What is so remarkable about the sQGP discovered at RHIC ?

(strongly coupled Quark Gluon Plasma)

Why are nuclear physicists reading Volume II Of Prof. Ichimaru's Plasma books?

Why are nuclear physicists looking over The shoulders of Prof. Thomas at Li atoms?

What desperation led them to seek answers In The Elegant adS_5XS_5 Universe ??

M.Gyulassy, L. McLerran nucl-th/0405013, Nucl.Phys.A in press

M.Gyulassy: Erice Lectures 8/30/04

http://nt3.phys.columbia.edu/people/gyulassy/Talks/2004.08.30_Erice/

Answer:

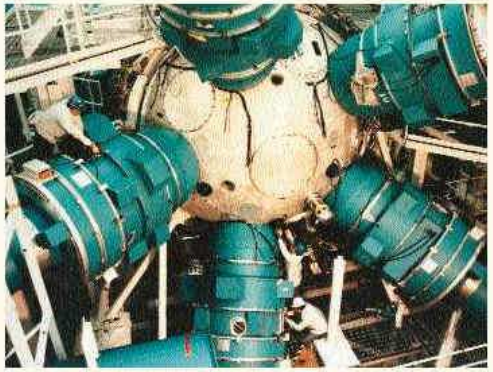
Unexpected Experimental Discoveries at RHIC
have forced a paradigm change in the field

weak coupling wQGP => strong coupling sQGP

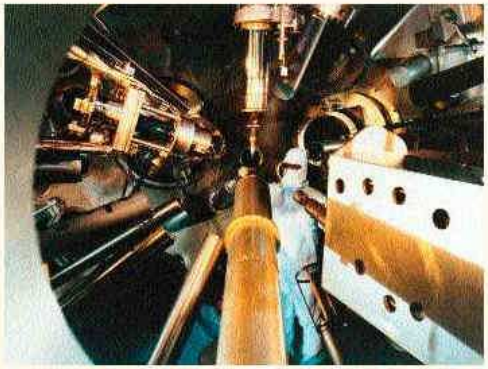
New concepts and tools must be developed
to gain a better understanding of the new physics

Purpose of this RBRC workshop is to discuss and compare
Ideas in different fields with similar phenomena

Strongly Coupled Matter From 10^{-6} to 10^{12} K

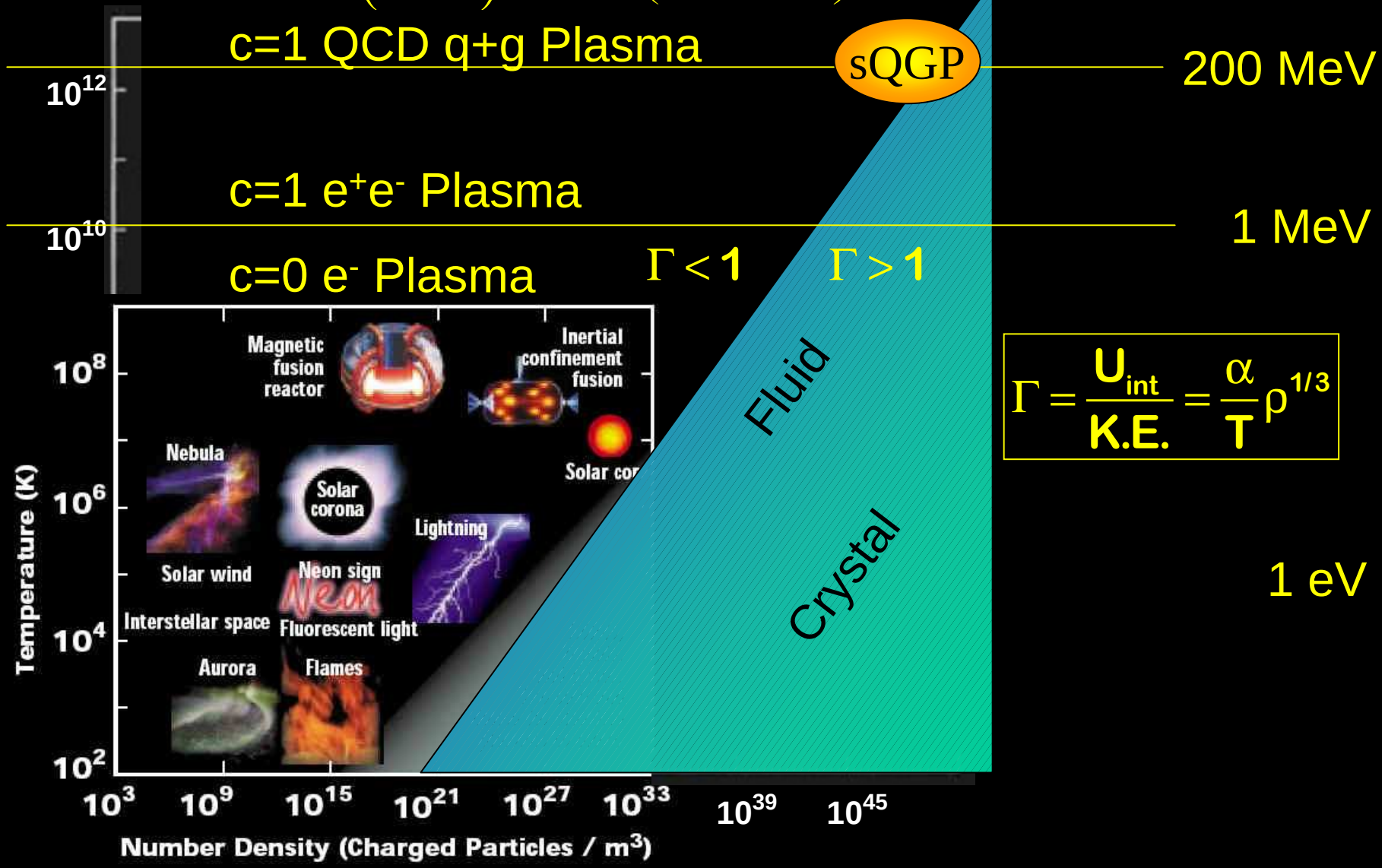


The combustion chamber at the Nova laser fusion facility (Lawrence Livermore Labo- ratory, USA). Inside the combustion chamber at the Nova laser fusion facility (Lawrence Livermore Laboratory, USA) The Euratom Joint Research Centres and Associated Centre



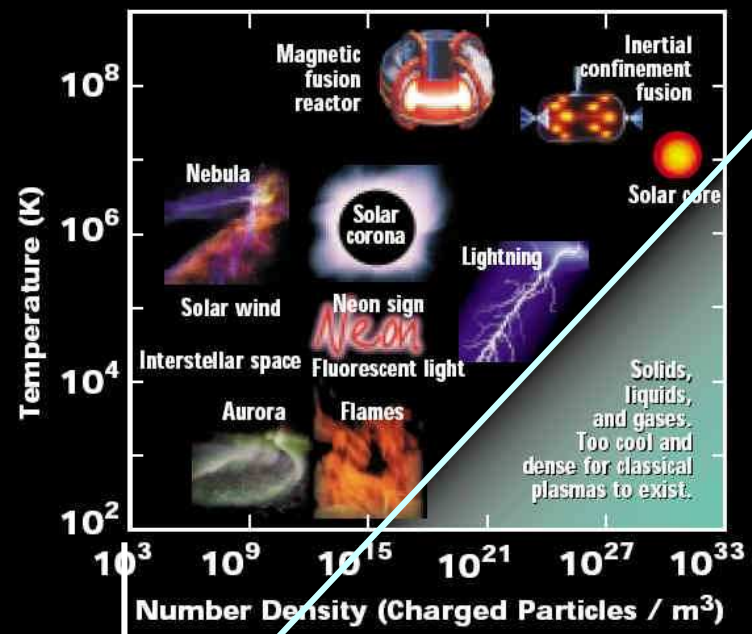
Inside the combustion chamber at the Nova laser fusion facility (Lawrence Livermore Laboratory, USA).

$$\rho_{QGP} \approx 4T^3 = 30\rho_A \left(\frac{T}{\Lambda_{QCD}}\right)^3 = \frac{10^{45}}{m^3}\left(\frac{T}{2\times 10^{12}K}\right)^3$$



$$\Gamma = \frac{U_{int}}{K.E.} = \frac{\alpha}{T}\rho^{1/3}$$

http://fusedweb.pppl.gov/CPEP/Images/CPEP-Fusion-2000-EN-Front.PDF



$\hbar = c = 0$

$\hbar = 1, c = 1$

weak $\Gamma < 1$

strong $\Gamma > 1$

$\hbar = 1, c = 0$

10^{-6}

Li6

$N=10^5$, $dx= 10^{-5}$ m

$T<T_F = 10^{-6}$ K

$\Gamma = U_{int}/T = 0.3$

Strongly coupled quantum liquids

Theoretical Equation of State of QCD matter

Lattice QCD

F.Karsch et al, PLB 478 (00) 477

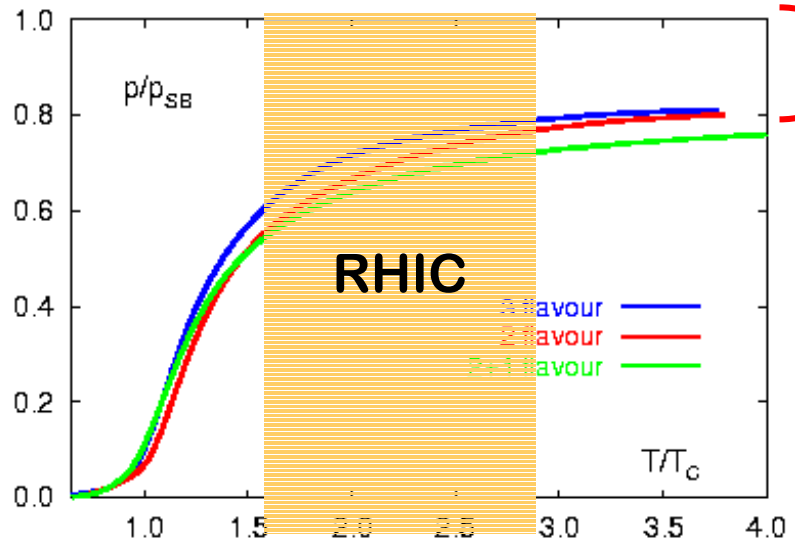
16^3X4 improved action and staggered q

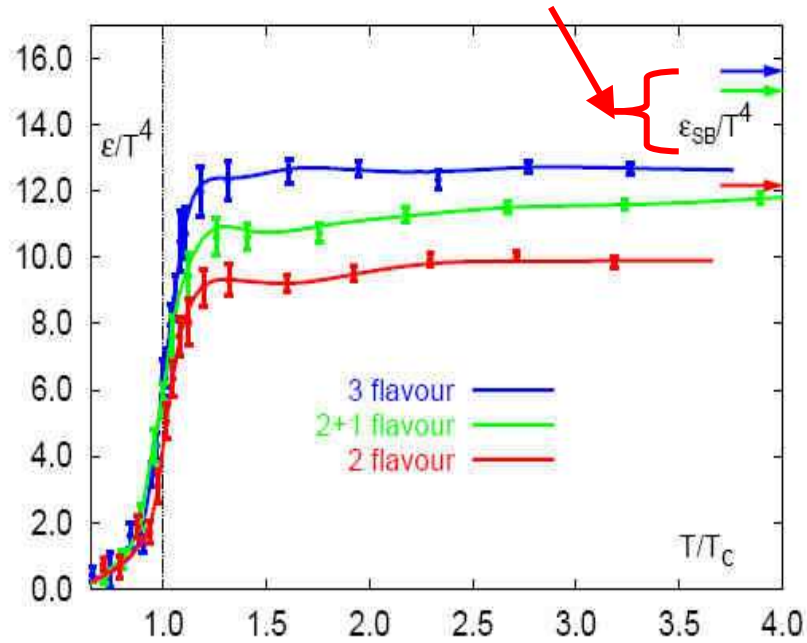
$M_{u,d}$~T/4 ,M_s~T

Pressure $P_{QCD}(T)$

!Seems perturbative at T>2 T_c

Only 20% deficit in P and ε and S

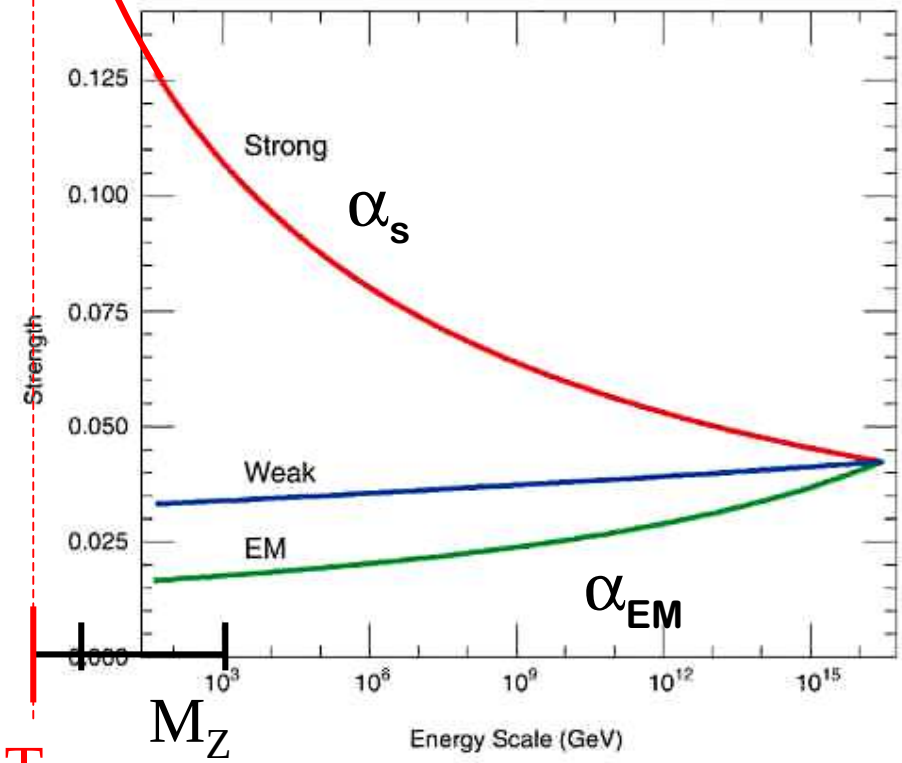




Is QGP a *w*QGP = weakly coupled "dielectric" plasma ?

$\alpha_s \approx 1$

QCD Asymptotic Freedom => at high enough T
State of matter should be a weakly coupled QGP (wQGP)



M_Z

T_c

FIGURE 2.4 Variation and convergence of the effective coupling strengths for the three forces—strong, weak, and electromagnetic (EM)—as a function of the energy scale of the interaction. The figure is drawn for a minimal supersymmetric extension of the Standard Model. Without supersymmetry, the three couplings do not precisely meet. Image courtesy of J. Bagger, K. Matchev, and D. Pierce, Johns Hopkins University.

$$\Gamma_{QCD} = \frac{\alpha(T)}{T}\rho^{1/3} \approx 0.13\, g^2$$

$$\approx \frac{1}{\mathrm{Log}(T/100\,\mathrm{MeV})}$$

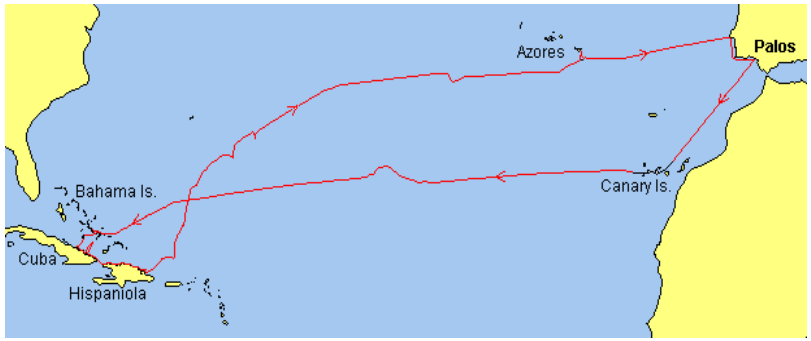
Tempting to expand
Physics in coupling
$g<<1$ $\Gamma<<1$

And even more optimistically

$1/\mathrm{Log}(1/g) <<1$

Ed Shuryak: "One may have an absolutely correct theory and still make *accidental* discoveries…"

Columbus' Theory:
(1) world is not flat, $E_2 \Rightarrow S_3$
(2) if he goes west he should eventually come to India



But he discovered something else was on the way…

We set out at RHIC we find wQGP. But 1000 experimentalists found something else on the way… the sQGP !

Failure of weak coupling perturbative QCD expansion

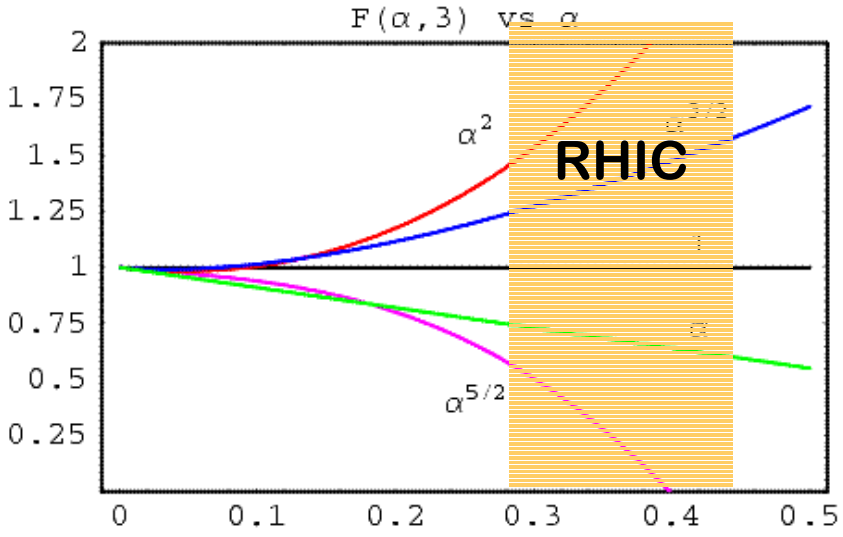
High Temperature QCD Perturbation Theory

(E.Braaten and A. Nieto, PRL 76 (96) 1417)
(C.Zhai and B. Kastening, PRD 52 (95) 7232)

Quark – Gluon Plasma Pressure

$$P = \frac{\pi^2}{90} T^4 \left(2_s 8_c + \frac{7}{8} 2_s 3_c 2 n_f\right) F(\alpha, n_f)$$

$$F(\alpha, 3) = 1 - 0.9\alpha + 3.3\alpha^{3/2} + (7.1 + 3.5 \log \alpha)\alpha^2 - 20.8\alpha^{5/2} + (?)\alpha^3 + \ldots$$



$\alpha(T)$

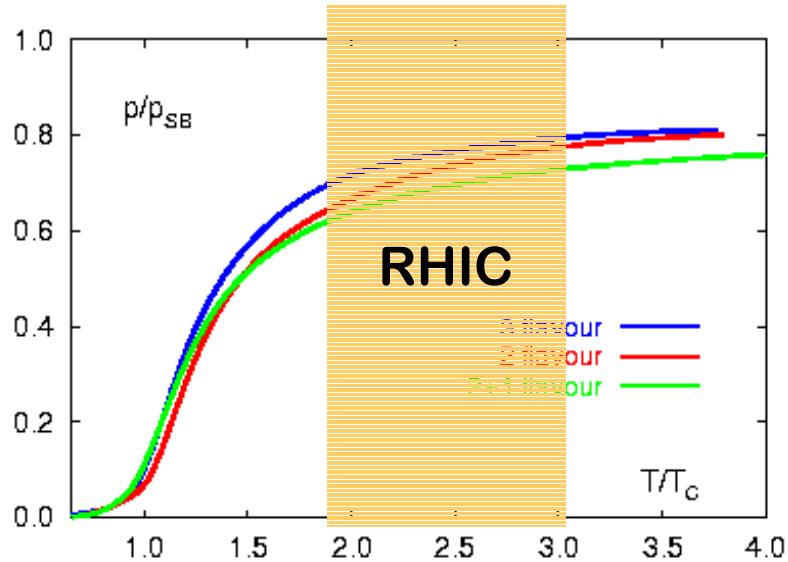
Lattice QCD

F.Karsch et al, PLB 478 (00) 477

16^3X4 improved gauge and staggered q

$M_{u,d}$~T/4 ,M_s~T

QGP ≠ *w*QGP

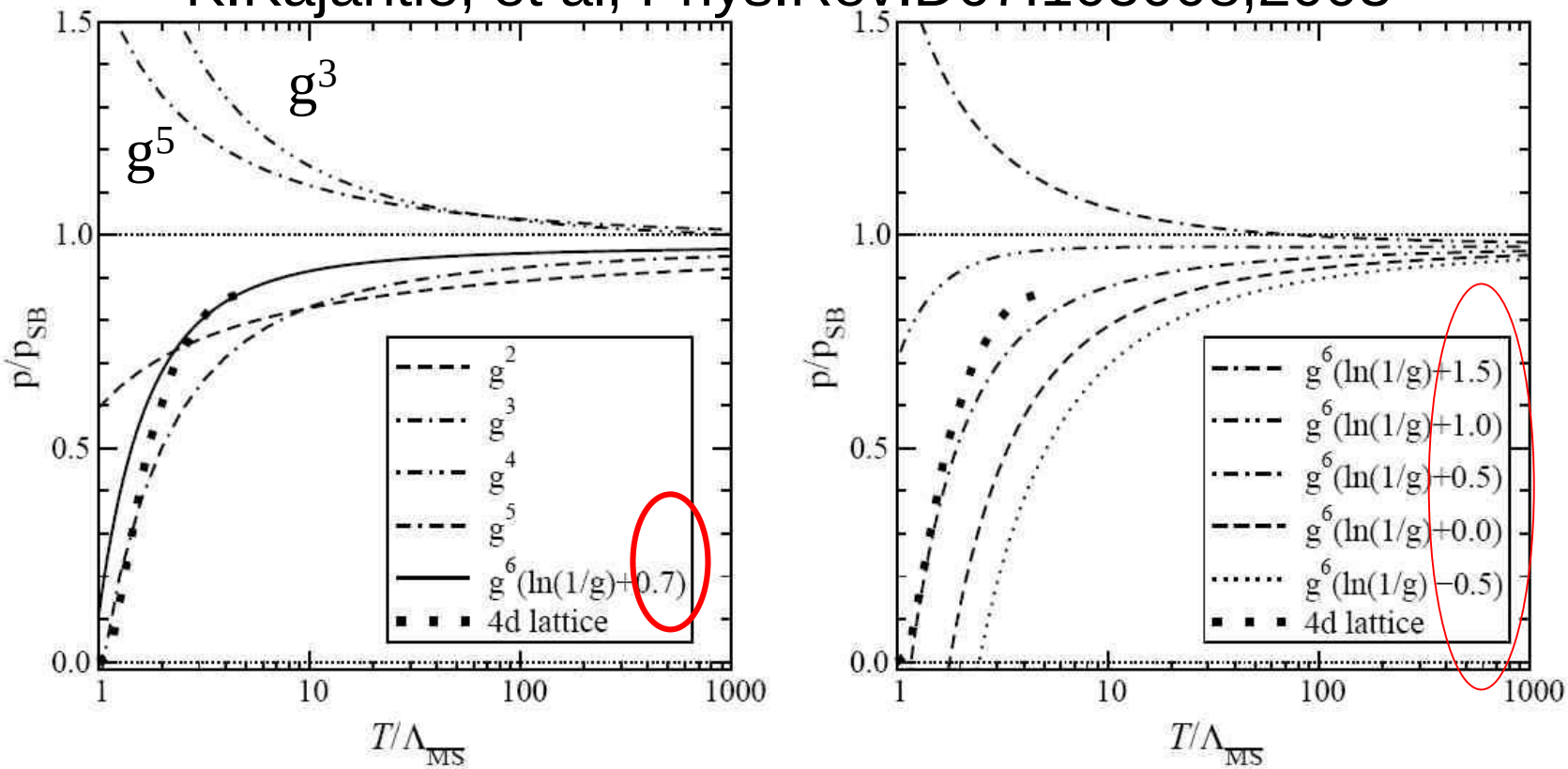


T / T_c

One can "fit" LQCD P(T) with O(g^6 Log1/g) pQCD + "small Fudge"

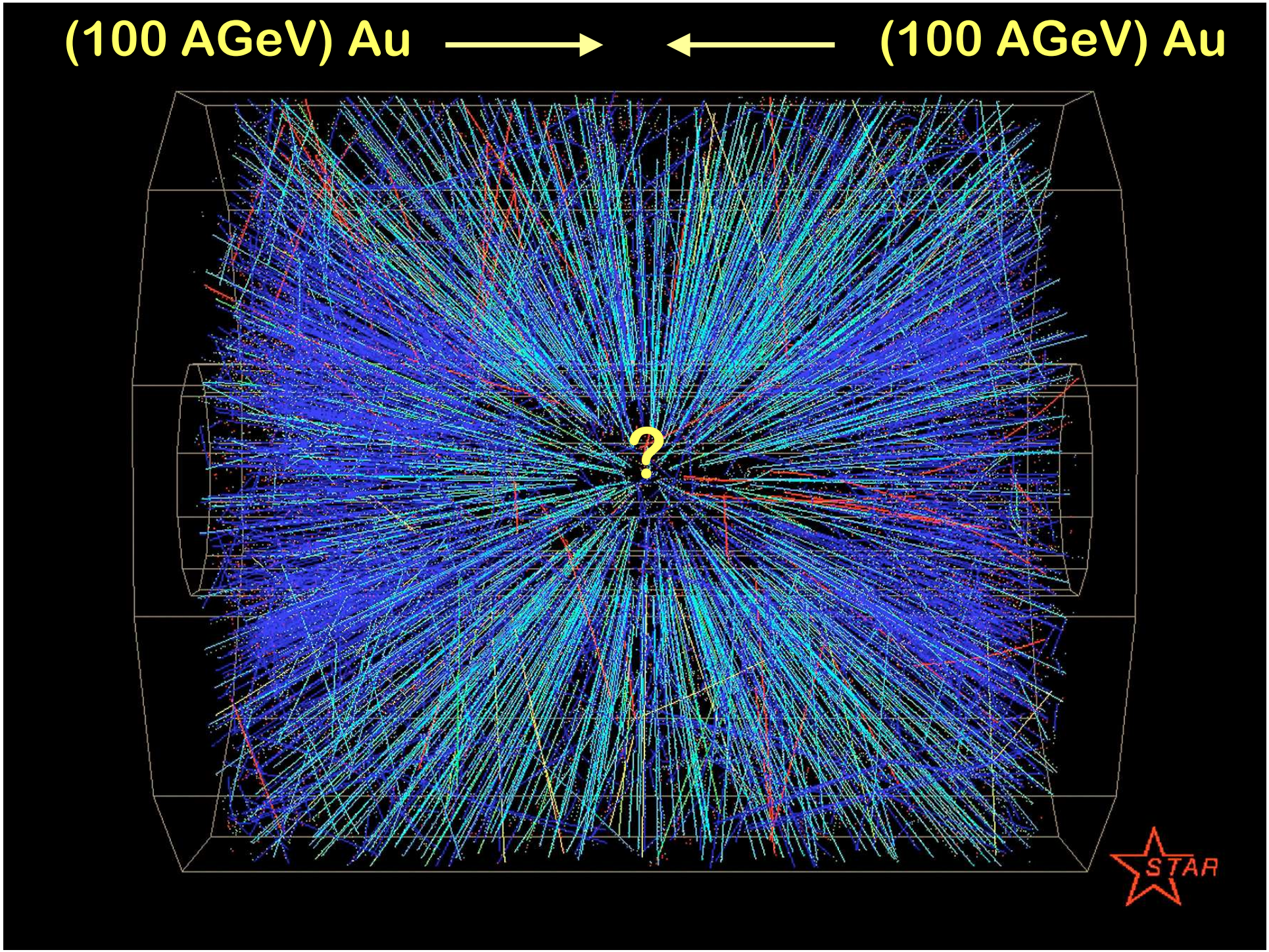
IF Log1/g >>1

K.Kajantie, et al, Phys.Rev.D67:105008,2003



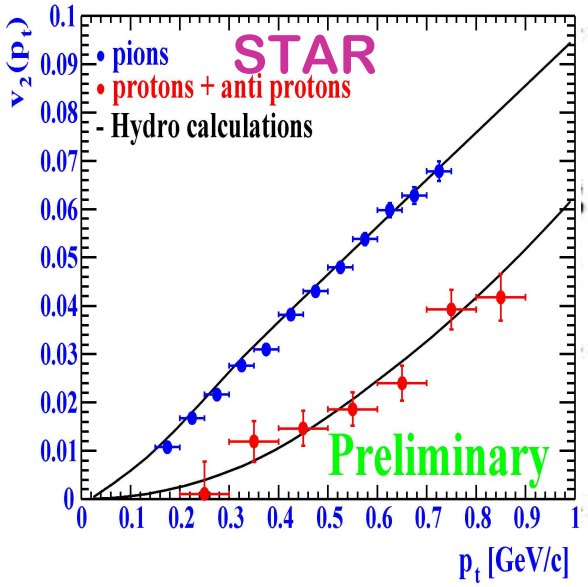
The perturbative expansion of $p(T,\mu=0)|_{N_f=0}$ (Kajantie *et al.*) plotted against the 4d lattice data of G. Boyd *et al.*, hep-lat/9602007.

The PROBLEM is that for $T<10^3\ T_c$, g>1 and Log1/g < 0

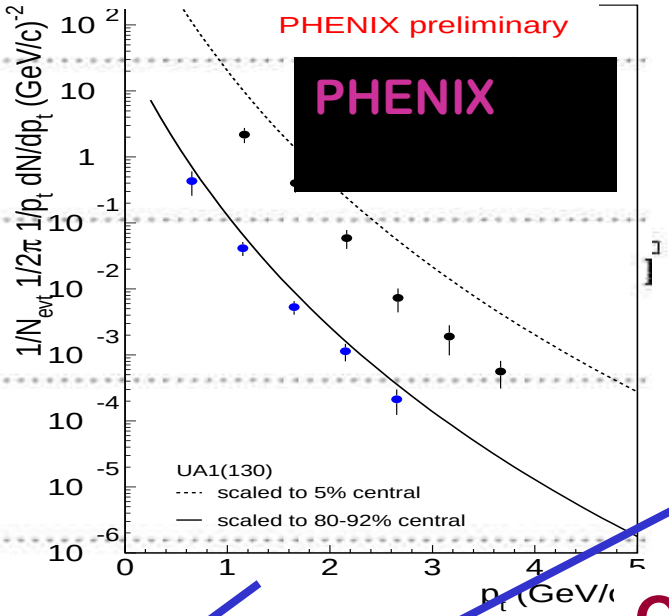

(100 AGeV) Au
(100 AGeV) Au
?
STAR

Day 1 New Physics at RHIC

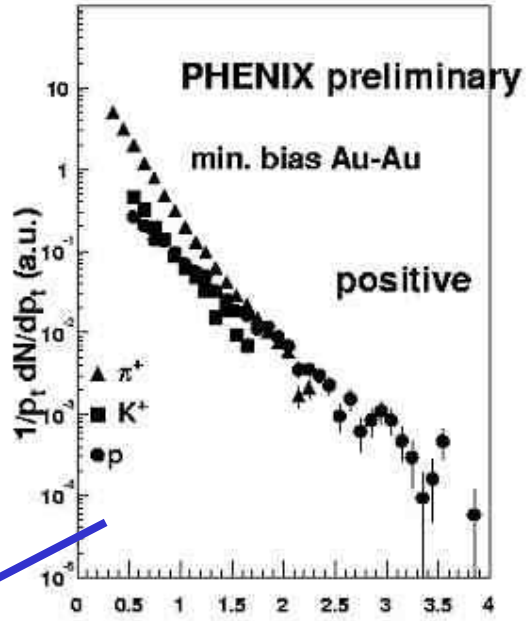
Collective Flow



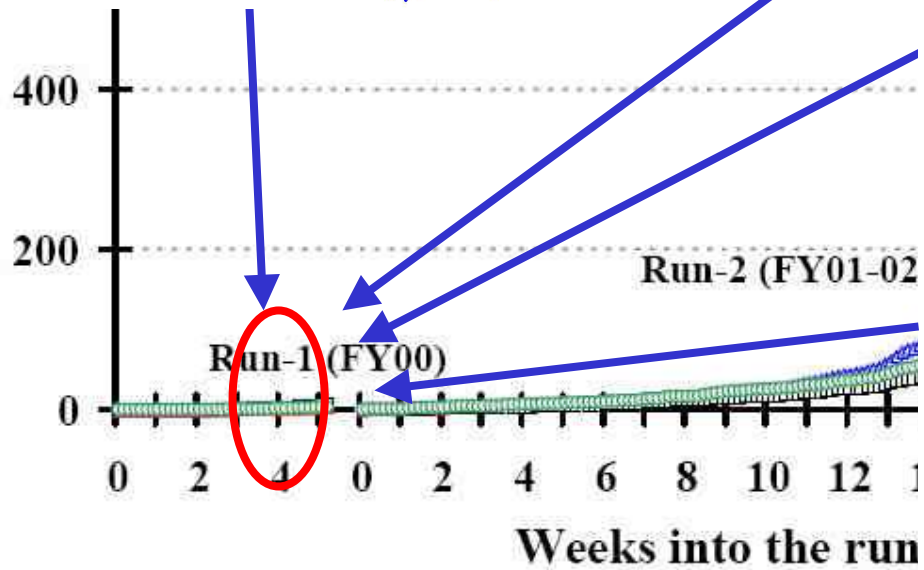
Jet Quenching

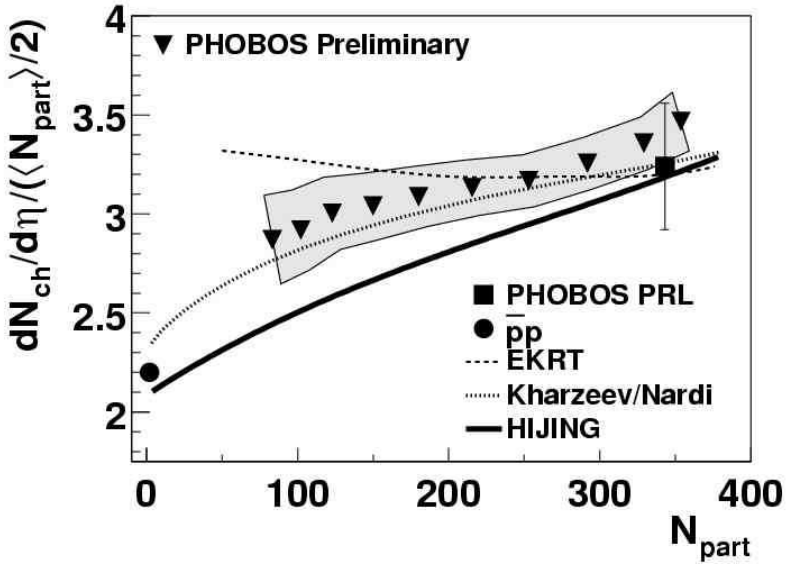


Baryon anomaly

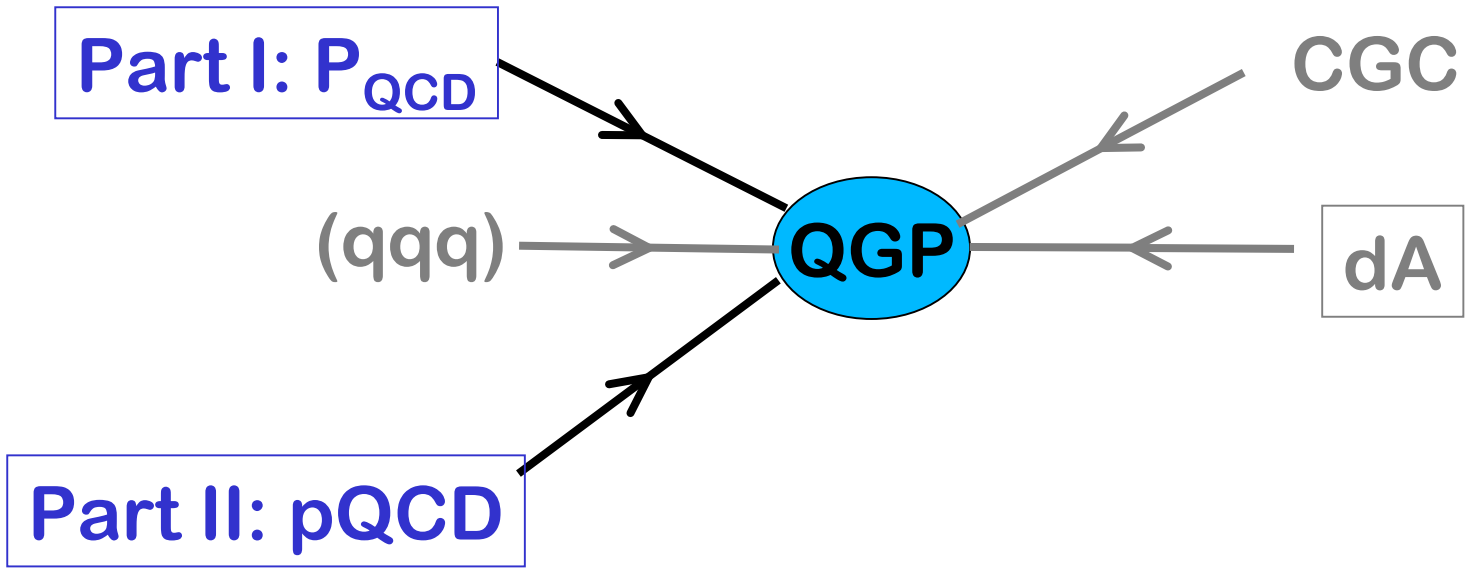


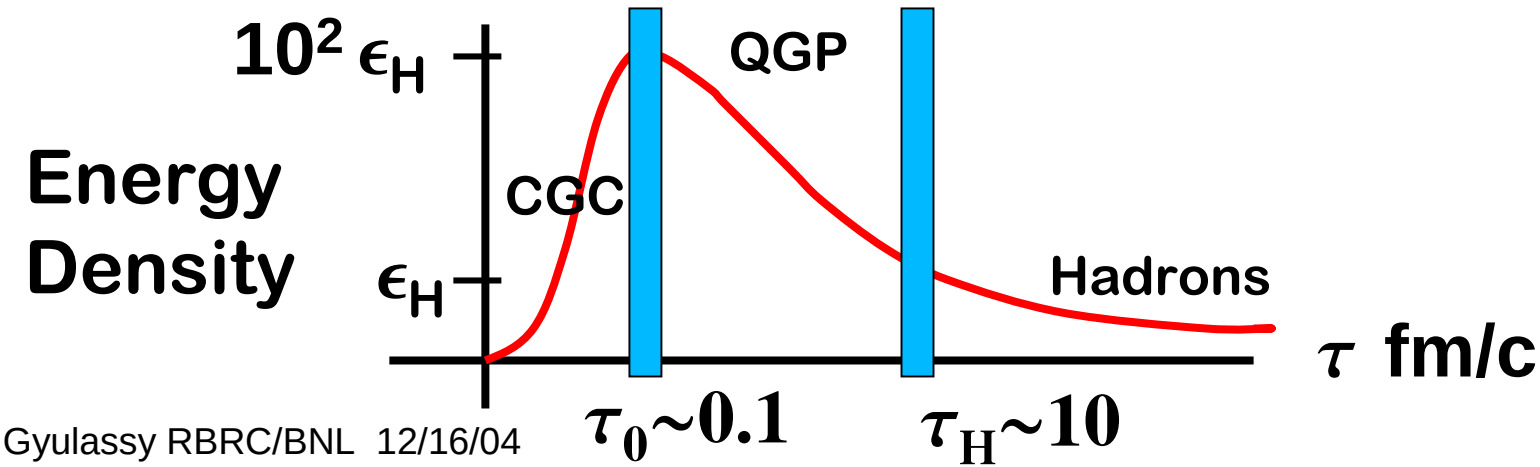
CGC Saturation



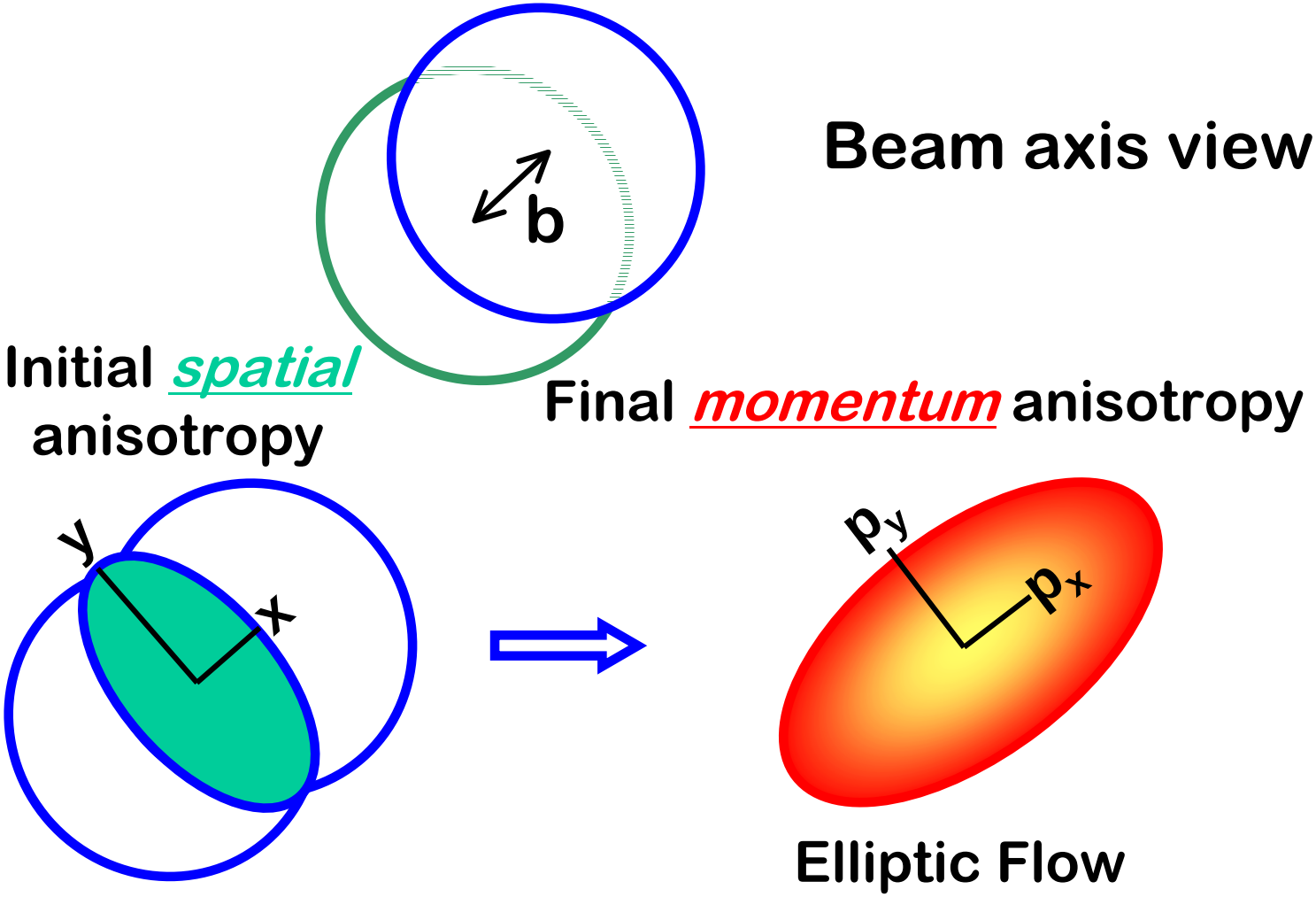


Probes of the Physics in Nuclear Collisions





Finite Impact Parameter Collisions are ϕ Anisotropic



Bulk Collective Flow of QCD matter

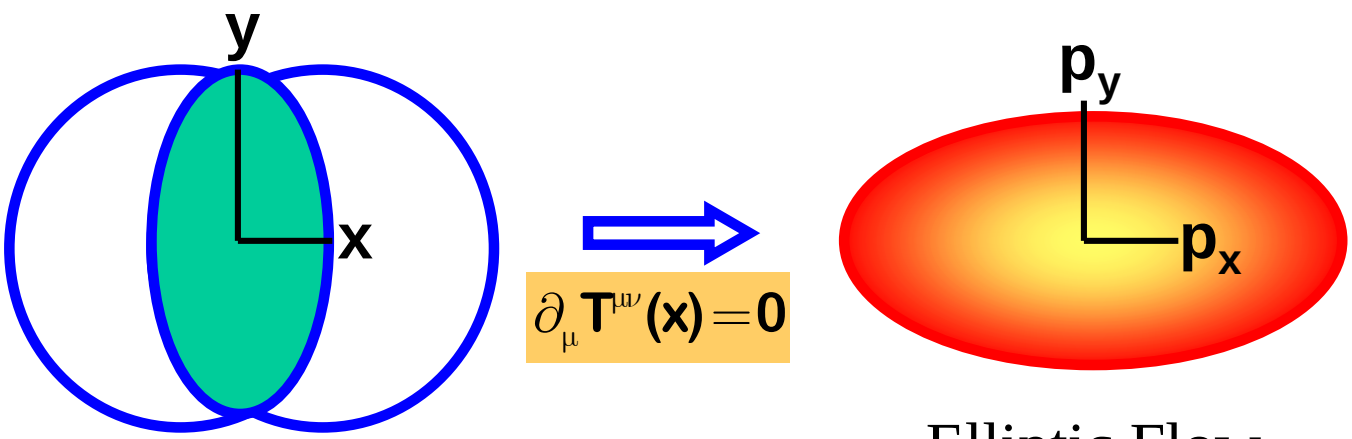
$$\partial_\mu T^{\mu\nu} = \partial_\mu \left\{ u^\mu u^\nu (\varepsilon(T) + P(T)) - g^{\mu\nu} P(T) \right\} = 0$$

QCD EOS

W. Greiner, H. Stocker(1974)
P.Kolb, U. Heinz et al (2000)
D.Teany, E. Shuryak
T. Hirano, Y. Nara

Initial *spatial* anisotropy

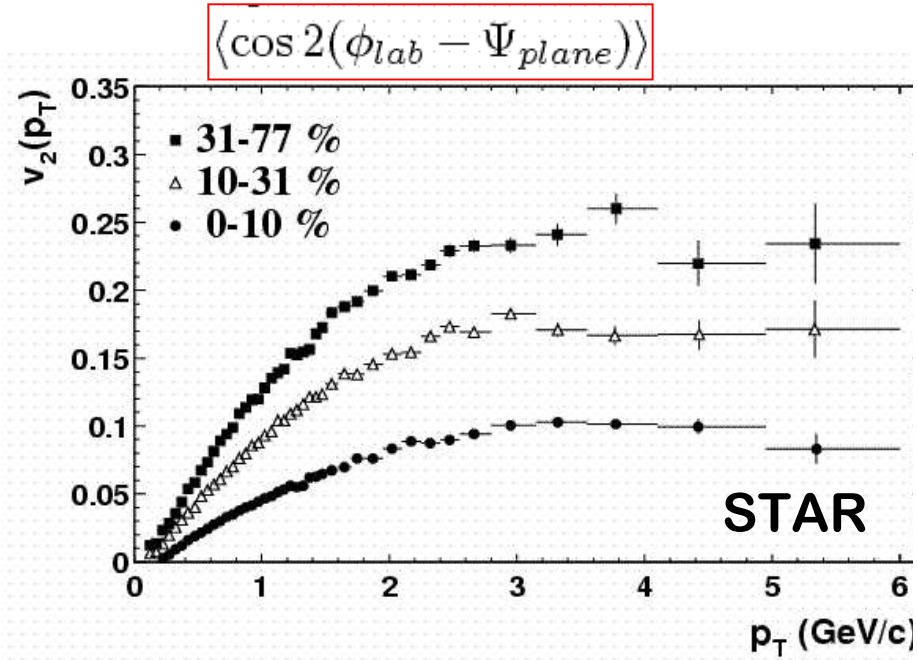
Final *momentum* anisotropy

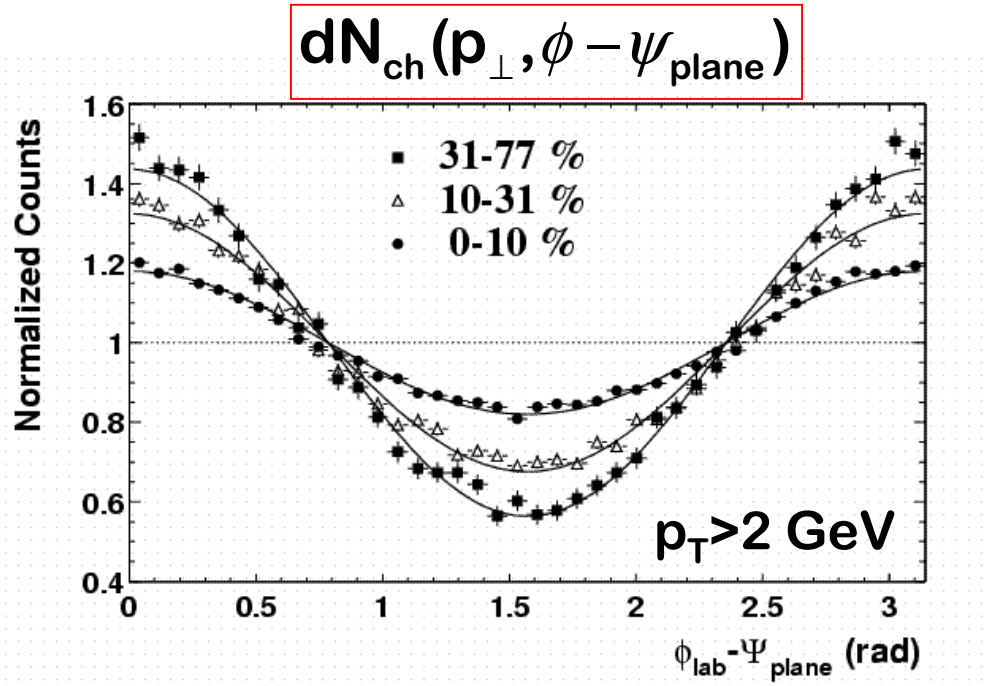


Elliptic Flow

$$\frac{dN}{dy\,dp_T^2\,d\phi} = \rho(y, p_T)\left\{1 + 2v_2(p_T)\cos(2\phi) + \cdots\right\}$$

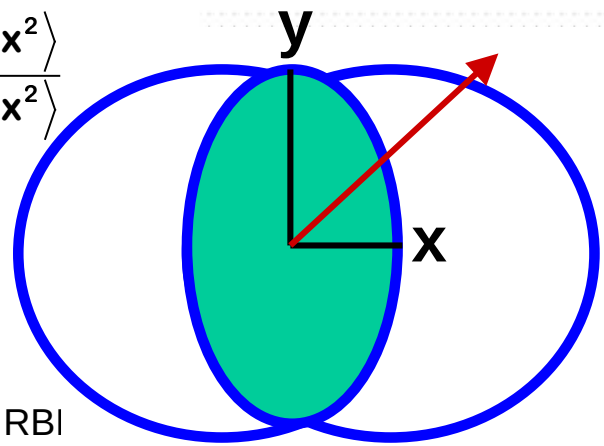
Conclusive evidence for bulk elliptic collective flow at $T=10^{12}$ K





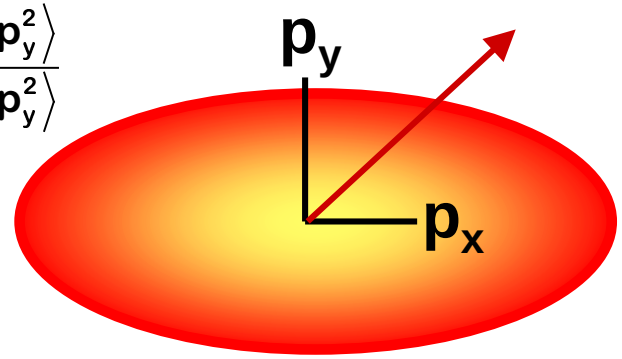
Initial *spatial* anisotropy

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



Final *momentum* anisotropy

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$



Conclusive evidence for bulk elliptic collective flow at $T=10^{-6}$ K

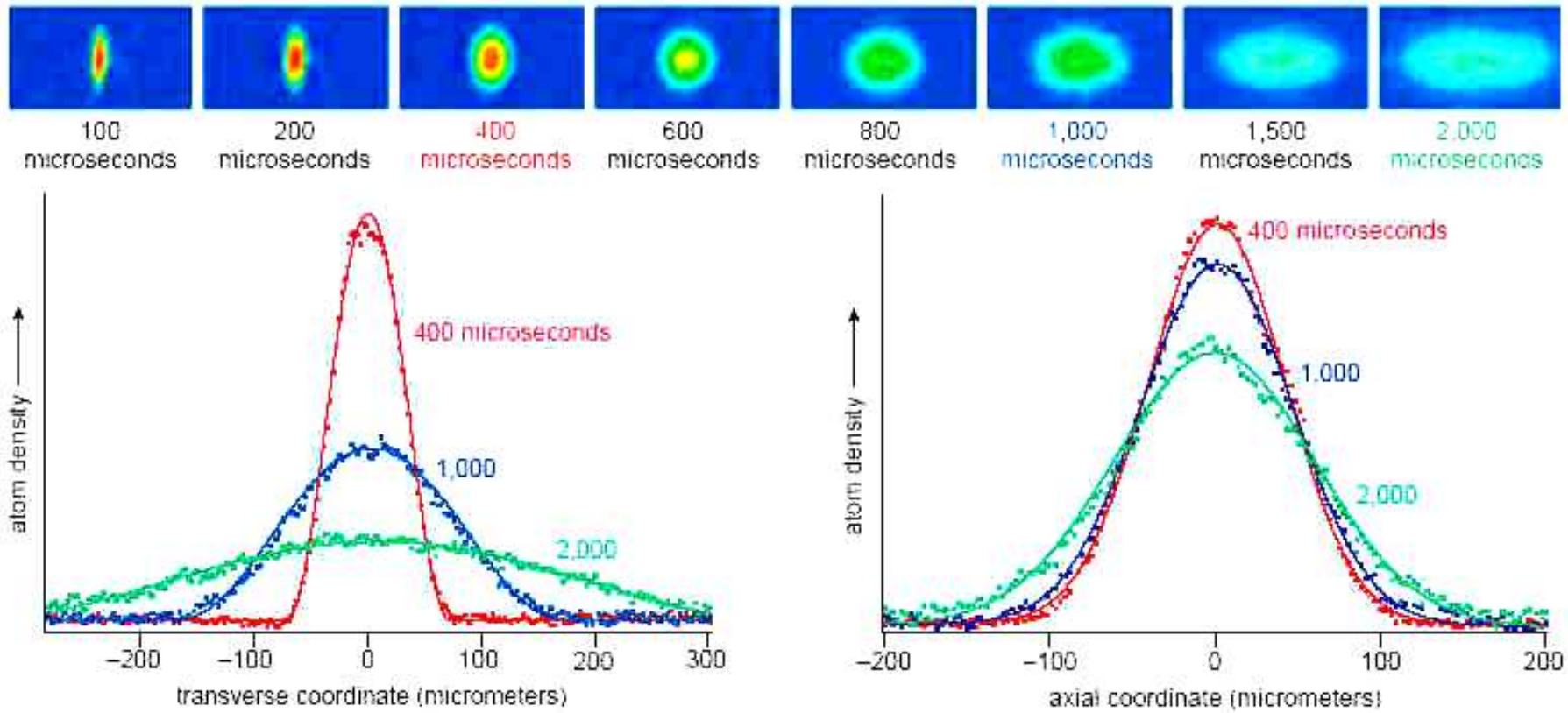
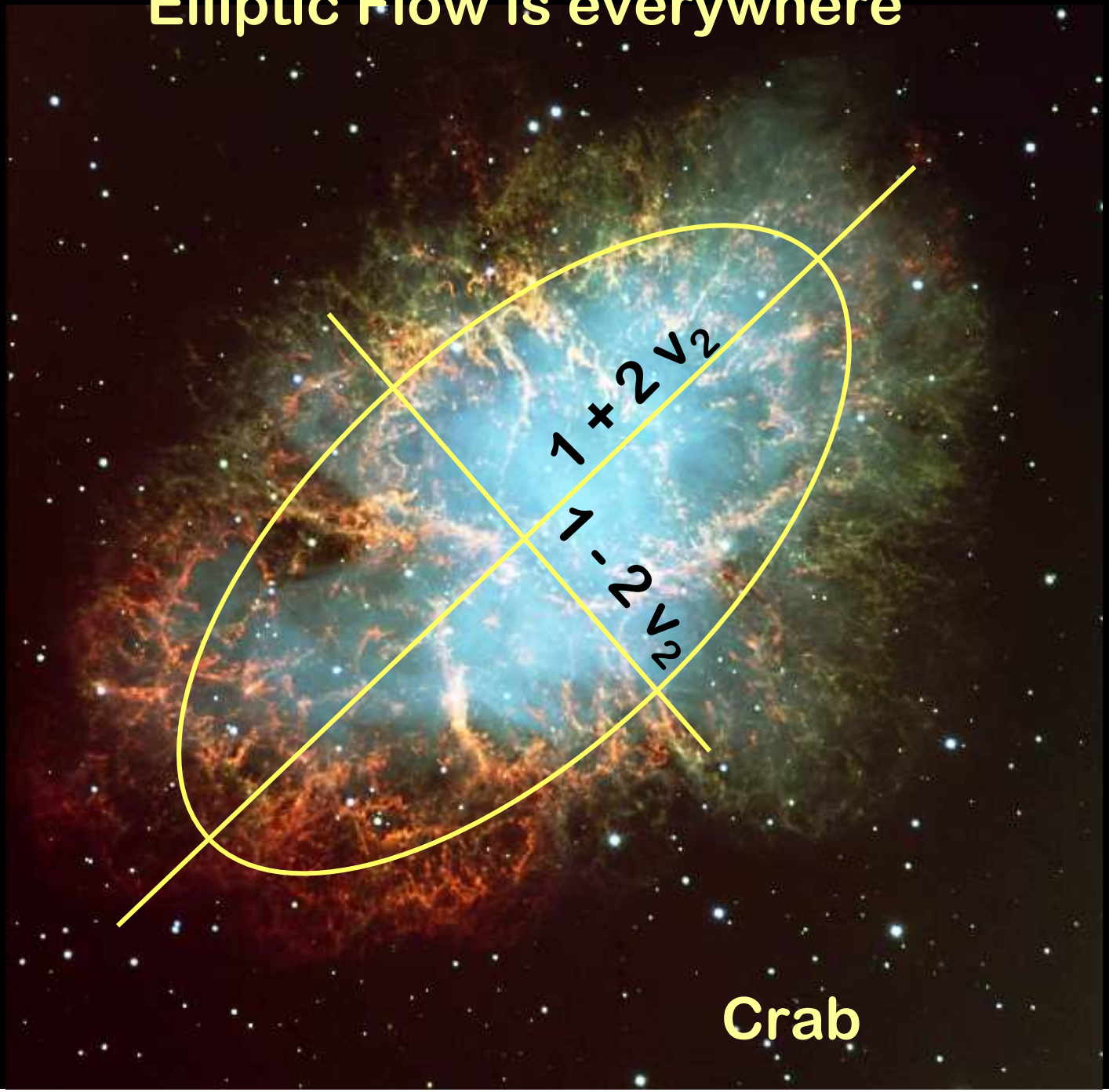


Figure 8. Experimental data confirm the anisotropic expansion of a cloud of ^{6}Li atoms. Sequential images capture the change in shape and density of the gas cloud as it warms. The gas remains degenerate, and strongly interacting, for about 400 microseconds after release (shown in the first three frames). After 400 microseconds, the high initial velocity of the atoms causes the cloud to continue changing shape in the same manner, although the atoms are no longer strongly interacting. Quantitative measurements derived from these images show that the atoms spread out much more rapidly transverse to the axis of the cloud *(left graph)* than along it *(right graph)*.

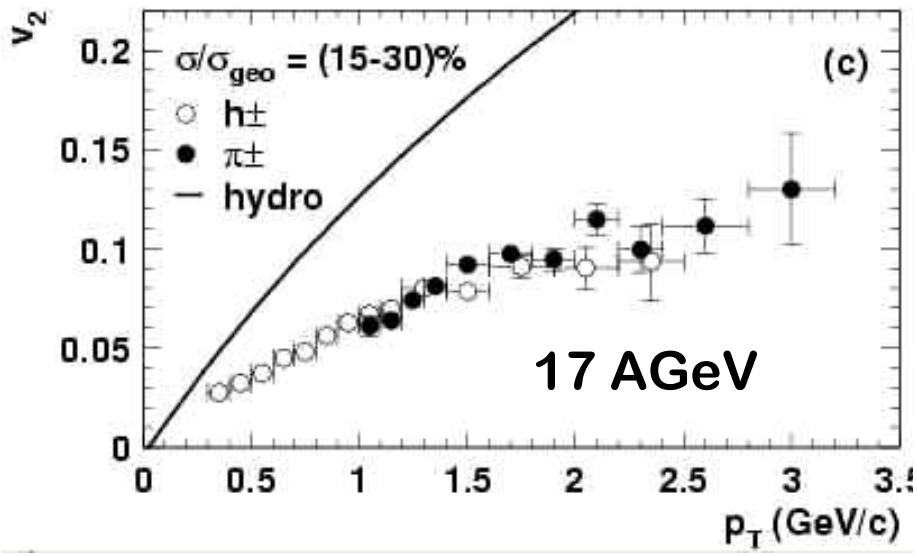
Elliptic Flow is everywhere



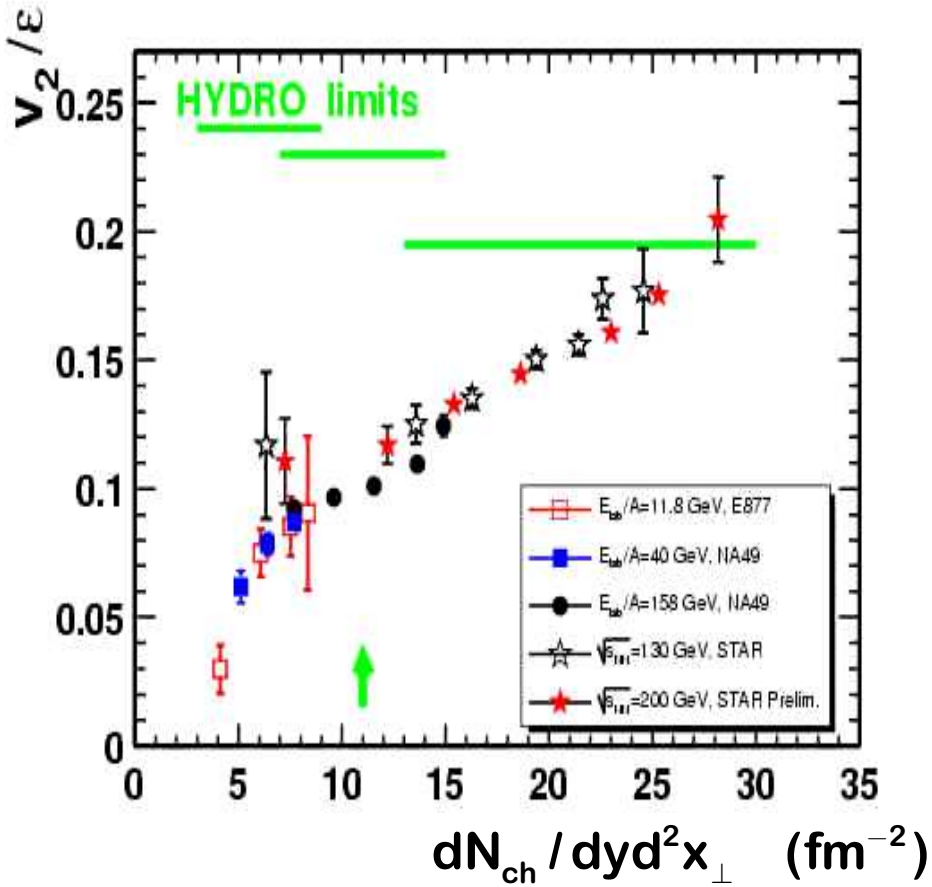
But Nonviscous Hydrodynamics never worked on nuclear scale before !

$v_2(E_{cm} < 200$ AGeV) < hydrodynamic predictions

CERES

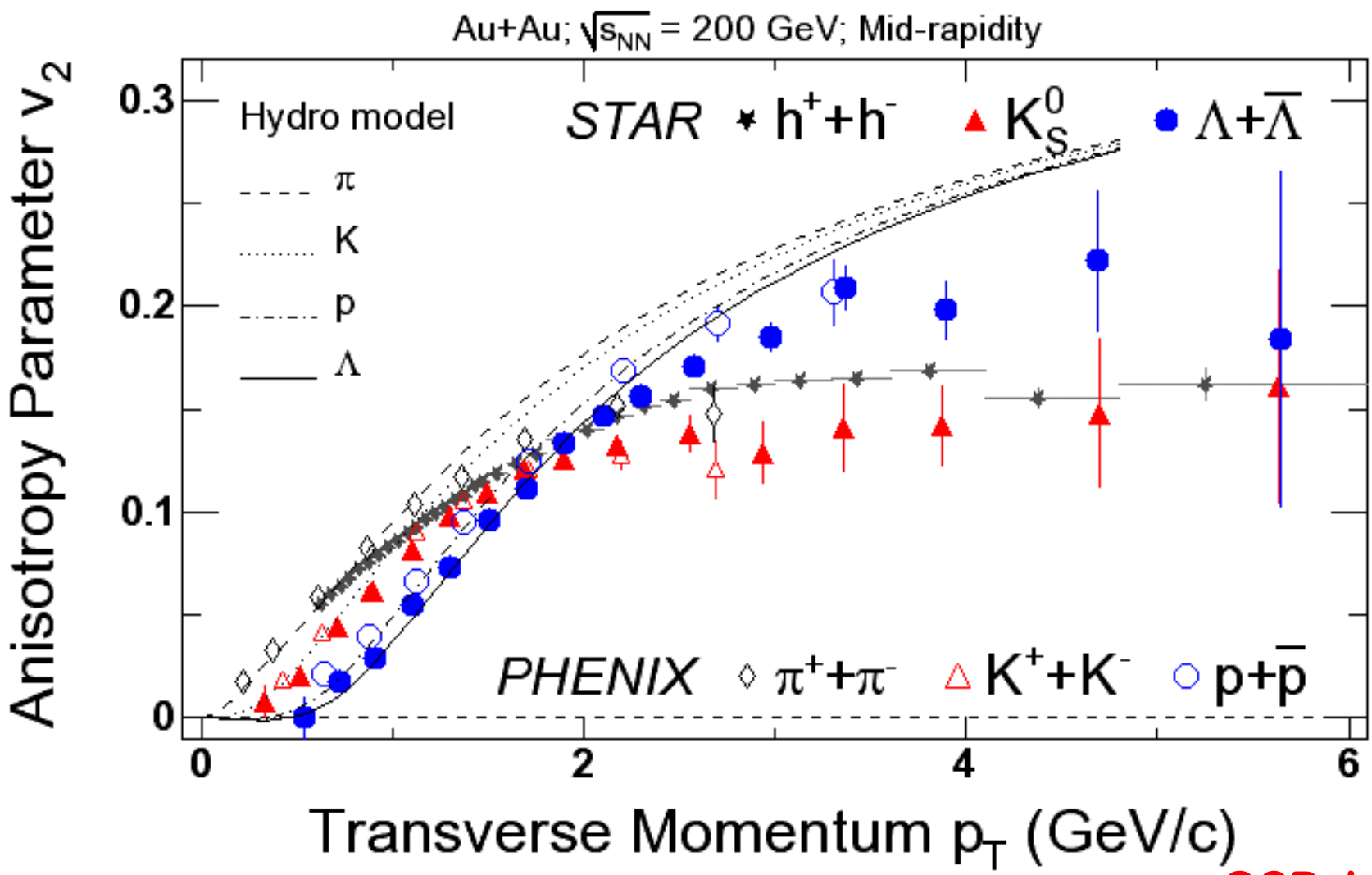


CERES/SPS



S.Voloshin STAR/NA49
Kolb,Heinz,Huovinen hydro

sQGP Fingerprint at RHIC = Fine Structure of elliptic flow



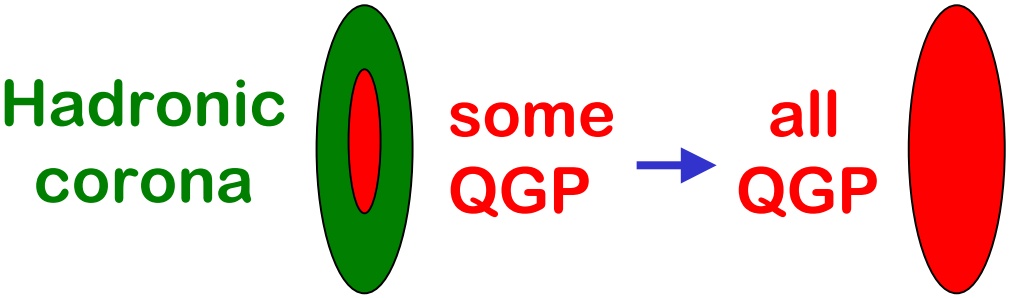
Bulk P_{QCD} Hydro

qqq Coalescence

pQCD Jets

Discrepancy of hydro $v_2(p_T)$ slope at lower energies is due to Normal highly dissipative Hadronic corona

Hydro+RQMD:
Teaney, Shuryak



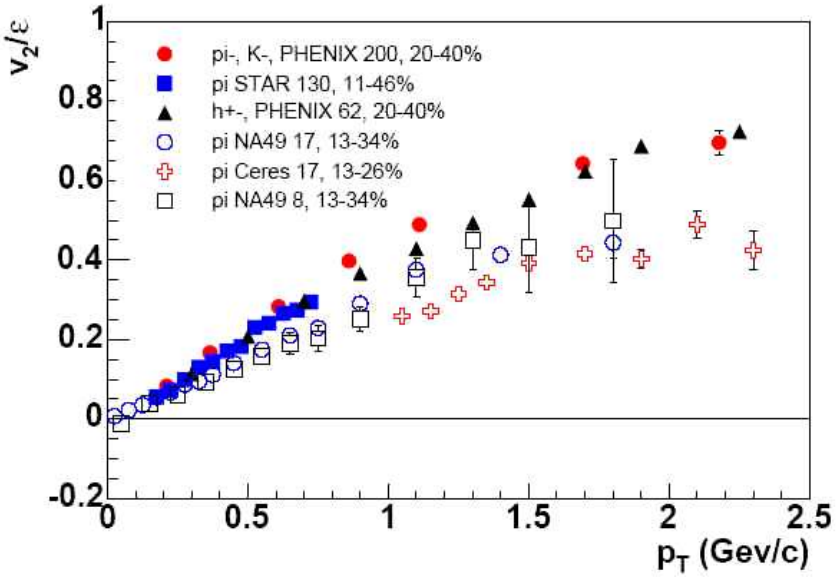


FIG. 16: $v_2(p_T)/\varepsilon$ versus p_T for mid-central collisions at RHIC (filled symbols) and SPS (open symbols). Dividing by eccentricity removes to first order the effect of different centrality selections across the experiments.

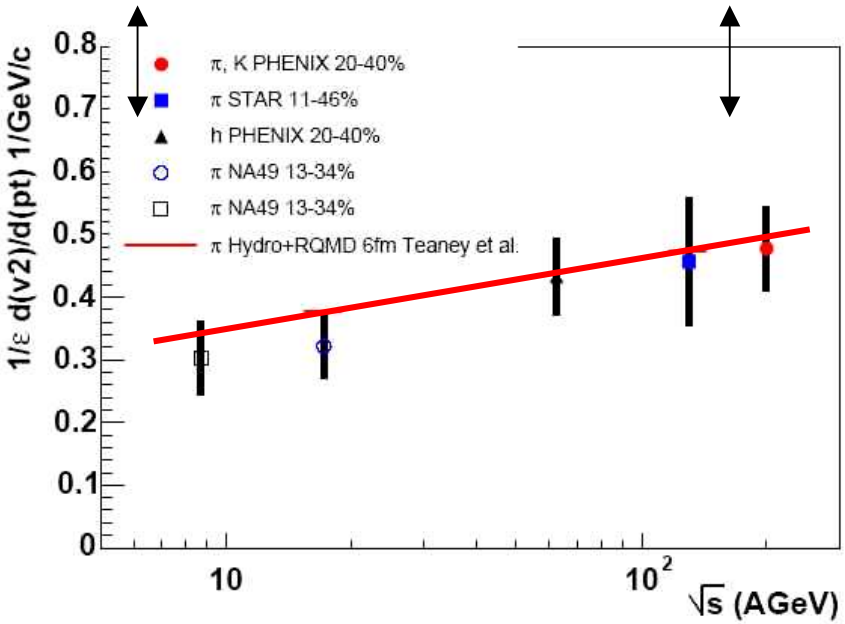


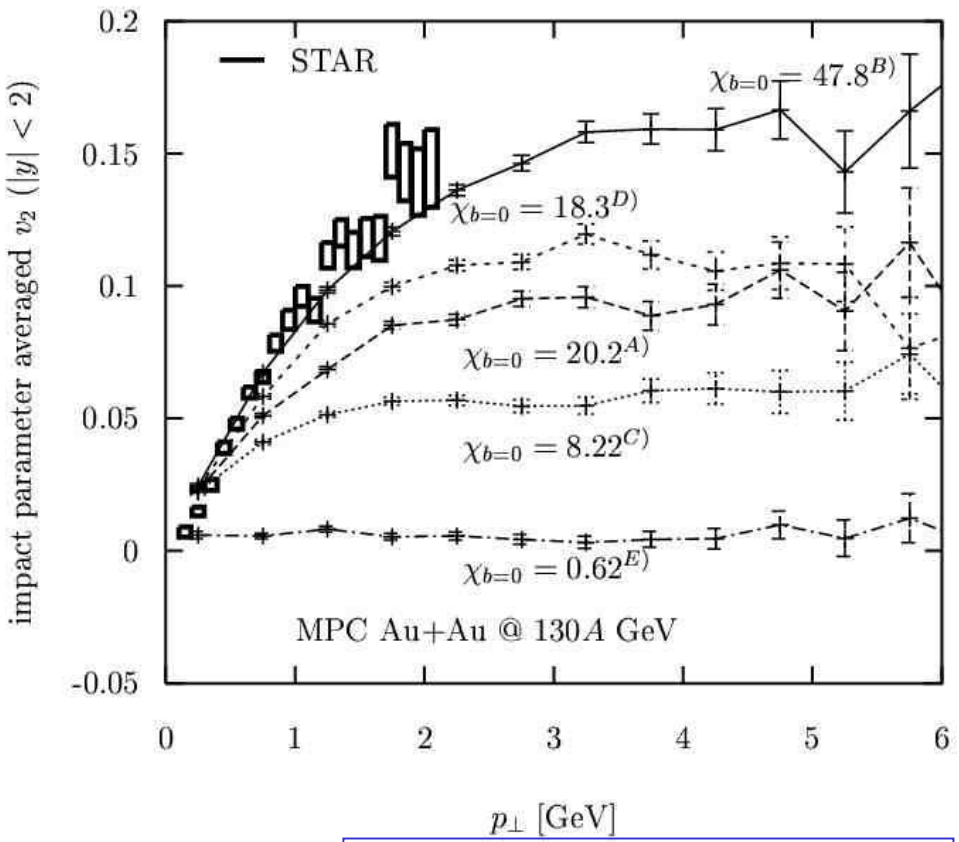
FIG. 17: The slope of the scaled elliptic flow, $(dv_2/dp_T)/\varepsilon$, for mid-central collisions at RHIC (filled symbols) and the SPS (open symbols). The slope is calculated for the data $p_T < 1$ GeV/c. The solid error bars are the systematic errors that include the systematic error on v_2 and ε.

PHENIX:nucl-ex/0410003

The sQGP must be almost a perfect fluid !

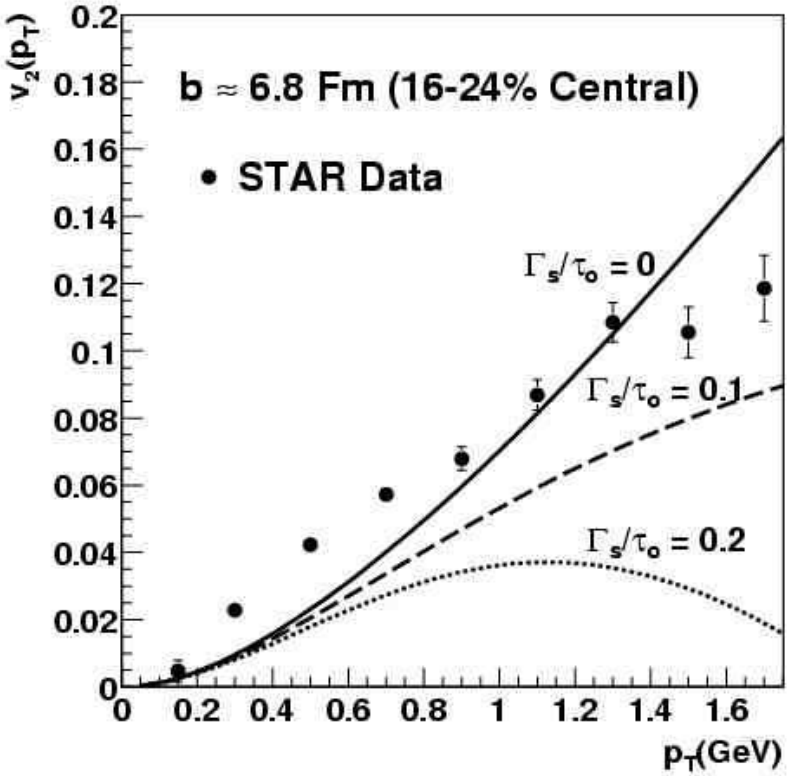
Gluon Transport

D.Molnar, MG (01)



Navier-Stokes

D.Teaney (03)



Opacity $\chi = \int d\tau\, \sigma\, \rho \approx \frac{dN_g}{dy} \frac{\sigma_g}{\pi R^2}$ **must be >> pQCD**

Dissipative Hydrodynamics in μ_B=0 limit

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = \left\{(\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}\right\} + \tau^{\mu\nu}$$

Flow velocity field $u^\mu(x,t)$ and temperature field T(x,t)

1+1D Hubble

$$\frac{d\epsilon}{d\tau} + \frac{1}{\tau}(\epsilon + p) = \left(\tfrac{4}{3}\eta + \xi\right)/\tau^2$$

Bjorken

sound

$$\omega = u_s q - \frac{i}{2}\frac{1}{\epsilon + P}\underbrace{\left(\zeta + \frac{4}{3}\eta\right)}_{\text{Damping}} q^2, \qquad u_s^2 = \frac{\partial P}{\partial \epsilon}$$

Shear viscosity

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\boldsymbol{x}\, e^{i\omega t} \langle [T_{xy}(x), T_{xy}(0)] \rangle$$

Kubo

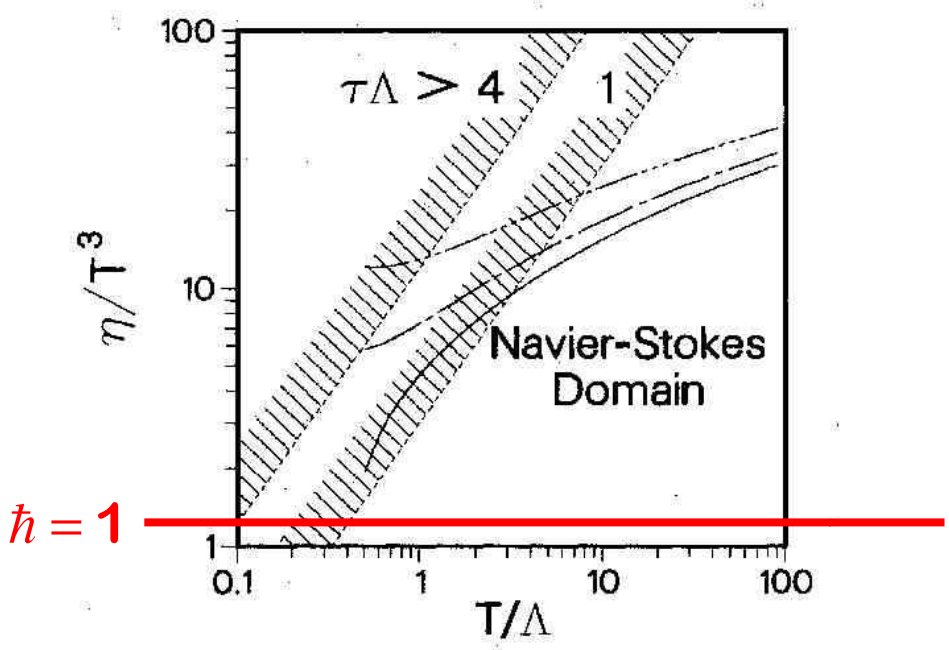
$$\eta = \tfrac{1}{5}(\varepsilon + P)\,\lambda = \sigma_{\text{entropy}}\left(\frac{T\lambda}{5}\right)$$

Gas kinetic theory

PHYSICAL REVIEW D VOLUME 31, NUMBER 1 1 JANUARY 1985

Dissipative phenomena in quark-gluon plasmas

P. Danielewicz* and M. Gyulassy



$$\frac{\eta}{\sigma} \approx \frac{T\,\lambda_{tr}}{5} = \frac{T}{5\,\sigma_{tr}\,\rho}$$

$$\sigma_{tr} \approx \frac{2}{T^2}\,\alpha^2 \ln \alpha^{-1}$$

pQCD

$$\frac{\eta}{\sigma} \approx \frac{0.1}{\alpha^2 \ln 1/\alpha} \sim 1$$

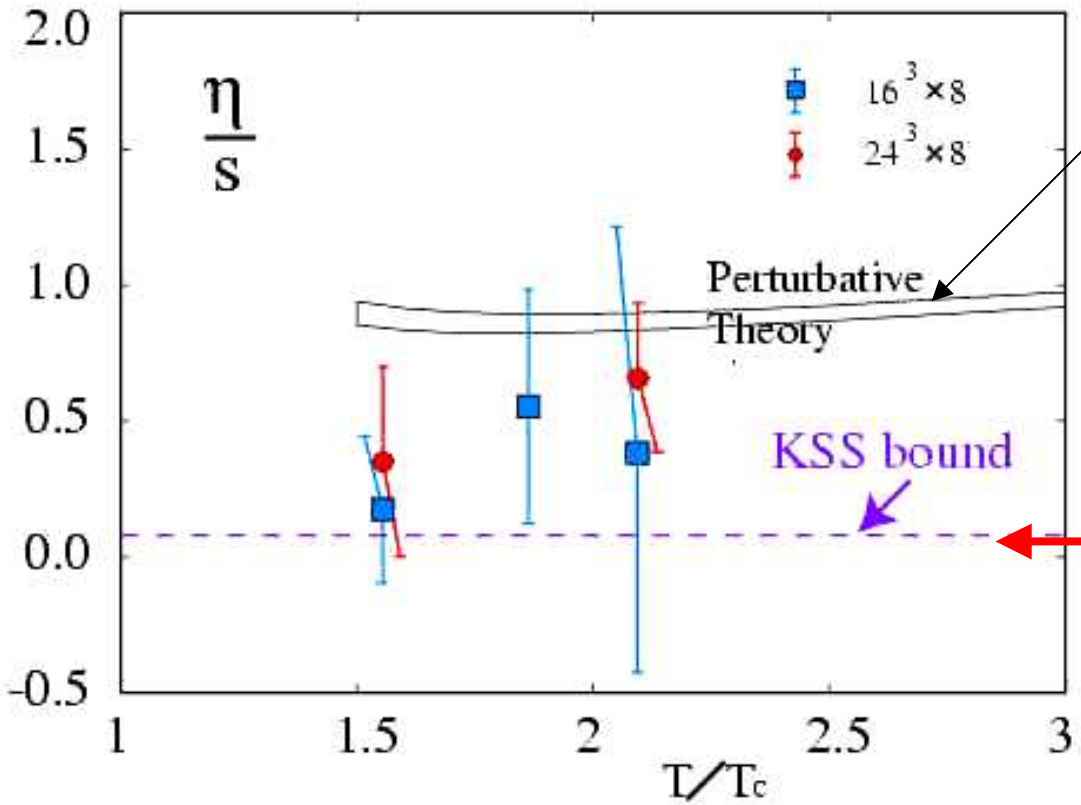
Uncertainty bound $\lambda_{tr} > \frac{\hbar}{3T} \Rightarrow \frac{\eta}{\sigma} > \frac{1}{15}$

with $\sigma \sim 16\,T^3$ then $\eta/T^3 \sim 1$

Transport coefficients of gluon plasma

Lattice QCD vs pQCD vs N=4 SUSY

Lattice QCD: A.Nakamura and S.Sakai, hep-lat/0406009



P.Arnold et al
JHEP 0305:051,2003

$$\frac{T\,\lambda_{pQCD}}{5} \approx \frac{(0.3)^2}{\alpha^2 \log 1/\alpha} \sim 1$$

$$\left(\frac{\eta}{\sigma}\right)_{adS/CFT} = \frac{1}{4\pi}$$

N=4 SUSY

g^2N_c -> Inf

$$\frac{T\lambda_{min}}{5} \approx \frac{\hbar = 1}{15}$$

N=4 SUSY: Policastro, Son, Starinets (2001)
Kovtun,Son,Starinets (2004)

pQCD: Danielewics, MG, …. (1985)

A.Buchel, J.T.Liu and A.O.Starinets,
``Coupling constant dependence of the shear viscosity in N = 4 supersymmetric Yang-Mills theory,"
arXiv:hep-th/0406264.

Thus for large 't Hooft coupling $g^2_{YM} N_c \gg 1$ the correction to the ratio of shear viscosity to the entropy density in $\mathcal{N} = 4$ supersymmetric Yang-Mills theory is *positive*,

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{135}{8}\zeta(3)\,(2g^2_{YM} N_c)^{-3/2} + \cdots\right) . \qquad (4.7)$$

But for g^2N_c=10-20 correction is < 20% to 1/4π !

$$\frac{4\pi\eta}{\hbar\sigma}$$

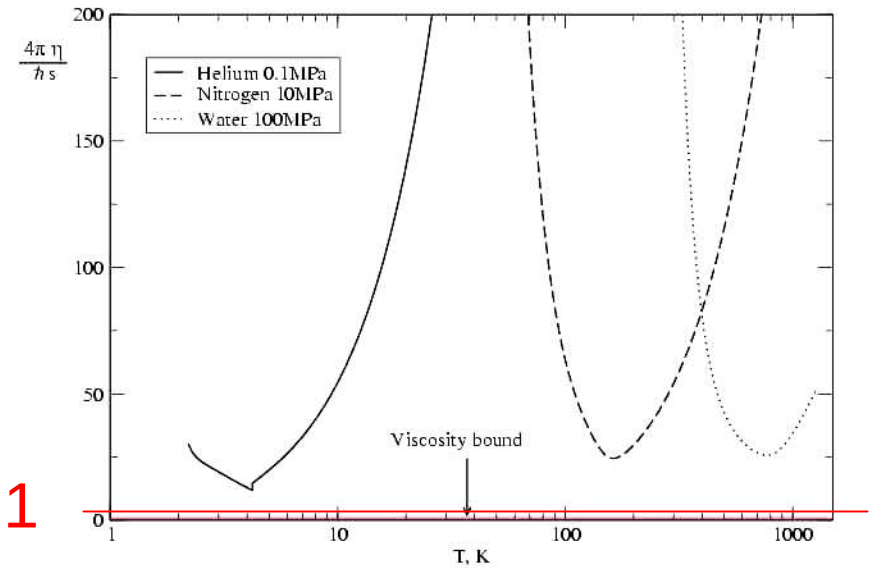


Figure 1: The viscosity-entropy ratio for some common substances.

Kovtun,Son,Starinets 04

adS/CFT
Universal lower bound conjecture

Relaxation time of strongly coupled Yukawa systems

Tomoyasu Saigo, August Wierling and Satoshi Hamaguchi

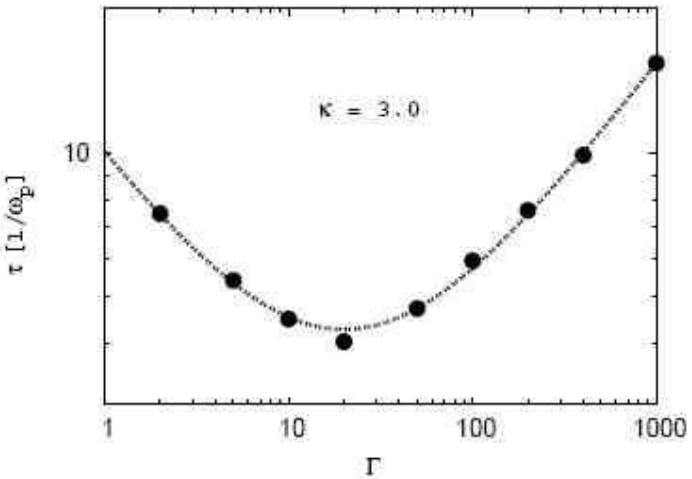


Figure 2: The relaxation time τ as a function of Γ for $\kappa = 3.0$. The fitting curve is based on a form $\tau = a\sqrt{\Gamma} + b/\sqrt{\Gamma} + c$.

We find that the flows retains the initial information for a long time in both weakly and strongly coupled regimes. In the weakly coupled regime, the initial information is retained due to the low collision frequencies. In the strongly coupled regime, it is also retained due to the relatively rigid structure of the system, analogous to the dynamics of ideal crystals.

S. Ichimaru et al., Statist

Viscosity in EM Plasmas

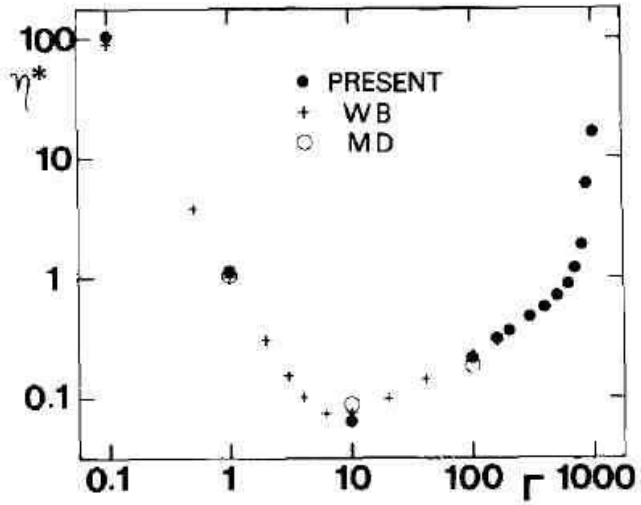


Fig. 33. The reduced shear viscosity $\eta^* \equiv \eta/Mn\omega_p a^2$ calculated on the basis of eqs. (4.15)–(4.17) (solid circles, ref. [77]). The crosses refer to the calculation by Wallenborn and Baus [72], the open circles to the MD simulation result [160].

Strongly Coupled Plasmas (Ichimaru Vol 2)

Important Role of dynamic correlations at large Γ

$V_i(k) \equiv Z^2\, v(k)/\varepsilon_e(k,0)$ represents the Fourier-transformed interionic potential and $\varepsilon_e(k,0)$ static screening function of the electrons, eq. (3.116). They then evaluated the shear viscosity η v aid of the collision term in the static LFC approximation, eq. (2.81):

$$\frac{\sigma_{tr}}{T} = \frac{1}{\eta} = \frac{1}{5\pi^2 (k_B T)^3} \int_0^\infty dk \int_0^\infty dw \, \frac{k^3 V_i(k)^2 [1 - G_i(k)]}{|\tilde{\varepsilon}_i(k, kw)|^2} \exp\left(-\frac{mw^2}{k_B T}\right),$$

where

$$\tilde{\varepsilon}_i(k,\omega) = 1 - V_i(k)\,[1 - G_i(k)]\,\chi_i^{(0)}(k,\omega)$$

and $\chi_i^{(0)}(k,\omega)$ is the free-particle polarizability of the ions, eq. (2.77).

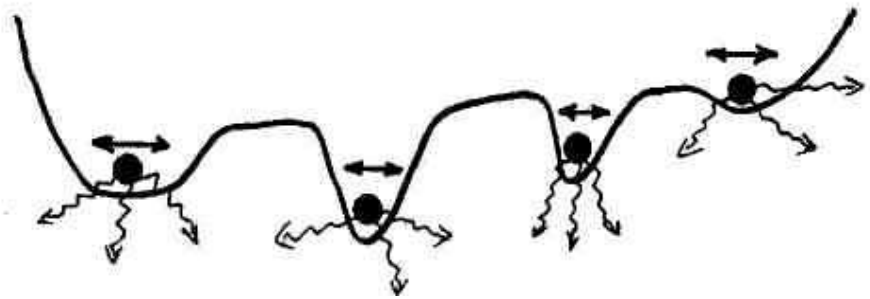
In table 9, we list the computed values of the reduced shear viscosity $\eta^* \equiv \eta / M n_i \omega_p a^2$

Quasilocalized charge approximation in strongly coupled . . . 15

Vol. 1

Dielectric screening

Golden, Kalman, Plas.Phys. 2000



"Optically Trapped Fermi Gases"
American Scientist Vol. 92,
May-June 2004 (pg. 238-245)

J. E. Thomas, M.E. Gehm

Unitarity Limited
Resonance scattering

Precise control via
Magnetic field

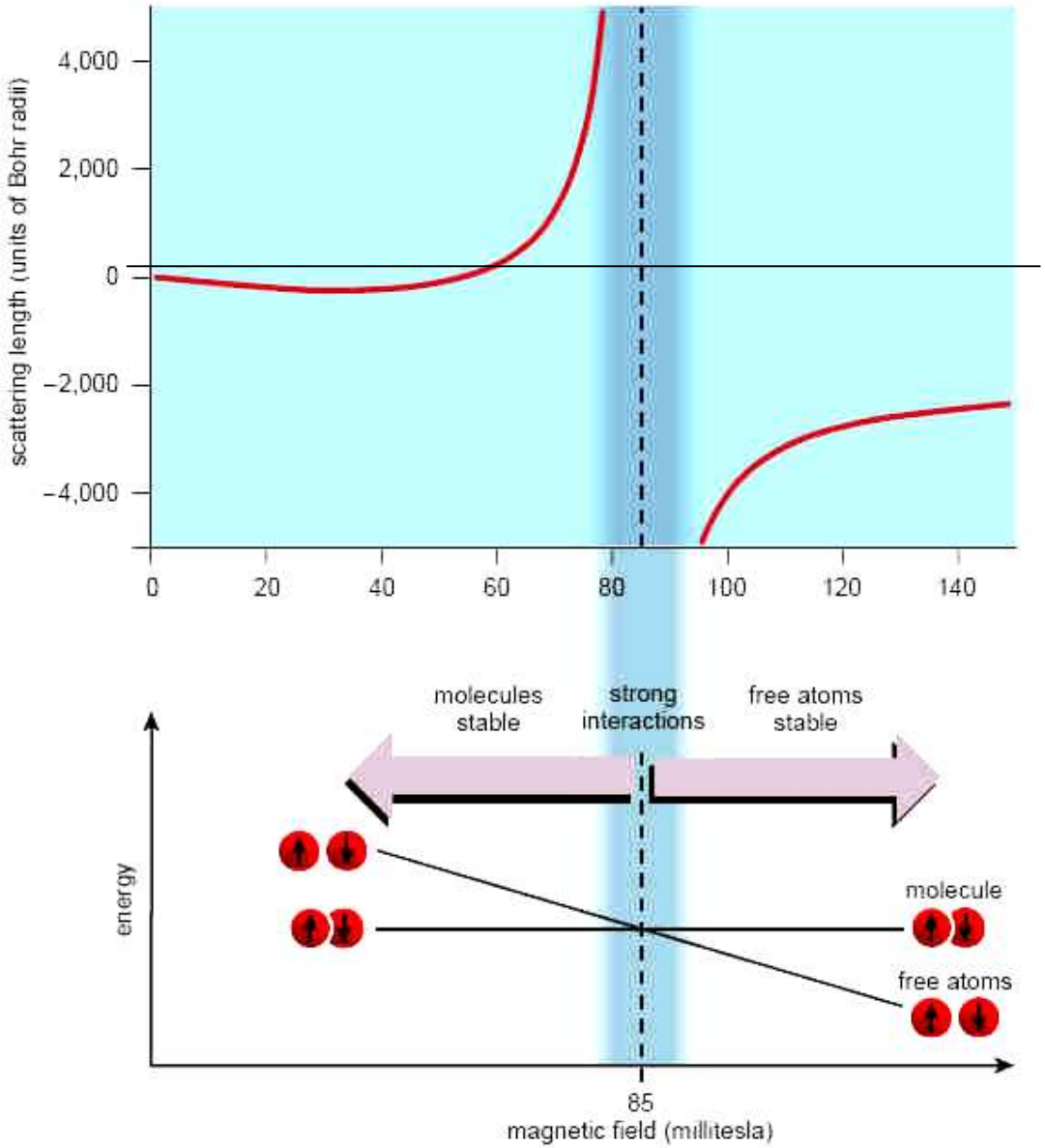


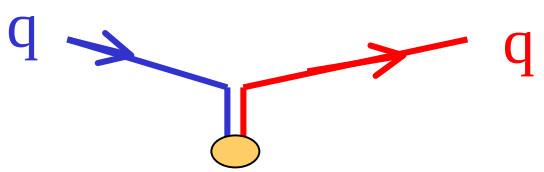
Figure 5. Feshbach resonance changes the behavior of a degenerate Fermi gas. This phenomenon causes the distance at which the atoms influence one another—their "scattering length"—to increase dramatically when a magnetic field of a particular strength is applied (*top*). (A positive scattering length corresponds to repulsion; negative to attraction.) In the case of ^{6}Li atoms, Feshbach resonance takes place at 85 millitesla. In a weaker magnetic field, a molecule has a lower en-

Another idea that will be discussed at this meeting

Perhaps sQGP is driven to local equilibrium by macroscopic Yang-Mills instabilities (Mrowczinski(88); Thoma; Arnold …(04))

One major catch in non-Abelian weakly coupled plasmas

Fastest process is color diffusion that Neutralizes macro YangMills fields (Selikhov, MG, PLB(93), …, Manuel, Mrowczinski(04))



Soft color rotation In g<<1 limit

$$\tau_{color} \sim \frac{1}{g^2 \mathrm{Log}(1/g) T} << \tau_{momentum} \sim \frac{1}{g^4 \mathrm{Log}(1/g) T}$$

Color conductivity

$$\sigma_c \approx \frac{T}{\mathrm{Log}(1/g)} << \tau_{mom} \omega_{pl}^2$$

sQGP is more like an insulator than conductor

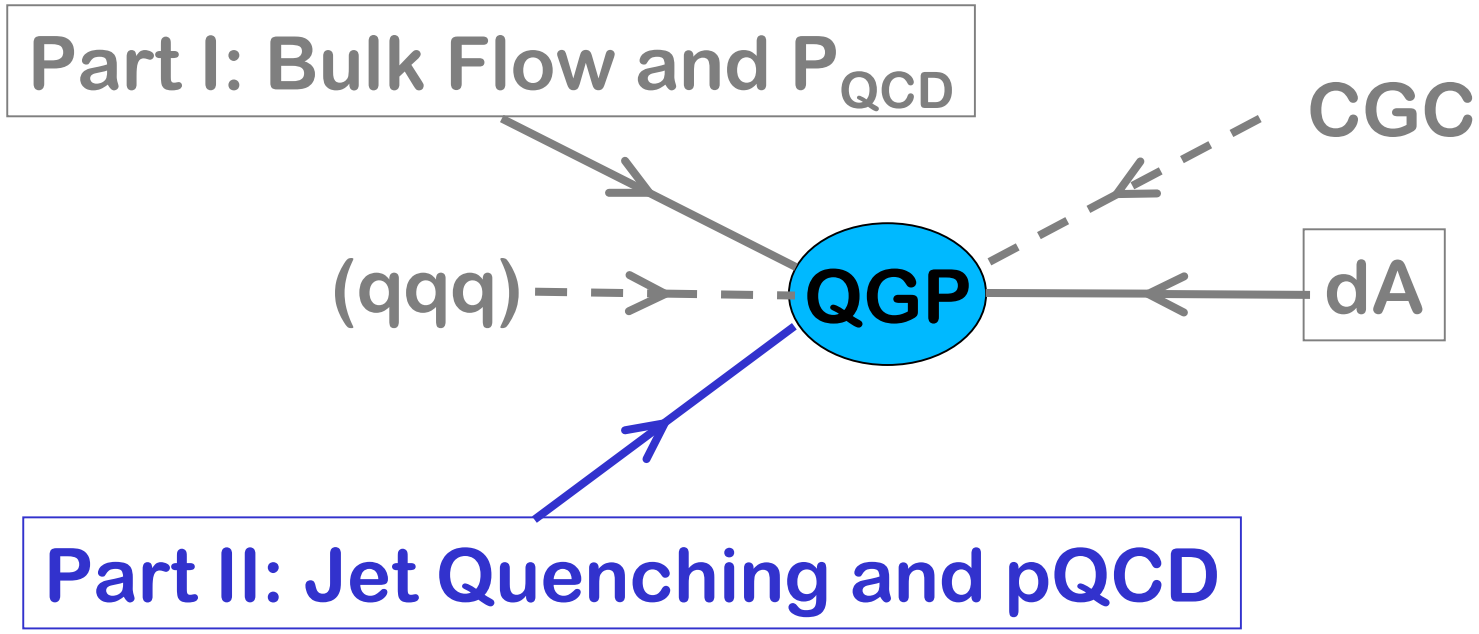
Conclusion Part I:

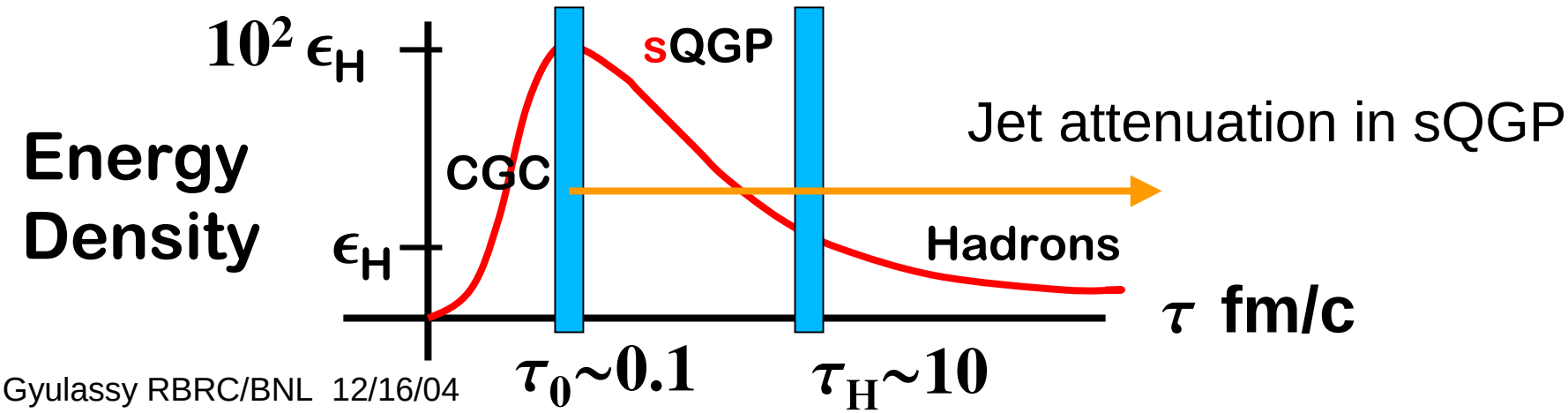
QCD pressure P_{QCD} accounts well for the fine structure (p_T , m_h) of elliptic flow at RHIC

Even more remarkably, the QGP at $T<3T_c$ Seems to saturate the *minimal* viscosity bound!

QGP found at RHIC = new form of strongly coupled plasma sQGP

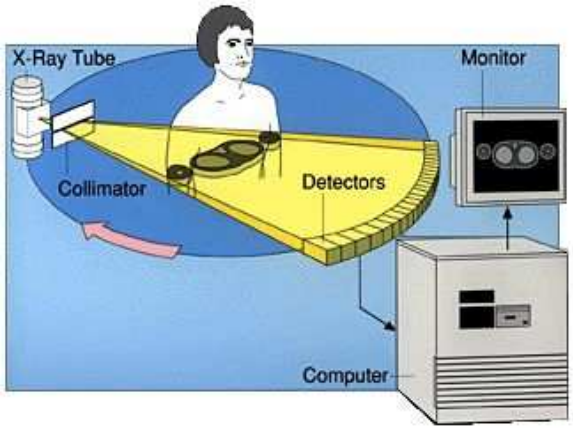
To understand better the physics we need to study and compare to SCM in other fields


Part I: Bulk Flow and P_{QCD}
CGC
(qqq)
QGP
dA
Part II: Jet Quenching and pQCD

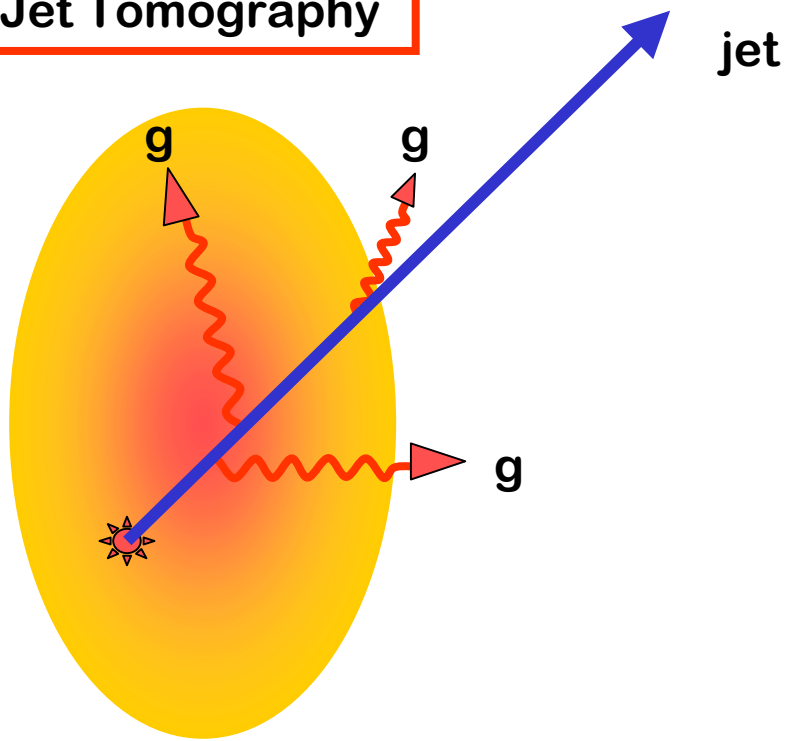

$10^2\ \epsilon_H$
Energy Density
ϵ_H
CGC
sQGP
Jet attenuation in sQGP
Hadrons
τ fm/c
$\tau_0 \sim 0.1$
$\tau_H \sim 10$

External Probes and sQGP Diagnostics: Jet Quenching

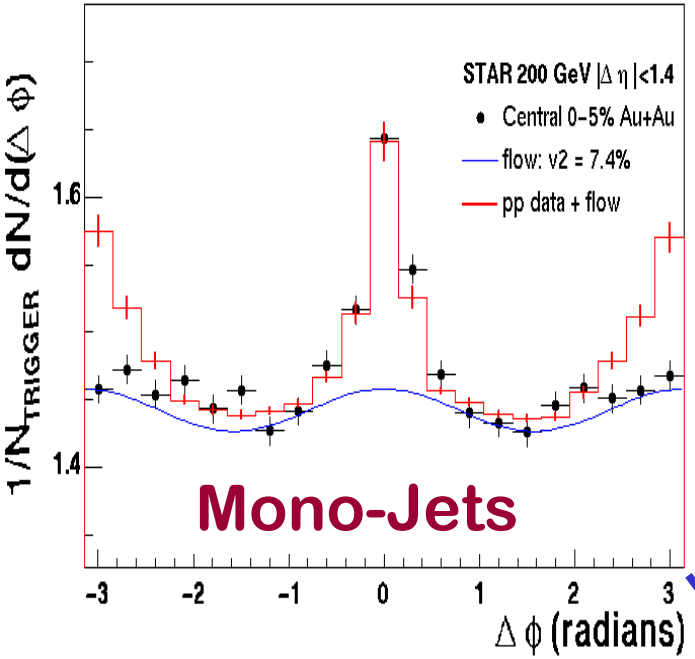
MG, P. Levai, I.Vitev, X.N. Wang,...

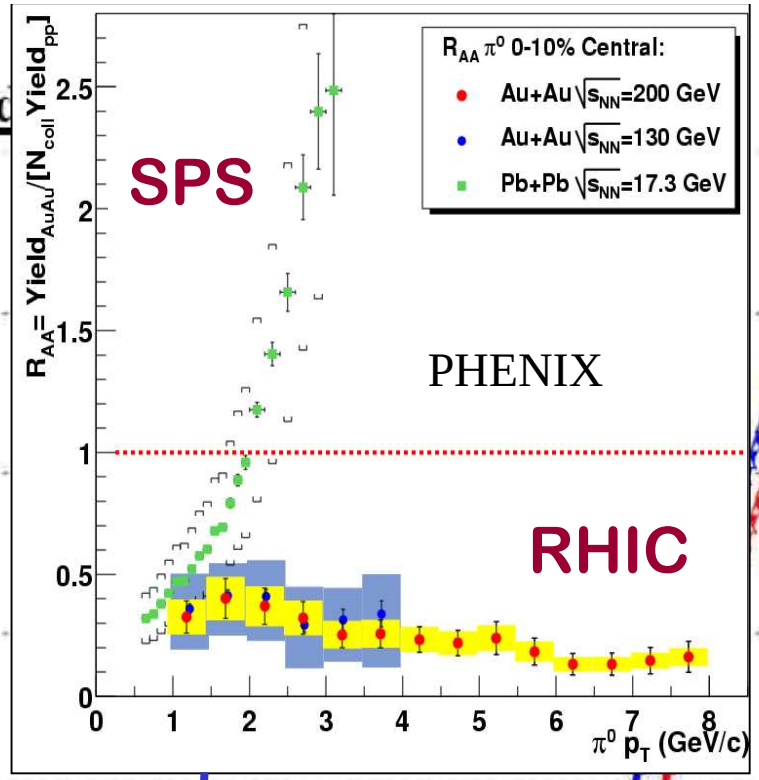


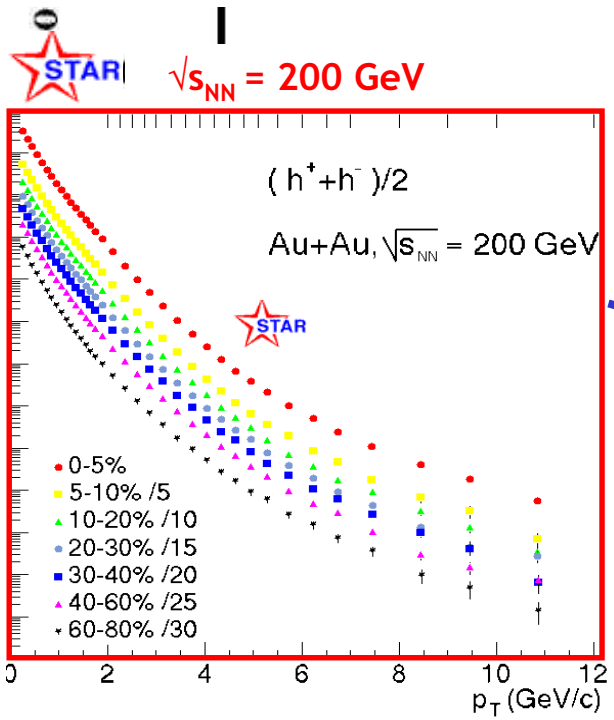
Jet Tomography

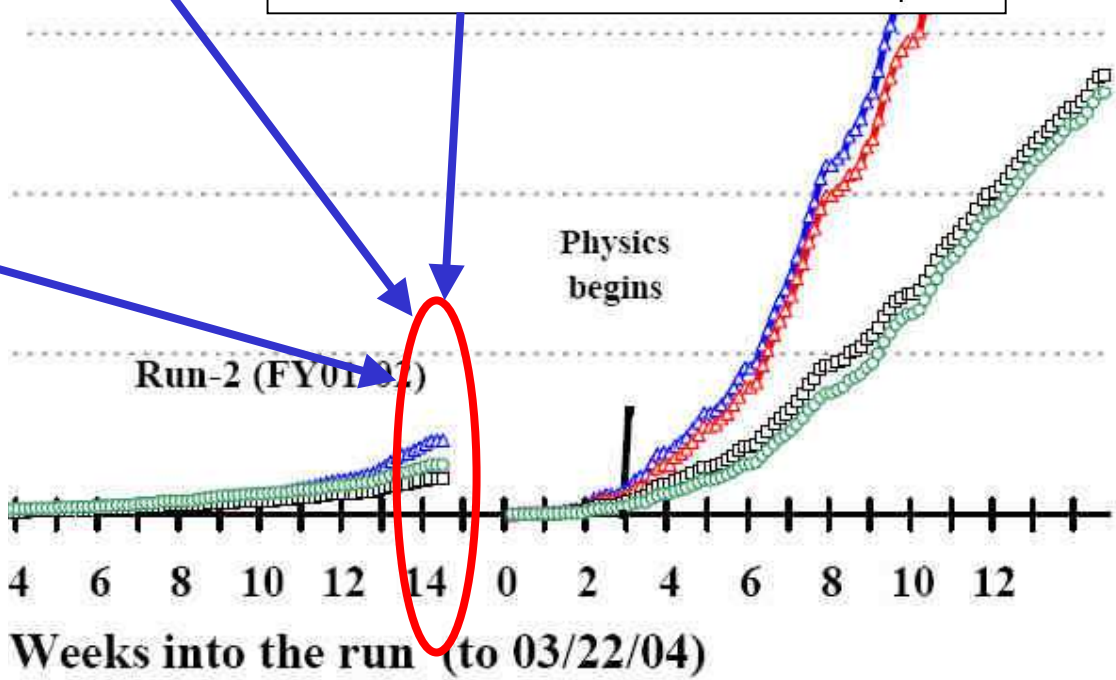


$$\Delta E_{GLV} \sim C_2 \alpha_s^3 E_0 \int d\tau\, \tau \rho_{glue}(\tau, r(\tau))$$


STAR 200 GeV |Δ η |<1.4
Central 0-5% Au+Au
flow: v2 = 7.4%
pp data + flow
Mono-Jets
1/N_TRIGGER dN/d(Δ φ)
Δ φ (radians)

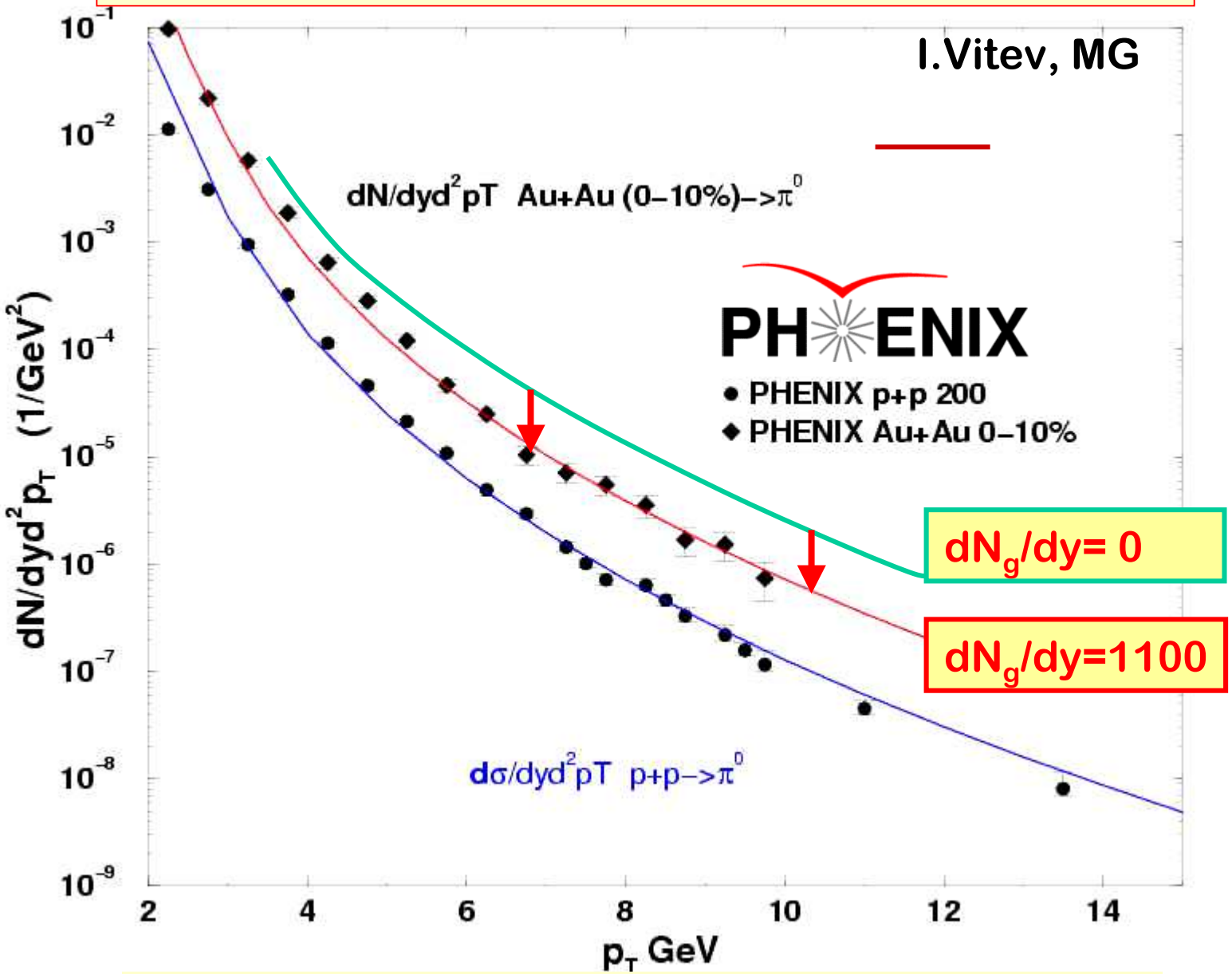

R_AA π⁰ 0-10% Central:
Au+Au √s_NN=200 GeV
Au+Au √s_NN=130 GeV
Pb+Pb √s_NN=17.3 GeV
SPS
PHENIX
RHIC
R_AA= Yield_AuAu/[N_coll Yield_pp]
π⁰ p_T (GeV/c)


STAR
√s_NN = 200 GeV
(h⁺+h⁻)/2
Au+Au, √s_NN = 200 GeV
STAR
0-5%
5-10% /5
10-20% /10
20-30% /15
30-40% /20
40-60% /25
60-80% /30
p_T (GeV/c)


Physics begins
Run-2 (FY01/02)
Weeks into the run (to 03/22/04)

Absolute scale pQCD jet tomography

GRV
EKS
BKK
GLV

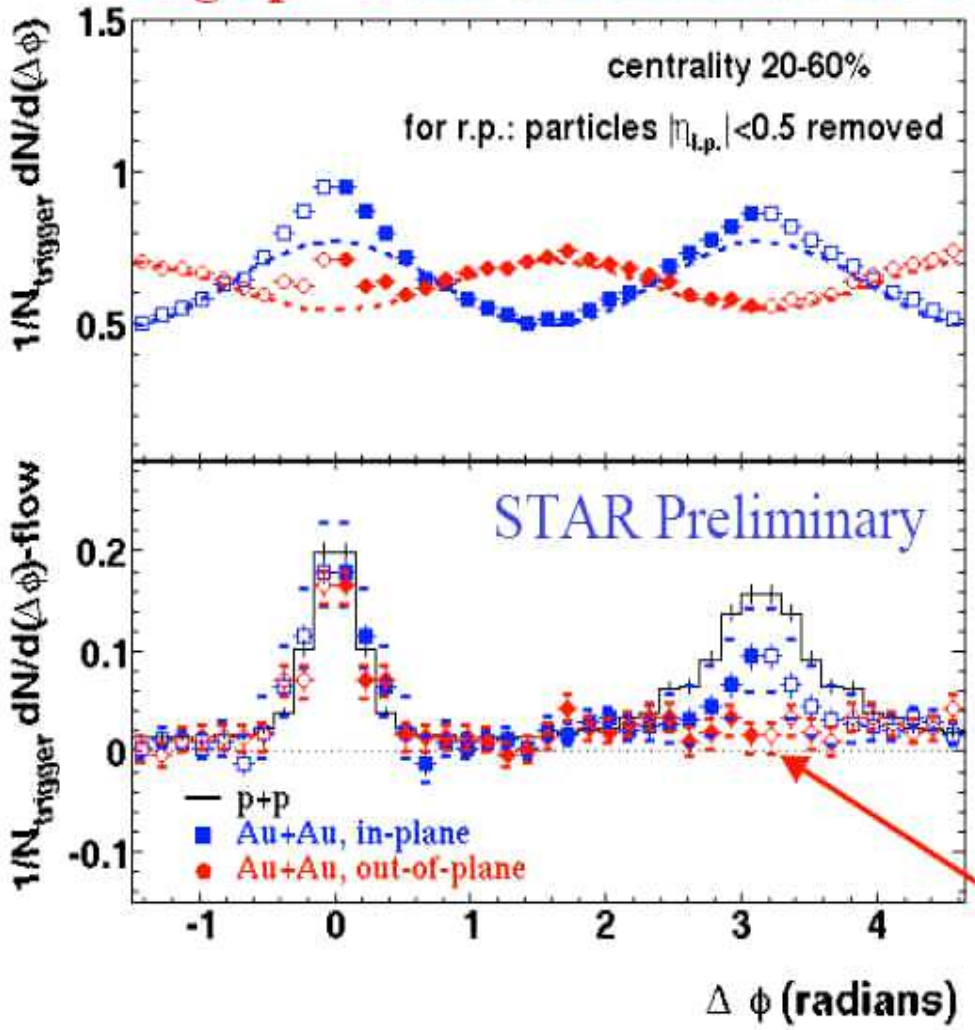


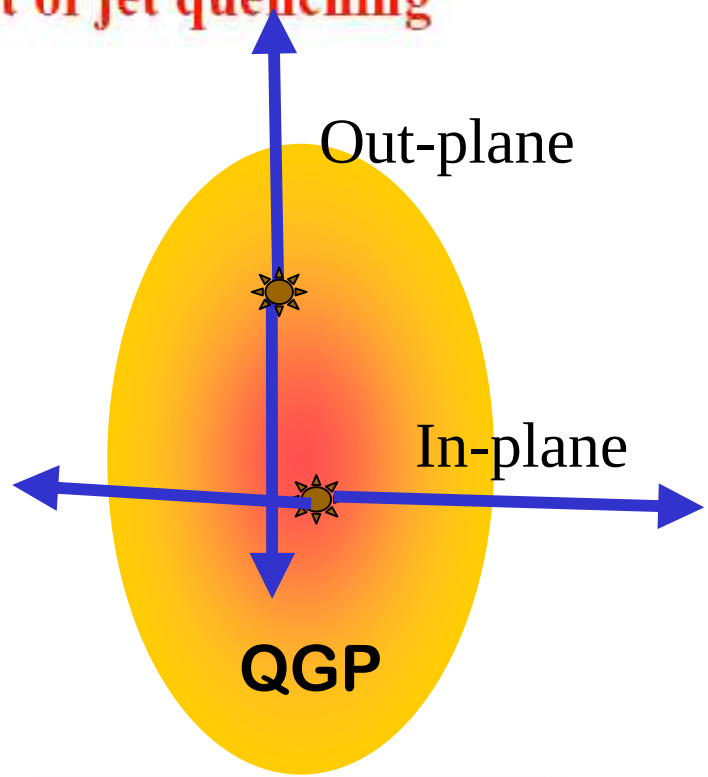
$$dN_{AB\to\pi} = T_{AB} \otimes \left(f_{a/A} \otimes f_{b/B}\right)^{shad}_{\Delta k_T} \otimes d\sigma_{ab\to c} \otimes P(\Delta E) \otimes D_{\pi/c}$$

K. Filimonov: STAR

Di-Hadron Tomography

High pt v2 and correlation : the test of jet quenching





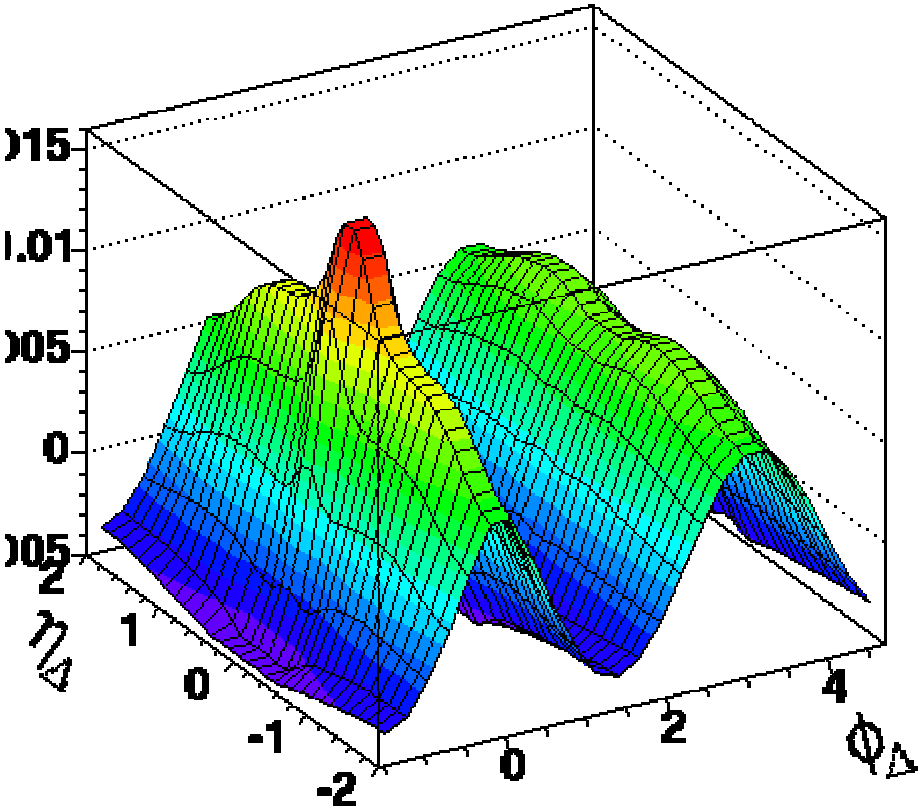
Back-to-back suppression is larger in the out-of-plane direction

13

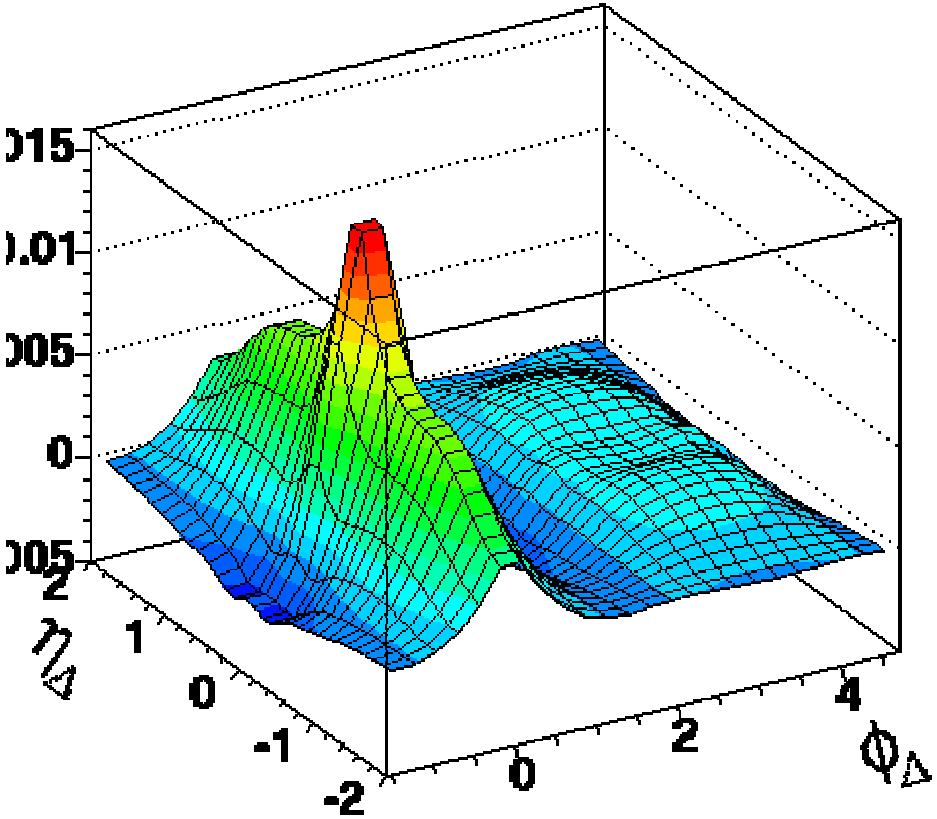
STAR *Prelim* : p_t Correlations at 200 AGeV

Mid-central Au+Au

Mini-jets + Collective flow



$v_2(y)$ subtracted

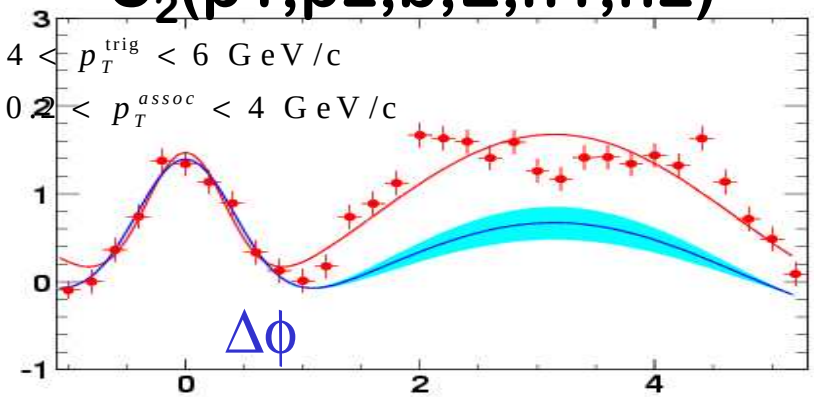
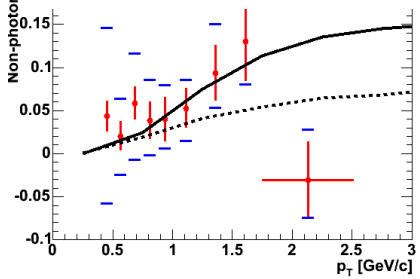
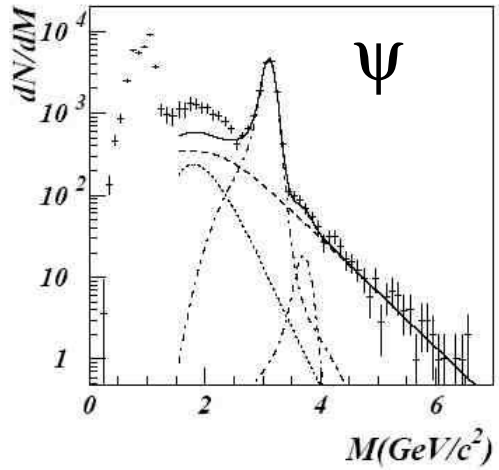
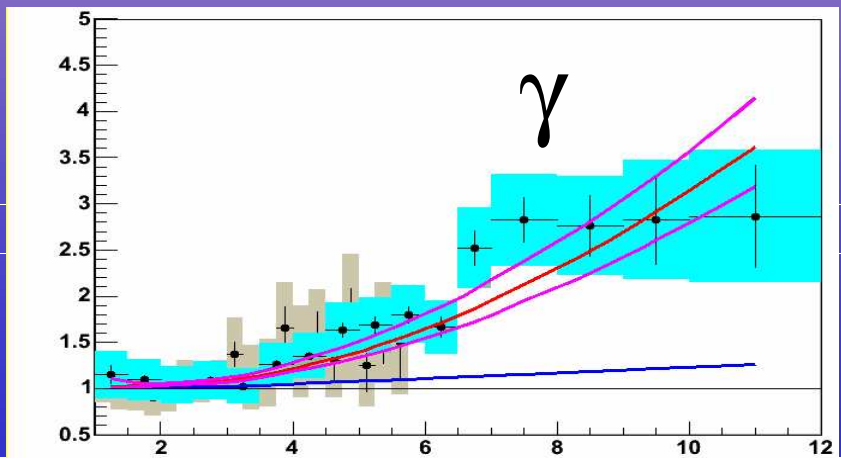


New high pT , rapidity, azimuth correlation tools
M.Daugherity DNP 10/04: Univ. Texas

Future diagnostic probes of the sQGP

- 12D Correlations
- Heavy Quarks
- Direct Photons
- Leptons

C_2(p1,p2,b,E,h1,h2)



Charm Flow quench