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Why does the the Quark-Gluon Plasma at RHIC behave as an ideal fluid?

Edward Shuryak, Stony Brook

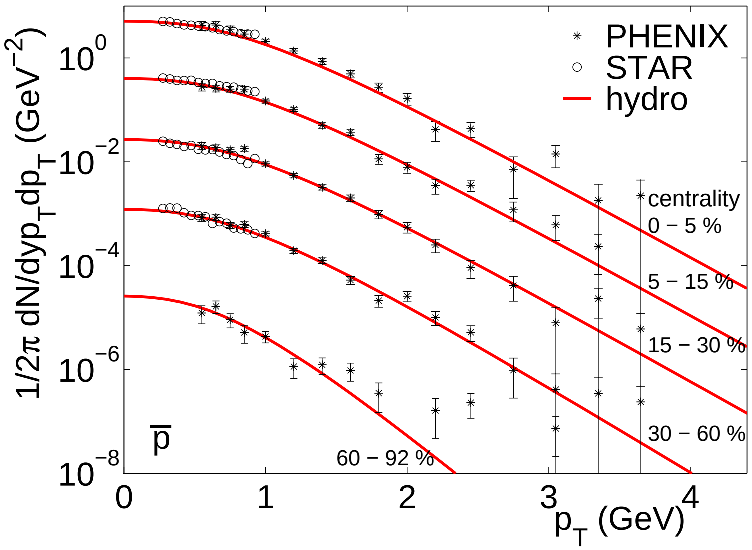
- **Hydrodynamics is the theory, not a model** $<=$ **Indeed** $l \ll L$
- **EoS predicted by the theory (lattice QCD) is quantiatively confirmed** $=> T_c \approx 170\, MeV$**, latent heat** $\approx .7 - .8 GeV/fm^3$**.**
- **QGP at RHIC** $\neq$ **weakly interacting quasiparticle gas**
- **its transport properties are such that QGP at RHIC is the most perfect liquid known (viscosity/entropy** $\eta/s \sim .1$ **is much less than for e.g. water!**

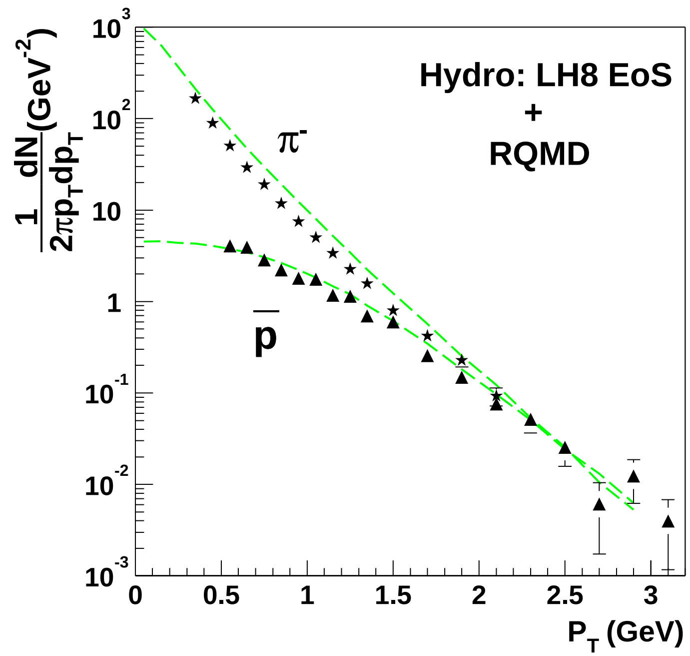
• In fact QGP at RHIC ($T = (1-3)T_c$) is in a strongly interacting regime. What that means? We start to understand, with much help from two other (recently discovered) examples

• Trapped ultracold atoms at scattering length $a \to \infty$

• $\mathcal{N} = 4$ SUSY YM=CFT at strong coupling $g^2 N_c >> 1$ (AdS/CFT duality <=> string theory)

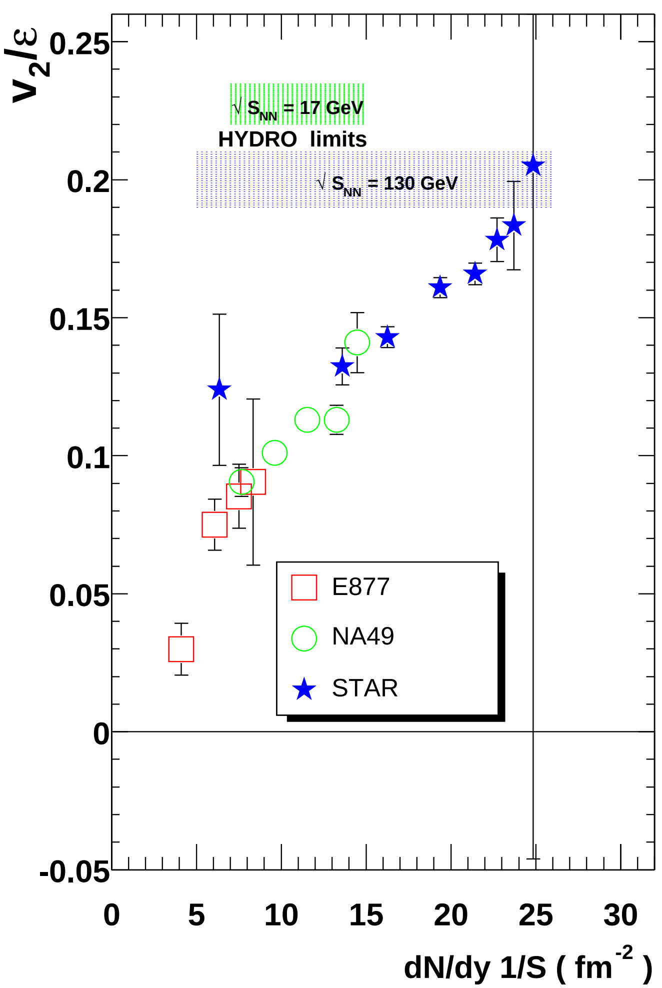
• New exotic qg, gg plus also "old" $\bar{q}q$ bound states: zero binding lines inside the QGP phase are crucial, even for EoS but more so for viscosity

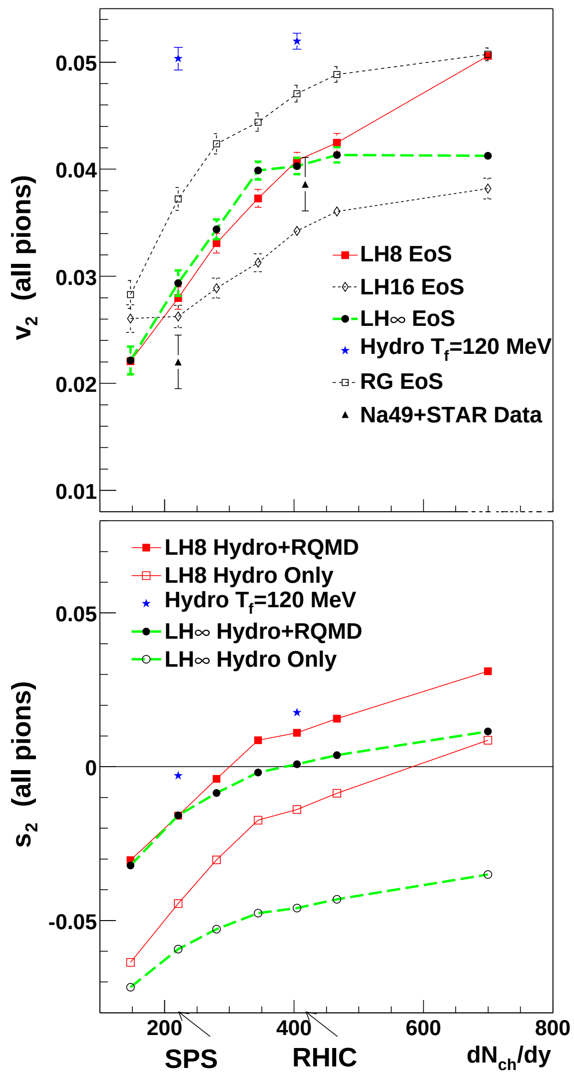




Teaney, Lauret, ES: chemically frozen resonance gas at the hadronic stage => new EoS. It helps: see e.g. $\bar{p}$ (P.Kolb and R.Rapp, Phys.Rev. C67:044903, 2003): without any fitting params, excellent description of the data (note also excellent agreement between exps)

At RHIC the dN/dp_t^2 of $\bar{p}$ crosses with π^- at $p_t \approx 2GeV$, exactly as hydro boosts predicts: so hydro works for only 99 % pf the particles. How far in p_t should hydro work? Limits are set by viscosity (see a talk by Teaney).

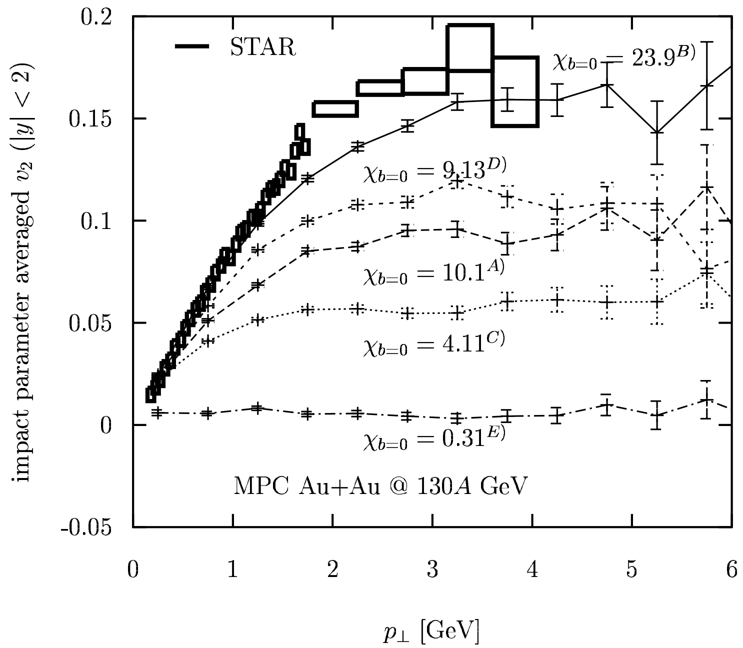




From Teaney, Lauret, ES (shown already at QM99, so it is well documented prediction). The rize is due to large QGP pressure. The red curve has the latent heat (LH) =800 MeV/fm^3, it is is the closest to the lattice EoS is also the best fit to all flow data at SPS and RHIC. The “hydro limit” in the STAR fig is for wrong $T_{freezeout} = const(b)$, while the “theory” ones has a correct freezeout (via RQMD).

It is only possible to get elliptic flow if the quasiparticle rescatte
is increased by big factor ~ 50 relative to the pQCD expectations.

The Figure (from Gyulassy and Molnar) shows how the measured effect (boxes) can be reached if matter opacity of matter grows. The smallest value (gg scattering in pQCD) shows no collective effects whatsoever. The rescattering cross section should be boosted by a big factor => small viscosity



Gluon elliptic flow for Au+Au at $\sqrt{s} = 130A$ GeV from Boltzmann eqn., with transport opacities $\chi_{b=0} = 0.31, 4.11, 9.13, 10.1$ and 23.9.)

A crush course on viscosity

• Ideal hydro $=>$ all dynamics is local. Viscosity is $\sim l_{m.f.p.}/L$ corrections due to finite mean free path (or other nonzero correlation lengths).

• Example: scaling boost-inv. (Bjorken) flow (axially symmetric)

$$\frac{1}{\epsilon + p}\frac{d\epsilon}{d\tau} = \frac{1}{s}\frac{ds}{d\tau} = -\frac{1}{\tau}\left(1 - \frac{\Gamma_s}{\tau}\right); \qquad \Gamma_s = \frac{4}{3}\frac{\eta}{\epsilon + p} = \frac{4}{3}\frac{\eta}{Ts}$$

one finds in the r.h.s. exactly the combination also known as the sound attenuation length. It is the micro scale which substitutes $l_{m.f.p.}$ if the quasiparticle language is inadequate.

$$\Gamma_s \ll \tau$$

Theory/Phenomenology of QGP viscosity

- Weak coupling or perturbative framework: large, $\eta/T^3 \sim const/g^4 log(1/g) >>> 1, const \sim 100$ at small $g << 1$

If so, $l \sim few\, fm$ and no hydro at RHIC ! (Recall the Gyulassy-Molnar plot here)

- However, in the strong coupling ($\mathcal{N} = 4$ supersymmetric Yang-Mills or CFT) Polycastro, Son, Starinets, Phys. Rev. Lett. 87 (2001) 081601 (not yet in QCD!) $T\Gamma_s = \frac{4}{3}\frac{\eta}{s} = \frac{1}{3\pi}$.

If used for RHIC QGP $\Gamma_s \sim .1\, fm$ If so, excellent hydro, but no parton cascades...

- QGP viscosity: Teaney, hep-ph/0301099 from $v_2(p_t)$ data $=> \Gamma_s \sim .1 fm$ or $\frac{\eta}{s} \sim 1/10$ the most perfect fluid ever

The second best known liquid, He^4 at high pressure, has $\frac{\eta}{s} \sim 1$, water at notmal conditions about 40.

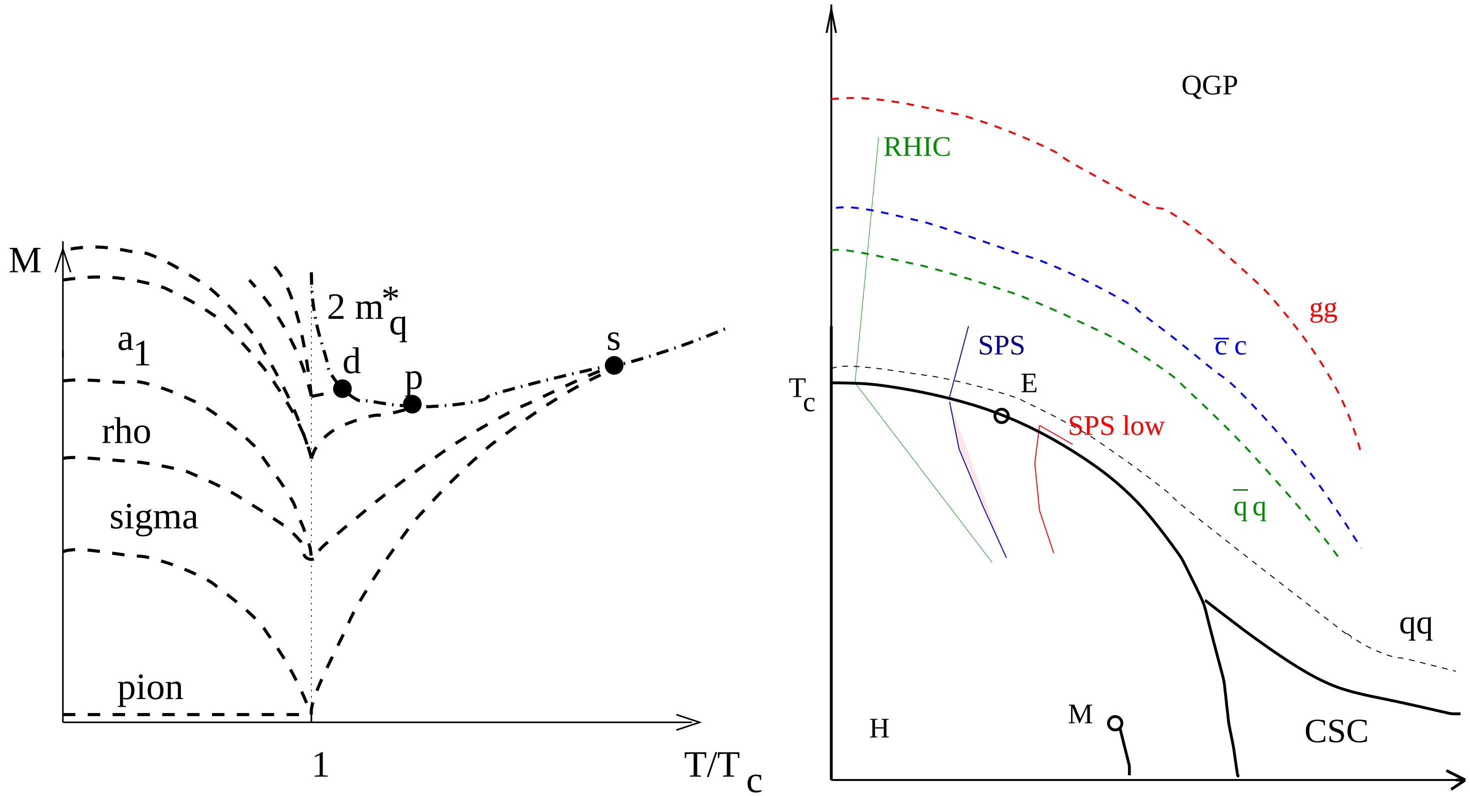
Are there hadrons above T_c, in Quark-Gluon Plasma?

• **Old point of view: most hadrons (including $J/\psi = \bar{c}c$ but not $\Upsilon = \bar{b}b$) melt there.**
• **Exceptions: the pion (+sigma etc chiral multiplet) was believed to survive as resonance e.g.NJL-based papers or T.Schafer+ES, PLB 356:147,1995**

• **New lattice results from Bielefeld group and Asakawa-Hatsuda (using the maximal entropy method) found bound η_c at 1.5T_c, very recently Asakawa-Hatsuda (hep-lat/0309001) have argued that the de-binding point is $1.6 < T_\psi < 1.9 T_c$.**

• **One important point: near T_c the q,g quasiparticles are not light, then their mass decreases and at high T grows again as predicted by pQCD $M \sim gT$**

ES and I.Zahed,hep-ph/0307267

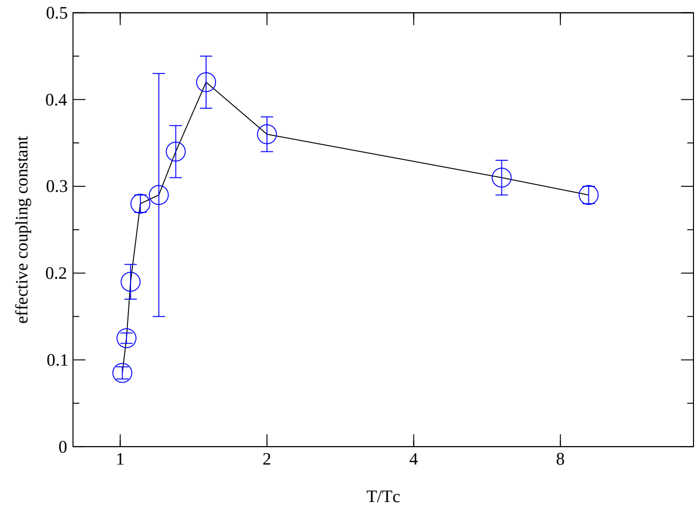


A general view of the endlines for $\bar{q}q$ and also colored composites like qg, gg. Another famous colored dimer is the qq, the Cooper pair of color superconductivity

Why some hadrons may survive above T_c?

ES and I.Zahed,hep-ph/03072

- **The loophole in the old argument: α_s kept frozen in the QGP as in-vacuum**
- **New idea: at $T > T_c$ the charge continues to run to larger values, stopped by the Debye screening only. $\alpha_s \sim 1/2$ is reached**



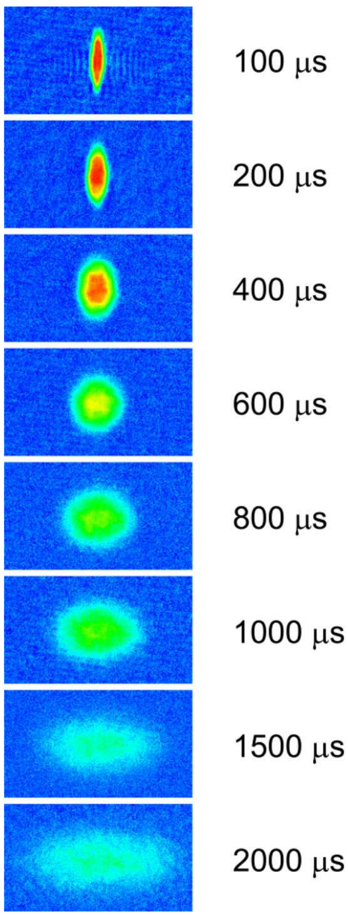
G.Brown,C.H.Lee, M.Rho and ES, hep-ph/0312175 $\bar{q}q$ **bound states for $T_c < T < T_{zerobinding}$: relativistic effects $(1 - \vec{v}_1\vec{v}_2)+$ spin-spin, plus the nonperturbative forces due to instanton-antiinstanton molecules $=>$ $M_\sigma, M_\pi => 0$ at $T => T_c$**

- **The main idea: large (unitarity limited) cross sections at the endlines $=>$ "sticky molasses"**

Elliptic flow with trapped Li^6 atoms:

K.M.O'Hara et al, Science 298,2179, 2002

T.Bourdel et al, PRL 91 020402 , July 11 2003



Magnetic field $B \sim 800G$ shifts (via the Feschbach resonance $|f = 1/2, m_f = 1/2 > <=> |f = 1/2, m_f = -1/2 >$) and makes the 38-th vibrational Li_2 state to exactly zero energy => infinite scattering length a, very large size and lifetime ~ 1 sec.

Normally gas is transparent, $l \ll L$, and expands without collisions isotropically

But in the strong coupling regime $l \ll L$ it explodes hydrodynamically !, see the figure

Cross section can be changed by many orders of magnitude, but the EoS changes by $\sim 20\%$ only ! (like in QGP and CFT... why?)

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

Hadronization by Adiabatic Capture?

- 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

Where the QGP pressure at $T = (1-3)T_c$ comes from?

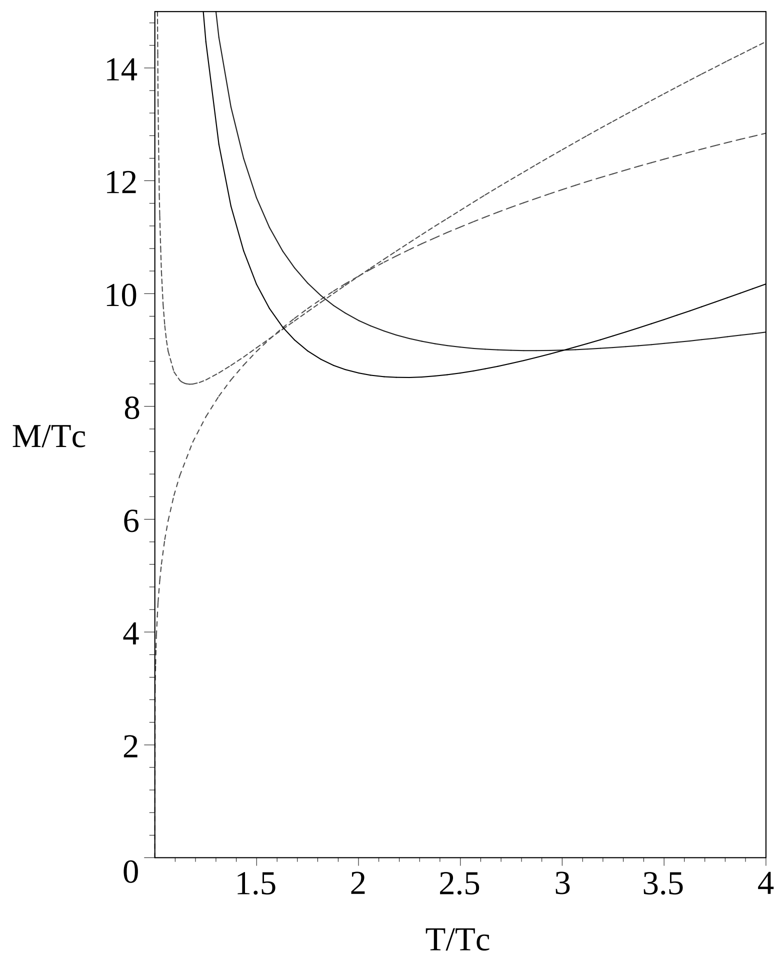
• **Gas of quasiparticles: (A. Peshier, B. Kampfer, O. P. Pavlenko and G. Soff,Phys. Rev. D 54, 2399 (1996); P. Levai and U. W. Heinz,Phys. Rev. C 57, 1879 (1998)) need light ones, e.g. at $T = 1.5T_c$ LH had**

$$M_g \approx 420\, MeV, M_q \approx 300\, MeV$$

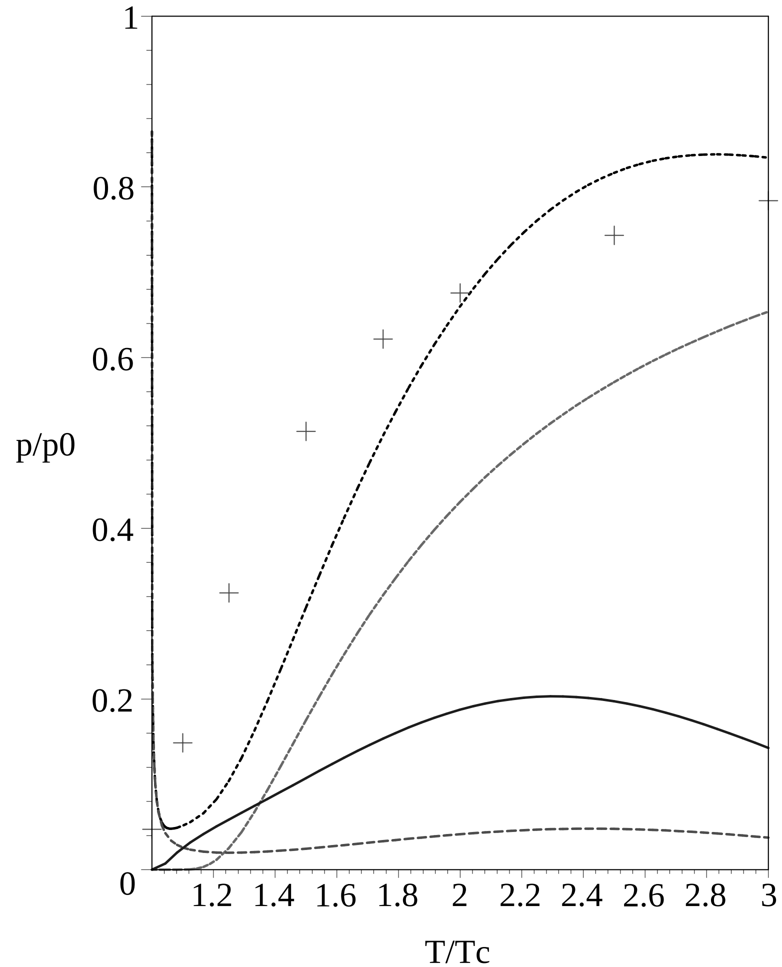
while direct lattice studies (by Karsch et al) found much heavier ones instead

$$M_g \approx 540\, MeV, M_q \approx 620\, MeV$$

• **How important is it? The Boltzmann factors for quarks are $exp(-M_q/T) = .28$ for LH former values but only 0.075 for the latter ones**



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

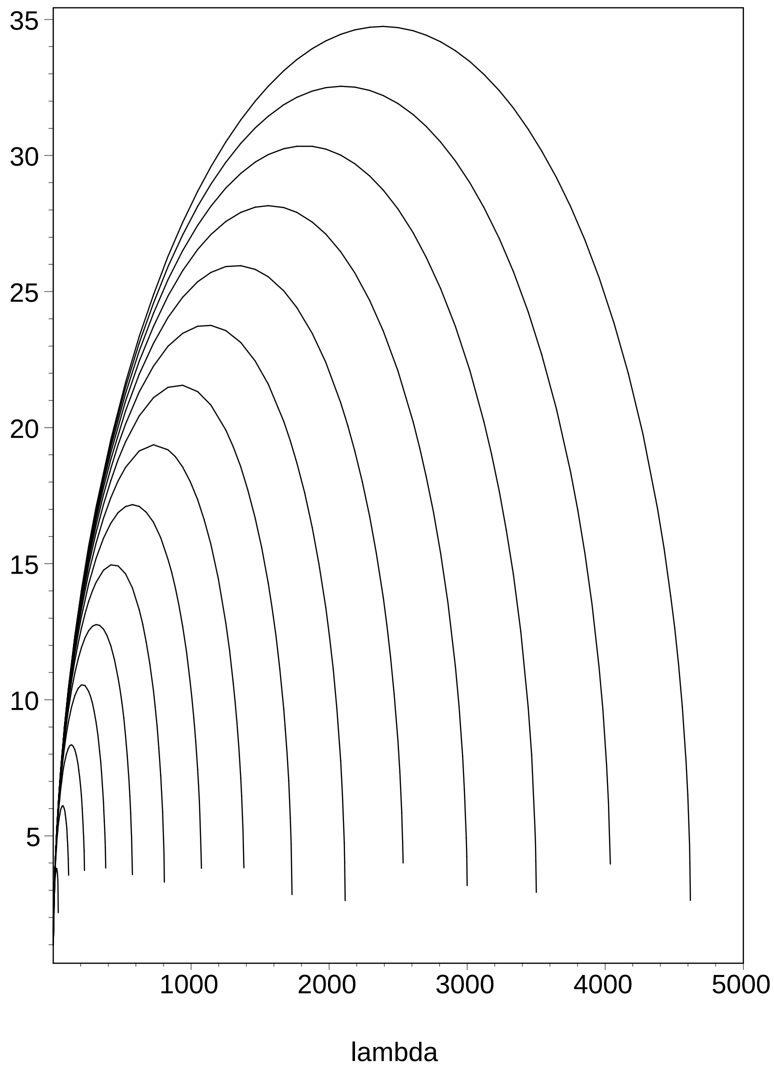


The QGP pressure: crosses are lattice thermodynamics for $N_f = 2$ (Karsch et al,2000), the lines represent the contributions of $q+g$ quasiparticles, mesons $\pi - \rho ...$, exotics (gg_8, qg_3) and total (the upper curve).

A plasma phase at a supercritical coupling

• 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 $\lambda = g^2 N_c \gg 1$?
• Unexpected help from the string theory AdS/CFT correspondence by Maldacena turned the strongly coupled gauge theories to a classical problem in gravity albeit in 10 dimensions
• Free energy at large λ is $F = (3/4 + O(1/\lambda^{3/2}))F_{free}(T)$

• Zahed +ES, hep-th/0308073: at strong coupling matter is made of binary composites gg, qg, qq with large angular momentum $l \sim \sqrt{\lambda}$ whose spectrum can be calculated



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

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

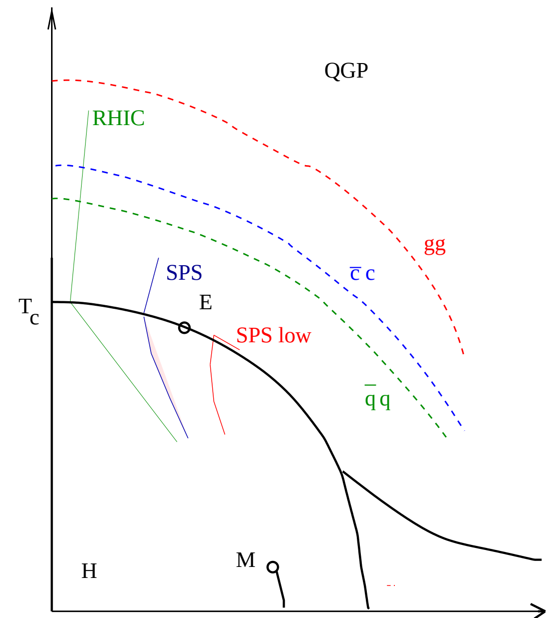
Small C - nonrelat. atoms, Balmer series... New regime at large $C >> 1$: families of relativistic deeply bound states, with large orbital momentum balancing the supercritical Coulomb

Summary

• QGP at RHIC is surprisingly good fluid, with $\eta/s \sim 1/10$ smaller than ever seen before

• This disagrees with pQCD (weak coupling) but does agree with the strong coupling regime Connection to string theory via Ads/CFT correspondence by Maldacena.

• All s-wave mesons plus glueballs plus many exotic bound states qq, qg, gg do not melt at T_c, but at zero binding lines.



• Those generate about 1/2 pressure at RHIC and, presumably, strong (unitarity limited) rescattering e.g. $\bar{q}q <=>$ meson

• Amazingly similar to trapped Li^6 atoms. with ''only'' 19 orders difference in energy scale