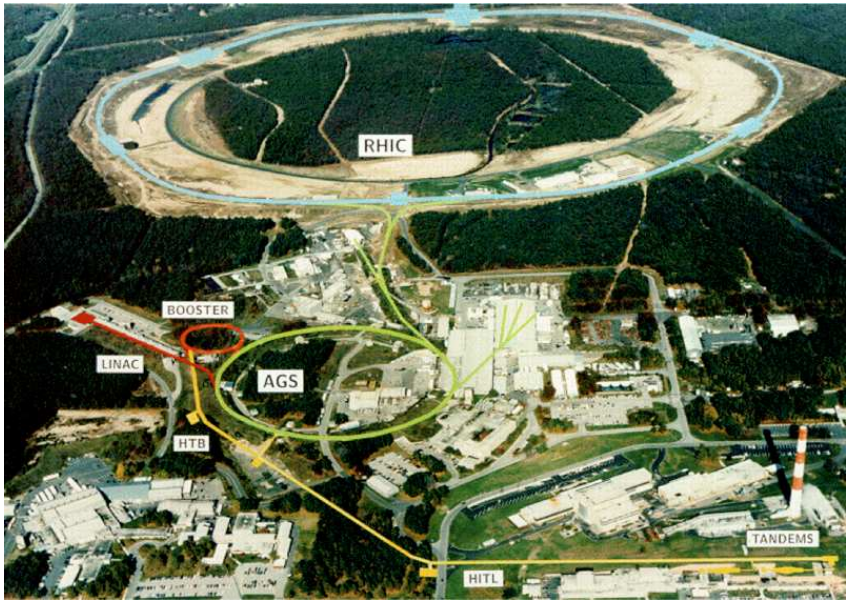
Quark-Gluon Plasma Physics at RHIC and at the LHC*

Ulrich Heinz, The Ohio State University



Hadron Collider Physics Symposium 2006,
Duke University, May 22-26, 2006

*Work supported by the U.S. Department of Energy (DOE)

The "two souls" of the LHC:

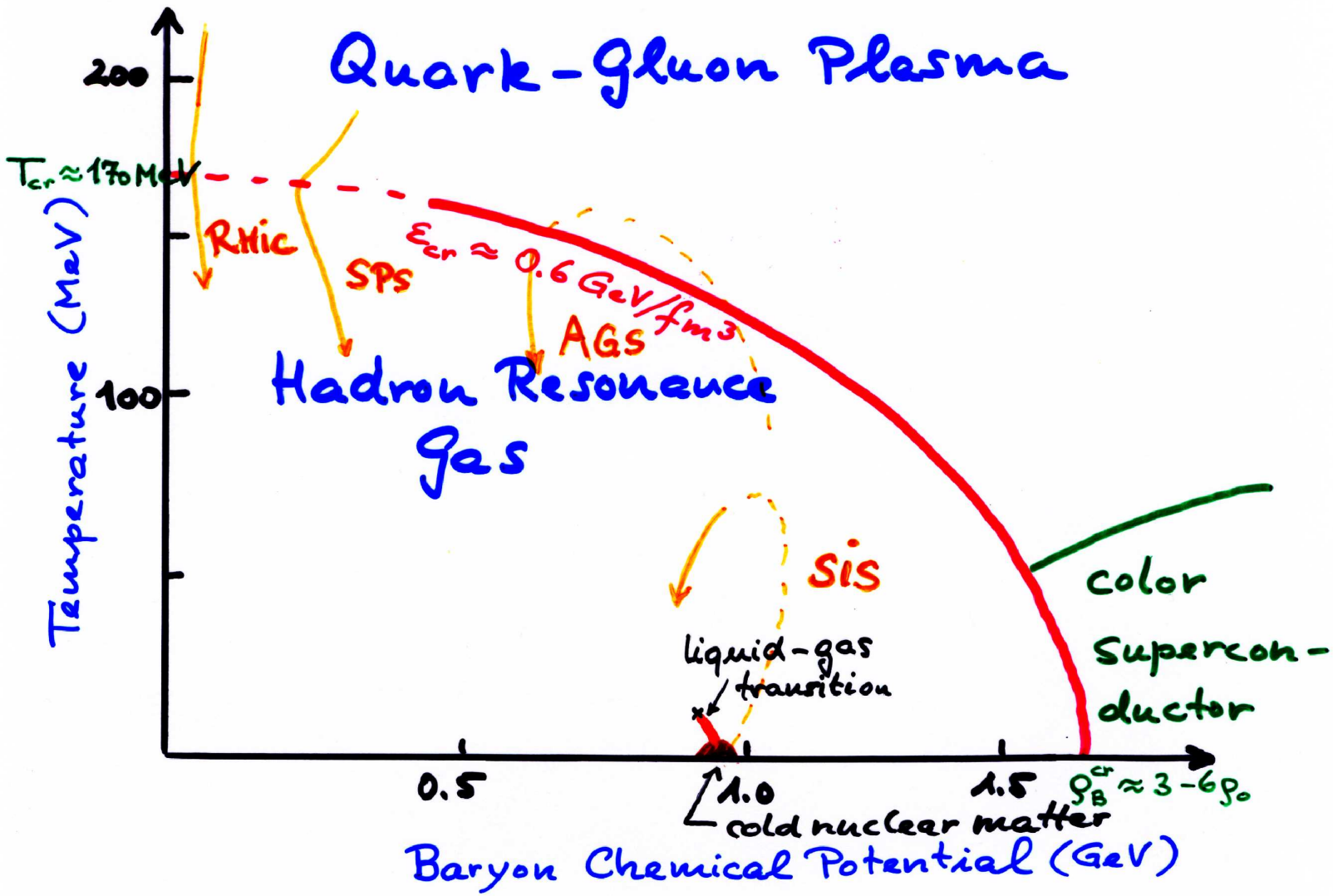
p+p @ $\sqrt{s} = 14$ TeV:

- **particle physics** at the **highest collision energies**
- extract rare "ultrahard" processes from huge soft background to explore fundamental interactions beyond the Standard Model

Pb+Pb @ $\sqrt{s} = 1100$ TeV ($= 5.5\,A$ TeV):

- **condensed matter/plasma physics** at the **highest energy densities**
- re-create the thermalized matter of the Early Universe in "Little Bangs"
- focus on collective dynamics of bulk of soft particles; diagnose properties of this matter with hard penetrating probes
- study the quark-hadron phase transition in thermal QCD

The QCD Phase Diagram and Heavy-Ion Collisions



Particle Physics ↔ Heavy-Ion Physics ⇔ Atomic Physics ↔ Condensed Matter Physics

Questions driving the Heavy-Ion Program:

- What is the equation of state of QCD matter?
- How did hadrons first form, and what is the origin of the mass of visible matter in the universe?
- What are the properties of matter at the highest energy densities?
  - degrees of freedom?
  - viscosity?
  - color and heat conductivity?
  - transport of conserved charges (susceptibilities)?
- Which microscopic QCD mechanisms control non-equilibrium dynamics and thermalization of dense QCD matter?
  - parton energy loss?
  - plasma instabilities?
  - color turbulence and dynamical chaos?
- How does the medium affect hadronization of hard partons, and how does it react to their energy loss?

Key parameters at RHIC and LHC:

Au+Au @ RHIC:

$$\left.\frac{dN}{dy}\right|_{y=0} \approx 1000$$

- initial peak energy density: $e_0 \simeq 30\,\text{GeV/fm}^3$ at $\tau_{\rm eq} \simeq 0.6\,\text{fm}/c$
- initial peak temperature: $T_0 \simeq 360\,\text{MeV} \gtrsim 2\,T_{\rm cr}$
- QGP lifetime: $\tau_{\rm QGP} \simeq 5-7\,\text{fm}/c$
- final radial expansion velocity: $\langle v_\perp \rangle \gtrsim 0.6\,c$
- final HBT volume: $V_{\rm hom} \equiv R_{\rm out} R_{\rm side} R_{\rm long} \simeq 125\,\text{fm}^3$

Pb+Pb @ LHC:

$$\left.\frac{dN}{dy}\right|_{y=0} \approx 3000-4000$$

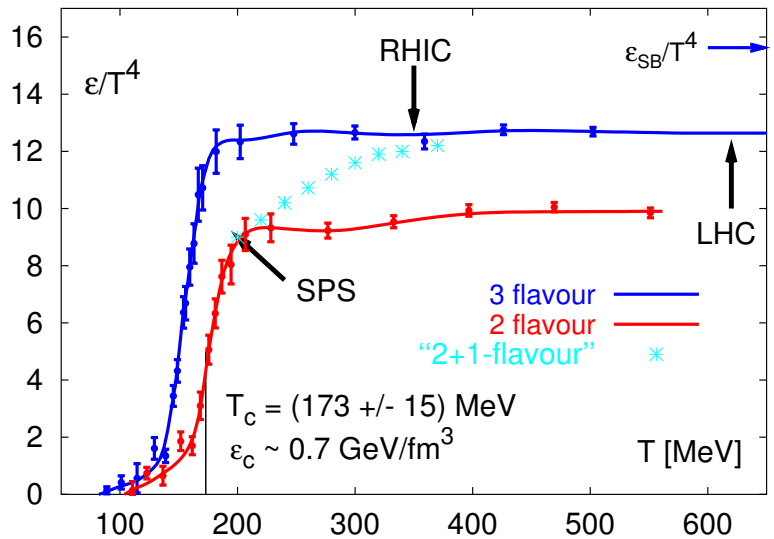
- **denser:** $e_0 \simeq 550-800\,\text{GeV/fm}^3$ at $\tau_{\rm eq} \simeq 0.2\,\text{fm}/c$
- **hotter:** $T_0 \simeq 750-830\,\text{MeV} \simeq (4.5-5)\,T_{\rm cr}$
- **longer-lived:** $\tau_{\rm QGP} \simeq 22-30\,\text{fm}/c$
- **faster expanding:** $\langle v_\perp \rangle \gtrsim 0.7\,c$
- **bigger fireball:** $V_{\rm hom} \simeq 400-500\,\text{fm}^3$

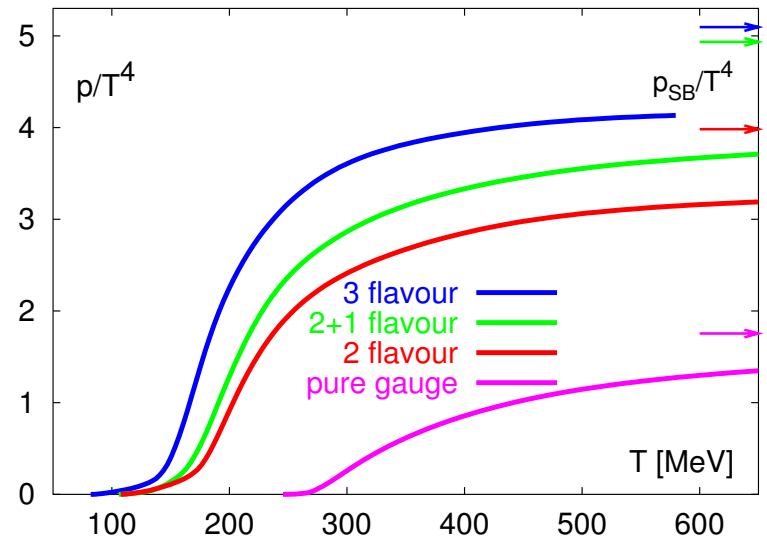
+ much higher rates for penetrating probes!

$\Rightarrow$ ideal laboratory for studying bulk QCD matter

The QCD equation of state at zero baryon density

F. Karsch and E. Laermann, hep-lat/0305025, in "Quark-Gluon Plasma 3"





- Critical temperature $T_{\rm cr} = 173 \pm 15\,\text{MeV}$ $(\approx 100\,000 \times T_{\text{center of sun}})$
- Critical energy density $\varepsilon_{\rm cr} \simeq 0.7\,\text{GeV/fm}^3$
- $\varepsilon \approx 0.8\,\varepsilon_{\rm SB}$ for $T \gtrsim 1.3\,T_{\rm cr}$, $\varepsilon \approx 3\,p$ for $T \gtrsim 2\,T_{\rm cr}$

$\Longrightarrow$ Weakly coupled QGP? NO!

Collective flow tests the Equation of State:

Hydrodynamic equations, ideal fluid limit:

($\dot{f}$ = time derivative in local rest frame, $\partial\cdot u$ = local expansion rate)

$$\dot{n}_B = -n_B\,(\partial\cdot u)$$

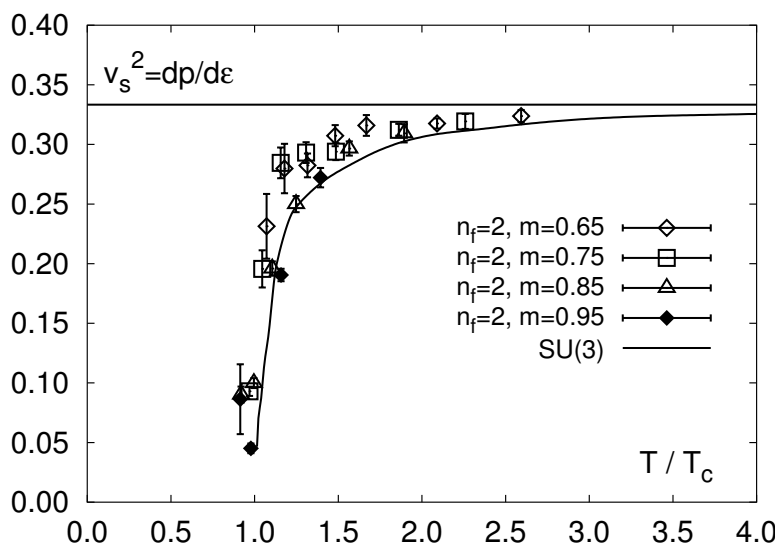
$$\dot{\varepsilon} = -(\varepsilon + p)\,(\partial\cdot u)$$

$$\dot{u}^\mu = \frac{\nabla^\mu p}{\varepsilon + p} = \frac{c_s^2}{1+c_s^2}\frac{\nabla^\mu \varepsilon}{\varepsilon}$$

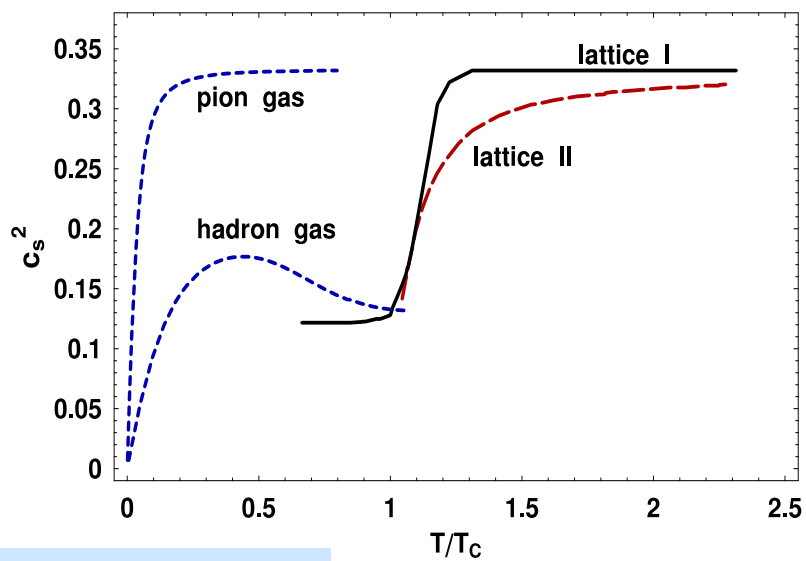
- flow driven by pressure gradients $\nabla^\mu p$
- acceleration $\frac{\nabla^\mu p}{\varepsilon+p}$ closely related to

speed of sound $c_s^2 = \frac{\partial p}{\partial \varepsilon}$

Karsch+Laermann, hep-lat/0305025



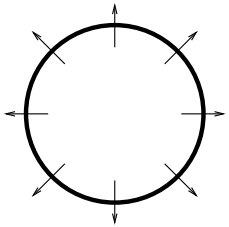
Chojnacki et al., nucl-th/0410036



"Softest point" near $T = T_{\rm cr}$

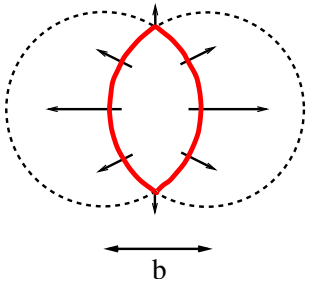
"Flavors" of transverse flow:

Radial flow:



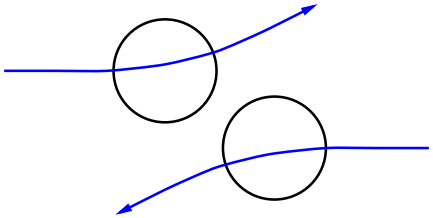
- $\longrightarrow$ the only type of transverse flow in $b = 0$ collisions between equal spherical nuclei
- $\longrightarrow$ integrates pressure history over entire expansion stage
- $\longrightarrow$ observable via effect of $\langle v_\perp \rangle$ on slope of $m_\perp$ spectra

Elliptic flow ($b \neq 0$ or collisions between deformed nuclei, e.g. U+U):



- $\longrightarrow$ peaks at midrapidity
- $\longrightarrow$ requires spatial deformation of reaction zone at thermalization
- $\longrightarrow$ magnitude of signal probes degree and time of thermalization
- $\longrightarrow$ shuts itself off as dynamics reduces deformation (H. Sorge)
- $\longrightarrow$ sensitive to Equation of State during first $\sim 5\,\mathrm{fm}/c$

Directed flow ($b \neq 0$, $y \neq 0$):



- $\longrightarrow$ generated very early while nuclei penetrate each other
- $\longrightarrow$ dominated by early non-equilibrium processes
- $\longrightarrow$ becomes weaker with increasing collision energy

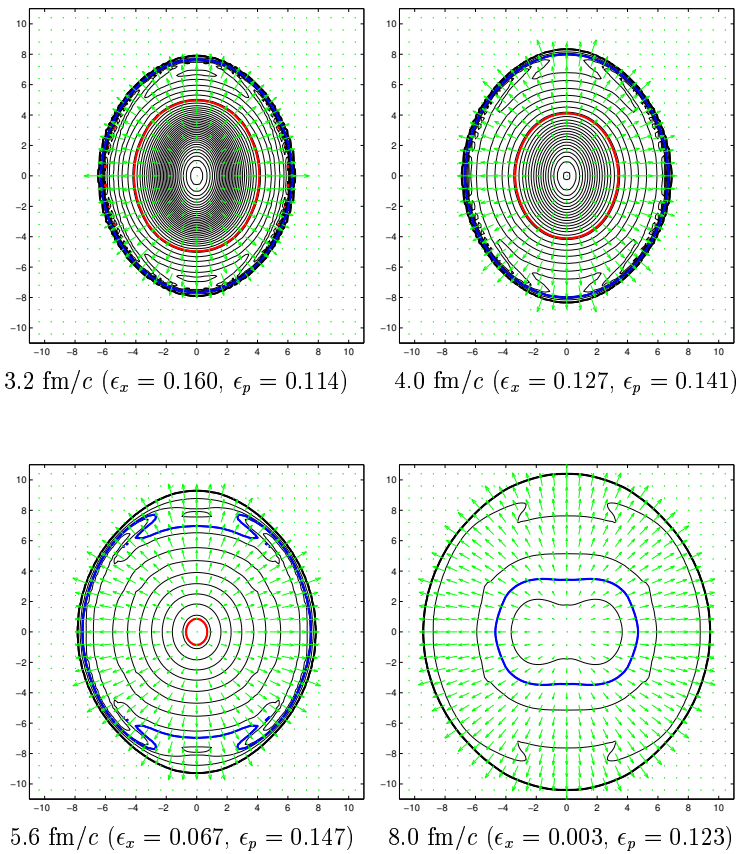
Flow = unavoidable consequence of thermalization!

QGP $\Longrightarrow$ an (approximately) thermalized system of quarks and gluons

$\Longrightarrow$ thermal pressure gradients $\Longrightarrow$ **collective flow**

Radial and elliptic flow from hydrodynamics:

Au+Au at $b = 7$ fm



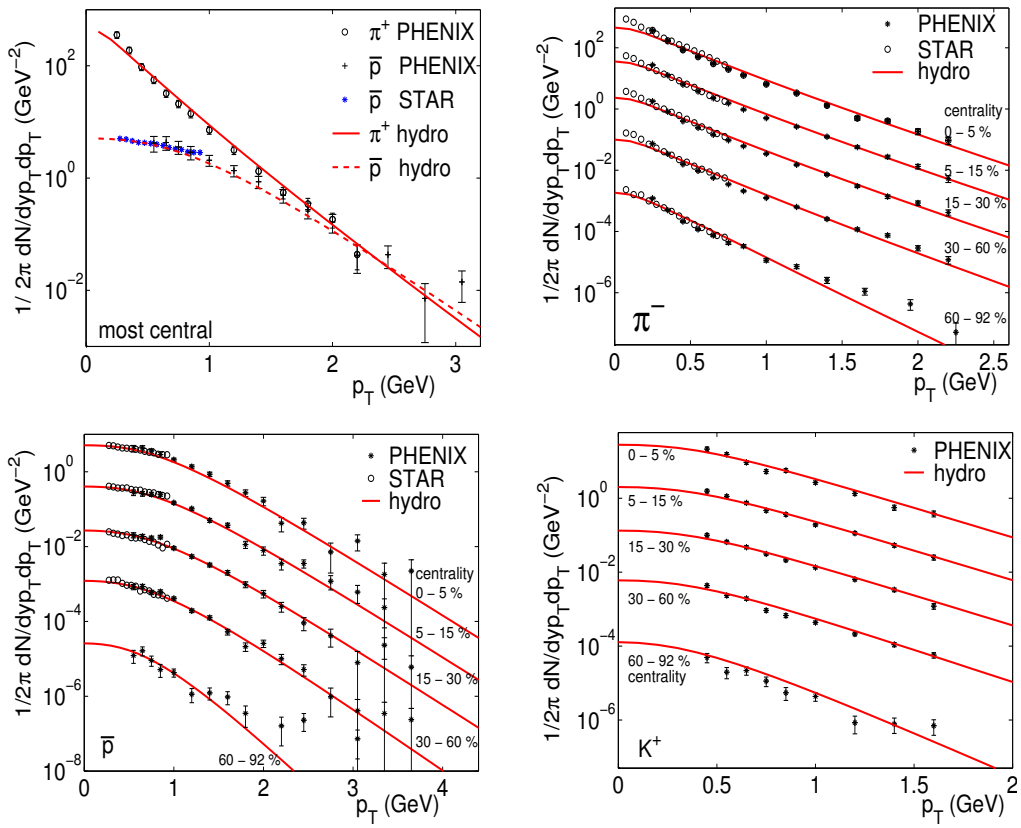
3.2 fm/c ($\epsilon_x = 0.160$, $\epsilon_p = 0.114$) 4.0 fm/c ($\epsilon_x = 0.127$, $\epsilon_p = 0.141$)

5.6 fm/c ($\epsilon_x = 0.067$, $\epsilon_p = 0.147$) 8.0 fm/c ($\epsilon_x = 0.003$, $\epsilon_p = 0.123$)

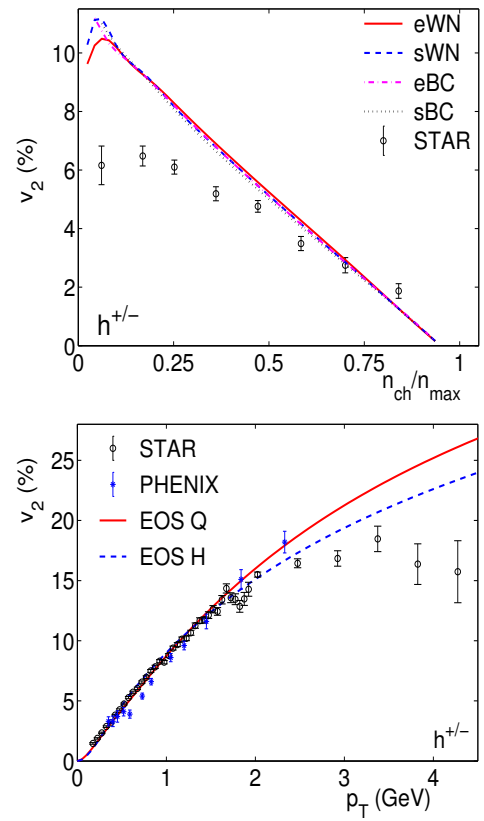
- when do elliptic and radial flow develop?
- how is elliptic flow related to the time-dependent spatial deformation $\epsilon_x = \dfrac{\langle\langle y^2 - x^2 \rangle\rangle}{\langle\langle y^2 + x^2 \rangle\rangle}$?
- how do radial and elliptic flow depend on the EOS?
- what is the source deformation at freeze-out?
- is there enough time before freeze-out to change sign of ϵ_x?

Successes of hydrodynamics at RHIC:

Single particle spectra from central and peripheral Au+Au @ 130 A GeV (STAR, PHENIX):



Centrality and momentum dependence of elliptic flow v_2 (STAR, PHENIX, PHOBOS):



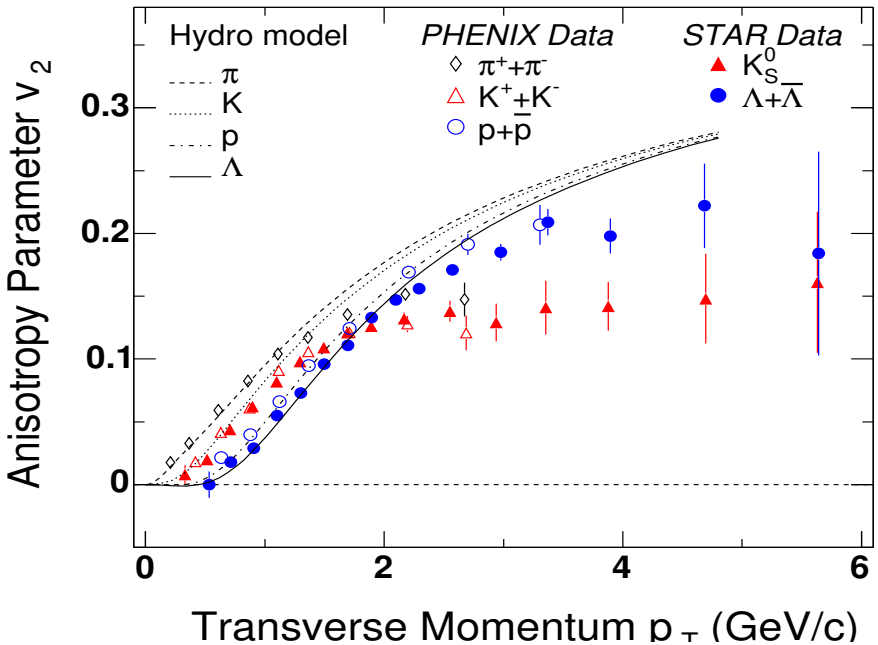
Model parameters fixed with π, $\bar{p}$ spectra at $b = 0$; all other spectra predicted (UH & P.Kolb, hep-ph/0204061).

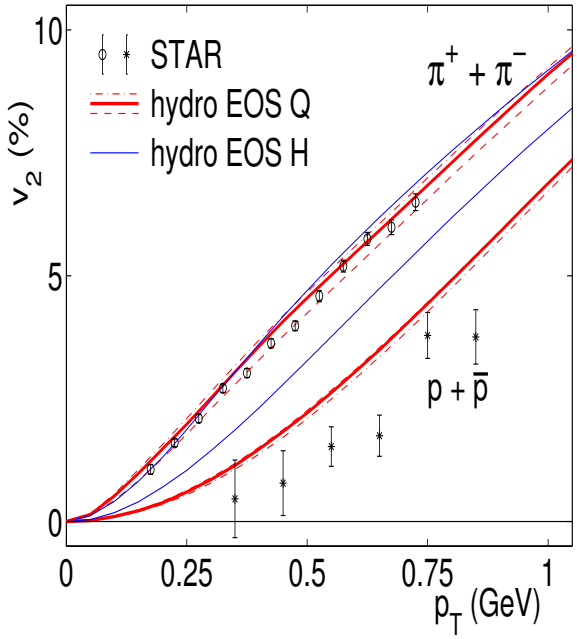
$$v_2 = \langle \cos(2\phi) \rangle$$

Final radial flow $\langle v_\perp \rangle > 0.5\, c \Longrightarrow$ bang!

Rest mass dependence of differential elliptic flow (the "fine structure")

STAR Coll., PRL 87, 182301 (2001) and PRL 92, 052302 (2004); PHENIX Coll., PRL 91, 182301 (2003)





Data follow the hydrodynamically predicted rest mass dependence of $v_2(p_\perp)$ out to $p_\perp \sim 1.5$ GeV for mesons and out to $p_\perp \sim 2.3$ GeV for baryons

$\Longrightarrow$ bulk of matter ($> 99\%$ of all particles) behaves hydrodynamically!

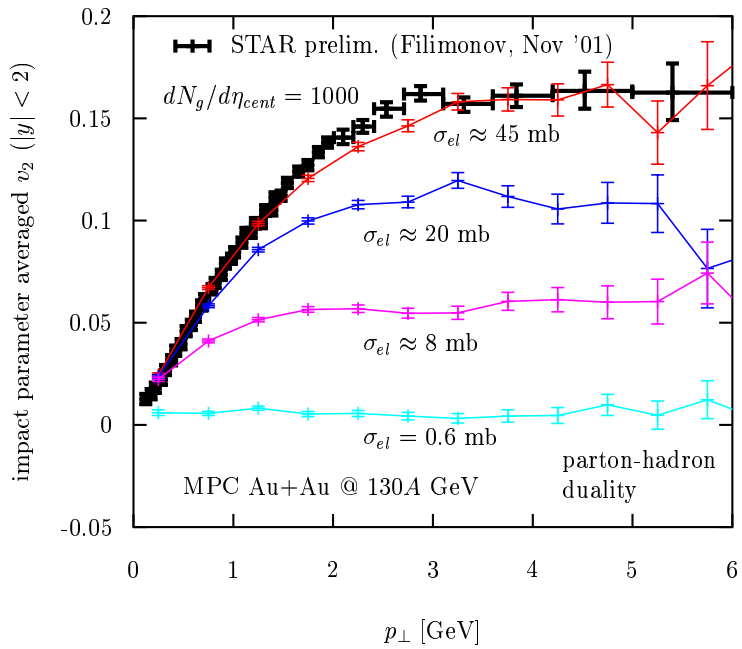
Note: mass-splitting of v_2 ("fine structure") sensitive to EOS!

so hydro works –

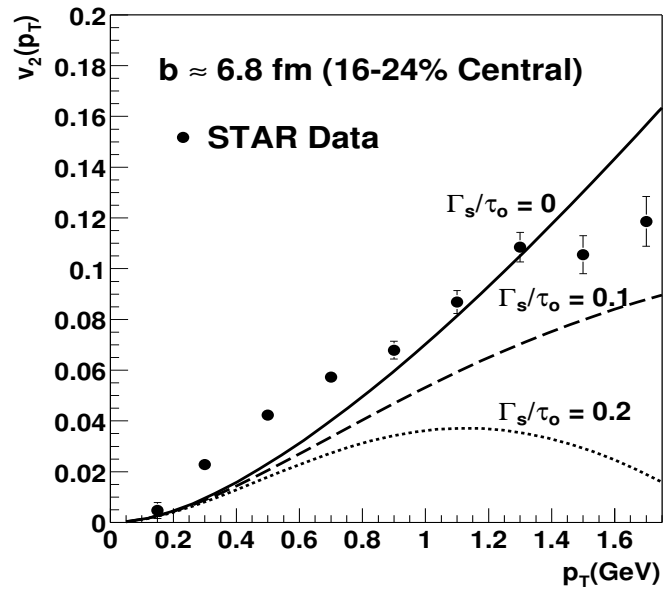
why? what does this mean?

Breakdown of hydrodynamics at high $p_\perp$: upper limits for the QGP viscosity

D. Molnár and M. Gyulassy, NPA 697 (2002) 495



D. Teaney, PRC 68 (2003) 034913



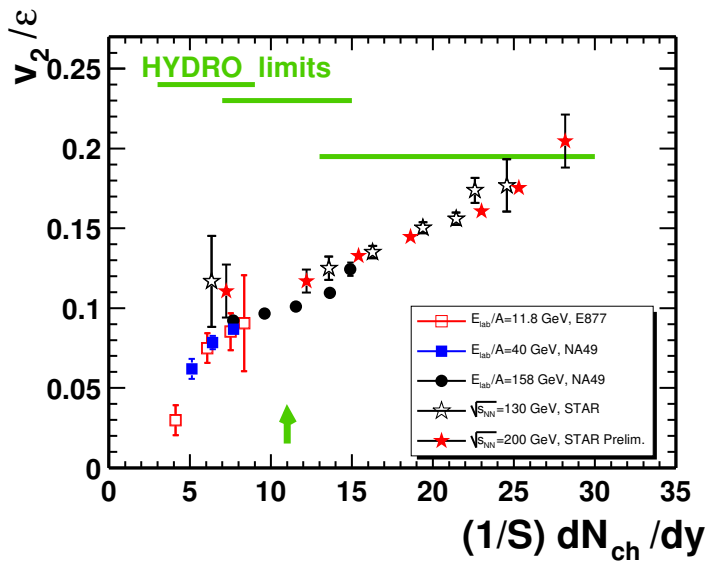
$$\Gamma_s = \frac{4}{3}\eta/(T\cdot s)$$

- For sufficiently (very) large $\sigma_{\rm el}$, $v_2(p_\perp)$ from covariant parton transport model MPC follows hydrodynamic curve at low $p_\perp$ and reproduces observed saturation at high $p_\perp$
- Similar pattern is seen in viscous hydrodynamics: viscous corrections increase $\sim p_\perp^2$
- v_2 data suggest $\frac{\Gamma_s}{\tau} < 0.1$, close to minimum viscosity $\frac{\eta}{s} = \frac{\hbar}{4\pi}$ (Son et al. 2002)

QGP seems to be the most perfect (real) fluid ever observed!

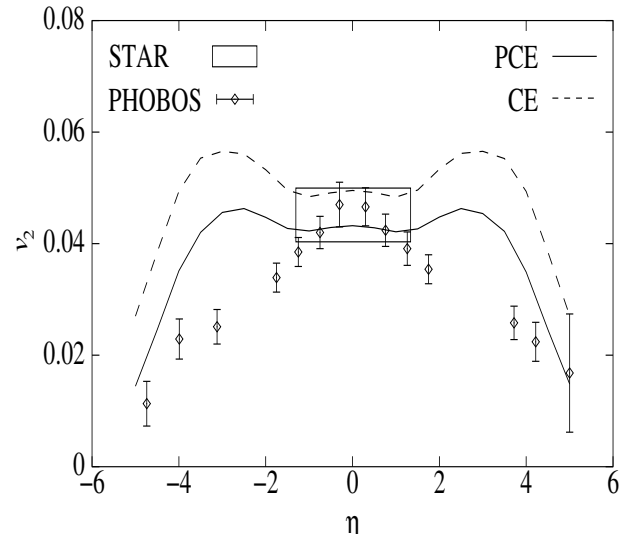
Limits of ideal hydro: smaller, less dense systems

STAR, PRC 66 ('02) 034904; NA49, PRC 68 ('03) 034903



3d hydro:

T. Hirano, PRC 65 ('02) 011901; 66 ('02) 054905



- $\frac{v_2^{\text{measured}}}{v_2^{\text{hydro}}}$ scales with $\frac{1}{S}\frac{dN_{\text{ch}}}{dy} \propto s_{\text{init}}$
- $e_{\text{init}} > 10\,\text{GeV/fm}^3$ needed for v_2 to saturate before hadronization and exhaust ideal hydro limit!
- hydrodynamics predicts non-monotonic v_2/ϵ: between AGS and RHIC it decreases, due to softening of EOS by quark-hadron transition (Kolb, Sollfrank, UH, PRC 62 (2000) 054909)
- data show instead monotonous increase of v_2/ϵ with $\sqrt{s}$!?

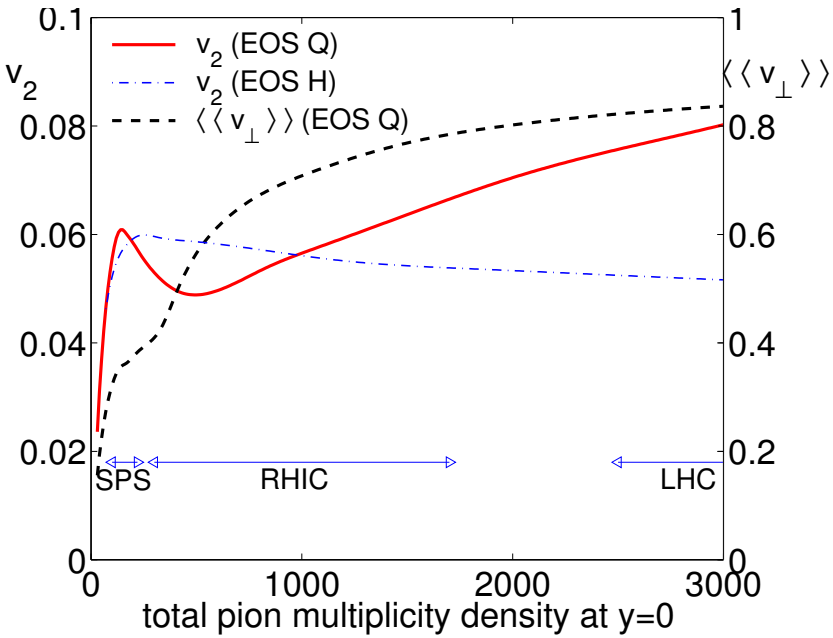
What's going on??

Breakdown of ideal hydro: the viscous hadron fluid

Excitation function of elliptic flow:

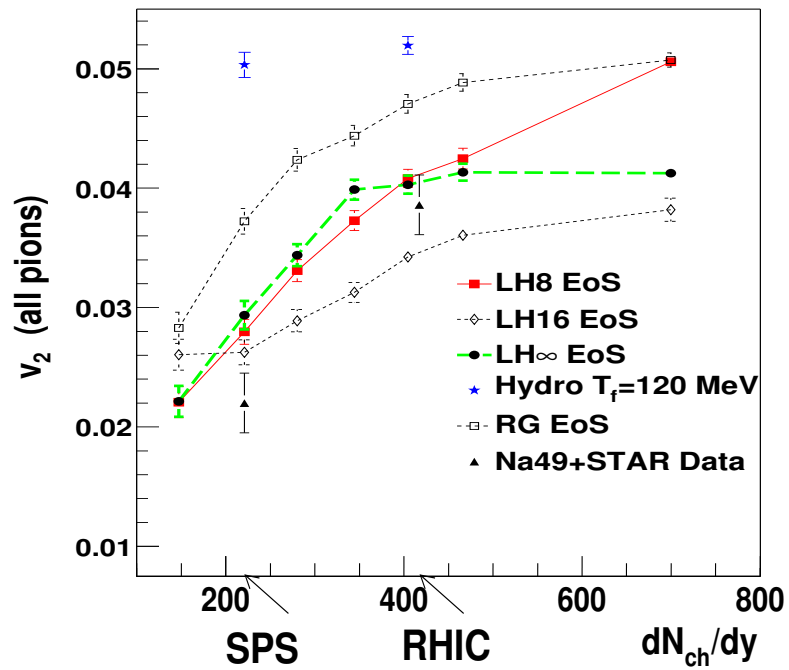
Ideal hydro

P. Kolb, J. Sollfrank, U.H., PRC 62 ('00) 054909



Hydro + RQMD

D. Teaney, J. Lauret, E. Shuryak, nucl-th/0110037



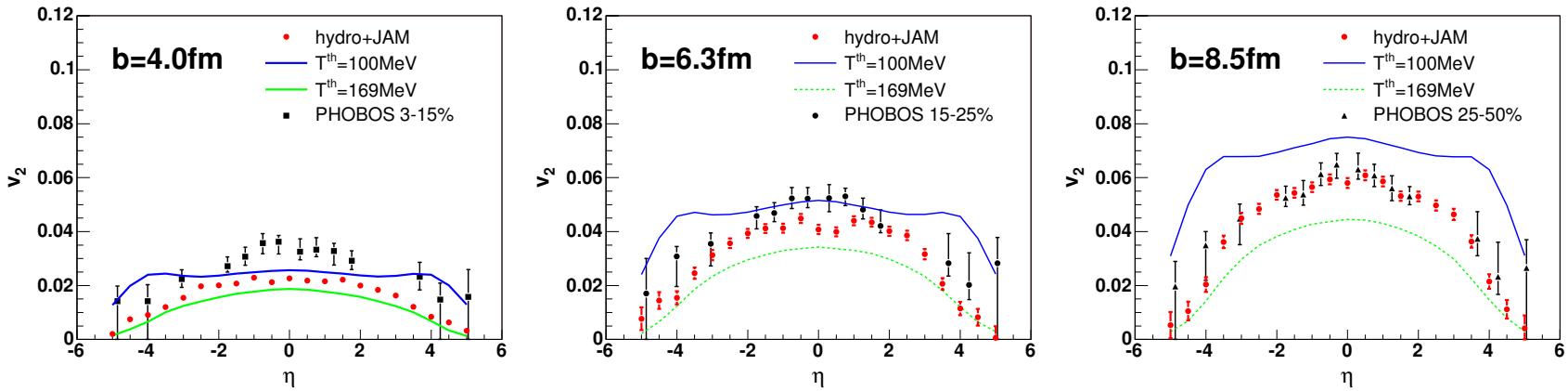
Hadron resonance gas is very viscous and does not respond strongly to spatial eccentricity $\Longrightarrow$ non-monotonic behaviour of v_2 resulting from dip in c_s^2 near phase-transition is erased!

$\Longrightarrow$ The inability of the viscous hadronic phase to build elliptic flow kills the phase transition signature!

Late hadronic dissipation explains all (?) observed deviations from perfect fluidity

(T. Hirano, UH, D. Kharzeev, R. Lacey, Y. Nara, PLB 636 (2006) 299)

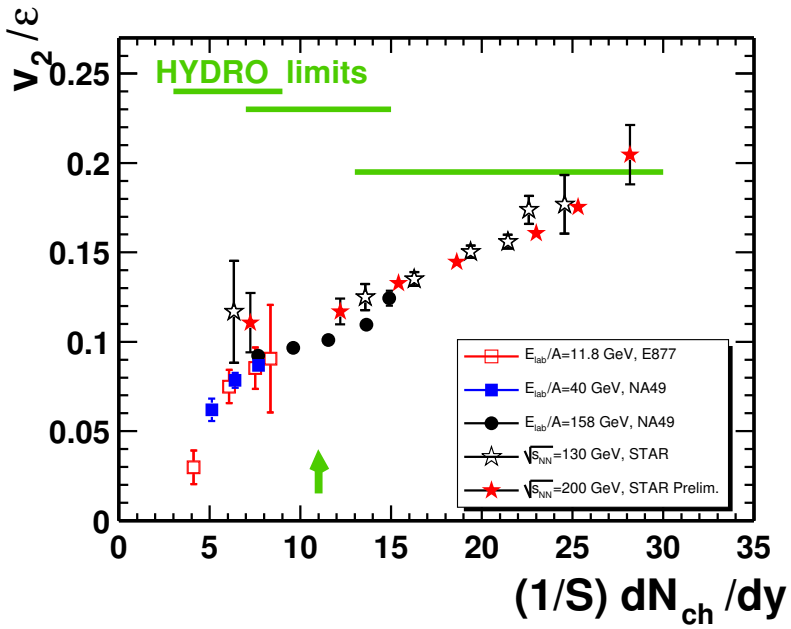
3D Hydro+Cascade Model: Ideal fluid dynamics for QGP above T_c, hadronic cascade(JAM) below T_c (similar to Bass & Dumitru (1D), Teaney & Shuryak (2D))

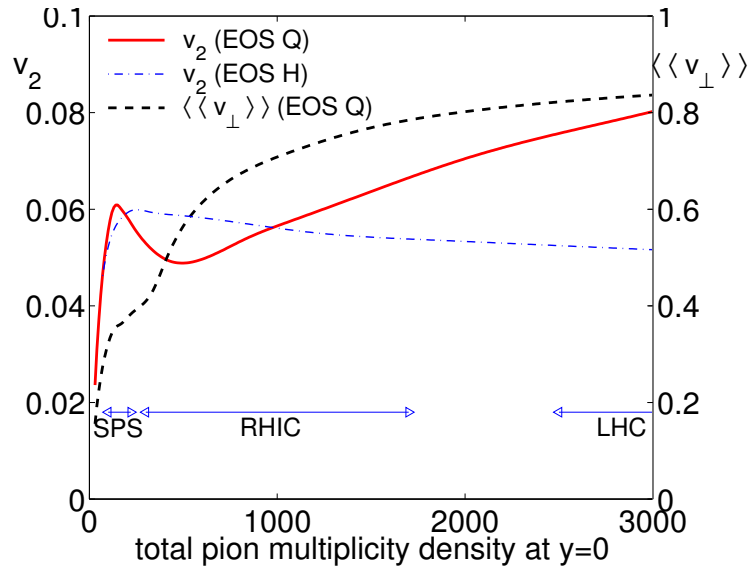


- Not enough elliptic flow from perfect QGP fluid – hadronic contribution to v_2 is required
- Treating hadronic stage as ideal fluid overpredicts v_2 in peripheral collisions and at forward rapidities
- Dissipation in hadronic cascade brings theory in line with data (except for small b – excess in data due to event-by-event geometry fluctuations? (Miller & Snellings))

Will the sQGP become a pQGP at the LHC?

The first day of Pb beam at LHC will tell!





What causes the fast thermalization at RHIC?

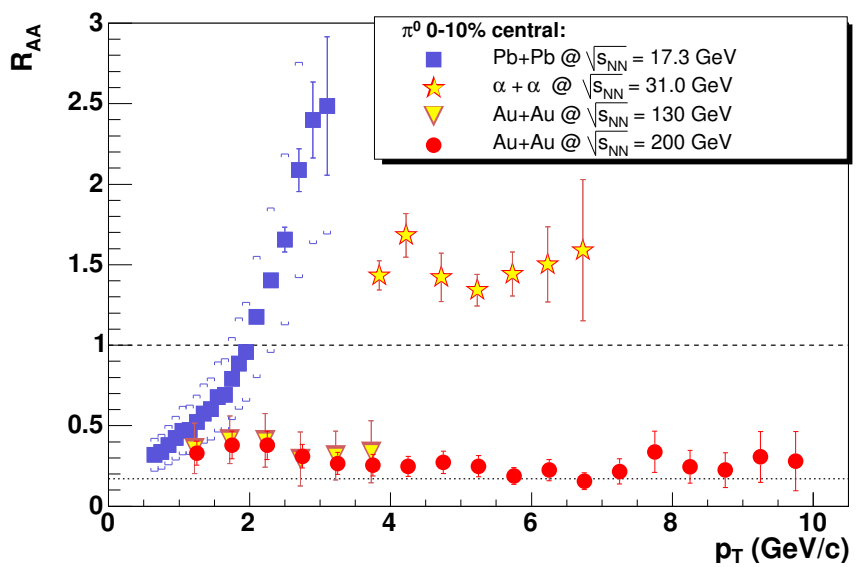
Study behaviour of non-thermal partons!

Suppression of high p_T hadron production in Au+Au:

$$R_{AA}(p_T;b) = \frac{\frac{dN_{AA}}{dp_T}(b)}{N_{\rm coll}(b)\frac{dN_{pp}}{dp_T}}$$

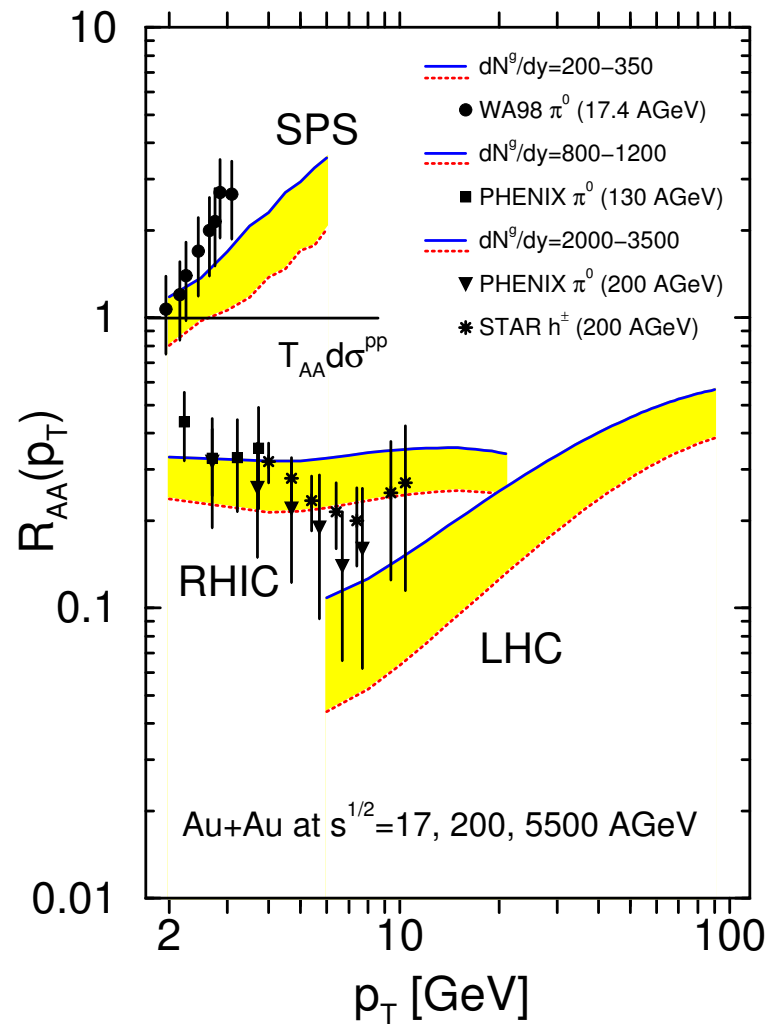
Au+Au at $\sqrt{s} = 130$ and $200\ A$ GeV

PHENIX Coll., PRL 88 (2002) 022301; PLB 561 (2003) 82



M. Gyulassy and I. Vitev,

PRL 89 (2002) 252301



$\Longrightarrow \quad \frac{dN_g}{dy} = 1000 \pm 200$

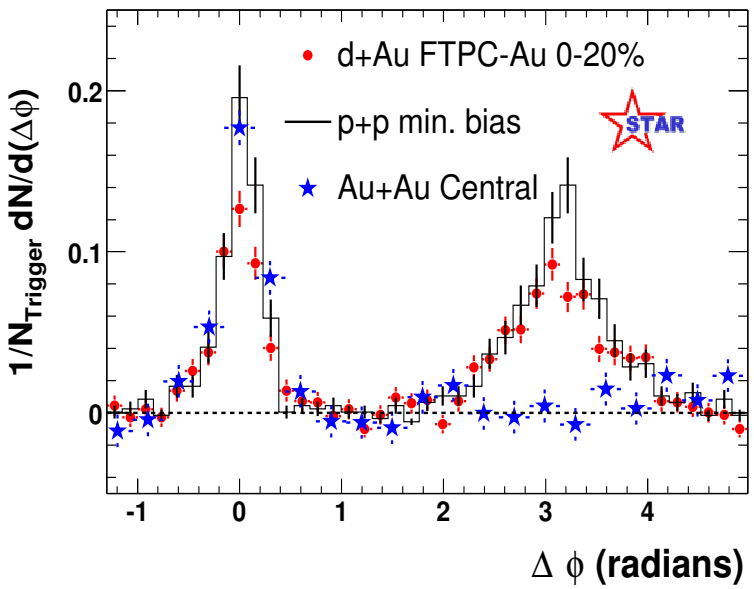
$\Longrightarrow \quad \langle e \rangle (\tau_0 = 0.2\,\mathrm{fm}) \approx 20\,\mathrm{GeV/fm^3}$!

High-p_T suppression absent in d+Au $\Longrightarrow$ suppression in Au+Au not due to nuclear wavefunction (e.g. CGC) but a final state effect

Jet quenching in central Au+Au collisions:

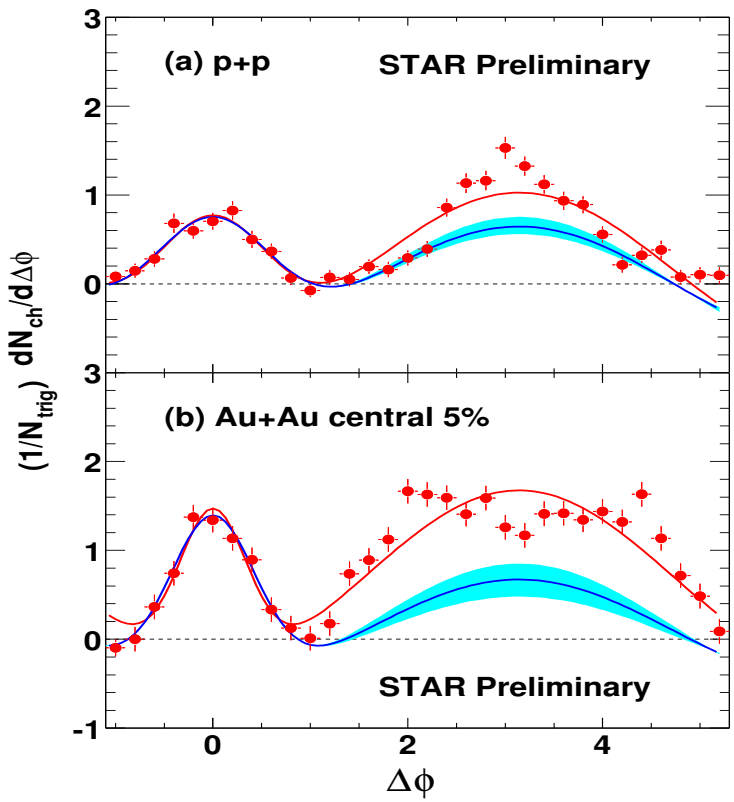
STAR Coll., PRL 91 (2003) 072304

$p_T^{\rm assoc} > 2\,$GeV



STAR Coll., F. Wang, Quark Matter 2004

$0.15 < p_T^{\rm assoc} < 4\,$GeV



- trigger particle for near-side jet has $4 < p_T < 6\,$GeV
- away-side jet ($p_T > 2\,$GeV) visible in p+p and d+Au, but fully quenched in central Au+Au
- energy of quenched jet appears as additional multiplicity of low-p_T particles opposite to trigger particle
- $\Longrightarrow$ "thermalization" of intermediate-p_T jets!

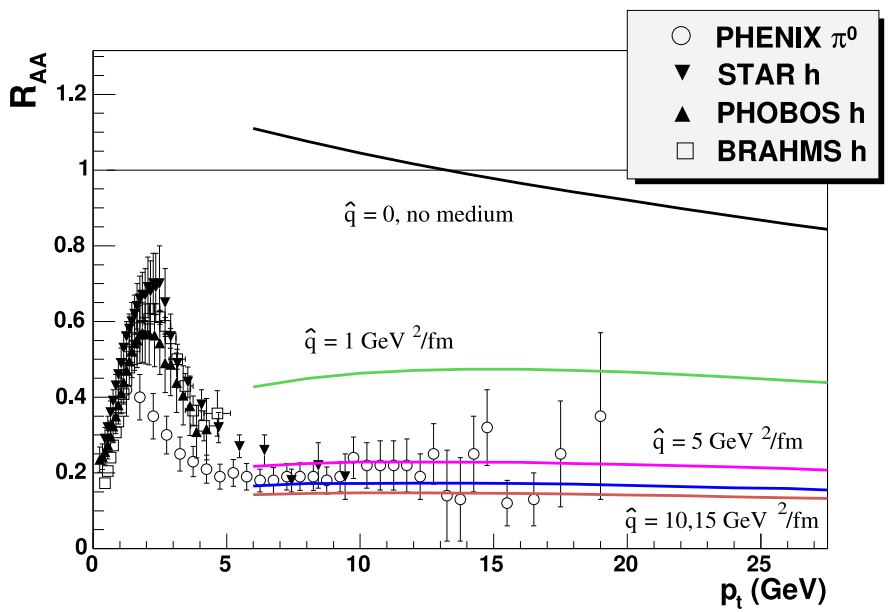
The "opacity problem"

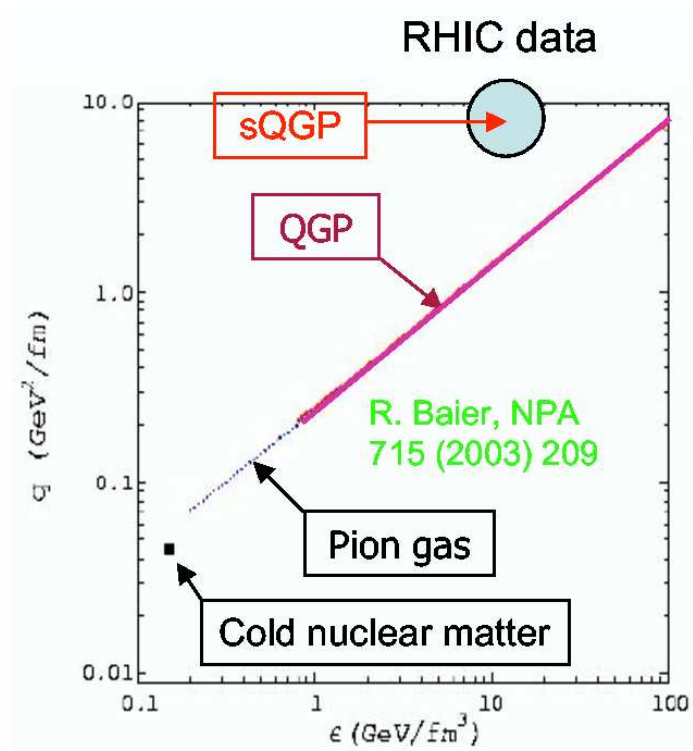
Bjorken 1982: collisional energy loss $\Longrightarrow$ "monojet production"

Gyulassy, Wang, et al. (80's): radiative energy loss dominates

Baier, Dokshitzer, Mueller, Peigne, Schiff (1996), Zakharov (1997), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), . . . : Non-abelian radiative energy loss controlled by "transport coefficient" $\hat{q} = \frac{\mu_D^2}{\lambda}$; perturbatively $\hat{q}(\tau) \approx 2e^{3/4}(\tau)$.

Eskola et al., NPA 747 (2005) 511





Jet quenching observed at RHIC requires about 5 times larger $\hat{q}$!

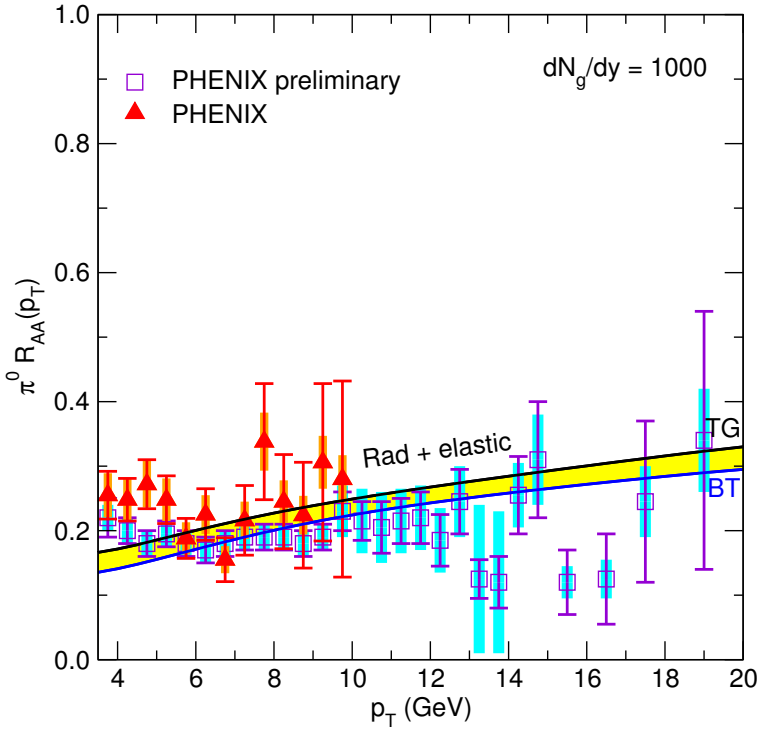
The return of elastic collisional energy loss:

Mustafa (2005), Mustafa & Thoma (2005):
At RHIC, elastic energy loss can compete with radiative loss.

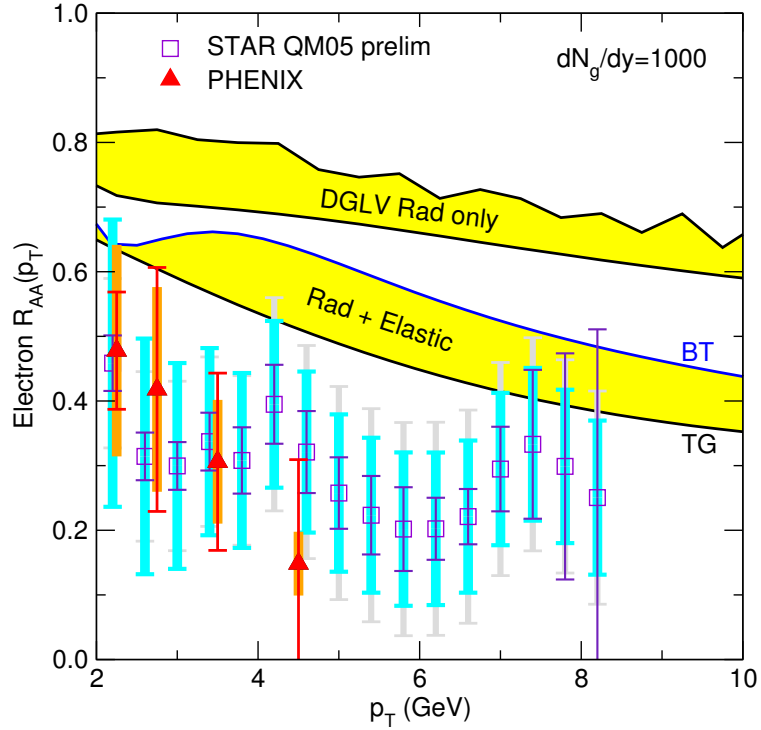
But both together still not sufficient to explain RHIC data:

Wicks, Horowitz, Gyulassy, Djordjevic, nucl-th/0512076

π^0



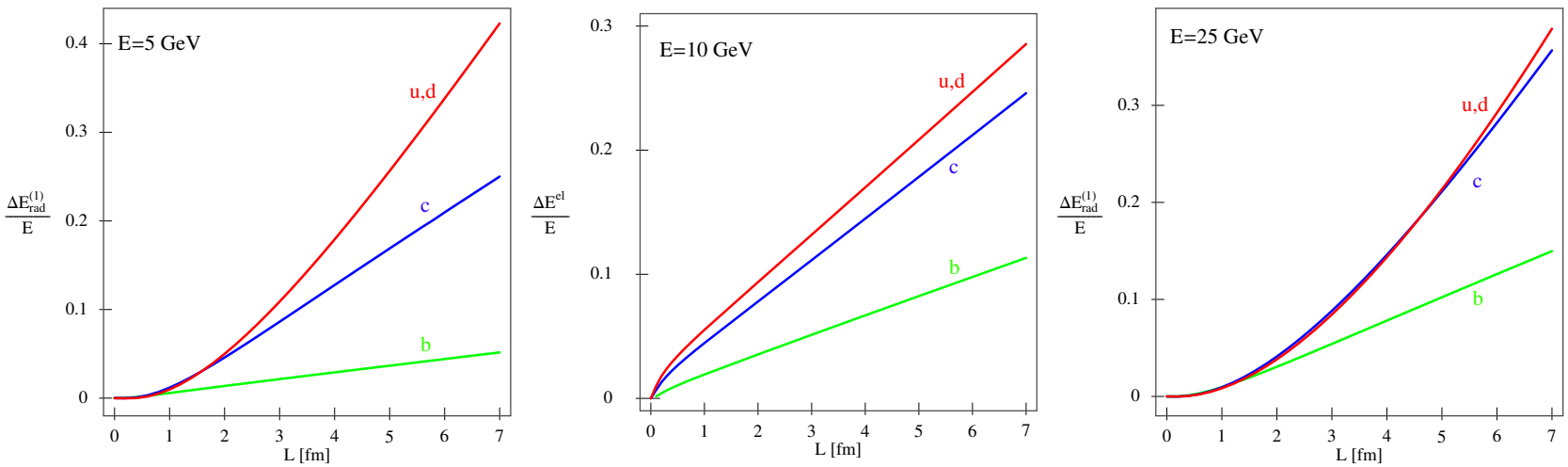
e from c and b decay



How to tell elastic from radiative energy loss

M. Djordjevic, nucl-th/0603066

radiative (low E_T) elastic radiative (high E_T)



- Elastic collisional energy loss always depends linearly on path length L
- Radiative energy loss shows non-abelian quadratic L dependence for small mass and/or high E_T of leading parton
- Study azimuthal angle dependence of energy loss in non-central Au+Au/Pb+Pb or central U+U collisions (Kuhlman and UH, PRL 94 (2005) 132301)

Anomalous viscosity and energy loss from color chaos

Asakawa, Bass, Müller, hep-ph/0603092

- Viscosity in an expanding fluid $\Longrightarrow$ local momentum anisotropies $\sim \eta$
  (Heiselberg, Wang 1996; Teaney 2003)
- Anisotropic momentum distributions $\Longrightarrow$ plasma instabilities (Weibel 1959, Mrówczyński 1988-2003, Arnold, Lenaghan & Moore 2002-2006, Rebhan, Romatschke & Strickland 2003-2005)
- Plasma instabilities $\Longrightarrow$ turbulent (color) magnetic fields
  $\Longrightarrow$ anomalous viscosity and energy loss of (color) charged particles, $\eta_B \sim 1/\langle B^2 \rangle \sim 1/\eta$
  (Malone et al. 1975, Niu et al. 1978-1980)

$\Longrightarrow$ large viscosity leads to small anomalous viscosity $\Longrightarrow$ self-regulating!

Collisional and turbulent mean-field scattering rates add
$\Longrightarrow$ total viscosity $\eta^{-1} = \eta_{\rm coll}^{-1} + \eta_B^{-1}$

For $g \ll 1$ Asakawa et al. find $\eta_B \sim \dfrac{s}{g^{3/2}}$ while $\eta_{\rm coll} \sim \dfrac{s}{g^4 \ln g}$.

So at early times (high T, small g) anomalous viscosity η_B may dominate and render η anomalously small!

Ongoing activities and challenges

- Viscous hydrodynamics $\Longrightarrow$ extract η from data

  (Muronga, Teaney, Chaudhuri, UH, Pratt)

- elliptic flow of thermal photons and dileptons

  $\Longrightarrow$ window on earlier times at higher p_T

  $\Longrightarrow$ "watch" how collectivity develops

  (Chatterjee, Frodermann, UH, Srivastava 2006)

- Jet cones deformed and bent by expanding medium ("parton wind")

  (Wiedemann et al. 2005)

- Intermediate-p_T hadrons from recombination of flowing quarks

  $\Longrightarrow$ soft collectivity affects hard particle production

  (Fries et al., Molnar et al., Ko et al., Hwa et al. 2003-2005)

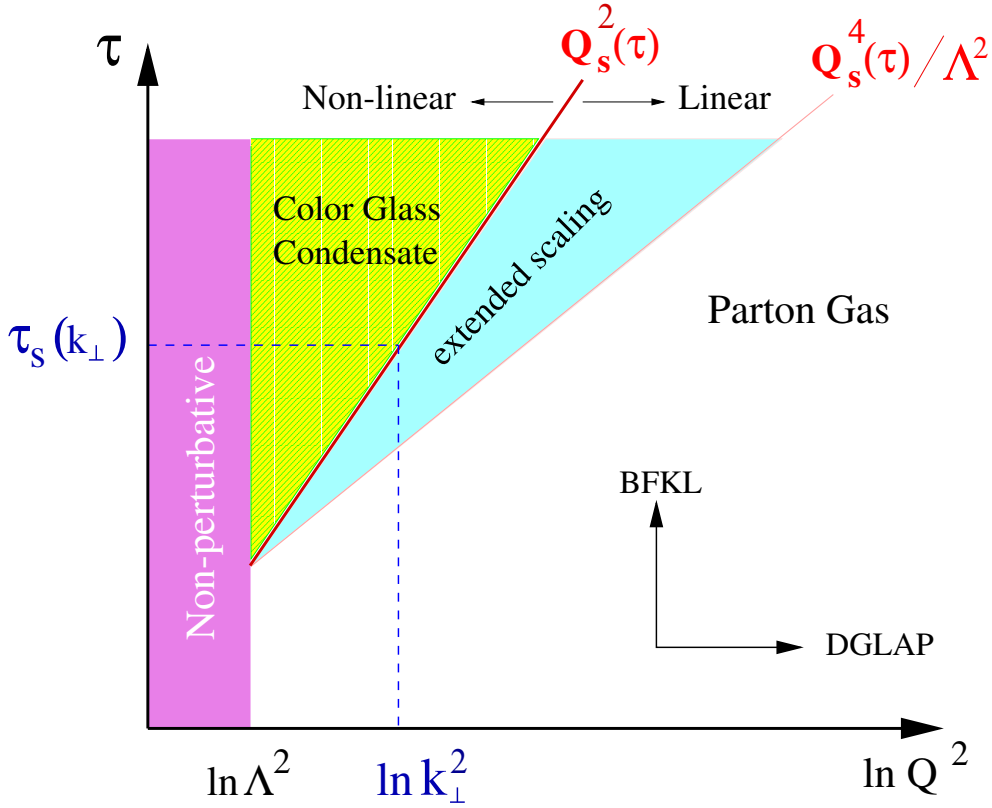
- Mach cones on soft medium induced by fast colored partons

  $\Longrightarrow$ hard particles affect soft collective dynamics

  (Shuryak et al., Chaudhuri & UH, 2005)

Hard $\leftrightarrow$ soft interplay yields key insights into QCD matter properties and transport coefficients

Gluon saturation physics: QCD at the highest parton densities



$\tau = \ln(1/x)$

At low x gluons with transverse momenta $k_\perp < Q_s(x)$ become dense and condense into a "Color Glass Condensate" ($A_\mu \sim 1/g$).

For $Q_s(x) \gg \Lambda_{QCD}$ this condensate is weakly coupled ($\alpha_s(Q_s) < 1$) but non-linear in the gluon density.

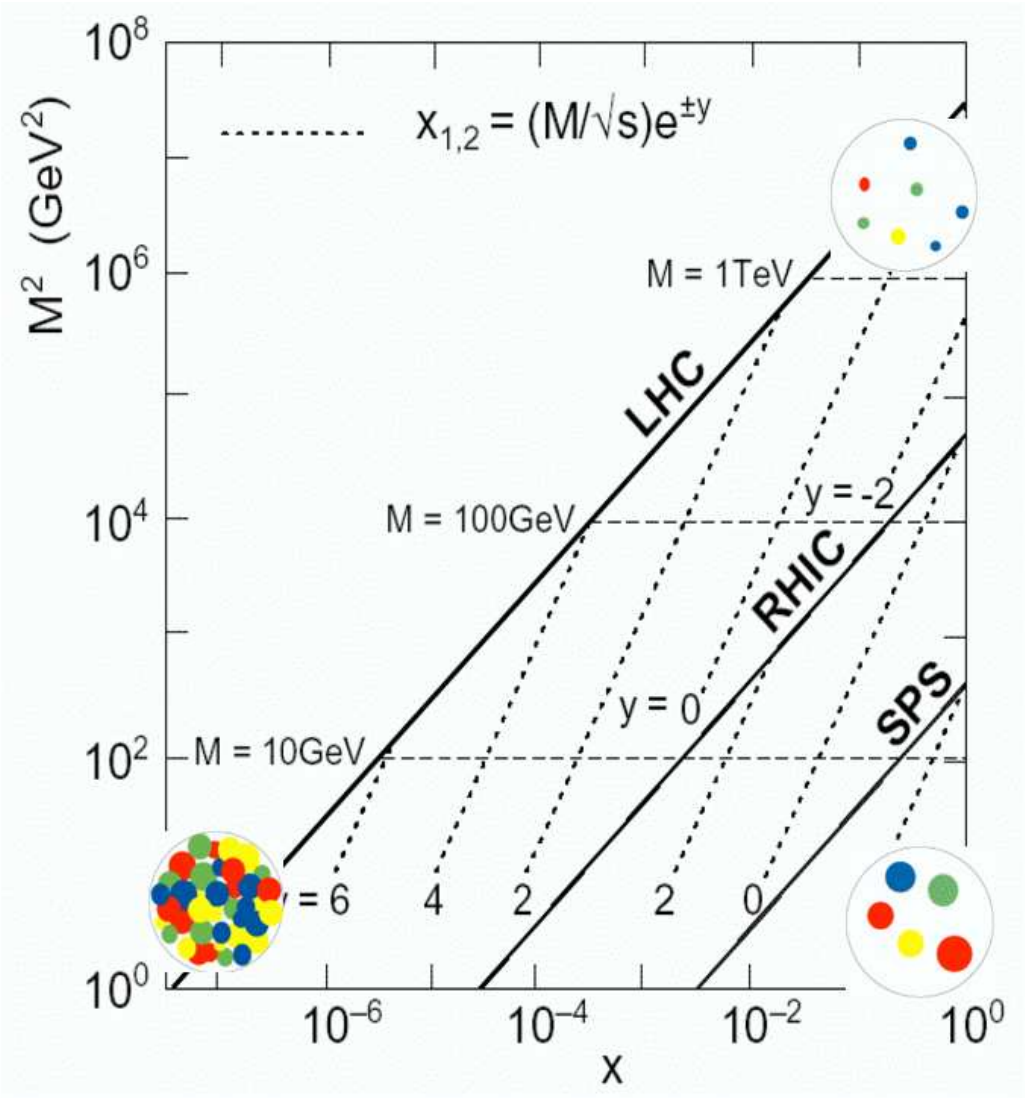
$\Longrightarrow$ **Classical color fields, classical chromodynamics with quantum corrections**

$\Longrightarrow$ Kovchegov-Balitsky/JIMWLK equation allows to predict multiplicities, cross sections, etc. at high energies from low-energy data.

At high energy, $Q_s(x, A) \sim (x_0/x)^\lambda A^{1/3}$ is the only scale in play

$\Longrightarrow$ **"geometric scaling"**

The accessible kinematic range at RHIC and LHC



Small x

- $y = 0$ @ LHC $\Leftrightarrow$ $y = \pm 3$ @ RHIC
- midrapidity parton production at LHC dominated by CGC physics?
- tests of saturation phenomena
  - bulk observables, dN/dy
  - $p_\perp$-spectra in scaling regime (unless buried by collective flow?!)
  - rapidity dependence
  - . . .

Large Q^2

- abundant yields of hard probes
- precise tests of matter properties
  - color field strength
  - collective flow
  - parton energy loss
  - QGP viscosity
  - . . .

Instead of conclusions . . .

Why the LHC should start with a short Pb run

Just a few days of Pb beam before the start of p+p program will yield

- $\left.\frac{dN_{\rm ch}}{dy}\right|_{y=0} \Longrightarrow$ death of many models, test of CGC
- verify $T_{\rm chem} = T_{\rm cr} = 170\,$MeV, independent of centrality (LQCD)
- $v_2^{\rm ch,\pi,p}(p_\perp) \Longrightarrow$ perfect fluidity of QGP @ LHC?
- $p_\perp$ spectra of a number of identified hadron species $\Longrightarrow$ test of collective flow + quark recombination vs. CGC geometric scaling
- fireball source sizes from HBT radii
- . . .

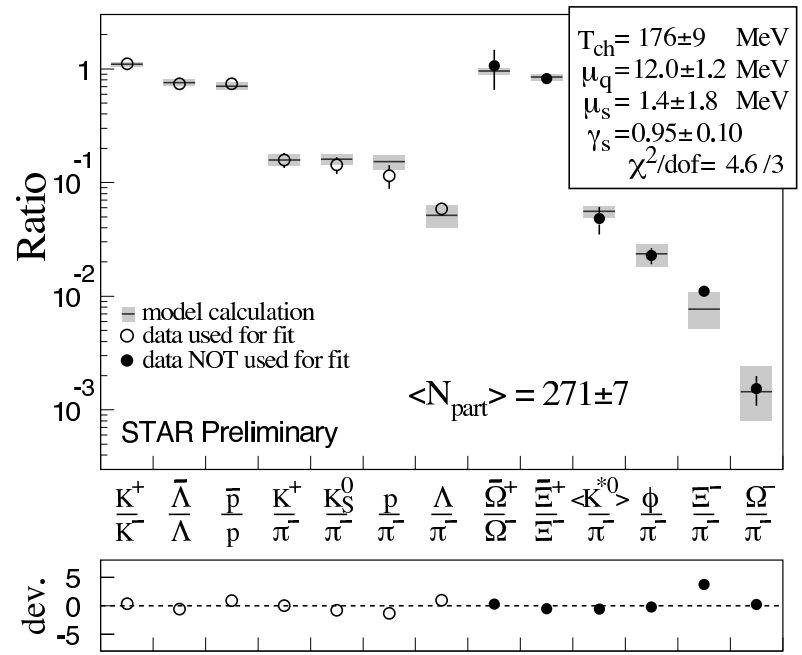
$\Longrightarrow$ **dozens of pioneer papers on the validity of key ideas and predictions and on QGP bulk properties while ATLAS and CMS are still searching for their first Higgs and SUSY particles . . . !**

Supplements

Chemical Freeze-out at $T_{\rm had} \simeq 170$ MeV

Central Au+Au @ 130 A GeV

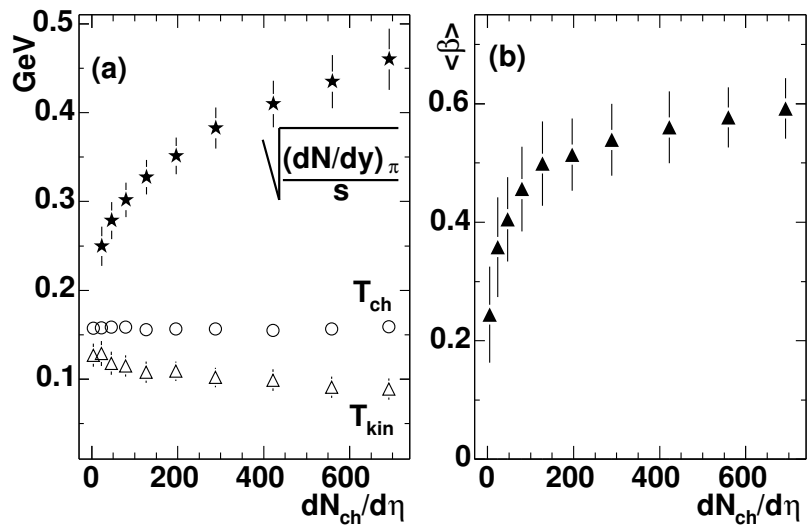
(STAR Coll., G. van Buren, QM2002)



Abundance ratios of stable hadrons decouple in maximum entropy state of "apparent chemical equilibrium" with $T_{\rm chem} \simeq T_{\rm had} \simeq 170$ MeV.

$T_{\rm chem}$ insensitive to expansion rate:

STAR Coll., PRL 92 (2004) 112301



$\Longrightarrow$ **phase transition!**

Note: Hadron abundances are in statistical, not in kinetic chemical equilibrium!

Requires pre-hadronic phase with large strangeness correlation volume.