NSAC heavy ion subcom., June 2-3 2004

Evolution of RHIC physics (from a theory perspective)

Edward Shuryak
Department of Physics and Astronomy
State University of New York
Stony Brook NY 11794 USA

Outline of the talk

In real time order:

- sQGP: photons, dileptons
- Intermediate p_t and jet quenching
- Hydro and EoS works: QGP has remarkably small viscosity
- Freezeouts: resonances, HBT and corr.of nonidentical hadrons
- Connection to strongly coupled atoms, N=4 SUSY
- Connections to wider QCD issues: spin and diffreaction

A field in transition:

• Strongly coupled QGP and New Spectroscopy

•Multiple bound states, 90% of them colored? If so, it explains several puzzles related to lattice results, as well as small viscosity observed

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)

Digression 1, my 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,

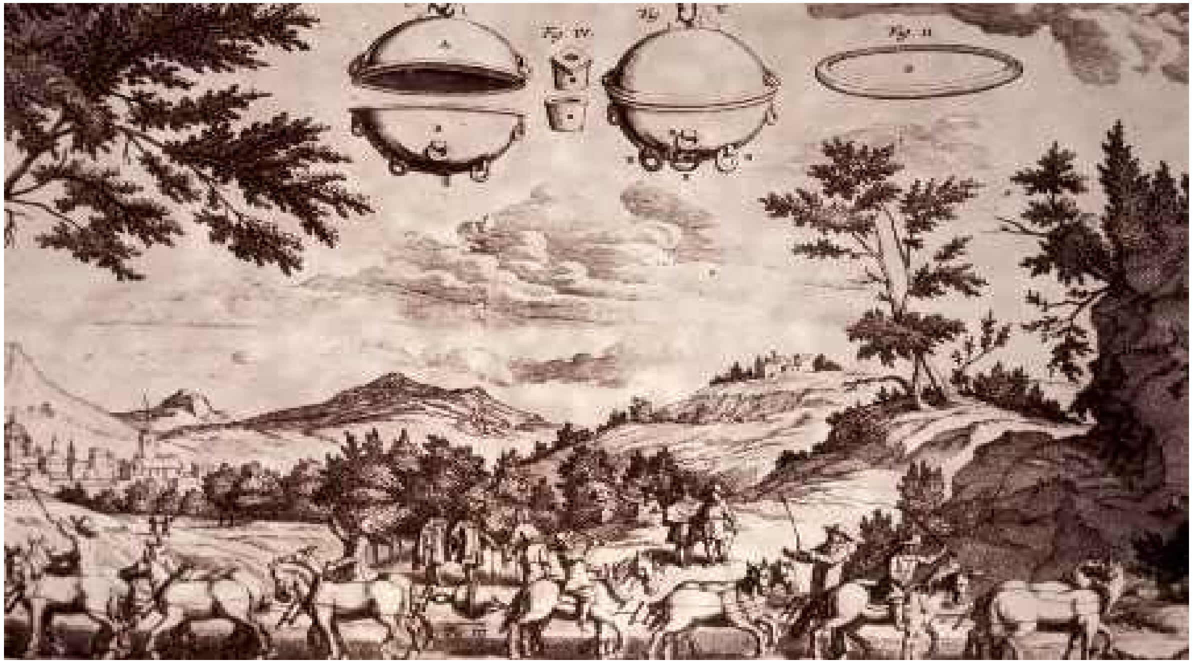
The Bag term, $p=\#T^4-B$

$\varepsilon=\#T^4+B$ is our Dark Energy

- The QGP, as any plasma, screens them, and is nearly free from them
- So, when QGP is produced, the vacuum tries to expel it

Magdeburg hemispheres 1656

(recall here pumped out Magdeburg hemispheres By von Guericke in 1656 we learned at school)



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

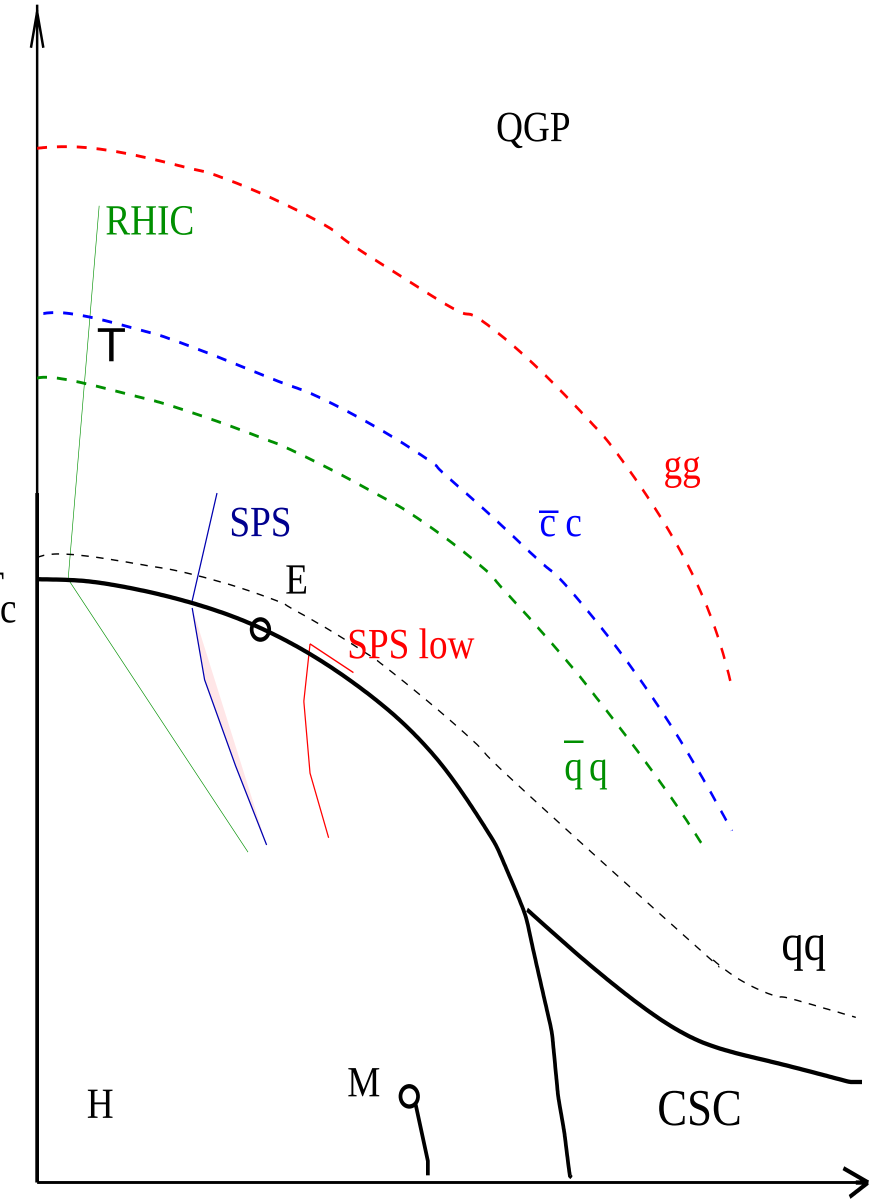
- **QGP was looked at as a much simpler thing, to be described by pQCD. We now see it is also rather complicated matter, sQGP…**

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…



Our map is the QCD Phase Diagram, which includes ``zero binding lines" (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

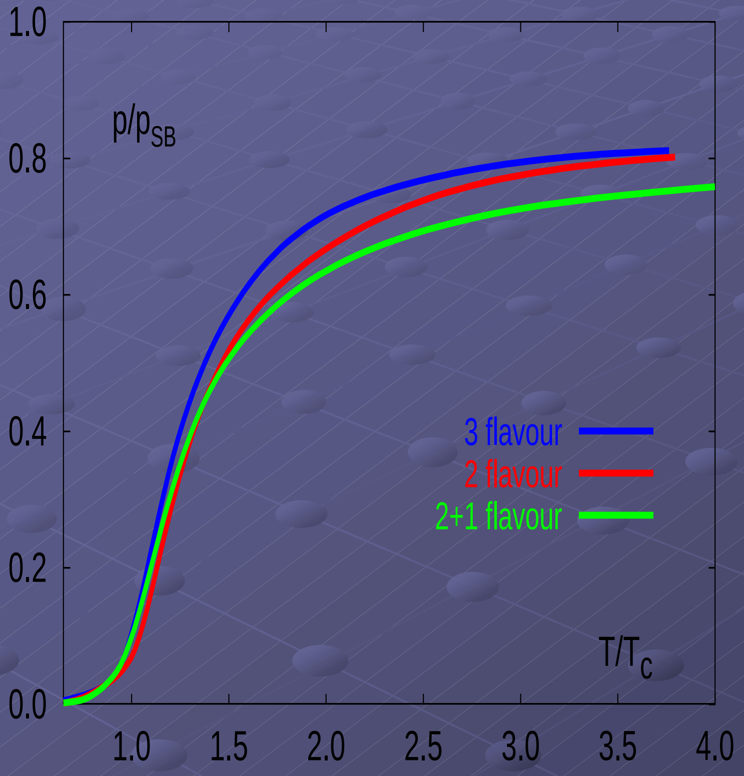
(Large puzzle to be discussed: Why does QGP flow?)

But we start with lattice puzzles

- Since Matsui-Satz and subsequent papers it looked like even J/\psi,\eta_c dissolves in QGP (thus the QGP signal)
- And yet recent works (Asakawa-Hatsuda,Karsch et al) have found, using correlators and MEM, that they survive up to T\approx 2.5 Tc . What went wrong?

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**

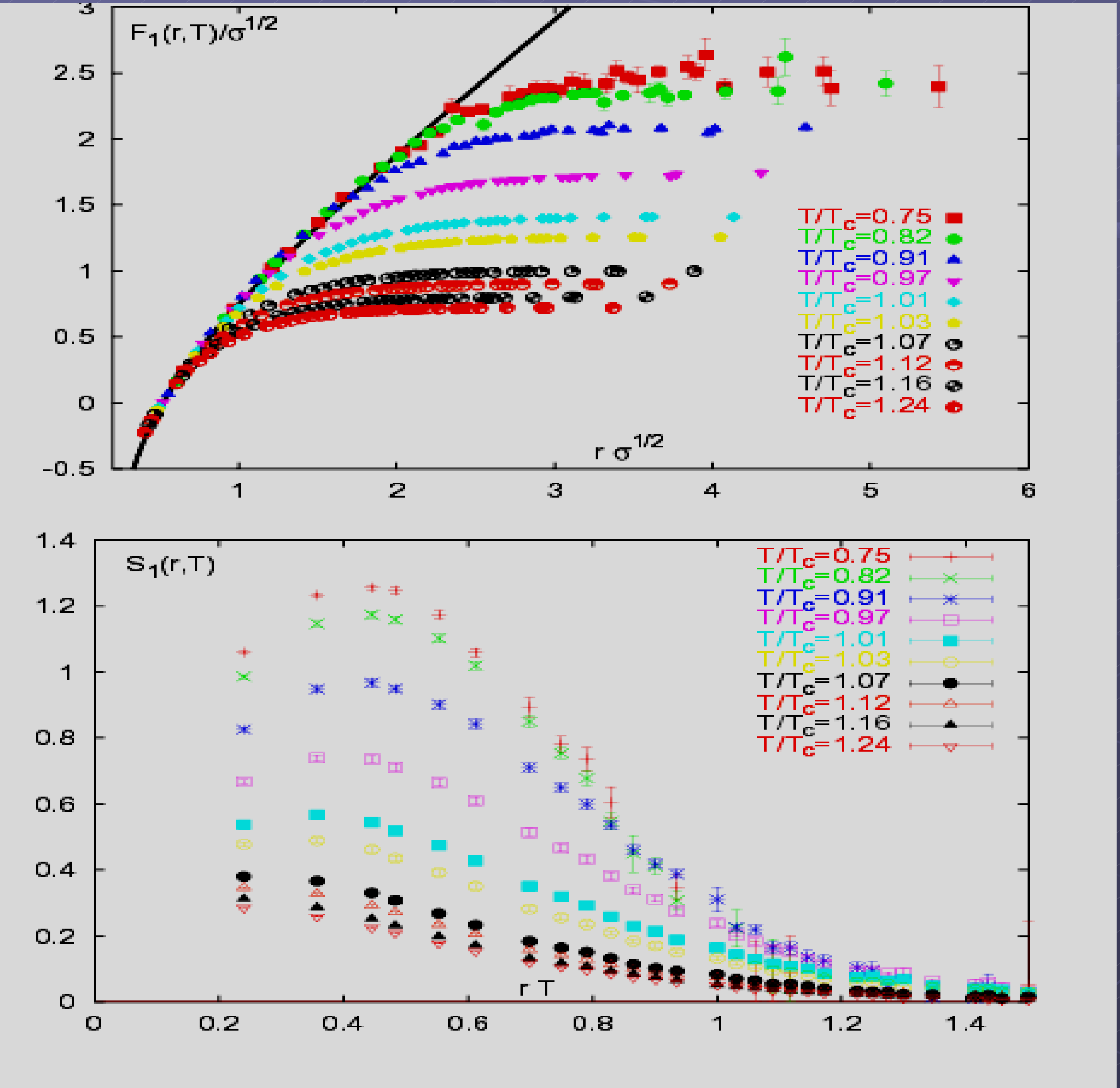
- p/p(SB)=.8 from about .3 GeV to very large value. Interpreted as an argument that interaction is relatively weak (0.2) and can be resumed, although pQCD series are bad...

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

(The pressure puzzle, cont.)

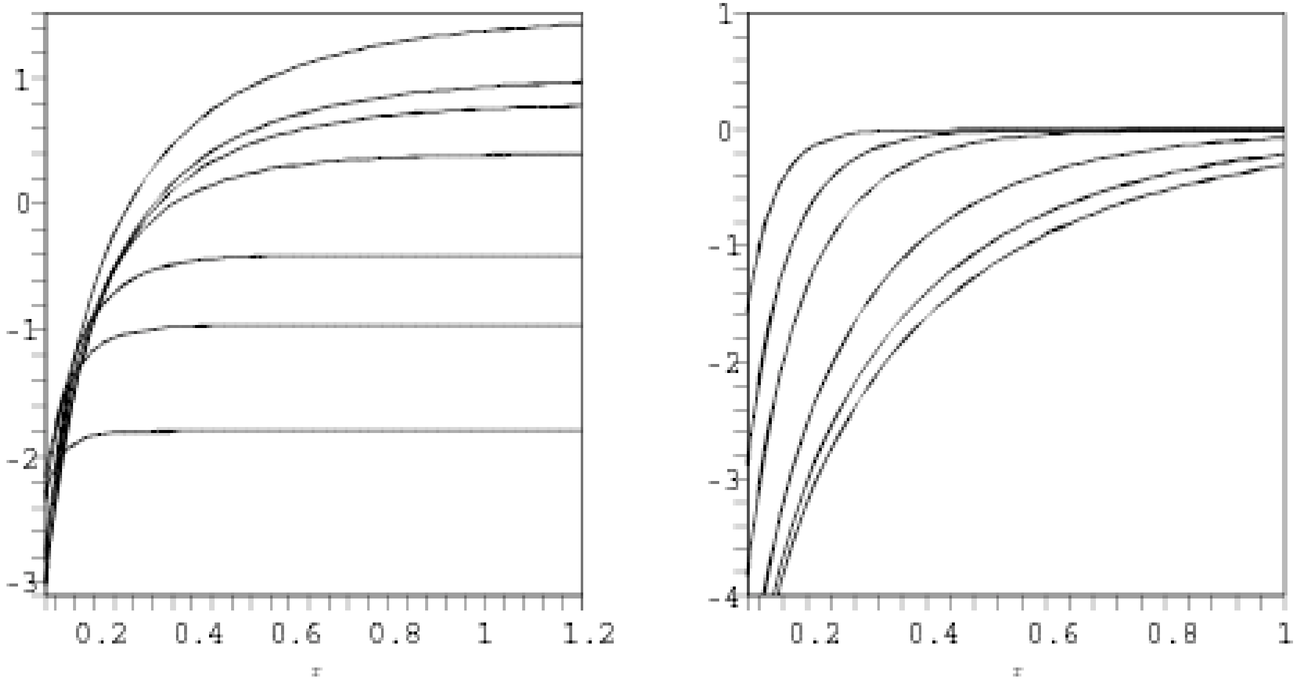
- How quasiparticles, which according to direct lattice measurements are heavy (Mq,Mg = 3T) (Karsch et al) can provide enough pressure? (exp(-3)»1/20)
- (The same problems appears in N=4 SUSY YM, where it is parametric, exp(-$\lambda^{1/2}$) for large λ´ g^2N_cÀ 1)

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**

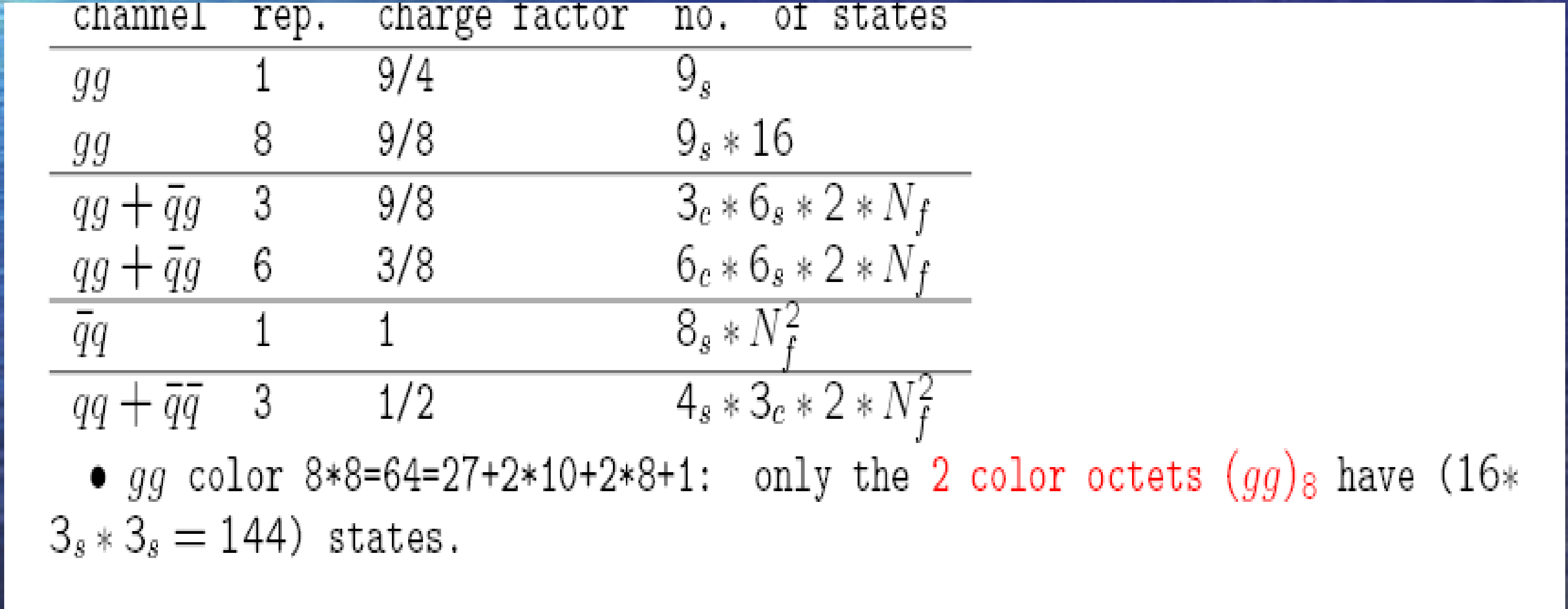
New potentials (cont): after the entropy term is subtracted, potentials become much deeper



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

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

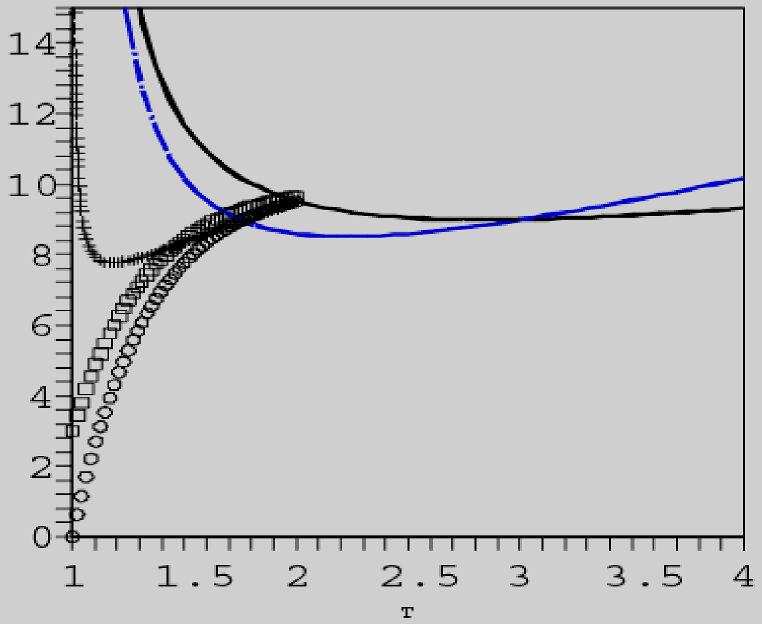
- **In QGP there is no confinement => Hundreds of colored channels may have bound states as well!**



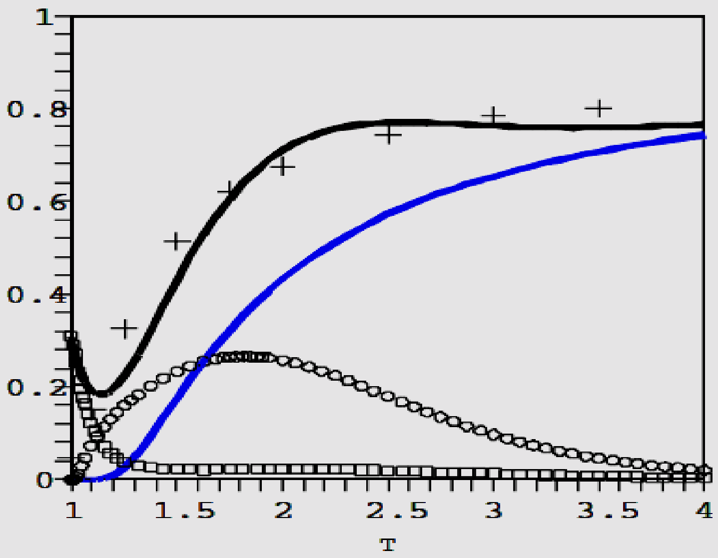
channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

- 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.

These puzzles seem to be 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).

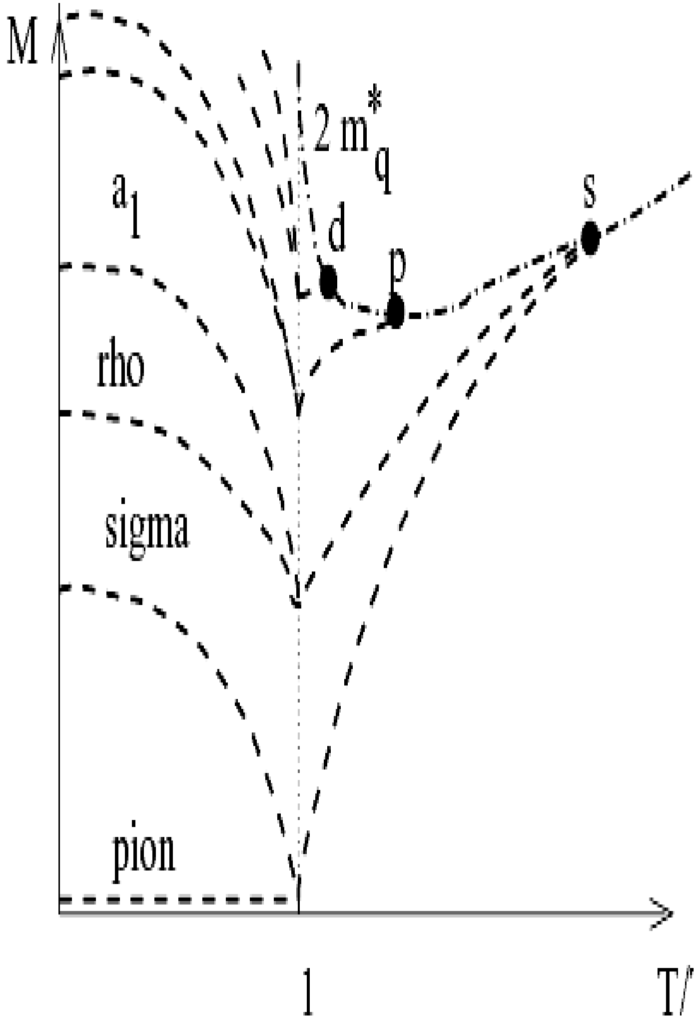
Early time:
The penetrating probes, γ, $l^+ l^-$

- Are there quarks at early time or only classical glue ? =>
- Vector mesons are still there in QGP, in spite of deconfinement
- Their longitudinal component is lighter than the transverse one (Brown,Lee,Rho,ES)
- They are degenerate with axial ones, rather there are L, R-handed ones=>

$$\bar{L}\gamma_\mu L, \bar{R}\gamma_\mu R$$

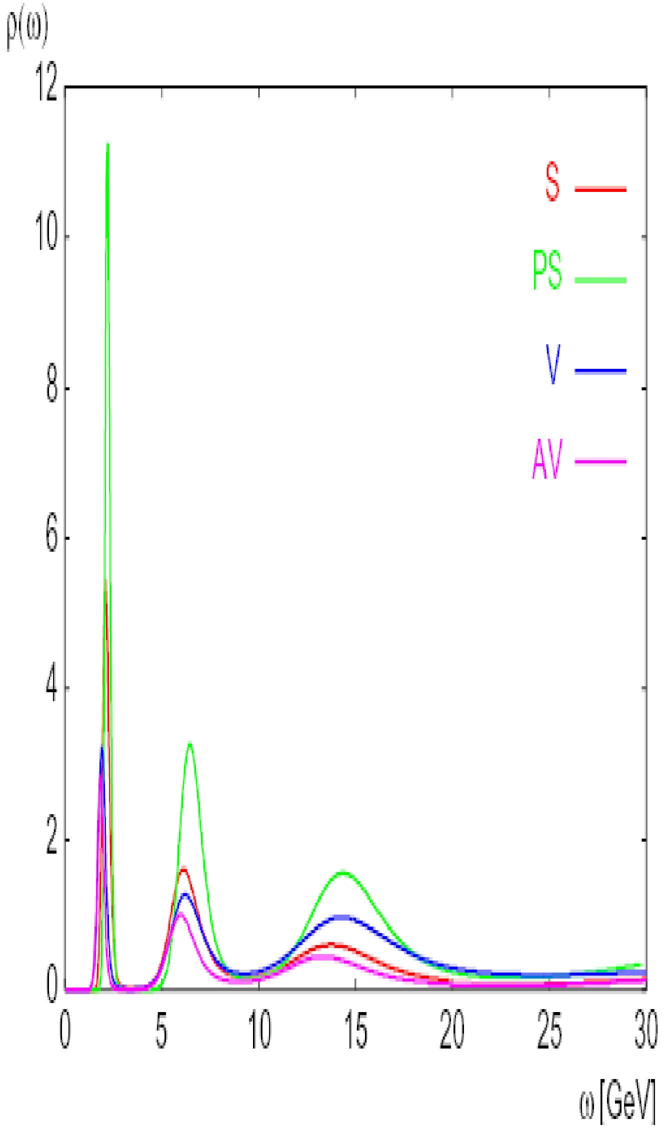
Dileptons from new bound states in QGP?

- 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



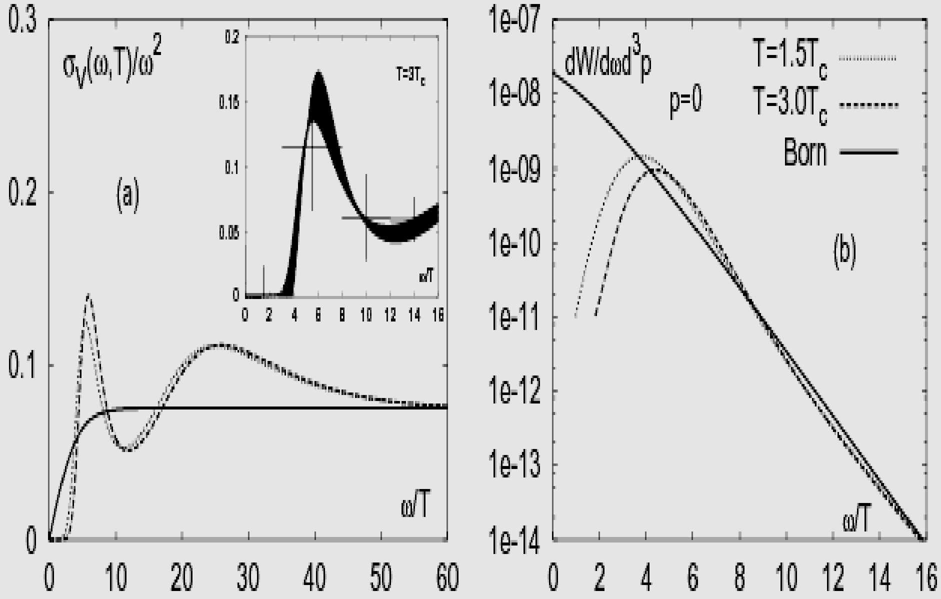


Figure 2: Reconstructed vector spectral function σ_V in units of ω^2 at zero momentum (a) and the resulting zero momentum differential dilepton rate (b) at $T/T_c = 1.5$ (doted line) and 3 (dashed line). The solid lines give the free spectral function (a) and the resulting Born rate (b). The insertion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

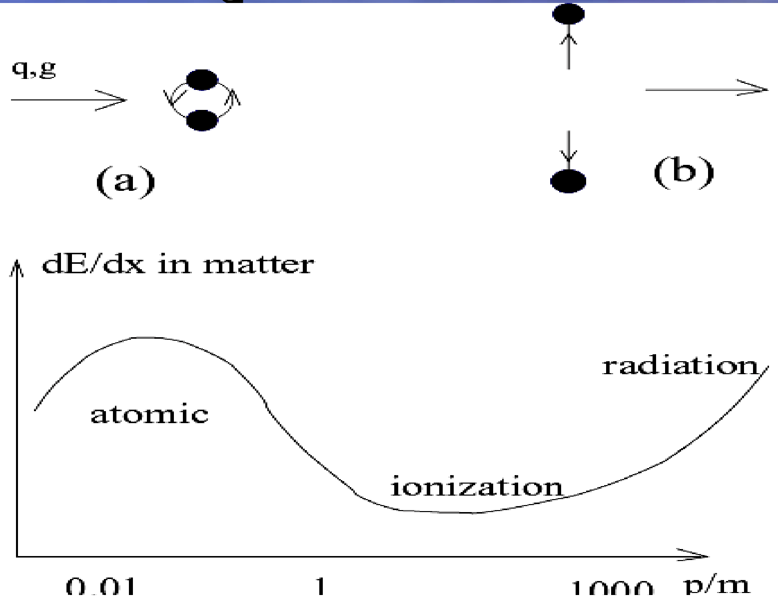
Jet quenching by ``ionization" of new bound states in QGP?

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

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

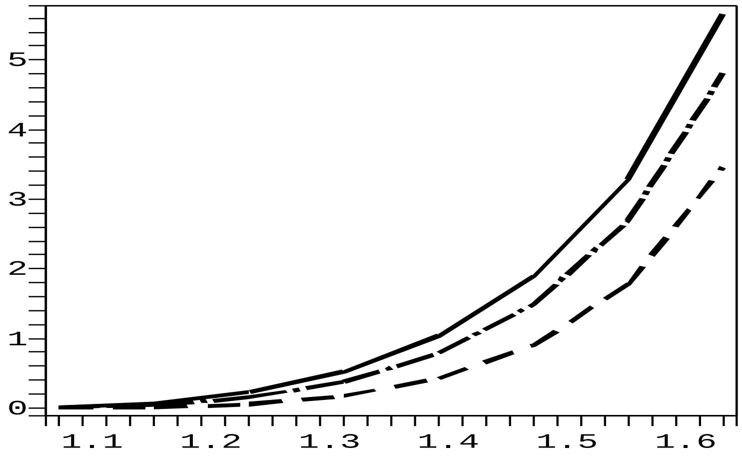
Cannot work in hadronic phase – cofinement

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



Preliminary results for ionization Losses, dEdx (GeV/fm) vs T/Tc, For gluon jet with 15,10,5 GeV

Losses are NOT in the forward cone!



The main result from ``soft” ($p_t$<2 GeV) physics at RHIC: AuAu 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)

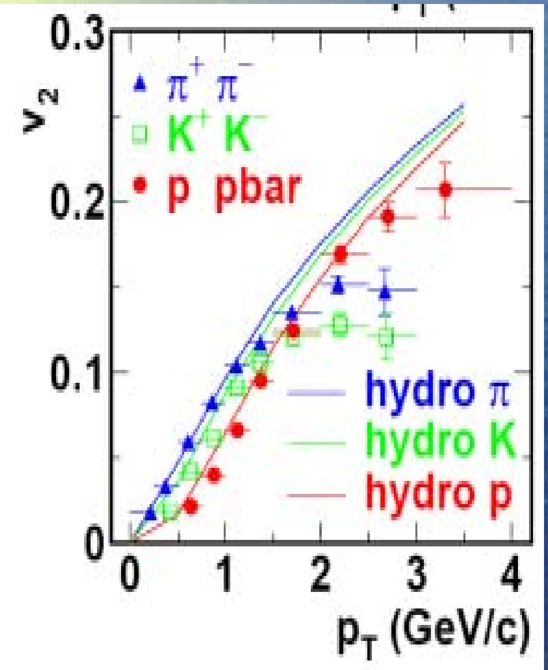
Good equilibration (including strangeness) is seen in particle rations (as at SPS)

- **the zeroth order in l/L is called an ideal hydro with a local stress tensor.**

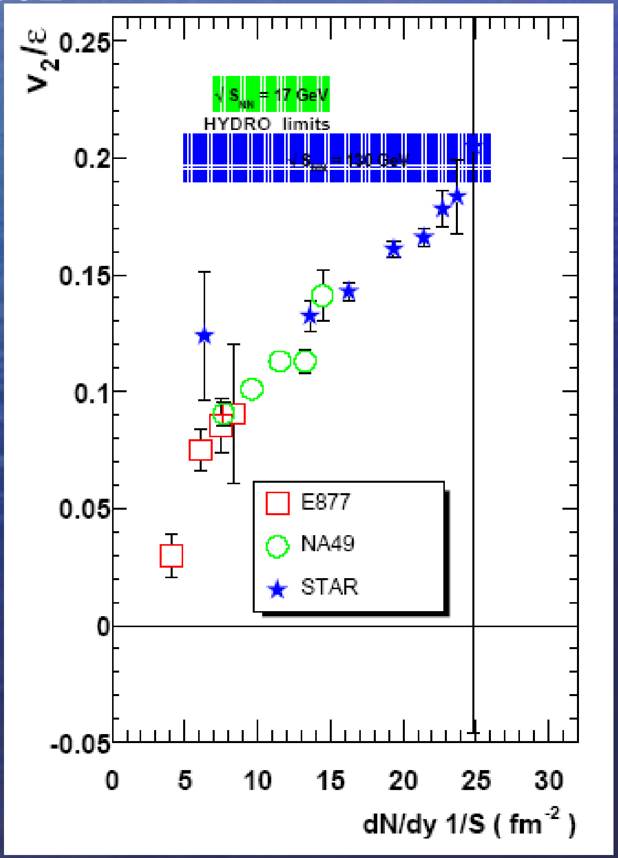
- **Viscosity is the first order O(l/L) effect, » velocity gradients. Note that η» l» 1/σ n is inversely proportional to the cross section and is (the oldest) strong coupling expansion tool**

How do we know that? From very robust collective flows, especially the Elliptic Flow $v_2=<\cos(2\phi)>$ well described by hydrodynamics

PHENIX, PRL91('03)182301.



STAR, PRC66('02)034904



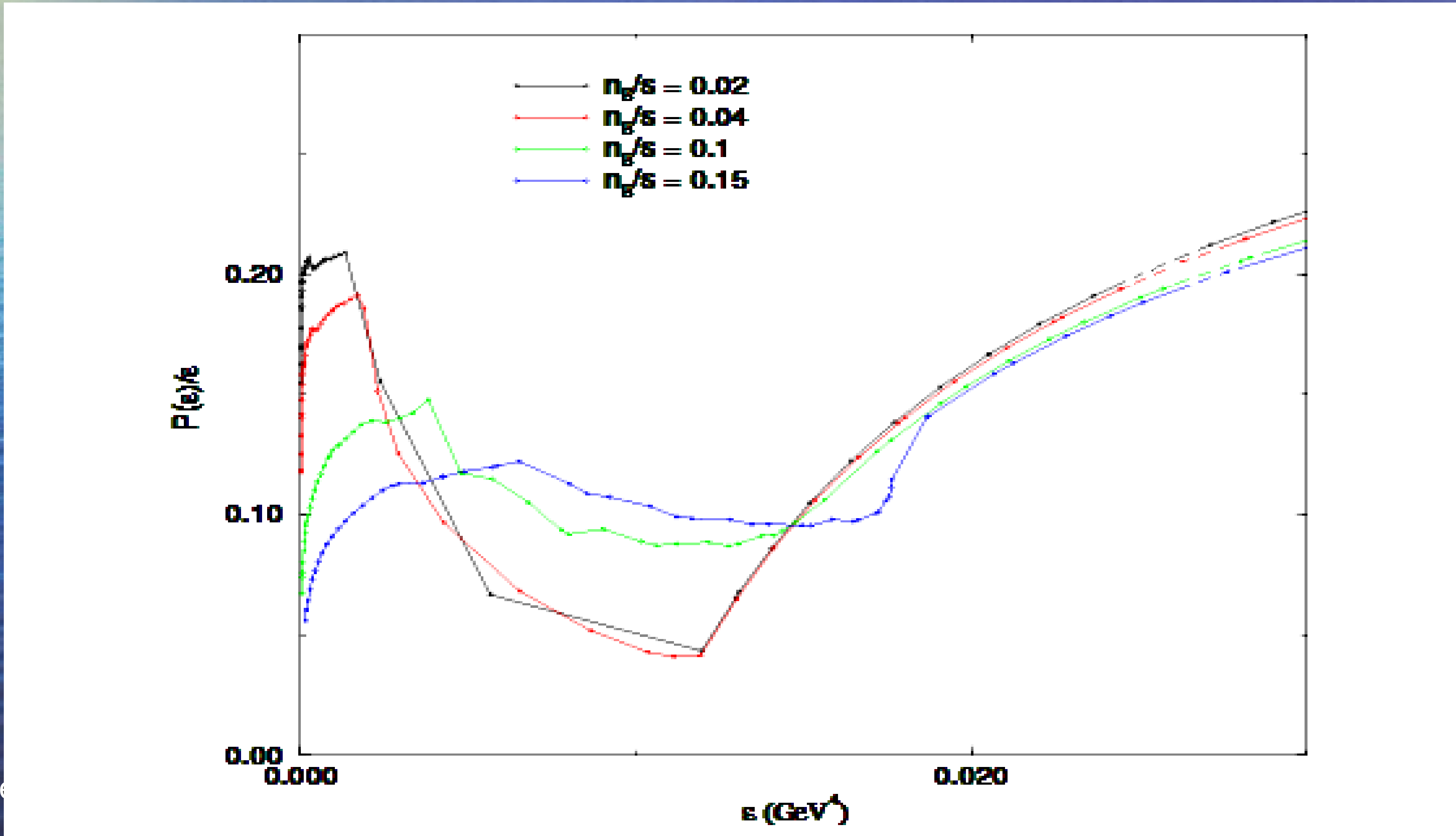
Elliptic flow rapidly rises with energy Because we have surpassed ``The softest point" and Entered the QGP with high p/ε ratio!

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

EoS along fixed n_B/s lines

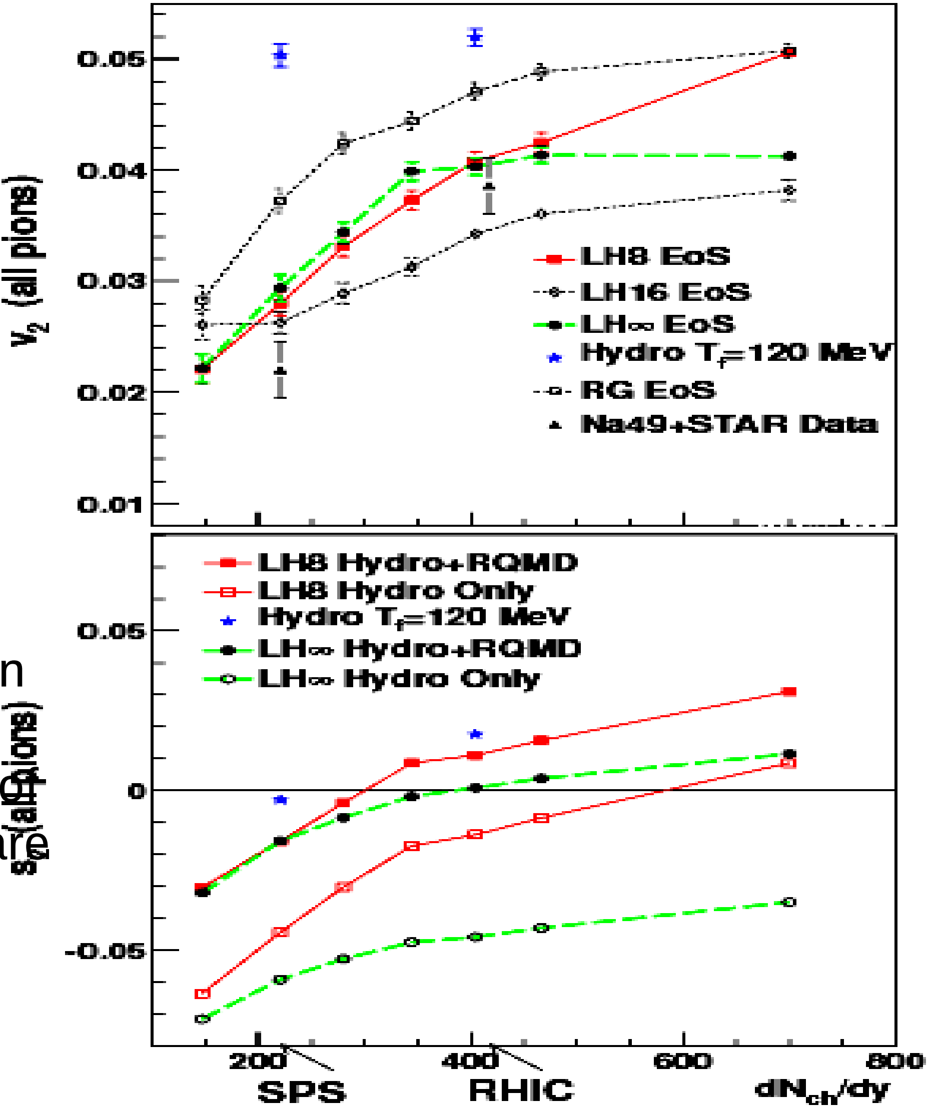
M.Hung,ES,hep-ph/9709264,prc.

RHIC



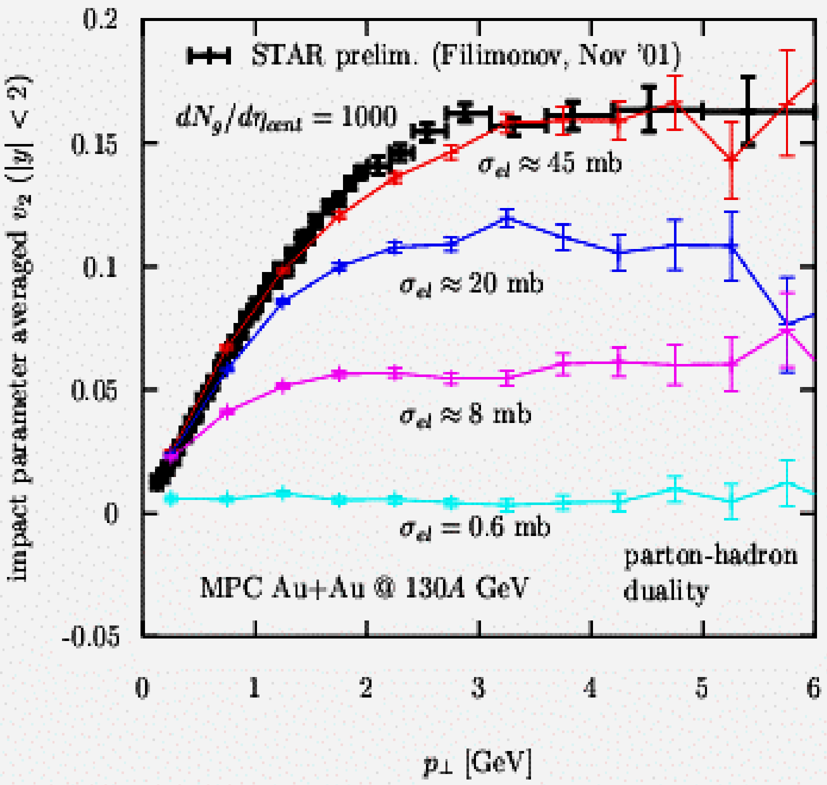
Next goal is to fix the EoS (p(ε)) and viscosity (η(ε)):

- In order to do so one has to study all flows a a function of collision energy and centrality



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

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

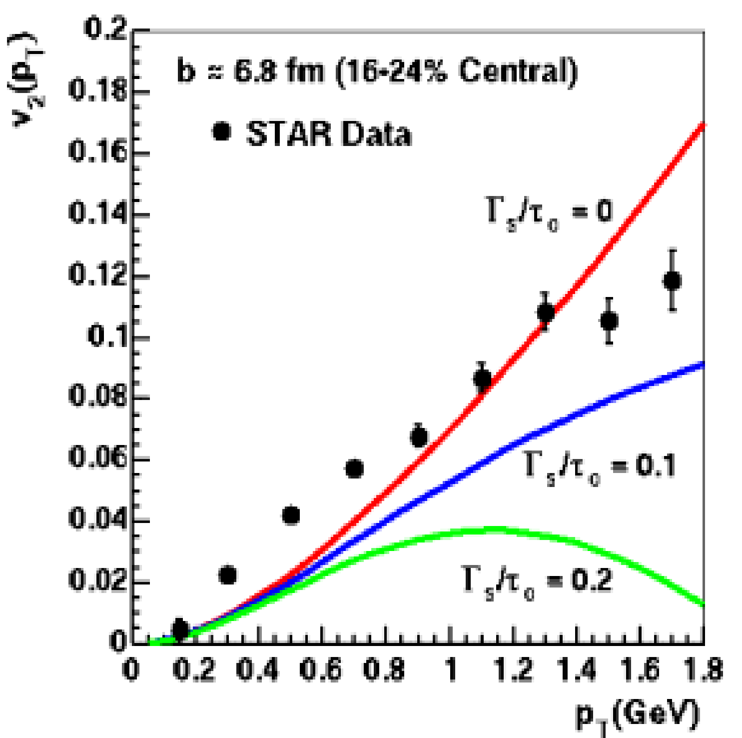
- viscous corrections

1st order correction to dist. fn.:

Corr» $(\eta/s)p_t^2$

=> η/s ¼ 1/10

The most ideal liquid ever seen?

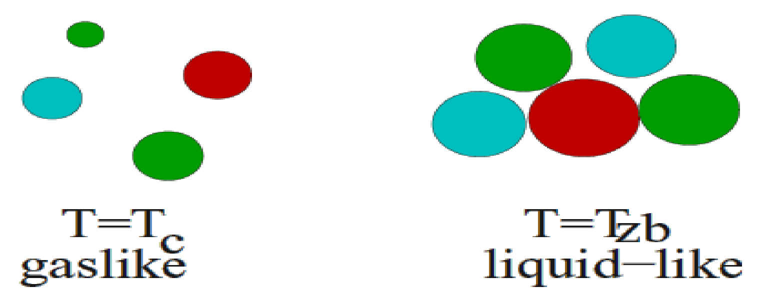


Intermediate p_t=(2-5) GeV: late (hydro) or early time?

- Baryons behave different from mesons: why?
- Proton-triggered jets are there (Phenix): so it is early time. Coalescence thus unlikely. (Di)quark knockout?
- How large is jet quenching? Hadron triggere is surface-biased. Photon-triggered jets are needed.
- Large v_2 close to its ``geometric limit” for surface emission (ES,2002)

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

Hadrons swell near z.b. lines and make a liquid:



This is how small mean free path (viscosity) and zero binding lines and can be related!

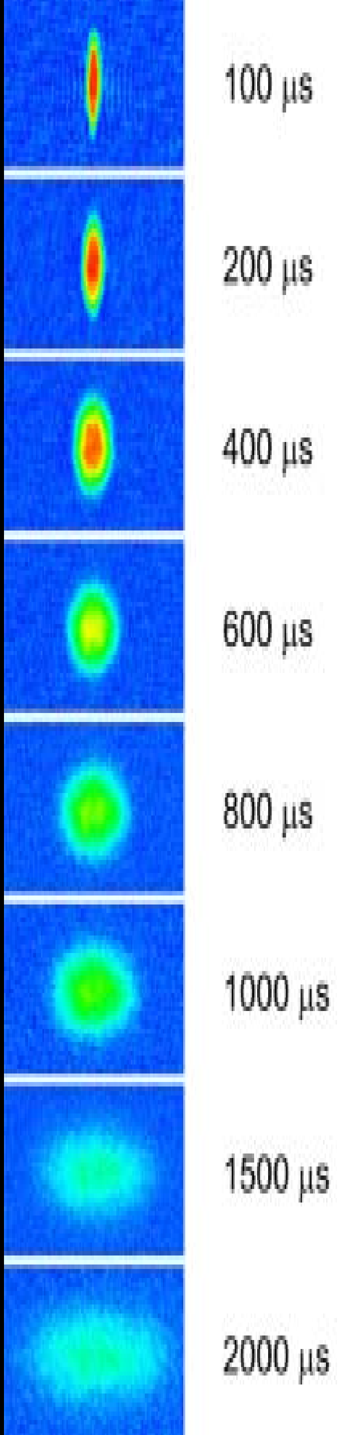
(SZ) (q.p.+ q.p. <=> bound state): a resonance

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

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 !



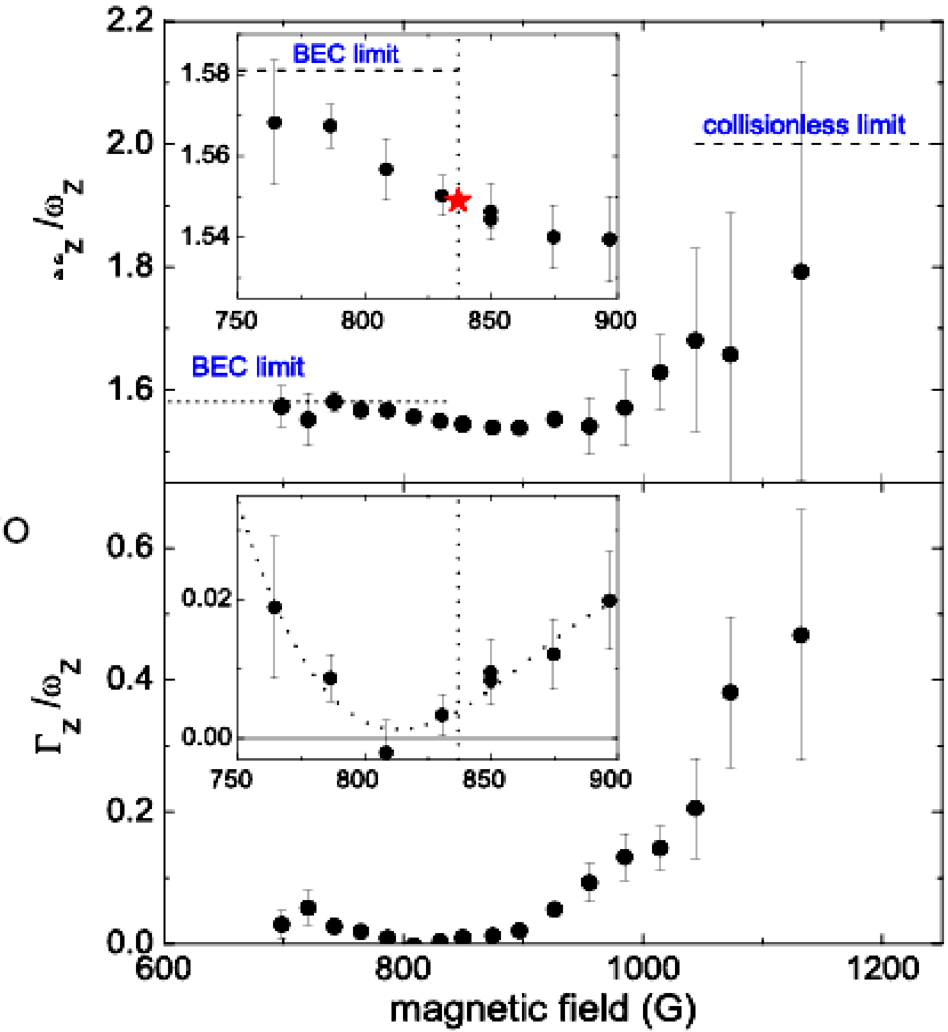
Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime

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%!**

Very recent studies of small oscillations reveals reduced damping and hydro frequency:

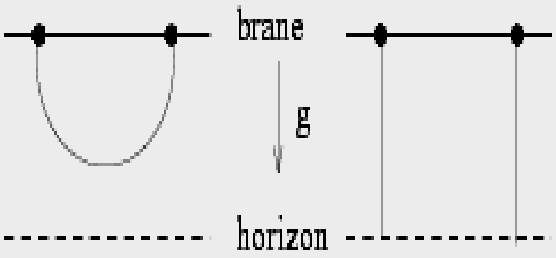
Bartenstein et al, cond-mat/0403716 (may 9th 2004) have studied small oscillations in lowest two modes.



Unexpected help from the string theorists, AdS/CFT correspondence

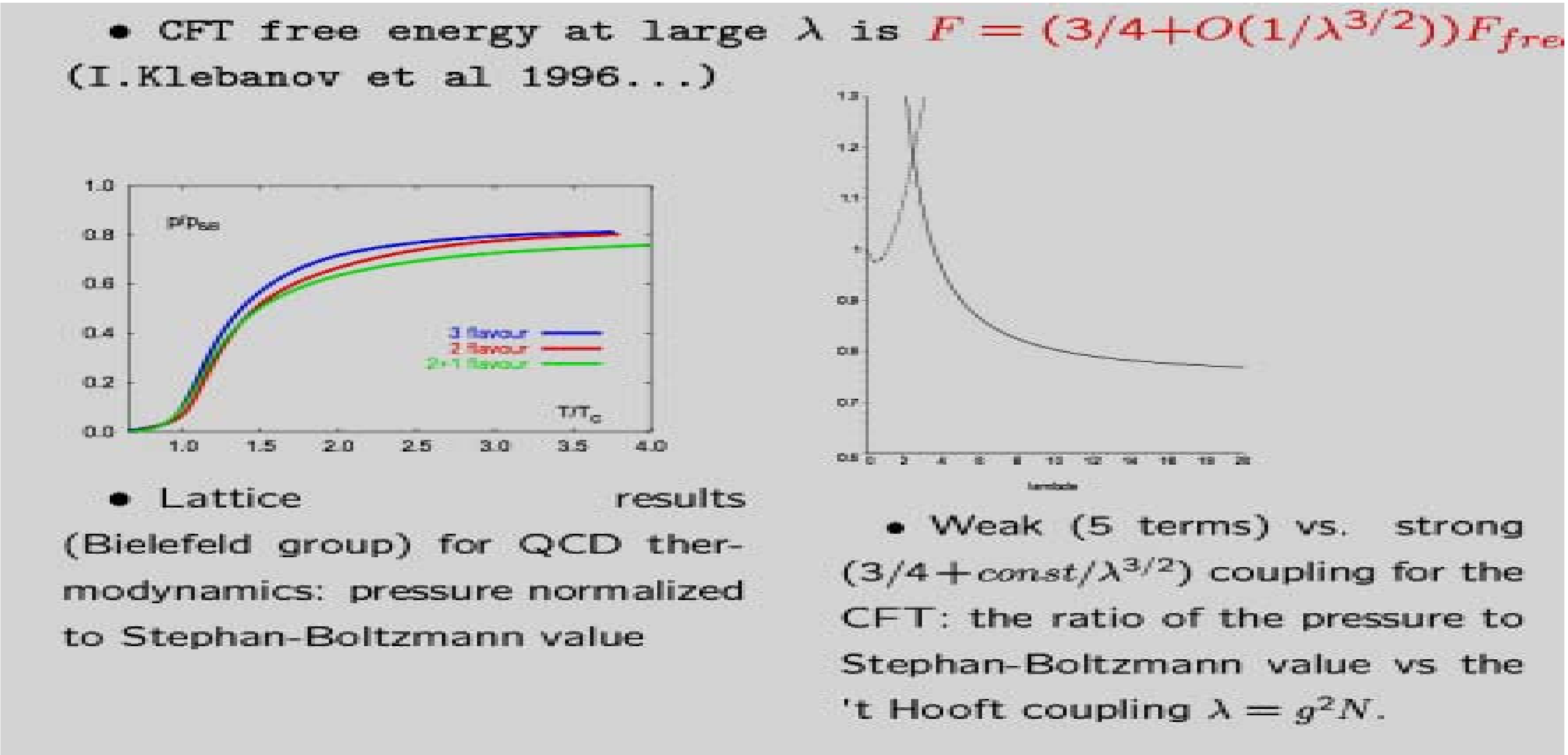
- The $\mathcal{N}=4$ SUSY Yang Mills gauge theory is conformal (CFT) (the coupling does not run). At finite T it is a QGP phase at ANY coupling. If it is weak it is like high-T QCD => gas of quasiparticles. What is it like when the coupling gets strong $\lambda = g^2 N_c \gg 1$?
- AdS/CFT correspondence 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:



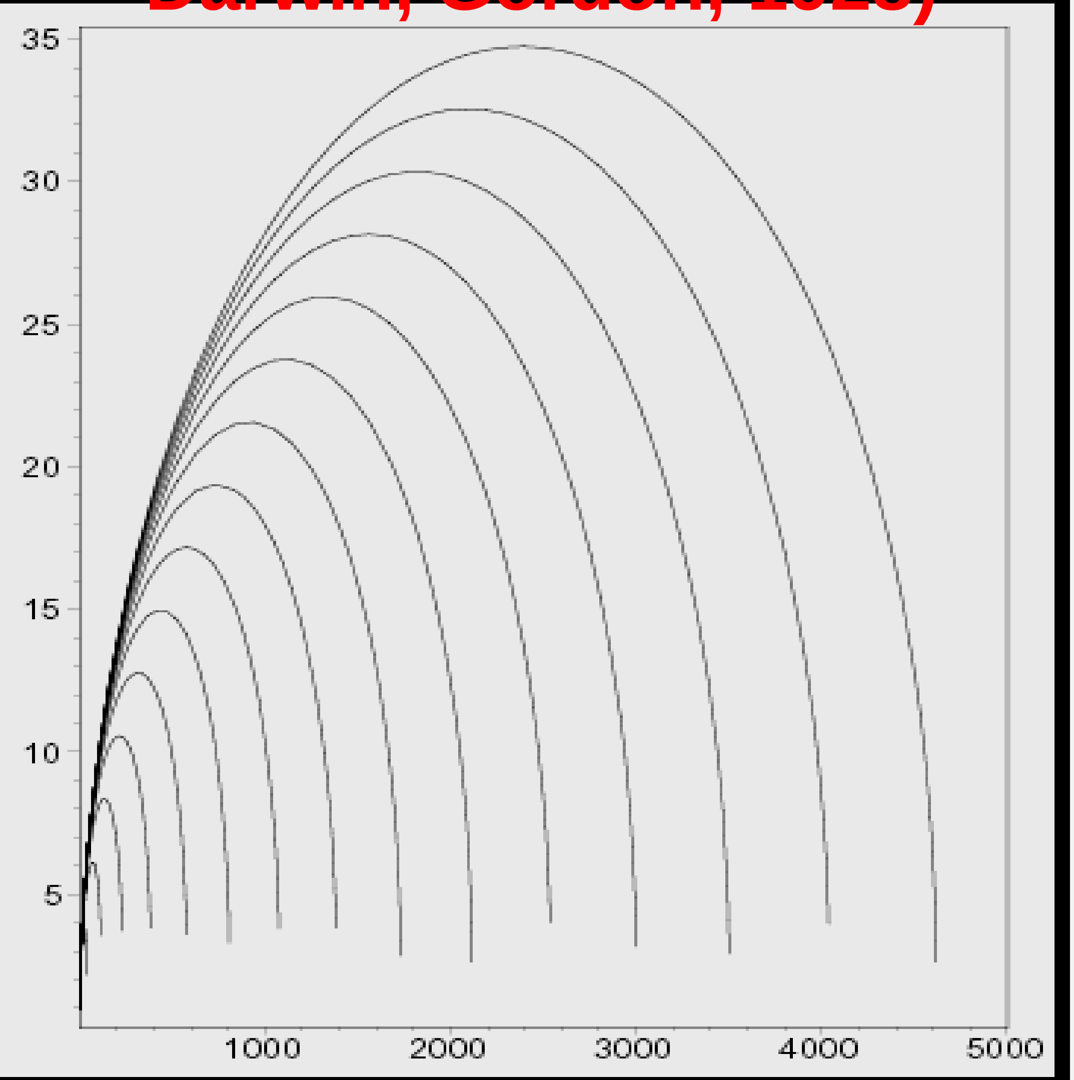
- CFT free energy at large λ is $F = (3/4 + O(1/\lambda^{3/2}))F_{fre}$ (I.Klebanov et al 1996...)

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

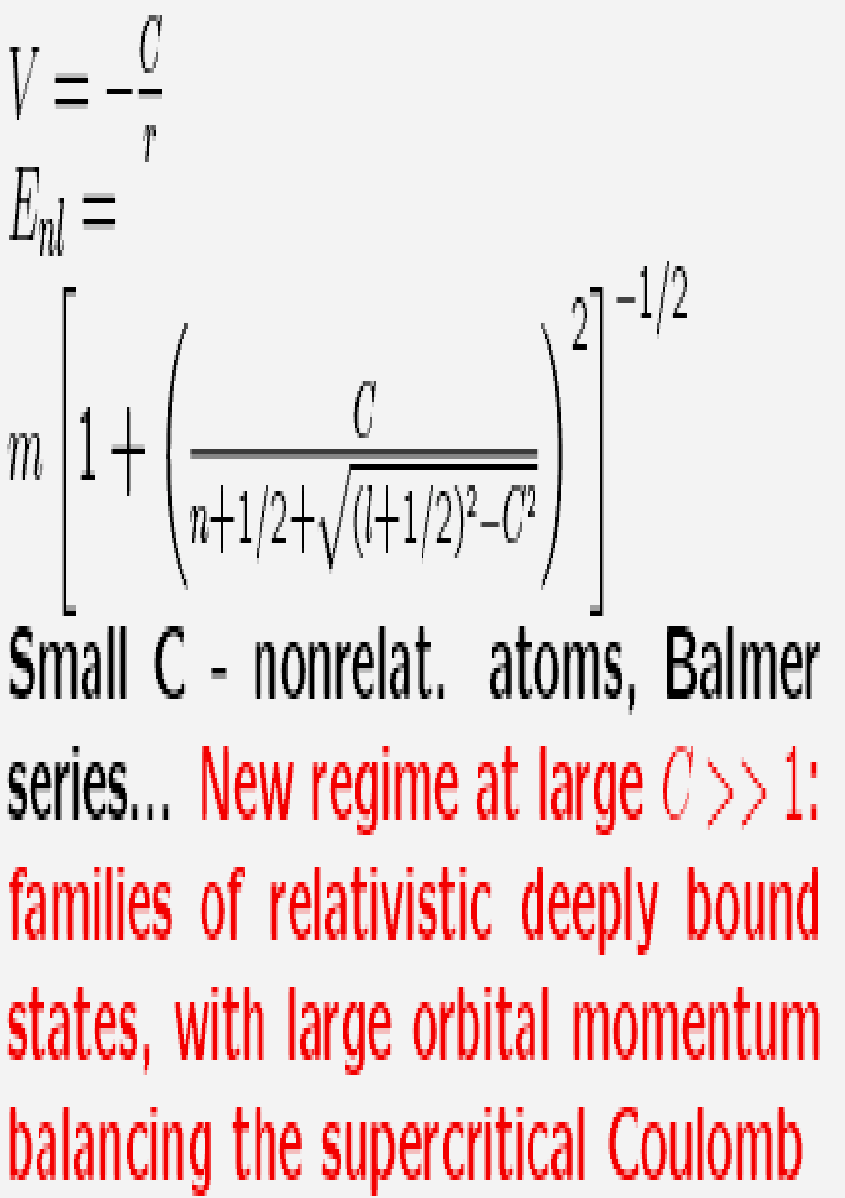
- Weak (5 terms) vs. strong ($3/4 + const/\lambda^{3/2}$) coupling for the CFT: the ratio of the pressure to Stephan-Boltzmann value vs the 't Hooft coupling $\lambda = g^2N$.

The viscosity/entropy => $\eta/s=1/4\pi$ (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)



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

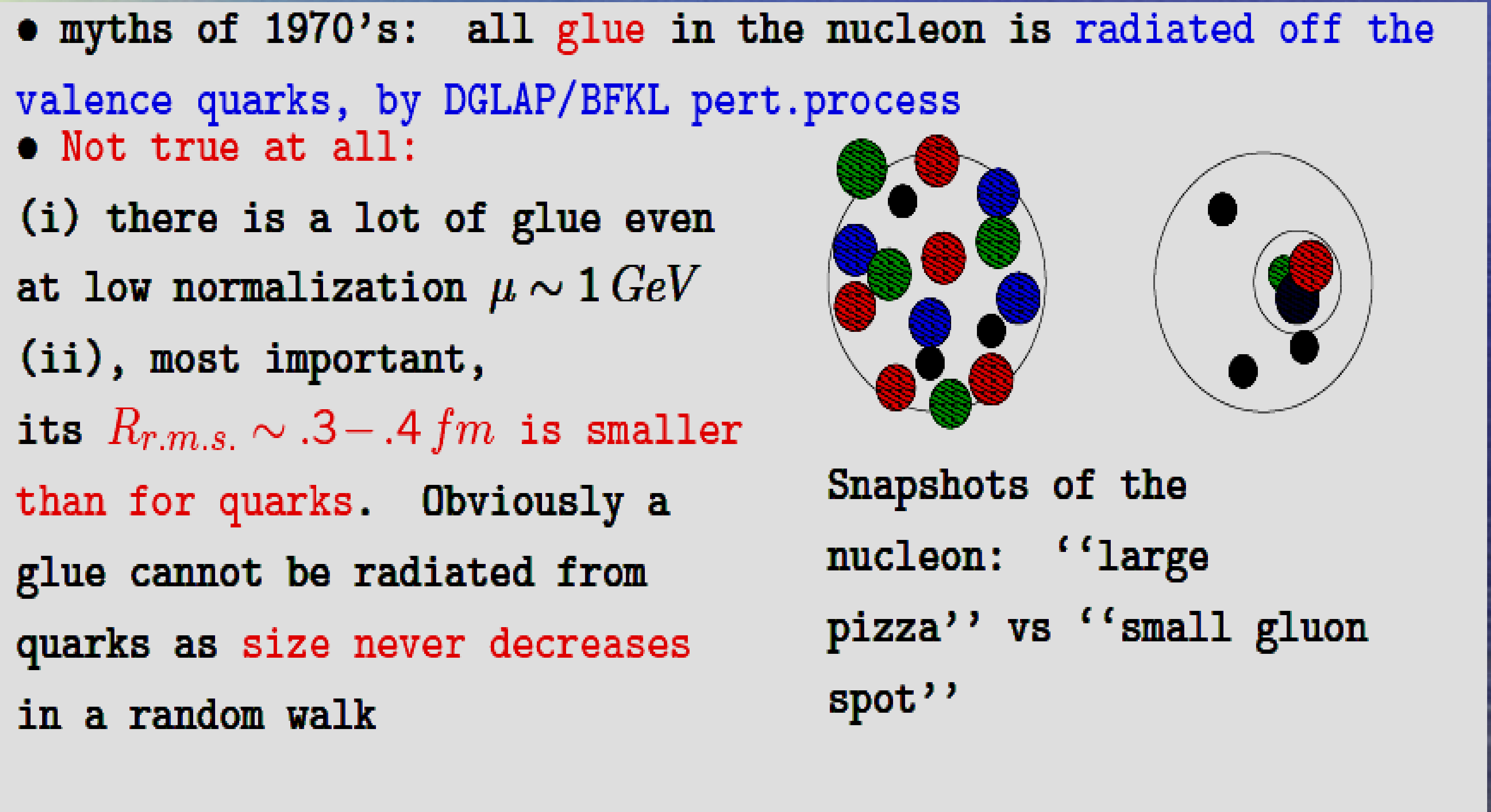
$$E_{nl} = m\left[1+\left(\frac{C}{n+1/2+\sqrt{(l+1/2)^2-C^2}}\right)^2\right]^{-1/2}$$

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

Returning to very early time: more puzzles for RHIC community to solve! (relating pp and AA)

- Why glue in a proton is in a small spot? R» .3 fm ¿ R(em). Are those associated with a polarized quark?
- Is the CGC very inhomogeneous as a result? Are those clusters the QCD sphalerons?
- How all of it is related to spin physics and diffractive pp?

Puzzle of small gluon spot (seen in diffractive DIS and other diffractive phenomena => ``pomerons are small-size" objects, why?



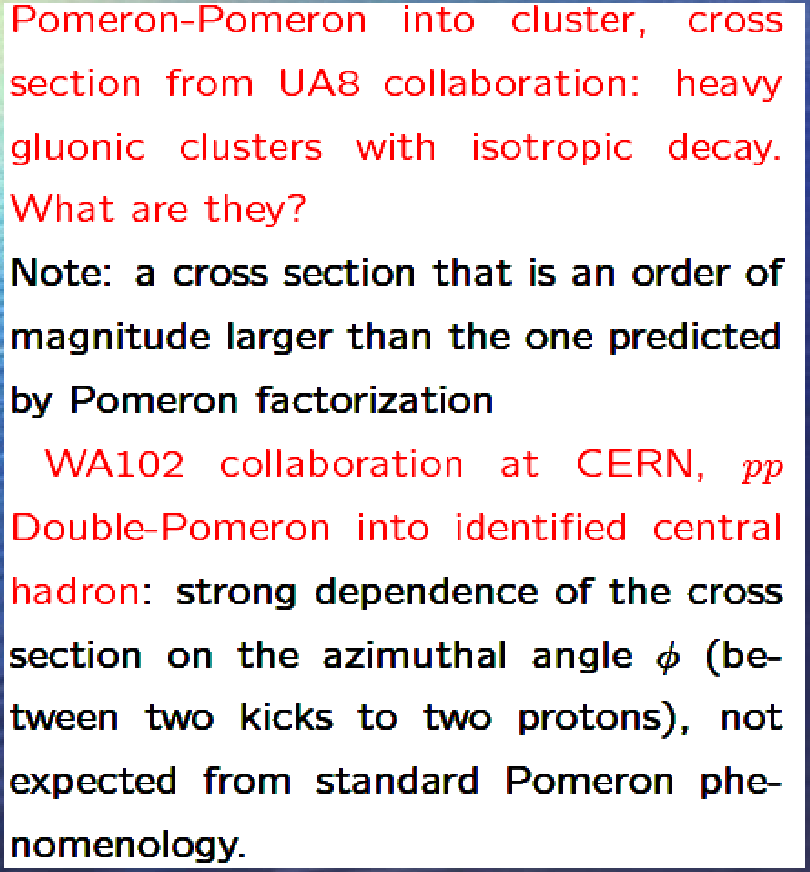
- myths of 1970's: all glue in the nucleon is radiated off the valence quarks, by DGLAP/BFKL pert.process
- Not true at all:

(i) there is a lot of glue even at low normalization $\mu \sim 1\, GeV$

(ii), most important, its $R_{r.m.s.} \sim .3 - .4\, fm$ is smaller than for quarks. Obviously a glue cannot be radiated from quarks as size never decreases in a random walk

Snapshots of the nucleon: ``large pizza'' vs ``small gluon spot''

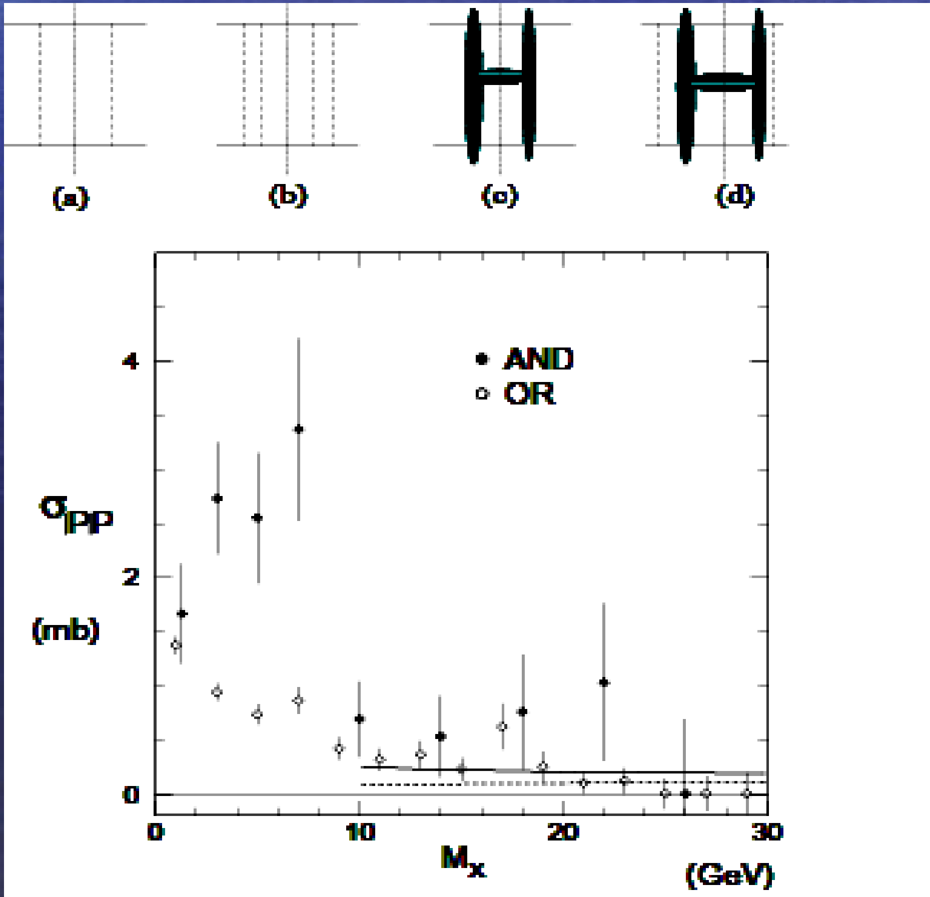
Puzzle of gluonic clusters produced in Pomeron-Pomeron collisions: what are they? (QCD sphalerons?)



Pomeron-Pomeron into cluster, cross section from UA8 collaboration: heavy gluonic clusters with isotropic decay. What are they?

Note: a cross section that is an order of magnitude larger than the one predicted by Pomeron factorization

WA102 collaboration at CERN, pp Double-Pomeron into identified central hadron: strong dependence of the cross section on the azimuthal angle ϕ (between two kicks to two protons), not expected from standard Pomeron phenomenology.



Puzzle of single-spin asymmetry: why is it so large, in DIS and pp?

Two things are needed:

- Chirality flip of the quark
- T-odd final state interaction of the outgoing quark

And yet the effect is so large as 10-20% !

(instantons?)

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.
- Instructuve analogies with other strongly coupled systems – atomic and field theory (AdS/CFT)

(Conclusions continue)

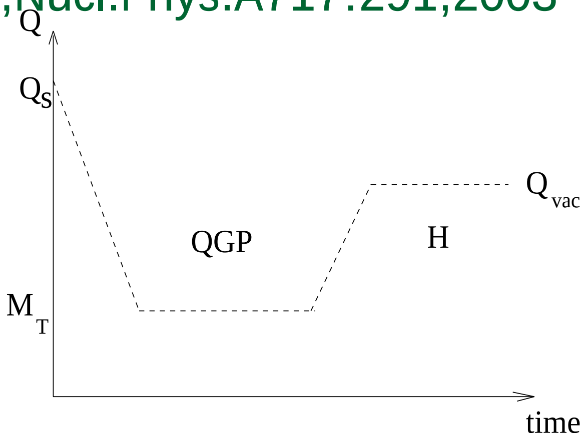
- Early probes: dileptons and photons remain to be studied (g=>q,new states?)
- Intermediate p_t (baryons) to be understood
- Large p_t : pQCD regime yet to be reached
- Wider puzzles in pp are related to the nature of nonpert.QCD at Q» 1 GeV and CGC, those combine heavy ion program with

spin and diffractive physics.

Additional slides

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

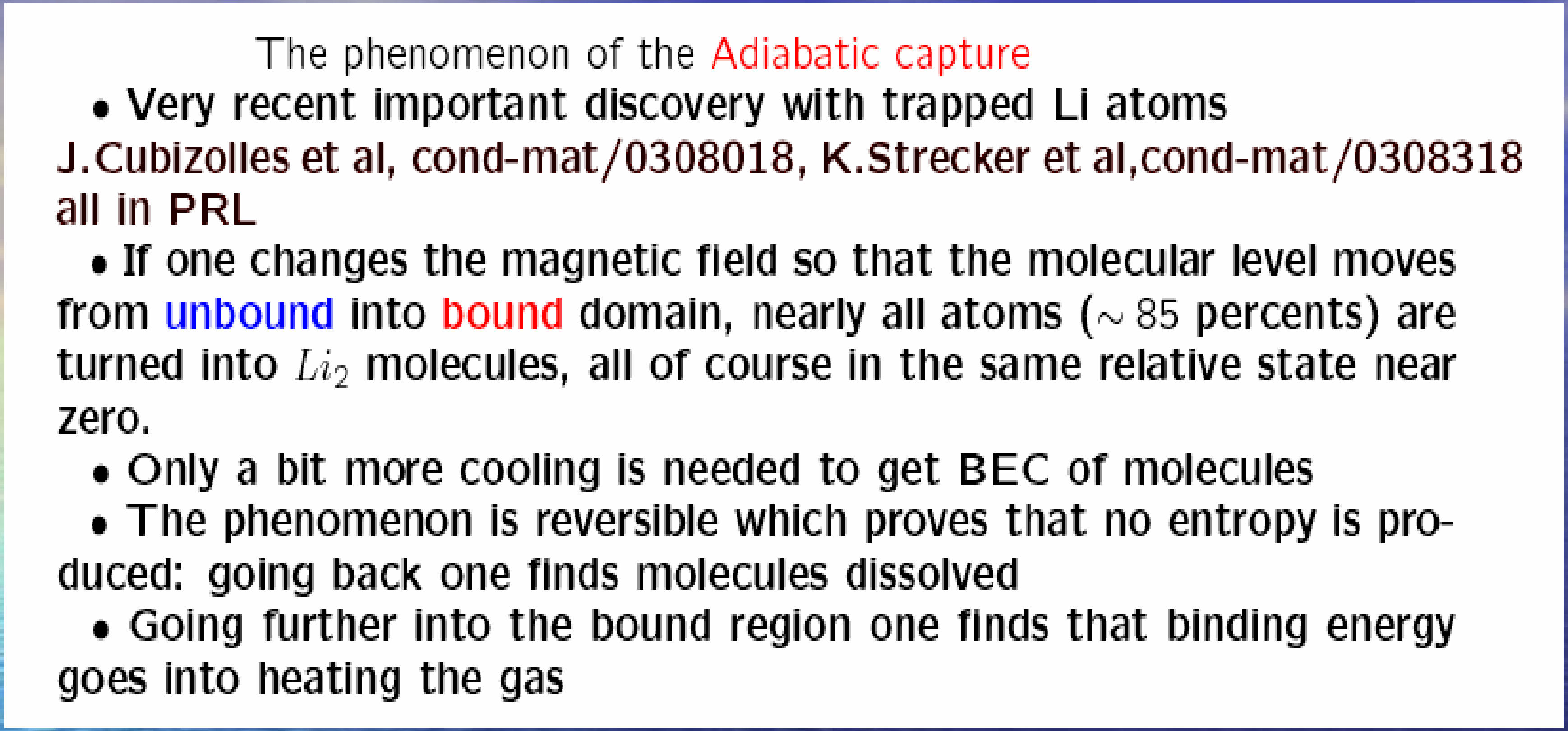
While Md is not yet large: here α(M_d) may be » 1 (?)

(M_d¼ 2T» 350-400 MeV only)

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

- $(4/3)\alpha_s\ (M/M_d) > 1.68$
- 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)

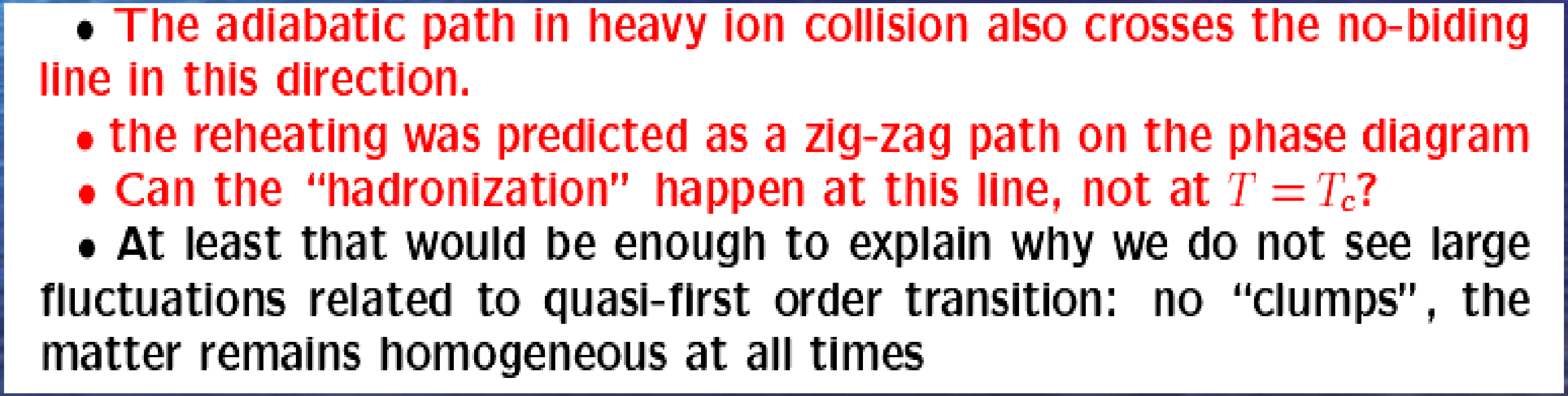


The phenomenon of the Adiabatic capture

- 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

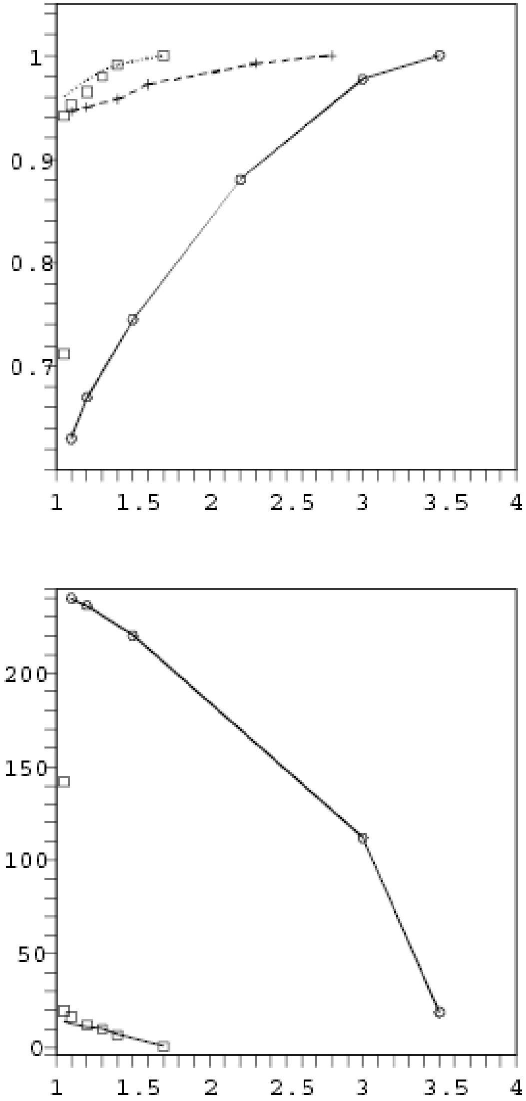


- The adiabatic path in heavy ion collision also crosses the no-biding line in this direction.
- the reheating was predicted as a zig-zag path on the phase diagram
- Can the “hadronization” happen at this line, not at $T = T_c$?
- At least that would be enough to explain why we do not see large fluctuations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

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.



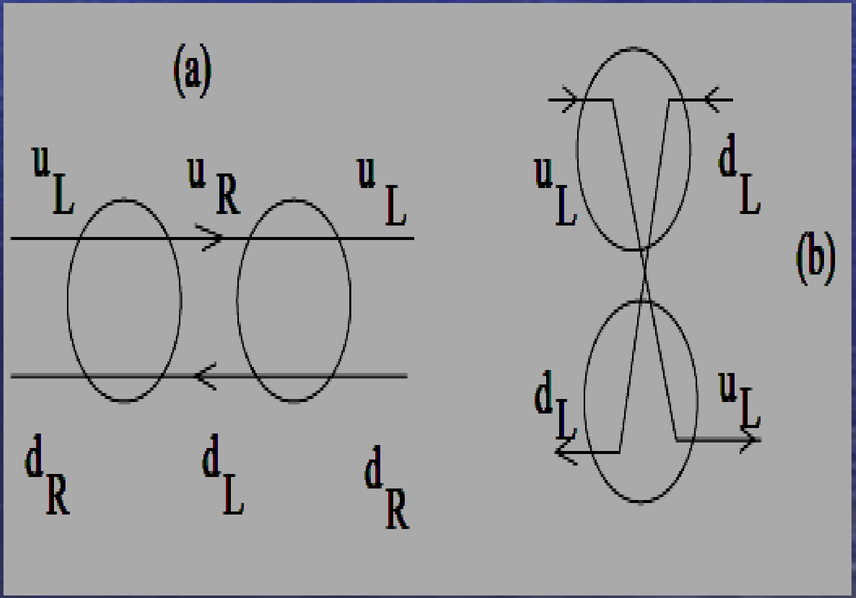
If a Coulomb coupling is too strong, falling onto the center may occur: but it is impossible to get a binding comparable to the mass

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

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

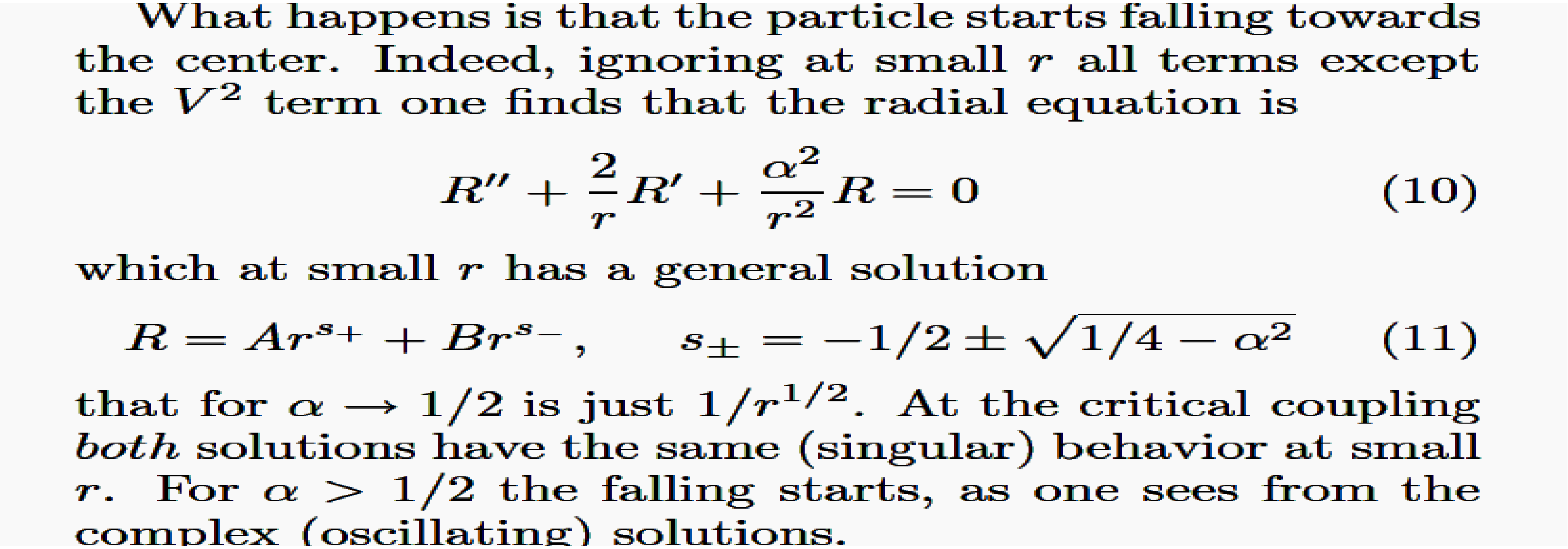
(also called ``hard glue” or ``epoxy”, as they survive at $T>T_c$

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



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

$$R'' + \frac{2}{r}R' + \frac{\alpha^2}{r^2}R = 0 \tag{10}$$

which at small r has a general solution

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

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).

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.**

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

What can we learn from other strongly coupled systems?

Trapped Li atoms at Feshbach resonance

N=4 SUSY YM at strong coupling

New ideas

Vectors in QGP and dileptons

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