I.Zahed, hep-ph/0403127

- **In QGP there is no confinement => Hundreds of colored channels may 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.

Motivation 2: RHIC produces ``matter", not a fireworks of partons

What it means?

l << L

(the micro scale) << (the macro scale)
(the mean free path) << (system size)
(relaxation time) << (evolution duration)

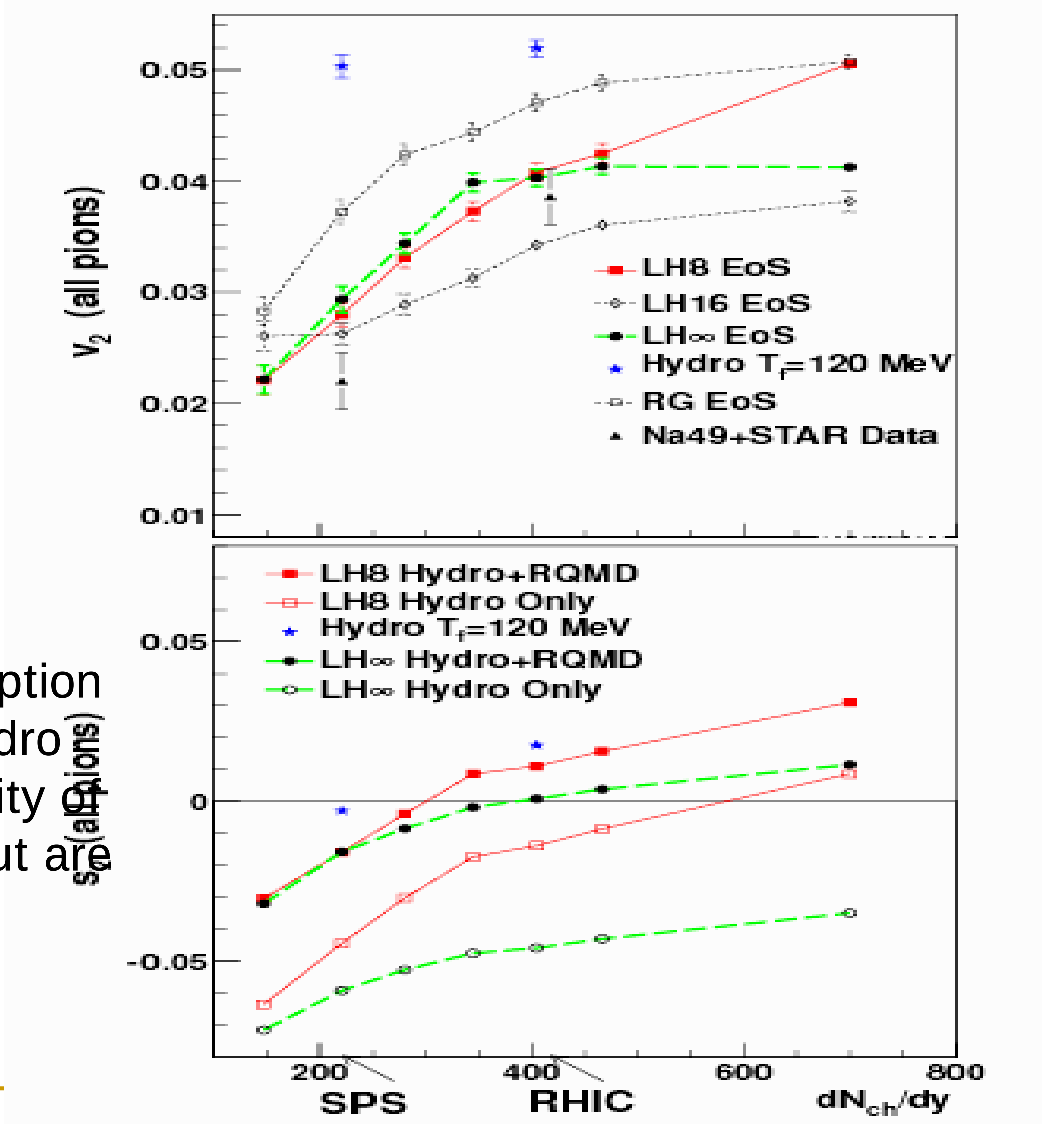
- **Good equilibration (including strangeness) is seen in particle rations (as at SPS)**
- **the zeroth order in l/L , an ideal hydro, works well (except in hadroic phase)**

- **Viscosity is the O(l/L) effect, » velocity gradients. Note that l» 1/(σ n) and hydro is (the oldest) strong coupling expansion tool. η/s» .1 ¿ 1**

How to determine Eos p(ε) and viscosity η(ε)?

- To study all flows as a function of collision energy and centrality,
- In the meantime, as a function of rapidity…

(Hydro+RQMD gives a better description
Of energy dependence than pure hydro
D.Teaney et al.('01)) because viscosity of
hadronic matter and correct freezeout are
included



Motivation 3: lattice puzzles

- Since Matsui-Satz and subsequent papers it looked like even $J/\psi,\eta_c$ dissolves in QGP (thus it was a QGP signal)
- And yet recent works (Asakawa-Hatsuda,Karsch et al) have found, using correlators and MEM, that they survive up to about T=2Tc . What was wrong?

- Resolved now by a correct treatment, with entropy term (the heat transfer) removed

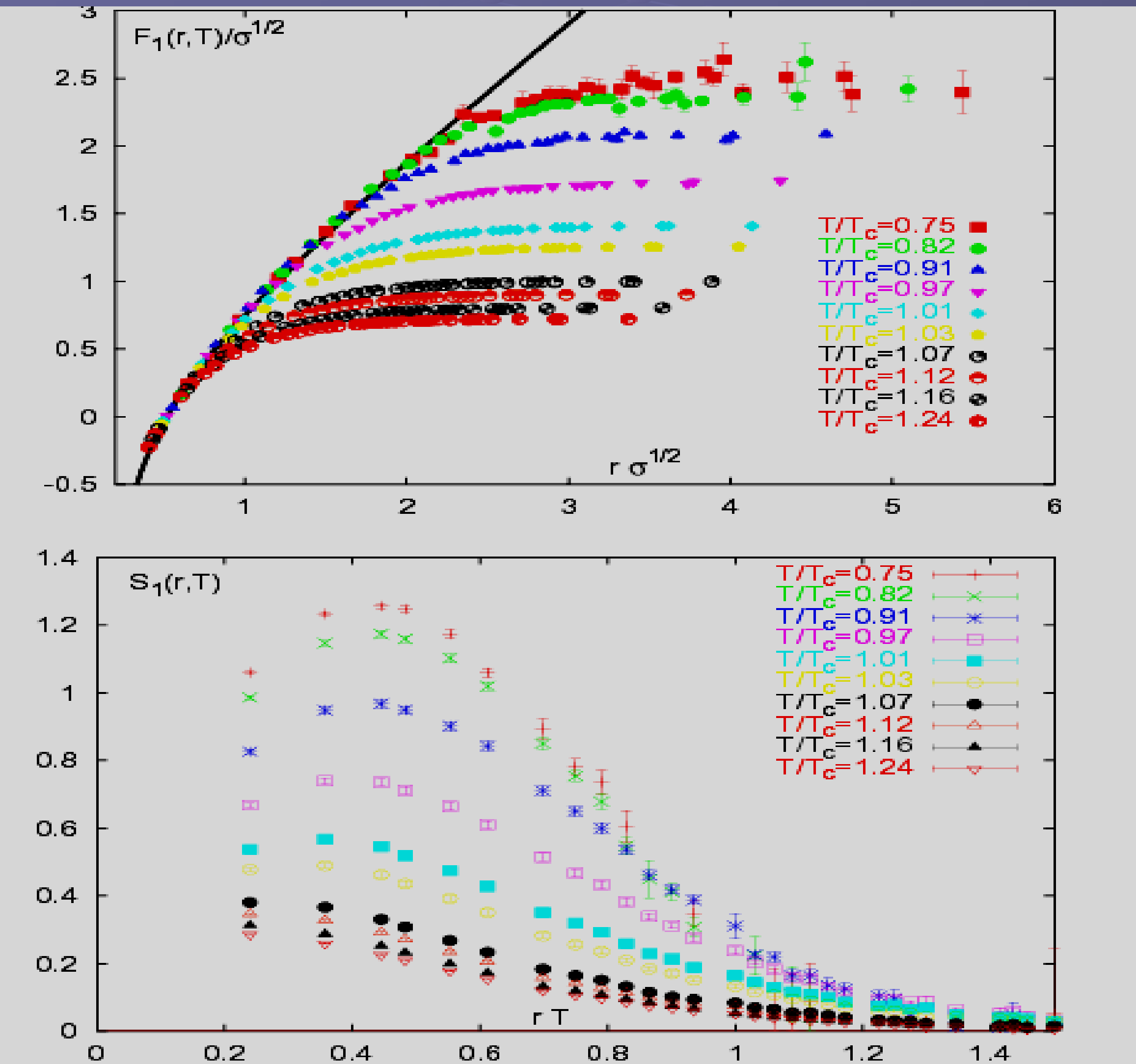
- The lattice potentials come from a correlator of static quarks. Then the free energy

  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 of F over T

- This **makes potentials much deeper and the effective coupling stronger**.

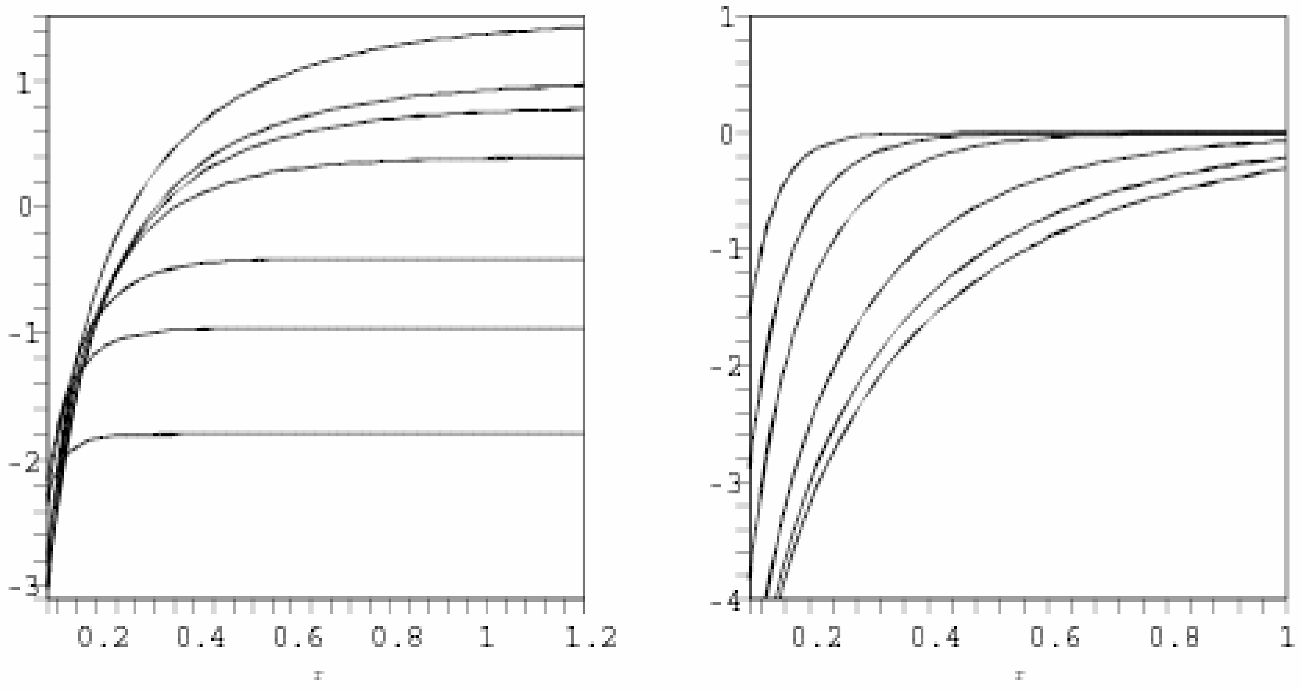
- when we put it into Schredinger (or Klein-Gordon, Dirac) eqns (ES,Zahed 03) charmonium gets bound up to about 2 Tc, as observed from correlators

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**

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

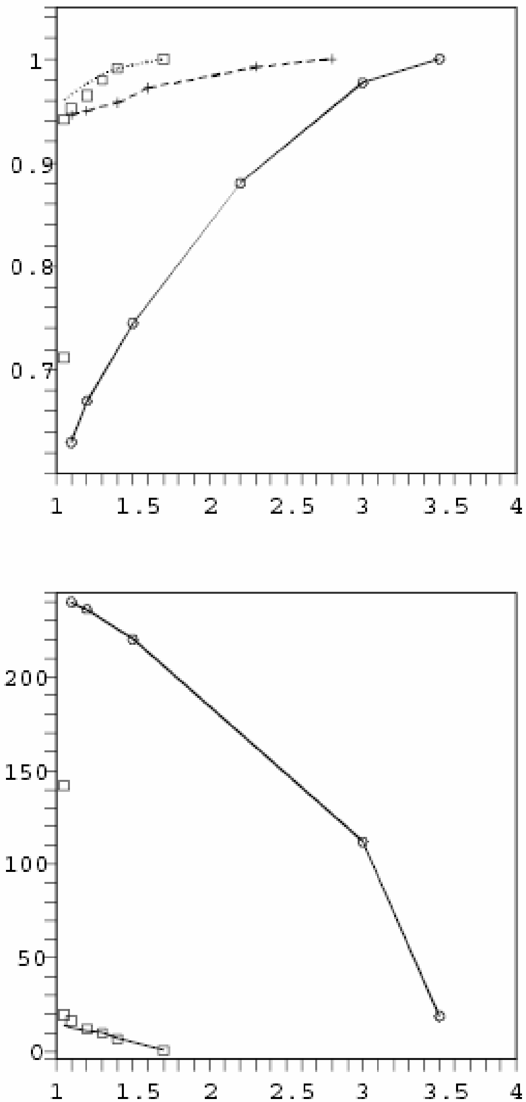


this is how potential I got look like for T = 1; 1.2; 1.4; 2; 4; 6; 10Tc, from right to left, from ES,Zahed hep-ph/0403127

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 Bielefeld 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.



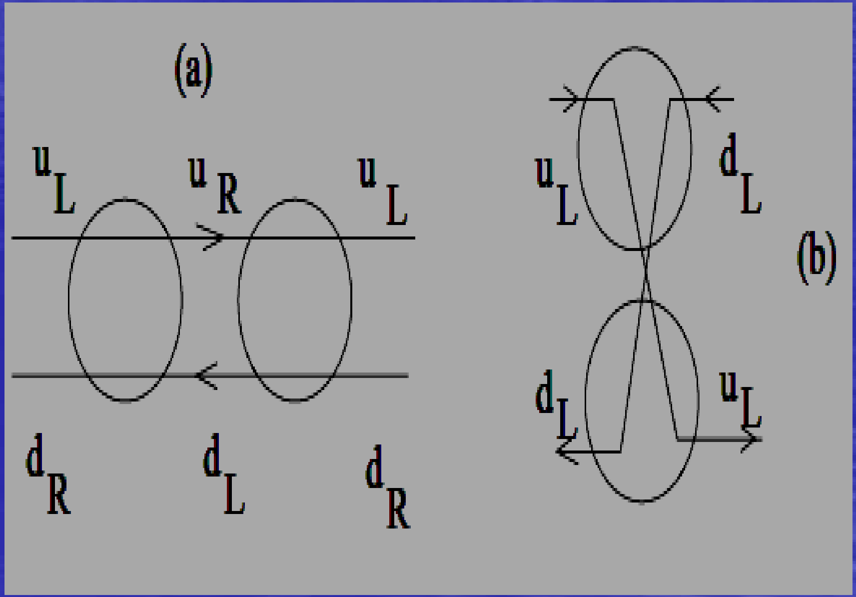
If a Coulomb coupling is too strong, falling onto the center may occur: but it is impossible to get a binding comparable to the mass

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

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

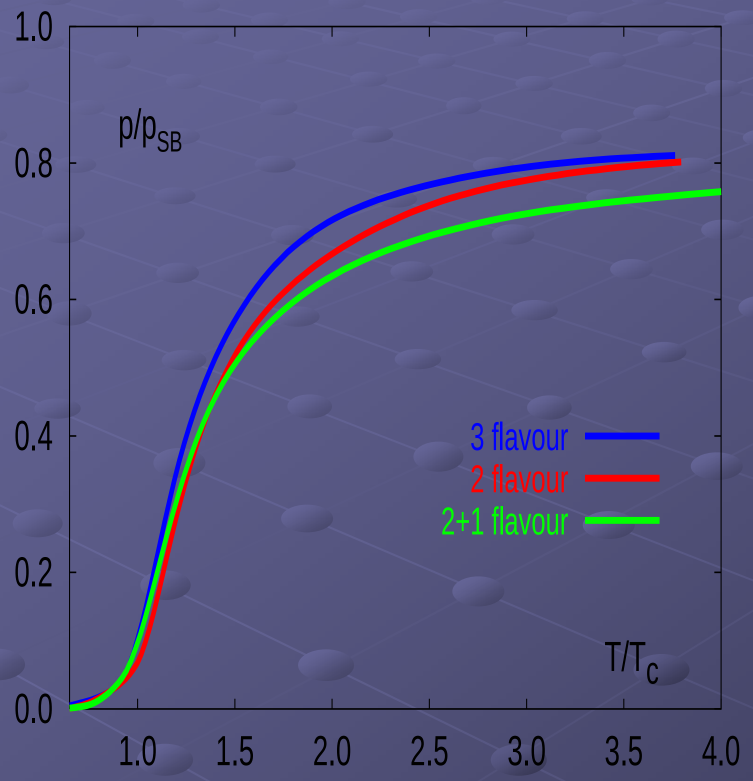
(also called ``hard glue" or ``epoxy", as they survive at $T>T_c$

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



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**

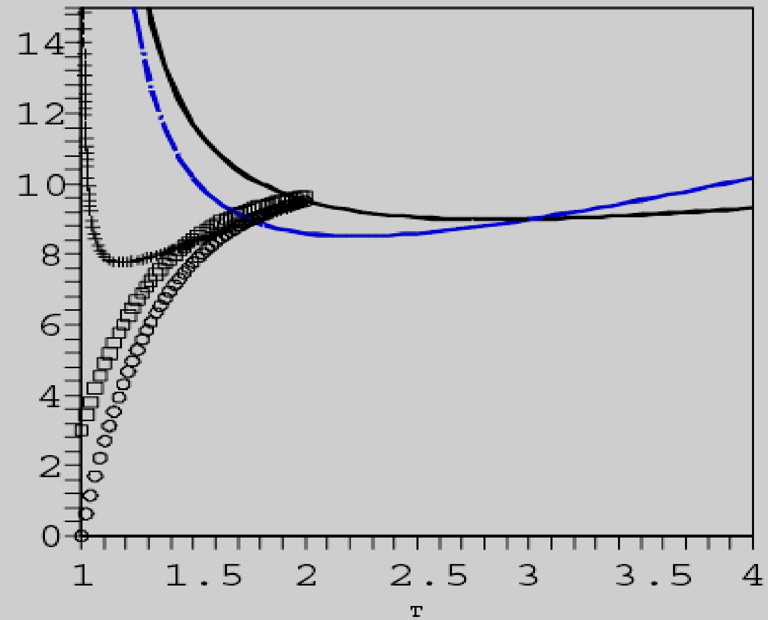
- p/p(SB)=.8 from about .3 GeV to very large value. Interpreted as an argument that interaction is relatively weak (0.2) and can be resumed, although pQCD series are bad...

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

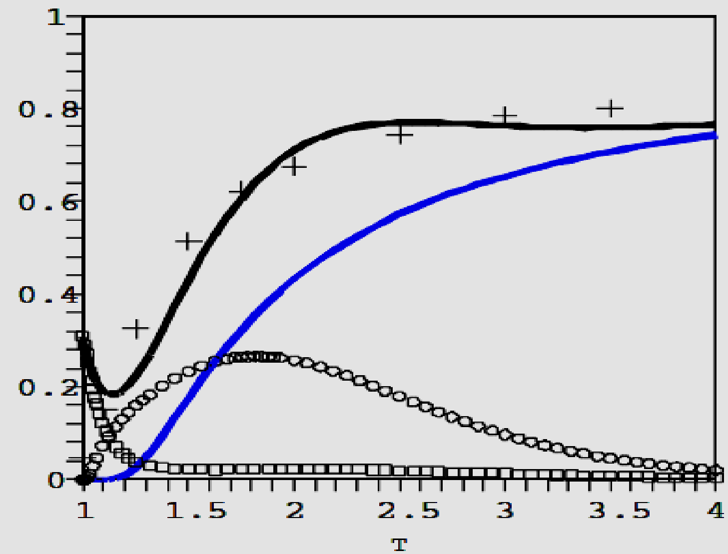
(The pressure puzzle, cont.)

- 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^2N_cÀ 1)

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 $M^8_{gg}(T)$



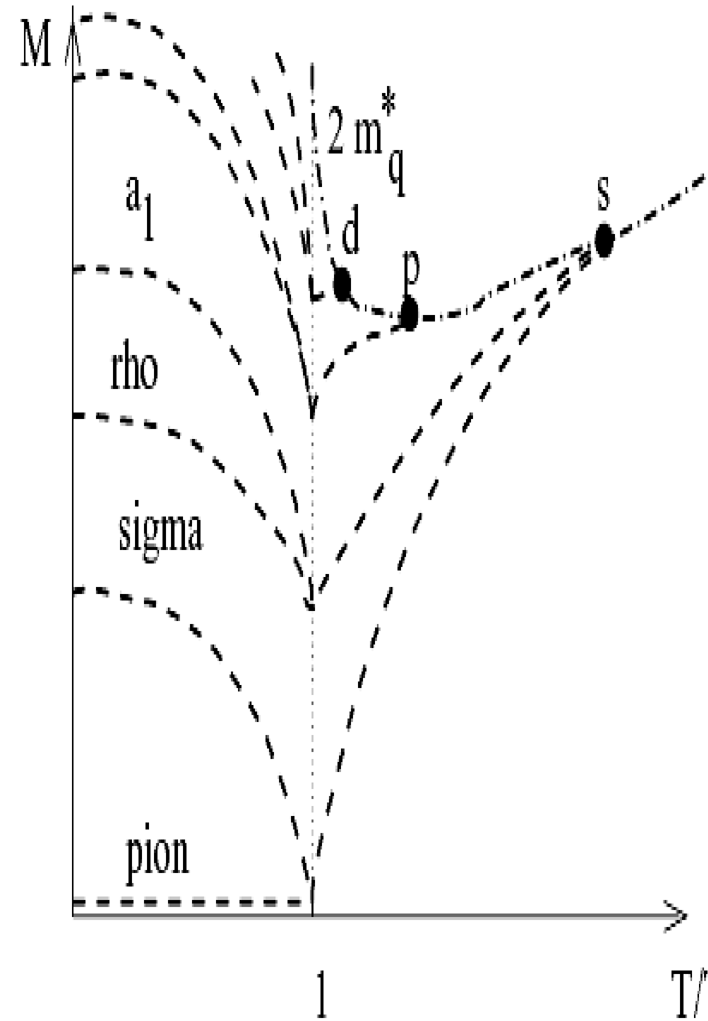
The QGP pressure: crosses are lattice thermodynamics for $N_f = 2$ (Bielefeld,2000), the lines represent the contributions of $q + g$ quasiparticles, "mesons" $\pi - \rho \ldots$, colored exotics (gg_8, qg_3) and total (the upper curve).

Quark mass and the interaction strength (“α_s”) via dileptons

- Two objects can be seen: T,L bound states ($T<T_{z.b.}$» 2 T_c) and the near-threshold enhancement (``bump”, any T)
- Why bump? Because attraction between anti-q q in QGP enhances annihilation
- Example: pp(gg) ! t t at Fermilab has a bump near threshold ($2m_t$) due to gluon exchanges. The nonrelat. Gamow parameter for small velocity $2\pi\,(4/3)\alpha_s/v > 1$

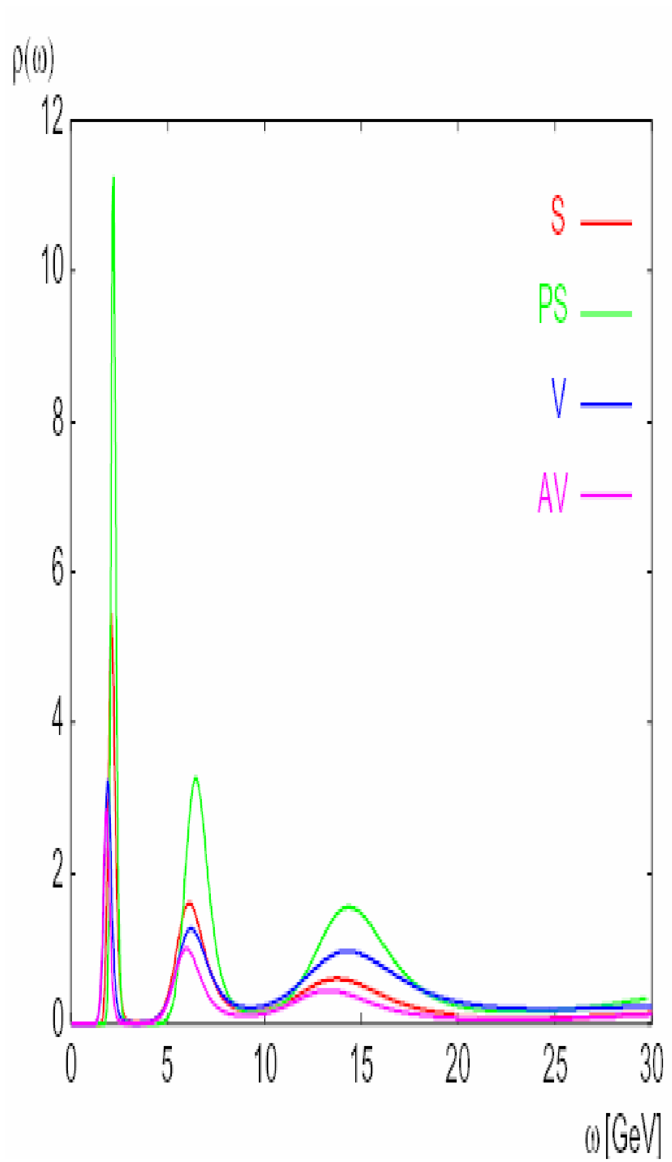
Dileptons from new bound states in QGP?

- 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 $M \approx .5GeV$ 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 $m_\rho - 2\,GeV$



Asakawa-Hatsuda, $T=1.4T_c$

Karsch-Laerman, T=1.5 and 3 Tc



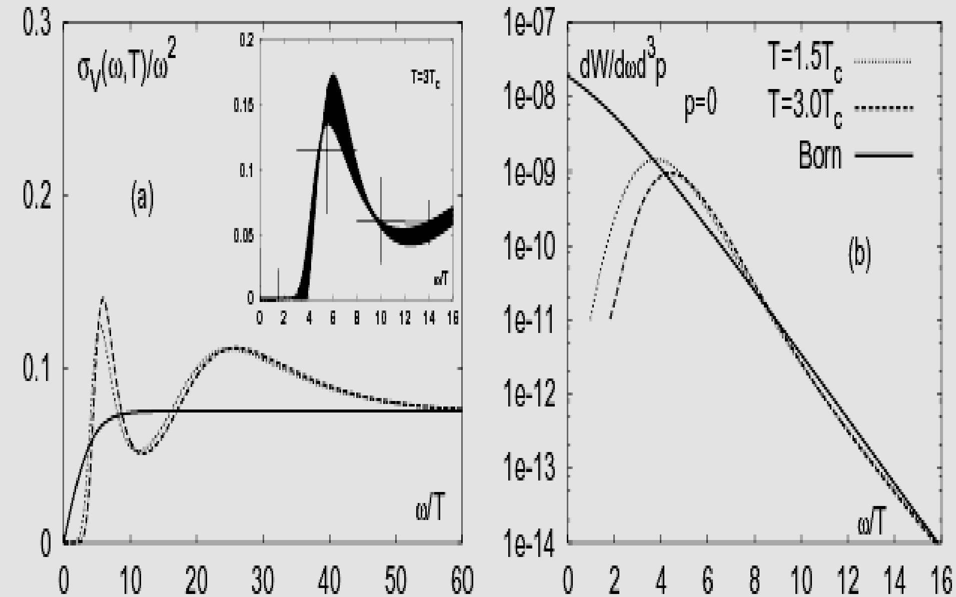


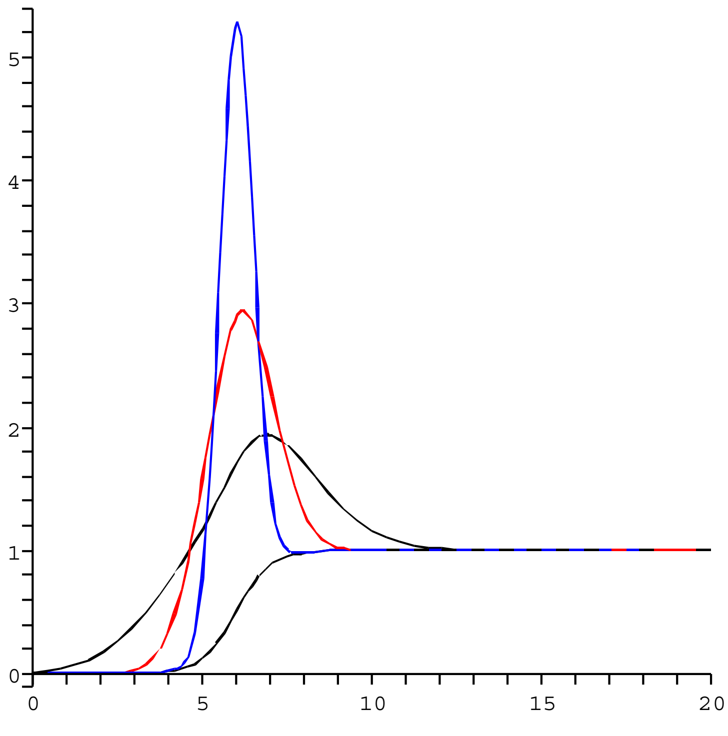
Figure 2: Reconstructed vector spectral function σ_V in units of ω^2 at zero momentum (a) and the resulting zero momentum differential dilepton rate (b) at $T/T_c = 1.5$ (doted line) and 3 (dashed line). The solid lines give the free spectral function (a) and the resulting Born rate (b). The insertion 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).

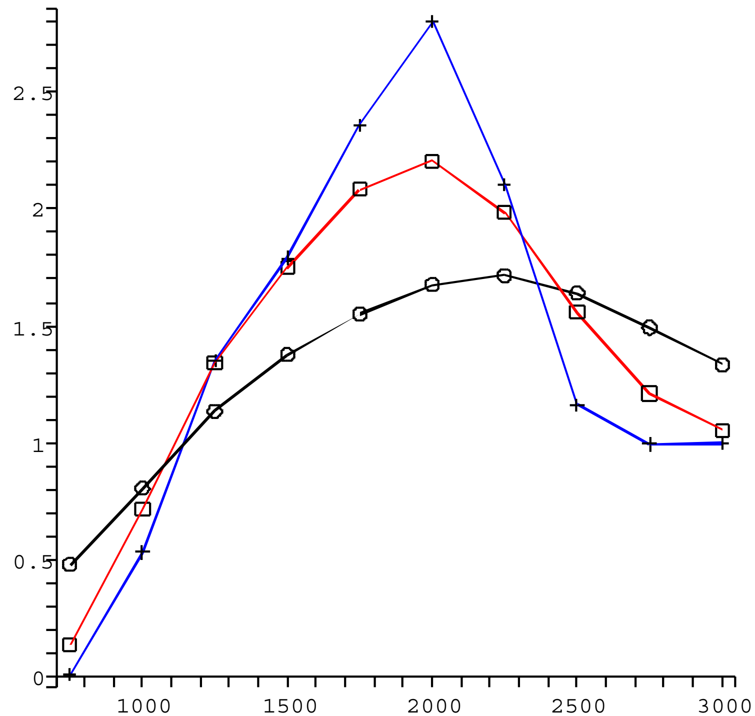
Fe w

QUARK-HADRON DUALITY AND BUMPS IN QCD:

Operator product expansion tells us that the integral Under the spectral density should be conserved (Shifman, Vainshtein, Zajkharov 78).

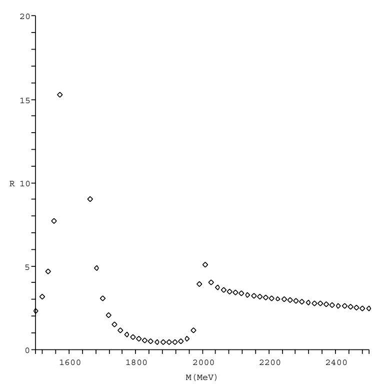
Three examples which satisfy it (left) the same after realistic time integral Over the expanding fireball (as used in Rapp+ES paper on NA50), divided by a ``standard candle” (massless quarks) (right)

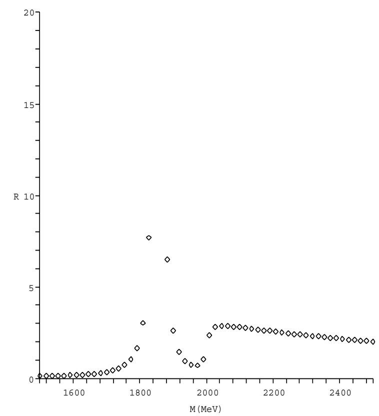


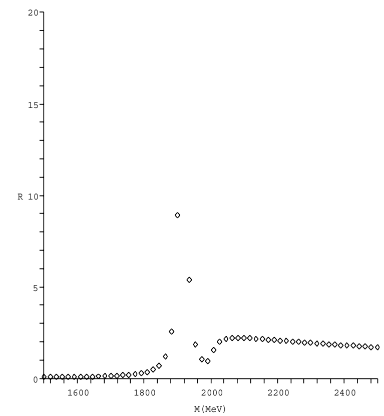


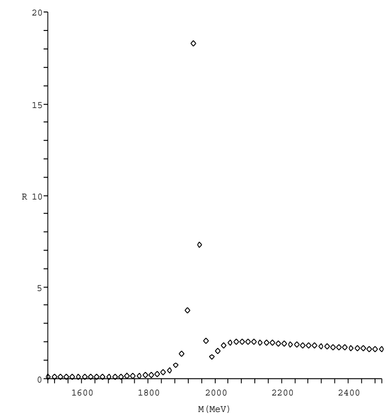
Study of near-endpoint and near-threshold annihilation rate

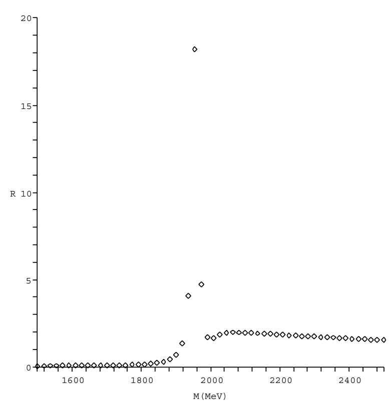
using non-rel. Green function for lattice-based potential (+ instantons) (Jorge Casalderrey +ES 2004) $Im\Pi(M)$ for T=1 .. 2 T

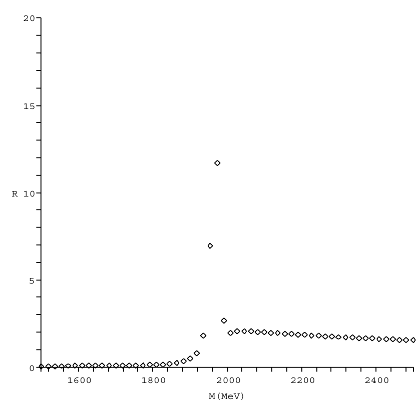












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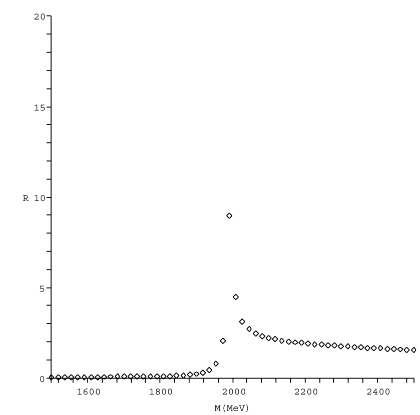
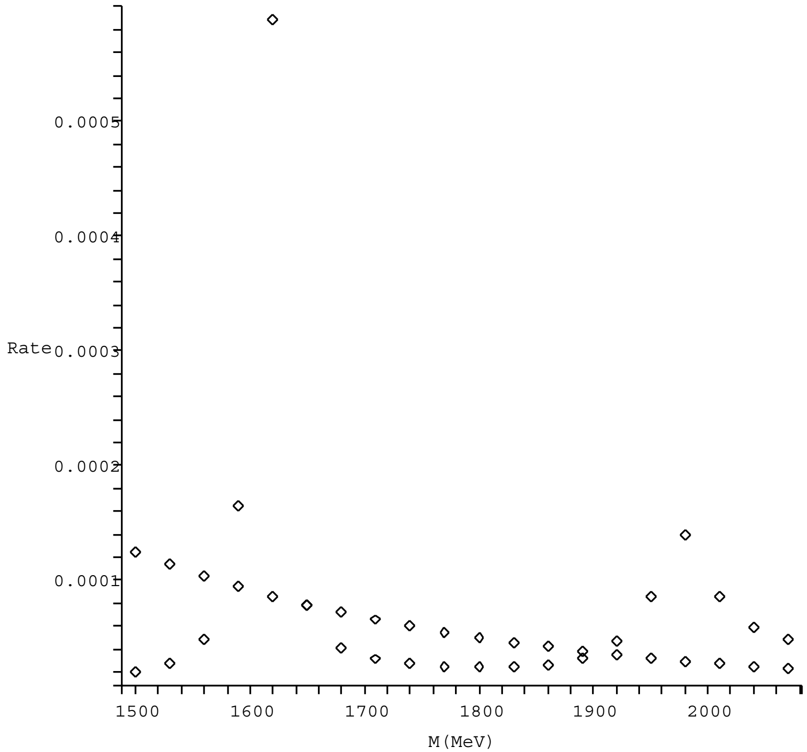
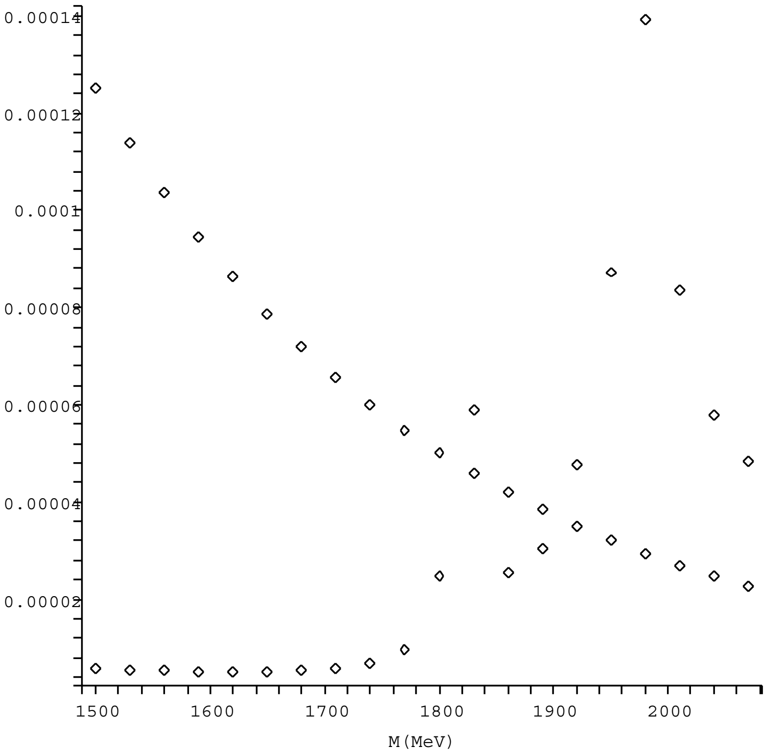


How those states/bumps look like after one integrates over the time?

Smooth curves are wQGP or ``standard candle" with massless free quarks

Curves with peaks are for longitudinal (left) and transverse (right) ρ,ω





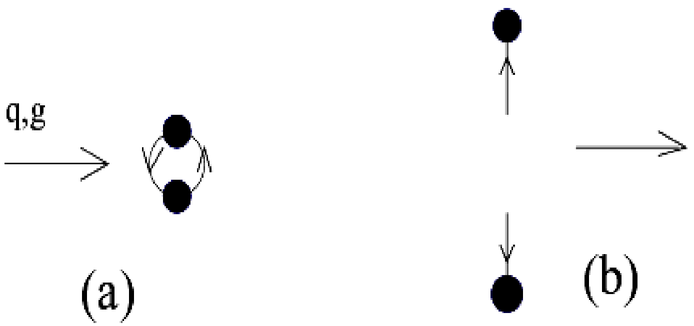
Jet quenching by ``ionization” of new bound states in QGP?

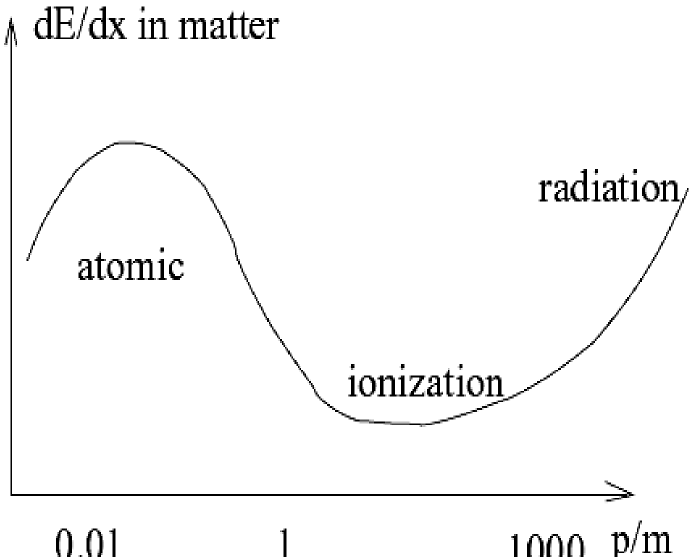
- Can we observe (much more multiple) colored states directly?

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

Cannot work in hadronic phase - cofinement

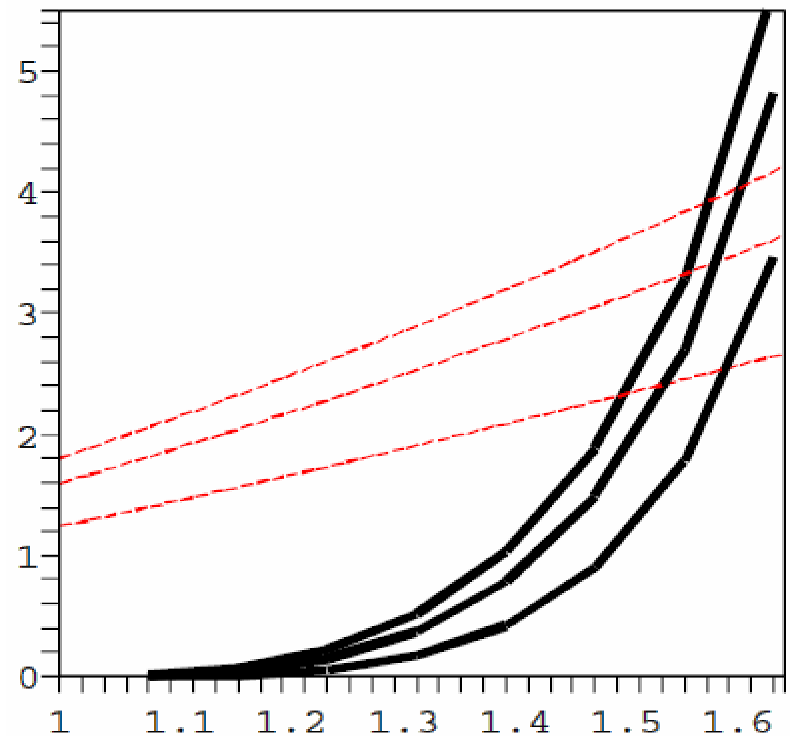
If it is true, the ‘‘lost energy’’ can never be recovered (unlike for radiative losses)





Calculation of the ionization rate ES+Zahed, hep-ph/0406100

- Smaller than radiative loss if L>.5-1 fm
- Is there mostly near the zero binding lines,
- Thus it is different from both radiative and elastic looses, which are simply proportional to density
- Relates to non-trivial energy dependence of jet quenching (smaller at 62 and near absent at SPS)



dE/dx in GeV/fm vs T/T_c for a gluon 15,10,5 GeV. Red-elastic, black -ionization

Conclusions:

we found at RHIC not what we expected but more (as Columbus)

- **QGP as a “matter” in the usual sense, not a bunch of particles, has been produced at RHIC**
- **Lattice EoS is about confirmed, $\Delta\ \varepsilon$ ¼ .8 GeV/fm^3. QGP seems to be the most ideal fluid known**

  η/s » .1

- **=> QGP at RHIC is in a strong coupling regime => New spectroscopy: many old mesons plus hundreds of exotic colored binary states.**
- **Dileptons is a way to measure masses of qs and the strength of their interactions, via resonances and near-threshold bumps**

Additional slides

Digression 3:

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

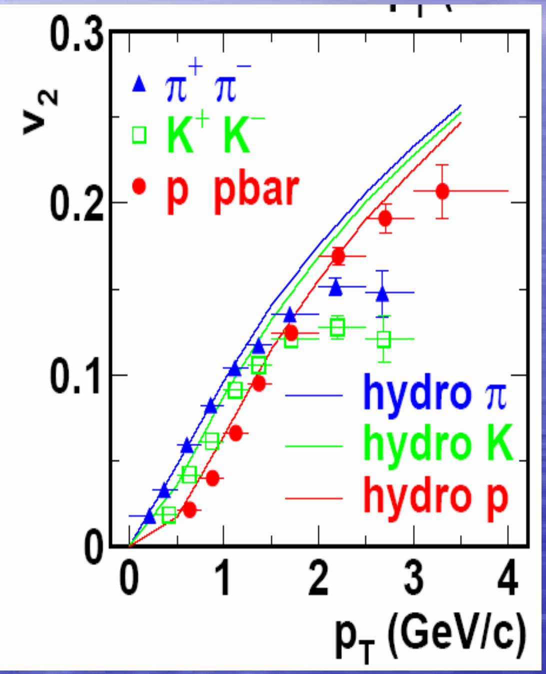
$$R = Ar^{s_+} + Br^{s_-}, \qquad s_\pm = -1/2 \pm \sqrt{1/4 - \alpha^2} \qquad (11)$$

that for $\alpha \to 1/2$ 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).

(Back to the main track)
Flows, especially the Elliptic Flow

PHENIX, PRL91('03)182301.



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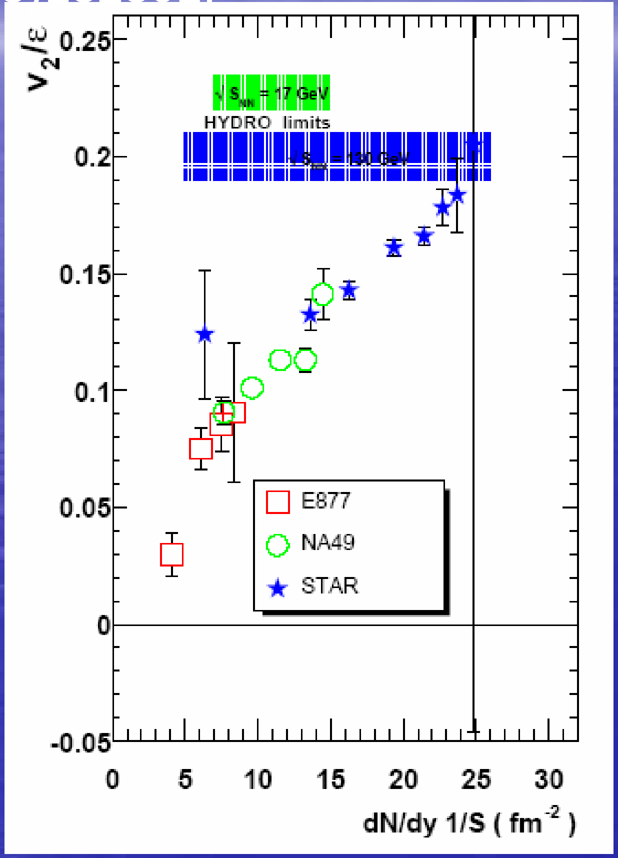


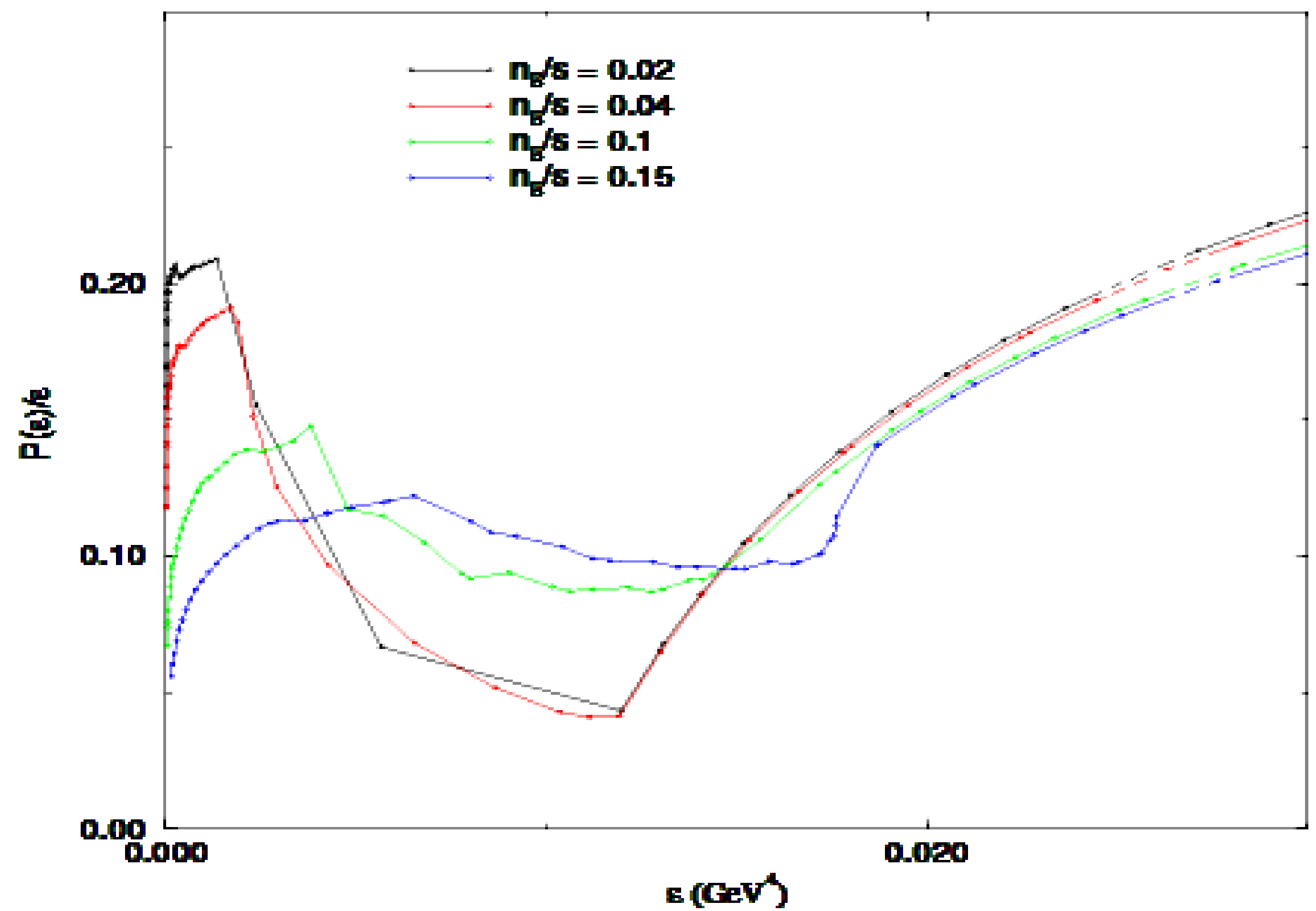
Elliptic flow rapidly rises with energy Because we have surpassed ``The softest point" and Entered the QGP with high p/ε ratio!

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

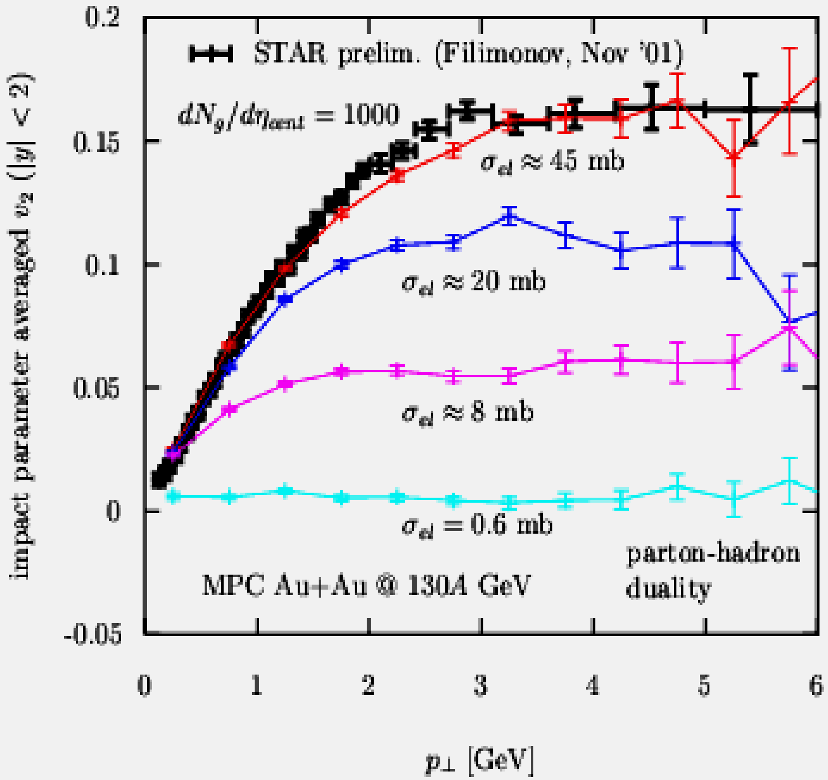
EoS along fixed n_B/s lines

M.Hung,ES,hep-ph/9709264,prc.

RHIC



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 $\times 1000$)**

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

(D.Teaney,2003)

Viscosity of QGP

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

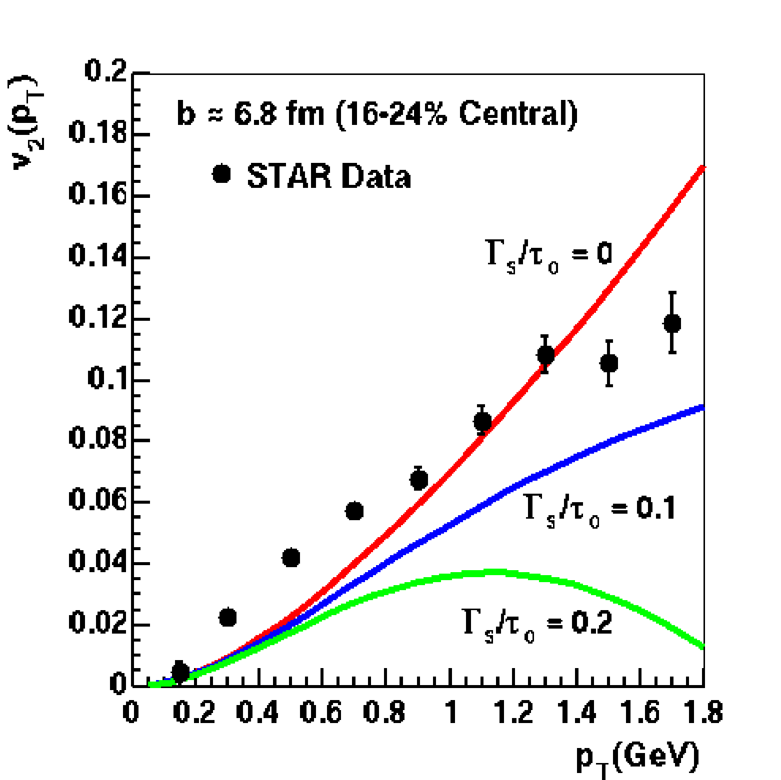
- viscous corrections

1st order correction to dist. fn.:

$$\text{Corr» } (\eta/s)p_t^2$$

Γ_s :Sound attenuation length

$=>\eta/s$ ¼ 1/10



Nearly ideal hydro !?

Digression 2, a 1980's motivation why we thought we should collide heavy ions, or:

The QCD vacuum vs the QGP

- The ``physical vacuum" is very complicated, dominated by ``topological objects", Vortices, monopoles and instantons
- Among other changes it shifts its energy down as compared to an "empty" vacuum,

The Bag terms, $p=\#T^4-B$

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

- The QGP, as any plasma, screens them, and is nearly free from them
- 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)

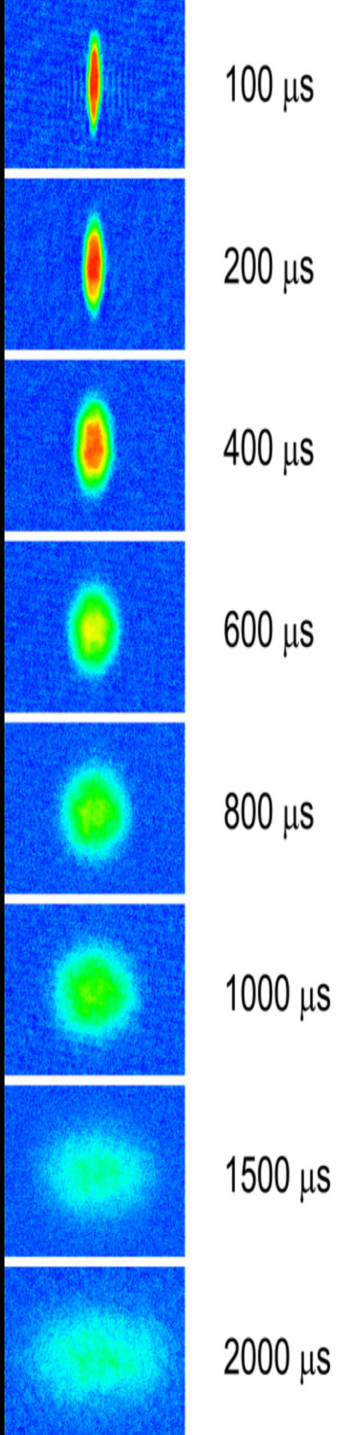
Resonance enhancement near zero binding lines: Explanation for large cross section? (ES+Zahed,03)

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?



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

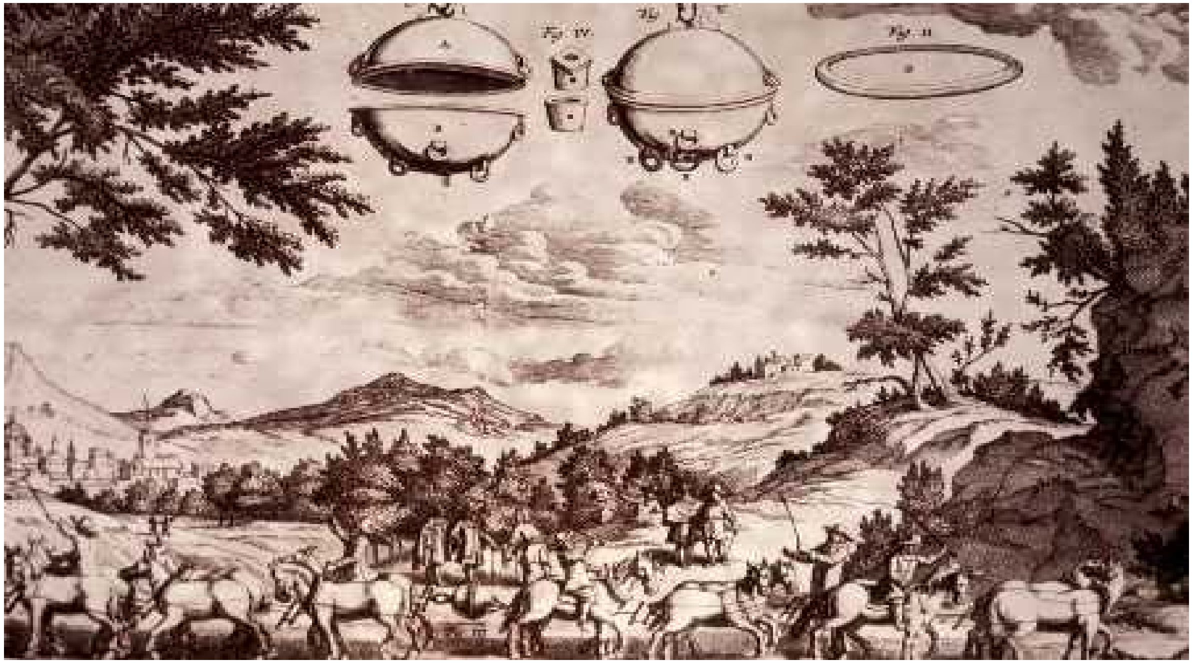
Micro-Bang !

Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime

The system is extremely dilute, but can be put into a hydro regime, with an elliptic flow, if it is specially tuned into a strong coupling regime via the so called Feshbach resonance

- **Although the cross section changes by huge (» 10^6) factor, the EoS is only changed by (once again!) 20%!**

Magdeburg hemispheres 1656



- We cannot pump the QCD vacuum out, but we can pump in something else, namely the Quark-Gluon Plasma

- QGP was looked at as a much simpler thing, to be described by pQCD. **We now see it is also quite complicated matter, sQGP...**

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**

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)

The phenomenon of the Adiabatic capture

- Very recent important discovery with trapped Li atoms

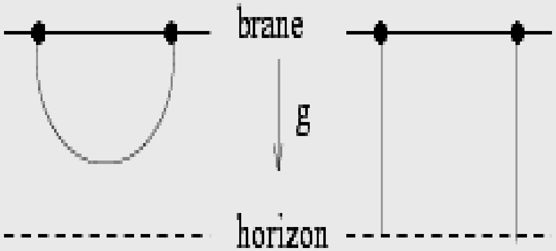
J.Cubizolles et al, cond-mat/0308018, K.Strecker et al,cond-mat/0308318 all in PRL

- If one changes the magnetic field so that the molecular level moves from unbound into bound domain, nearly all atoms (~ 85 percents) are turned into Li_2 molecules, all of course in the same relative state near zero.
- Only a bit more cooling is needed to get BEC of molecules
- The phenomenon is reversible which proves that no entropy is produced: going back one finds molecules dissolved
- Going further into the bound region one finds that binding energy goes into heating the gas

- The adiabatic path in heavy ion collision also crosses the no-biding line in this direction.
- the reheating was predicted as a zig-zag path on the phase diagram
- Can the "hadronization" happen at this line, not at $T = T_c$?
- At least that would be enough to explain why we do not see large fluctuations related to quasi-first order transition: no "clumps", the matter remains homogeneous at all times

Unexpected help from the string theorists, 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)

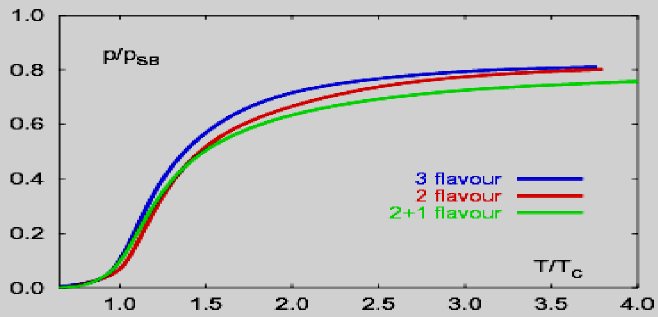


$$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$$

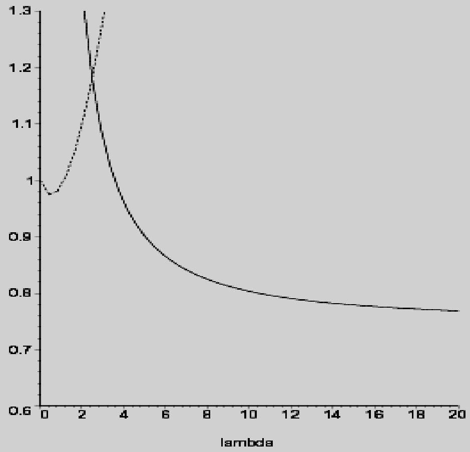
- becomes a sreened potential at finite T

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...)



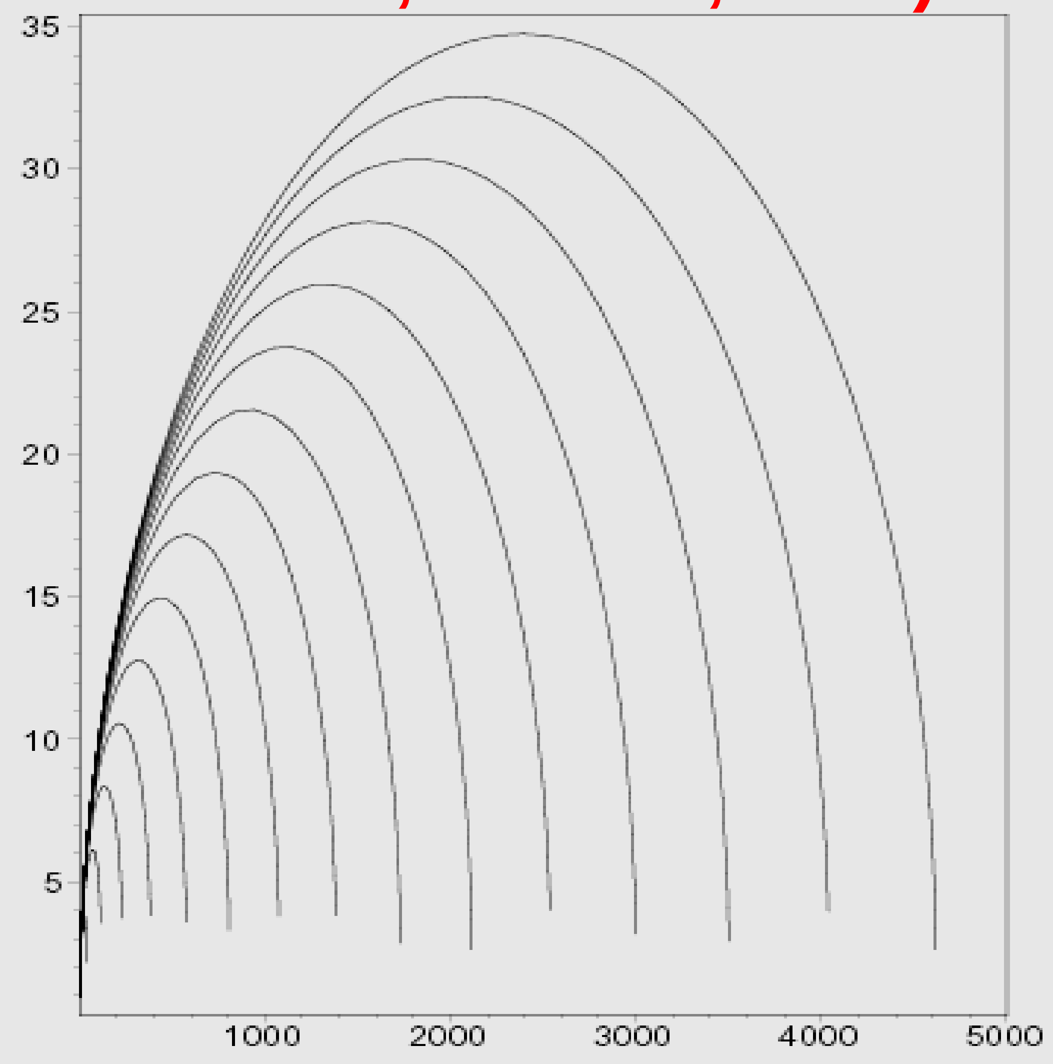
- Lattice results (Bielefeld group) for QCD thermodynamics: pressure normalized to Stephan-Boltzmann value



- 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 $\lambda = g^2N$.

The viscosity/entropy => η/s=1/4π (Policastro,.Son,Starinets, 2003) is very small

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



Effective coupling=g^2 N(colors)

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

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

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