The Quark-Gluon Plasma
at critical and supercritical couplings

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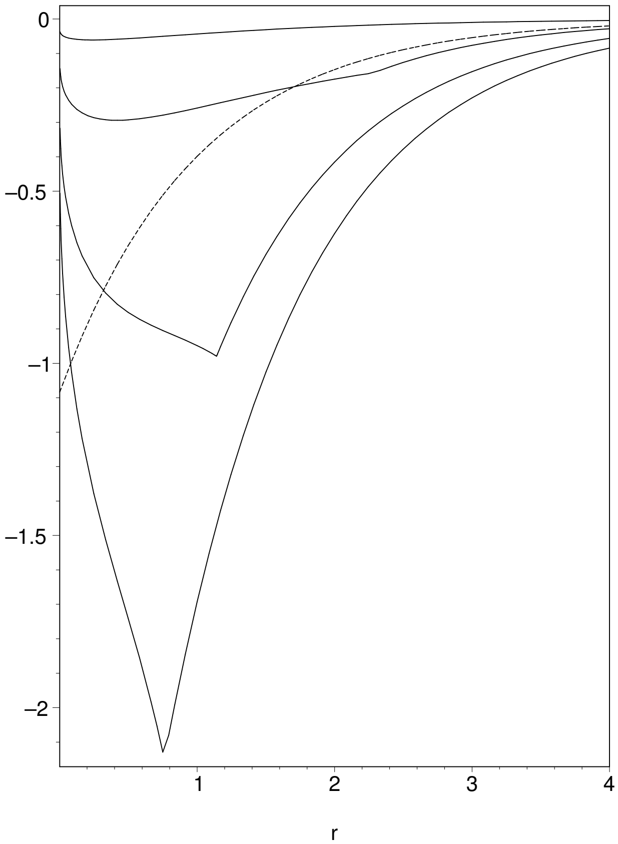
• Rethinking the QGP at $T = (1-3)T_c$: the near-cri
pling $\alpha_s \sim 1$ leads to loosely bound states and la
sections E.Shuryak and I.Zahed,hep-ph/0307267
• A gift from the string world: AdS/CFT and a
coupled plasma in ($\mathcal{N}$=4 SUSY YM)
• Explaining the puzzles of the ($\mathcal{N}$=4 CFT) plasm
supercritical coupling $g^2 N_c >> 1$: there are plent
bound states with a large orbital momentum (ES-
• Why hydrodynamics works so well at RHIC, wi
expected EoS, but surprisingly small viscous corre
• A gift from atomic physics: getting elliptic hy
from an extremely dilute cloud by shifting the res

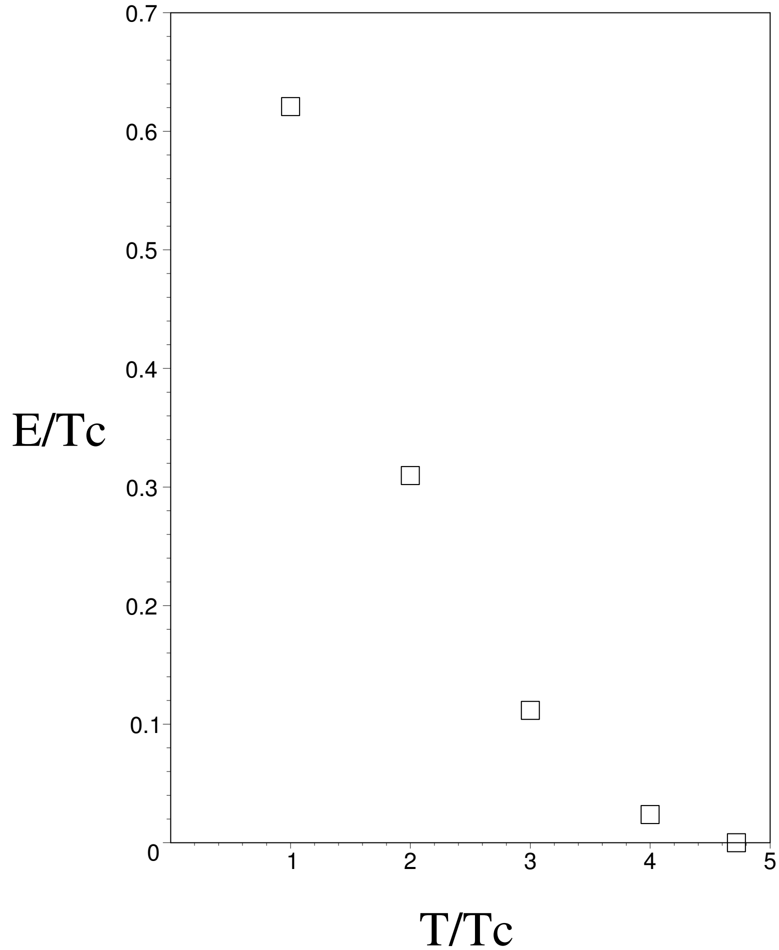
Are there hadrons above T_c, in Quark-Gluon

- **Old point of view: most hadrons (including J/ψ not $\Upsilon = \bar{b}b$) melt there.**
- **Exceptions: the pion (+sigma etc chiral multi believed to survive as resonance e.g.NJL-based T.Schafer+ES, PLB 356:147,1995**
- **The issue was reconsidered recently: ES and I.Za ph/0307267**
- **The loophole in the old argument: the gauge constant remains frozen in the QGP (as in-vacu monium potential, $\alpha_s \sim 1/3$.)**
- **New idea: at $T > T_c$ the charge continues to run values, stopped by the Debye screening only**

$$\frac{d^2\chi}{dx^2} + \left(\kappa^2 + \frac{4m_c}{3M_D}\frac{\alpha_s(x)}{x}e^{-x}\right)\chi = 0$$

The appearance of a level, at zero binding $E = 0$ **at** $\frac{4m_c}{3M_D}\alpha_s > 1.68$
For example, using $4/3\alpha_s = 0.471$ **from the Cornell and** $m_c = 1.32\,\mathrm{GeV}$**, as Satz et al did long ago, plus lattice one finds that** J/ψ **melts already at** T_c**.**





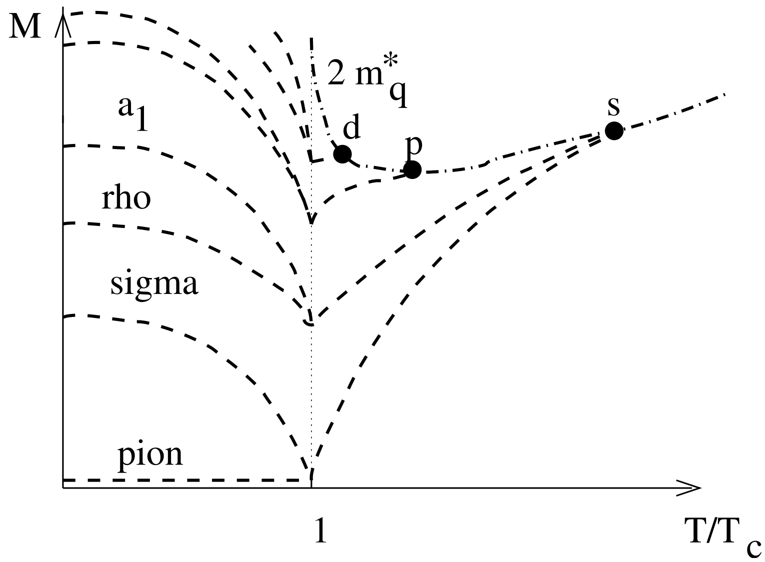
The combination $(M_c/M_D)rV(r)$, versus the distance rM_D. The dashed line corresponds to $4\alpha_s/3 = 0.471$, while the correspond to the running coupling constant, for $T = 1; 1.5; 3$ bottom up. The cusps occur when α_s reaches 1.

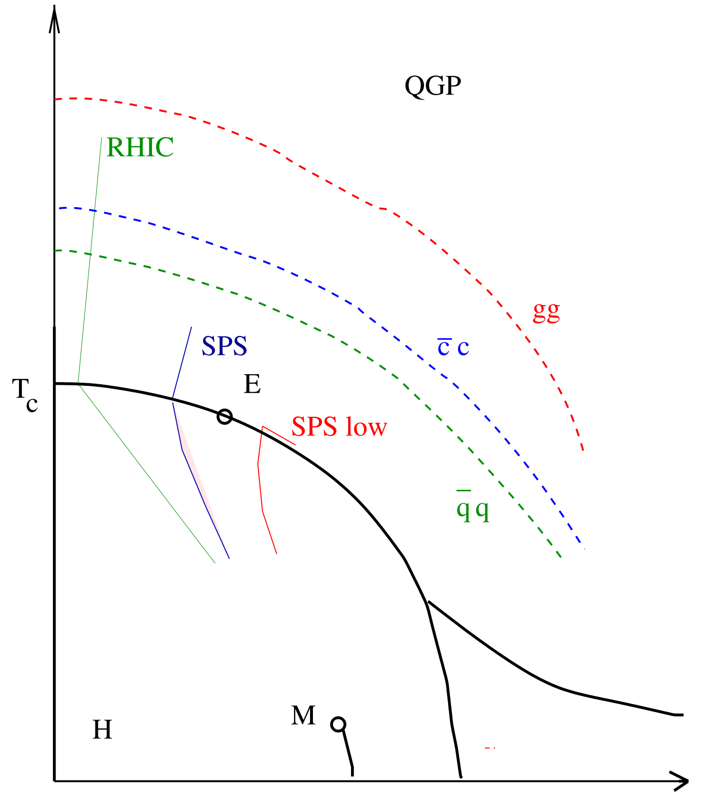
• But, if the running of the QCD coupling continu
screening length, we calcualted that charmoniun
bound till $T_{cc} = 1.62T_c$.

• Recent lattice results (Karsch etal found bou
$1.5T_c$, very recently Asakawa-Hatsuda (hep-lat/0
have shown the debinding point is in between 1.6
T_c.

• so this idea passed the first test

• **If so, there are also weakly bound states of $\bar{q}$**
type, the latter persisted till $T \sim 500\,MeV$ or so, plu
composites.

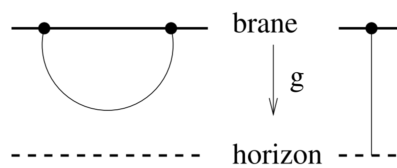




• **Why is it important? Because weakly bound st**
deuteron) means huge "unitarity limited" scatter
sections.

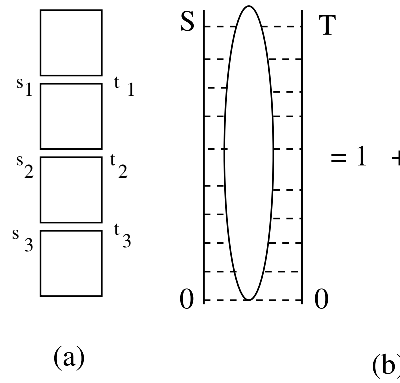
A plasma phase at a supercritical co

- The $\mathcal{N}$=4 SUSY Yang Mills gauge theory is c
(CFT) (the coupling does not run). At finite T
a plasma phase at ANY coupling, including ve
$\lambda = g^2 N_c \gg 1$.
- Unexpected help from the string theory AdS/CF
spondence by Maldacena turned the strongly coupl
theories to a classical problem in gravity albeit in 1
sions
- Example: a modified Coulomb's law (by Maldacena)
$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$



- Free energy at large λ is $F = (3/4 + O(1/\lambda^{3/2}))F_f$

G. Semenoff and K.Zarembo,hep-th/0202156. have shown that a modified 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** $y = (S+T)/$

Expansion of the kernel in the first power of $(S -$

to an oscillator potential and the problem is easil

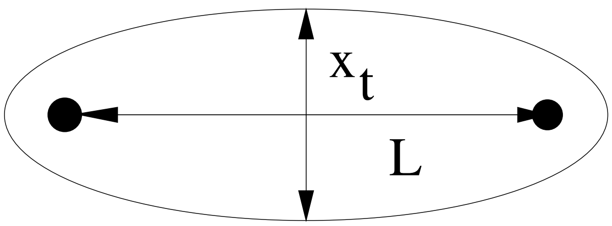
$\Gamma(x,y) =\approx \mathrm{C}_0\, e^{-\sqrt{\lambda}\, x^2/4\pi}\, e^{\sqrt{\lambda}\, y/2\pi}$

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

the same parametric form but different coefficie

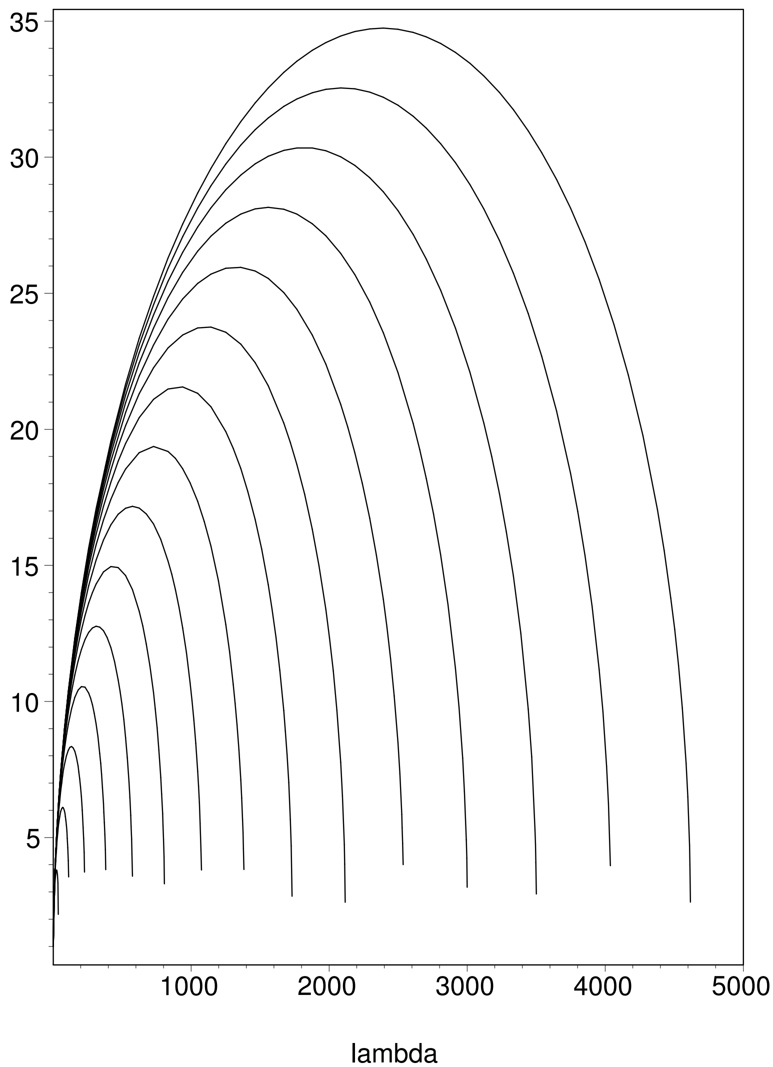
0.318 **while the exact Maldacena value is 0.228.**

• We observed that the exchanged gluons move
superluminal speed $v \sim \delta t/L \sim \lambda^{1/4} \gg 1$
• Some higher order diagrams have extra $\lambda d^4 x \sim O($
body Bethe-Salpeter
• vertices distributed in a quasi-string regime



• The main idea: the modified Coulomb law can
even for relativistic bound states, with $v \sim 1$.

• Using a Klein-Gordon eqn $(E - V)^2 - m^2 = p^2, V$
with a Coulomb potential, by WKB or exactly, one
the spectrum. (Known from about 1930).



$E_{nl} =$

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

Small C - nonrelat. ator

regime at large $C >> 1$: fa

relativistic deeply bound st

which large orbital momen

ances the supercritical Coul

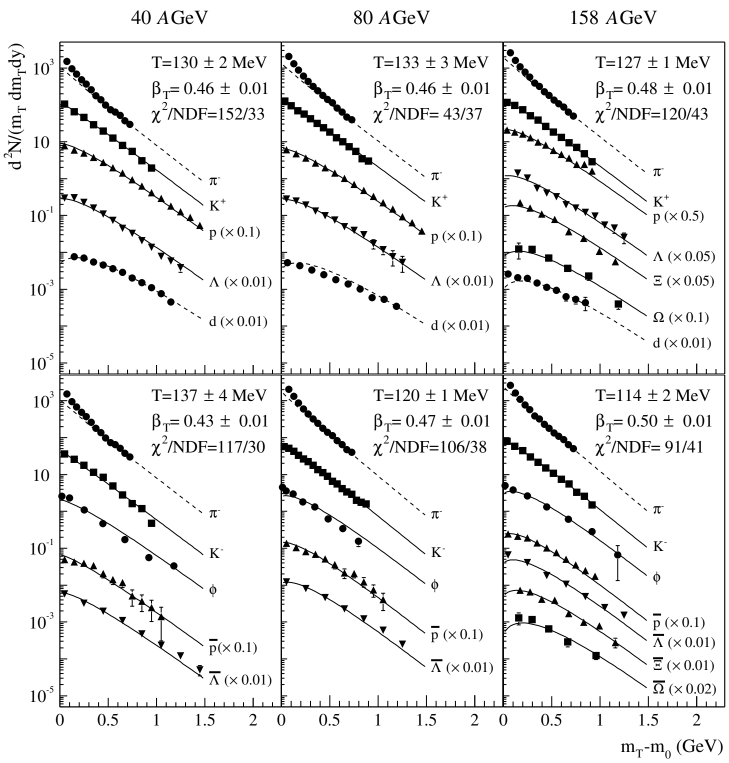
• These states in fact dominate the matter: thei
are $\sim T$ much smaller than those of original quas
$\sim \lambda^{1/2}T$.

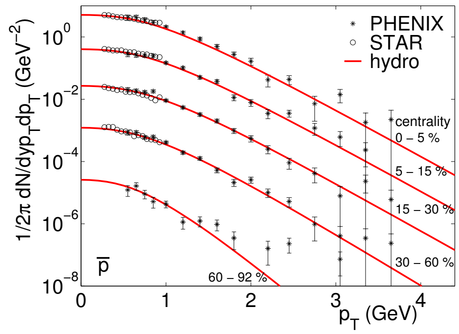
At strong coupling only those compound states
mally excited, • Furthermore, the density of state
shown not to depend on λ.

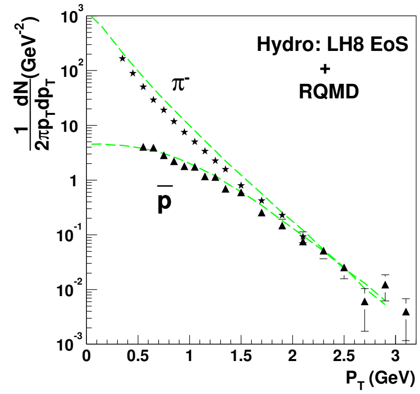
The composites carry large angular momentum
$1/\sqrt{\lambda}$ and $\int_{l_{min}}^{l_{max}} dl^2 = l_{max}^2 - l_{min}^2 \approx \lambda^0$ thus the fre
$\mathbf{F} = \mathrm{C} N_c^2 T^4$ and without dependence on λ

• (The oscillator-kind spectrum $M \sim constnT$ sor
plained states have been inferred by Starinets
Teaney before, by a direct calculation of the st
sor correlator – via graviton propagator in AdS m

Hydrodynamics and radial flow at SP



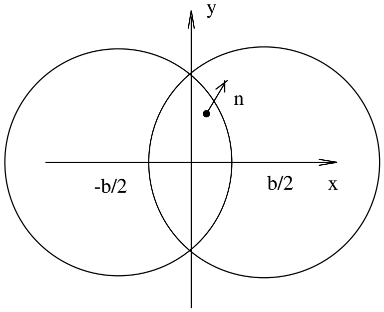




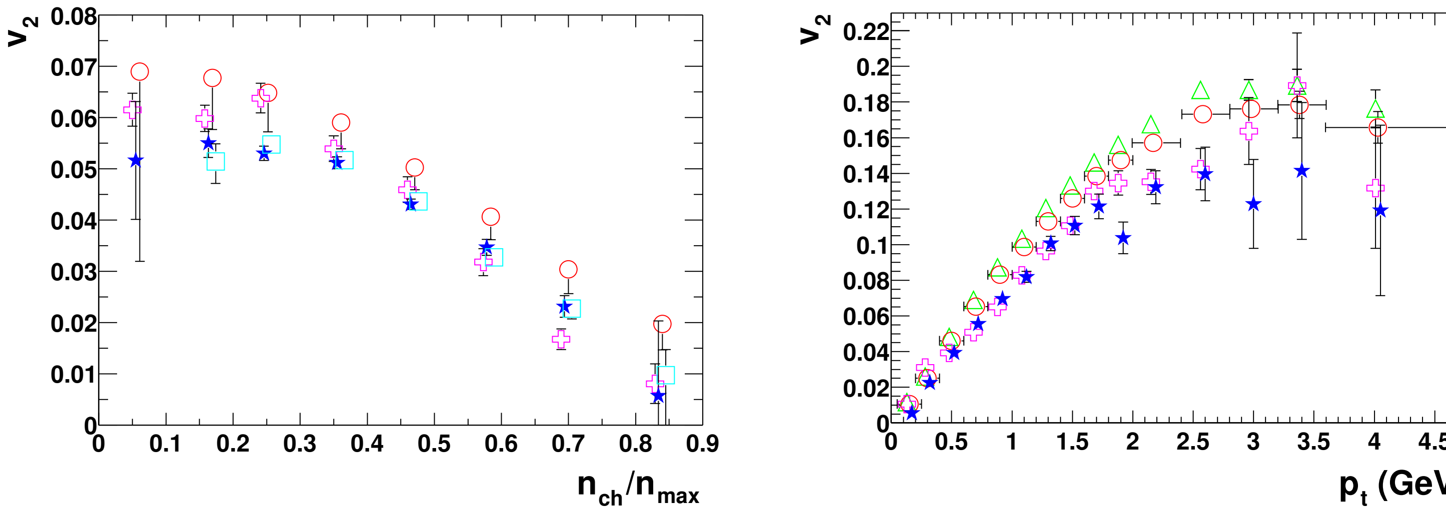
The SPS (NA49) and RHIC spectra: all species till d can be well fitted with the same velocity and T_f

at RHIC more $\bar{p}$ are observed than π^- for $p_t > 2GeV$, exactly as hydro boosts predicts!

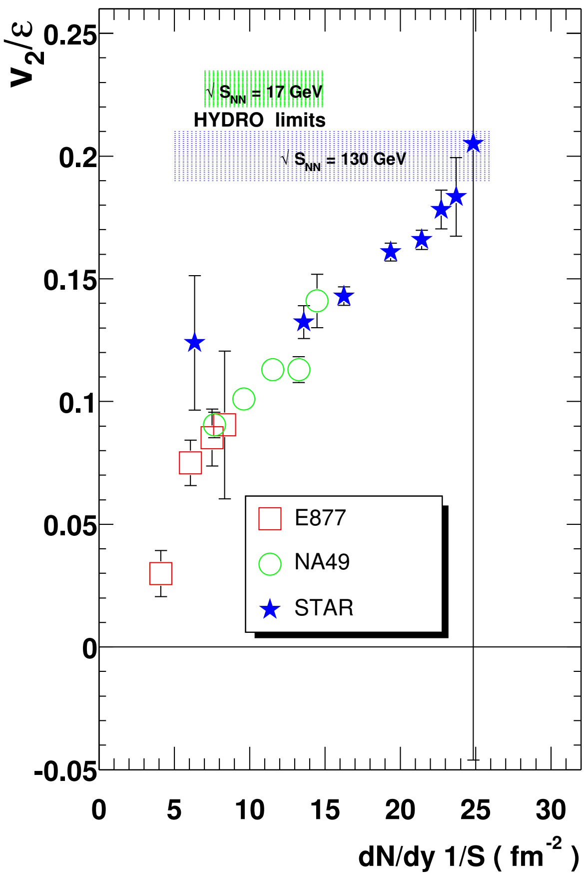
Elliptic flow starts with the "initial almond" (for no
collisions) and is described by Fourier harmonics

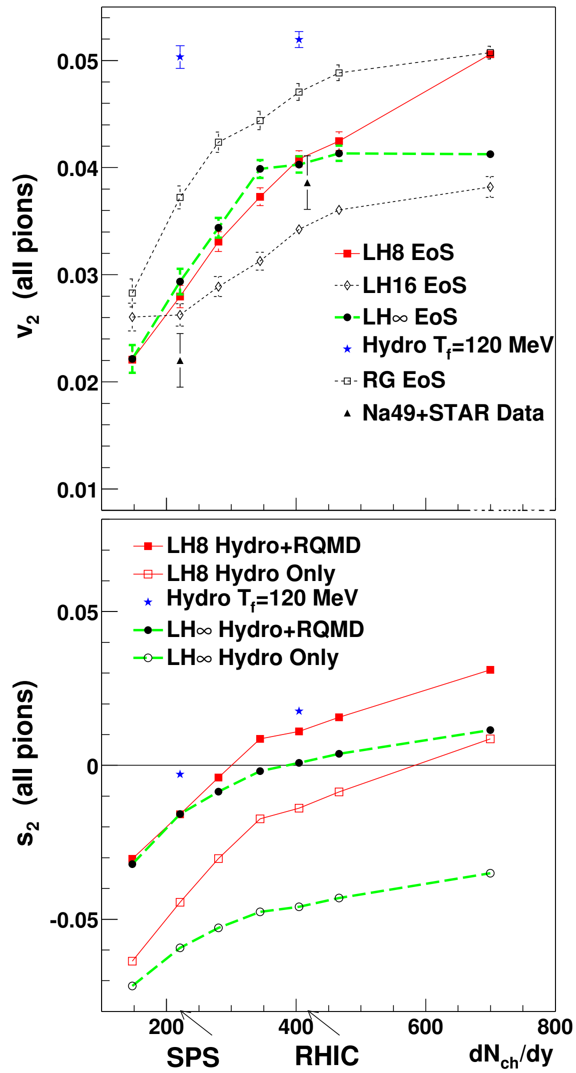


$$\frac{dN}{d\phi} = \frac{v_2}{2\pi} + \frac{v_2}{\pi}\cos(2\phi) + \frac{v_4}{\pi}\cos(4\phi) +$$



Elliptic flow versus (a) centrality and (b) p_t for Au + Au at $\sqrt{s_{NN}}$
several methods of v_2 extraction, all from STAR at RHIC.

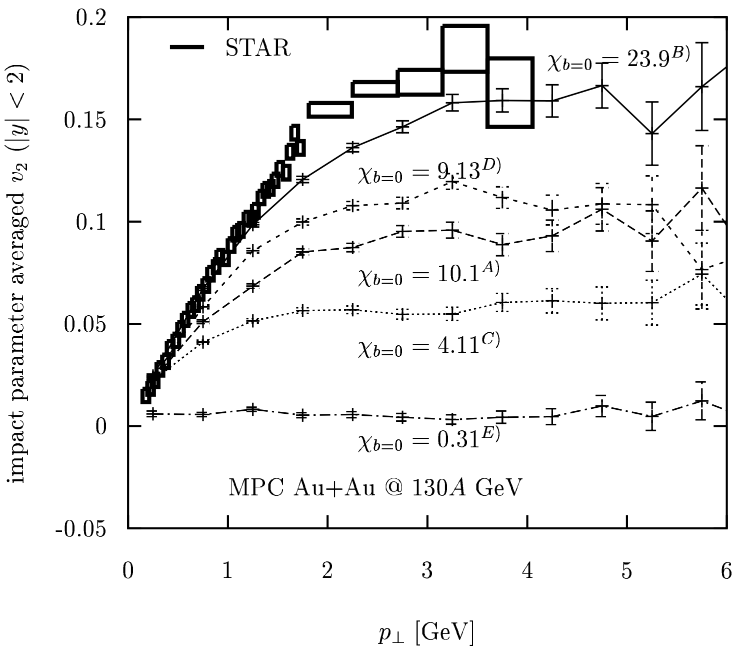




From T
ret, ES
ready at
is well
predicti
curve ha
heat (
MeV/fm
closest t
EoS is a
fit to all
SPS and

It is only possible to get elliptic flow if the qua
rescattering is increased by big factor ~ 50 relativ
pQCD expectations.

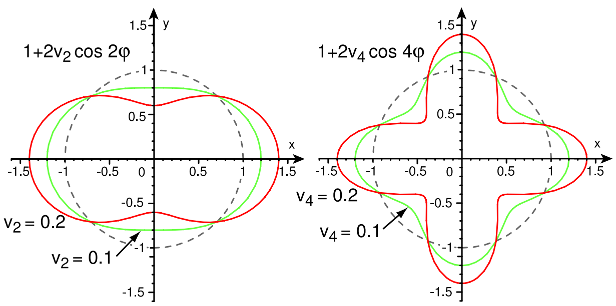
The Figure (from Gyulassy and Molnar) shows how the meas (boxes) can be reached if matter opacity of matter grows. est value, roughly corresponding to gg scattering in pQCD collective effects whatsoever, and the rescattering cross sec be boosted by a big factor before the effect appears.

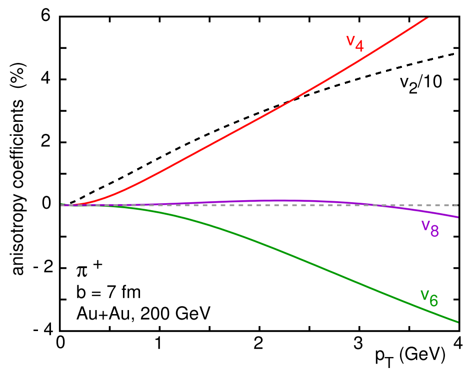


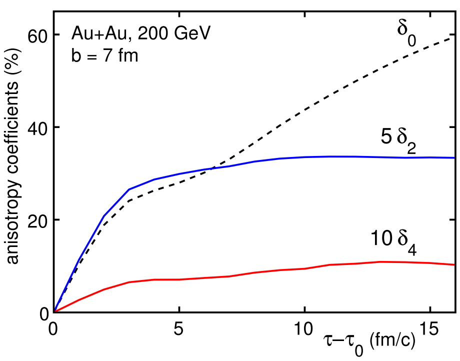
(Gluon elliptic flow for Au at $\sqrt{s} = 130A$ GeV with t port opacities $\chi_{b=0} =$ 4.11, 9.13, 10.1 and 23.9

The next moment v_4

- **D.Teaney+ES, PRL 1999, The unusual "nutcra lution at $b > 8\,fm$ which is more square than ellipt**
- **Recently P.Kolb 2003 calculated $v_n(b, p_t)$ in a sy way**







Rumors are this is seen by STAR, in good agreement with hydro once again...

The viscous corrections to hydro

• Ideal hydrodynamics assumes that all the dynam
cal, it ignores the finiteness of the mean free p
other correlation lengths).

• Including the first $O(l/L)$ dissipative terms, e
boost-inv. (Bjorken) and axially symmetric hydro

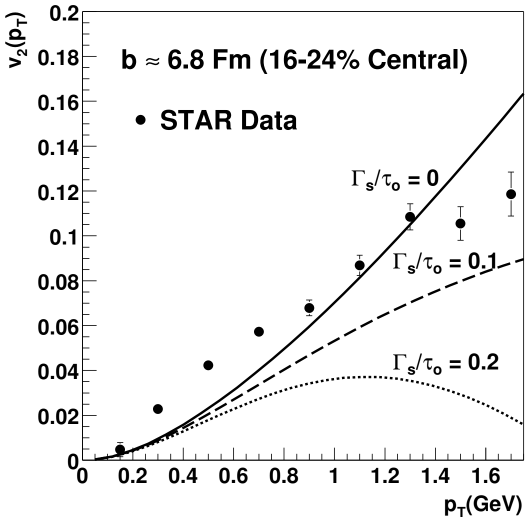
$$\frac{1}{\epsilon + p}\frac{d\epsilon}{d\tau} = \frac{1}{s}\frac{ds}{d\tau} = -\frac{1}{\tau}\left(1 - \frac{\Gamma_s}{\tau}\right)$$

one finds in the r.h.s. exactly the combination w
appears in the sound attenuation length $\Gamma_s =$
which tells us at which times one cannot neglect
cosity

• Following Derek Teaney, hep-ph/0301099, one
to extract it from the data, by looking at deviati
ideal hydro predictions.

• the viscous correction to particle distribution is co
determined $f = f_o(1 + \frac{\eta}{s} p^\alpha p^\beta \left\langle \nabla_\alpha u_\beta \right\rangle)$. Consequence
tions are $\sim \frac{\Gamma_s}{4\tau} \left(\frac{p_T}{T}\right)^2$

• We need QGP viscosity at earlier times.: thus
at elliptic flow. the fireball is spatially anisotropic
$\tau < 3fm/c$, when matter is in the QGP phase.



Elliptic flow v_2 as a function of p_T different values of Γ_s/τ_o. The da points are four particle cummula data from the STAR collaborati [?]. Only statistical errors are show The results for different Γ_s/τ shown The experimental da deviate from ideal hydro cur at $p_\perp \approx 1.6\,GeV$ which indicat $\Gamma_s/\tau \sim 0.05$ or so. Substitu ing here the relevant time τ $3fm/c$ we get surprisingly sm $\Gamma_s \sim .15fm$.

The theory of viscosity

- Developed for long time in the weak coupling per
framework: large, $\eta/T^3 \sim const/g^4 log(1/g) >>> 1, co$
at small $g << 1$
If so, $l \sim few\, fm$ and no hydro at RHIC ! (Recall the
Molnar plot here)

- However, in the strongly coupled plasma ($\mathcal{N} =$
Yang-Mills or CFT) Polycastro, Son, Starinets, P
Lett. 87 (2001) 081601 the value for the sound att
length

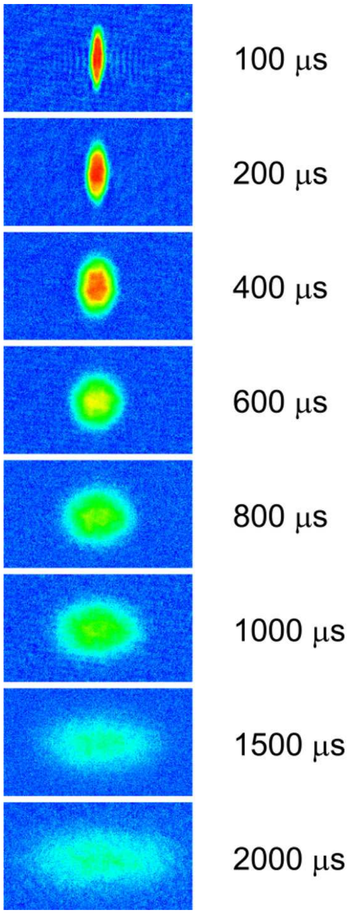
$$\Gamma_s = \frac{4}{3}\frac{\eta}{(\epsilon + p)} = \frac{1}{3\pi T} \sim .1\, fm$$

If so, excellent hydro

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 $B \sim 800 Gauss$ shifts the Feschbach resonance and makes the zero energy state, or infinite scattering length a. Normally $ak_f \ll 1$ and gas expands in collisionless way Isotropically
But in the strong coupling regime $ak_f \gg 1$ it explodes hydrodynamically !, see the figure
However the EoS hardly changes by 10%

Adiabatic capture

- Very recent important discovery

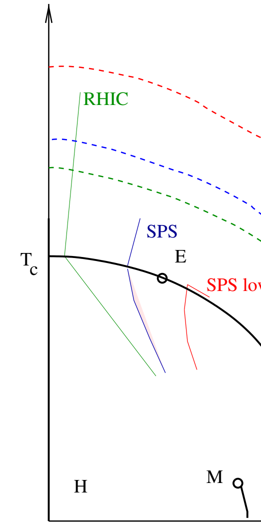
J.Cubizolles et al, cond-mat/0308018, K.Strecker et al,cond-

- If one change magnetic field so that the molecular level m

unbound to bound, with high efficiency (~ 85 percents) turned into Li_2 molecules, all of course in the same relative

- The phenomenon is reversible
- Going further into the bound region one finds that bind goes into heating the gas
- The adiabatic path in heavy ion collision also cr zero biding line in this direction. So a "hadronizat probably happen at this line, not at $T = T_c$

Summary



• All s-wave mesons and glueballs do not melt at T_c, but at around 1.5-3 T_c, which generates strong (unitarity limited) rescattering

• Viscosity corrections in QGP (for large b and at early tin for v_2) seem to be small $\Gamma_s/\tau < .1$

• This disagrees with pQCD or weak coupling but agrees l the strong coupling regime

• New connection to strongly coupled trapped Li^6 atoms

• New connection to string world, via Ads/CFT correspo Maldacena, to strongly coupled QGP. The puzzles of the C at the supercritical coupling are explained by the multiple de highly rotational states with masses $M \sim T$

Viscosity: an overview

• Transport in gases is done by atomic motion

$$\eta \sim Dmn \sim \frac{(mT)^{1/2}}{\sigma}$$

where D, m, n are diffusion coeff. mass and density
atomic cross section.

• Transport of energy/momentum in liquids is like
and done by transfer of atomic oscillations – phon

Frenkel, 1926: *"The fact to be explained is not the
but fluidity"*.

Large viscosity corresponds to small diffusion, he

$$\eta \sim \frac{T}{aD} \sim exp(+W/T + p/p0)$$

where a is atomic size and W is some activatio
needed to move an atom and p is pressure.

• **Especially well known special case is liquid He^4 where phonons and rotons are the well defined q cles, with small cross section: it is a *gas* once aga exp. had mean free path of $\sim 1cm$ scale, so no "normal component" but a "ballistic regime" wh particles just fly from their source by straight line**

The QGP quasiparticles beyond quarks and g

• **RHIC QGP is at** $T = 170 - 350 MeV$ **and effectively** $g^2 N_c \sim 12 >> 1$, **pQCD series are not converging. have a relatively strongly coupled plasma: what i**

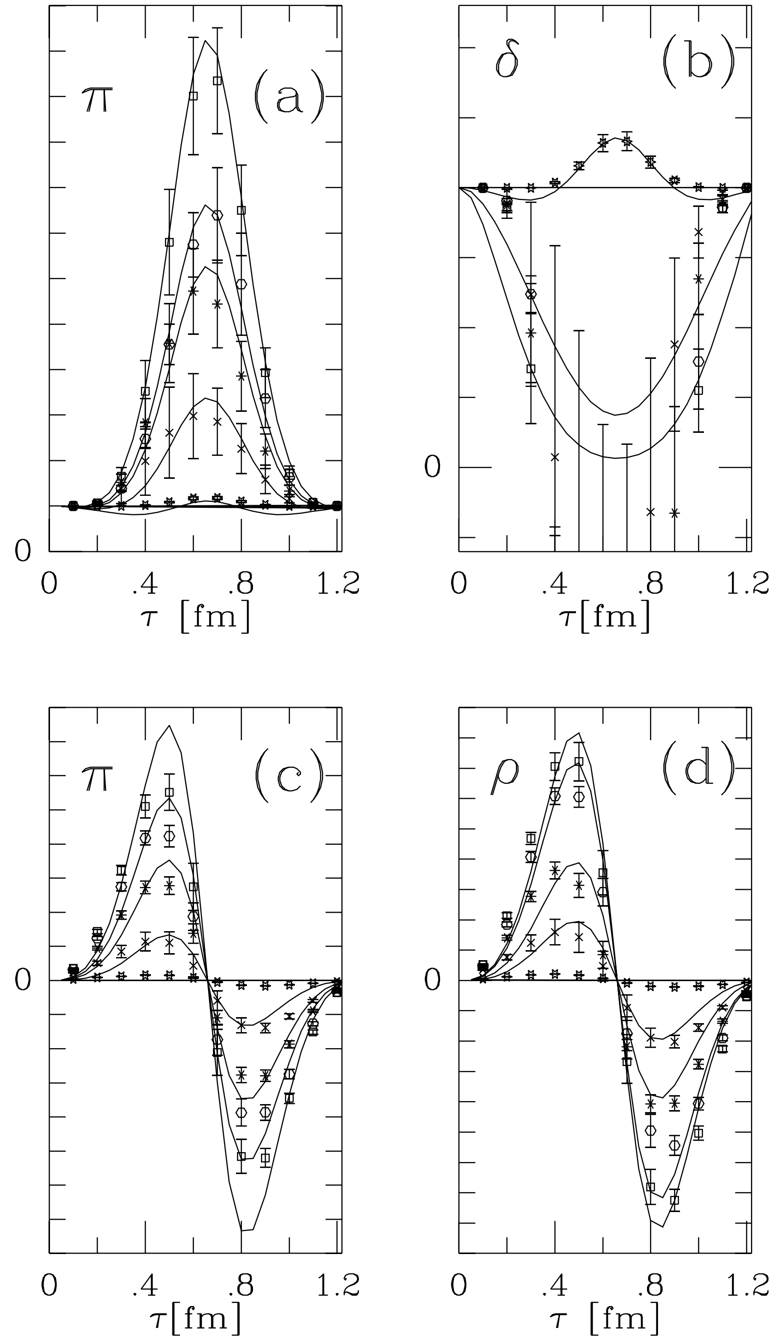
• **Lattice: e.g. Karsch hep-lat/0110111 gives effe** $1.6 - 3$, **from potential, and also plasma frequenci**

$$\omega_q(p = 0) \approx \omega_g(p = 0) \approx 3T \sim .5 - 1GeV$$

• **The sound: phonons are massless and still ha mean free path at small k**

• **The pions+sigma quartet (for 2 flavors): in longer Goldstone particles, but still exist**

The correlators (ratio to thermal $\bar{q}q$ propagators) Schafer, ES:CAN HADRONS SURVIVE THE CHIRAL PHASE TRANSITION? Phys.Lett.B356:147-152,1995 hep-ph/9506282 Instanton liquid above T_c breaks into finite clusters with top.Q=0



Also there are lattice results starting from DeTar w
small "screening masses" $< 2\pi T$ for pion/sigma in

• Instead of conclusions, a question:
why those lightest mode do not generate large v
small velocity close to T_c ? or small mean free pa
studied yet...