Strongly interacting quantum fluids: Experimental status

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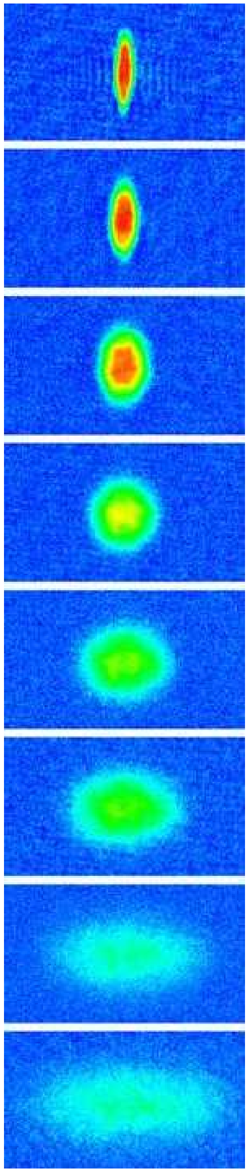
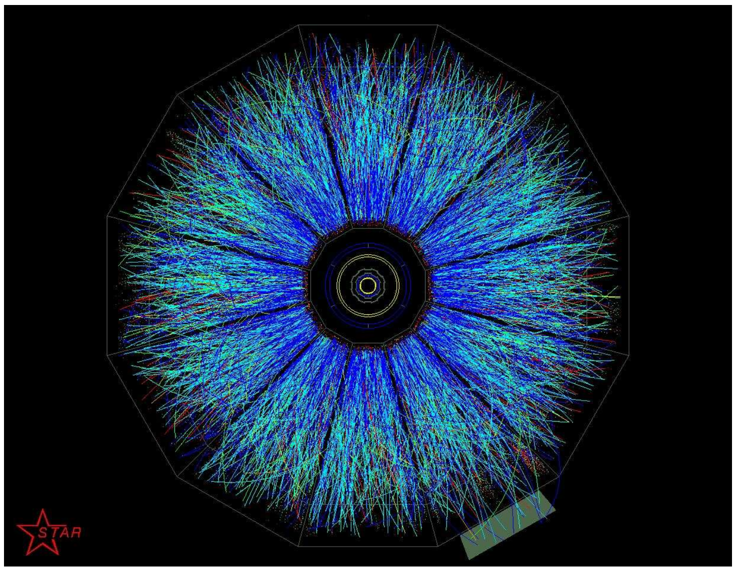
Perfect fluids: The contenders





QGP (T=180 MeV)

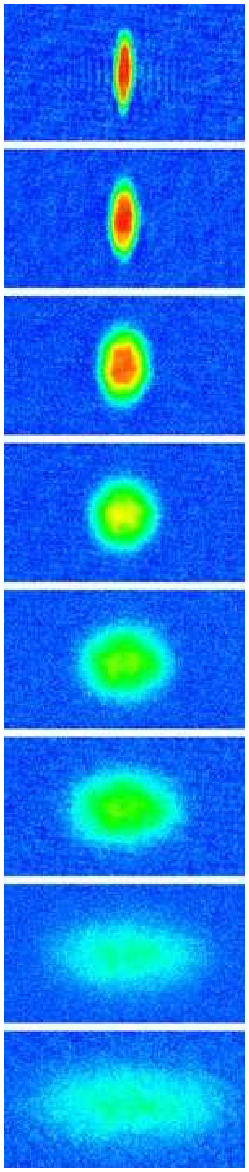
Liquid Helium

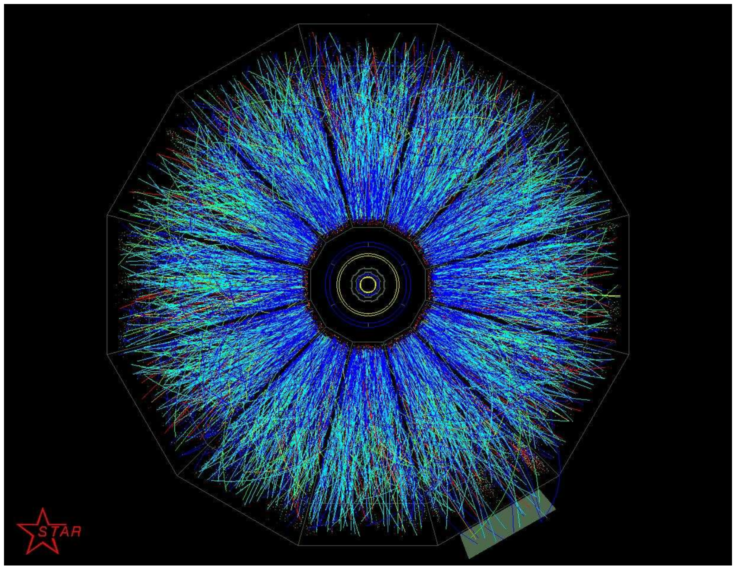
(T=0.1 meV)

Trapped Atoms

(T=0.1 neV)

Perfect Fluids: The contenders

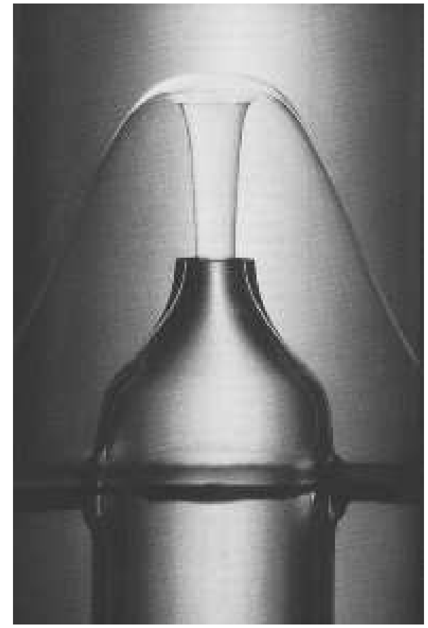




QGP $\eta = 5 \cdot 10^{11} Pa \cdot s$

Trapped Atoms

$\eta = 1.7 \cdot 10^{-15} Pa \cdot s$



Liquid Helium

$\eta = 1.7 \cdot 10^{-6} Pa \cdot s$

Consider ratios

η / s

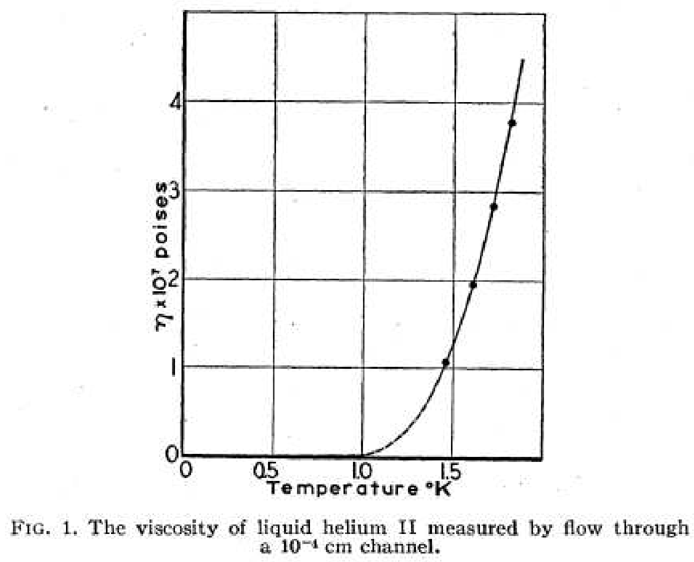
Perfect Fluids: Not a contender

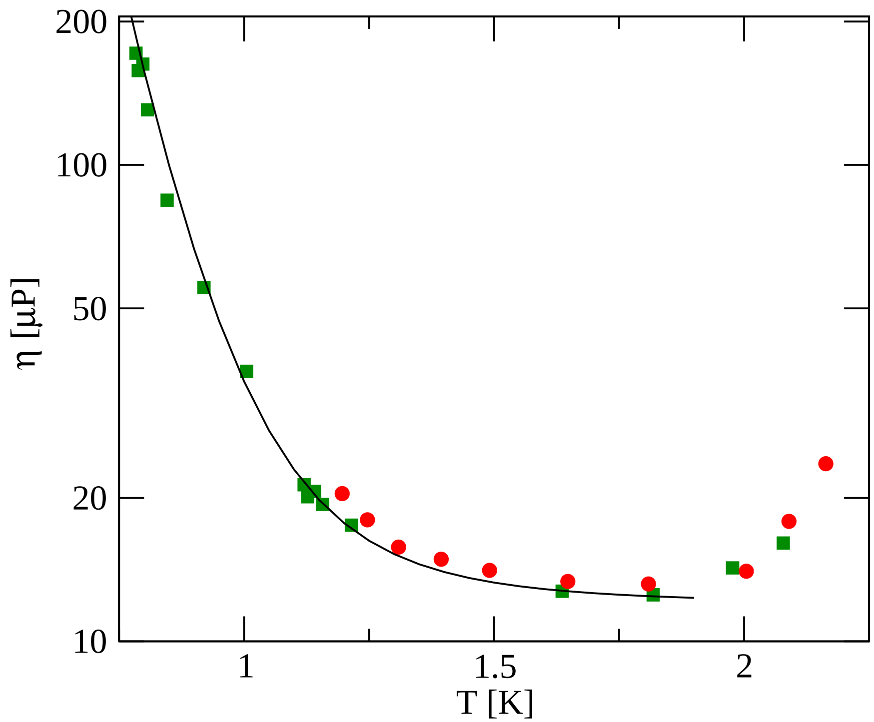
Queensland pitch-drop experiment

1927-2011 (8 drops)

$\eta = (2.3 \pm 0.5) \cdot 10^8 \, Pa \, s$

I. Experiment (liquid helium)





Kapitza (1938)

viscosity vanishes below T_c

capillary flow viscometer

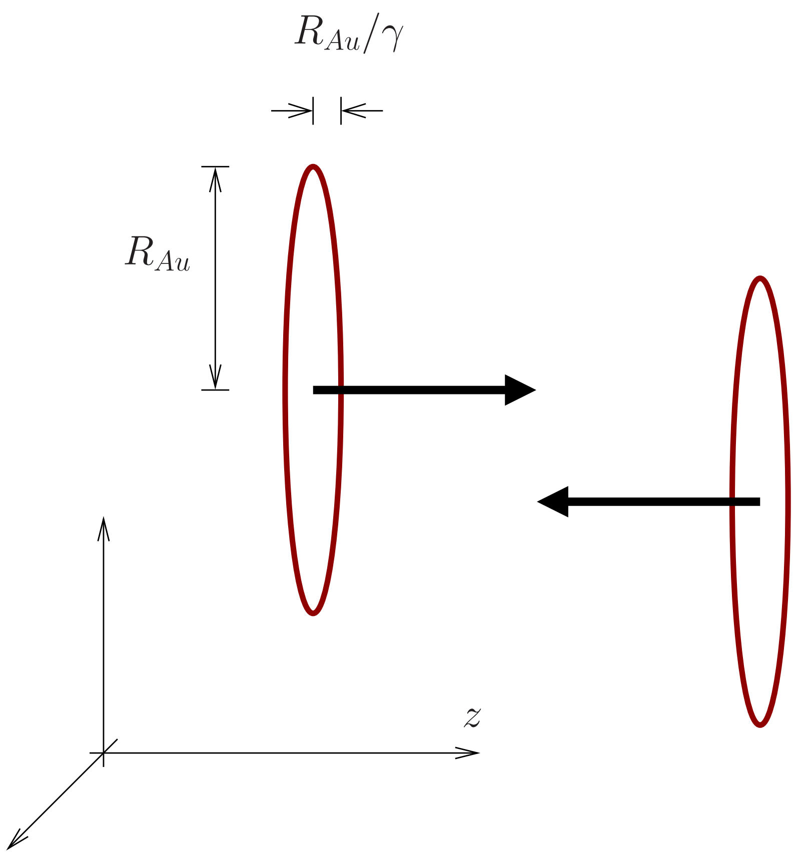
Hollis-Hallett (1955)

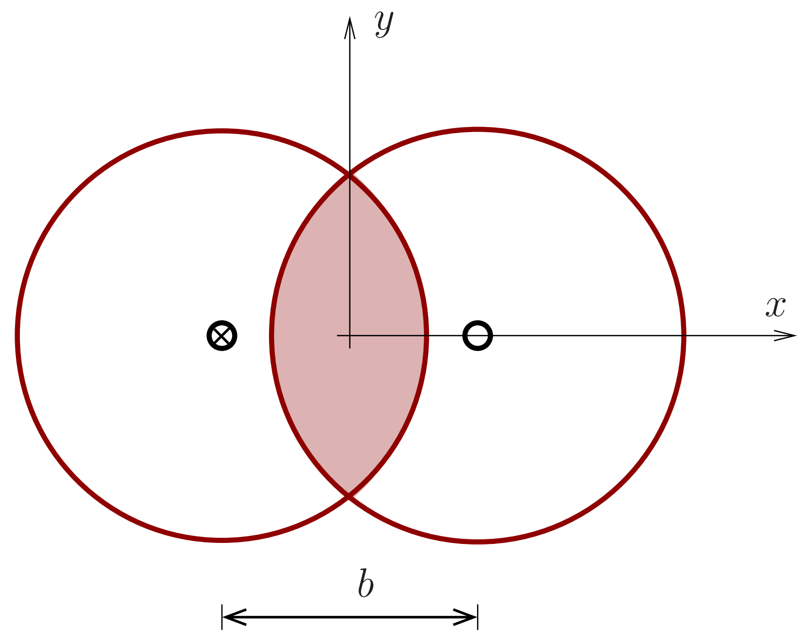
roton minimum, phonon rise

rotation viscometer

$$\eta/s \simeq 0.8\,\hbar/k_B$$

II. Heavy ion collision: Geometry





rapidity : $y = \frac{1}{2} \log \left(\frac{E + p_z}{E - p_z} \right)$

transverse momentum : $p_T^2 = p_x^2 + p_y^2$

Bjorken expansion

Experimental observation: At high energy ($\Delta y \to \infty$) rapidity distributions of produced particles (in both pp and AA) are "flat"

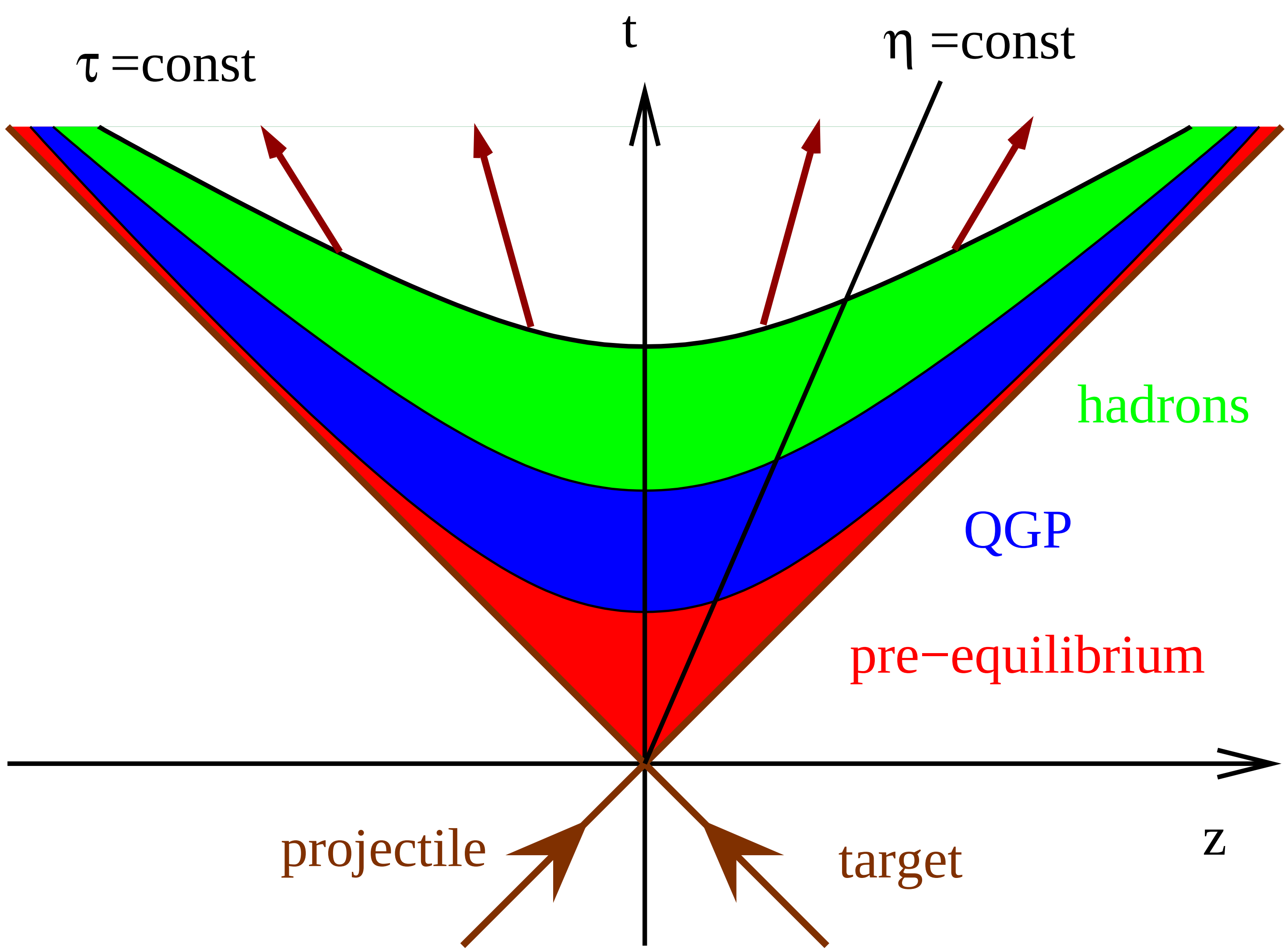
$$\frac{dN}{dy} \simeq const$$

Physics depends on proper time $\tau = \sqrt{t^2 - z^2}$, not on y

All comoving ($v = z/t$) observers are equivalent

Analogous to Hubble expansion

Bjorken expansion



Bjorken expansion: Hydrodynamics

Boost invariant expansion

$$u^\mu = \gamma(1, 0, 0, v_z) = (t/\tau, 0, 0, z/\tau)$$

solves Euler equation (no longitudinal acceleration)

$$\partial^\mu (s u_\mu) = 0 \qquad \Rightarrow \qquad \frac{d}{d\tau}\left[\tau s(\tau)\right] = 0$$

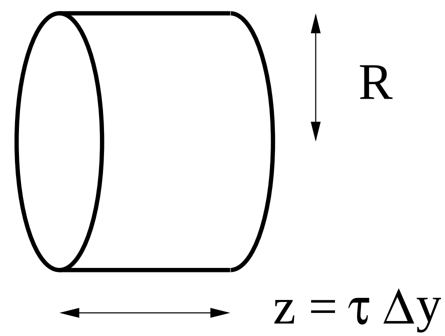
Solution for ideal Bj hydrodynamics

$$\boxed{s(\tau) = \frac{s_0 \tau_0}{\tau}} \qquad\qquad T = \frac{const}{\tau^{1/3}}$$

Exact boost invariance, no transverse expansion, no dissipation, ...

Numerical estimates

Total entropy in rapidity interval $[y, y + \Delta y]$



$$S = s\pi R^2 z = s\pi R^2 \tau \Delta y = (s_0 \tau_0)\pi R^2 \Delta y$$

$$s_0 \tau_0 = \frac{1}{\pi R^2} \frac{S}{\Delta y}$$

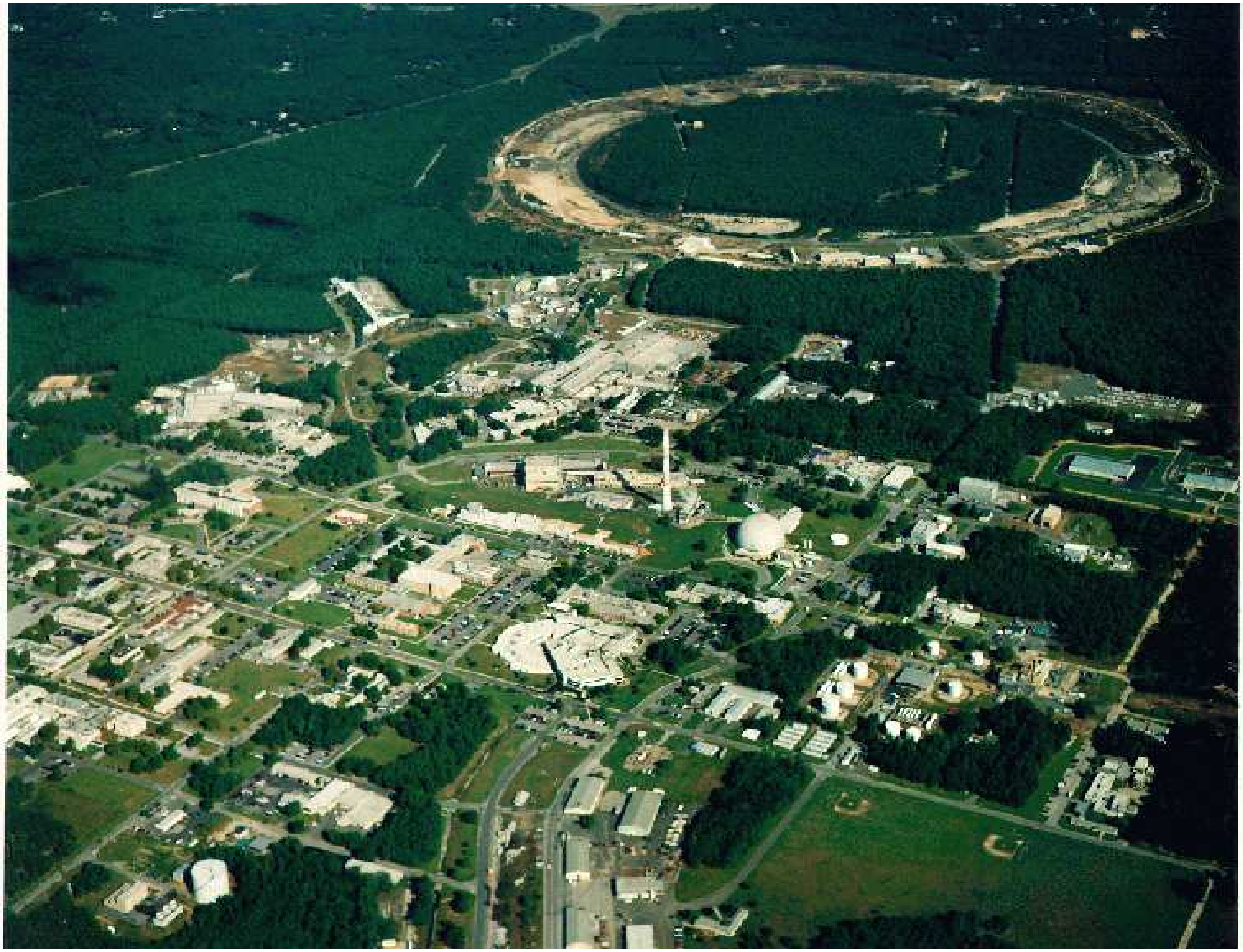
Use $S/N \simeq 3.6$

$$s_0 = \frac{3.6}{\pi R^2 \tau_0} \left(\frac{dN}{dy} \right) \qquad \text{Bj estimate}$$

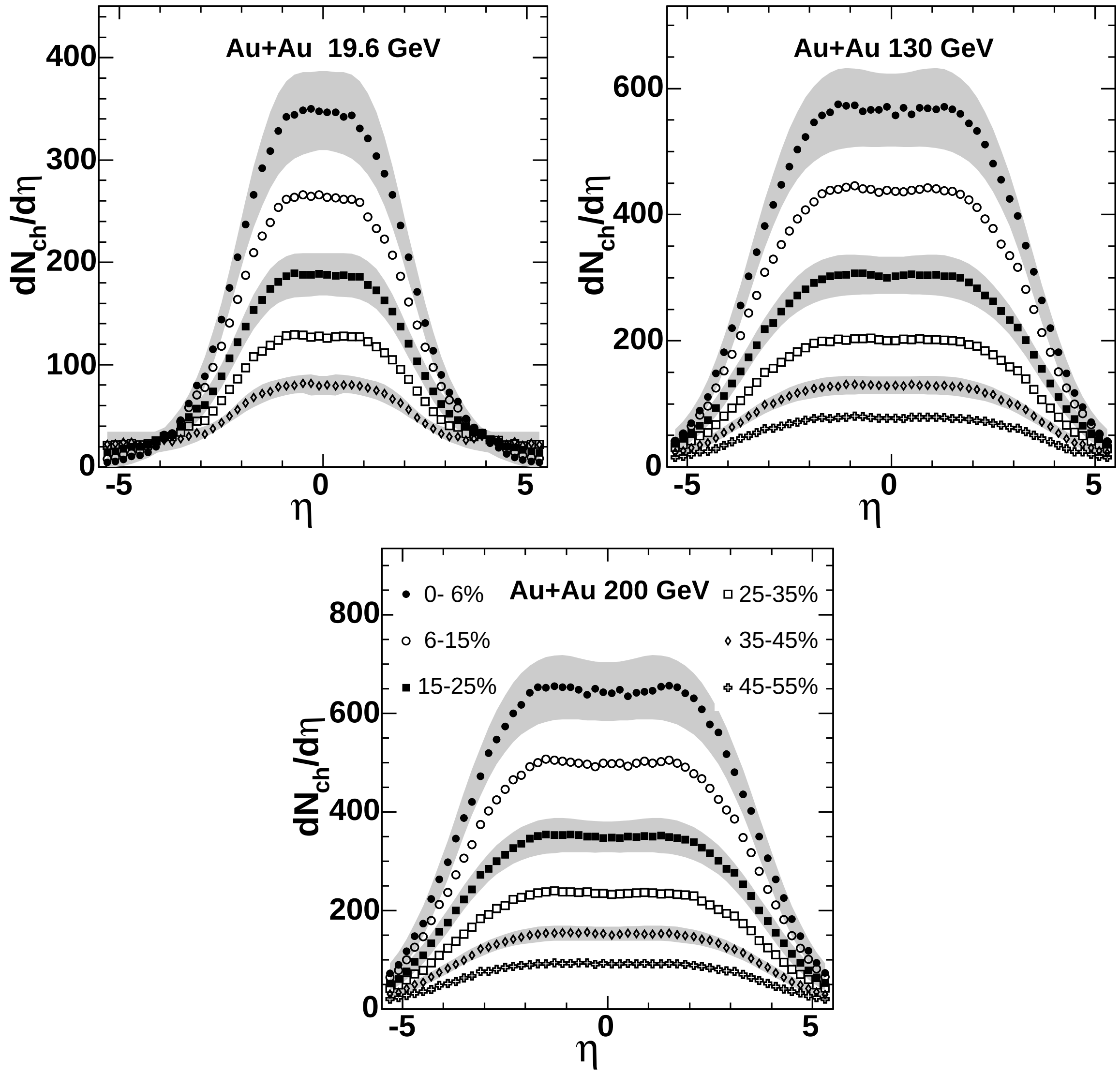
$$\epsilon_0 = \frac{1}{\pi R^2 \tau_0} \left(\frac{dE_T}{dy} \right)$$

Depends on initial time τ_0

BNL and RHIC

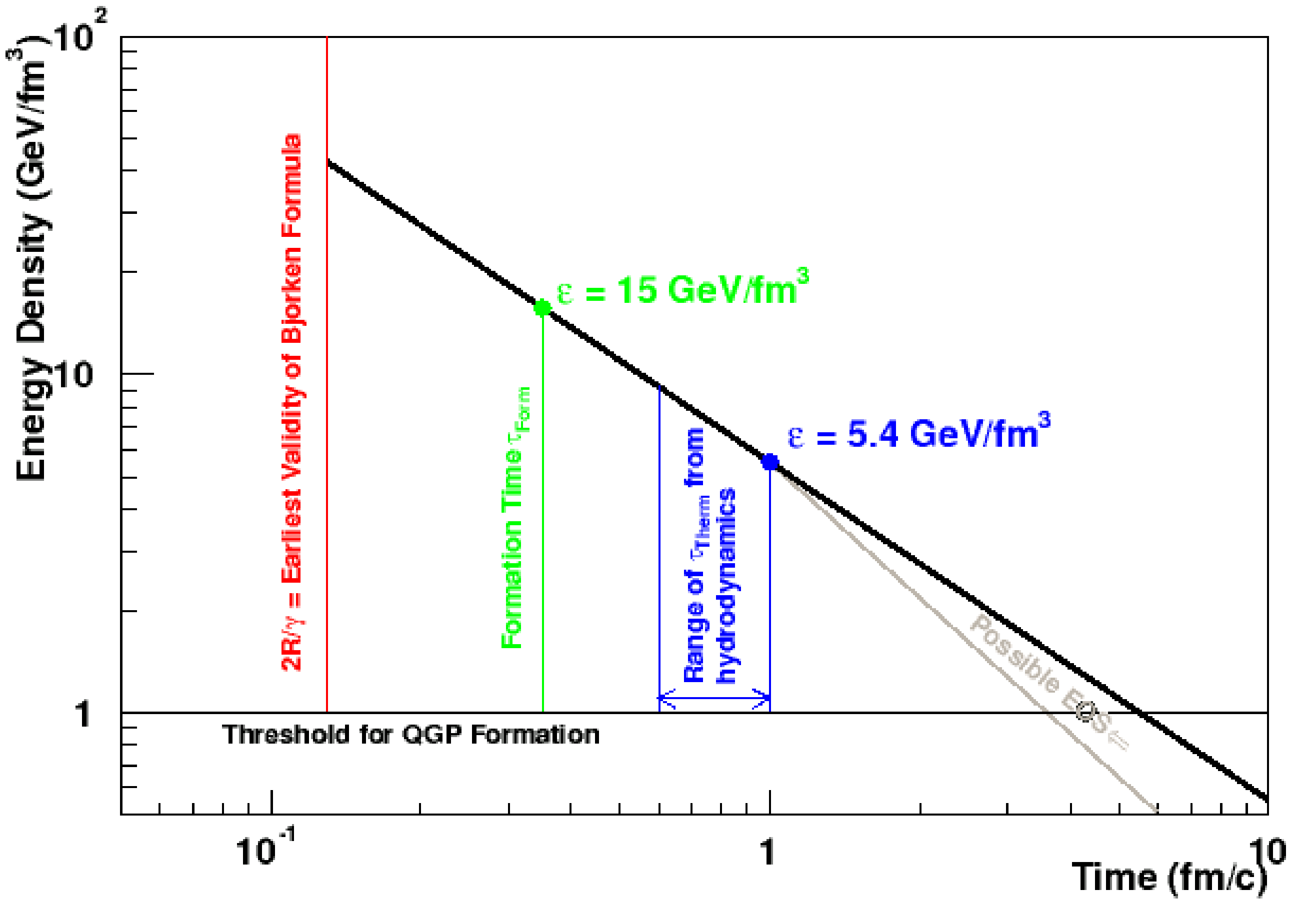


Multiplicities

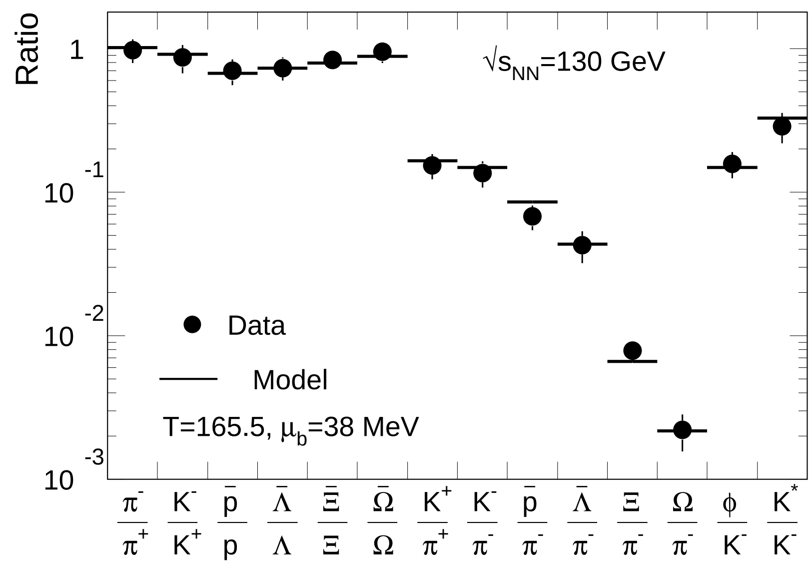


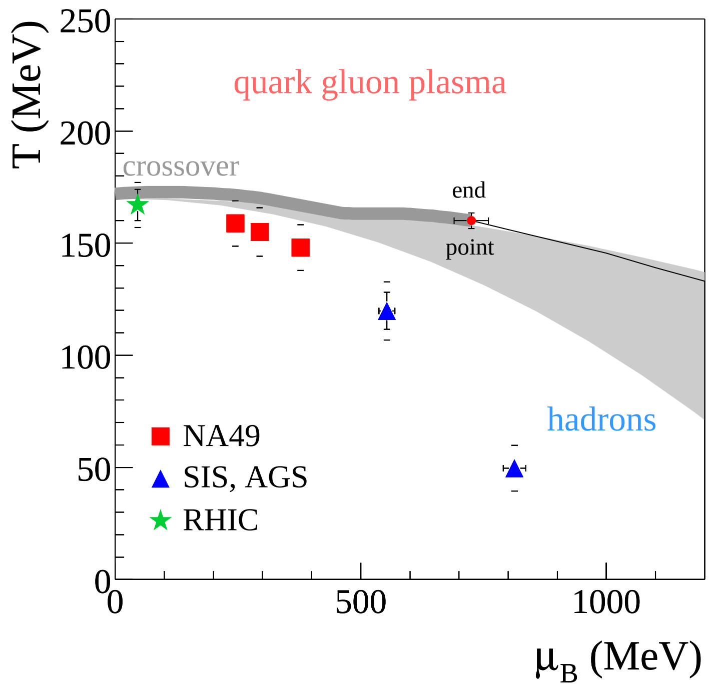
Phobos White Paper (2005)

Bjorken expansion



Chemical equilibrium at freezeout



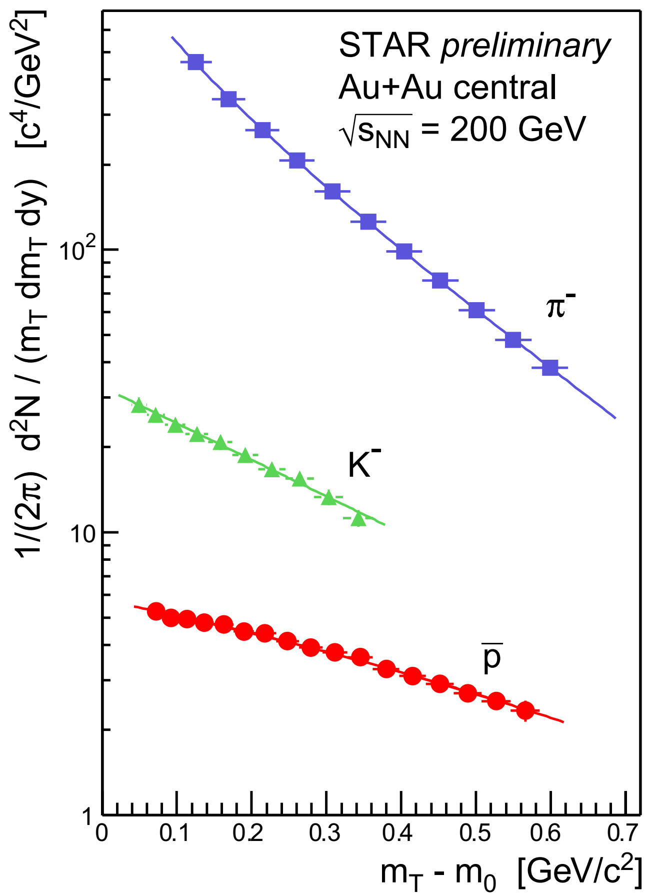


Andronic et al. (2006)

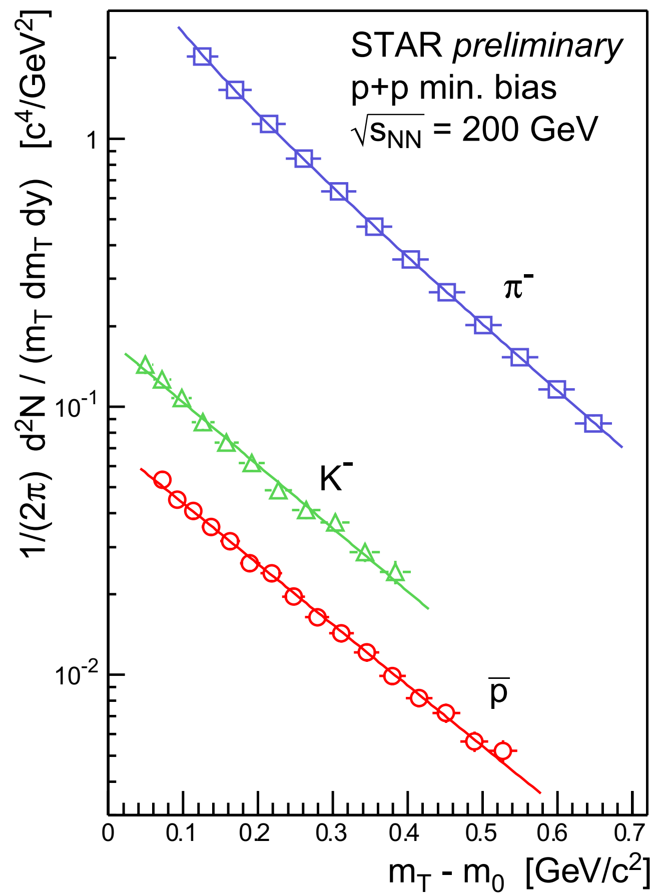
Collective behavior: Radial flow

Radial expansion leads to blue-shifted spectra in Au+Au

Au+Au



p+p



$v_T \sim 0.6c!$

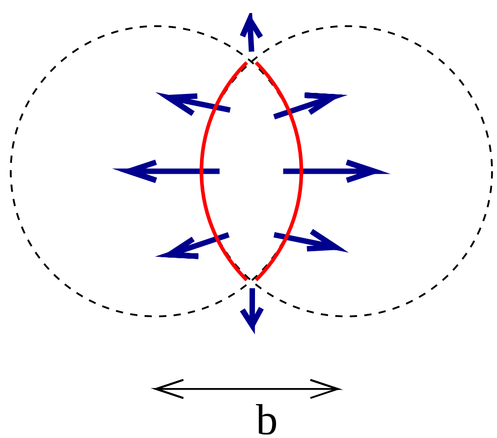
$m_T = \sqrt{p_T^2 + m^2}$

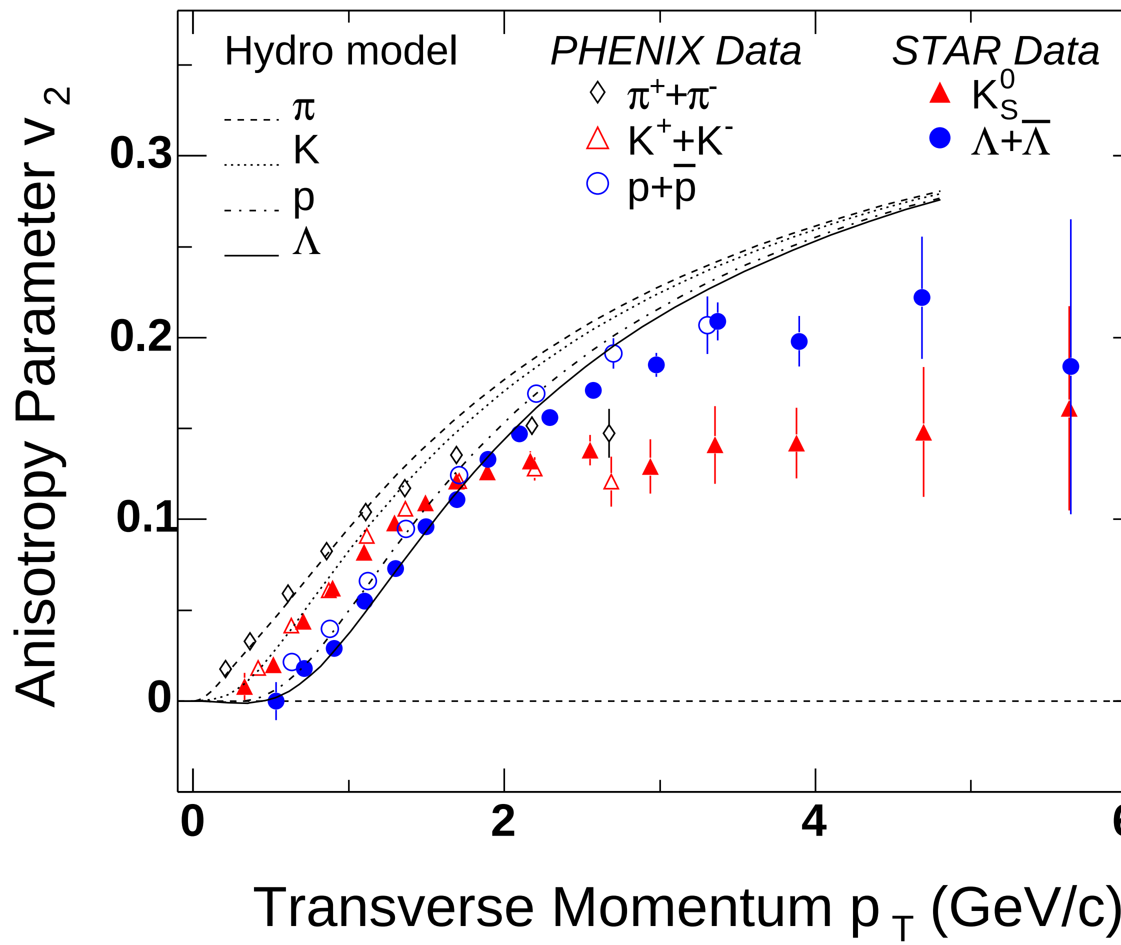
Collective behavior: Elliptic flow

Hydrodynamic expansion converts

coordinate space anisotropy

to momentum space anisotropy

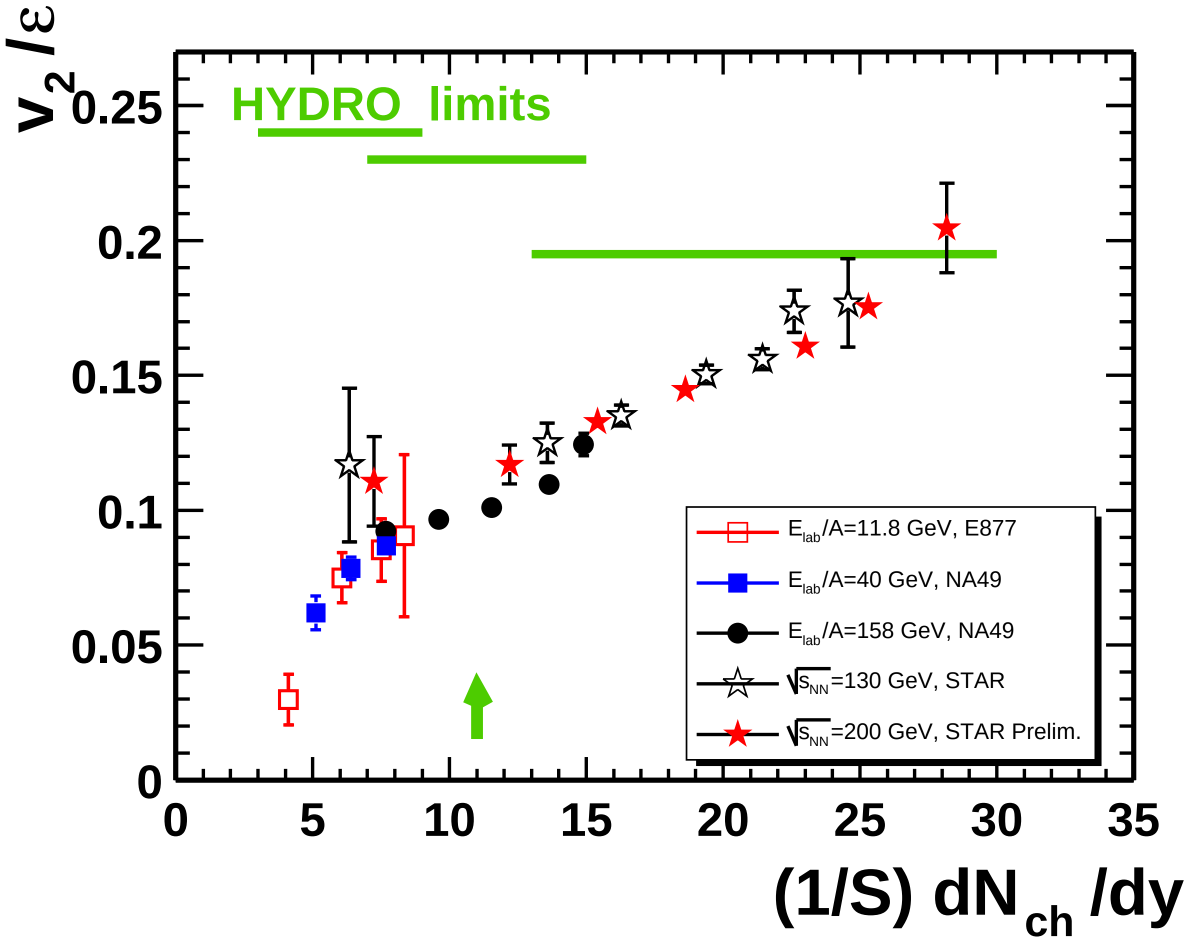




source: U. Heinz (2005)

$$p_0 \left. \frac{dN}{d^3p} \right|_{p_z=0} = v_0(p_\perp)\,(1 + 2v_2(p_\perp)\cos(2\phi) + \ldots)$$

Elliptic flow II: Multiplicity scaling



source: U. Heinz (2005)

Viscous Corrections

Longitudinal expansion: Bj expansion solves Navier-Stokes equation

entropy equation
$$\frac{1}{s}\frac{ds}{d\tau} = -\frac{1}{\tau}\left(1 - \frac{\frac{4}{3}\eta + \zeta}{sT\tau}\right)$$

Viscous corrections small if $\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s} \ll (T\tau)$

early	$T\tau \sim \tau^{2/3}$	$\eta/s \sim const$	$\eta/s < \tau_0 T_0$
late	$T\tau \sim const$	$\eta \sim T/\sigma$	$\tau^2/\sigma < 1$

Hydro valid for $\tau \in [\tau_0, \tau_{fr}]$

Viscous corrections to T_{ij} (radial expansion)

$$T_{zz} = P - \frac{4}{3}\frac{\eta}{\tau} \qquad T_{xx} = T_{yy} = P + \frac{2}{3}\frac{\eta}{\tau}$$

increases radial flow (central collision)

decreases elliptic flow (peripheral collision)

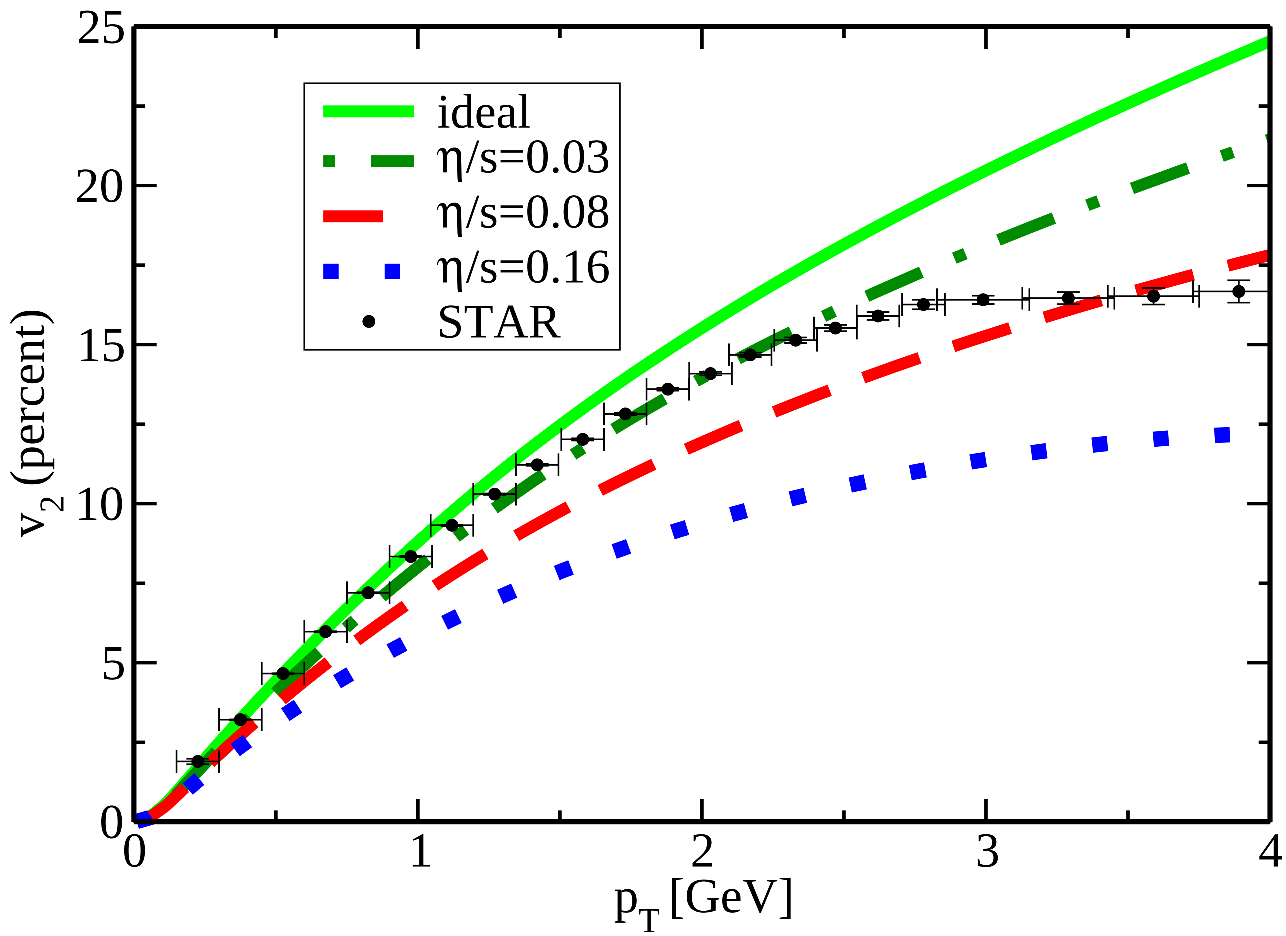
Modification of distribution function

$$\delta f = \frac{3}{8}\frac{\Gamma_s}{T^2} f_0(1+f_0) p_\alpha p_\beta \nabla^{\langle\alpha} u^{\beta\rangle}$$

Correction to spectrum grows with $p_\perp^2$

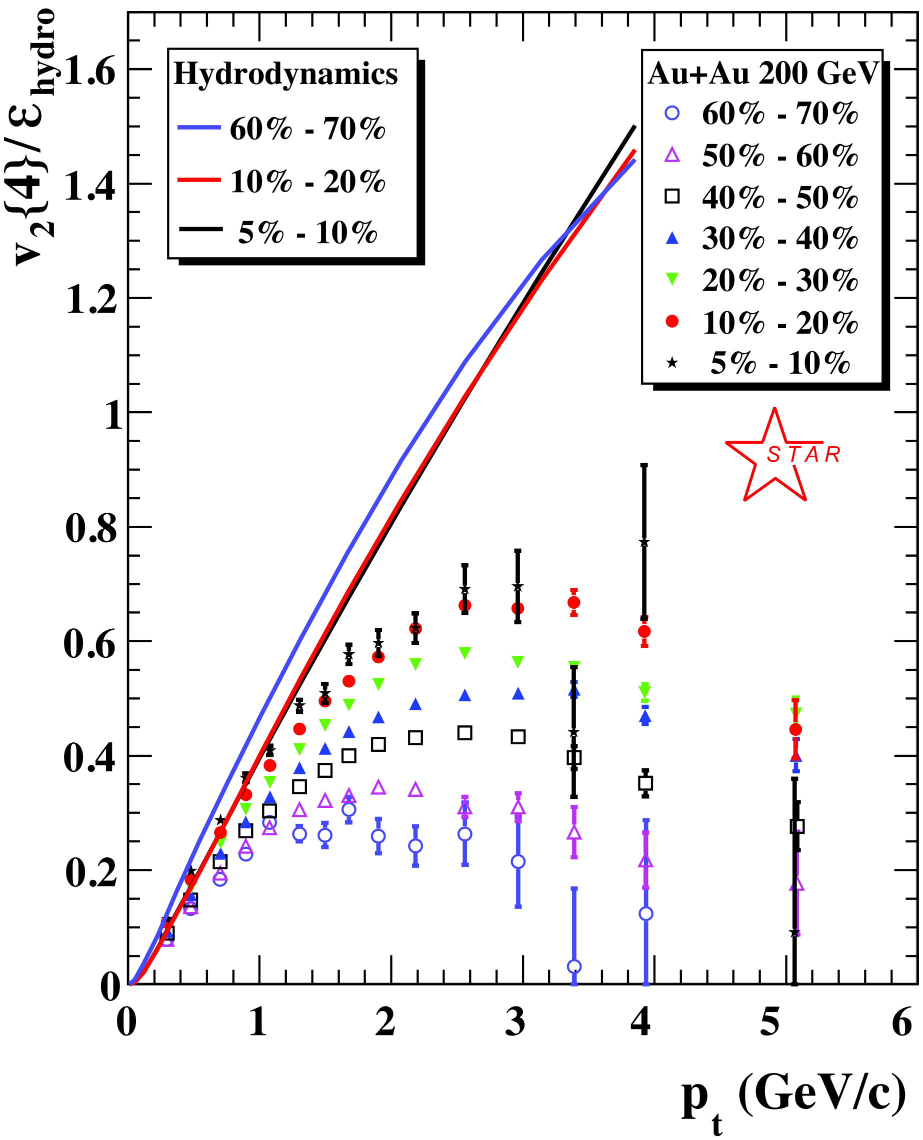
$$\frac{\delta(dN)}{dN_0} = \frac{\Gamma_s}{4\tau_f}\left(\frac{p_\perp}{T}\right)^2$$

Elliptic flow III: Viscous effects



Romatschke (2007), Teaney (2003)

Elliptic flow IV: Systematic trends



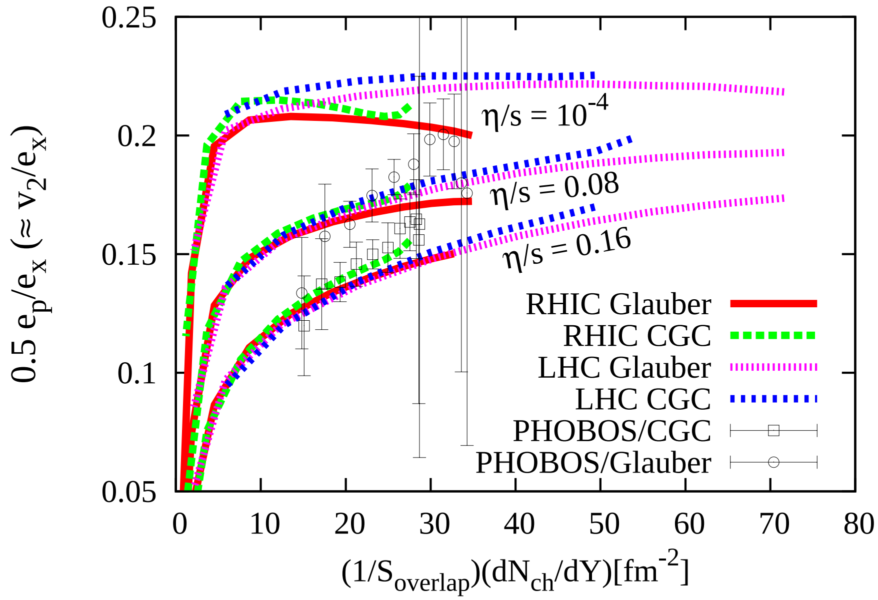
source: R. Snellings (STAR)

Deviation from ideal hydro

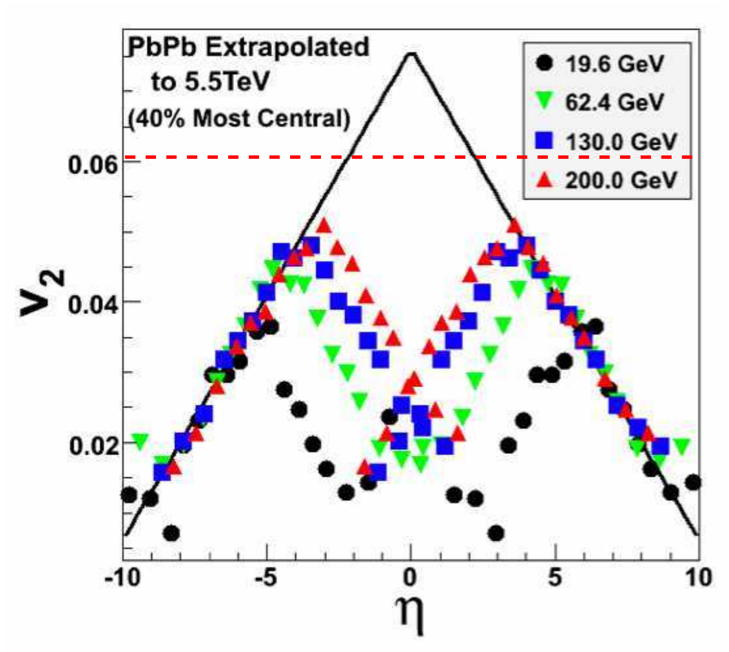
increases for more peripheral events

increases with $p_\perp$

Elliptic flow V: Predictions for LHC



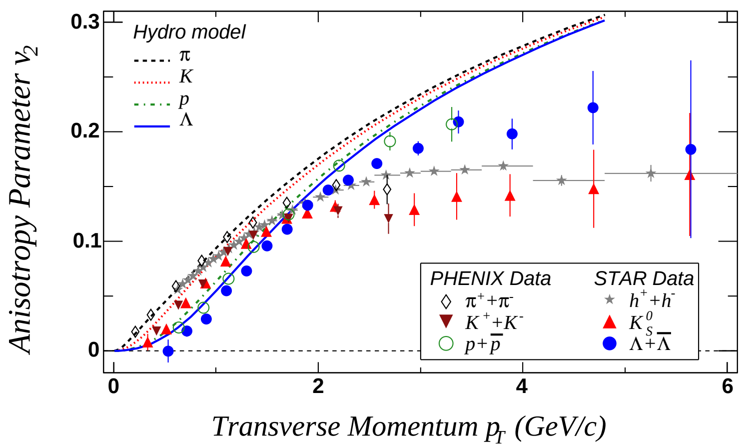
Romatschke, Luzum (2009)

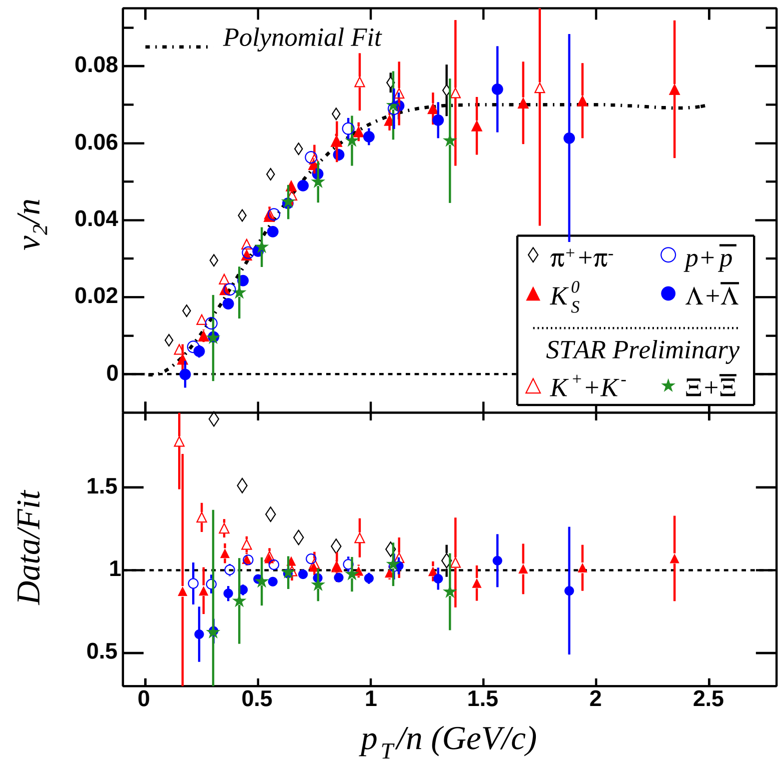


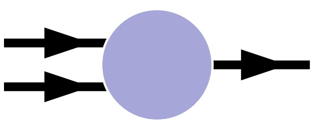
Busza (QM 2009)

Elliptic flow VI: Recombination

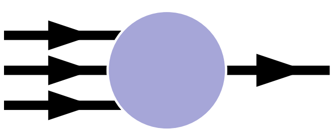
"quark number" scaling of elliptic flow







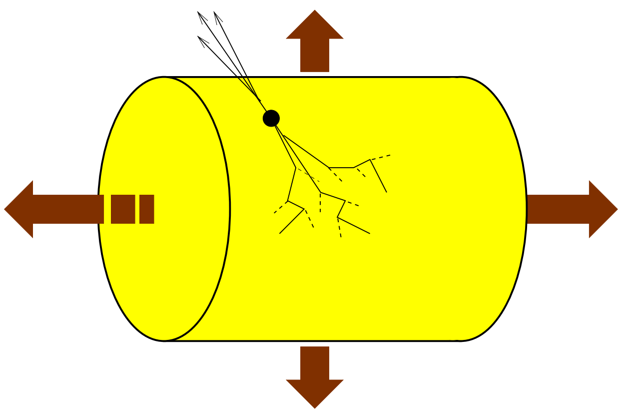
(qq̄) (mes) $$p_\perp^{mes} = 2p_\perp^{qu}$$

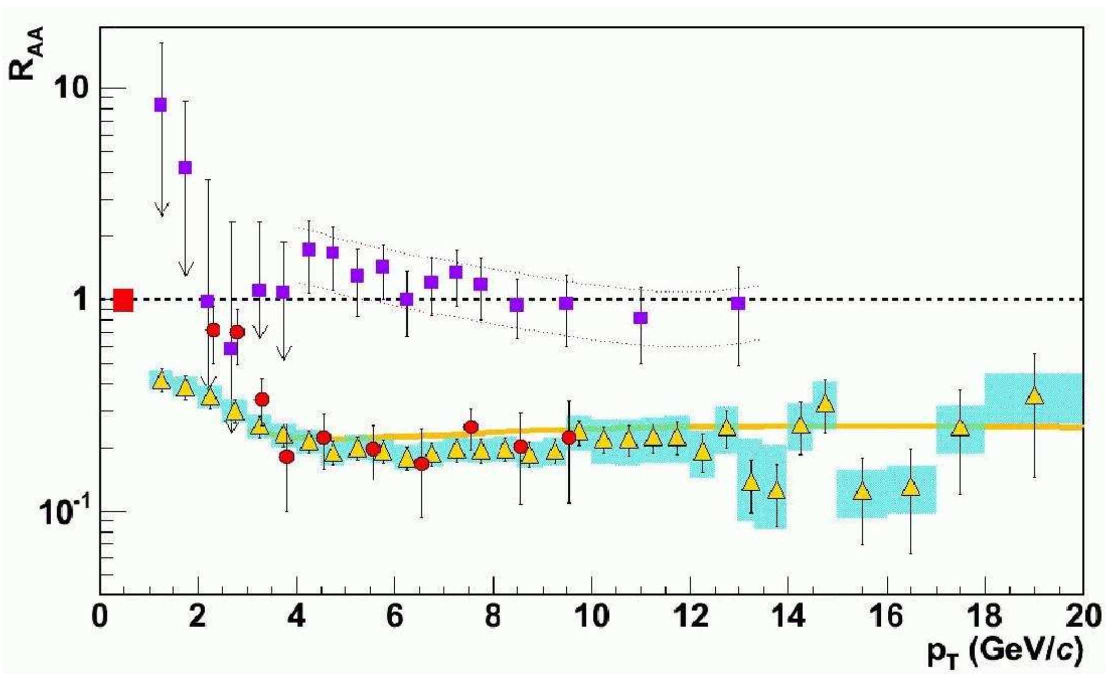


(qqq) (bar) $$p_\perp^{bar} = 3p_\perp^{qu}$$

Jet quenching

$$R_{AA} = \frac{n_{AA}}{N_{coll} n_{pp}}$$

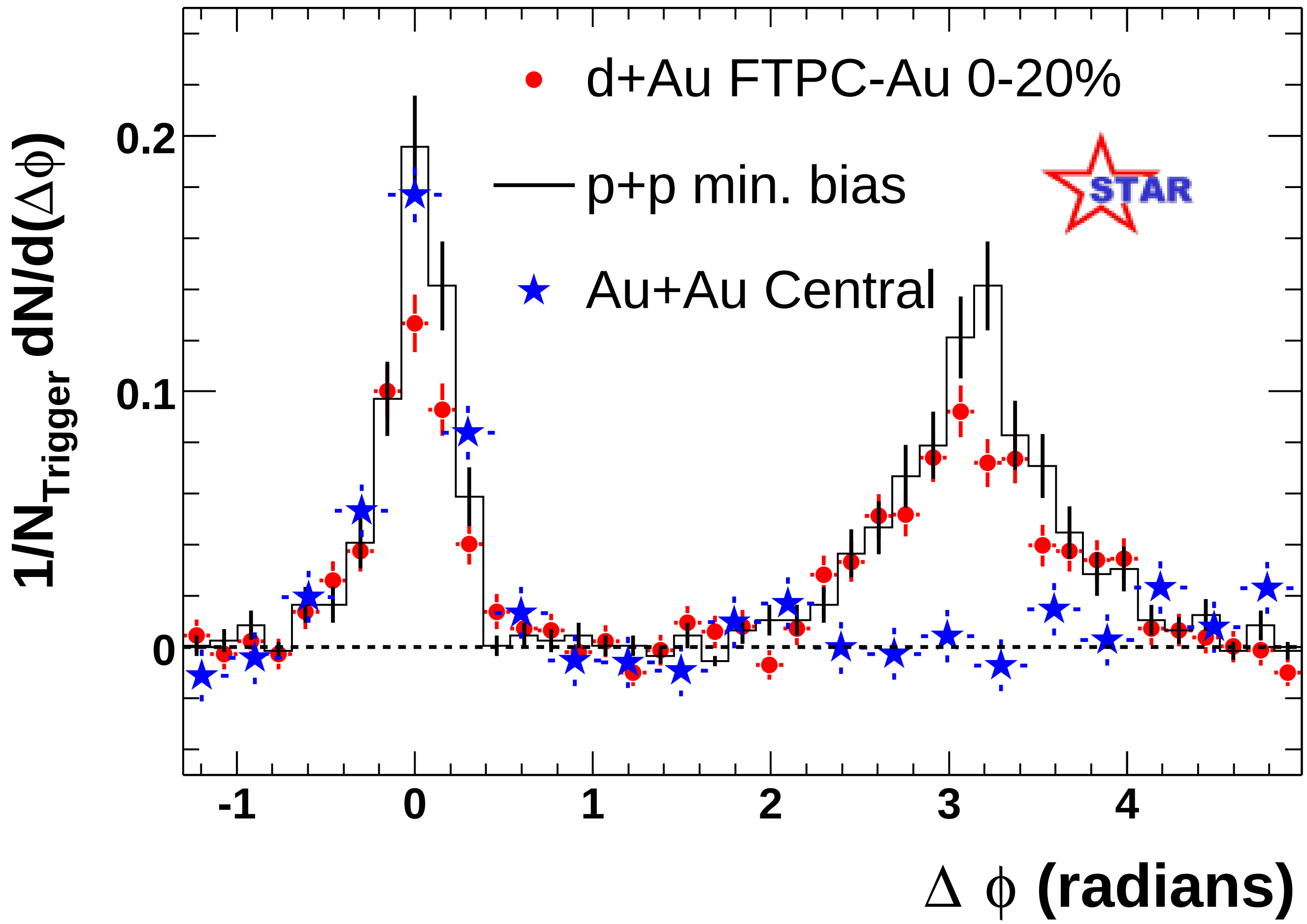




source: Akiba [Phenix] (2006)

Jet quenching II

Disappearance of away-side jet

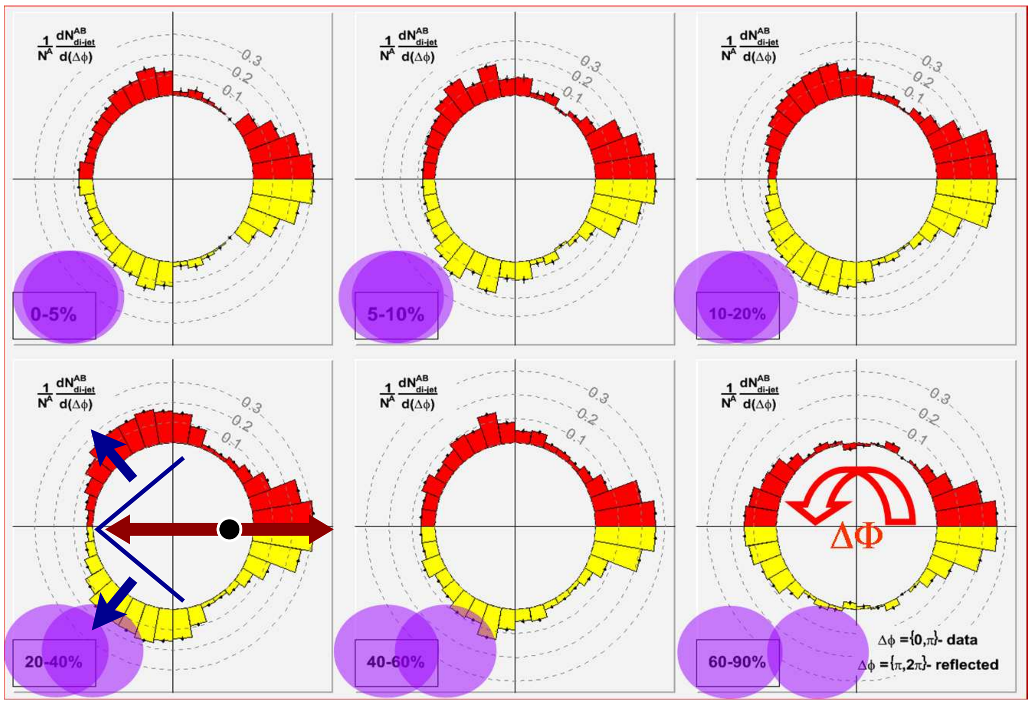


source: Star White Paper (2005)

Jet quenching III: The Mach cone

azimuthal multiplicity $dN/d\phi$

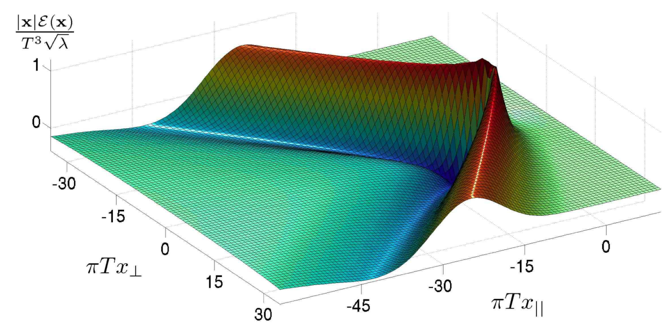
(high energy trigger particle at $\phi = 0$)



source: Phenix (PRL, 2006), W. Zajc (2007)

wake of a fast quark

in $\mathcal{N} = 4$ plasma

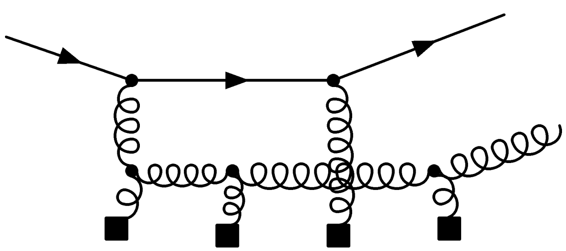


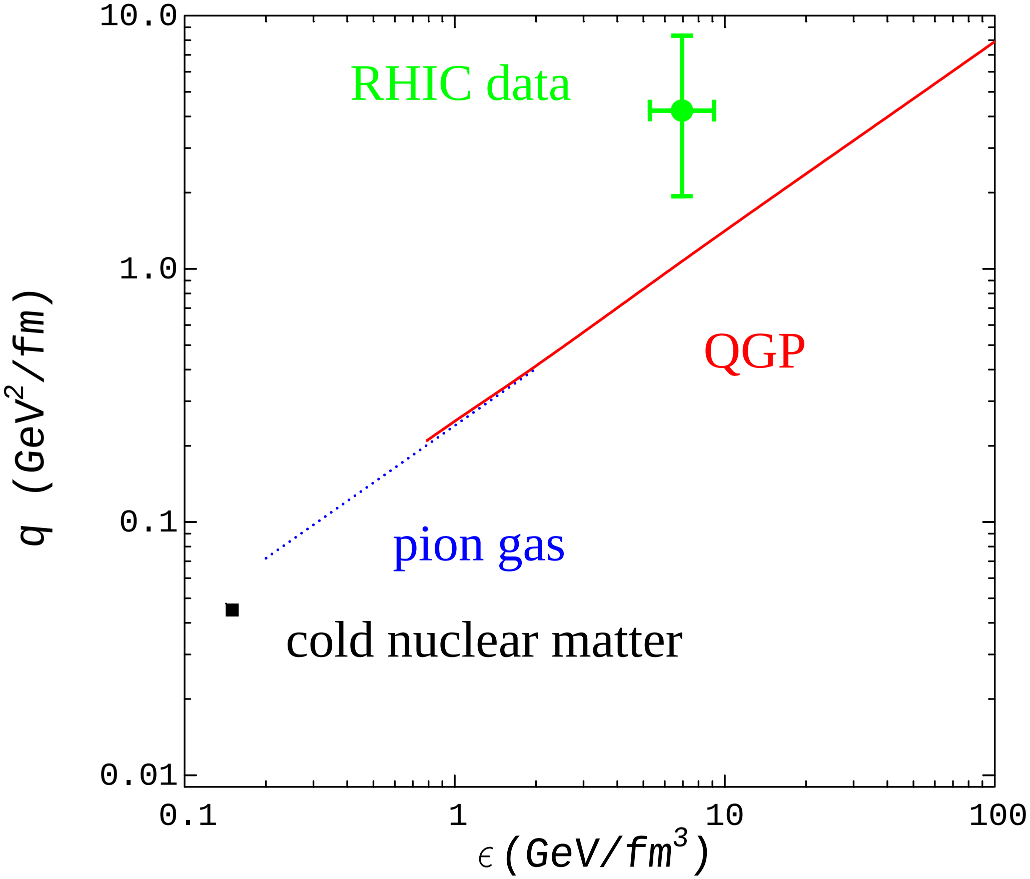
Chesler and Yaffe (2007)

Jet quenching: Theory

energy loss governed by

$$\hat{q} = \rho \int q_\perp^2 \, dq_\perp^2 \; \frac{d\sigma}{dq_\perp^2}$$





larger than pQCD predicts? relation to η? ($\hat{q} \sim 1/\eta$?)

also: large energy loss of heavy quarks

source: R. Baier (2004)

Where are (were) we?

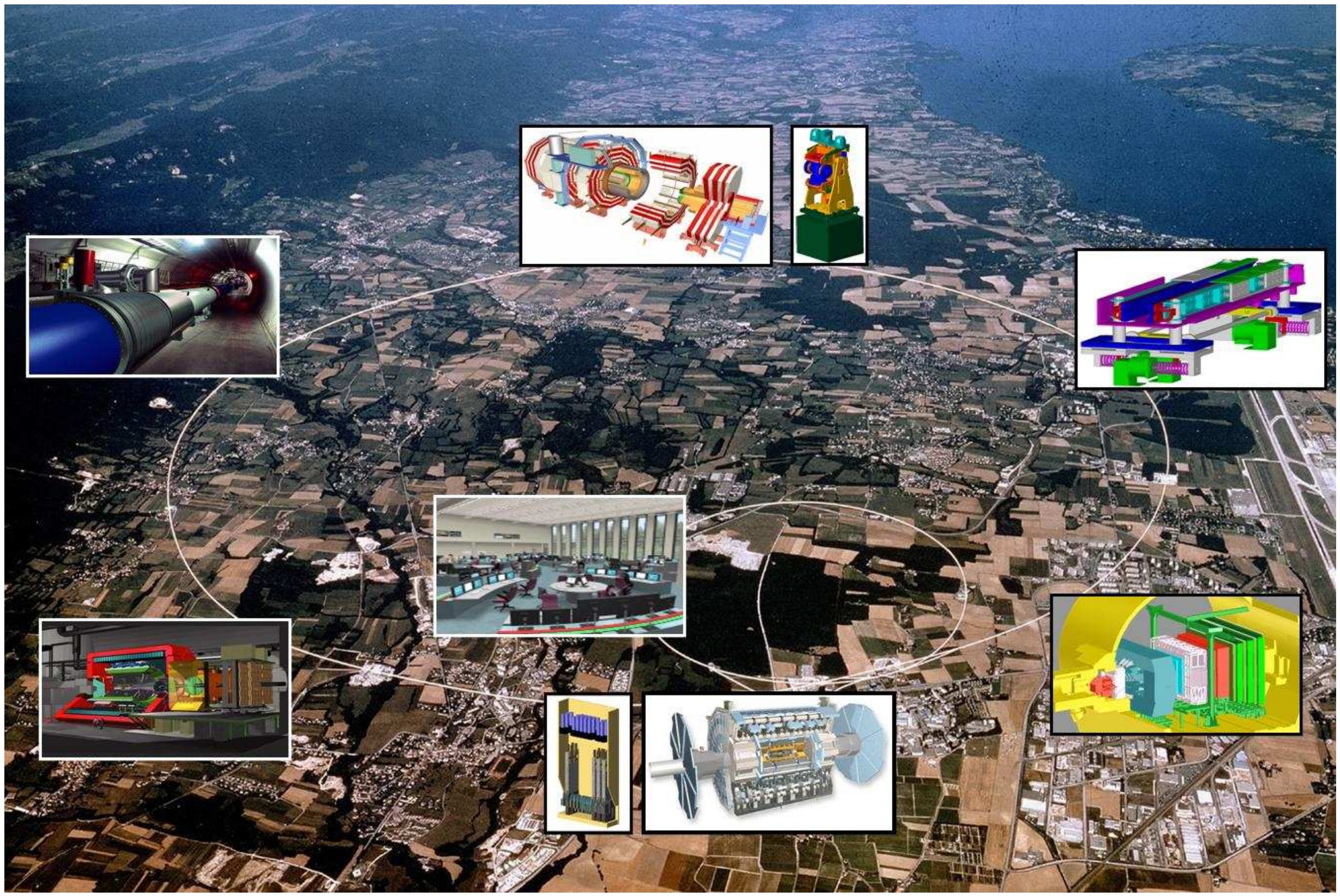
observe almost ideal fluid behavior, initial conditions well above critical energy density.

systematics require $0.1 < \eta/s < 0.4$; more studies needed, LHC elliptic flow will be very interesting.

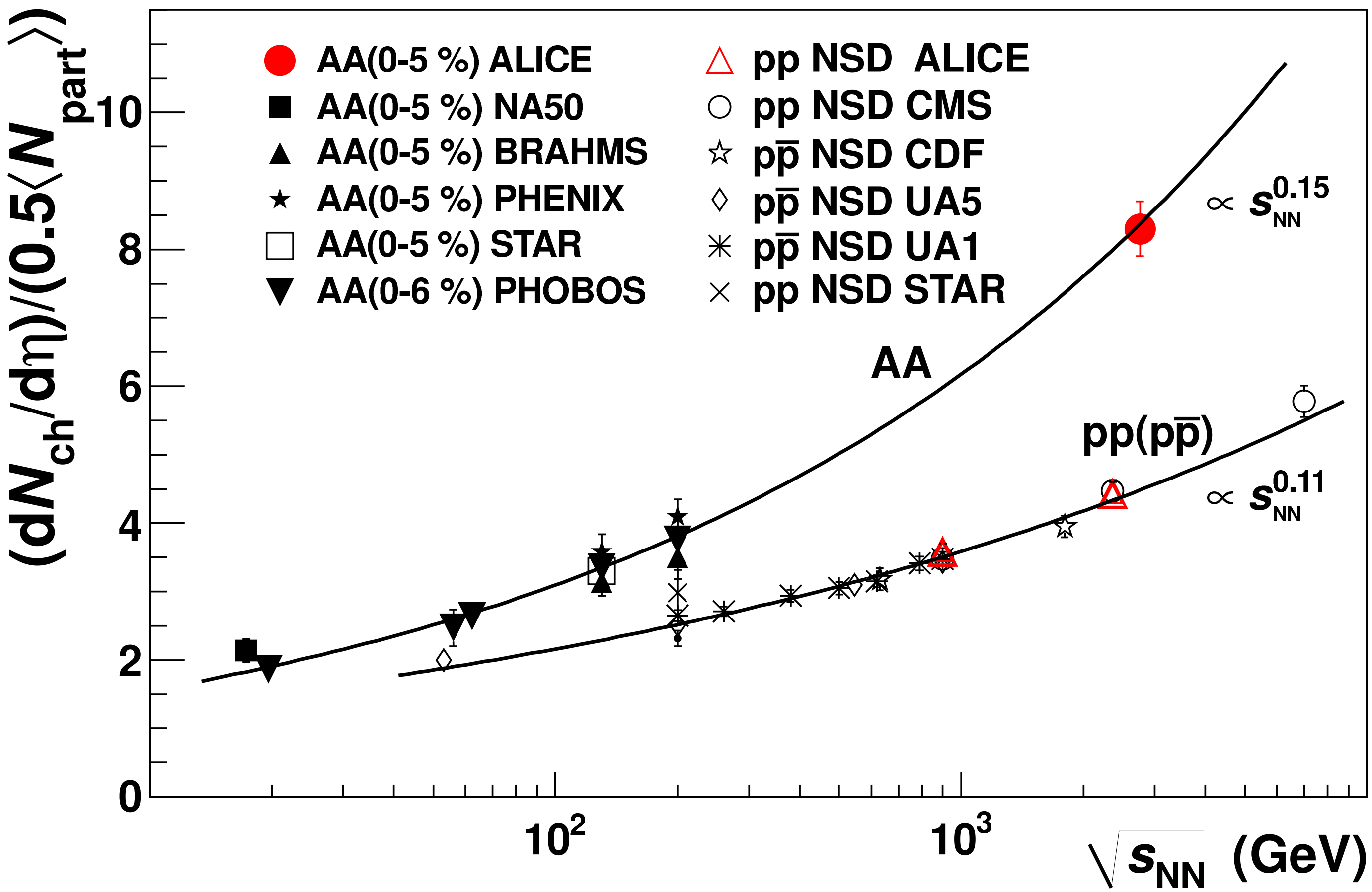
jet quenching large; very detailed studies under way. LHC will provide unprecedented range.

heavy flavors: large energy loss seen, flavor studies (c/b) under way.

LHC: Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV



Alice results: Multiplicity scaling with energy



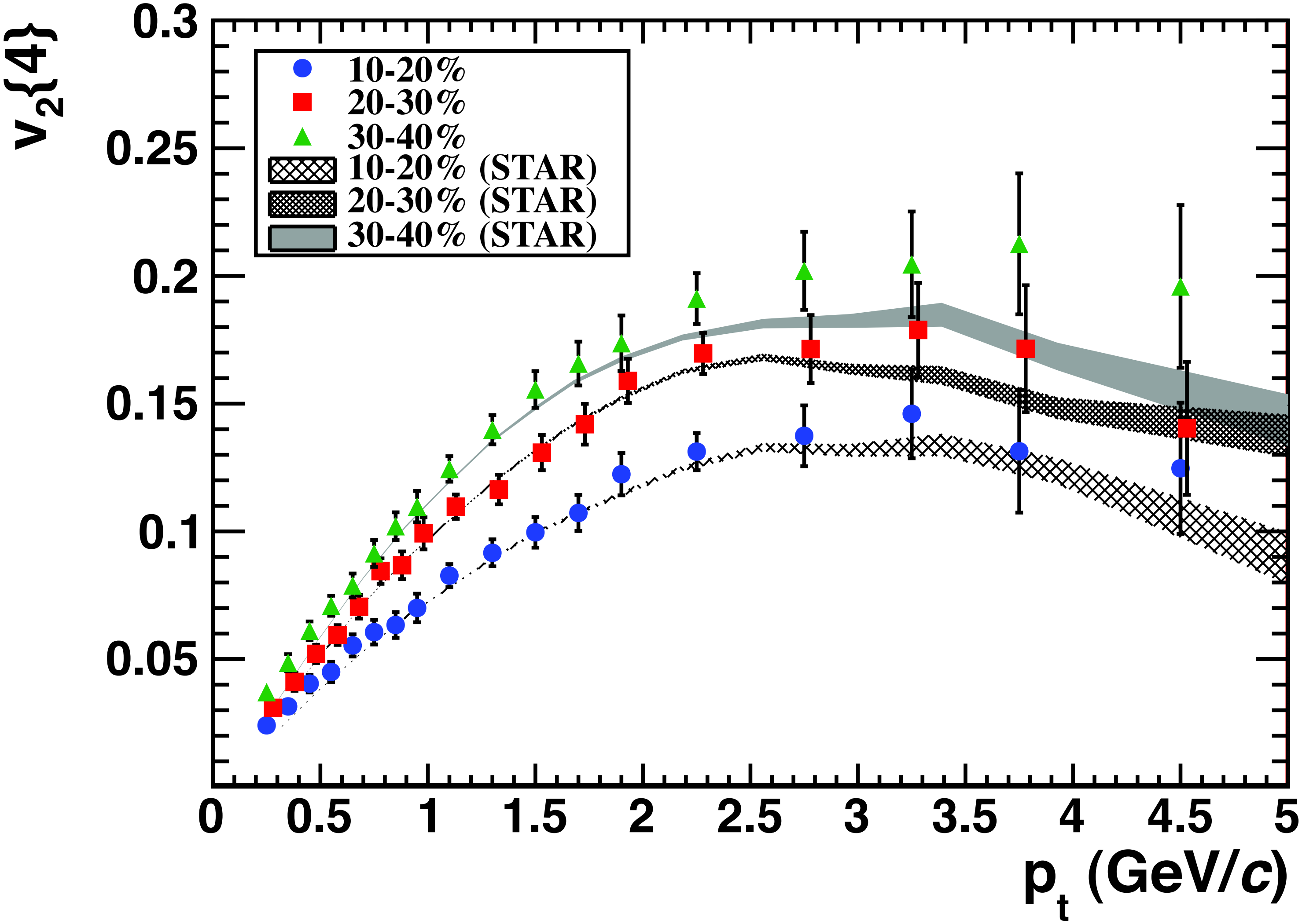
What does it mean?

Factor 2.2 in multiplicity: factor 2.85 in energy density, factor 1.3 in temperature (at fixed τ_0)

AA $\neq$ pp: extra multiplicity per participant pair.

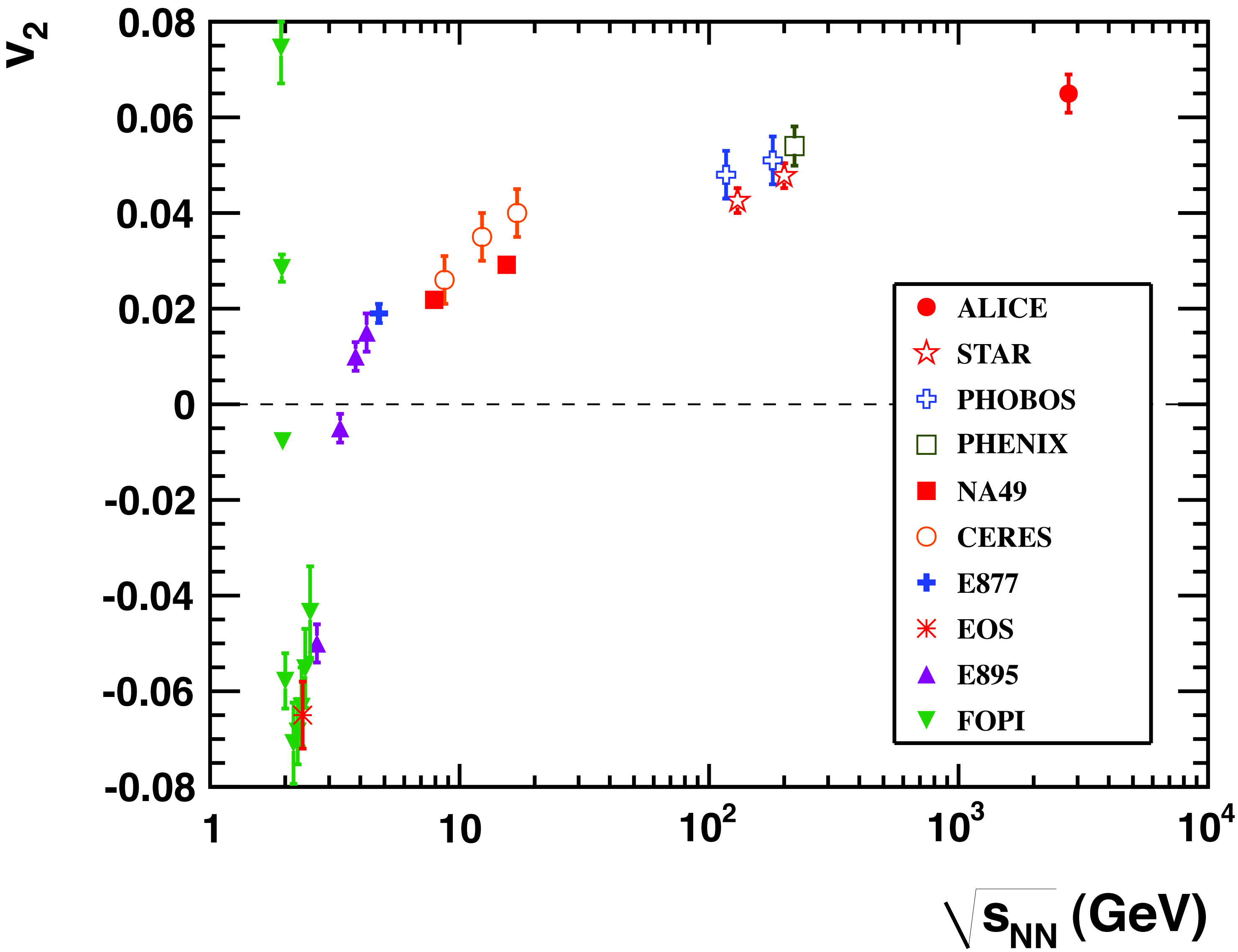
Simple saturation works better than improved saturation.

Alice flow



10-20%
20-30%
30-40%
10-20% (STAR)
20-30% (STAR)
30-40% (STAR)
v2{4}
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
pt (GeV/c)

Flow excitation function



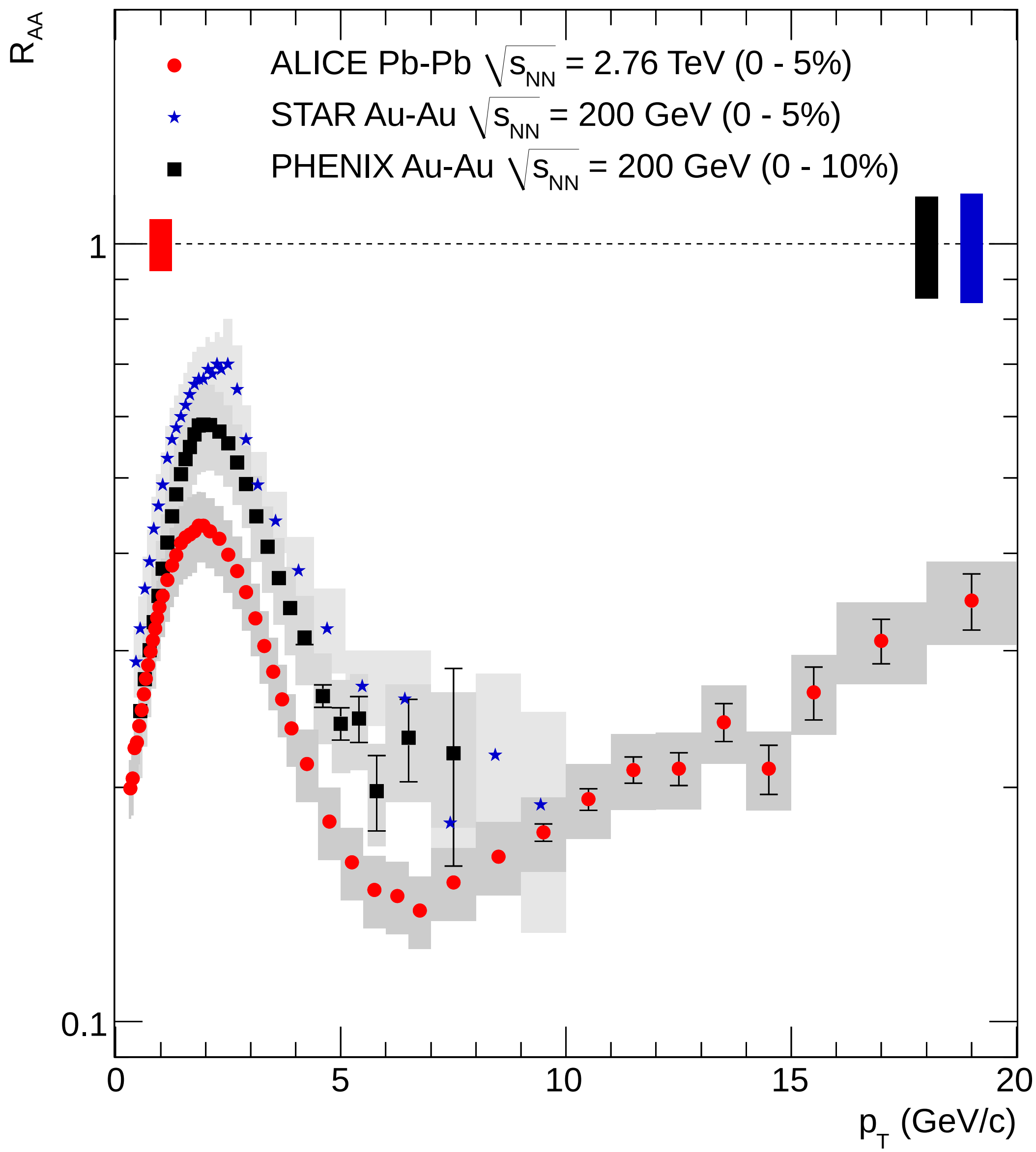
What does it mean?

Hydro rules! RHIC data not an accident.

Differential v_2 exactly equal to RHIC (!?)

Integrated v_2 somewhat high: mean p_T increase? acceptance?

Alice jet quenching

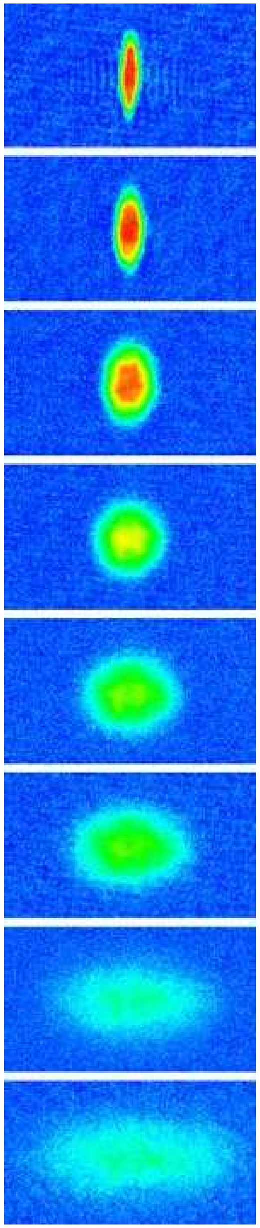


What does it mean?

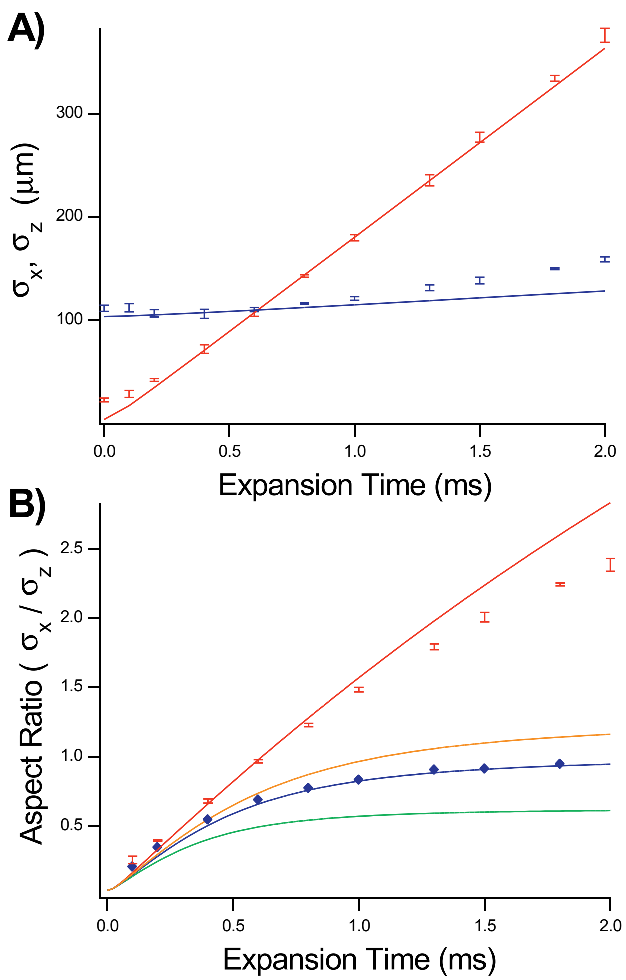
Suppresion at 10 GeV same as RHIC (!??)

But: p_T dependence no longer flat, agrees with predictions (expect factorization as $p_T \to \infty$).

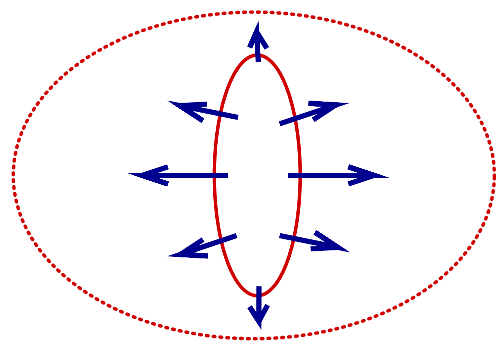
III: Almost ideal fluid dynamics in cold atomic gases



O'Hara et al. (2002)

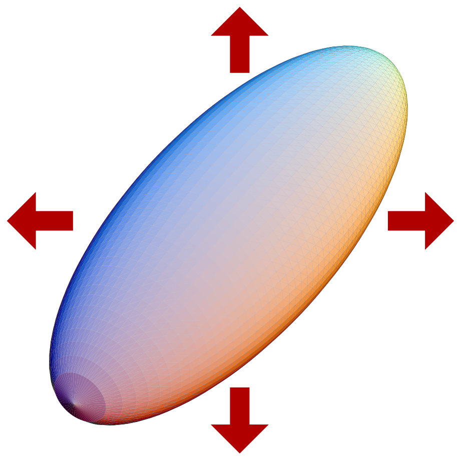


Hydrodynamic expansion converts coordinate space anisotropy to momentum space anisotropy



Almost ideal fluid dynamics: Collective modes

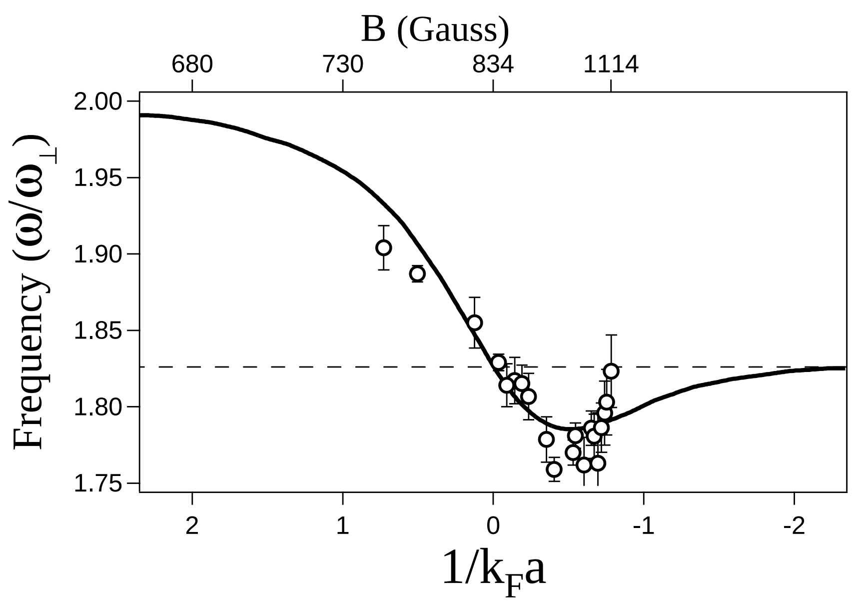
Radial breathing mode



Ideal fluid hydrodynamics ($P \sim n^{5/3}$)

$$\frac{\partial n}{\partial t} + \vec{\nabla} \cdot (n\vec{v}) = 0$$

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right) \vec{v} = -\frac{\vec{\nabla} P}{mn} - \frac{\vec{\nabla} V}{m}$$



Hydro frequency at unitarity

$$\omega = \sqrt{\frac{10}{3}}\,\omega_\perp$$

experiment: Kinast et al. (2005)

Dissipation (scaling flows)

Energy dissipation (η, ζ, κ: shear, bulk viscosity, heat conductivity)

$$\dot{E} = -\frac{1}{2}\int d^3x\,\eta(x)\left(\partial_i v_j + \partial_j v_i - \frac{2}{3}\delta_{ij}\partial_k v_k\right)^2 - \int d^3x\,\zeta(x)\,(\partial_i v_i)^2 - \frac{1}{T}\int d^3x\,\kappa(x)\,(\partial_i T)^2$$

Have $\zeta = 0$ and $T(x) = const$. Universality implies

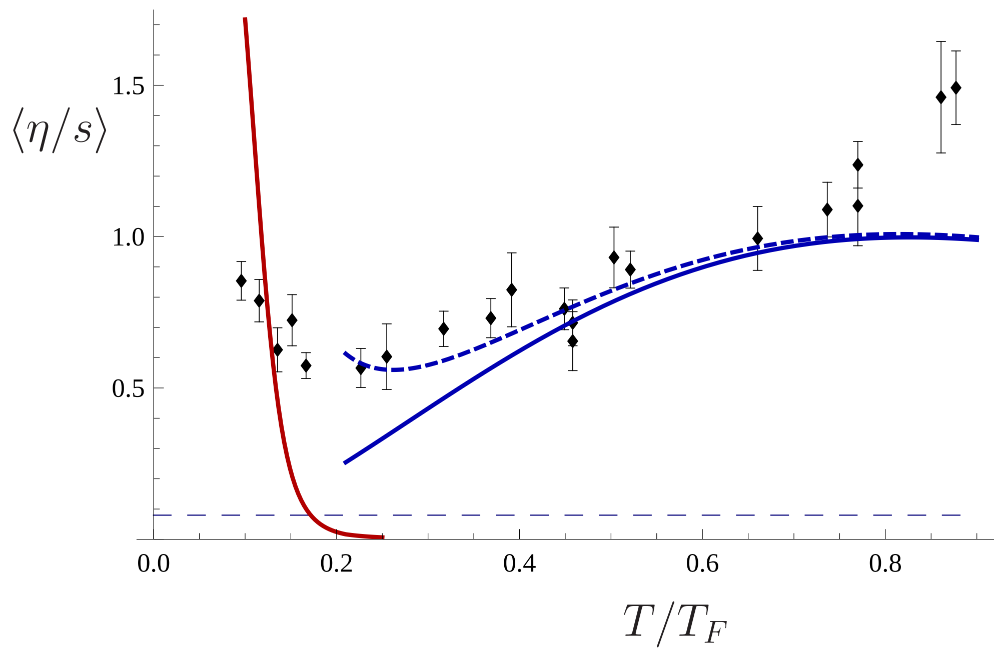
$$\eta(x) = s(x)\,\alpha_s\left(\frac{T}{\mu(x)}\right)$$

$$\int d^3x\,\eta(x) = S\langle\alpha_s\rangle$$

Collective modes: Small viscous correction exponentiates

$$a(t) = a_0 \cos(\omega t) \exp(-\Gamma\, t)$$

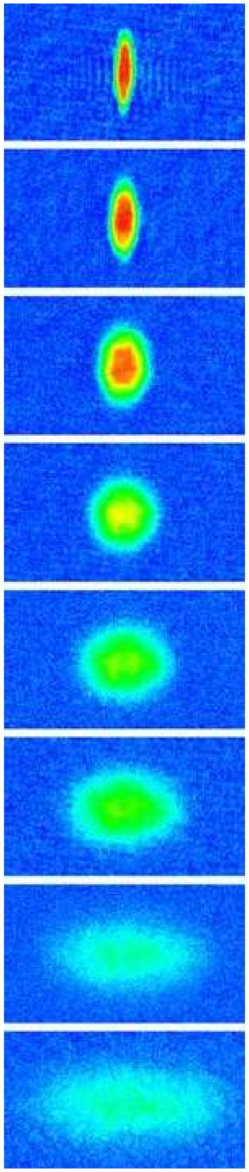
$$\langle \eta/s \rangle = (3N\lambda)^{1/3} \left(\frac{\Gamma}{\omega_\perp}\right) \left(\frac{E_0}{E_F}\right) \left(\frac{N}{S}\right)$$

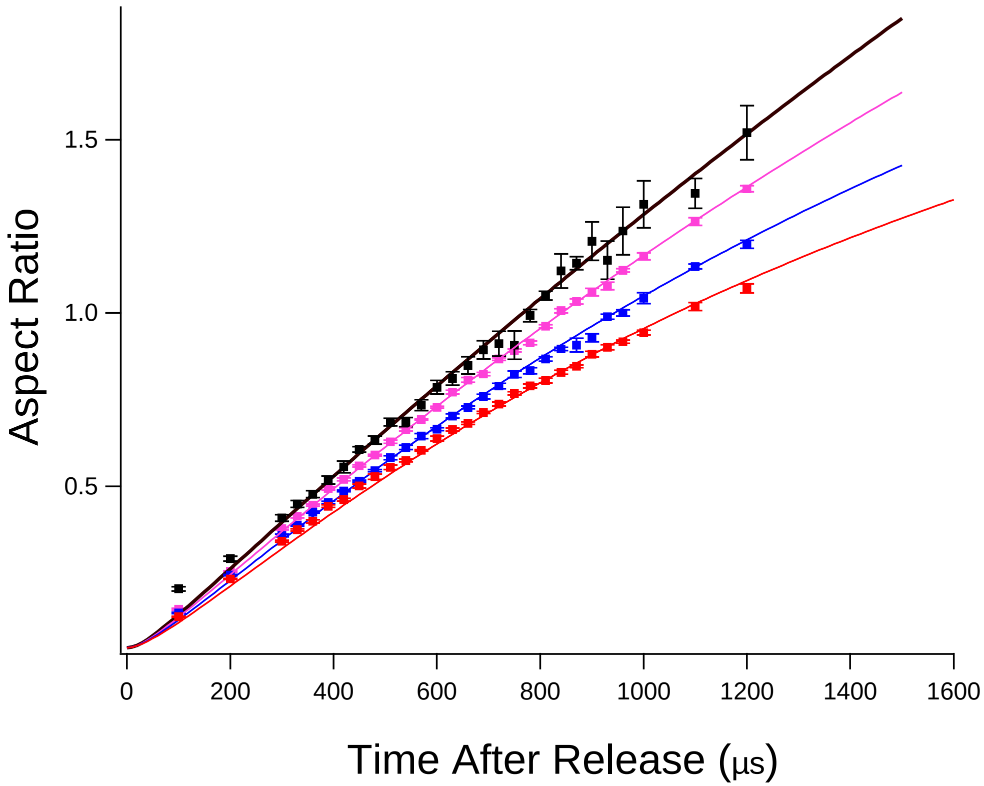


Kinast et al. (2006), Schaefer (2007)

Elliptic flow: High T limit

Quantum viscosity $\eta = \eta_0 \frac{(mT)^{3/2}}{\hbar^2}$





$\eta = \eta_0 (mT)^{3/2}$

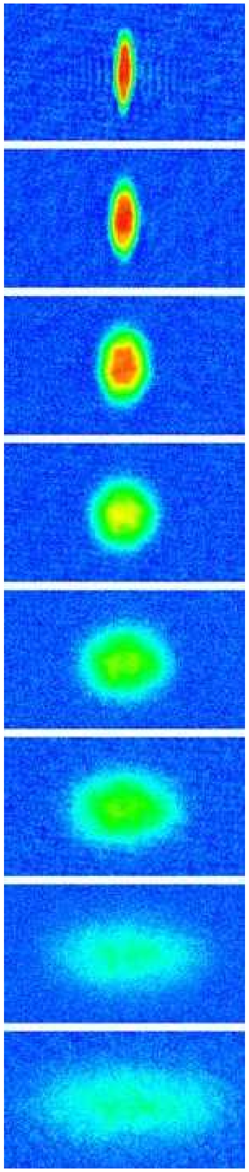
$\tau_R = \eta / P$

Cao et al., Science (2010)

fit: $\eta_0 = 0.33 \pm 0.04$

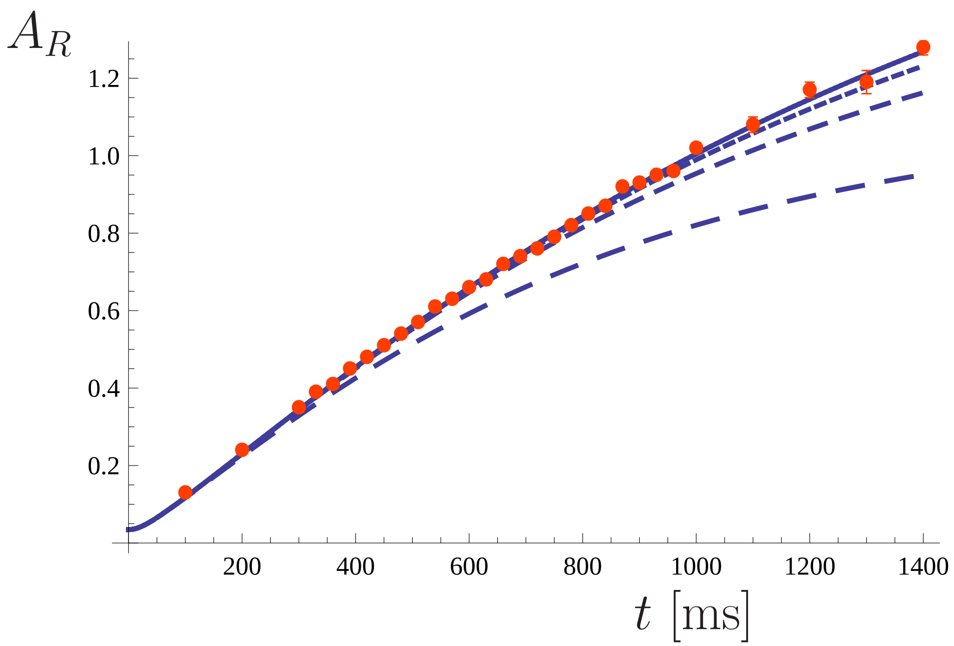
theory: $\eta_0 = \frac{15}{32\sqrt{\pi}} = 0.26$

Elliptic flow: Freezeout?



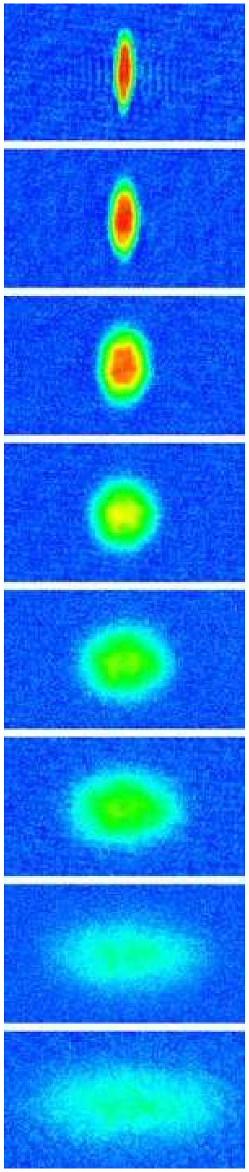
switch from hydro to (weakly collisional) kinetics

at scale factor $b_\perp^{fr} = 1, 5, 10, 20$



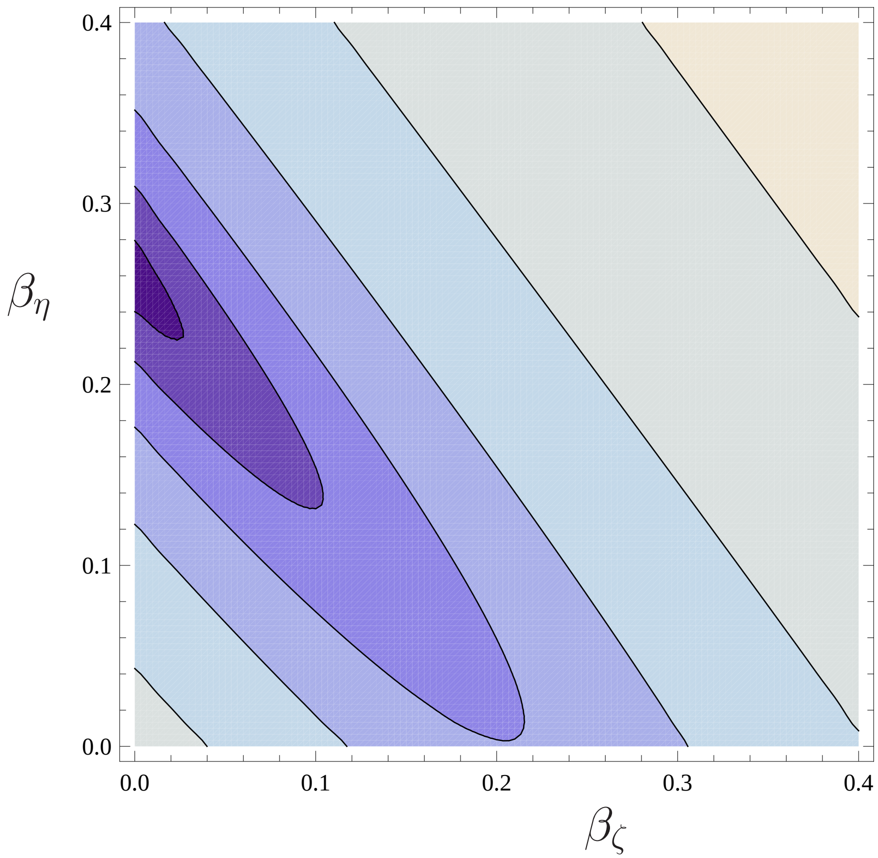
no freezeout seen in the data

Elliptic flow: Shear vs bulk viscosity



Dissipative hydro with both η, ζ

$$\beta_{\eta,\zeta} = \frac{(\eta,\zeta)}{n}\frac{E_F}{E}\frac{1}{(3\lambda N)^{1/3}}$$

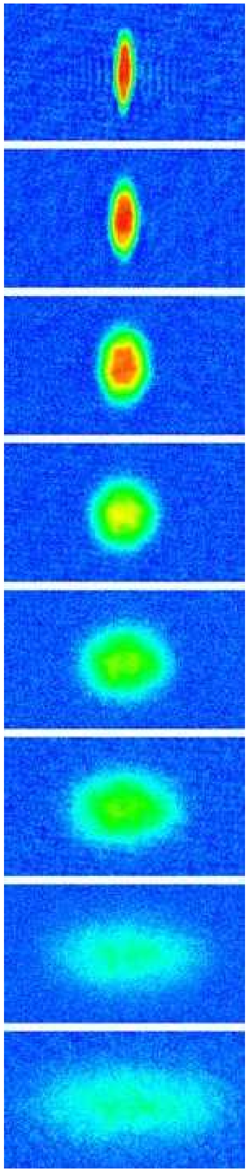


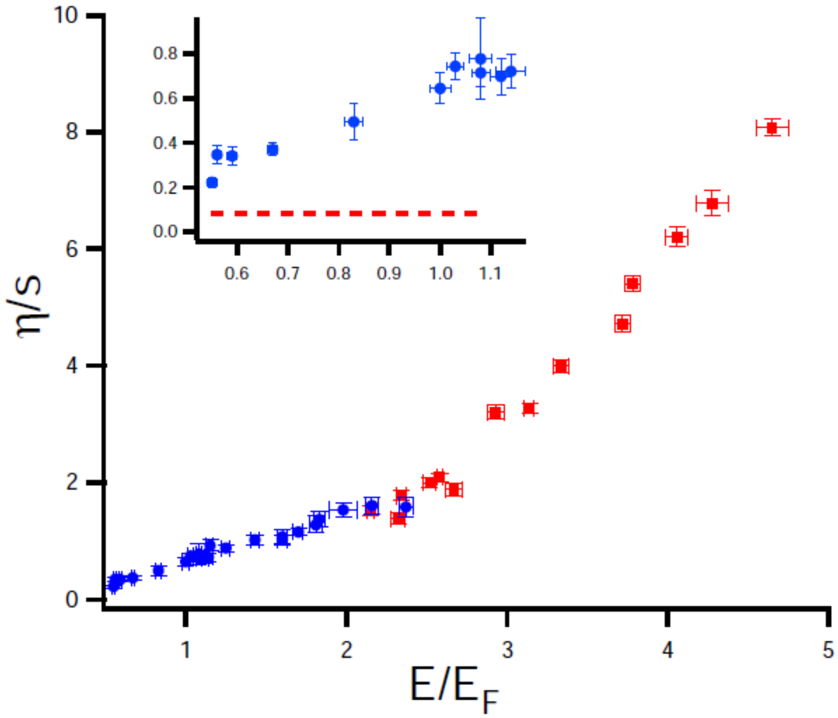
$\eta \gg \zeta$

Viscosity to entropy density ratio

consider both collective modes (low T)

and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$

Where are we?

Hydro rules: Consistent explanation of expansion and collective mode data, no freezeout seen in the data.

Collective mode data gives $\langle \eta/s \rangle < 0.4$.

Local analysis requires second order hydro or hydro+kinetics.

The bottom-line

Remarkably, the best fluids that have been observed are the *coldest* and the *hottest* fluid ever created in the laboratory, cold atomic gases (10^{-6}K) and the quark gluon plasma (10^{12}K) at RHIC.

Both of these fluids come close to a bound on the shear viscosity that was first proposed based on calculations in string theory, involving non-equilibrium evolution of back holes in 5 (and more) dimensions.