Some ideas about high-density QGP

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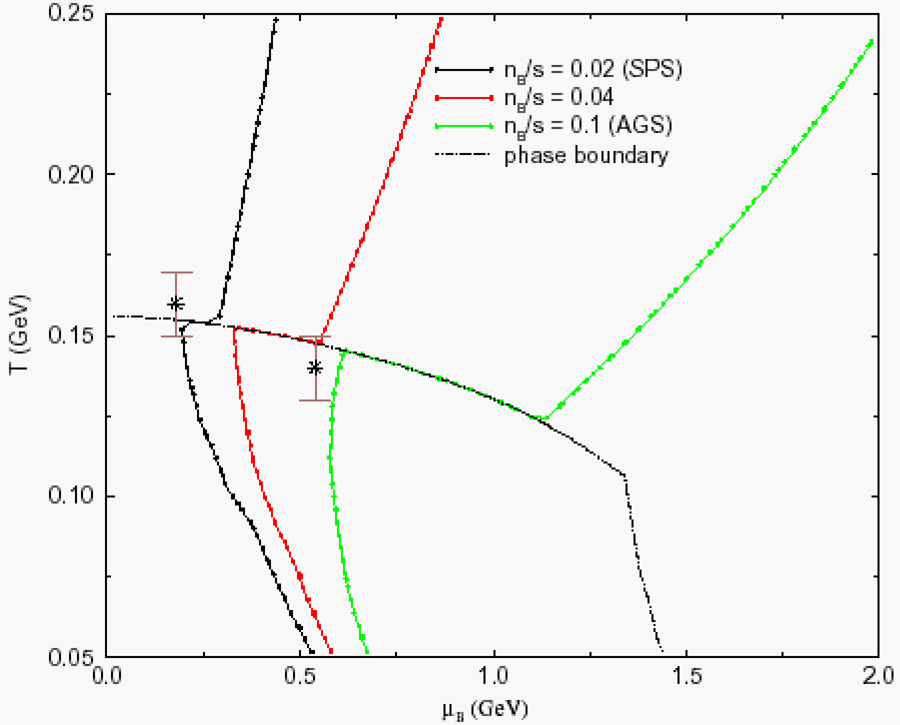
outlook

- Special excitaiton points, from low E upward
- Modified flows near the critical point
- Heavy N,Delta at T>Tc?
- Limits on color superconductivity at strong coupling
- Monopoles in strongly coupled plasma

The zigzags on the phase diagram

- Both bar.charge and entropy are conserved: n_b/s=const(t)
- In resonance gas and QGP different formulae: curves do not meet at the critical line
- Of course they are connected inside the mixed phase –heating while expanding due to latent heat



A decade old plot From C.M.Hung and ES, hep-ph/9709264,PRC

Crude zigzags start to appear, but far from being accurate enough…

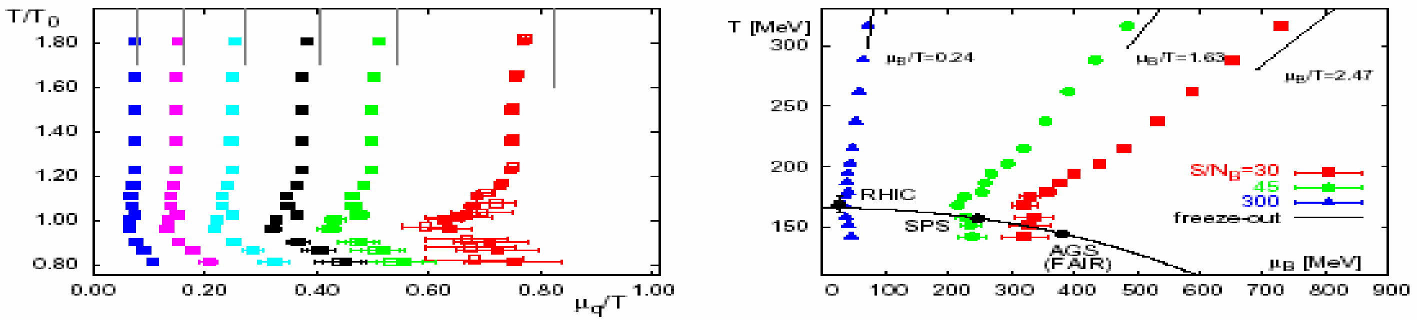
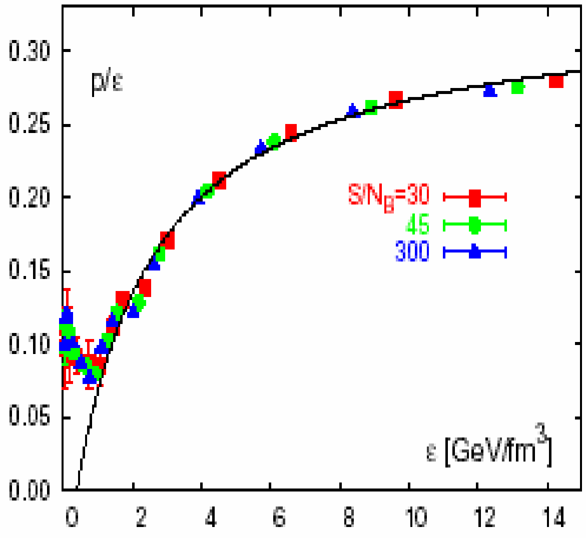
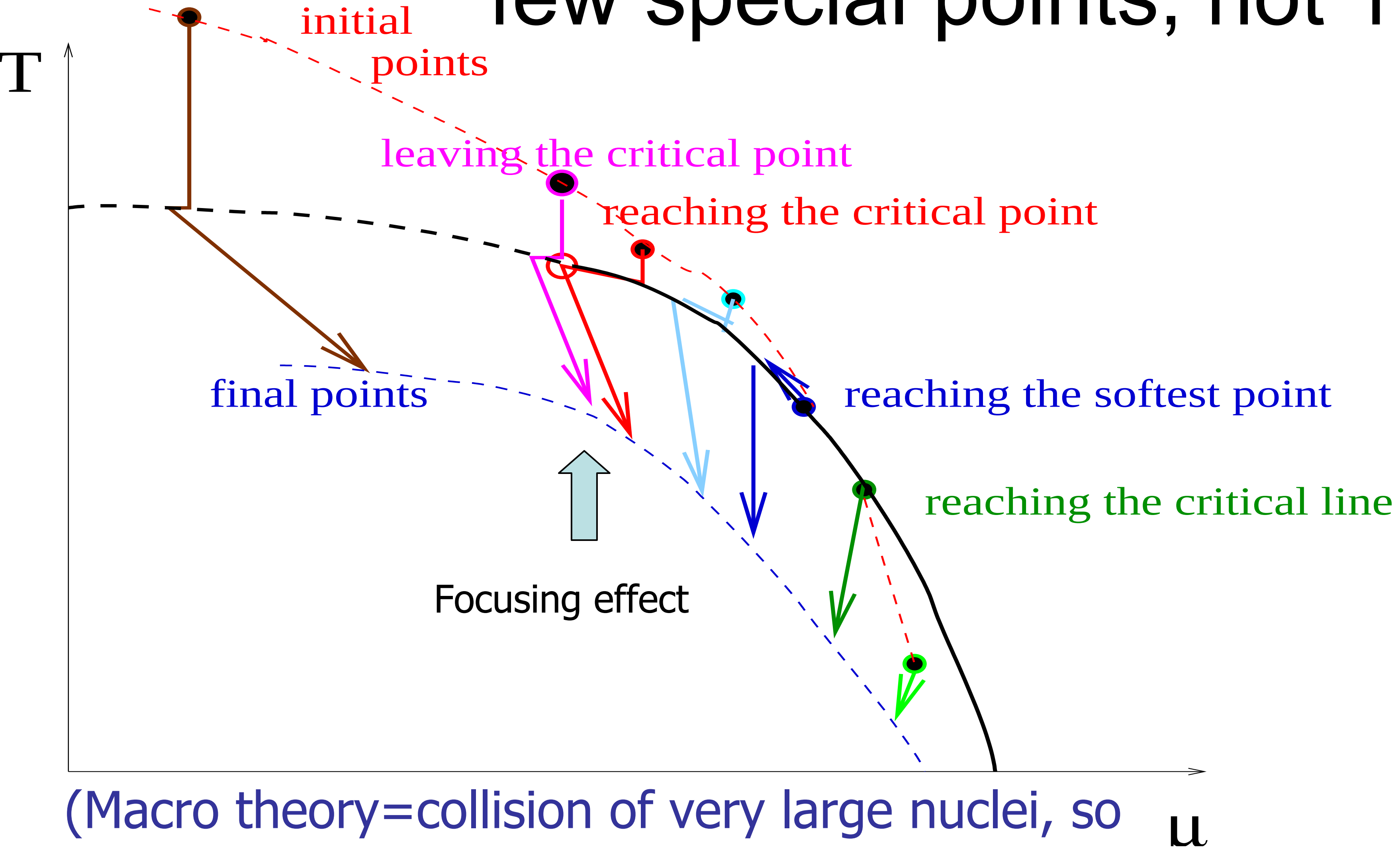


FIG. 3: Lines of constant entropy per quark number versus μ_q/T (left) and in physical units using $T_0 = 175$ MeV to set the scales (right). In the left hand figure we show results obtained using a 4th (full symbols) and 6th (open symbols) order Taylor expansion of the pressure, respectively. Data points correspond to $S/N_B = 300, 150, 90, 60, 45, 30$ (from left to right). The vertical lines indicate the corresponding ideal gas results, $\mu_q/T = 0.08, 0.16, 0.27, 0.41, 0.54$ and 0.82 in decreasing order of values for S/N_B. For a detailed description of the right hand figure see the discussion given in the text.



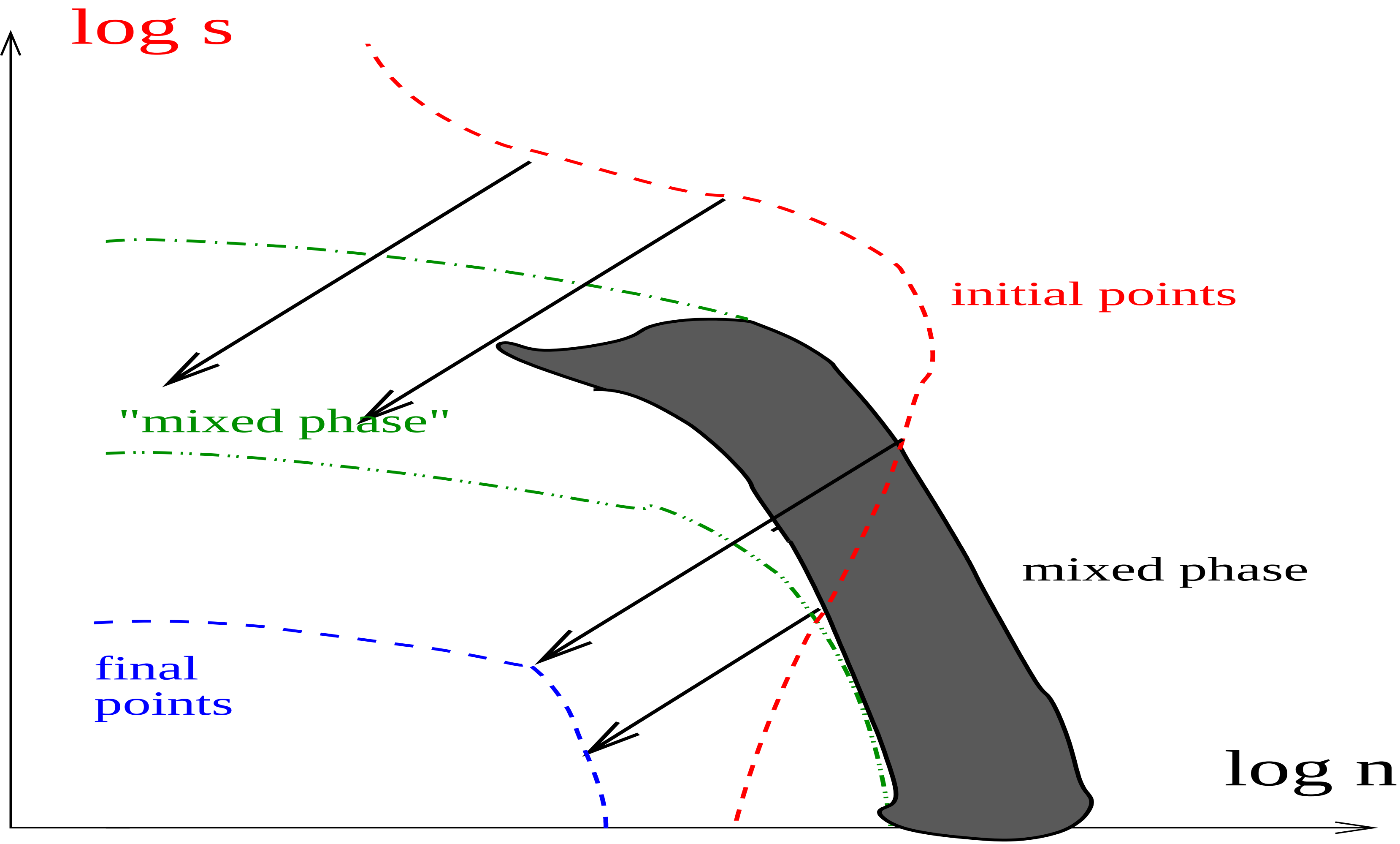
Effective eos along the line s/n_b=const also have a minimum at e=1 GeV/fm^3

Macro theory expects few special points, not 1!



(Macro theory=collision of very large nuclei, so Hydro is valid without doubt...)

The same thing in log(s)-log(n) coordinates **(now the cooling lines are all simple!)**



In passing: does (ideal) hydro work at low energy?

- Yes, radial flow

(which is less influenced by viscosity) is OK

- Important point: one has to do dynamical freezeout for each species and each system size!
- (not done by most hydro even for RHIC, important for s,y-dependences)

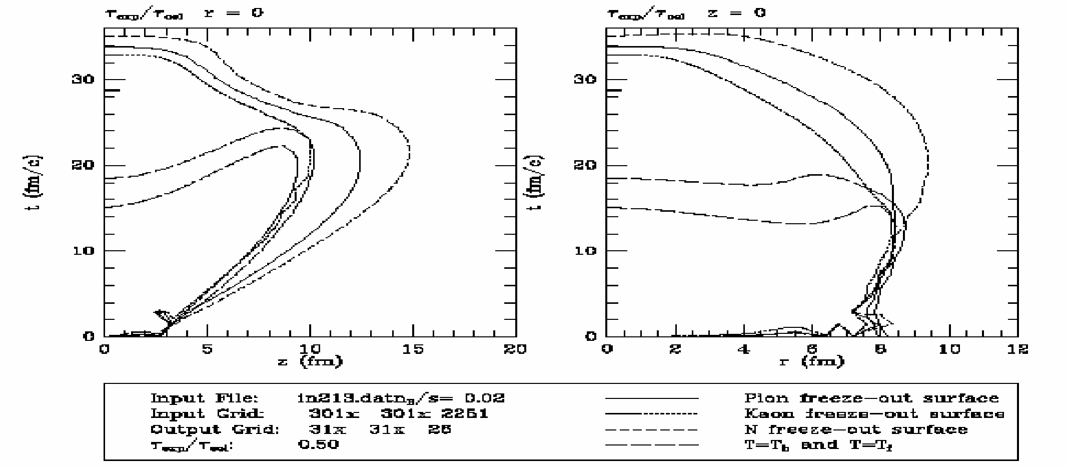
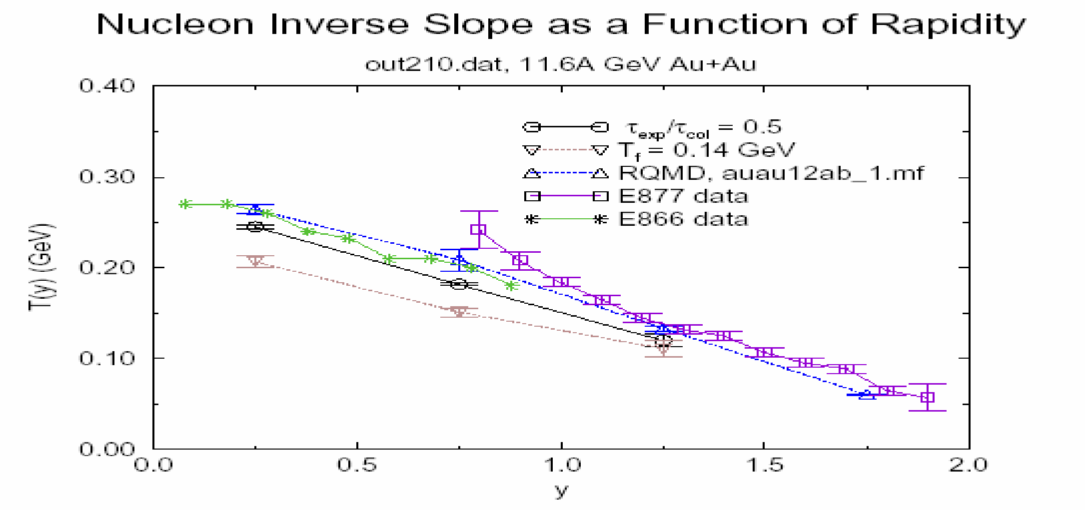


FIG. 12. Freeze-out surfaces for 160A GeV Pb+Pb



specific phenomena close to the QCD critical point: the role of **long-range ``sigma” exchange**

Signals suggested before

Stephanov,ES,Rajagopal (SSR):

- e-by-e fluctuations should be enhanced
- ``focusing" of adiabatic paths, which tend to end near the critical point

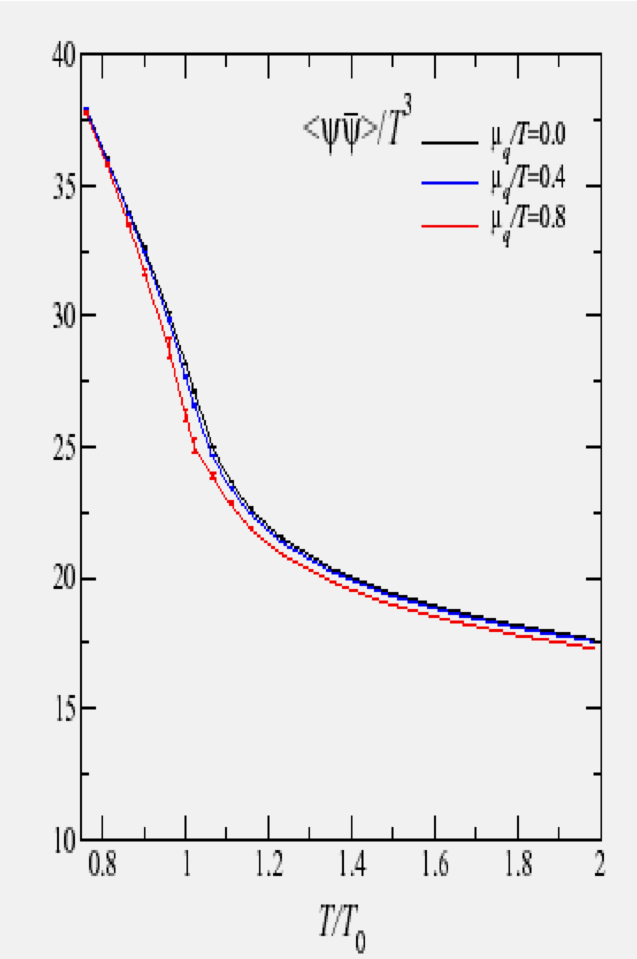
(worked in detail by Nonaka+Asakawa)

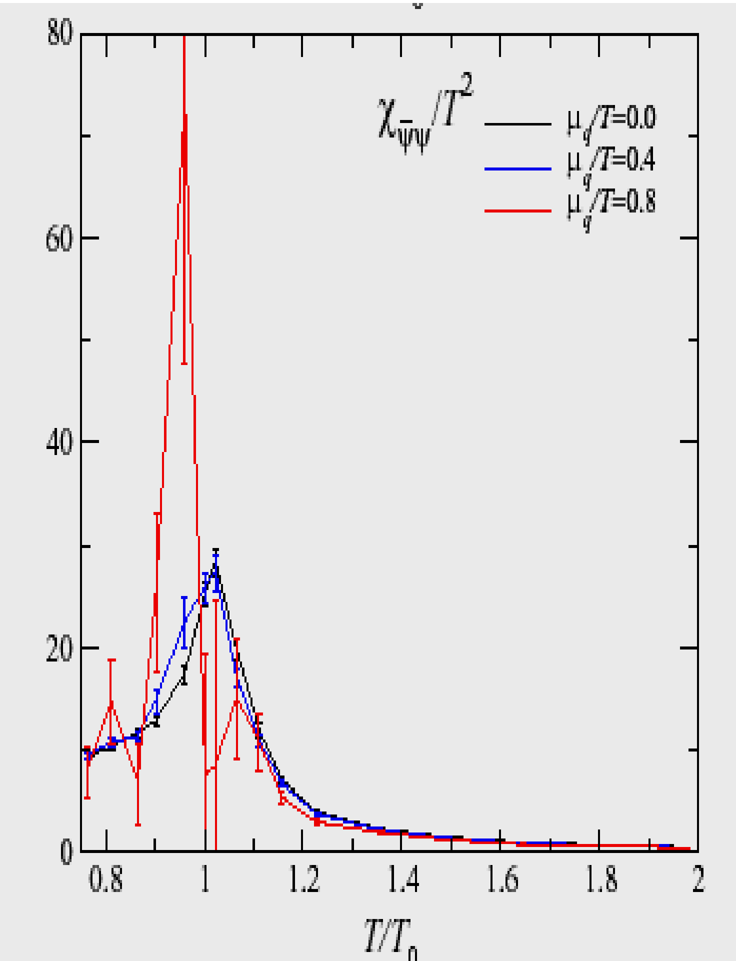
Unfortunately, both are very subtle!

chiral susceptibility seem to show hints toward massless sigma

(=> one has to reduce quark mass!

=> larger computers needed?)





The condensate changes little

But much higher peak in the chiral Succeptibility: **Ligter sigma**

(UK+Bielefeld data 05)

If sigma (screening mass) chages => NN interactions are modified

(ES,2005)

- **The well known Walecka model => near exact cancellation between the two potentials**

$$V = -\frac{g_s^2}{4\pi}\frac{e^{-rm_\sigma}}{r} + \frac{g_v^2}{4\pi}\frac{e^{-rm_\omega}}{r}$$

- **If one sigma-omega combination gets massless , huge change is expected**

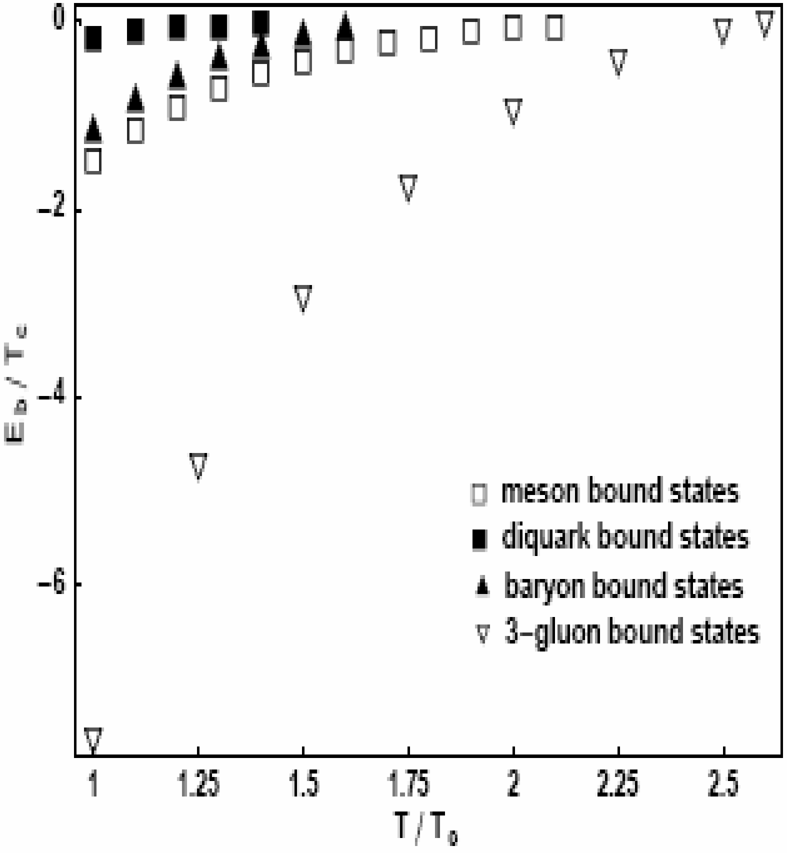
- **nuclear matter calculation is difficult to specify, but in general 100% modification is expected**

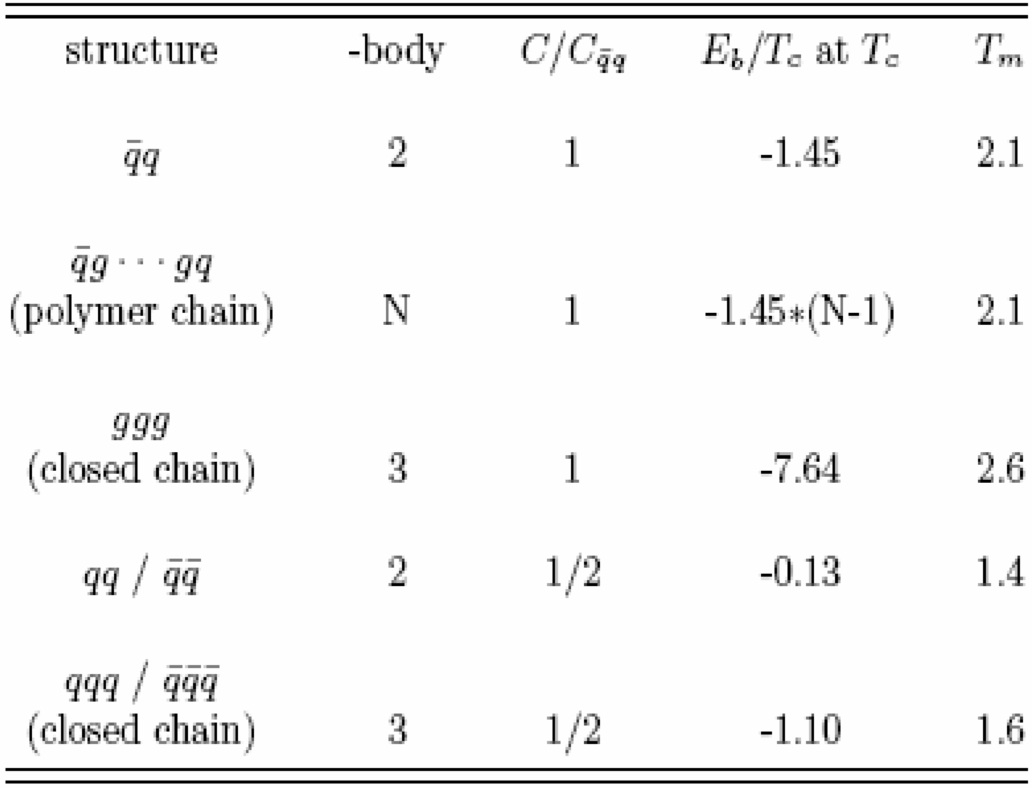
Additional rho mass shifts near the critical point

- **Mesons don’t have omega-induced repulsion => no cancellations**
- **V(vectors)=(2/3)V(baryons)**
- **in dileptons: NA60 does not see strongly shifted rho although there is an excess at M=400-500 MeV in a dilepton spectrum**
- **Tested at RHIC (STAR) near freezeout where rho mass is shifted 10% while width is unchanged**
- **(according to G.Brown+ES,03) sigma-induced attraction contributed about -30 MeV to the observed rho mass shift (and nothing to the width!)**
- **=>e.g. a reduction of m(sigma) by factor 2 leads to a factor 4 increase, to about 120 MeV**

Very heavy baryons in QGP?

Bound baryons above Tc? J.Liao+ES





structure	-body	$C/C_{\bar{q}q}$	E_b/T_c at T_c	T_m
$\bar{q}q$	2	1	-1.45	2.1
$\bar{q}g \cdots gq$ (polymer chain)	N	1	-1.45*(N-1)	2.1
ggg (closed chain)	3	1	-7.64	2.6
qq / $\bar{q}\bar{q}$	2	1/2	-0.13	1.4
qqq / $\bar{q}\bar{q}\bar{q}$ (closed chain)	3	1/2	-1.10	1.6

Baryons go from light to heavy because quark quasiparticles are heavy

(e.g. Mq is about 800 MeV at 1.5 Tc)

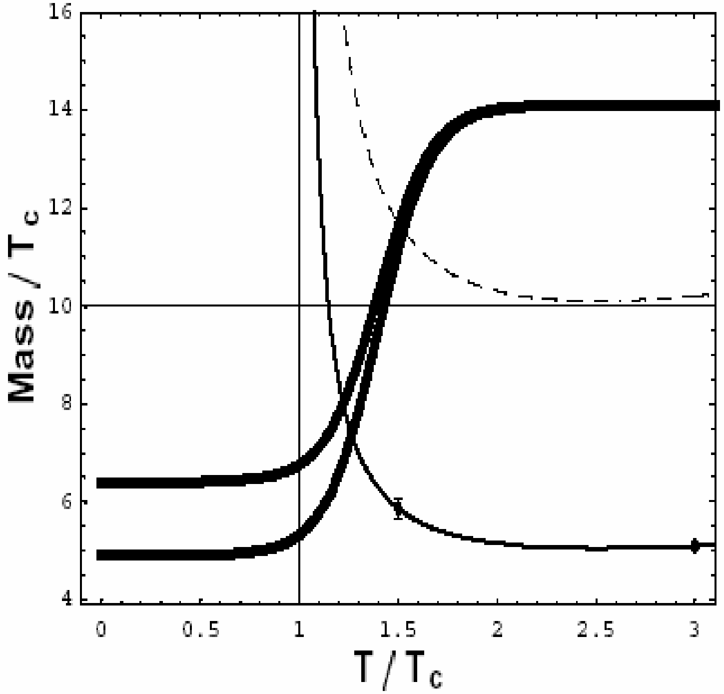


FIG. 5. Masses of various states studied in this work. The thin solid line is for quark and the dashed line is twice quark mass which is roughly for quark-gluon and diquark. The lower thick solid line is for nucleon states and the upper one for Δ states. These masses are used for calculation of Fig.7.

Unlike colored objects,
Such as q, qg, qq etc,
Baryons (N…) should
Evolve through the
QCD phase transition
Continuously
Their mass must grow
Into the sQGP side

This will generate T and mu derivatives! M” has a ``wiggle”!

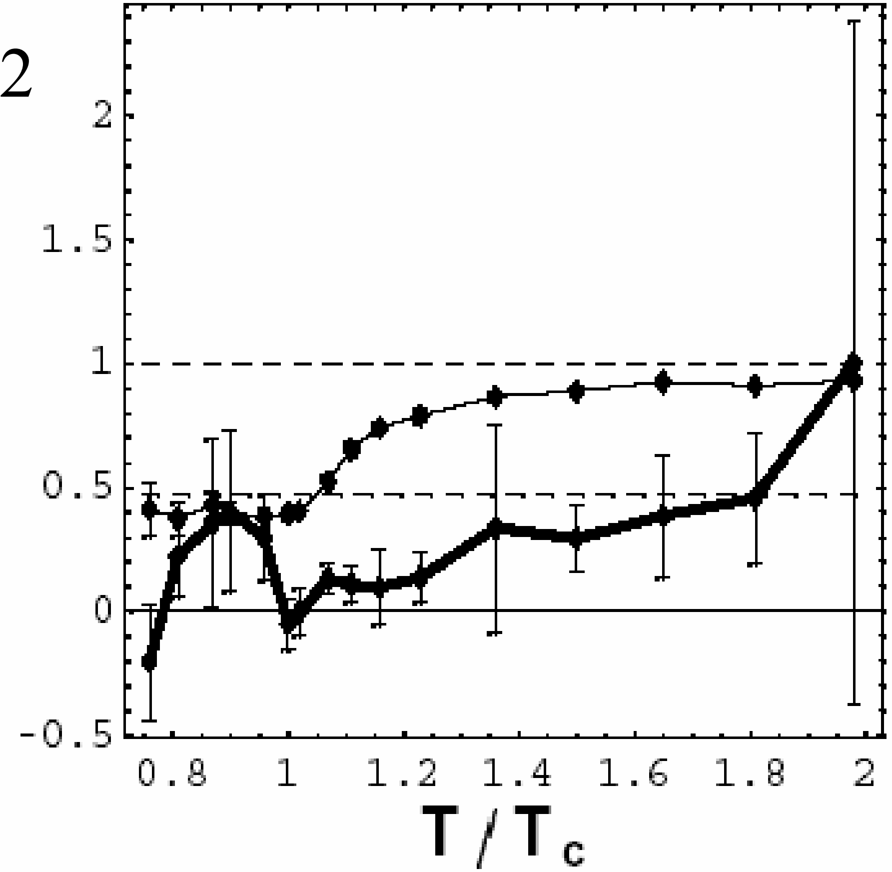
Baryons, not quarks dominate d4 and d6

$$\partial{}^\wedge 2\mu I / \partial{}^\wedge 2\mu = ((2I_3)/B){}^\wedge 2$$

Derivatives work like this:

- **For quarks d_In/d_n=1**
- **For N and Delta+, Delta0=1/9**
- **For Delta ++ and Delta -=1**

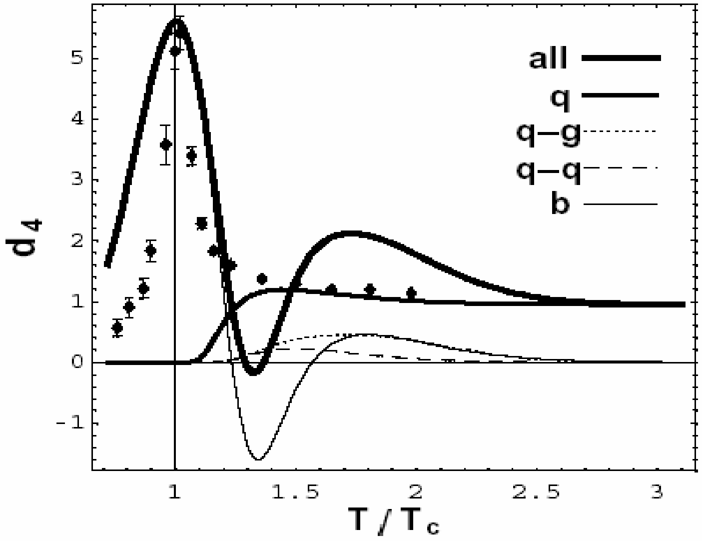
- **For 4 N and 16 Delta = .466**

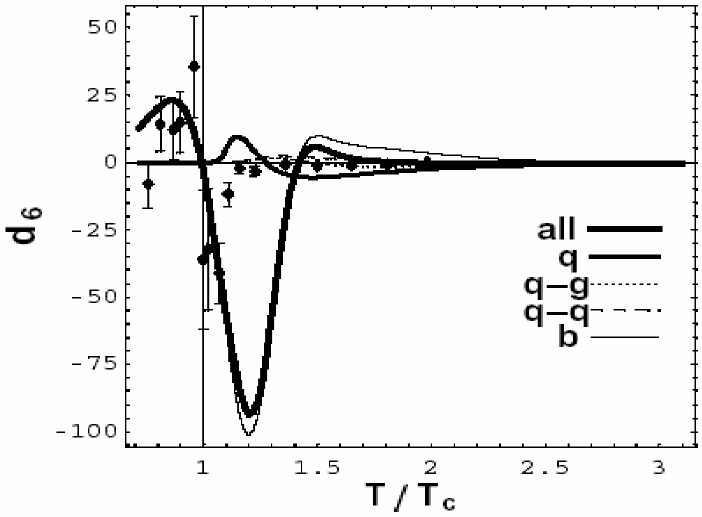


.46
N+Δ

FIG. 6. The susceptibilities ratios d_4^I/d_4 (the thin solid) and d_6^I/d_6 (the thick solid). The dashed lines correspond to ideal quark gas (upper) and ideal baryonic gas (lower).

How the contribution of Baryons (plus all others) look like:





The peak in d4 and a wiggle in d6 in UK_Bielefeld lattice data (points) are reproduced

The wiggles appear due to baryon mass dependence with an inflection point (M” changes sign)

Strongly coupled color superconductivity

- Tc/Ef is very small in conventional superconductors (10^-4 to 10^-2 high Tc)
- Color superconductivity with instanton-induced diquarks gave Tc/Ef about 1/10
- Recent experiments with trapped fermionic atoms at a->infinity provided a ``universal strongly coupled limit”

Tc/Ef=.27

Kinast et al, cond-mat/0502087

That should be the universal upper limit =>
it means Tc of about 100 MeV is (in principle) possible, if interaction is strong enough (Feshbach resonance also?)

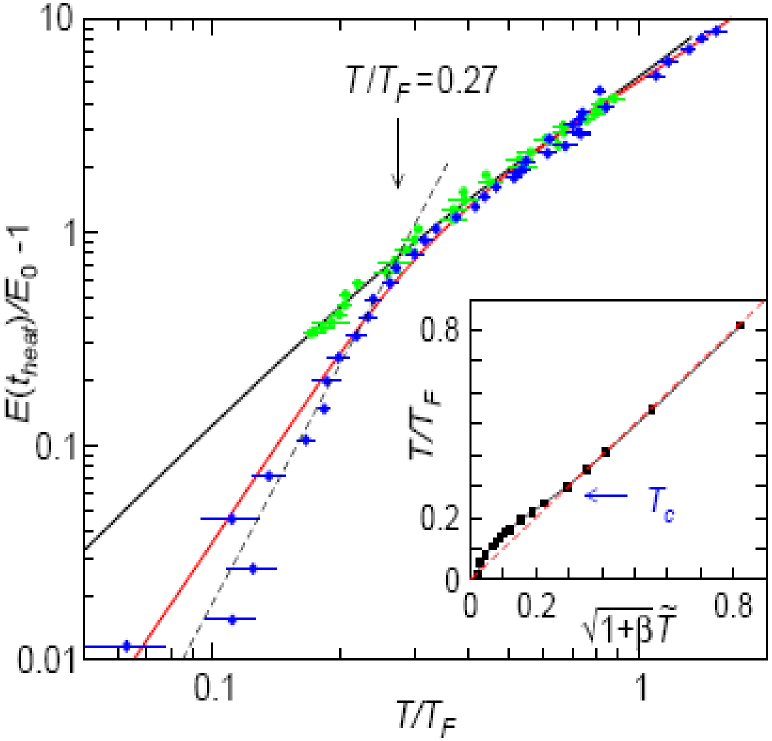


Figure 2: Energy input versus temperature from Fig. 1 after temperature calibration on a $log-log$ scale. The strongly-interacting Fermi gas shows a transition in behavior near $T/T_F = 0.27$. Green circles: noninteracting Fermi gas data; Blue diamonds: strongly-interacting Fermi gas data; Red (Black) curve: prediction for a unitary (noninteracting), Fermi gas in a Gaussian trap as in experiment; Black dashed line: best fit power law $97.3\,(T/T_F)^{3.73}$ to the unitary data for $T/T_F \leq 0.27$. The inset shows the calibration curve, which has been applied to the unitary data (blue diamonds). The red dashed line in the inset represents the diagonal, $T/T_F = \sqrt{1+\beta}\,\tilde{T}$. Here $E_0 \equiv E(T=0)$.

sQGP and (de)confinement

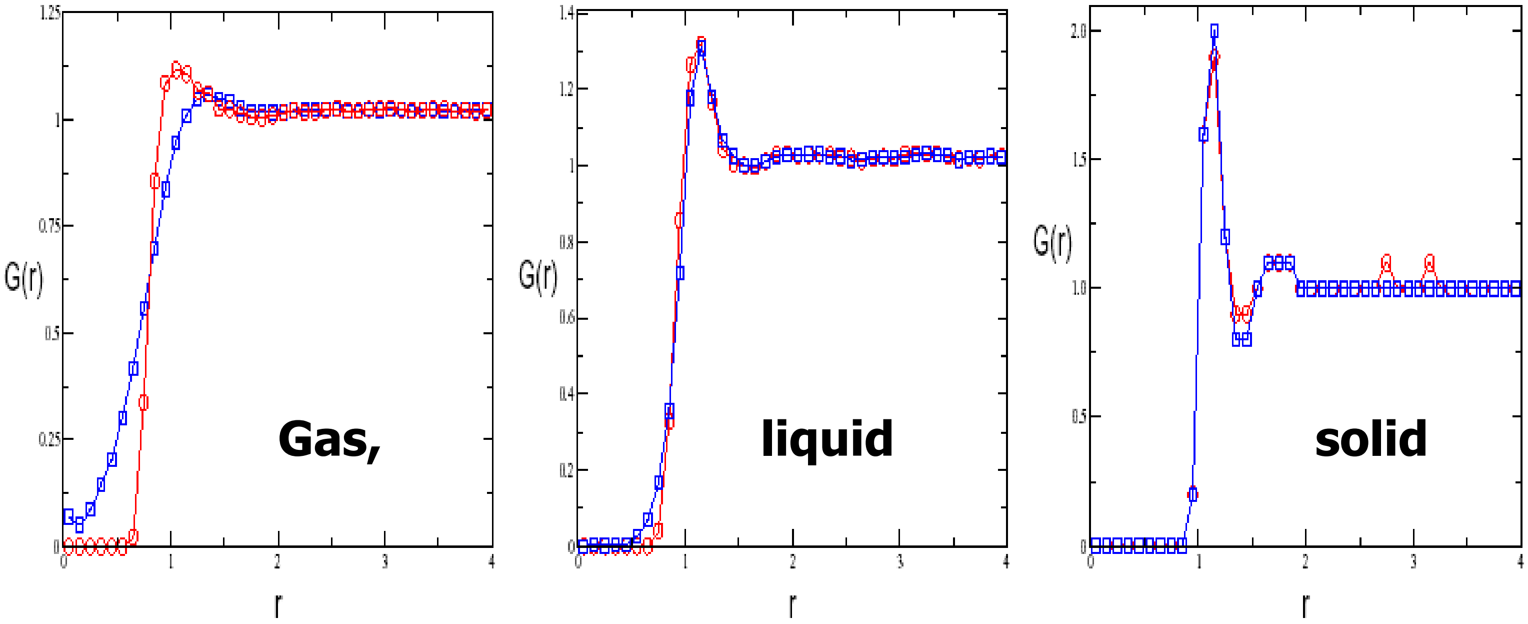
- For $SU(2)$ charge Q is a unit vector, $\vec{Q} = (Q^1, Q^2, Q^3)$

$$dx_i/dt = p_i/m,$$
$$dp_i/dt = (g^2/4\pi)\sum \vec{Q}_i \cdot \vec{Q}_j/r_{ij}^2,$$
$$d\vec{Q}_i/dt = (g^2/4\pi)\sum \vec{Q}_i \times \vec{Q}_j/|r_{ij}|$$

- Note: $d\vec{Q}_i^2/dt = 0$

Wong eqn **can be rewritten as**
x-p canonical pairs, 1 pair for SU(2), 3 for SU(3),
(as a so called Darboux variables).
We do su(2) => C is a unit vector on a sphere O(3)

Structure factor for cQGP



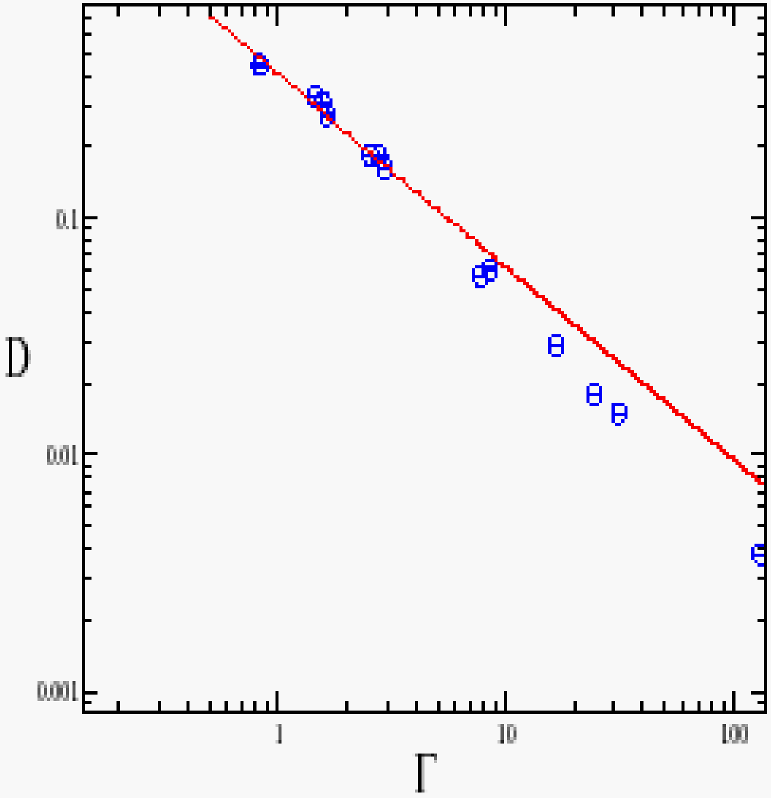
- G_d correlation function for $\Gamma = 0.83, 31.3, 131$, respectively; red circles correspond to $t^* = 0$, and blue squares correspond to $t^* = 6$
- $\Gamma = 0.83$ is a weak correlation between the particles; relaxes rather quickly with time
- The correlation is more robust for $\Gamma = 31.3$ (*liquid*)
- For $\Gamma = 131$ correlation is very stable (*solid*)

Self-diffusion

$$D(\tau) = \frac{1}{3N} \left\langle \sum_{i=1}^{N} \vec{v}_i(\tau) \cdot \vec{v}_i(0) \right\rangle$$

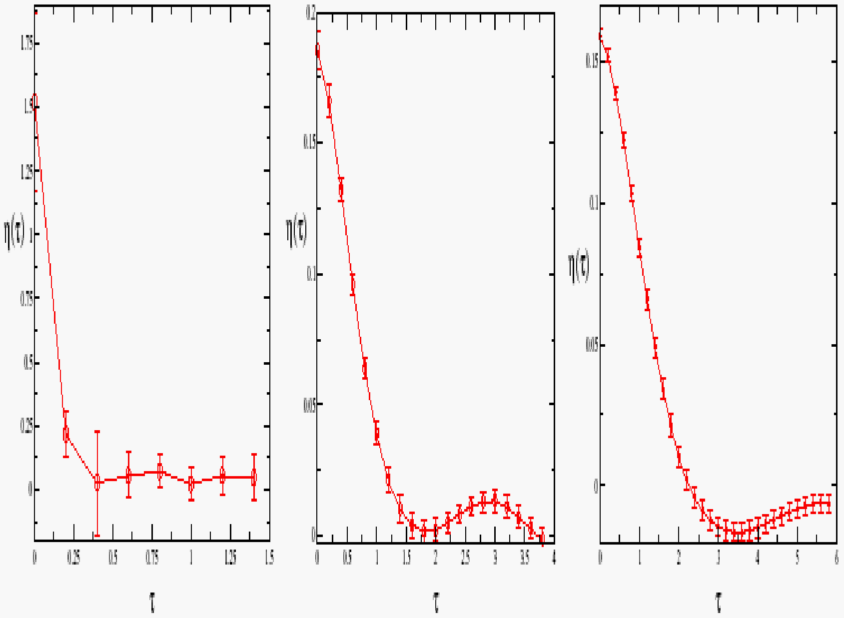
$$D = \int_0^\infty D(\tau)\, d\tau$$

$$D \approx \frac{0.4}{\Gamma^{4/5}}$$

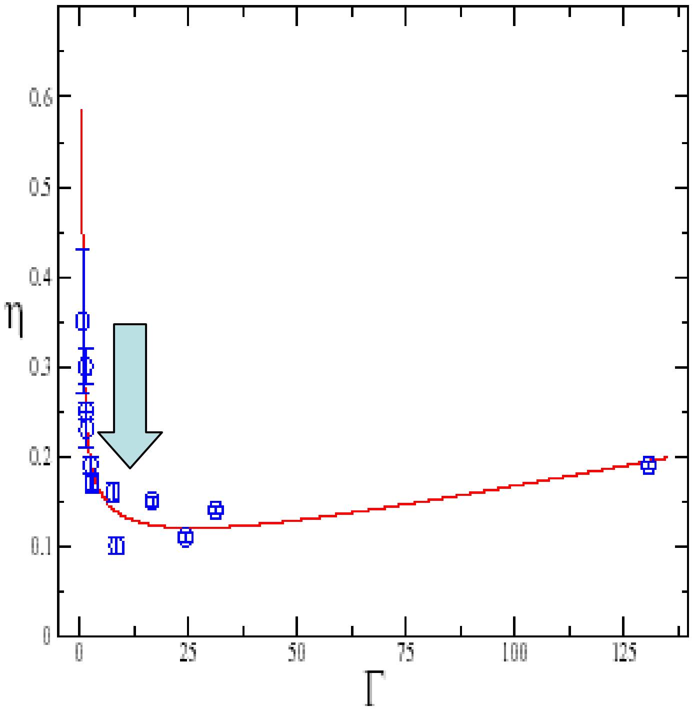


First results on viscosity:
QGP (blue arrow) is about the best liquid one can possibly make

translated to sQGP => eta/s=.3 or so, <<1 but >1/4pi limit



- Stress-tensor autocorrelation correlation function $\eta(t)$ for $\Gamma =$ 0.83, 31.3, 131



$$\eta \approx 0.001\,\Gamma + \frac{0.242}{\Gamma^{0.3}} + \frac{0.072}{\Gamma^{2}}$$

From sQGP to confinement…

- **Strongly coupled QGP <= very good liquid** =hydro works well, small viscosity and charm diffusion, large dE/dx at RHIC
- Qualitative agreement with such analog problems as (i) classical strongly coupled plasma (cQGP); (ii) cold trapped gases in strongly coupled regime; (III) AdS/CFT= N=4 SUSY YM
- And yet, **none of those have confinement. What is missing in the picture?**

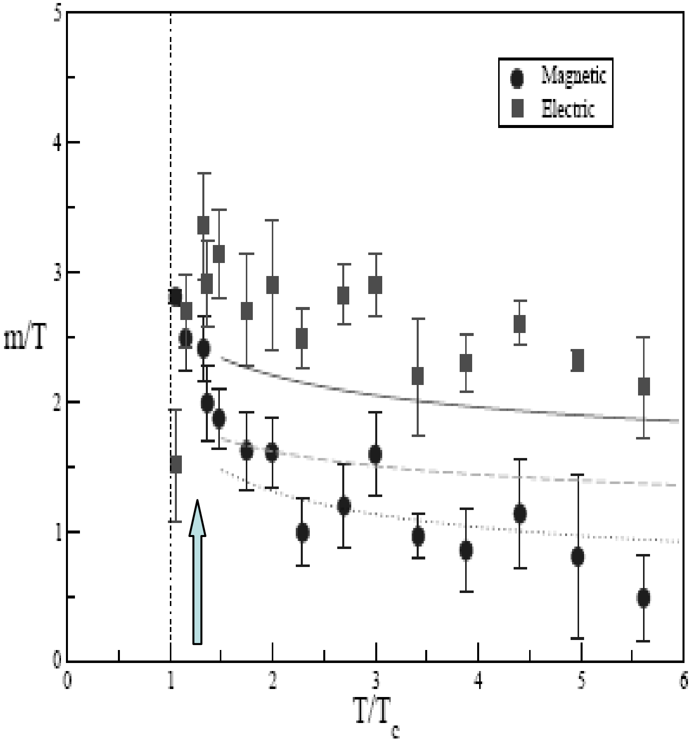
Understanding confinement

(and ``post-confinement” above the critical line) needs understanding of magnetically charged quasiparticles - monopoles

- N=2 SUSY YM (``Seiberg-Witten theory”) is a working example of confinement due to condenced monopoles
- It teached us that monopoles must be very light and weakly interacting (in IR) near the critical point
- This + Dirac condition => electric coupling must then be large
- Above Tc one gets to a point when gluons and monopoles have comparable masses and couplings =>
- **New conjecture: sQGP is a plasma of both electric and magnetic charges (yet to be studied)**

monopoles in QGP

- Dual superconductivity as a confinement mechanism (‘tHooft, Mandelstam 1980’s) require monopole condesation (nonzero VEV)
- But maybe we better look at T>T and study dyon dynamics without condensation when they are heavy/classical enough?
- Lorentz force on monopoles make them reflect from a region with E, even rotate around the E flux => compresses E into flux tubes even in classical plasma!



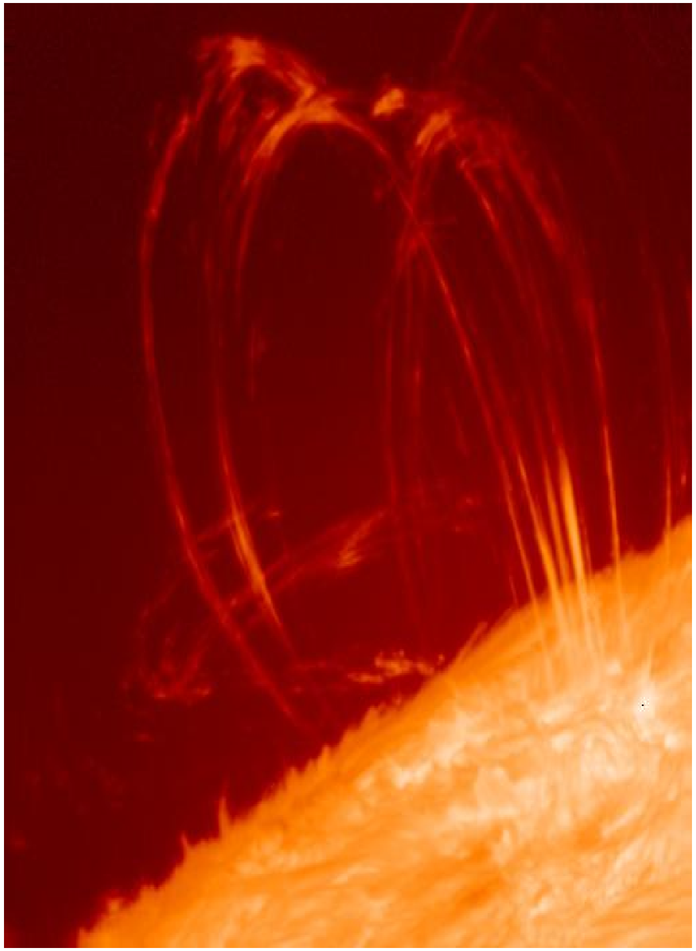
Electric and magnetic scrrening Masses, Nakamura et al, 2004
My arrow shows **the ``self-dual Point”**

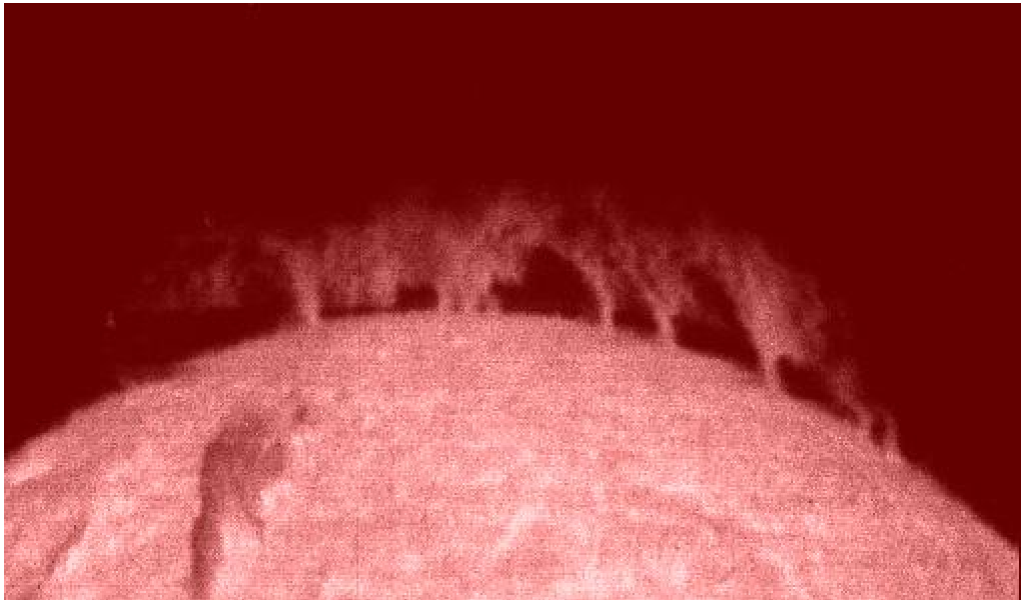
Can a flux tube exist without a dual superconductor?

- **Here are magnetic flux tubes at the Sun,**

where classical electrons rotate around it

- **B: about 1 kG,**
- **Lifetime: few months**

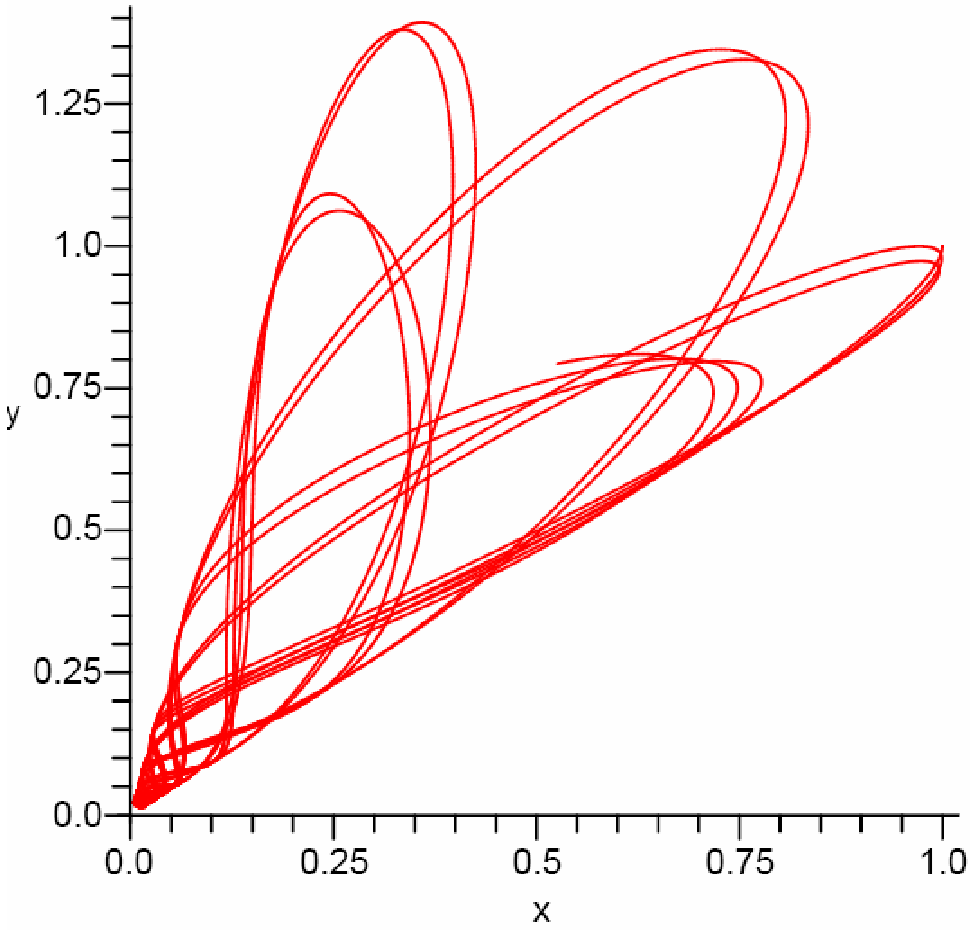




Let us however start with one monopole (dyon)+ one charge

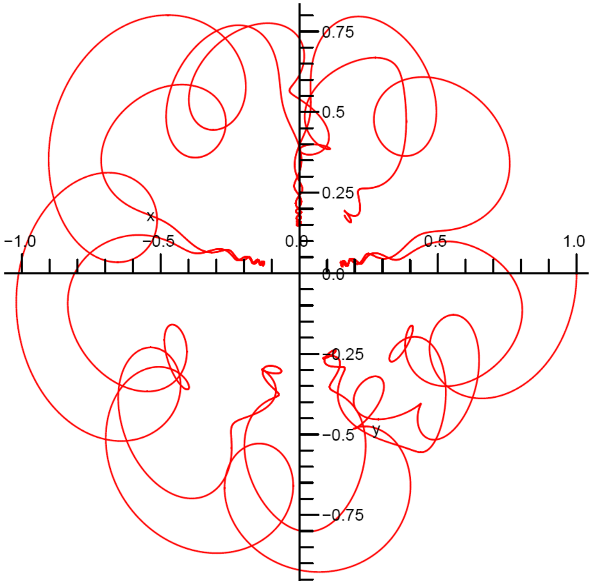
A.Poincare 110 years ago had explained that there is angular momentum of the field J | | to r
and that the motion is restricted to a cone

Monopole repels from a charge

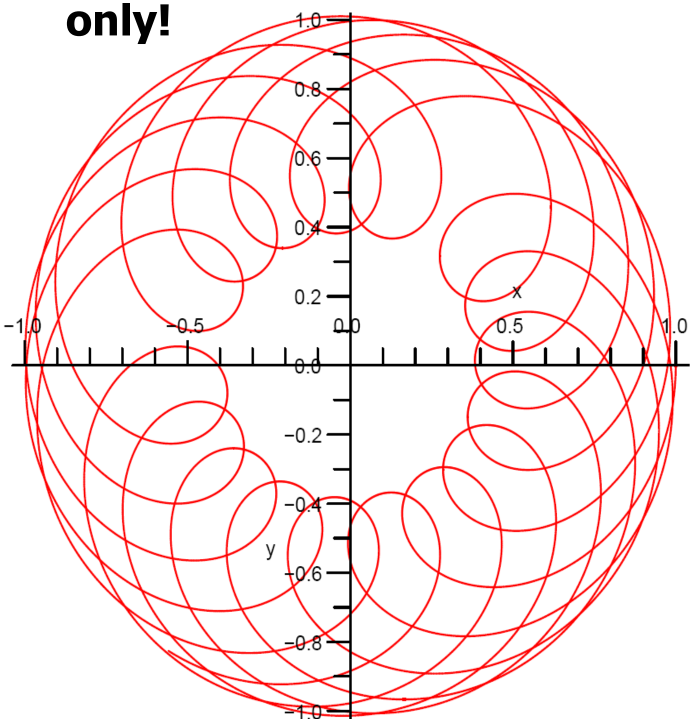


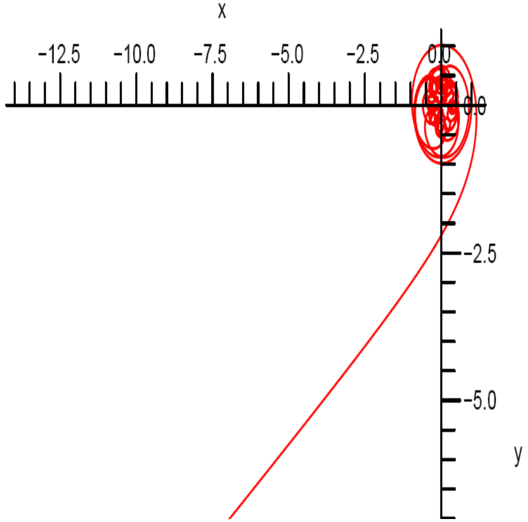
Here is my solution for a dyon with Attractive charge, preventing the escape to large r
Quantum system is like H atom…

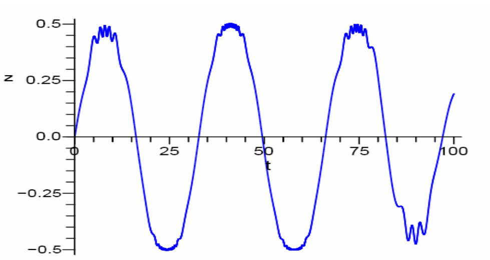
I found that **two charges** play ping-pong by a monopole without even moving!



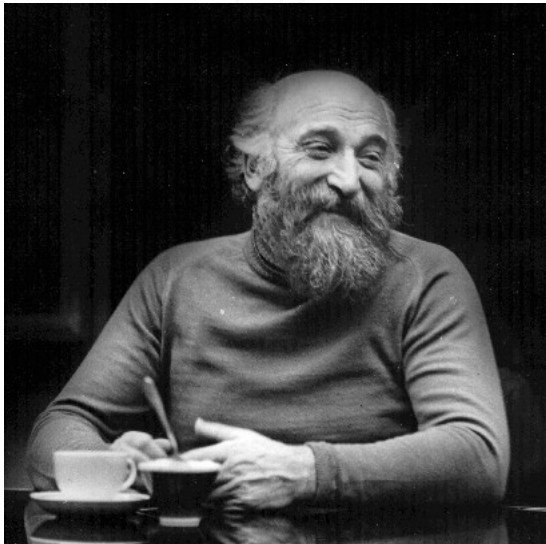
Chaotic, regular and escape trajectories for a monopole, all different in initial condition by 1/1000 only!







Dual to Budker's magnetic bottle



Summary

Excitation:

- **4 special points expected**
- **2 are related with 1st order line**
- **2 with the critical point**

- **The softest point corresponds to the logest lived fireball => (horn?)**
- Near critical point one expects a massless (sigma-omega) mode

=>V(pions) gets repulsive

=> Walecka cancellation is violated => stronger NN and rhoN attraction

- affect   N   Is it what is happening at 40 GeV according to NA49?
- Heavy N,Delta in QGP?
- Tc/Ef<.27 for CSC
- sQGP is being understood… Transport coeffients etc
- monopoles are needed for confinement