New Forms of QCD Matter
Discovered at RHIC

The Current Case for

1. Quark Gluon Plasma: sQGP
2. Color Glass Condensate: CGC

M.Gyulassy and L. McLerran

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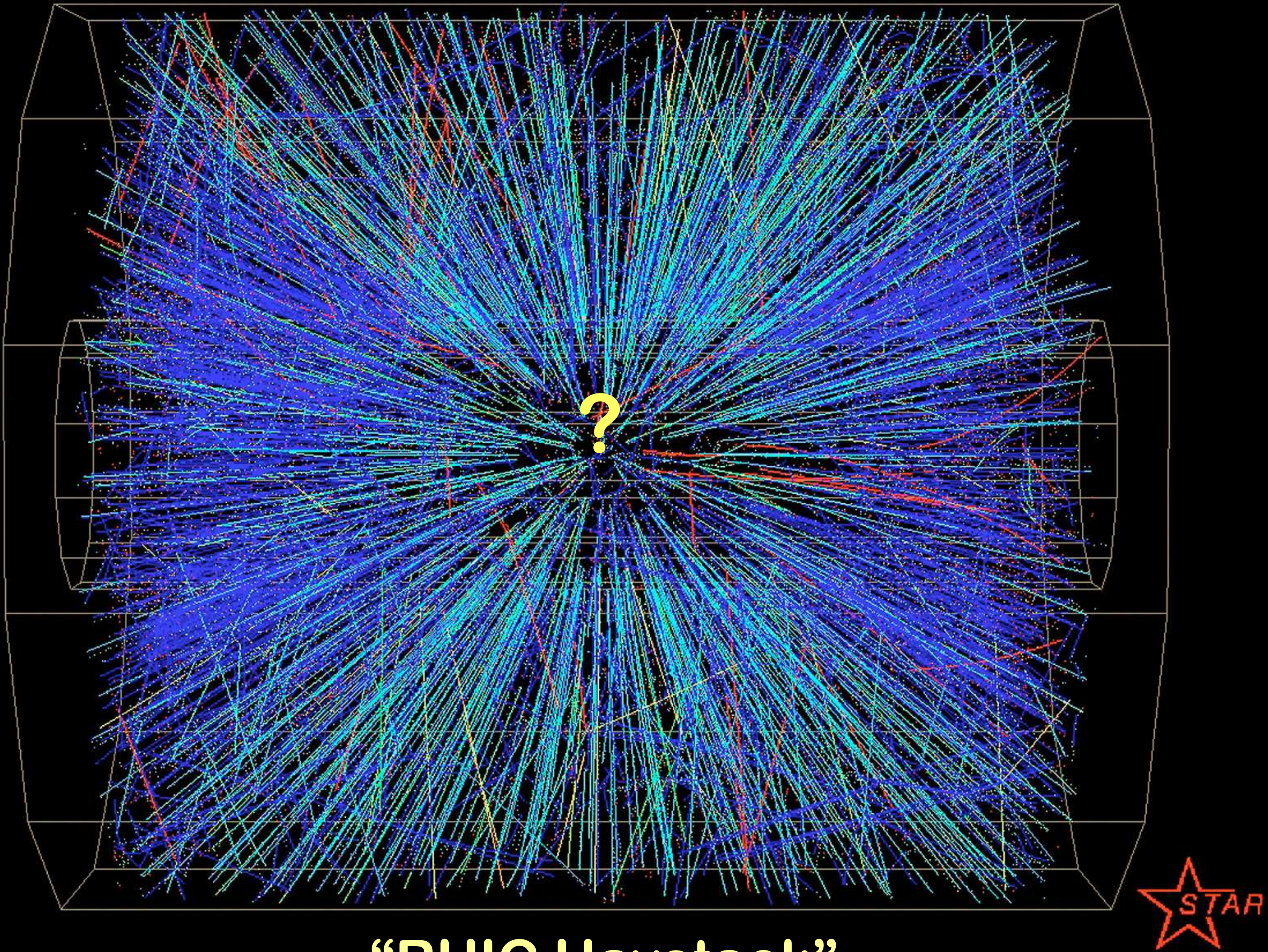
(100 AGeV) Au → ← (100 AGeV) Au



“RHIC Haystack”

Mining some of the new physics from the first 275 RHIC publications

22 (4 PRL) from BRAMHS

92 (15 PRL) from PHENIX

34 (6 PRL) from PHOBOS

127 (21 PRL) from STAR

Together with extensive SPS/CERN data base E_{cm}=5 - 20 AGeV

(108 NA49/35, 69 NA50/38, 26 CERES/NA45, 79 WA98/80, 32 na57/wa97)

Theoretical Mining Tools using Rigorous but idealized Limits of the Standard Model

1. Asymptotic free perturbative pQCD
   short wavelength (high p_T)

2. High temperature/density thermodynamics
   nonperturbative Lattice QCD
   Long Wavelength (low p_T)

3. High energy light cone QCD
   Color Glass Condensate (small x)

The Empirical Evidence for QGP @ RHIC

- Unique long wavelength collective properties
  - Elliptic flow ⇔ P_{QCD}
- Unique short wavelength dynamical properties
  - Jet Quenching ⇔ pQCD
- Conclusive Null Control with D+Au

Big Surprise: exp. QGP = sQGP

Growing case for CGC

- HERA e+p small x scaling ⇔ gluon saturation scale
- Energy and Nuclear Geometry dependence of Entropy production in Au+Au
- Deep gluon shadowing in high y D+Au

at RHIC: CGC is source of QGP

What is a QGP?
Theoretical limit of Ultra-Hot Matter

1975 QCD
Predicts

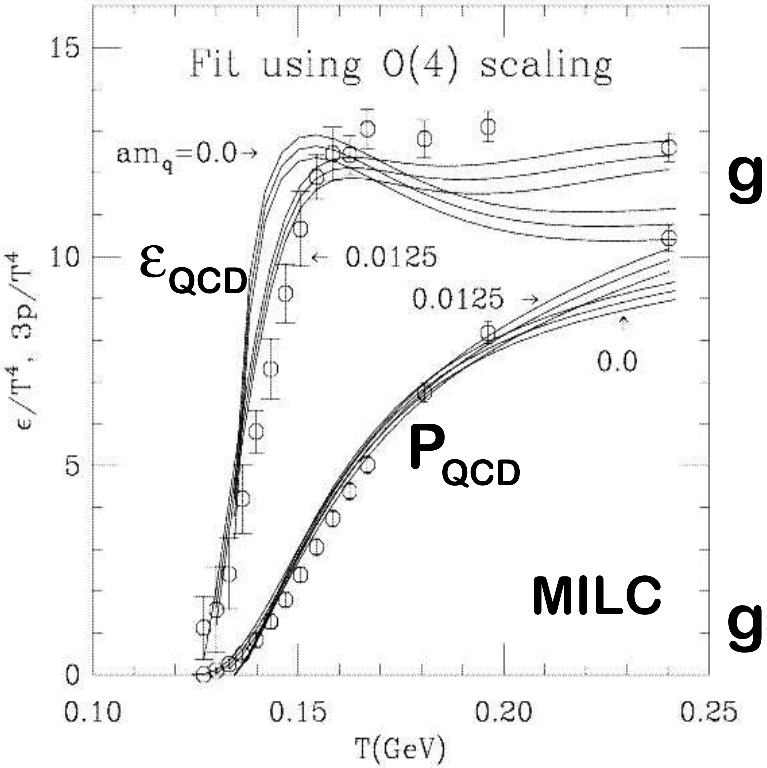
QGP

Asymptotic Freedom
Deconfinement
Chiral Symmetry

$$P_{QCD} \sim \tfrac{1}{3} K_{QCD} T^4 \boxed{- B_{vac}} \qquad \text{TDL}$$

$$\varepsilon_{QCD} \sim K_{QCD} T^4 + B_{vac}$$

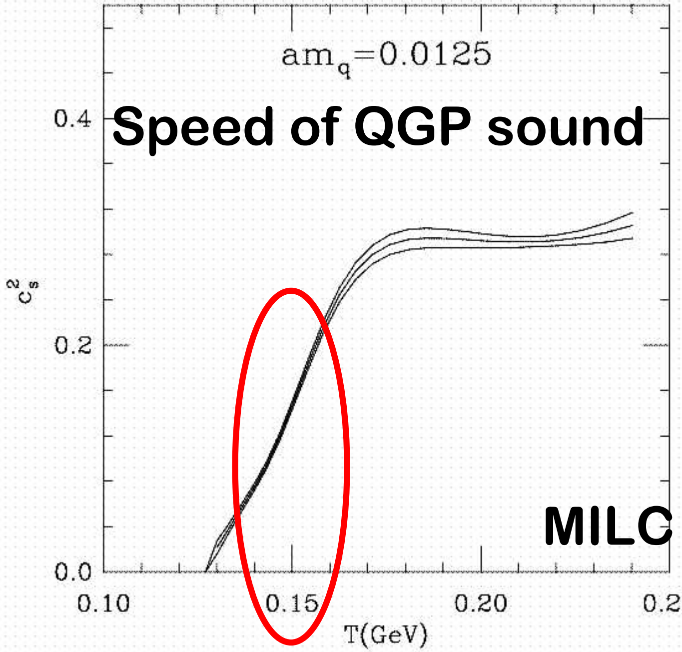
Equation of State



g=40

g=3

$$c_s^2 = dP/d\varepsilon$$



What is a CGC?
Theoretical limit of High energy Matter

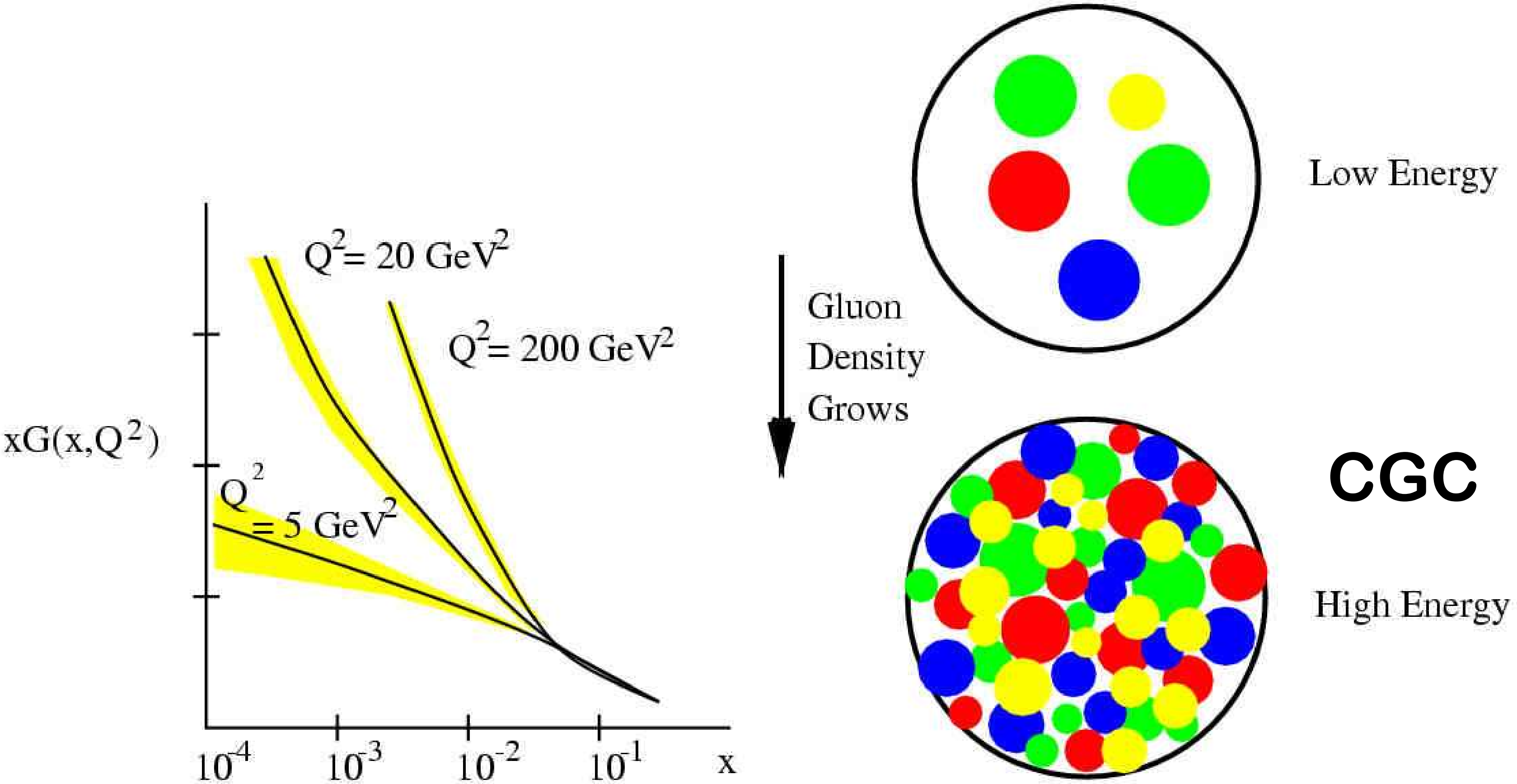
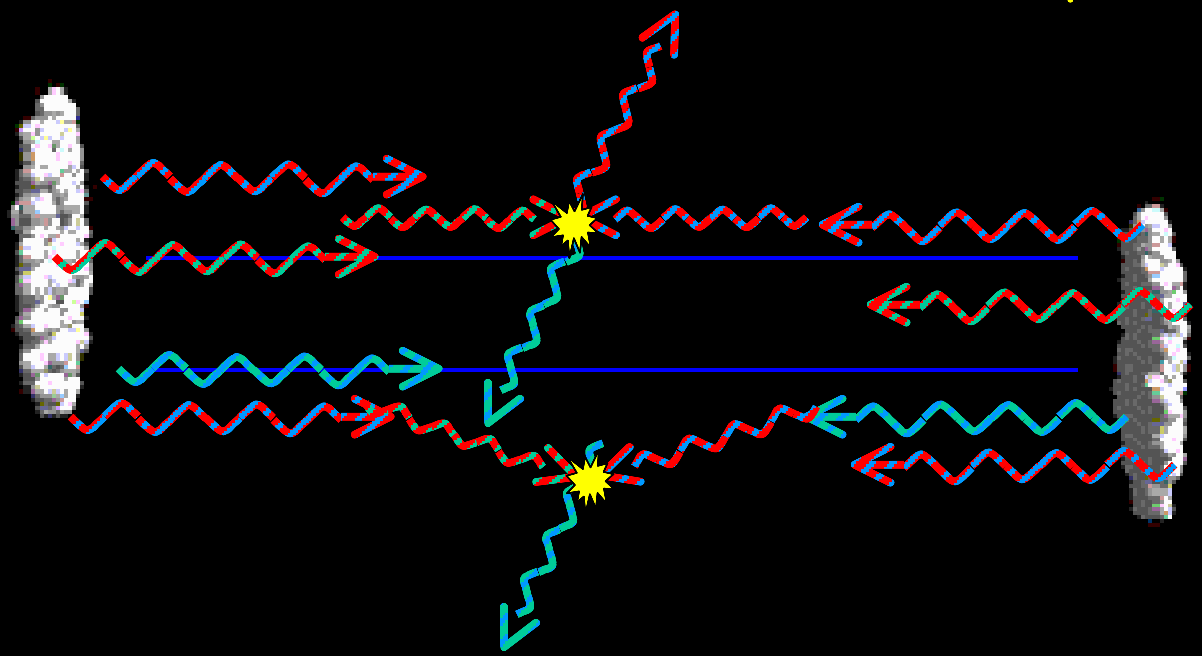


Figure 3: (a)The HERA data for the gluon distribution function as a function of x for various values of Q^2. (b) A physical picture of the low x gluon density inside a hadron as a function of energy

Gribov et al, McLerran Venugopalan … (see Blaizot)

QGP Formation

$g + g \rightarrow g + g \qquad p_T > Q_s(x, A)$



$g' + g' \rightarrow g \qquad p_T < Q_s(x, A)$

Color Glass Condensate Saturation Scale

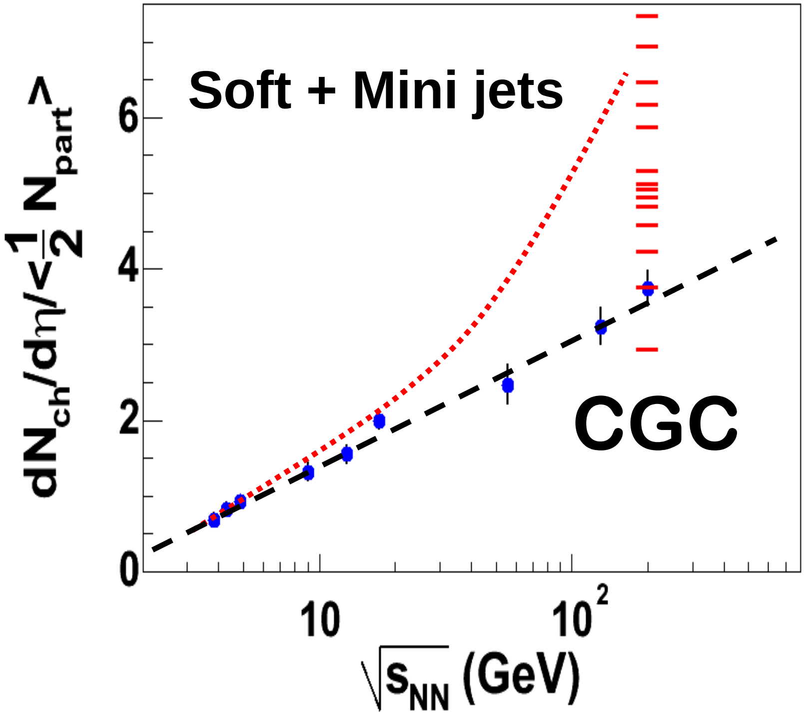
$$Q_s^2(x, A) \approx 1\,\mathrm{GeV}^2 \left(\frac{10^{-4}}{x}\right)^{0.3} A^{0.3}$$

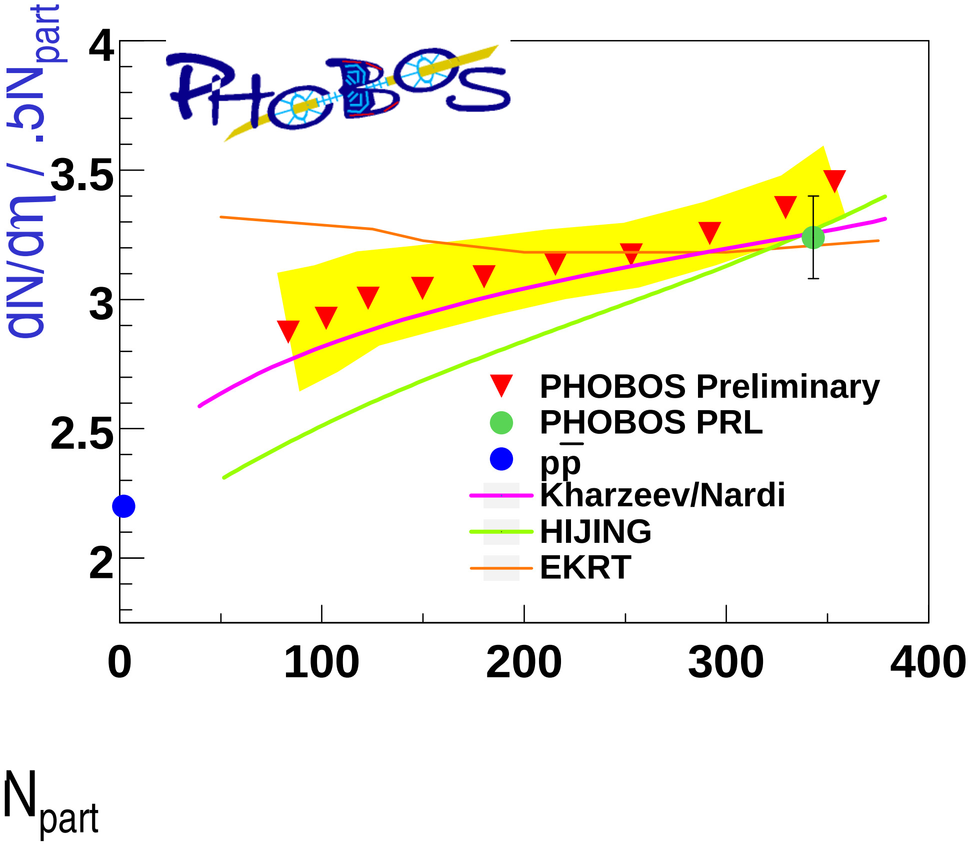
Entropy Production at RHIC

Slow Centrality and Energy Depend. of dN_{ch}/dy => CGC

P. Steinberg QM01

PHOBOS



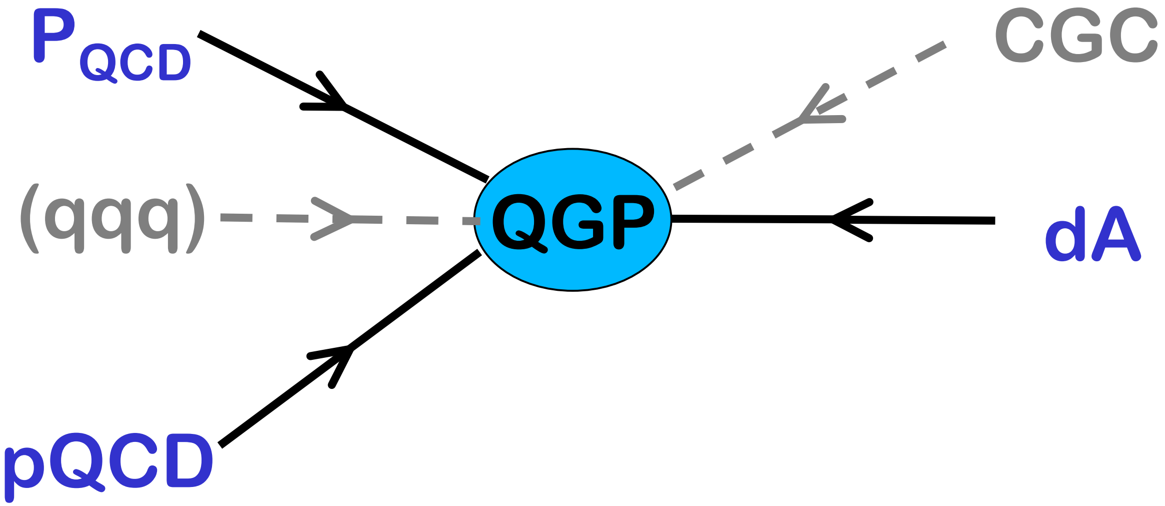


$dN_g/dy \sim 200$ **HIJING** $\Longrightarrow \rho_{glue}(\tau_0 = 0.2 \text{ fm/c}) \approx 5/\text{fm}^3$

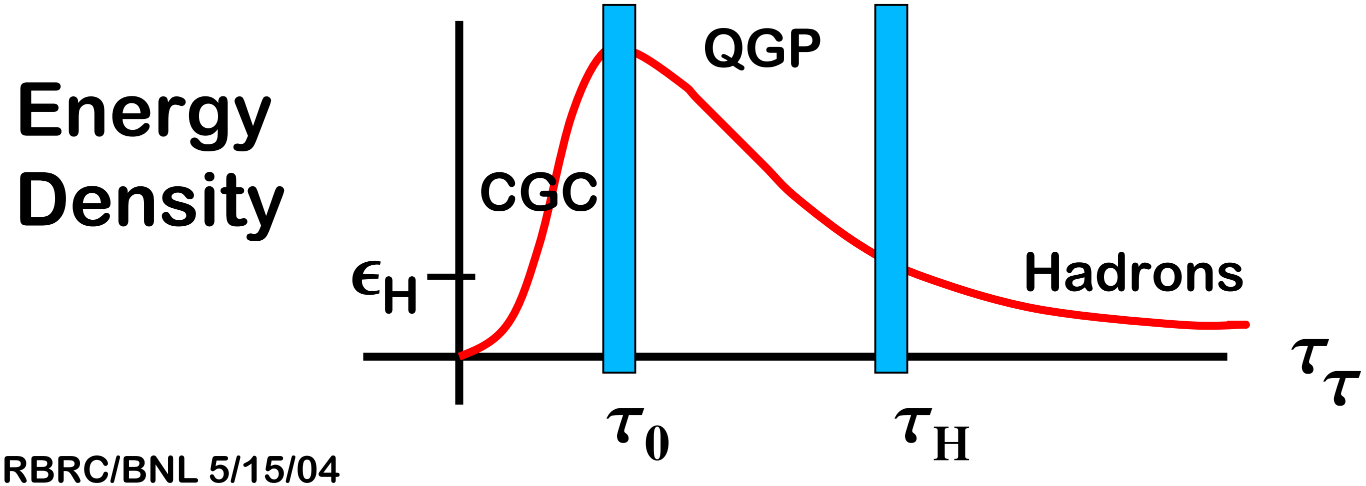
$dN_g/dy \sim 1000$ **CGC** $\Longrightarrow \rho_{glue}(\tau_0 = 0.2 \text{ fm/c}) \approx 25/\text{fm}^3$

XNWang, MG, PRL86(01)3496

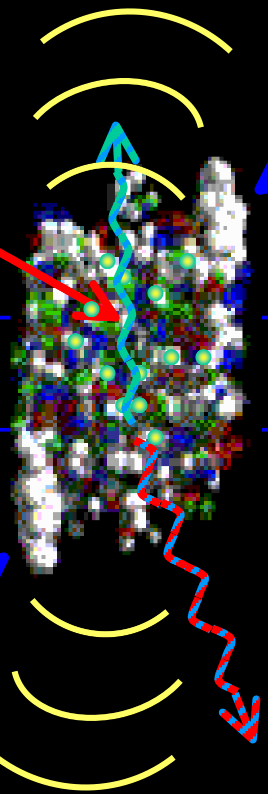
Finding the needles in the Haystack



Haystack = *pre* - QGP Formation dynamics
+ *post* - QGP Hadronic dynamics



QGP $\tau_o \sim 0.3 < \tau < \tau_H \sim 3$ fm/c



Quark Gluon Plasma

at $y_{cm}=0$

Baryon Spectators

$y_{cm} \approx 4$

Jets: $p_T > 10$ GeV/c

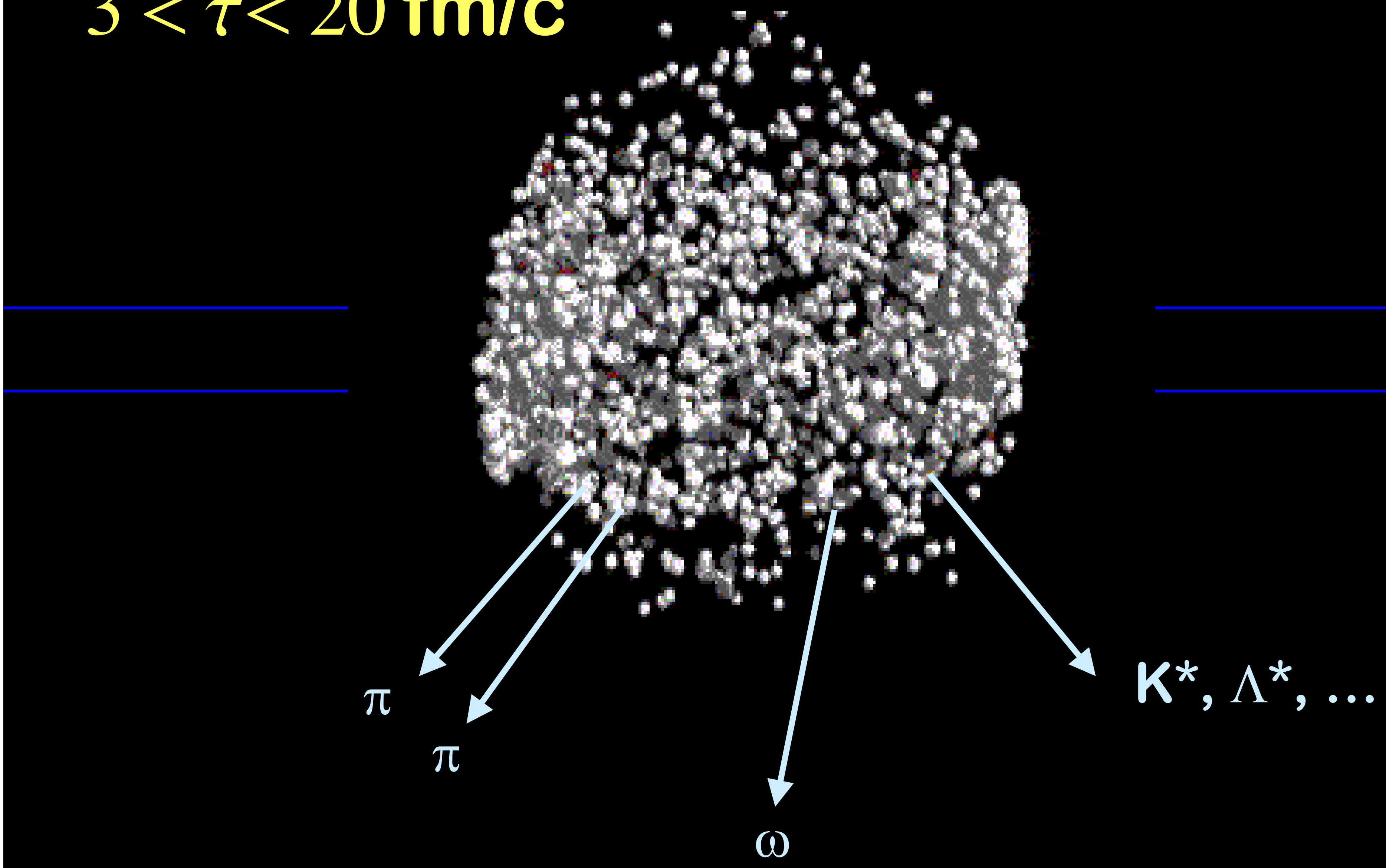
Baryon Spectators

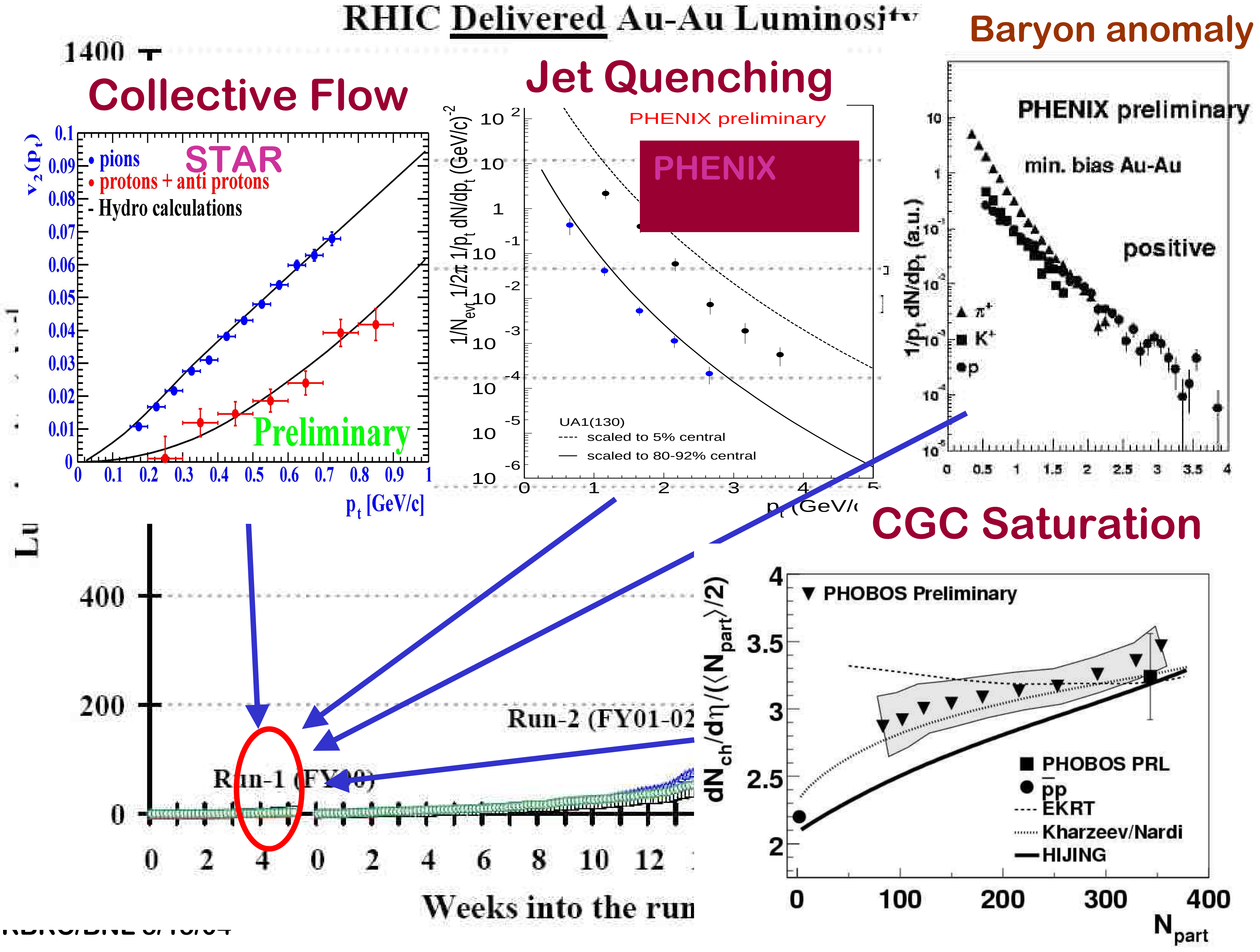
$y_{cm} \approx -4$

Collective Bulk Flow: $p_T < 1$ GeV/c

Post- QGP Hadro dynamics

$3 < \tau < 20$ **fm/c**





Collective Flow

Jet Quenching

Baryon anomaly

CGC Saturation

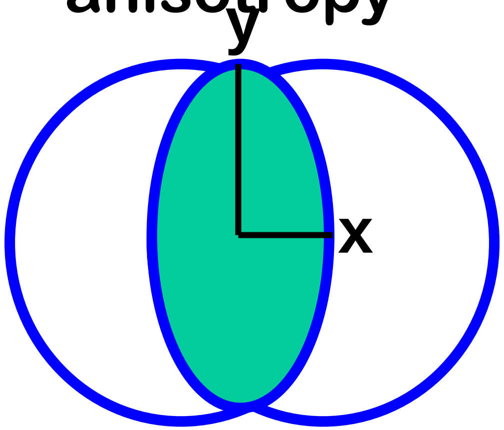
Bulk Collective Flow of QCD matter

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

QCD EOS

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

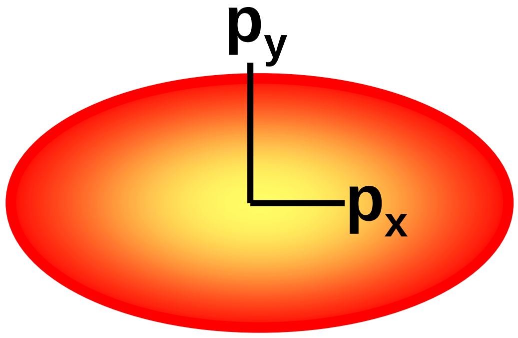
Initial *spatial* anisotropy



$$\Longrightarrow$$

$$\partial_\mu T^{\mu\nu}(x) = 0$$

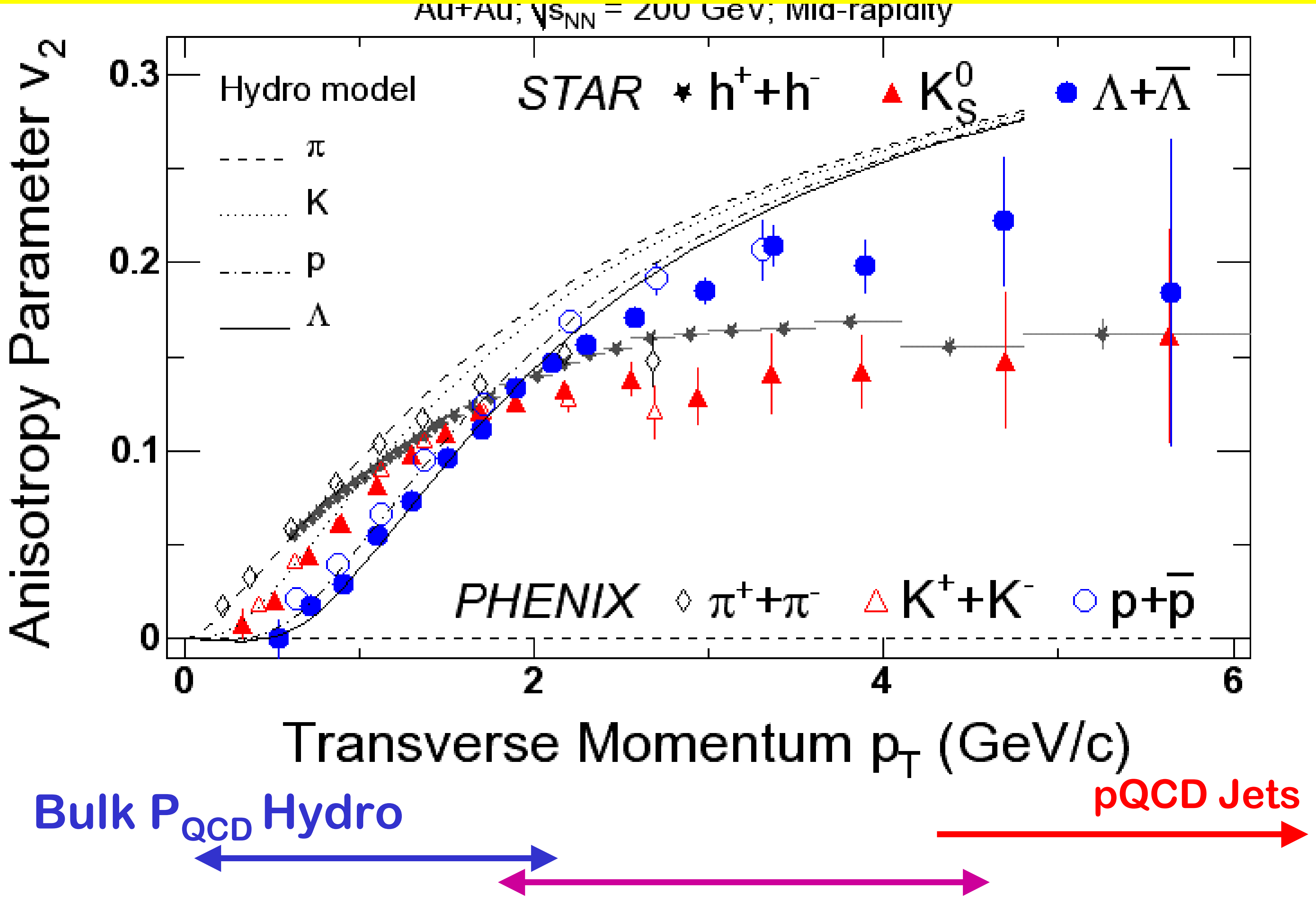
Final *momentum* anisotropy



Elliptic Flow

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

The QGP Fingerprint at RHIC = Fine Structure of collective flow $P_{QCD}(T)$



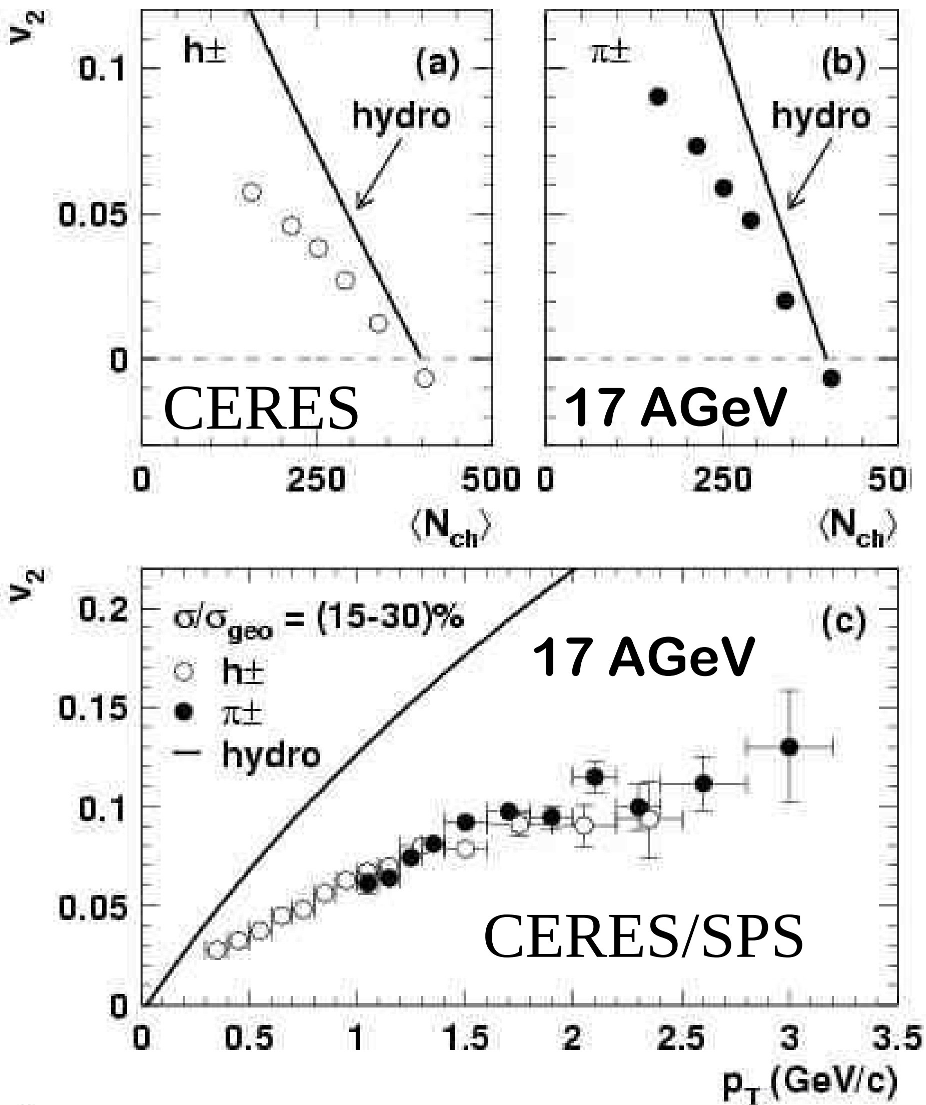
Bulk P_{QCD} Hydro

pQCD Jets

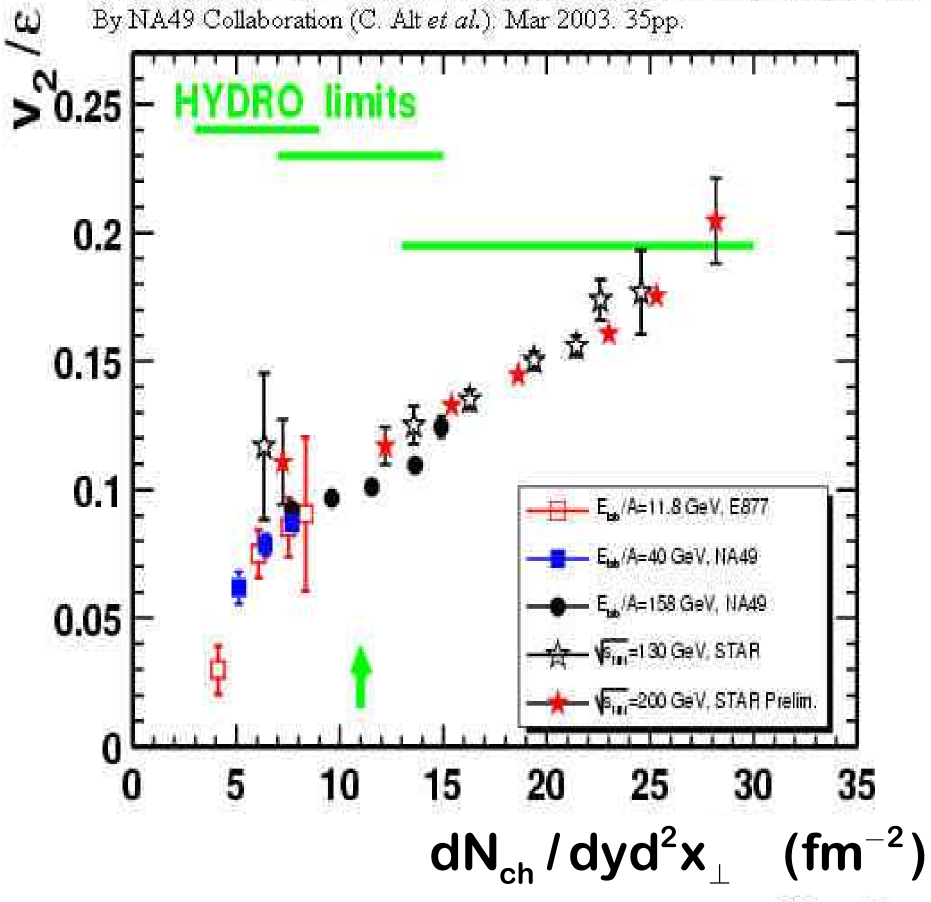
qqq Coalescence

Below RHIC energies, QCD hydro over-predicts elliptic flow!

$v_2(E_{cm})$ → **QGP hydro only works at RHIC**



2) DIRECTED AND ELLIPTIC FLOW OF CHARGED PIONS AND PROTONS IN PB + PB COLLISIONS AT 40-A-GEV AND 158-A-GEV.
By NA49 Collaboration (C. Alt *et al.*). Mar 2003. 35pp.



Conclusive evidence for
Long wavelength flow with unique fine structure

$v_2(p_T,m_h,b)$ consistent with $P_{QCD}(T)$

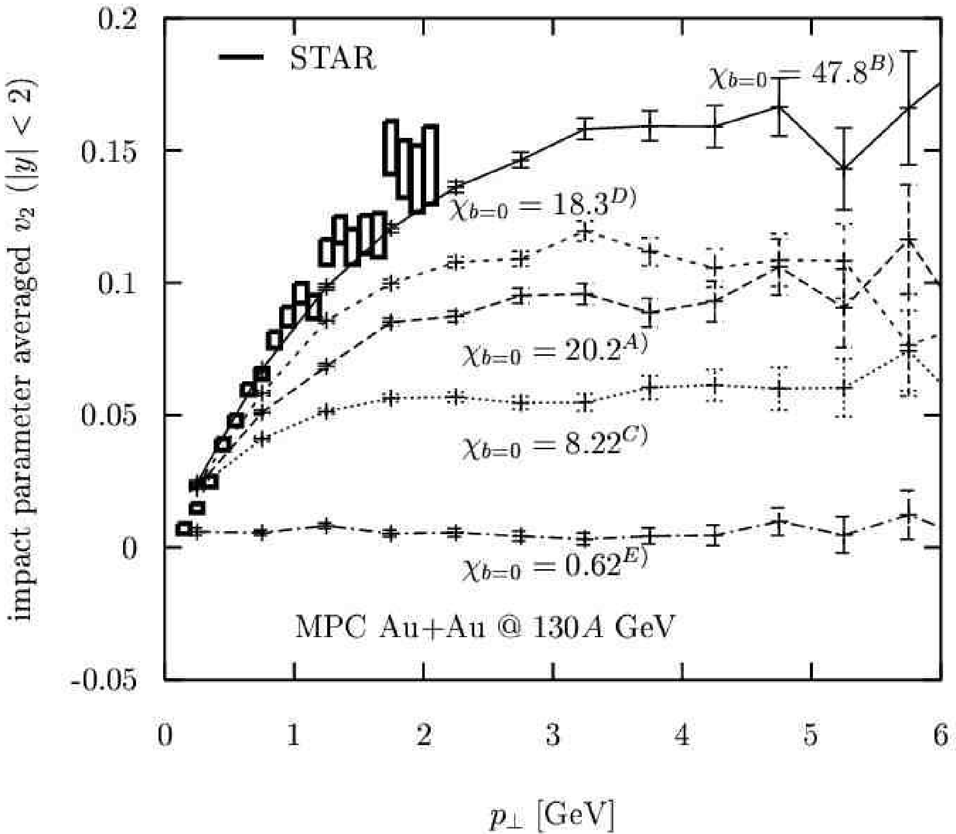
But how could Euler ideal fluid work?

It never worked on nuclear scale before!!

The QGP is almost a perfect fluid !

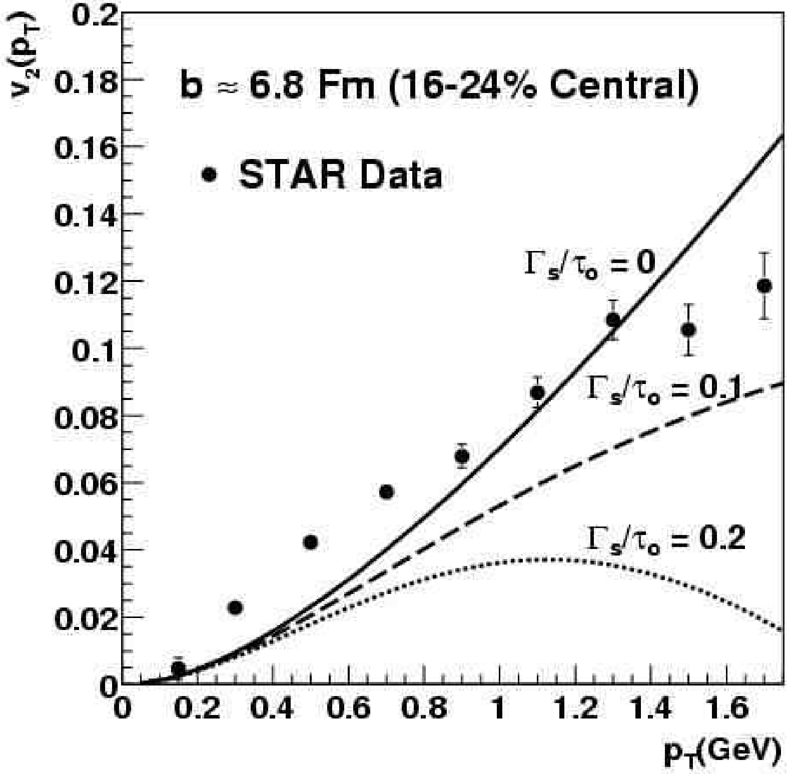
Gluon Transport

Molnar, MG (01)



Navier-Stokes

Teaney (03)

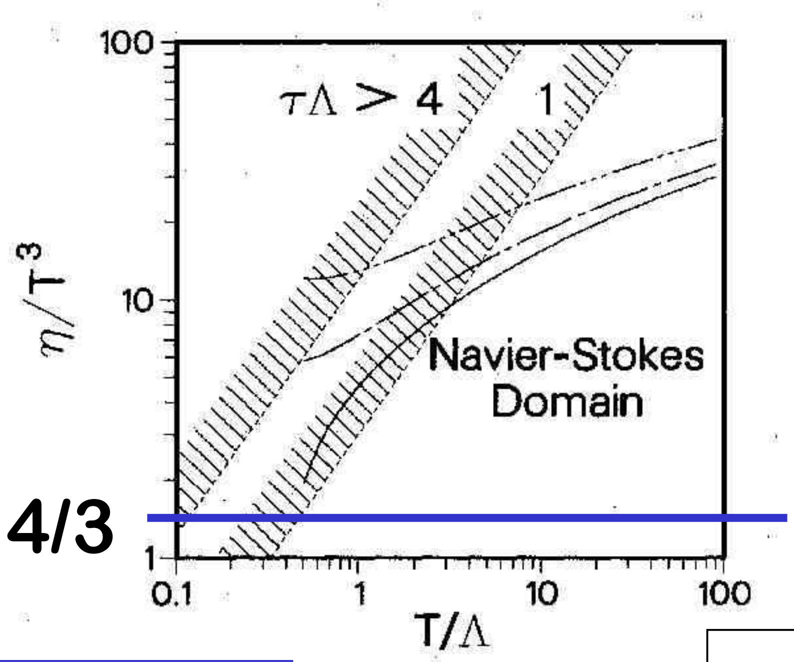


Opacity $$\boxed{\chi = \int d\tau\, \sigma\, \rho \approx \frac{dN_g}{dy}\frac{\sigma_g}{\pi R^2}}$$

Viscosity / Entropy density of QGP

$$\frac{\eta}{\sigma} \approx \frac{1}{3}\frac{\rho}{\sigma}\langle p\rangle \lambda \approx \frac{1}{12}\langle p\rangle \lambda \approx \frac{T\lambda}{4}$$

Ultra-rel. $\sigma = 4\rho \,, \langle p\rangle = 3T$



pQCD

Danielewicz, MG (85)

$$\frac{\eta}{\sigma} \approx \frac{\pi}{g^4 \log 1/g} \gg 1$$

$$\frac{\eta}{\sigma} \geq \frac{\hbar}{12}$$

Heisenberg Uncertainty
Danielewicz, MG

String Theory Bound

$$\frac{\eta}{\sigma} \geq \frac{1}{4\pi}$$

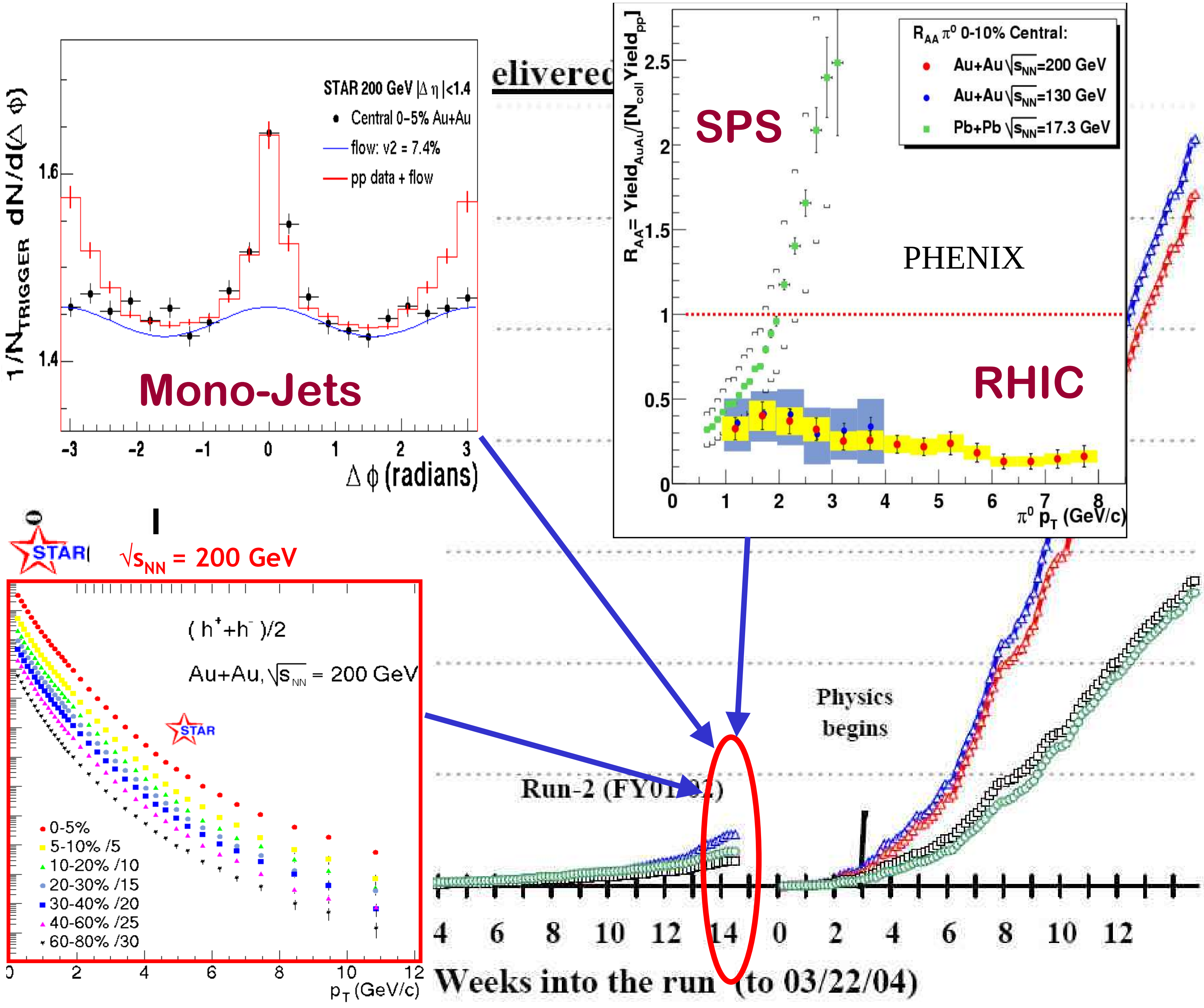
AdS_5/CFT N=4 SUSY
Policastro, Son, Starinets
(2001)

Conclusion 1

Not only does P_{QCD} account quantitatively for the fine structure (p_T , m_h) of elliptic flow at RHIC

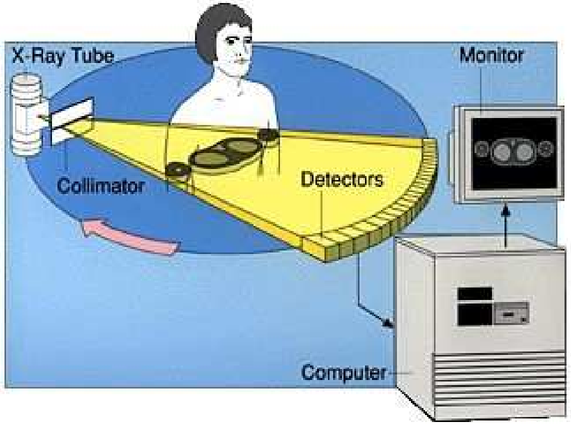
But, also the QGP at $T<3T_c$ saturates the *minimal* viscosity bound!

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

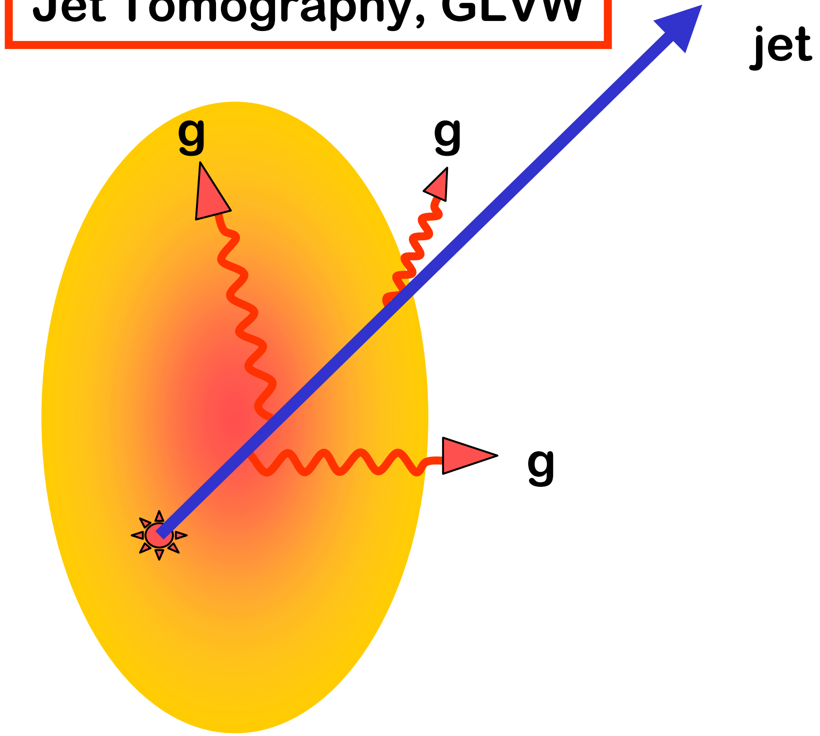
STAR 200 GeV |Δ η |<1.4
Central 0-5% Au+Au
flow: v2 = 7.4%
pp data + flow
$1/N_{TRIGGER}\ dN/d(\Delta\phi)$
1.6
1.4
-3
-2
-1
0
1
2
3
Δ φ (radians)
Mono-Jets
elivered
R_{AA} π^0 0-10% Central:
Au+Au $\sqrt{s_{NN}}$=200 GeV
Au+Au $\sqrt{s_{NN}}$=130 GeV
Pb+Pb $\sqrt{s_{NN}}$=17.3 GeV
R_{AA}= $Yield_{AuAu}/[N_{coll}\ Yield_{pp}]$
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
π^0 p_T (GeV/c)
SPS
PHENIX
RHIC
STAR
$\sqrt{s_{NN}}$ = 200 GeV
(h^++h^-)/2
Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
STAR
0-5%
5-10% /5
10-20% /10
20-30% /15
30-40% /20
40-60% /25
60-80% /30
0
2
4
6
8
10
12
p_T (GeV/c)
Physics
begins
Run-2 (FY01-02)
4
6
8
10
12
14
0
2
4
6
8
10
12
Weeks into the run (to 03/22/04)

Jet Quenching

MG, P. Levai, I.Vitev, X.N. Wang (see Wang)



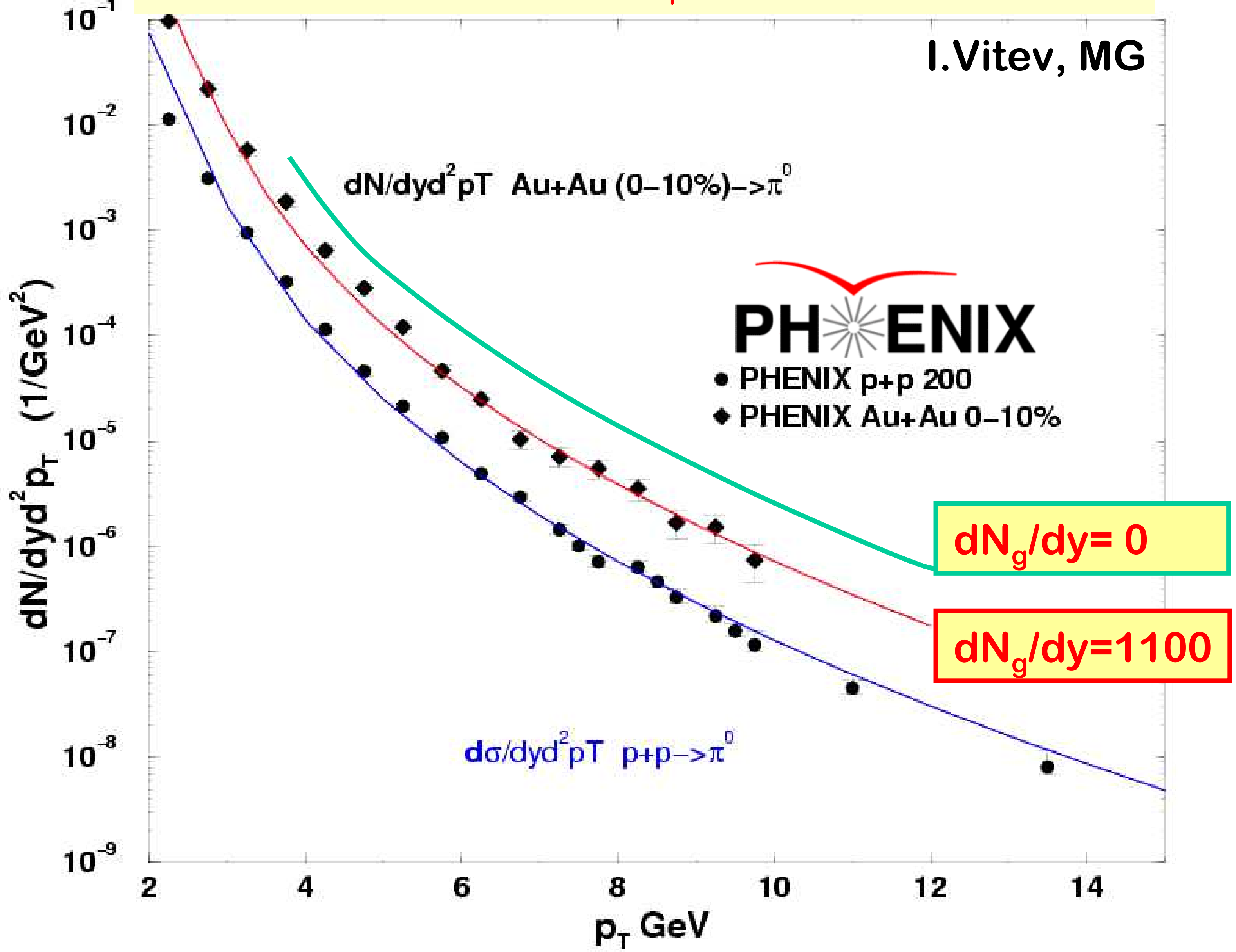
Jet Tomography, GLVW



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

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

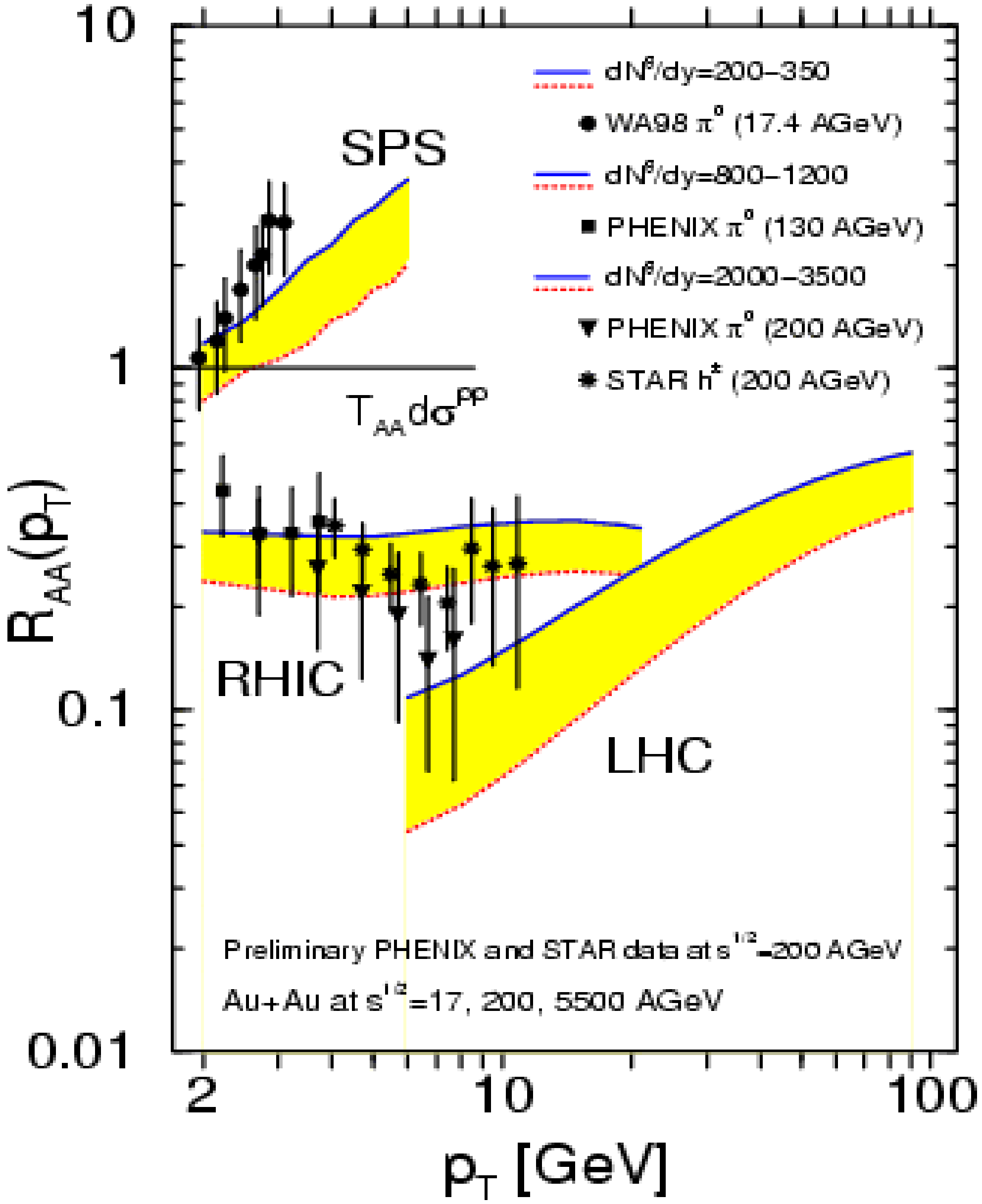
GRV
EKS
BKK
GLV



Absolute scale pQCD jet tomography

Single Hadron Tomography from SPS, RHIC, LHC

Ivan Vitev and MG, PRL 89 (2002)



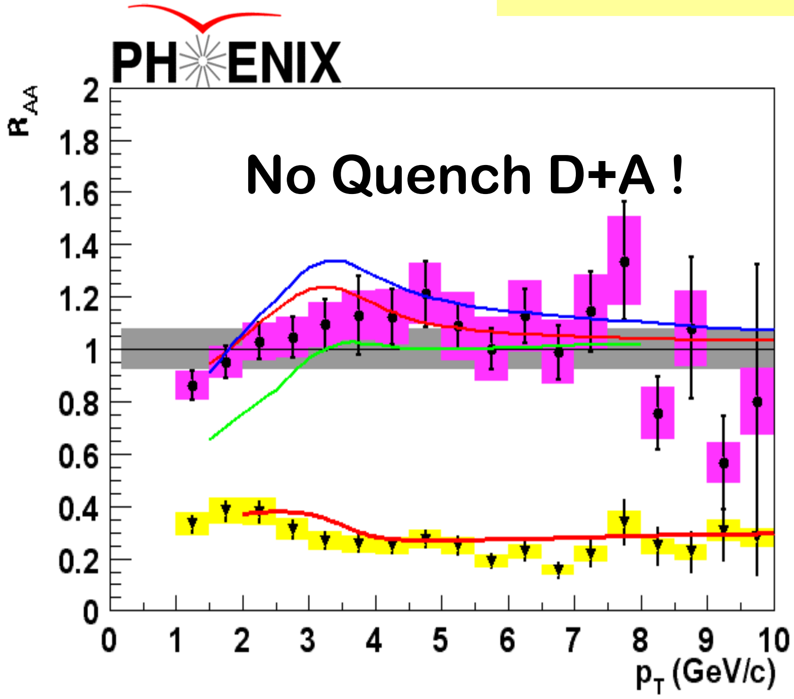
1) Cronin *enhancement* dominates at SPS

2) Cronin+Quench+Shadow conspire to give ~ flat R_{AA}~N_{part}/N_{bin} at RHIC dN_g/dy ~ 1000 -> ρ_g ~100 ρ_0

3) Predict sub N_{part} quench, positive p_T slope of R at LHC

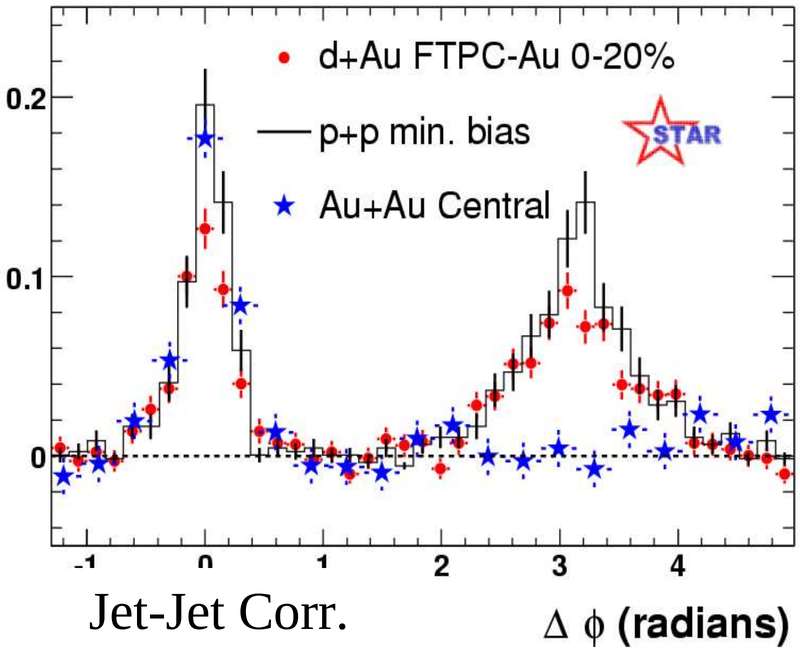
Third Line of Evidence at RHIC

“ Return of the Jeti ”



No Quench D+A !

Strong Quench A+A



Jet-Jet Corr.

dA=Critical Control Experiment

Conclusion 2

The nearly perfect fluid QGP seen through long wavelength collective flow

Has a predicted pQCD high opacity
To short wavelength $2\pi/p_T$ << 1 fm probes

Seen through jet quenching

$$(1) \quad P_{QCD} = v_2(p_T, m_h, b)$$

$$(2) \quad pQCD = R_{AA}(p_T, b) + I_{AA}(\phi, p_T, b)$$

Four independent calibrations of Initial QGP density

$$\varepsilon(\tau_0) \approx 100\,\varepsilon_0 = 15\ \mathrm{GeV/fm^3}$$

1. Bjorken Backward extrapolation

$$E_T/N_\pi = 0.5\ \mathrm{GeV}, \quad dN_\pi/dy = 1000,$$
$$\tau_0 = 1/p_0 = 0.2\ \mathrm{fm/c}, \quad V = (0.2\ \mathrm{fm})\pi R^2 = 30\ \mathrm{fm}^3$$
$$\varepsilon_{Bj} = 500\ \mathrm{Gev}/30\ \mathrm{fm}^3 = 100\,\varepsilon_0$$

2. Hydrodynamic initial condition needed for $v_2(p_T)$

$$\varepsilon_{Hydro} \sim \varepsilon_{Bj} \sim 100\,\varepsilon_0$$

KHH
TS
HN

3. Jet Tomography: $dN_g/dy = 1000$

$$\varepsilon_{Jets} \approx \varepsilon_{Bj} \approx 100\,\varepsilon_0$$

GLV
WW

4. Gluon saturation $p_T < Q_s$ predicted

$dN_g/dy = 1000$ at $Q_{sat} = 1$ GeV at $y=0$

MB
McV
EKRT

Conclusions:

Overwhelming <u>empirical</u> evidence
for a new form of matter sQGP
with unexpected properties

Growing evidence that its source is a
Gluon saturated CGC

Many puzzles remain (baryon/pi , HBT, ...)

Theoretical understanding is improving

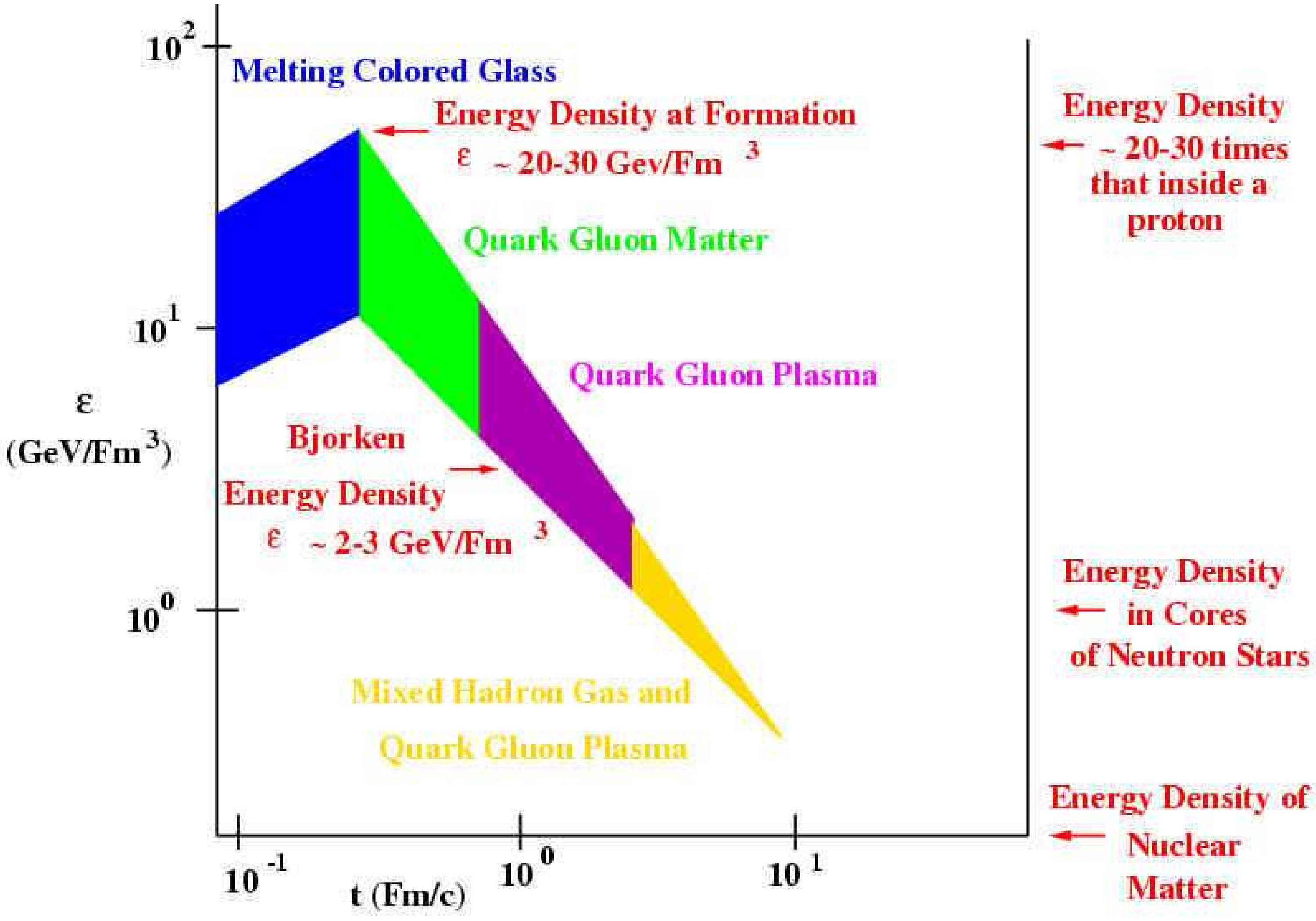
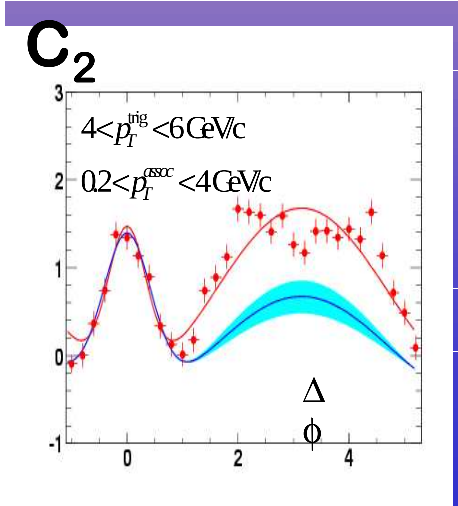


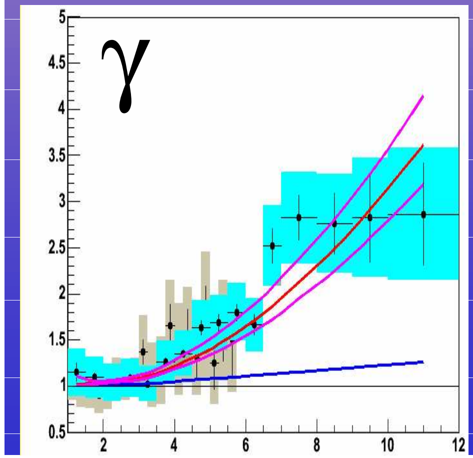
Figure 7: Bounds on the energy density as a function of time in heavy ion collisions.

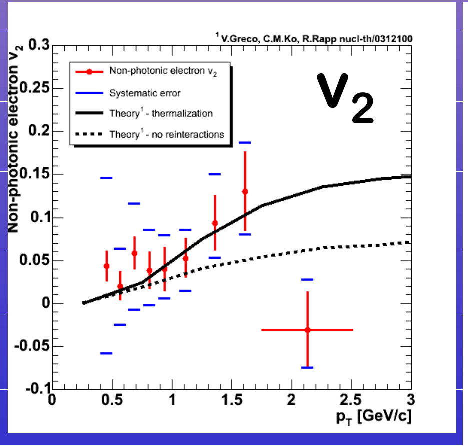
T. Ludlam, L. McLerran Phy. Today 2004

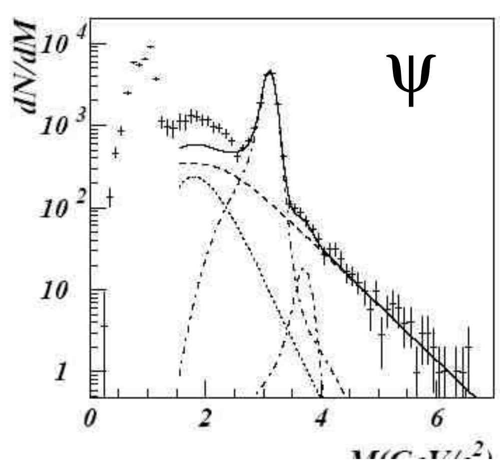
Needed future experiments

- 12D Correlations
  - Heavy Quarks
  - Direct Photons
  - Leptons
  - and its relation to CGC









Experimental Priorities

- Y=+- 3 test interplay QGP<->CGC ?

- $C_2(\underbrace{phi_1,phi_2,\ pt_1,pt_2,\ eta_1,eta_2}_{\text{6D microscope}};\ \underbrace{fl_1,fl_2,\ Mult,\ A,B,\ Ecm}_{\text{exp. knobs}})$

- Heavy Quark tomography

- Open Charm (enhancement?); J/Psi (suppression?)
- Charm Flow?

- Direct Photons thermometer
- Tagged direct photon -quark jets!

- Turn Ecm~20-200 and A=1-100 exp. knobs