The Physics of Relativistic Heavy Ion Collisions

18th National Nuclear Physics Summer School

July 23 - August 5, 2006

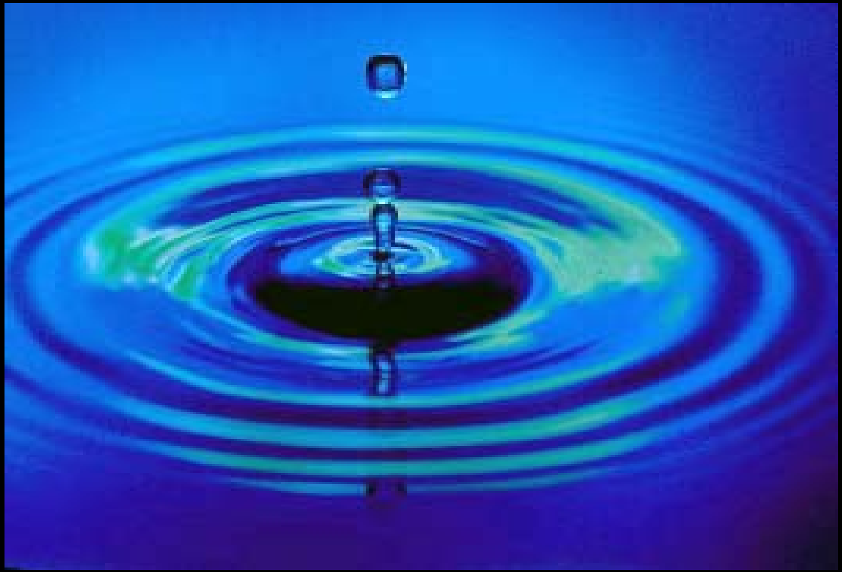
Indiana University, Bloomington, IN

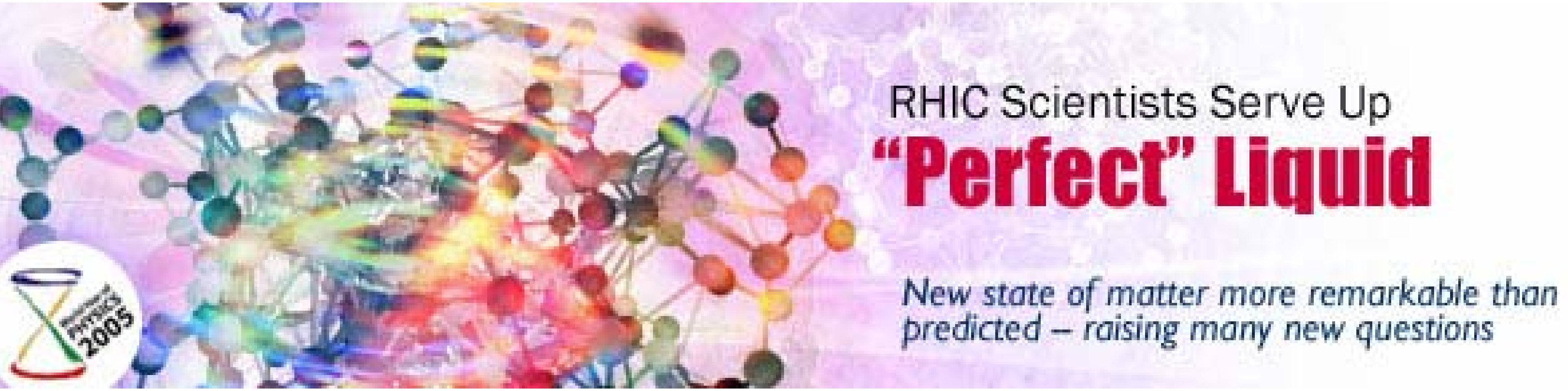
Lecture #3

18th National Nuclear Physics Summer School
Lectures July 31-August 3, 2006

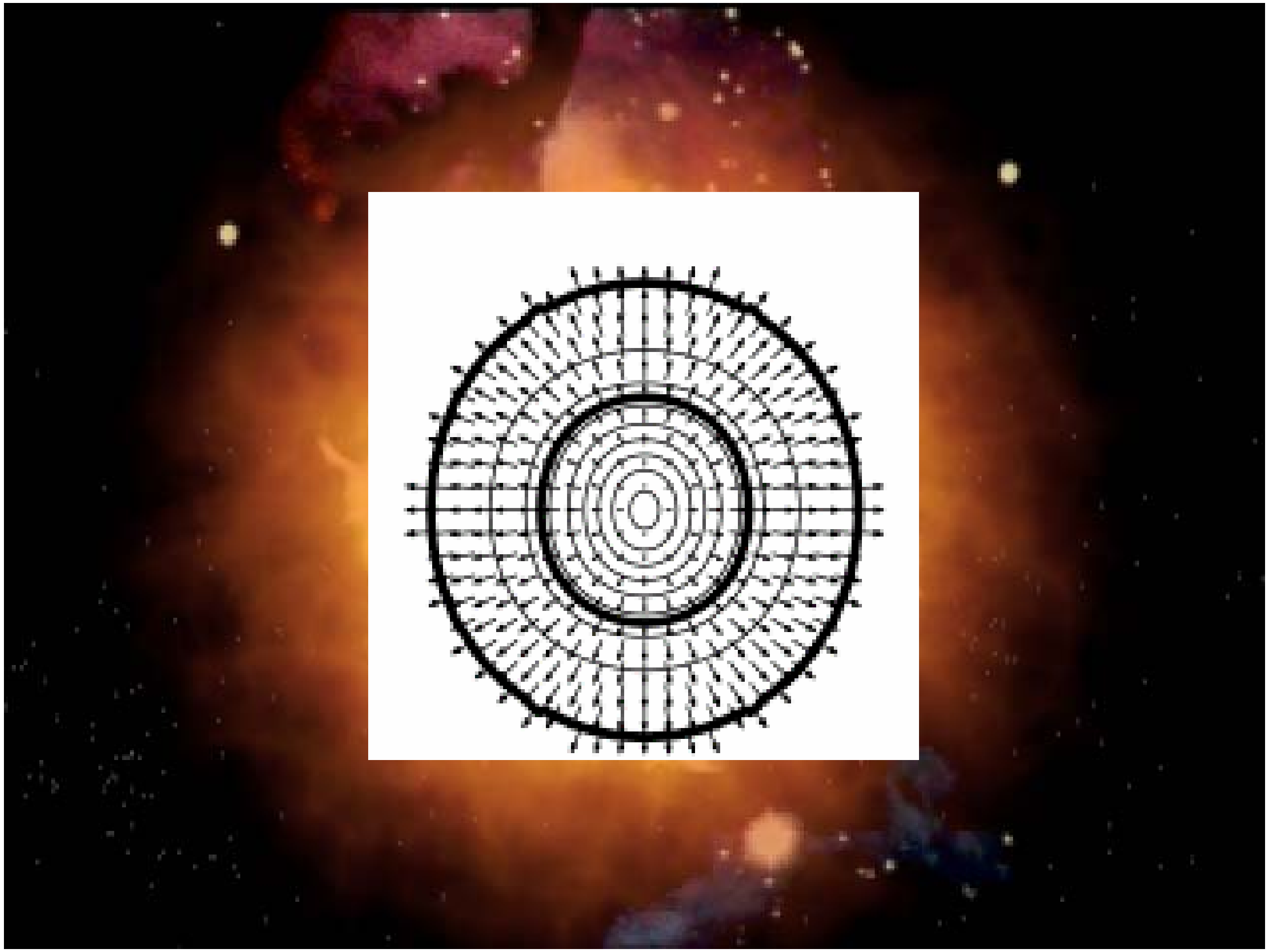
Associate Professor Jamie Nagle
University of Colorado, Boulder

The Perfect Liquid




RHIC Scientists Serve Up
"Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions

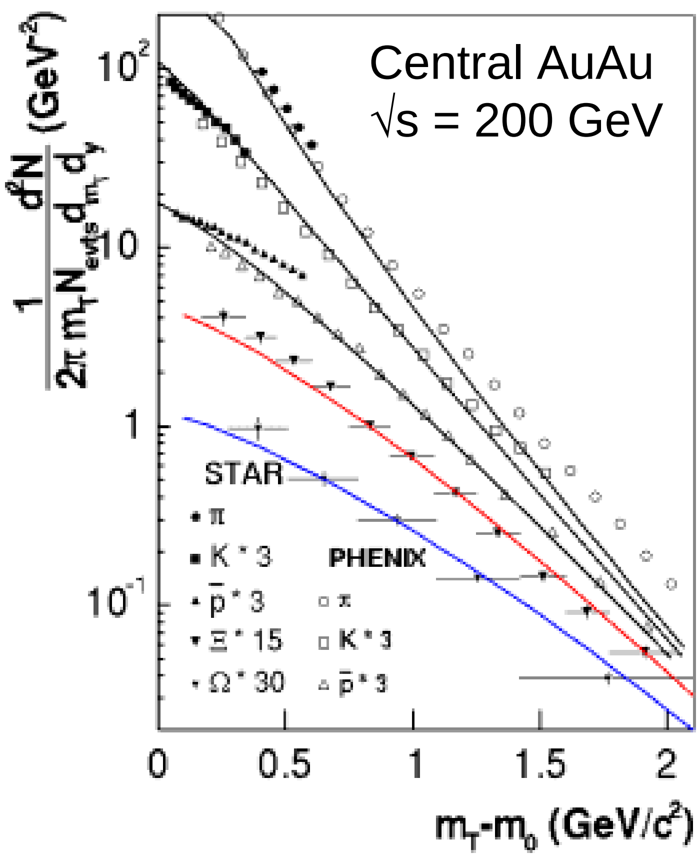
Exploding Fireball

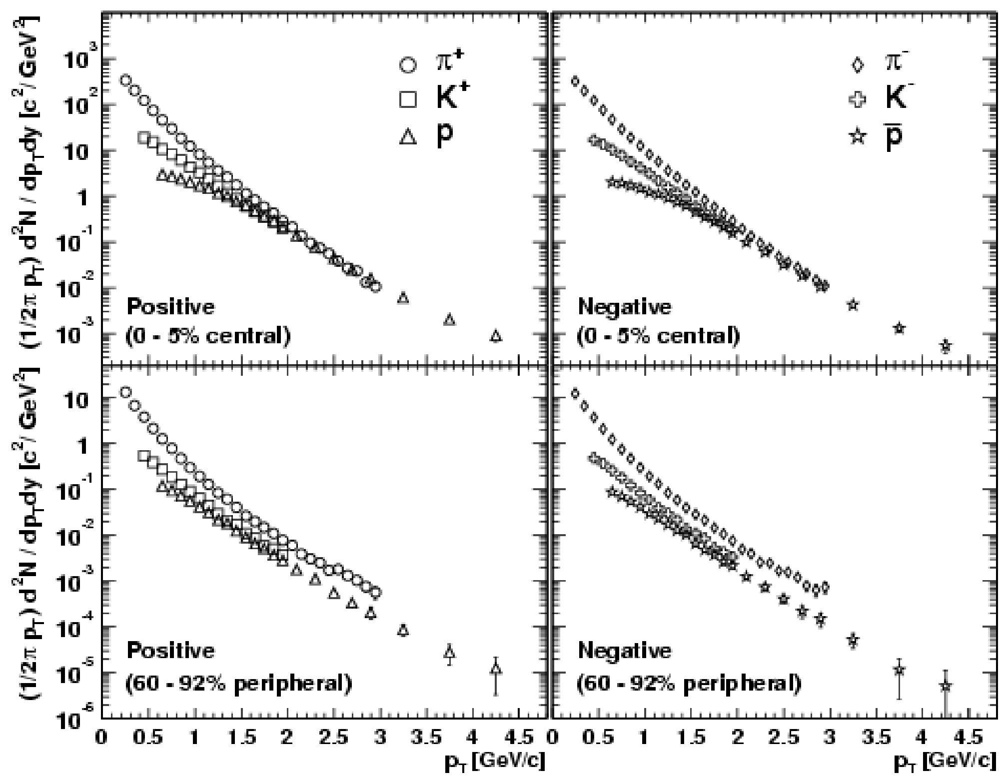


Radial Expansion

Static thermal source should have approximately Boltzmann energy distributions.

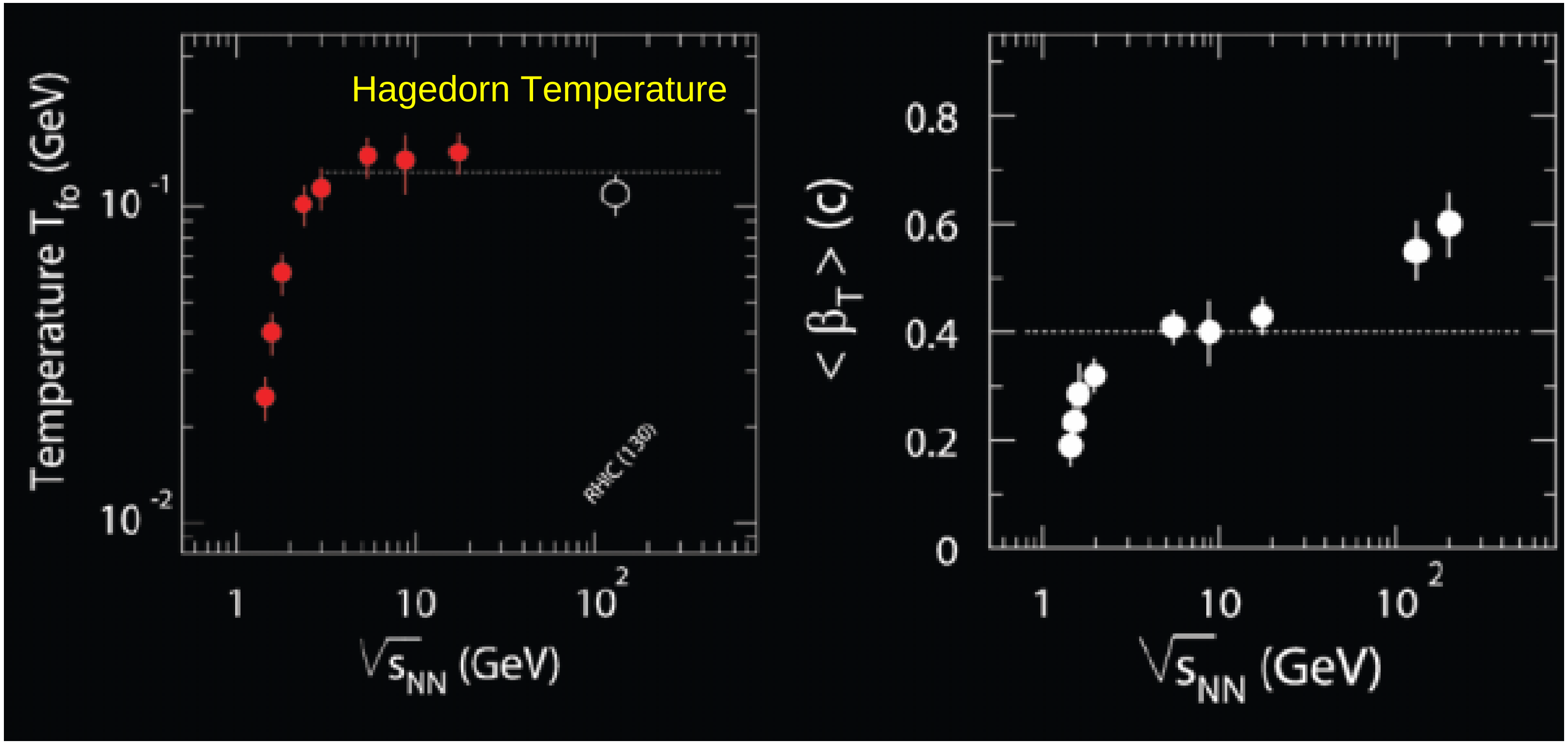
We often only look at pT distributions since it decouples original longitudinal momentum issue.





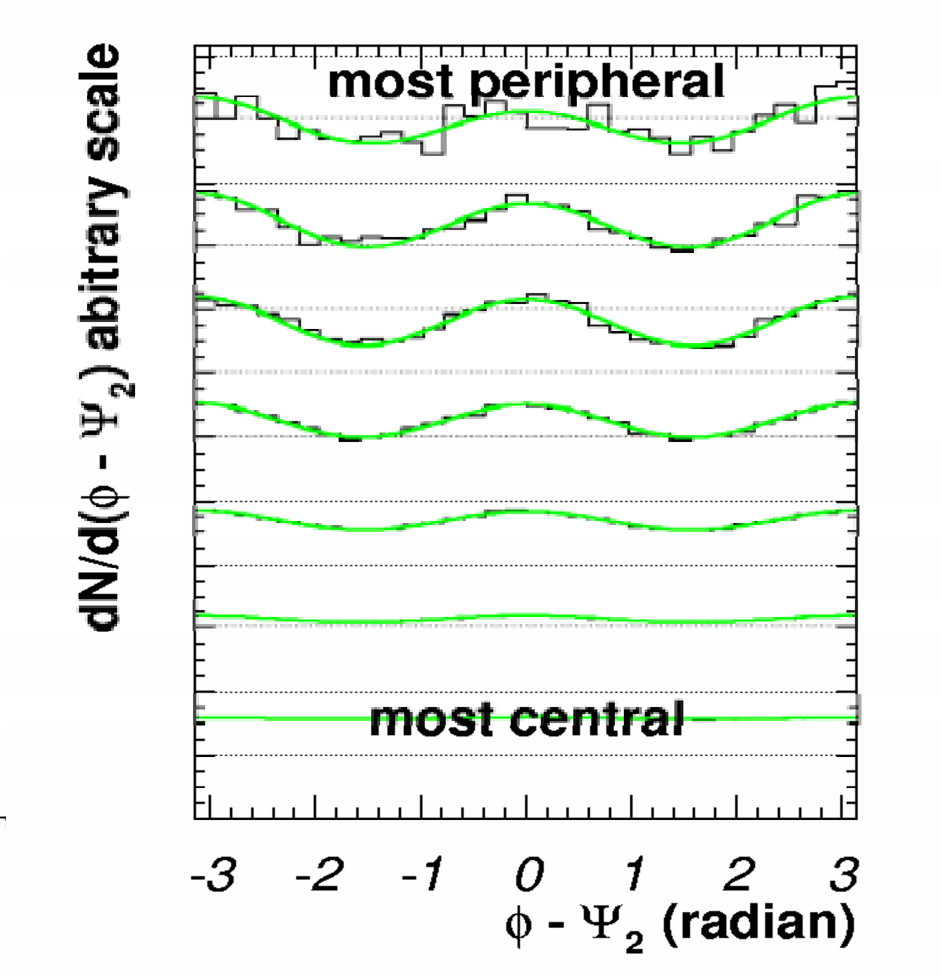
Temperature and Velocity Boost

Combining pT distributions for many hadrons and two particle correlations, one can extract an initial temperature and a velocity boost factor.



Note that T may not really be a temperature but could just be a phase space factor.

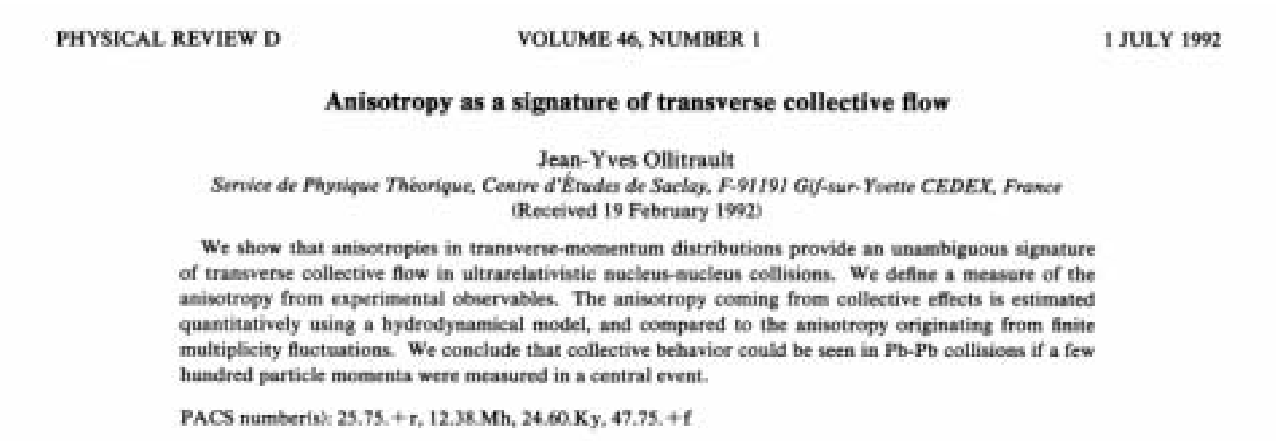
How Does the Matter Behave?



$$\frac{dN}{p_T dp_T dy d\varphi}(p_T \quad \ldots \quad b)\cos(2\varphi) + \ldots)$$

Simple answer is with a very high degree of collectivity.

Go Back to the Source…


PHYSICAL REVIEW D VOLUME 46, NUMBER 1 1 JULY 1992

Anisotropy as a signature of transverse collective flow

Jean-Yves Ollitrault
Service de Physique Théorique, Centre d'Études de Saclay, F-91191 Gif-sur-Yvette CEDEX, France
(Received 19 February 1992)

We show that anisotropies in transverse-momentum distributions provide an unambiguous signature of transverse collective flow in ultrarelativistic nucleus-nucleus collisions. We define a measure of the anisotropy from experimental observables. The anisotropy coming from collective effects is estimated quantitatively using a hydrodynamical model, and compared to the anisotropy originating from finite multiplicity fluctuations. We conclude that collective behavior could be seen in Pb-Pb collisions if a few hundred particle momenta were measured in a central event.

PACS number(s): 25.75.+r, 12.38.Mh, 24.60.Ky, 47.75.+f

Hydrodynamics

Hydrodynamic Equations

$$\partial_\mu T^{\mu\nu} = 0,$$ Energy-momentum conservation

$$\partial_\mu n_i^\mu = 0$$ Charge conservations (baryon, strangeness, etc…)

For perfect fluids (neglecting viscosity),

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu}$$

Need equation of state(EoS)
$P(e,n_B)$

Energy density   Pressure   4-velocity

Within ideal hydrodynamics, pressure gradient *dP*/*dx* is the driving force of collective flow.

→ Collective flow is believed to reflect information about EoS!
→ Phenomenon which connects 1st principle with experiment

Caveat: Thermalization, λ << (typical system size)

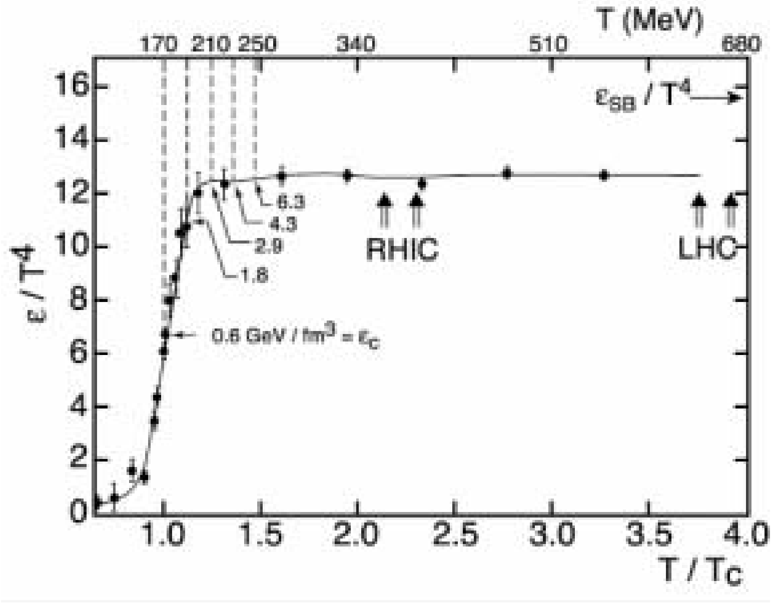
Hydrodynamics

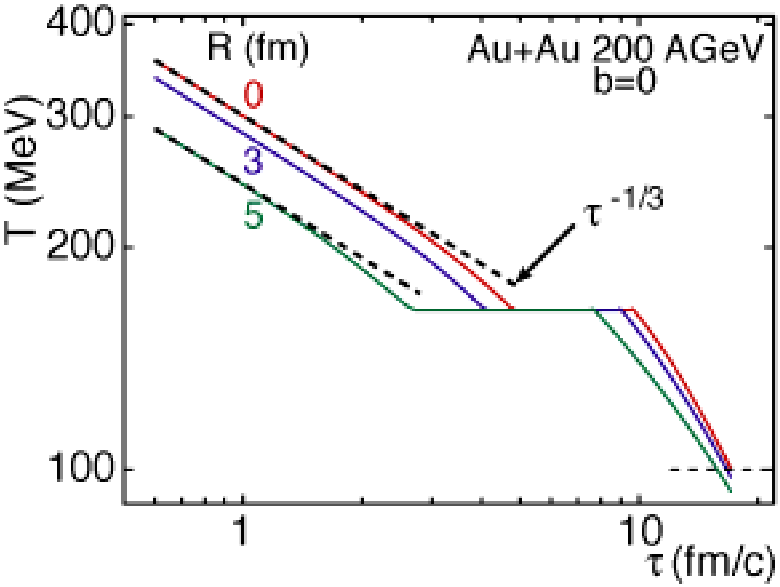
- Assume early equilibration

- Equations of Motion

$$\partial_\mu \left[(e+p)\, u^\mu u^\nu - p\, g^{\mu\nu} \right] = 0$$
$$\partial_\mu \left[s\, u^\mu \right] = 0$$

- Equation of State from lattice QCD

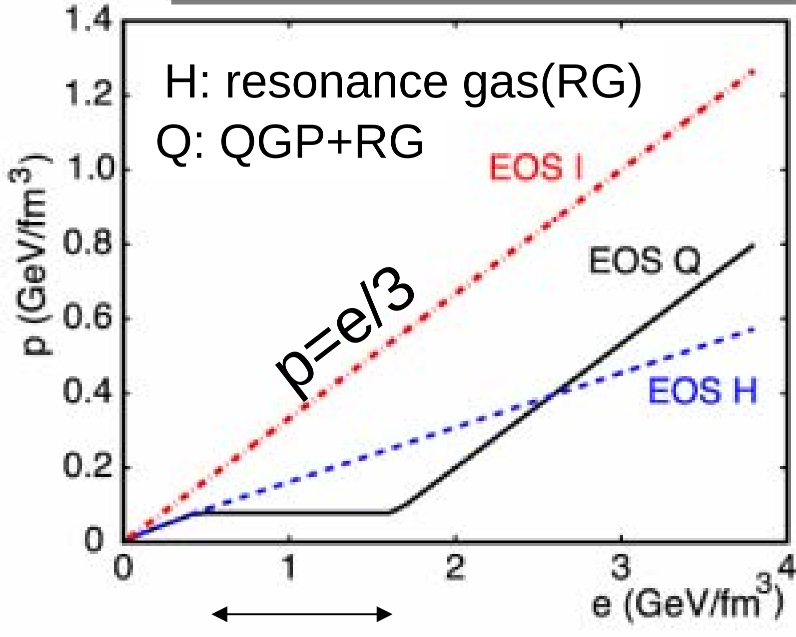




Equation of State

One can test many kinds of EoS in hydrodynamics.

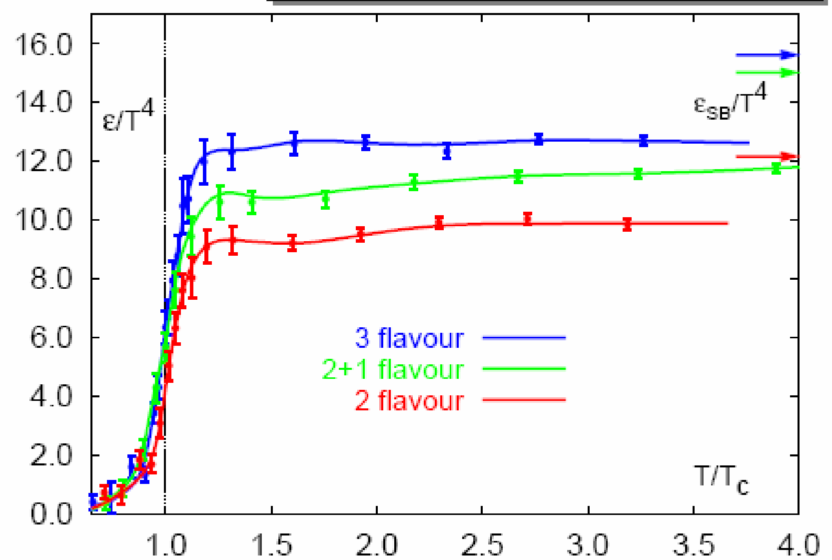
Typical EoS in hydro model



Latent heat

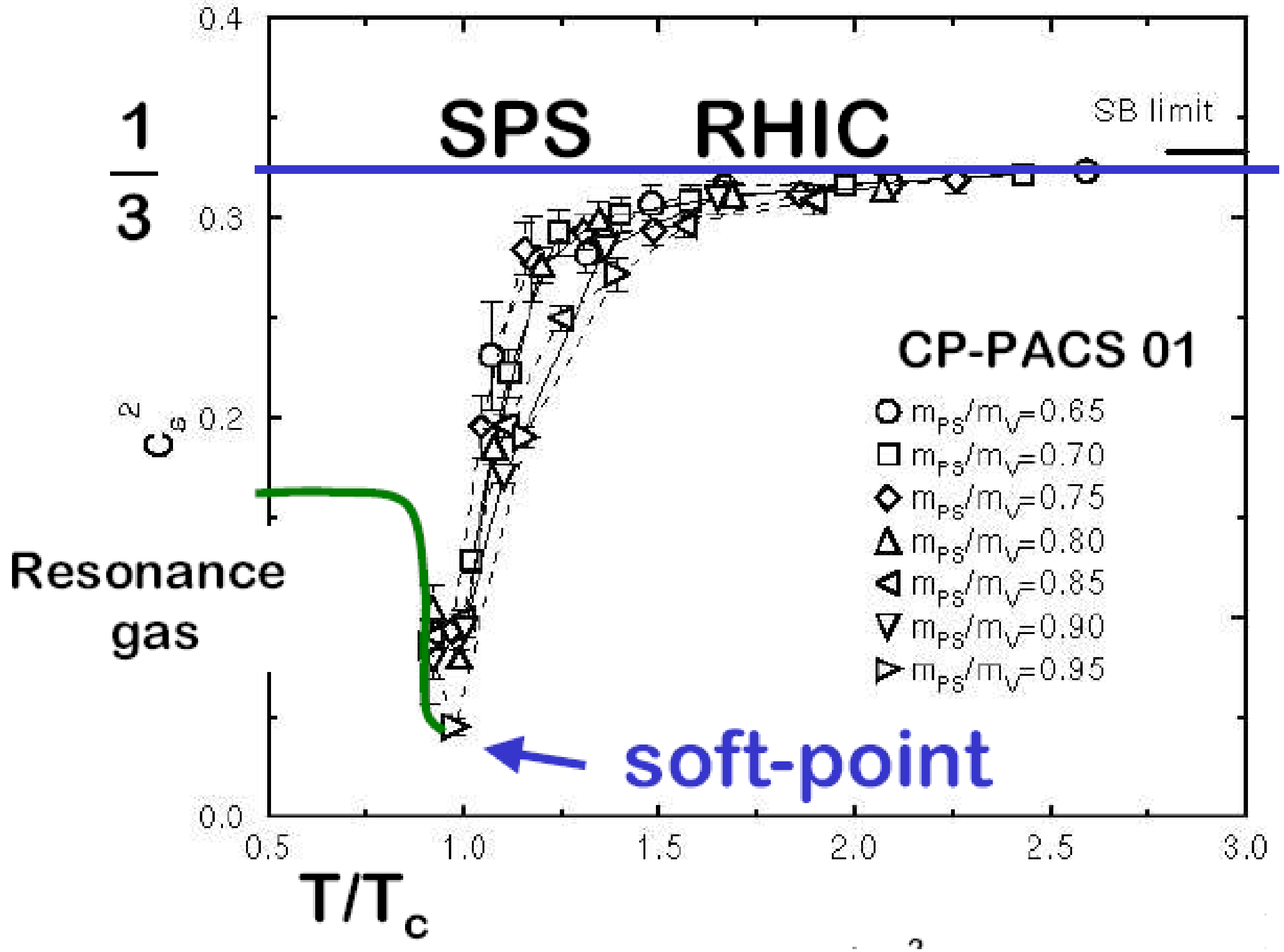
From P.Kolb and U.Heinz('03)

Lattice QCD simulations

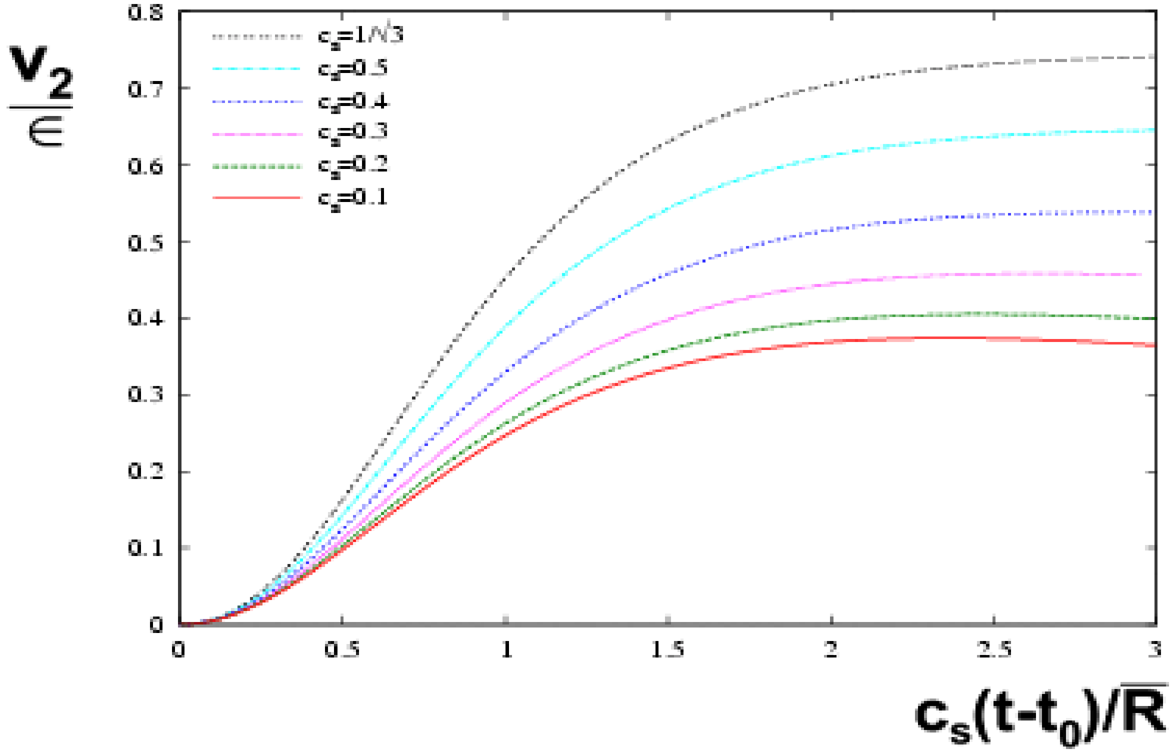


F.Karsch *et al.* ('00)

Speed of Sound



v2 and Speed of Sound

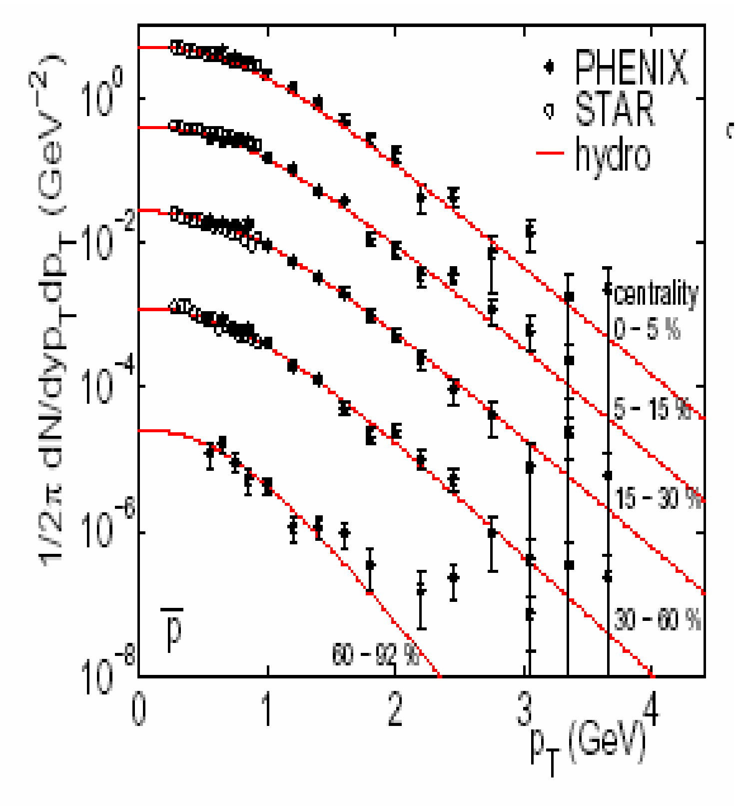


$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

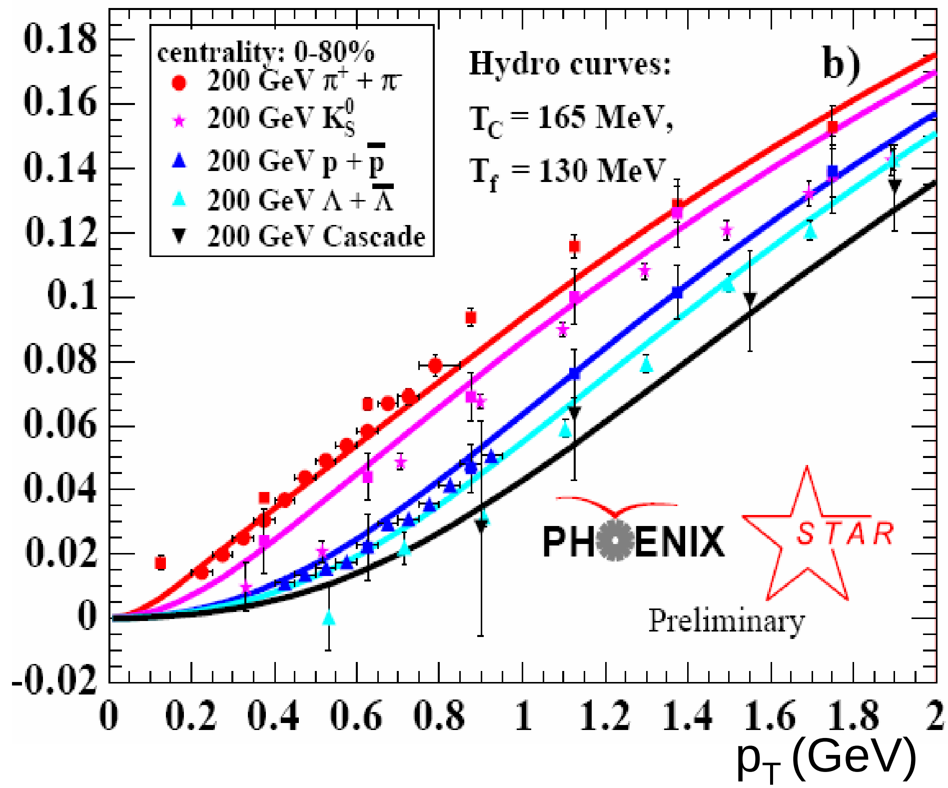
Bhalerao, Blaizot, Borghini, Ollitrault , nucl-th/0508009

Like a Perfect Fluid?

First time hydrodynamics without any viscosity describes heavy ion reactions.

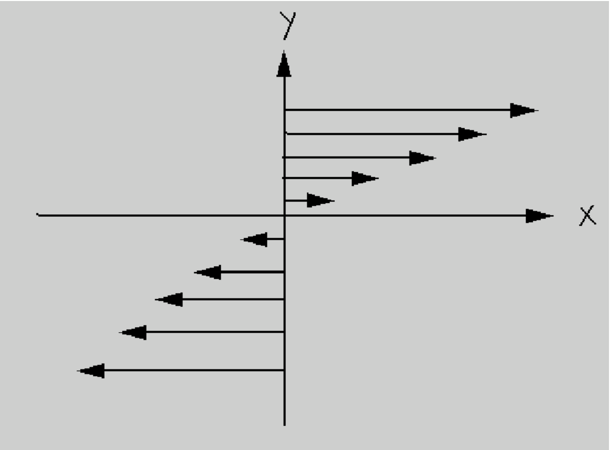


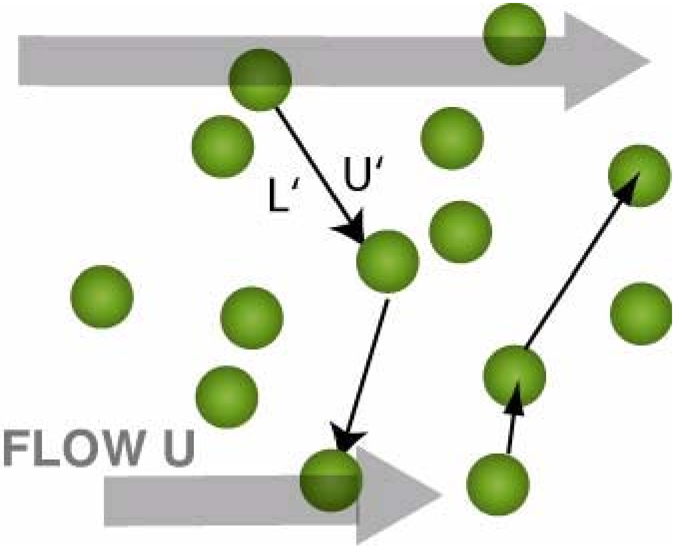
v2



Thermalization time t=0.6 fm/c and ε=20 GeV/fm^3

Viscosity

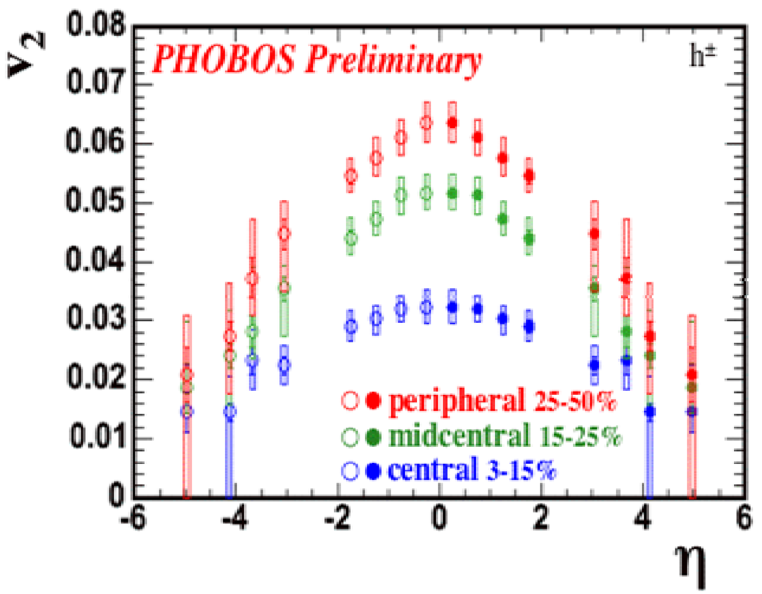


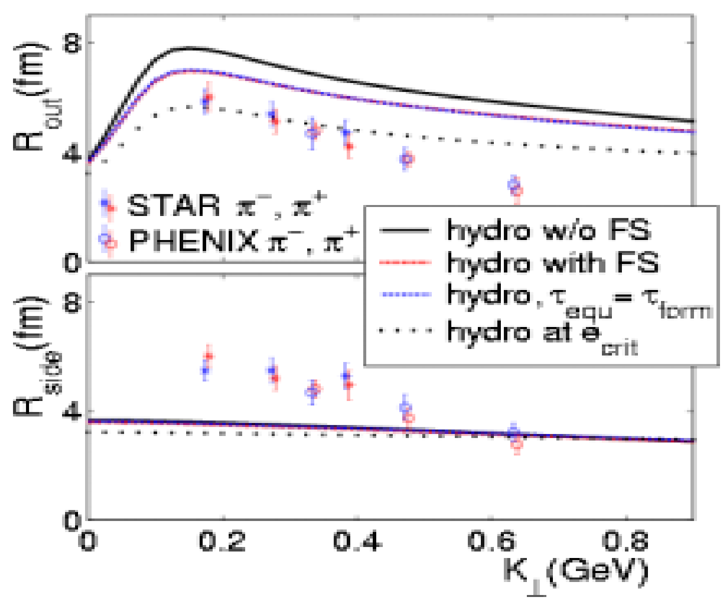


Caveats

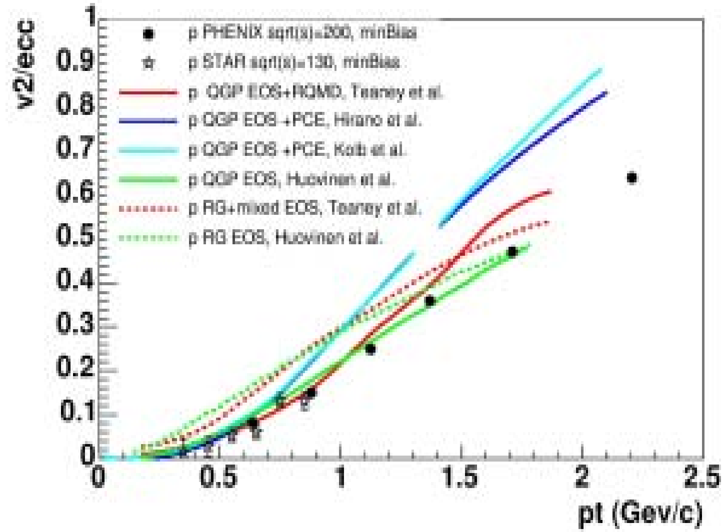
Hydrodynamic calculations are not yet fully three dimensional and thus do not fully describe the longitudinal motion.

Calculations of two particle correlations are not properly described.

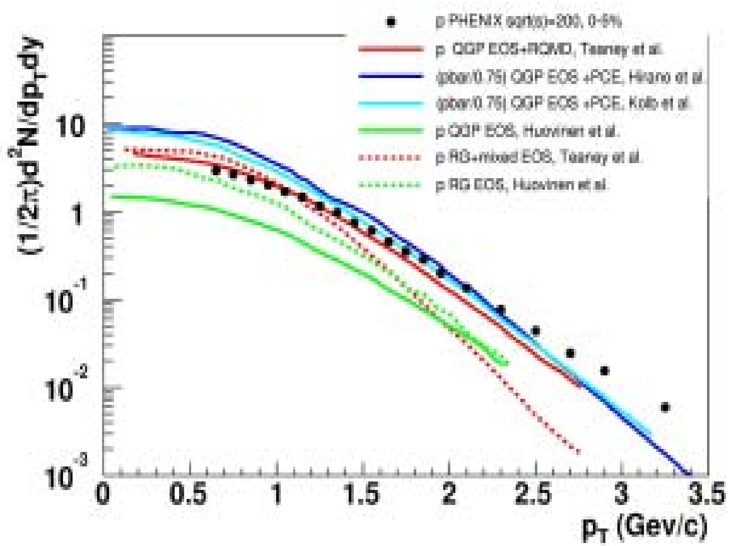




proton

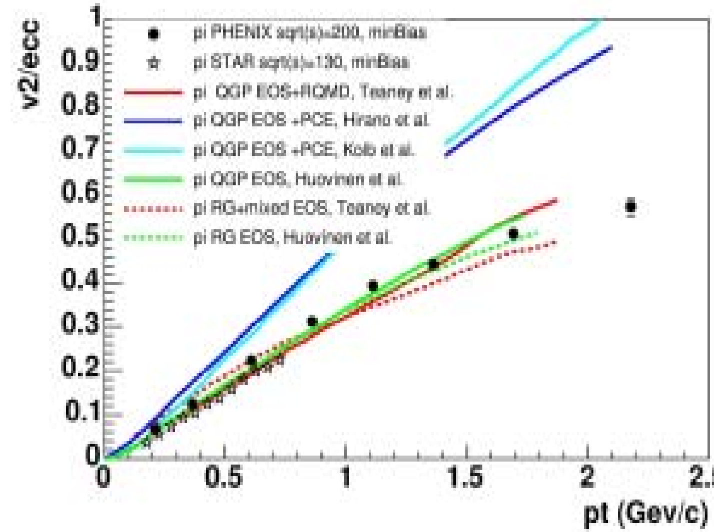


v2/ecc
pt (Gev/c)
p PHENIX sqrt(s)=200, minBias
p STAR sqrt(s)=130, minBias
p QGP EOS+RQMD, Teaney et al.
p QGP EOS +PCE, Hirano et al.
p QGP EOS +PCE, Kolb et al.
p QGP EOS, Huovinen et al.
p RG+mixed EOS, Teaney et al.
p RG EOS, Huovinen et al.



(1/2π)d²N/dp_T dy
p_T (Gev/c)
p PHENIX sqrt(s)=200, 0-5%
p QGP EOS+RQMD, Teaney et al.
(pbar/0.75) QGP EOS +PCE, Hirano et al.
(pbar/0.75) QGP EOS +PCE, Kolb et al.
p QGP EOS, Huovinen et al.
p RG+mixed EOS, Teaney et al.
p RG EOS, Huovinen et al.

pion



v2/ecc
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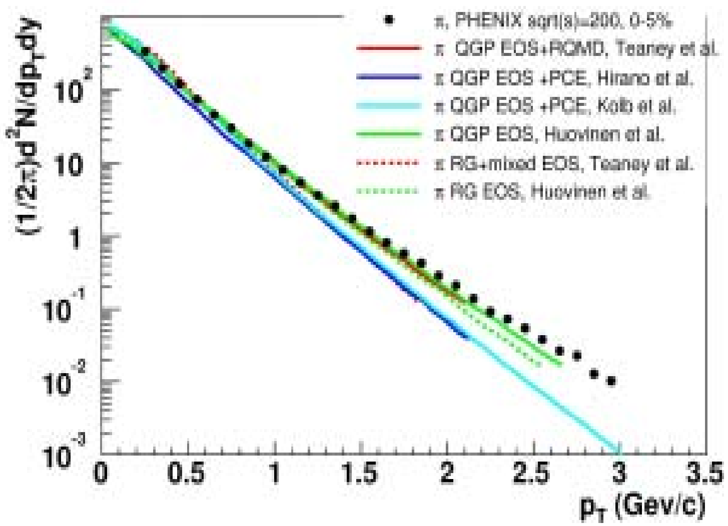

(1/2π)d²N/dp_T dy
p_T (Gev/c)
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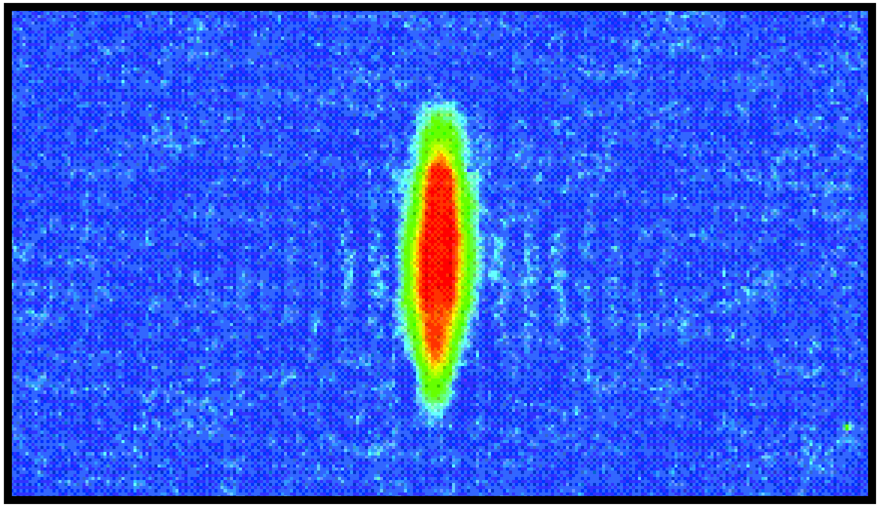
π QGP EOS +PCE, Kolb et al.
π QGP EOS, Huovinen et al.
π RG+mixed EOS, Teaney et al.
π RG EOS, Huovinen et al.

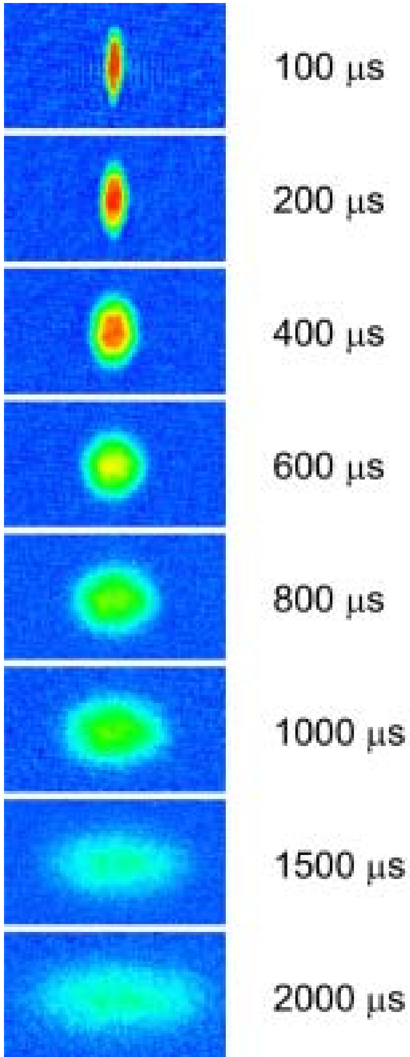
Scorecard

	QGP+mixed+RG				*mixed+RG*	*RG*
	Teaney	*Hirano*	*Kolb*	*Huovinen*	*Teaney*	*Huovinen*
latent heat (GeV/fm^3)	0.8	1.7	1.15	1.15	0.8	1.15
init. ϵ_{max} (GeV/fm^3)	16.7		23	23	16.7	23
init. $< \epsilon >$ (GeV/fm^3)	11.0	13.5			11.0	
τ_0 fm/c	1.0	0.6	0.6	0.6	1.0	0.6
hadronic stage	RQMD	partial chemical equil.	partial chemical equil.	full equil.	RQMD	full equil.
proton v2	yes	$<$ 0.7 GeV/c	$<$ 0.7 GeV/c	yes	no	no
pion v2	yes	no	no	yes	yes	yes
proton spectra	yes	overpredict	overpredict	no	no	no
pion spectra	yes	$<$ 1 GeV/c	$<$ 1 GeV/c	yes	$<$ 0.7 GeV/c	yes
HBT	Not available	No	Not available	No	Not available	Not available

Analogy in Atomic System

Same phenomena observed in gases of strongly interacting atoms





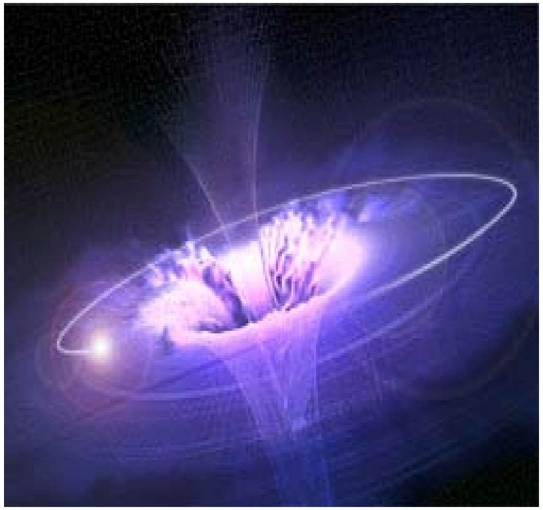
The RHIC fluid behaves like this, that is, a strongly coupled fluid.

String Theory and Black Hole Physics

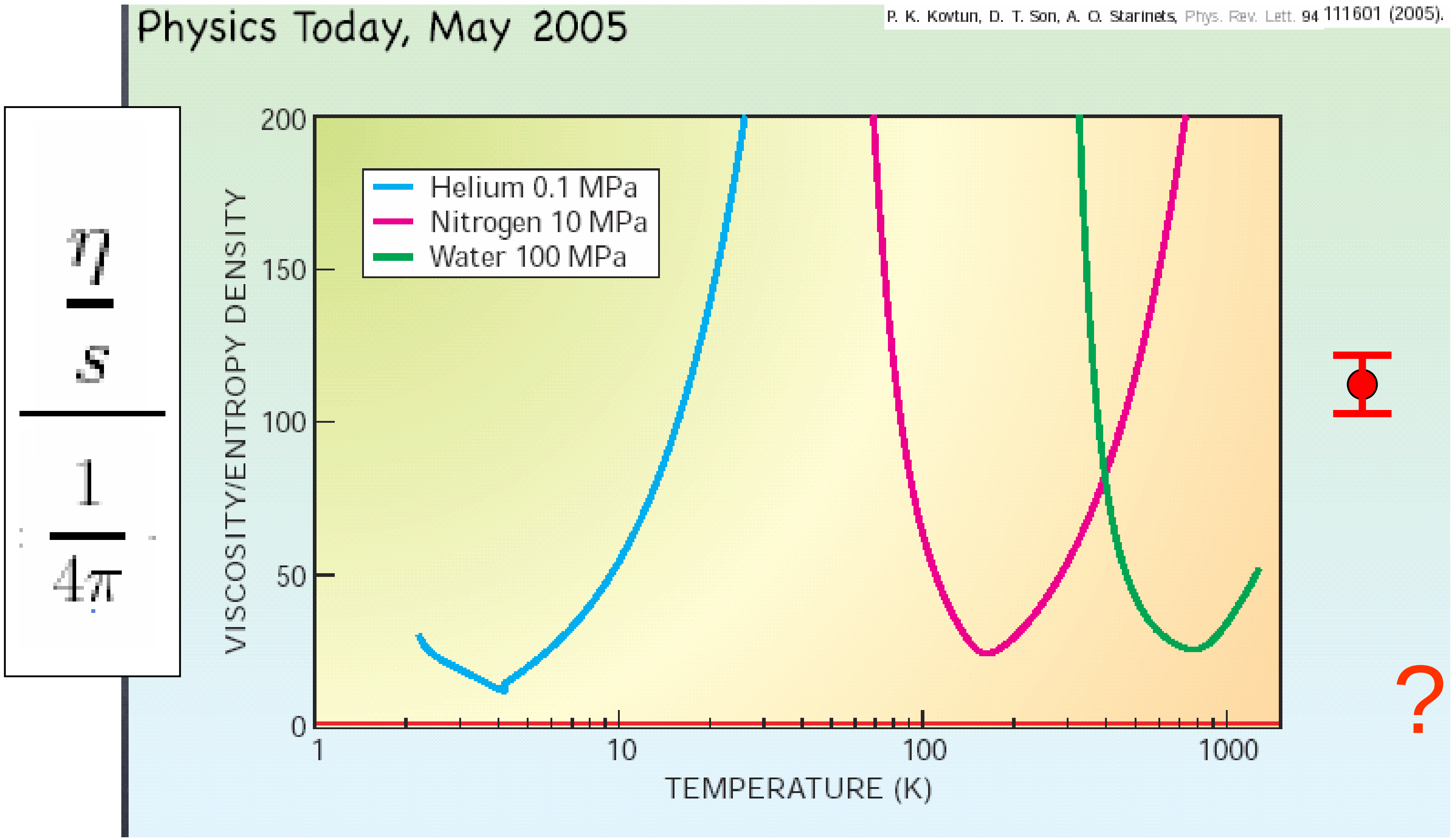
What could this have to do with quark gluon plasma physics?

The Maldacena duality, know also as AdS/CFT correspondence, has opened a way to study the strong coupling limit using classical gravity where it is difficult even with lattice Quantum Chromodynamics.

It has been postulated that there is a universal lower viscosity bound for all strongly coupled systems, as determined in this dual gravitational system.



Universal Viscosity Bound



Critical future goal to put the QCD data point on this plot

Heavier Quarks?

Does the Charm Flow at RHIC?

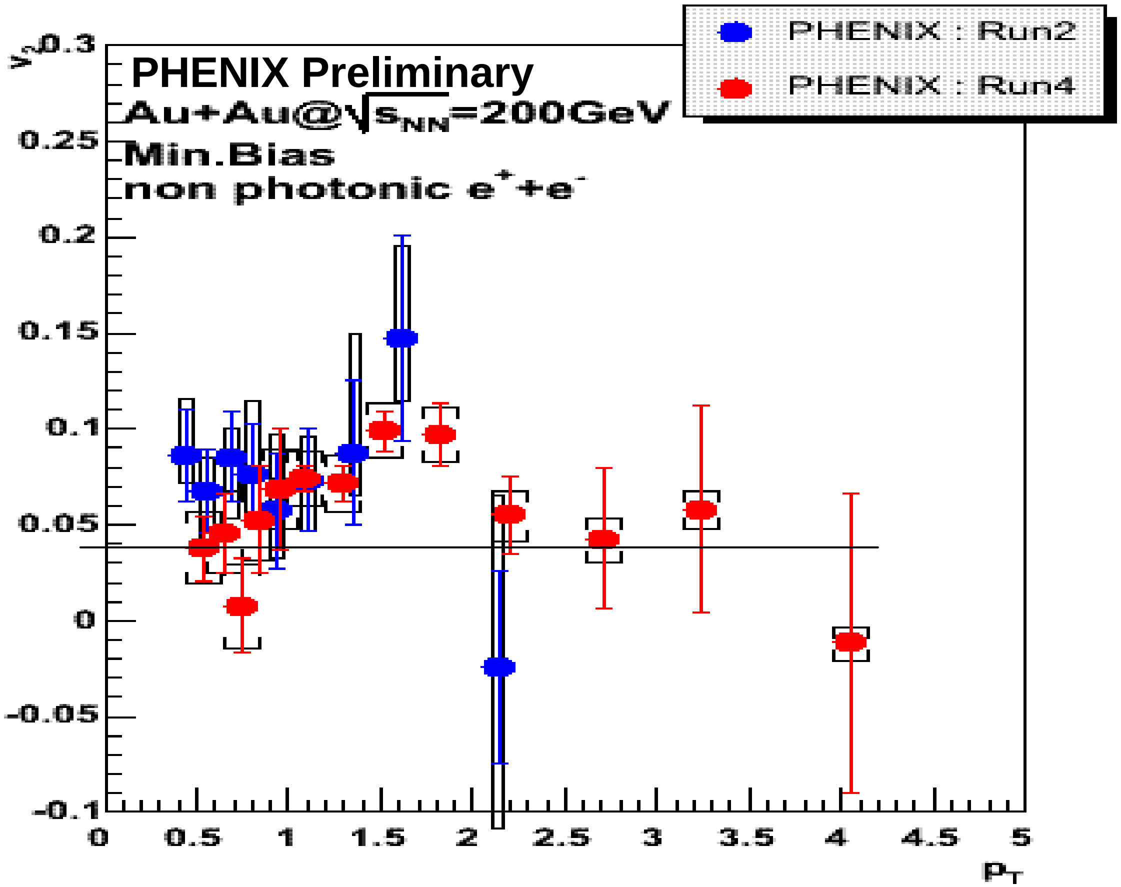
Batsouli, S; Kelly, S; Gyulassy, M; Nagle, J L;
(Columbia University) (University of Colorado at Boulder)

16 Dec 2002 . - 10 p

Published in: *Phys. Lett., B* 557 (2003) 26-32
citations recorded in [Science Citation Index]

Abstract: Recent PHENIX Au+Au -> e- + X data from open charm decay are shown to be consistent with two extreme opposite dynamical scenarios of ultra-relativistic nuclear reactions. Perturbative QCD without final state interactions was previously shown to be consistent with the data. However, we show that the data are also consistent with zero mean free path hydrodynamics characterized by a common transverse flow velocity field. The surprising coincidence of both D and B hydrodynamic flow spectra with pQCD up to p_T ~ 3 and 5 GeV, respectively, suggests that heavy quarks may be produced essentially at rest in the rapidly expanding gluon plasma. Possible implications and further tests of collective heavy quark dynamics are discussed.

Charm Hadron Flow

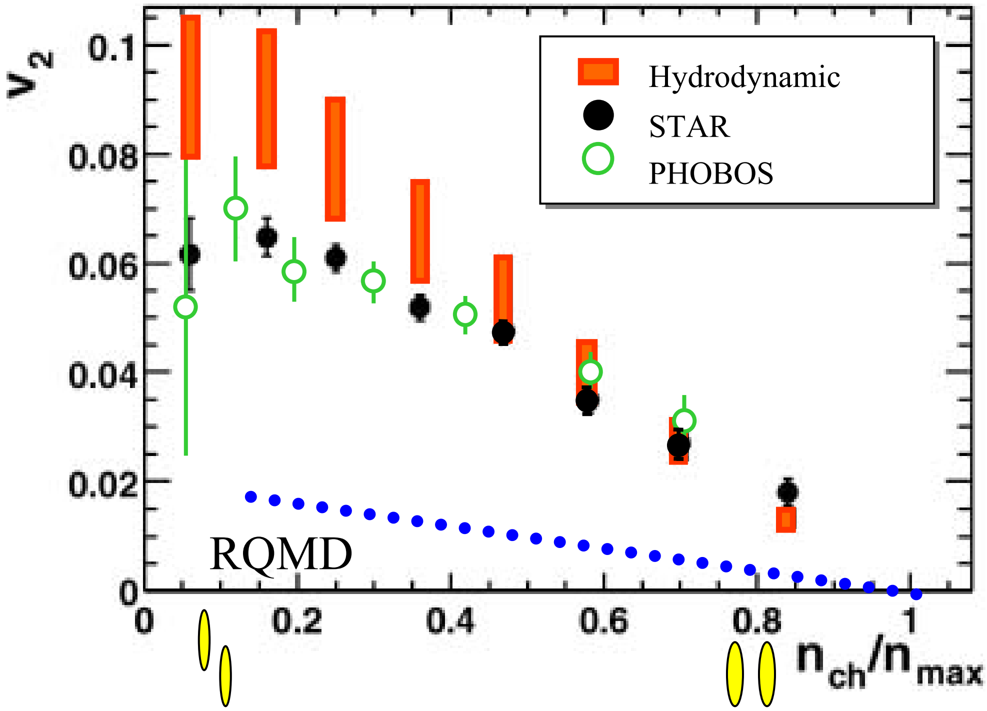


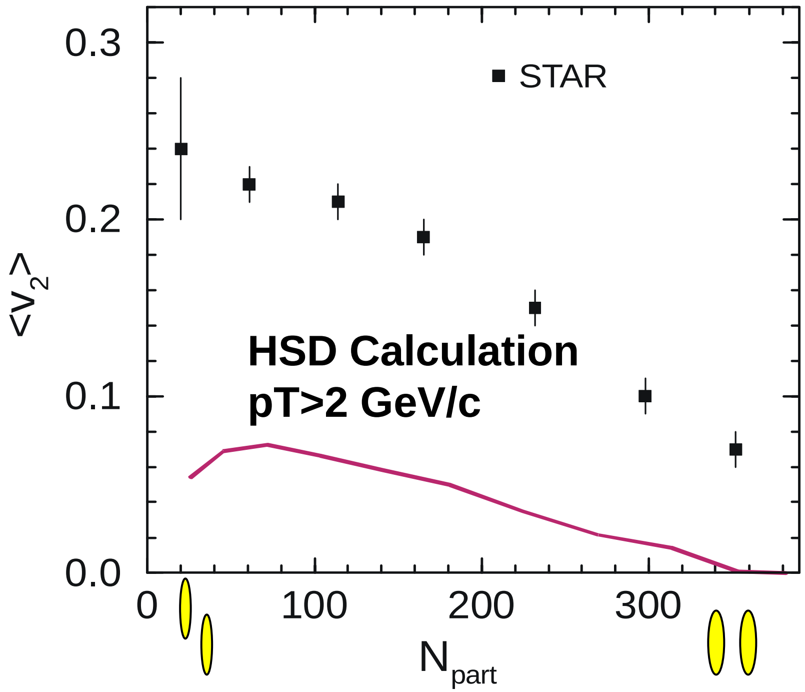
More about heavy quark measurements later.

Hadron Gas ?

What interactions can lead to equilibration in < 1 fm/c?

Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe data.

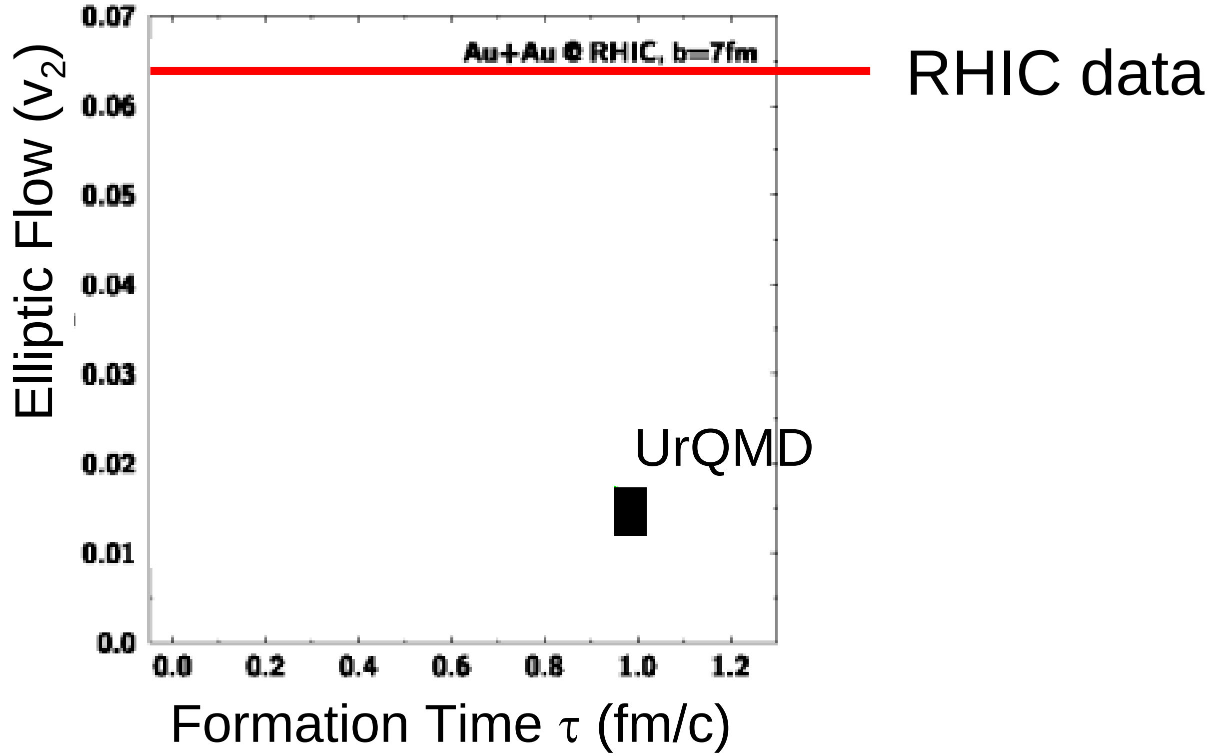




Clearly the system is not a hadron gas. Not surprising.

Hadron Formation Time

These string + hadronic transport models under-predict the collective motion by a factor of 4-10.

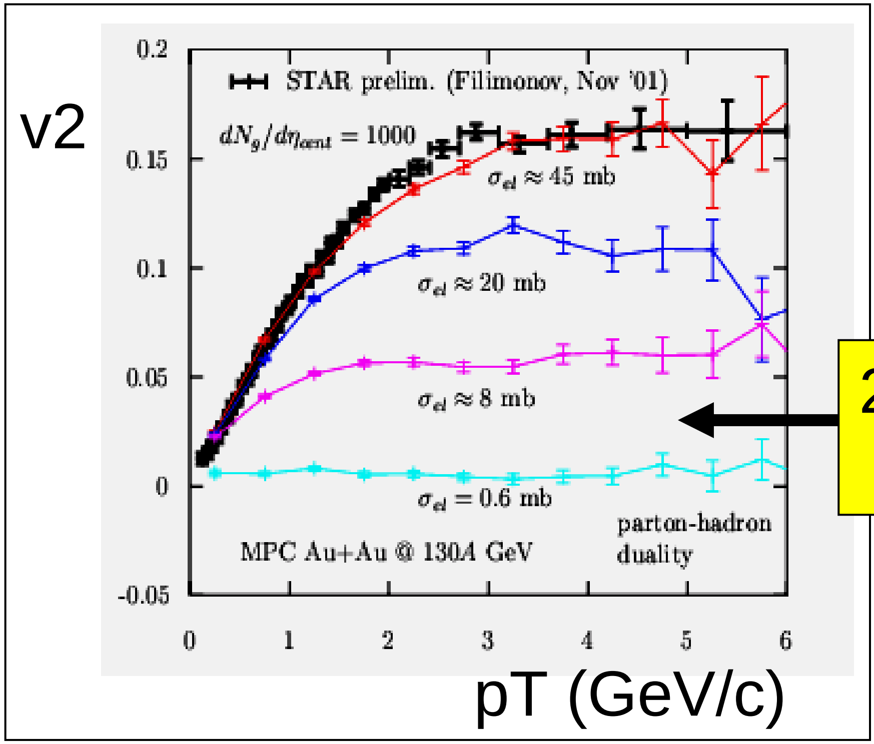


Only if we violate quantum mechanics and allow hadronic wavefunctions to fully form in $\tau \rightarrow 0$ can we reproduce the data.

Perturbative QGP ?

What interactions can lead to equilibration in < 1 fm/c?

Perturbative calculations of gluon scattering lead to long equilibration times (> 2.6 fm/c) and small v2.



2-2 processes with pQCD σ = 3 mb

R. Baier, A.H. Mueller, D. Schiff, D. Son, Phys. Lett. B539, 46 (2002).
MPC 1.6.0, D. Molnar, M. Gyulassy, Nucl. Phys. A 697 (2002).

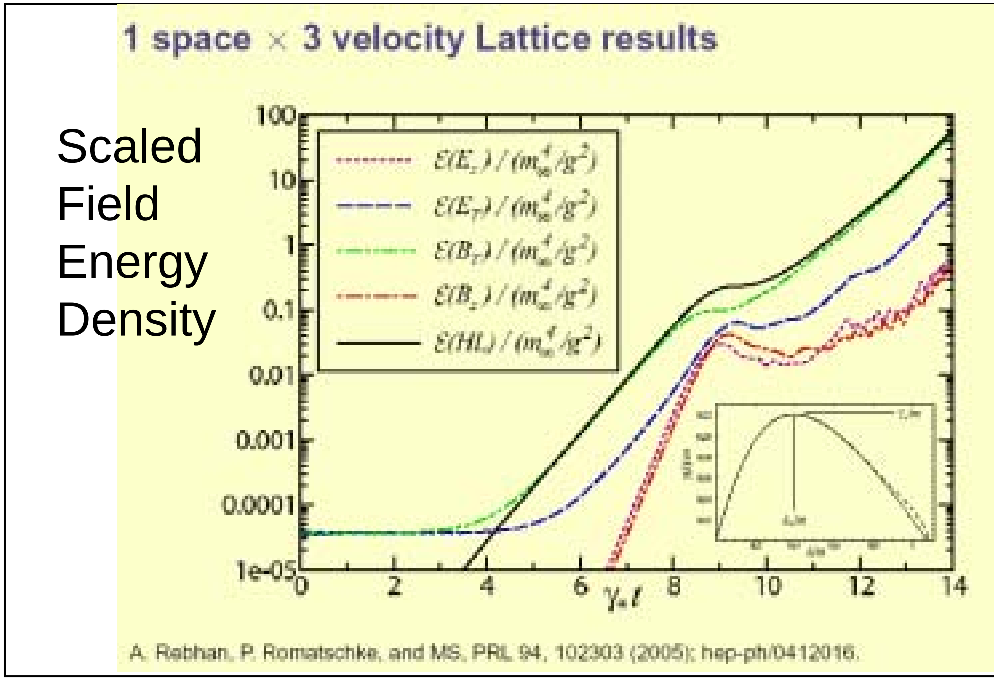
Clearly this is not a perturbative QGP. Not surprising.

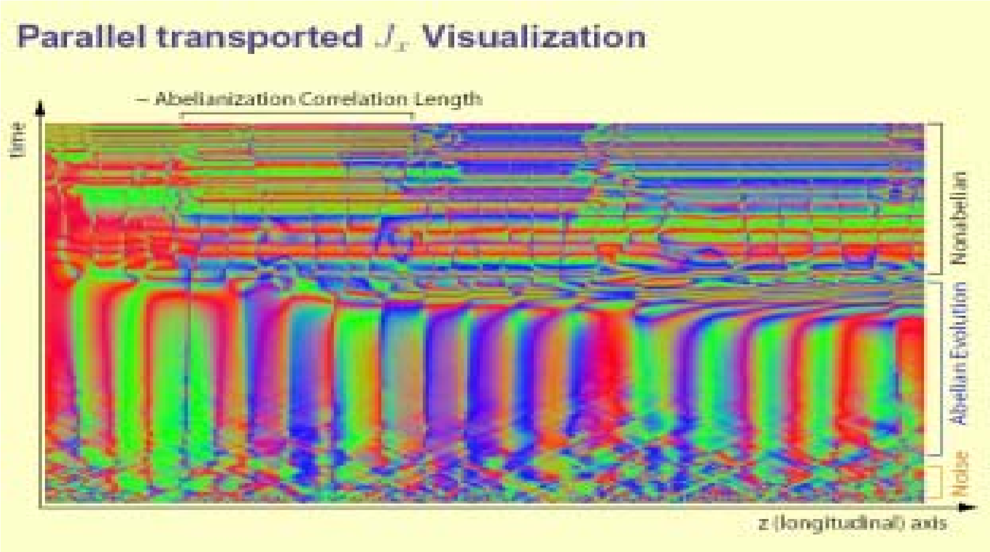
Plasma Instabilities ?

Exponential growth of color fields due to instabilities.

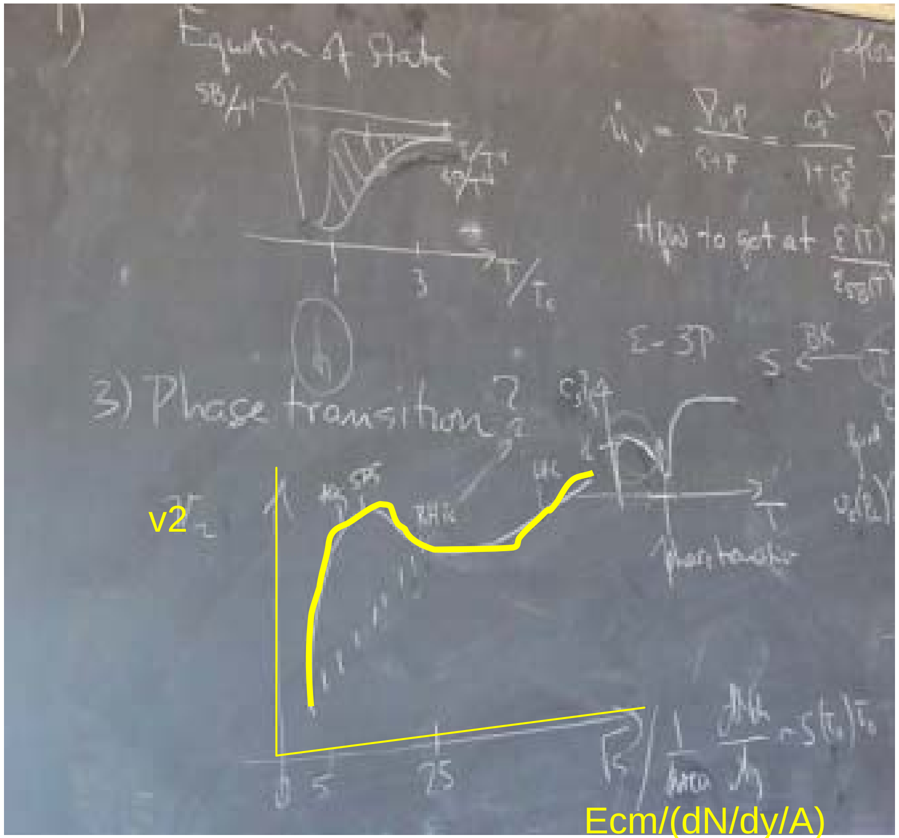
Very rapid isotropization.

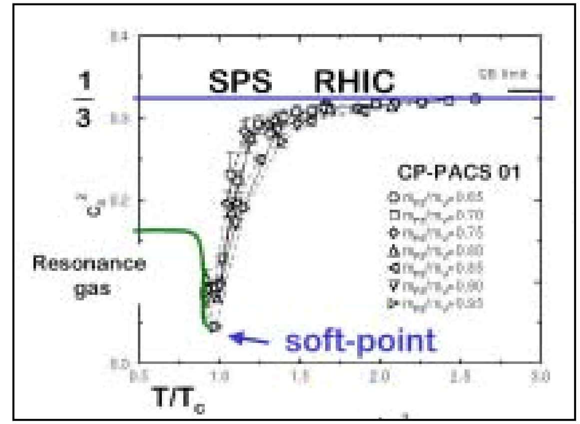
Rapid thermalization is still a mystery, but with exciting possible explanations.

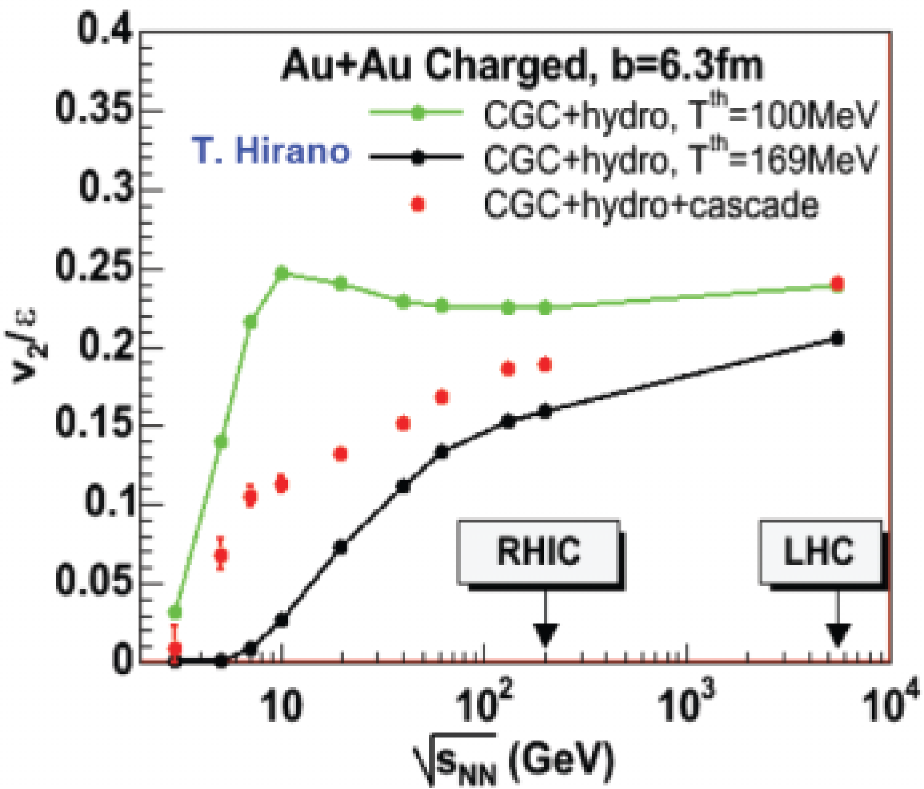




Energy Scan


v2
Ecm/(dN/dy/A)


1/3
SPS
RHIC
CP-PACS 01
Resonance gas
soft-point
T/T_c


Au+Au Charged, b=6.3fm
T. Hirano
CGC+hydro, T^th=100MeV
CGC+hydro, T^th=169MeV
CGC+hydro+cascade
v_2/ε
√s_NN (GeV)
RHIC
LHC
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
10
10^2
10^3
10^4

Perfect Liquid Summary

Hydrodynamic calculations give us a connection between the experimental data and the full time evolution and equation of state of the medium.

Caveat is that we need to better quantitatively test the degree of equilibration, include viscosity effects, and possible non-equilibrium final hadronic cascading.