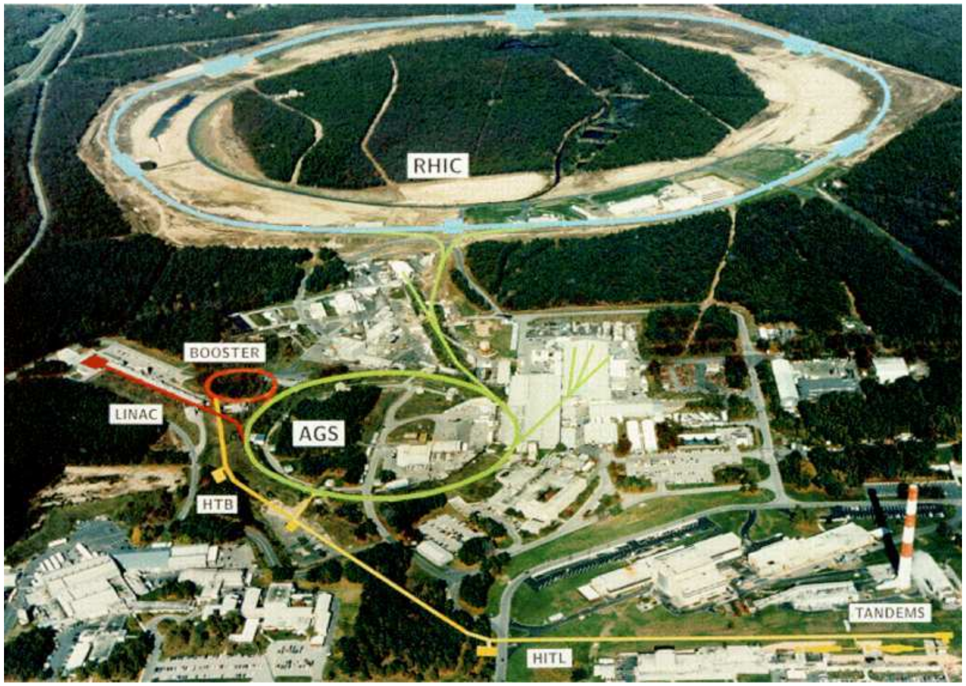
The Quark-Gluon Plasma at RHIC & LHC – from discovery to quantitative characterization*

Ulrich Heinz, The Ohio State University



Colloquium, Tsinghua University, Beijing, Oct. 21, 2010

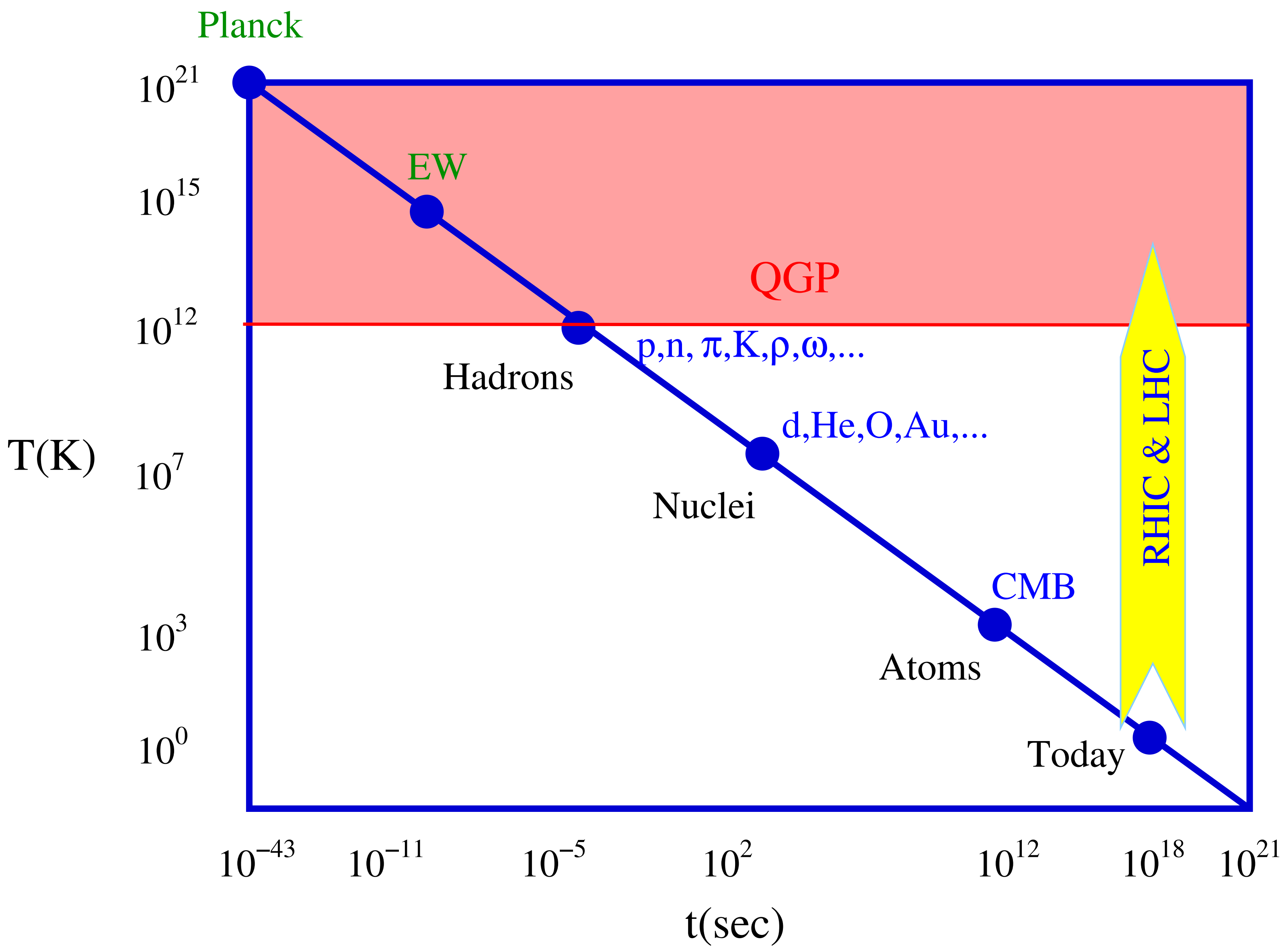
*Work supported by the U.S. Department of Energy (DOE)

1. **RHIC I (2000–2006)** (building on SPS Pb+Pb (1995–2000)):
   The discovery stage

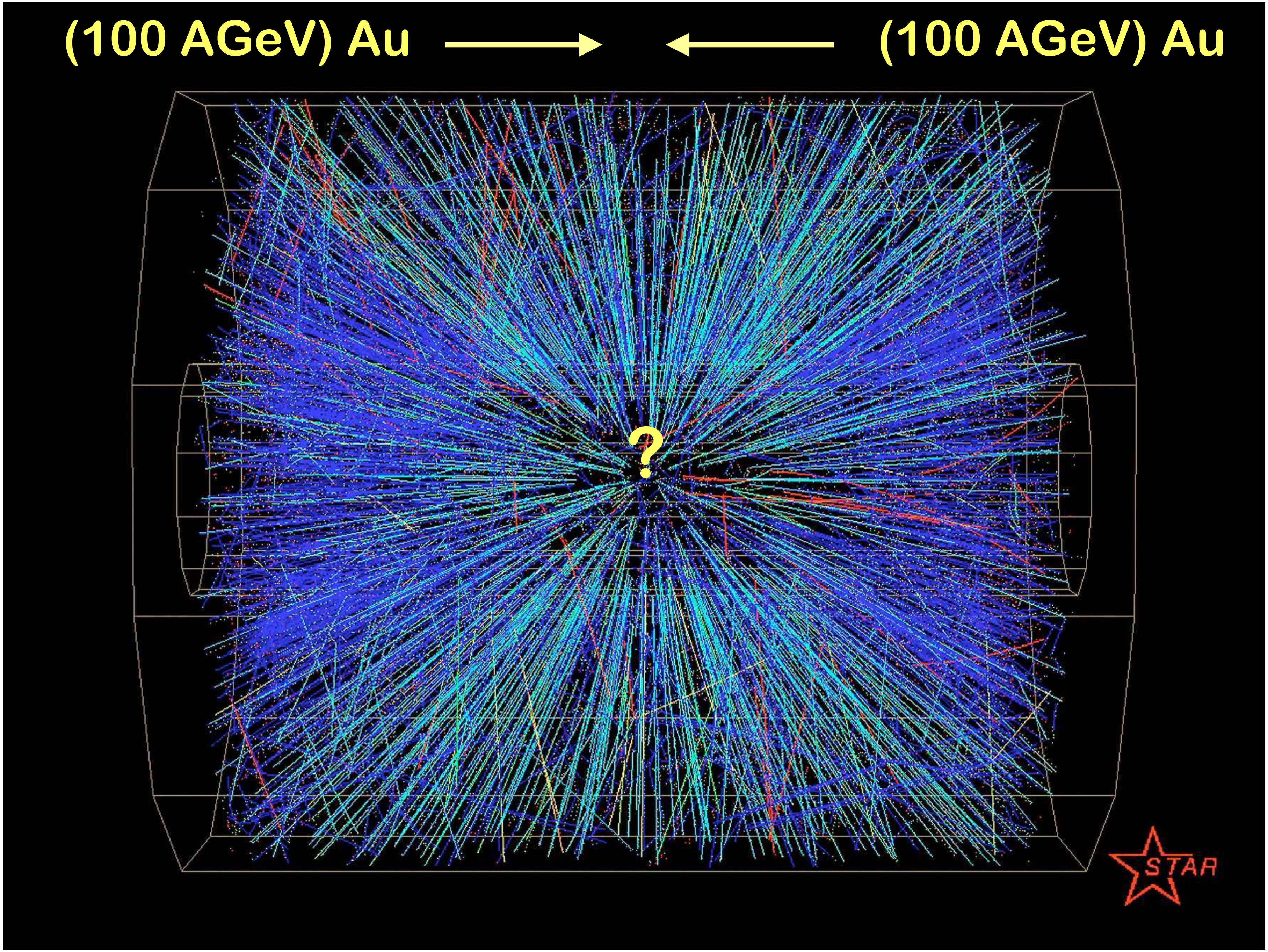
2. **RHIC II (2009–) and LHC Pb+Pb (2010–):**
   Towards quantitative characterization of QGP

   (and, of course, new discoveries – not part of this talk)

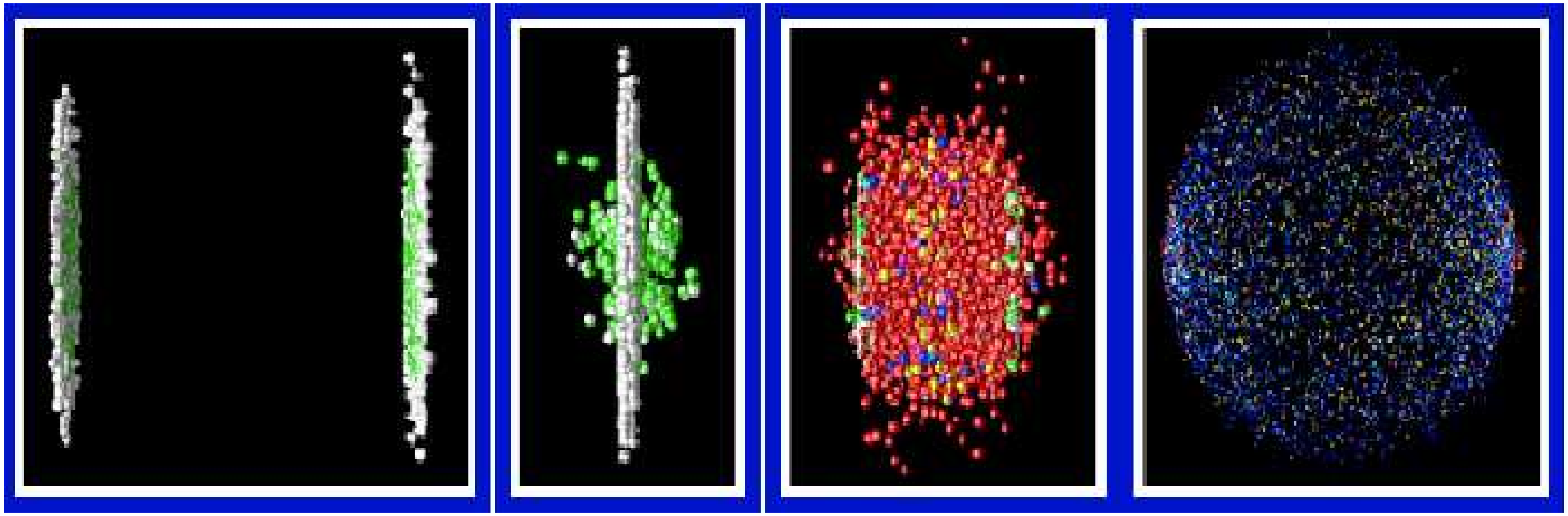
Recreating the Early Universe in the laboratory . . .



. . . with Little Bangs:



Stages of the "Little Bang":



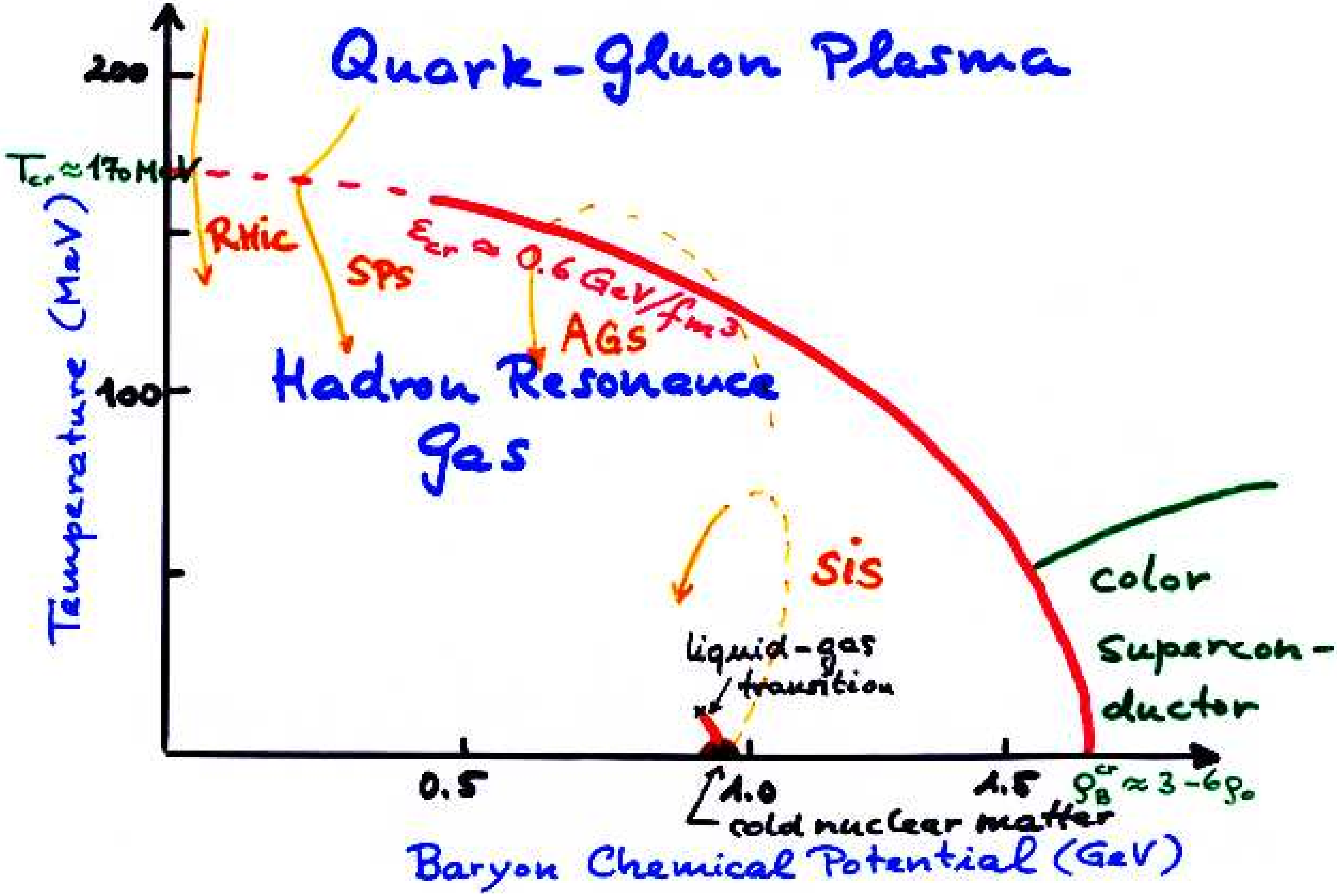
1. Two Lorentz-contracted disks (Au or Pb nuclei) approach each other

2. Hard collisions produce high-p_T particles

3. Soft collisions thermalize the quark-gluon plasma; the fluid expands hydrodynamically

4. The QGP hadronizes; the hadron gas continues to expands until freeze-out; hadrons reach the detector.

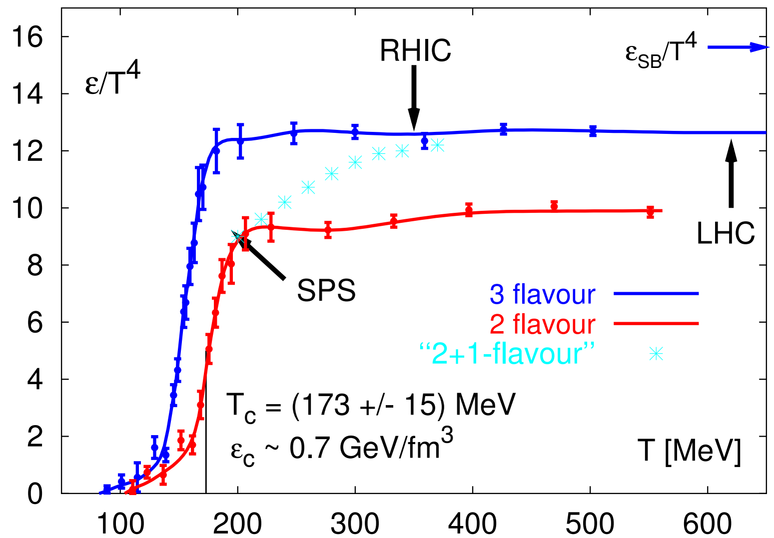
The QCD Phase Diagram and Heavy-Ion Collisions

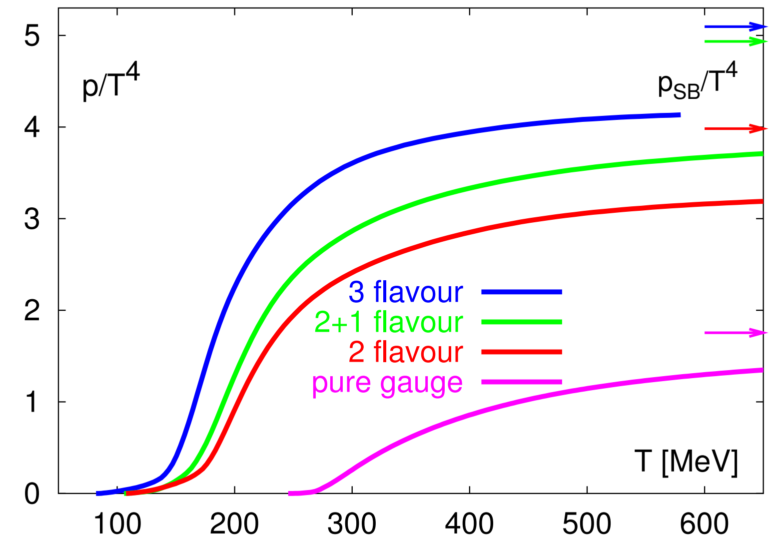


Particle Physics ↔ Heavy-Ion Physics ⟺ Atomic Physics ↔ Condensed Matter Physics

The QCD equation of state (EOS) at zero baryon density

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





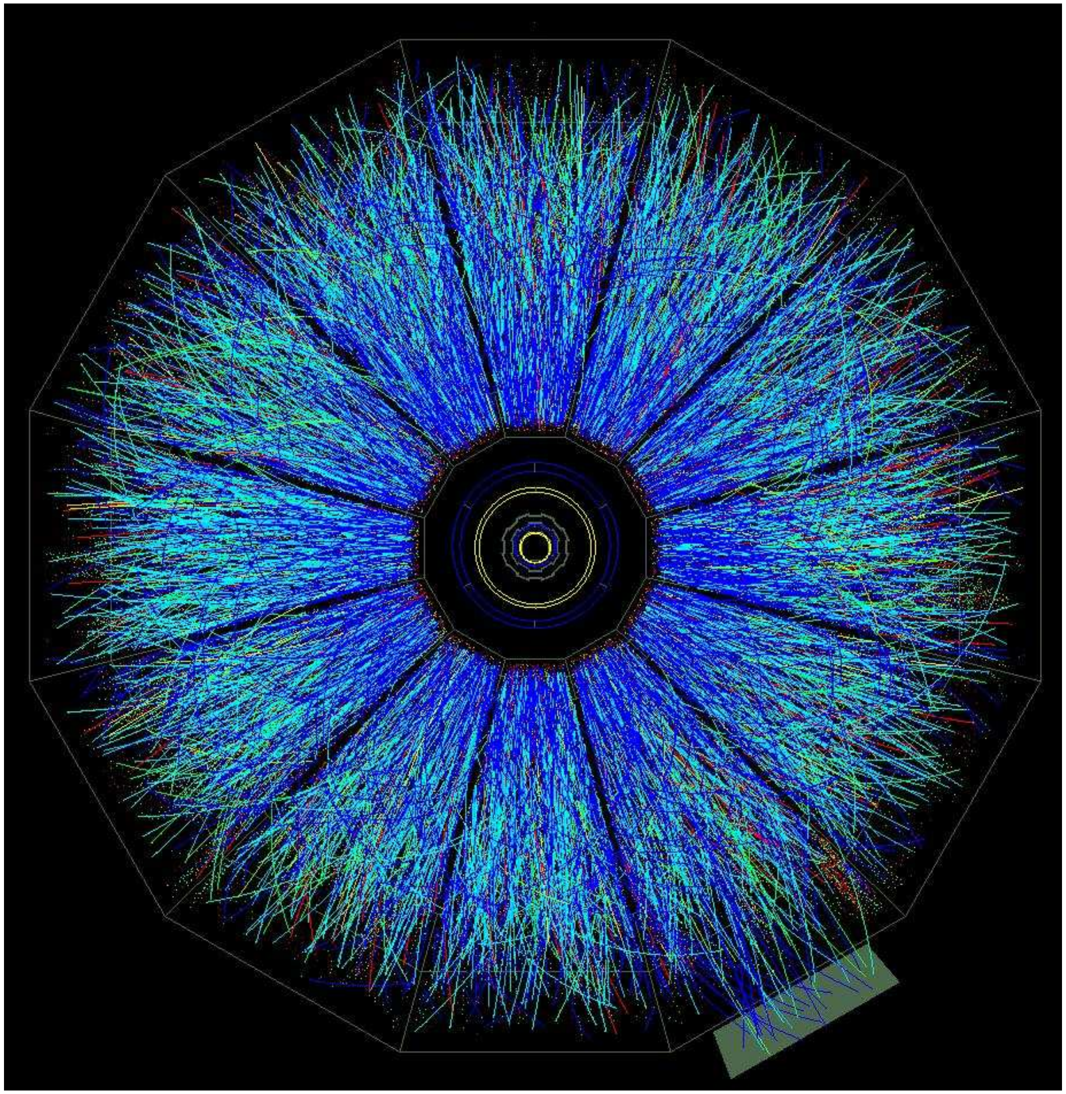
- Critical temperature $T_{\rm cr} = 173 \pm 15\,\text{MeV}$ $(\approx 100\,000 \times T_{\rm center\ of\ sun})$
- Critical energy density $\varepsilon_{\rm cr} \simeq 0.7\,\text{GeV/fm}^3$
- $\varepsilon \approx 0.8\,\varepsilon_{\rm SB}$ for $T \gtrsim 1.3\,T_{\rm cr}$, $\varepsilon \approx 3\,p$ for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

$\Longrightarrow$ Weakly coupled QGP? NO!

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?

How to extract physics from Little Bangs?



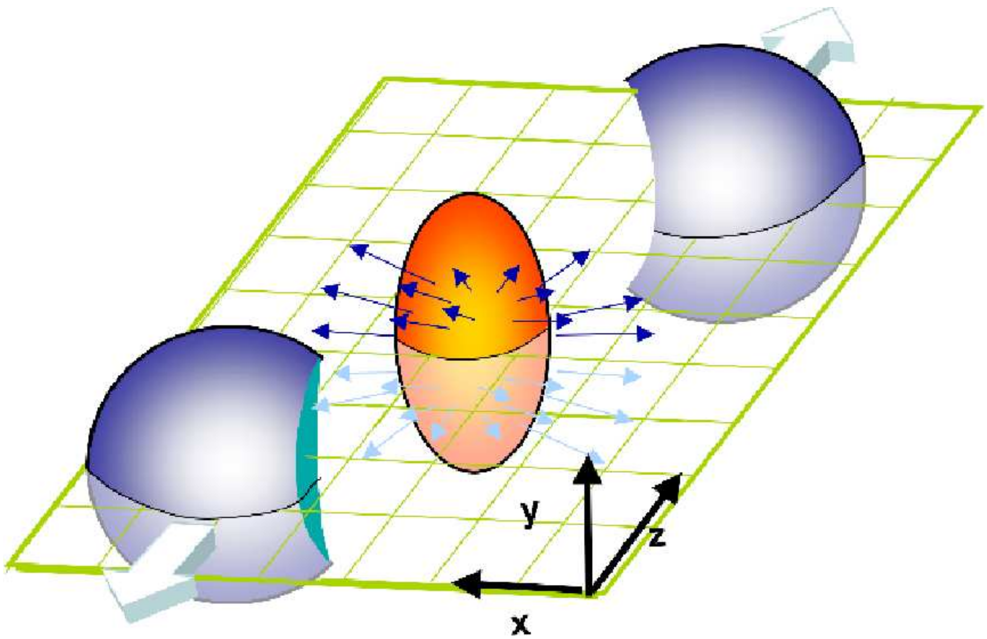
- hadron yield ratios (chemistry)
- hadron spectra (thermal radiation)
- collective flow (radial flow, flow anisotropies)
- hard direct probes (jets, charm, direct electromagnetic radiation)
- 2-particle correlations (HBT interferometry with femtometer spatial and yoctosecond temporal resolution)

Pillars of the QGP

Four key RHIC observations:

1. Strong anisotropic collective flow and $\sim$ perfect fluidity: The Little Bang
2. Quark Coalescence: Signs of color deconfinement
3. Primordial Hadrosynthesis at $T_c = 170\,\text{MeV}$: Statistical hadronization of the QGP
4. JET: Jet Emission Tomography of the QGP and thermalization of fast partons

1. Elliptic Flow



In non-central collisions the overlap region is elliptically deformed $\Longrightarrow$ anisotropic pressure gradients $\Longrightarrow$ anisotropic ("elliptic") collective flow.

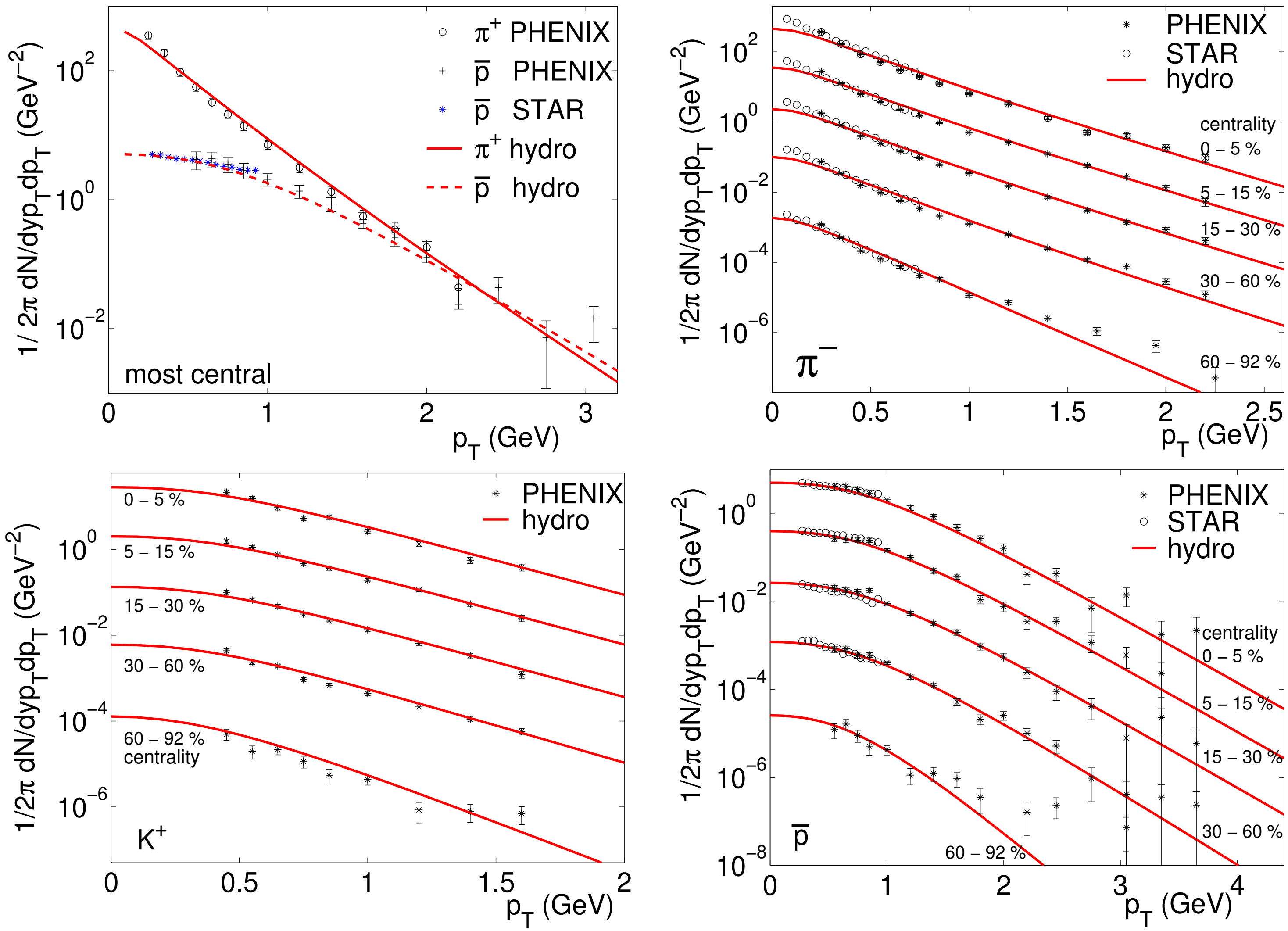
Elliptic flow

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

$$v_2(y, p_T, b) = \langle \cos(2\phi) \rangle_{y,p_T,b} = \frac{\int d\phi\, \cos(2\phi)\, \frac{dN}{dy\, p_T dp_T\, d\phi}(b)}{\int d\phi\, \frac{dN}{dy\, p_T dp_T\, d\phi}(b)}$$

Single particle spectra from Au+Au @ 130 A GeV

Year 1 data from the STAR and PHENIX Collaborations:



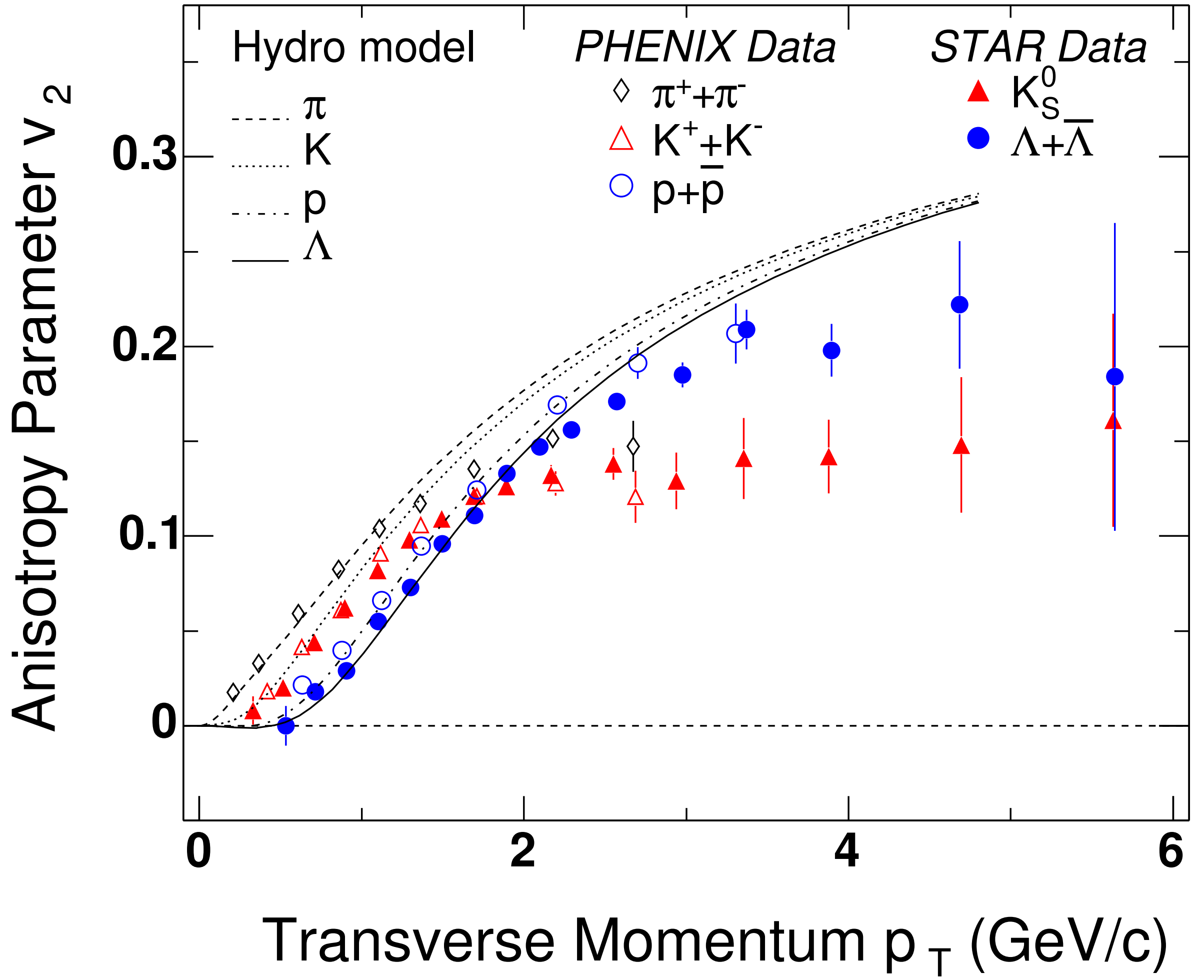
Theoretical curves: ideal fluid dynamics (UH & P.Kolb, hep-ph/0204061)

Model parameters fixed with π, $\bar{p}$ spectra at $b = 0$; all other spectra predicted.

Note: More than 99% of all hadrons are "soft", i.e. have $p_T < 2\,\mathrm{GeV}/c$!

Perfect fluidity: magnitude and mass dependence of elliptic flow

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

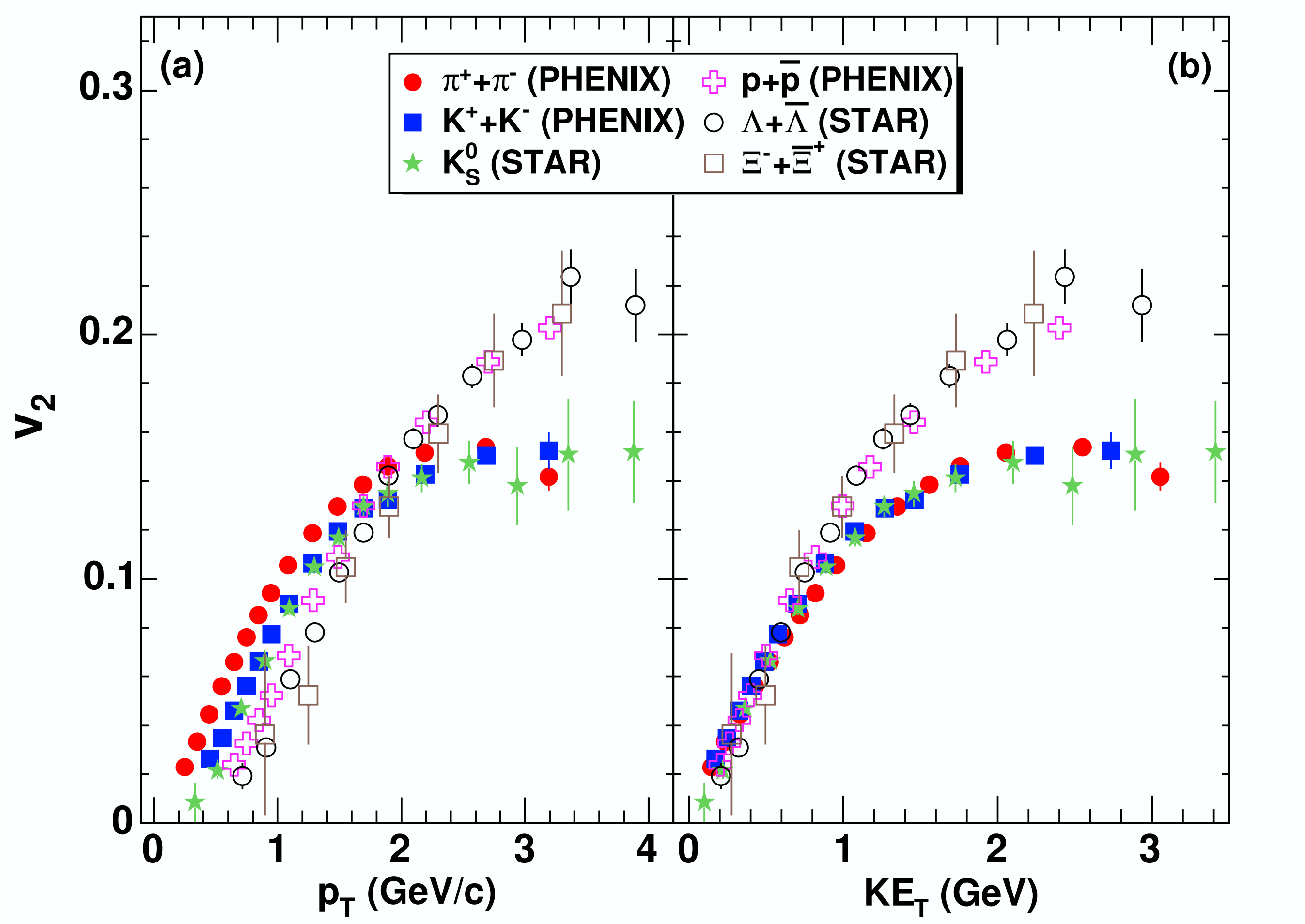


Data follow the hydrodynamically predicted rest mass dependence of $v_2(p_\perp)$ out to $p_\perp \sim 1.5\,\mathrm{GeV}$ for mesons and out to $p_\perp \sim 2.3\,\mathrm{GeV}$ for baryons

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

Perfect fluidity: m_T-scaling of elliptic flow at low p_T

PHENIX Coll., PRL 98, 162301 (2007)



$$\mathrm{KE_T} \equiv m_T - m_0 = \text{transverse kinetic energy}$$

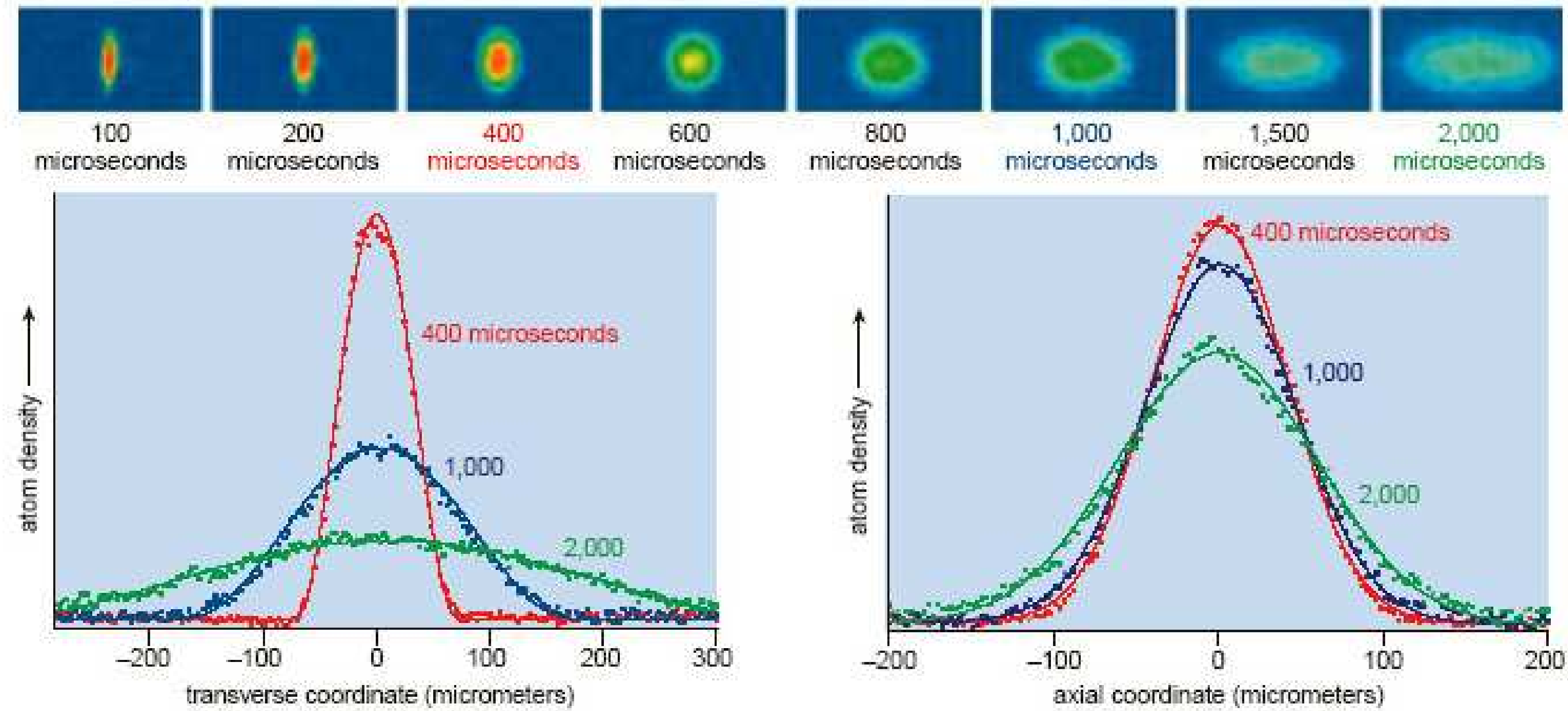
m_T-scaling = evidence for thermalization (almost too good . . . !)

so hydro works –

why? what does this mean?

Elliptic collective flow of strongly coupled atoms at $T = 10^{-6}$ K:

J.E.Thomas et al., Am. Scientist 92 (2004) 238



Interaction strength can be tuned (Feshbach resonance):
Strong interaction: elliptic collective flow
Weak interaction: ballistic expansion with aspect ratio $\to 1$

Success of ideal fluid dynamics requires QGP to be strongly coupled and almost inviscid!

2. Parton coalescence

Ko & Lin '02, Hwa & Yang '02, Greco et al. '03, Fries et al. '03, Molnár & Voloshin '03, Lin & Molnár '03

- Picture: - **coalescence of massive "dressed" valence quarks**
  - **no dynamical gluons**

- Basic equations: $qq \to \text{meson}$, $qqq \to \text{baryon}$

$$E\frac{dN_M(\boldsymbol{p})}{d^3p} = \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q \qquad |\psi_{\boldsymbol{p}}(\boldsymbol{q})|^2 \qquad f_\alpha(\boldsymbol{p}_\alpha, x) f_\beta(\boldsymbol{p}_\beta, x)$$

$$E\frac{dN_B(\boldsymbol{p})}{d^3p} = \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q_1 d^3q_2 |\psi_{\boldsymbol{p}}(\boldsymbol{q}_1, \boldsymbol{q}_2)|^2 f_\alpha(\boldsymbol{p}_\alpha, x) f_\beta(\boldsymbol{p}_\beta, x) f_\gamma(\boldsymbol{p}_\gamma, x)$$

hadron yield space-time wave-fn. quark distributions

assumes: rare process, weak binding, factorizable 2-body and 3-body density matrix, smooth spacetime distributions, 3D hypersurface (sudden approx.)

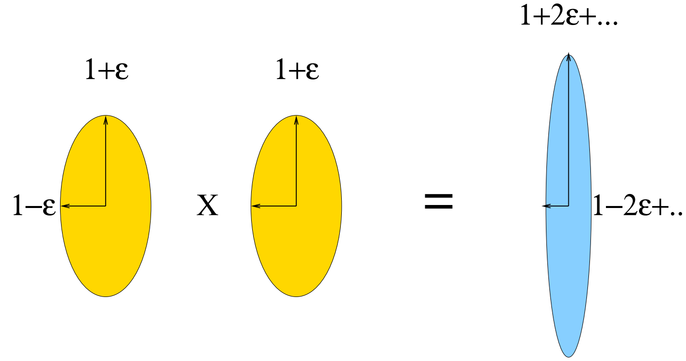
Can dominate over fragmentation for $p_\perp < 4–5$ GeV [Greco et al., Fries et al., PRL90 ('03)]

Quark number scaling at intermediate $p_\perp$: quark coalescence

D. Molnár and S. Voloshin, PRL 91 (2003) 092301

Narrow wave function limit ($\boldsymbol{q}=0$): $\frac{dN_M}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^2, \quad \frac{dN_B}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^3$

$$v_2^M(p_\perp) \approx v_2^a\left(\tfrac{p_\perp}{2}\right) + v_2^{\bar a}\left(\tfrac{p_\perp}{2}\right)$$
$$v_2^B(p_\perp) \approx v_2^a\left(\tfrac{p_\perp}{3}\right) + v_2^b\left(\tfrac{p_\perp}{3}\right) + v_2^c\left(\tfrac{p_\perp}{3}\right)$$



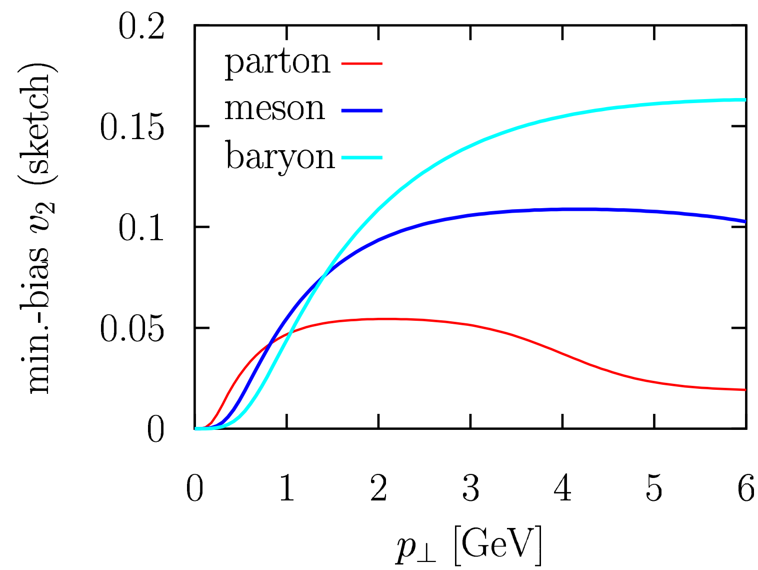
$\Rightarrow$ **Hadron v_2 amplified at high $p_\perp$:**

If all quark flavors have same v_2:

$3\times$ for baryons

$2\times$ for mesons

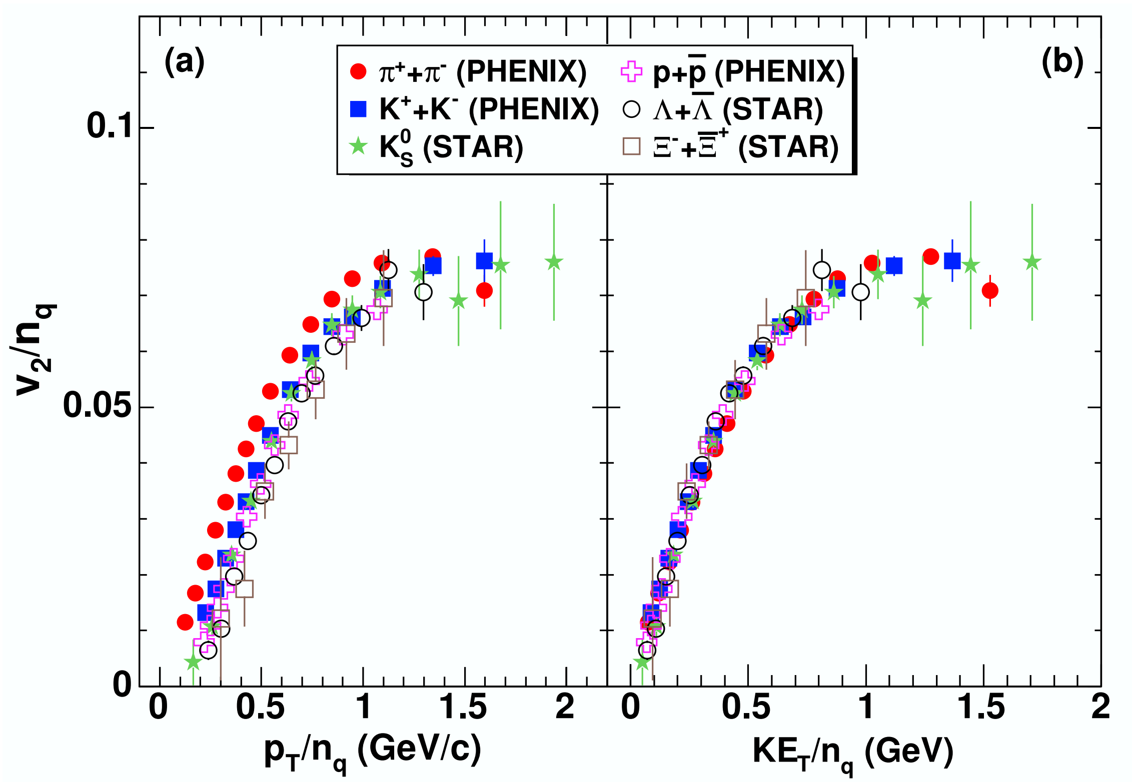
$$v_2^h(p_\perp) \approx n \times v_2^q(p_\perp/n)$$

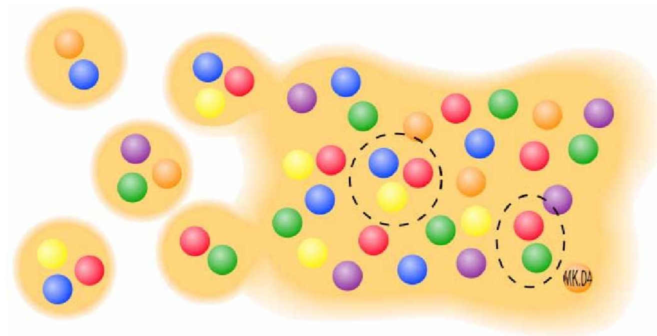


Note:
- Parton v_2 can be extracted only because it breaks away from hydro at high p_T!
- Coalescence model predicts scaling in p_T/n, not $\mathrm{KE}_T/n = (m_T - m_0)/n$!

Experimental extraction of parton elliptic flow

PHENIX Coll., PRL 98, 162301 (2007)





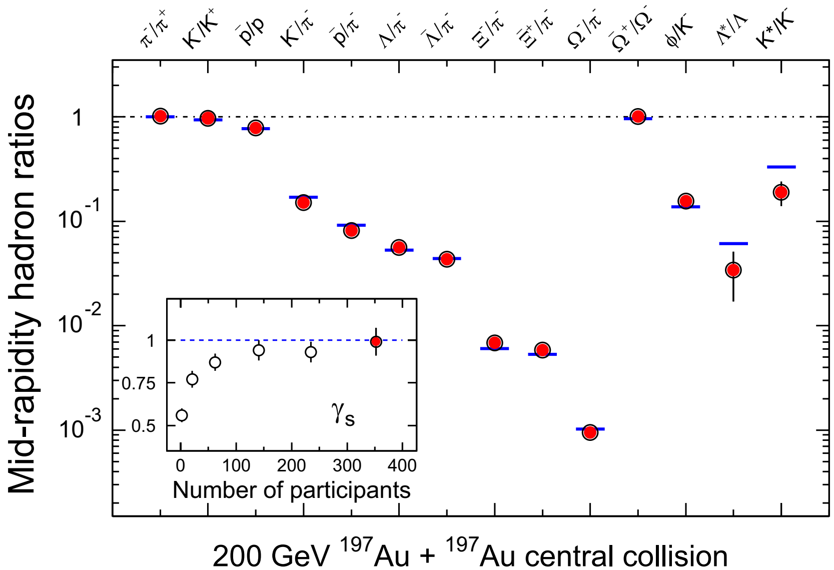
- Coalescence model yields unified description for $\pi, K, \phi, p, \Lambda, \Xi, \Omega, d$!
- RHIC data indicate $v_2^q \approx v_2^s$
- Parton elliptic flow follows hydro to $p_{T,\mathrm{break}} \approx 750\,\mathrm{MeV}$, saturates at $\approx 7\%$ in min. bias. collisions

Quark number scaling indicates dynamical role for deconfined quarks!

3. Measuring T_c: Primordial hadrosynthesis at $T_{\rm had} \simeq 170$ MeV

Au+Au @ 200 A GeV

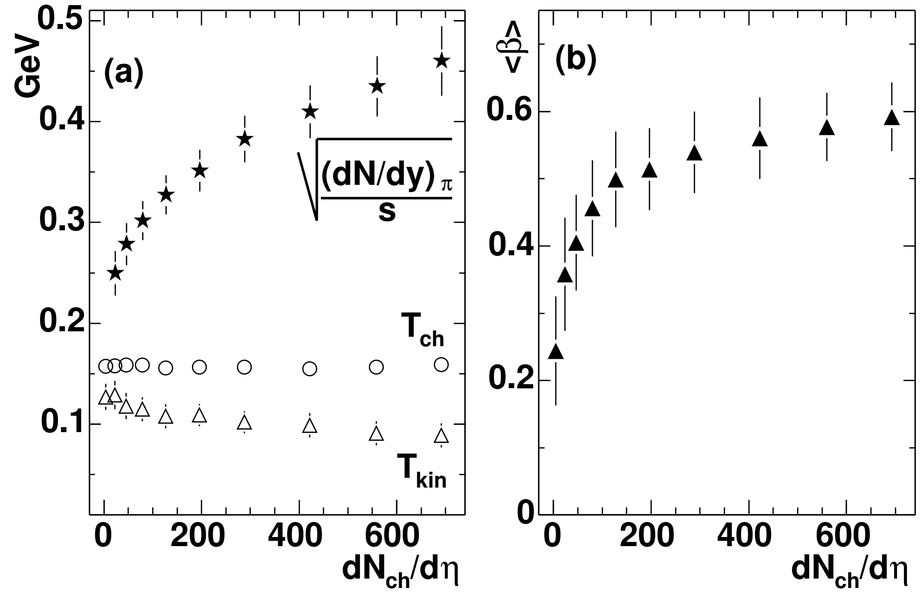
STAR Coll., NPA 757 (2005) 102



Abundance ratios of stable hadrons decouple in maximum entropy state of "apparent chemical equilibrium" with $T_{\rm chem} = 163{\pm}4$ MeV $\simeq T_{\rm had}$, $\mu_B = 24\pm$ 4 MeV, and $\gamma_s({\rm central}) = 0.99{\pm}0.07$.

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

STAR Coll., PRL 92 (2004) 112301



- Radial flow $\langle\beta\rangle$ increases with centrality
- $T_{\rm kin}$ decreases with centrality
- γ_s increases with centrality, approaching 1 in central collisions
- $T_{\rm chem}$ independent of centrality!

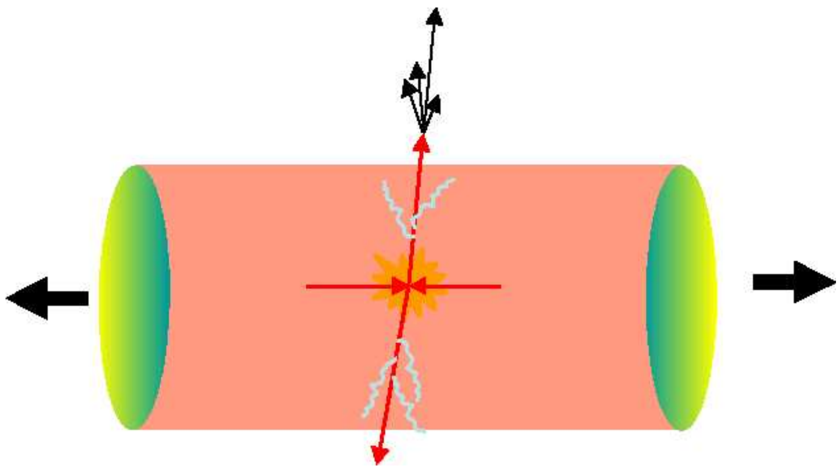
Note: Hadron abundances are in statistical, not in kinetic chemical equilibrium!

Requires pre-hadronic phase with large strangeness correlation volume.

Final hadronic chemical composition driven by phase transition

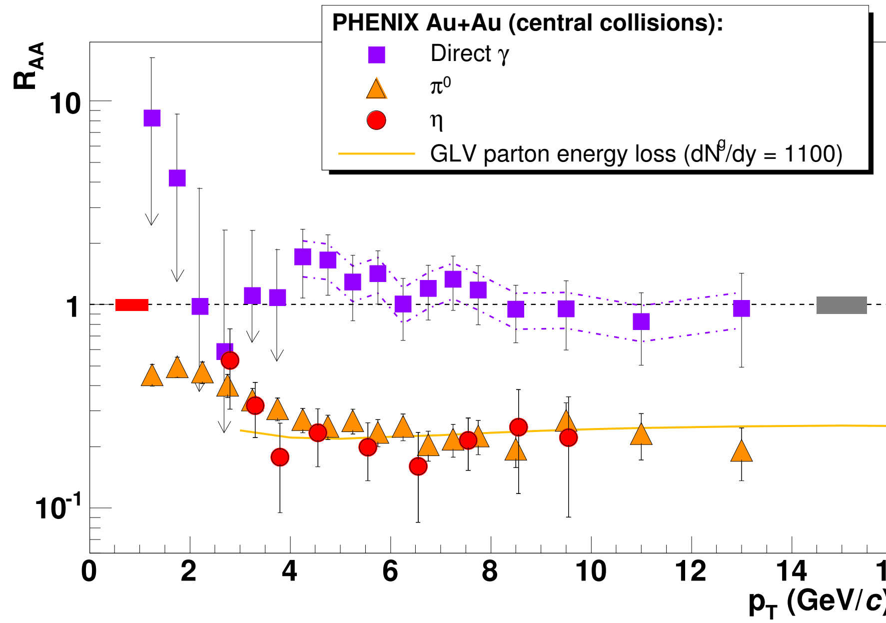
$\Rightarrow$ hadron abundances measure T_c!

4. JET: Suppression of high p_T hadrons in Au+Au



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

PHENIX Coll., PRL 96 (2006) 202301



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

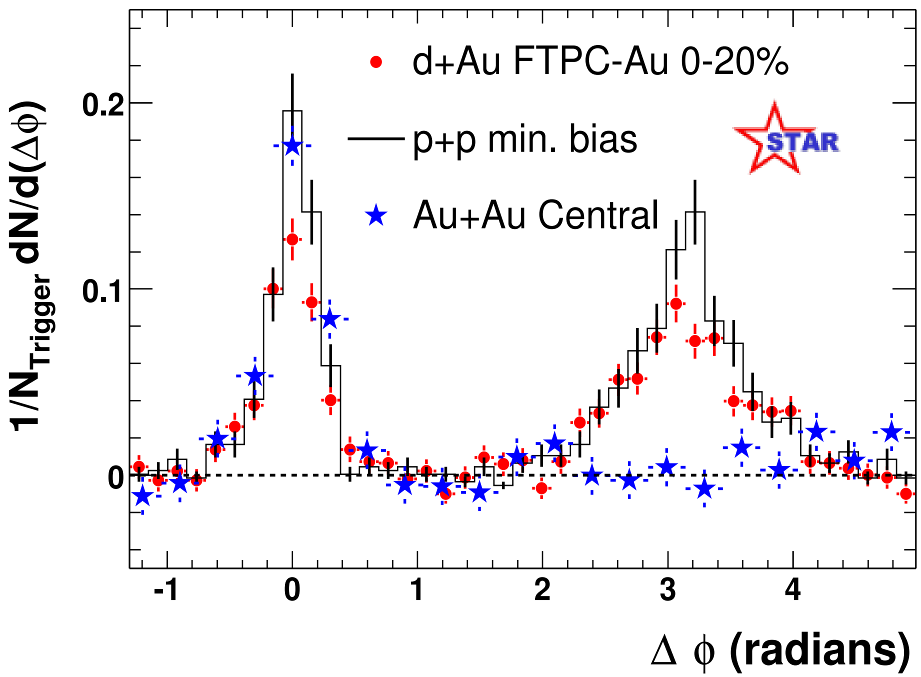
$$\Longrightarrow \quad \langle e\rangle(\tau_0{=}0.2\,{\rm fm}) \approx 20\,{\rm GeV/fm}^3\ !$$

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

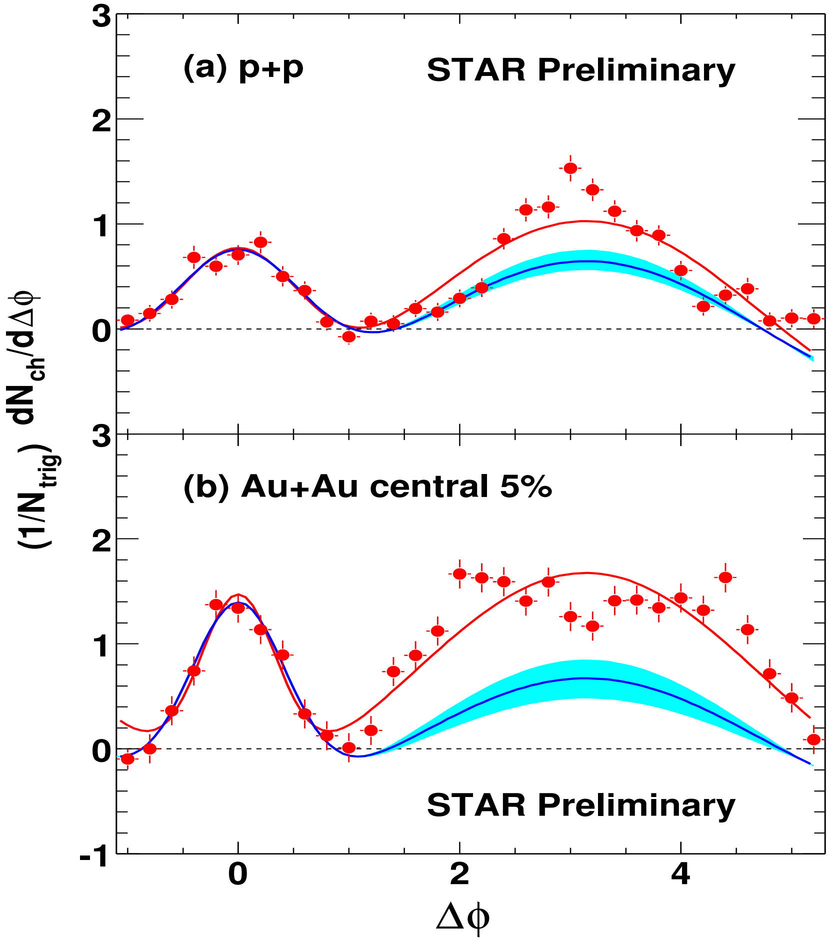
$p_T^{\rm assoc} > 2\,$GeV



- trigger particle for near-side jet has $4 < p_T < 6\,$GeV

STAR Coll., F. Wang, Quark Matter 2004

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



- away-side jet ($p_T > 2\,$GeV) visible in p+p and d+Au, but fully quenched in central Au+Au; in non-central collisions, away-side suppression depends on emission angle (i.e. path length)
- energy of quenched jet appears as additional multiplicity of low-p_T particles opposite to trigger particle; in central Au+Au $\langle p_T \rangle$ of away-side particles approaches bulk value
- $\Longrightarrow$ "thermalization" of intermediate-p_T jets!

RHIC I summary:

These data provide evidence for

- fast thermalization ($\tau_{\rm therm} < 1\,{\rm fm}/c$)
  at high initial density and temperature ($e_0 > 10\,e_{\rm cr},\ T_0 \sim 2\,T_{\rm cr}$).
- almost perfect fluidity (very low viscosity)
- dynamical deconfined quark degrees of freedom
- statistical hadronization through a phase transition at $T_{\rm cr} \approx 170\,{\rm MeV}$
- strong opacity to colored probes
- strong collective coupling among plasma constituents

These are qualitative statements. Can we be more precise?

- How large (or rather, small) is the QGP viscosity, exactly?
- How large is the energy loss dE/dx of a fast parton, exactly?
- How different is it for quarks and gluons, is it the same for heavy and light quarks?
- How large is the initial fireball temperature and density, exactly?
- When, exactly, does the medium reach local thermal equilibrium, if at all?
  When does it break down again? How long does the QGP live?
- How accurately can pQCD describe (i) the fireball medium? (ii) the interaction of hard probes with the medium?
- Do we need help from superstring theorists?!

1. **RHIC I (2000–2006)** **(building on SPS Pb+Pb (1995–2000)):**
   The discovery stage

2. **RHIC II (2009–) and LHC Pb+Pb (2010–):**
   Towards quantitative characterization of QGP
   (and, of course, new discoveries – not part of this talk)

Moving towards a quantitative characterization of the QGP

Questions:

- How large (or rather, small) is the QGP viscosity, exactly?
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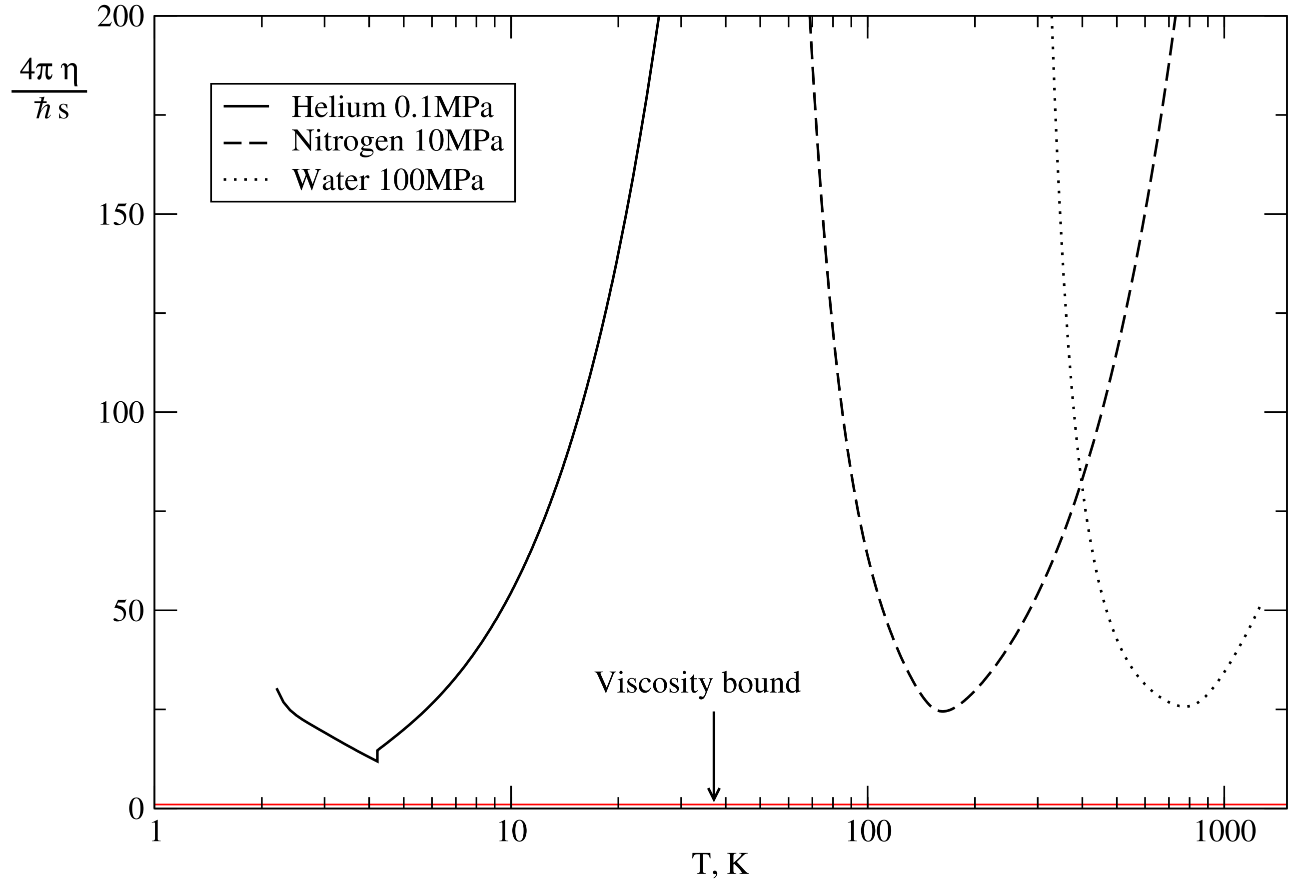
The AdS/CFT "universal" lower viscosity bound

Conjecture: $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$ (Policastro, Kovtun, Son, Starinets 2003, 2005)

Kovtun, Son, Starinets, PRL 94 (2005) 111601



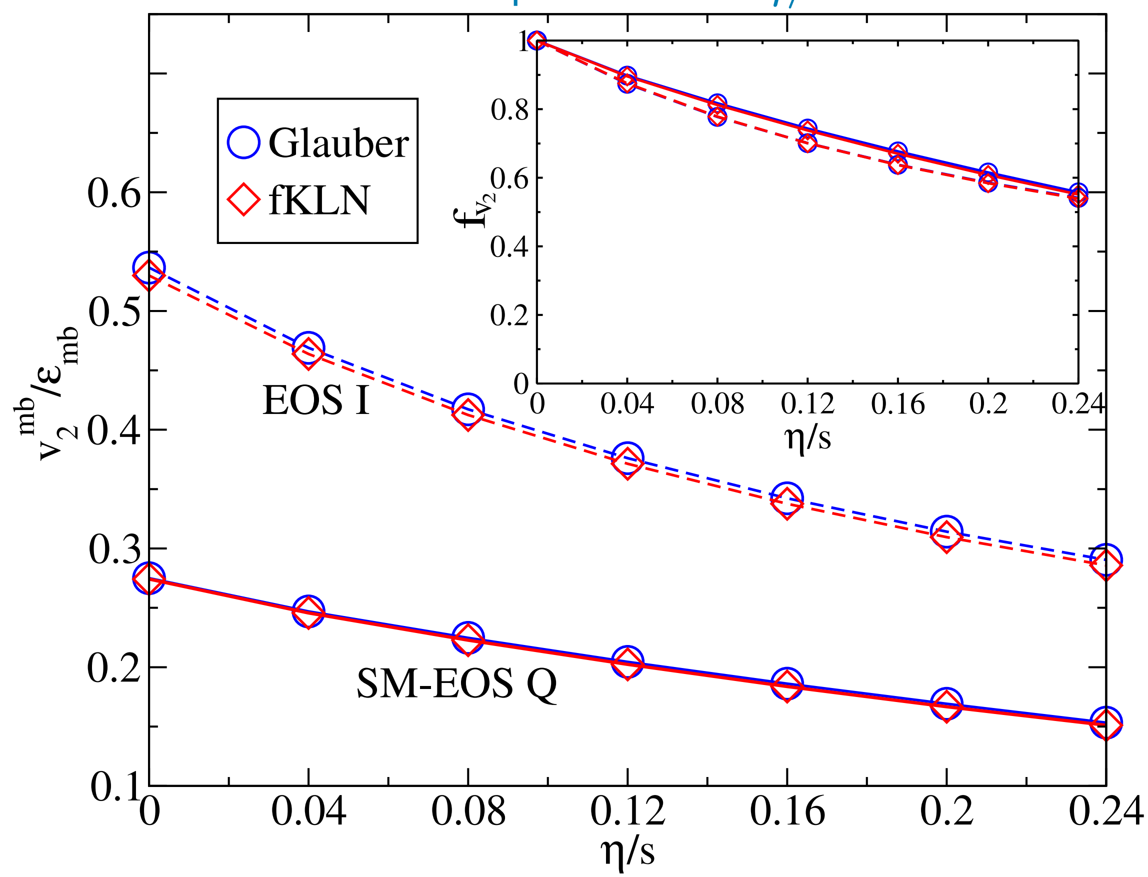
QGP viscosity appears close to this bound! How close?

Quantitative constraints on η require viscous hydrodynamics code.

Viscous suppression of eccentricity-scaled elliptic flow v_2/ε

(UH, Moreland, Song, arXiv:0908.2617)

Scaled elliptic flow vs. η/s



Shear viscosity η/s suppresses elliptic flow:

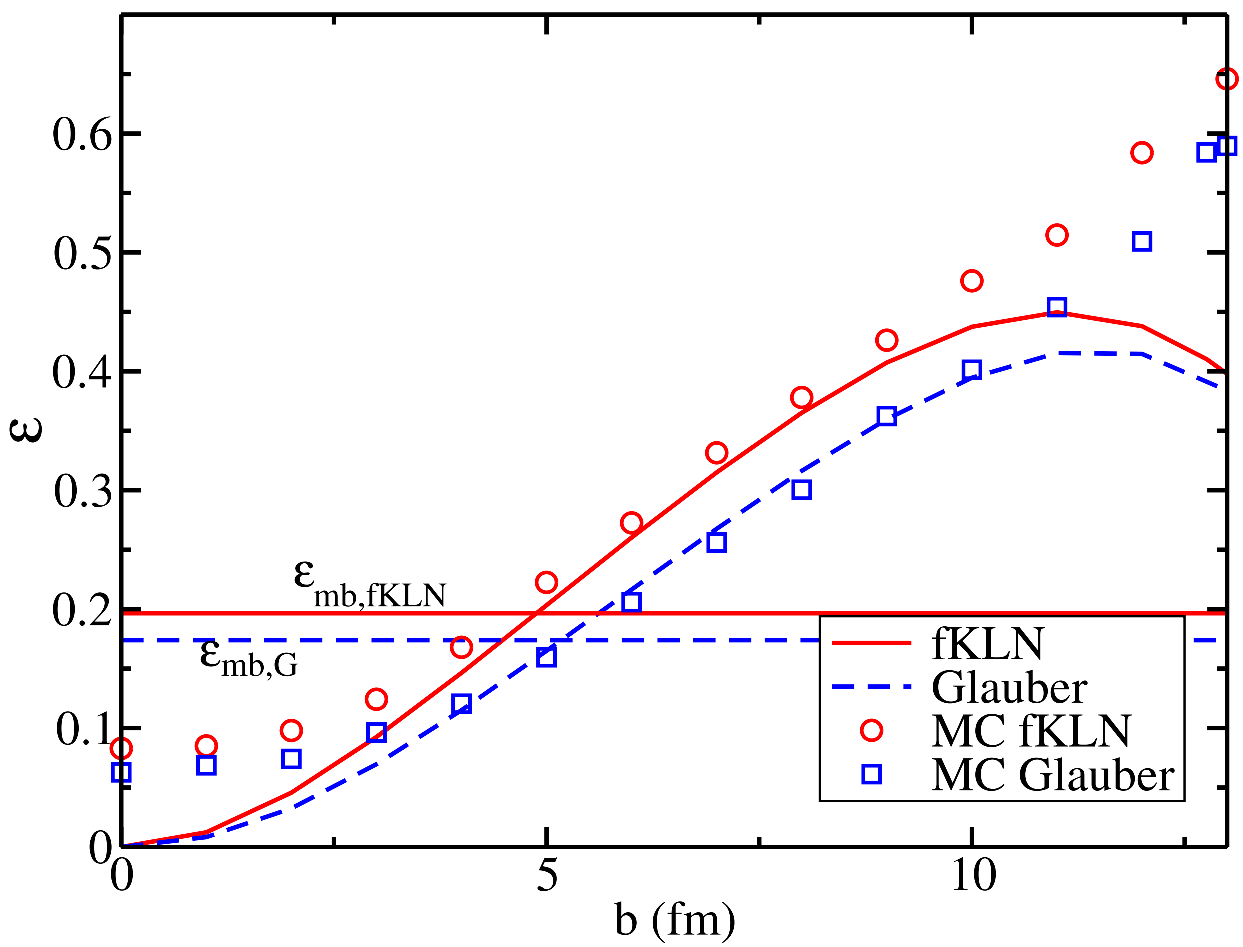
- $f_{v_2} = \frac{\left(v_2^{\rm mb}/\varepsilon_{\rm mb}\right)_{\rm viscous}}{\left(v_2^{\rm mb}/\varepsilon_{\rm mb}\right)_{\rm ideal}}$ (mb = min.bias)
- initial source eccentricity $\varepsilon = \frac{\langle\langle y^2-x^2\rangle\rangle}{\langle\langle y^2+x^2\rangle\rangle}$
- fKLN model: H.-J. Drescher et al., PRC 74 (2006) 044905
- curves calculated with `VISH2+1` – viscous Israel-Stewart hydro with longitudinal boost-invariance (H. Song 2007-2008)

- Even small $\eta/s \sim 1/4\pi$ leads to sizeable $(\sim 20\%)$ suppression of elliptic flow
  $\Longrightarrow$ easily measurable if ideal fluid baseline is known
- Viscous suppression of v_2/ε relative to ideal hydro is a unique function of η/s, independent of initial source eccentricity and $\approx$ independent of EOS.
- **But:** 15% uncertainty in initial source eccentricity up to $\Longrightarrow \mathcal{O}(100\%)$ uncertainty for η/s!

Uncertainties in the initial source eccentricity

(UH, Moreland, Song, arXiv:0908.2617)

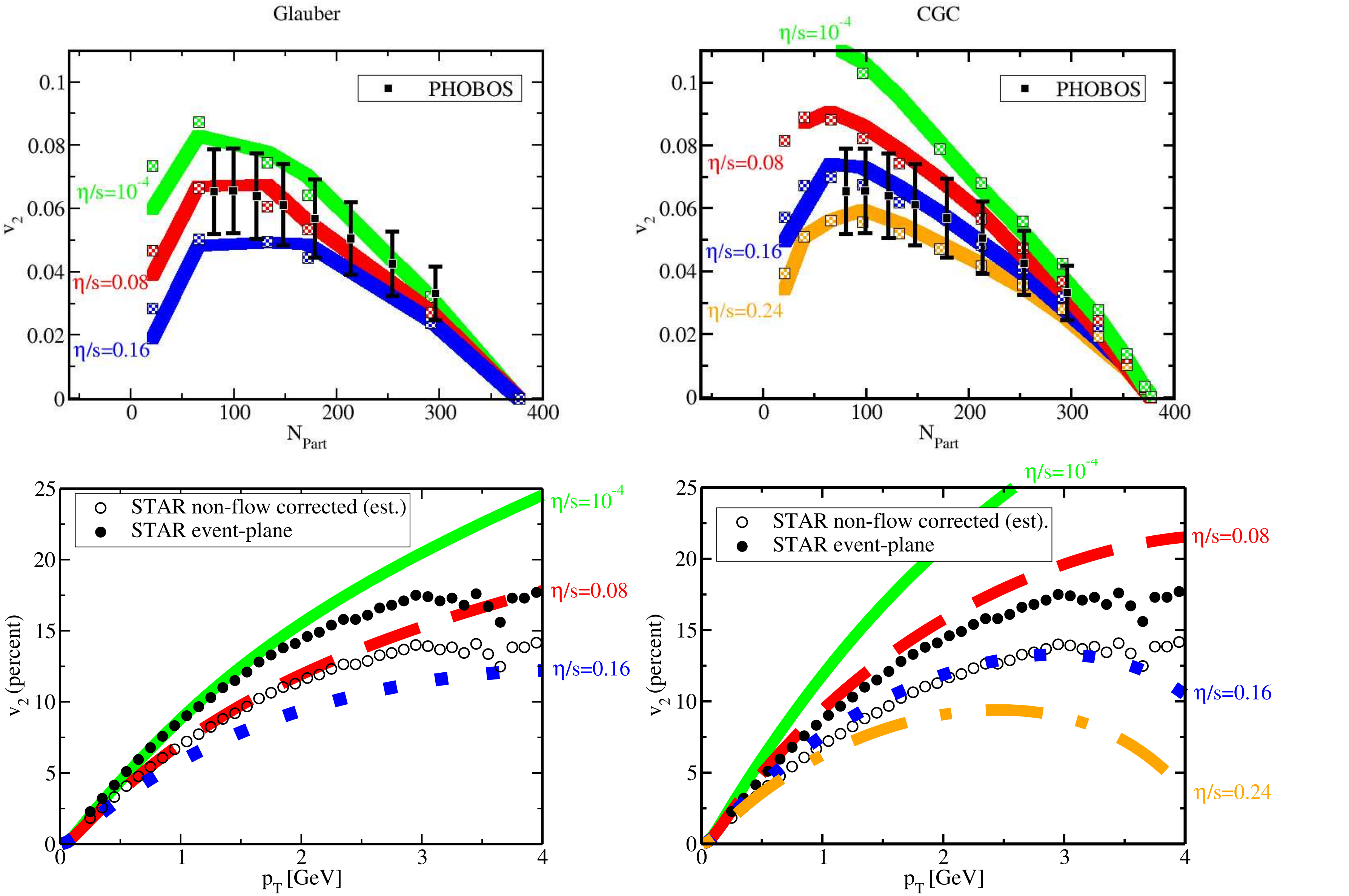
Initial source eccentricity vs. b



- CGC/fKLN model (Drescher et al.) gives larger source eccentricity than Glauber model,
- Minimum bias eccentricity 12% larger for fKLN than Glauber

Constraining η/s from charged hadron elliptic flow data

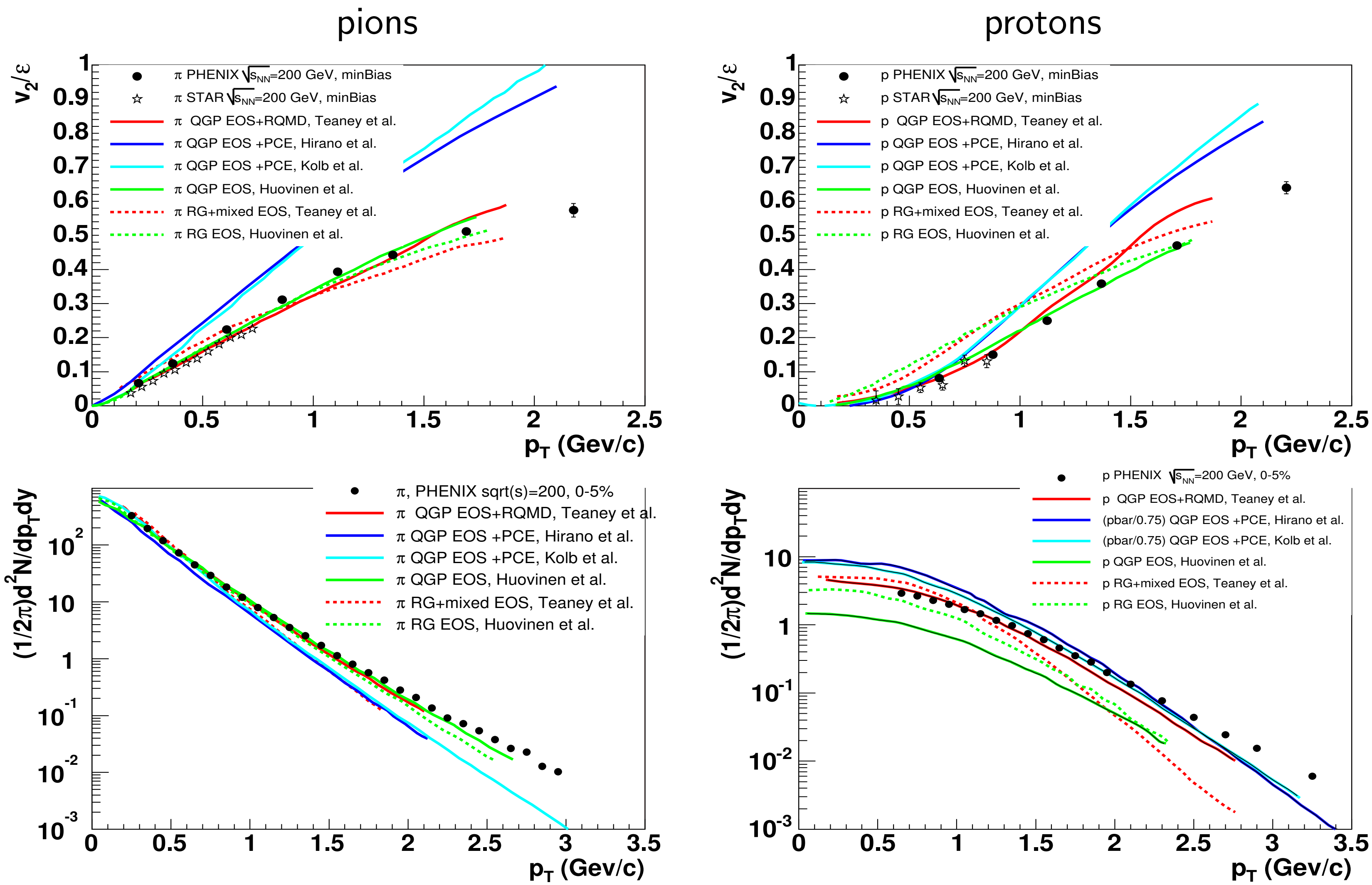
Luzum & Romatschke, PRC 78 (2008) 034915



- **Largest uncertainty ($\sim 100\%$): initial source eccentricity!**
- Others: EOS near T_c ($\sim 25-30\%$); chemical comp. below T_c (??); no pre-equilibrium transverse flow; late hadronic viscous effects not subtracted; bulk viscous v_2 suppression not subtracted
- "Conservative" upper limit: $\frac{\eta}{s} < \frac{6}{4\pi} \approx 0.5$ (Luzum & Romatschke '08)

At RHIC, hadronic viscosity & chemical non-equilibrium matter:

PHENIX White Paper, NPA 757 (2005) 184



All theory curves use the same hydrodynamics and EOS in QGP phase!

How we deal with the hadron phase makes all the difference . . .

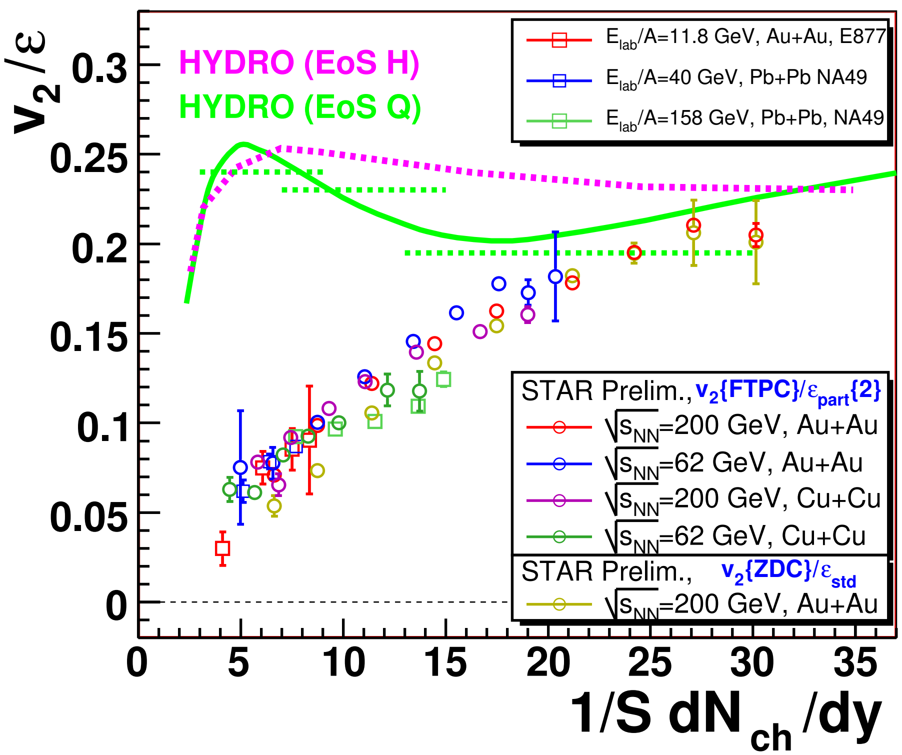
The only model that simultaneously fits all data is hydro+RQMD

(**Teaney & Shuryak 2001**) (see also Hirano et al. 2006 (3D hydro + JAM))

The importance of hadronic dissipation:

Centrality and $\sqrt{s}$ dependence of viscous suppression of v_2/ε

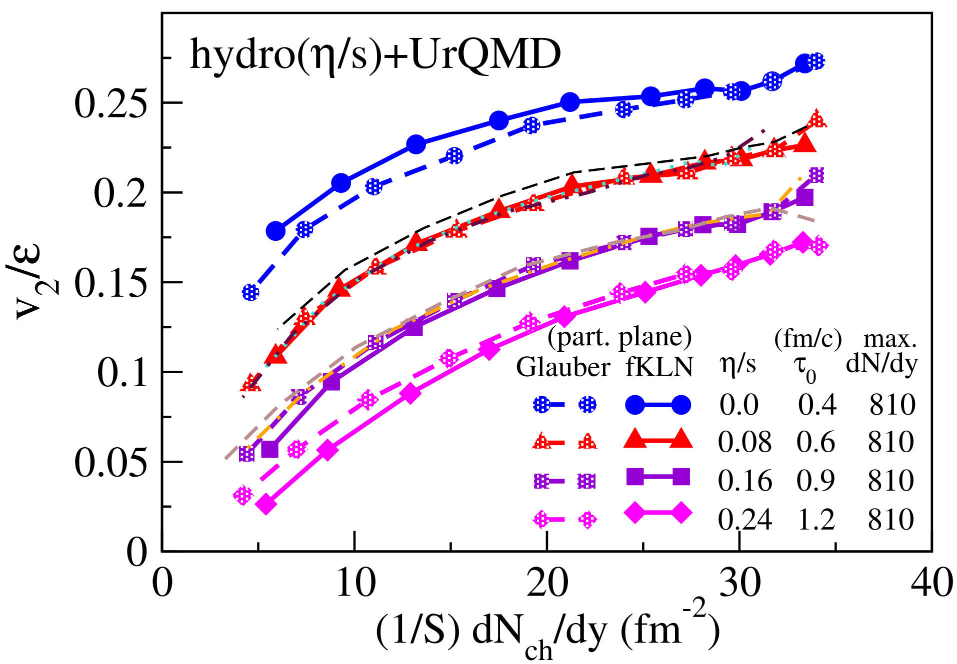
S. Voloshin [STAR Coll.], JPG 34 (2007) S883

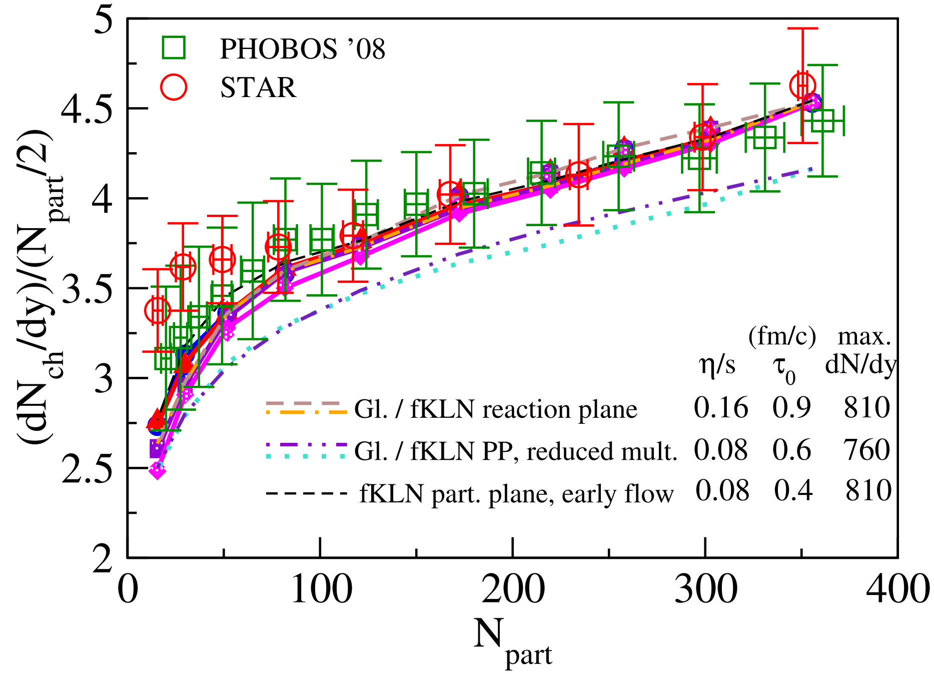


- Lower initial density $\Longrightarrow$ shorter lifetime of QGP $\Longrightarrow$ hadron phase more important
- Hadron gas is not a good fluid $\longrightarrow$ hadronic dissipation inhibits build-up of elliptic flow
- Need hybrid description: (viscous) hydro for QGP, UrQMD for hadron resonance gas (Bass et al., Teaney, Hirano et al.)

Extracting η/s from RHIC data: VISH2+1 $\oplus$ UrQMD

(H. Song, S. Bass, UH, T. Hirano, C. Shen, in preparation)

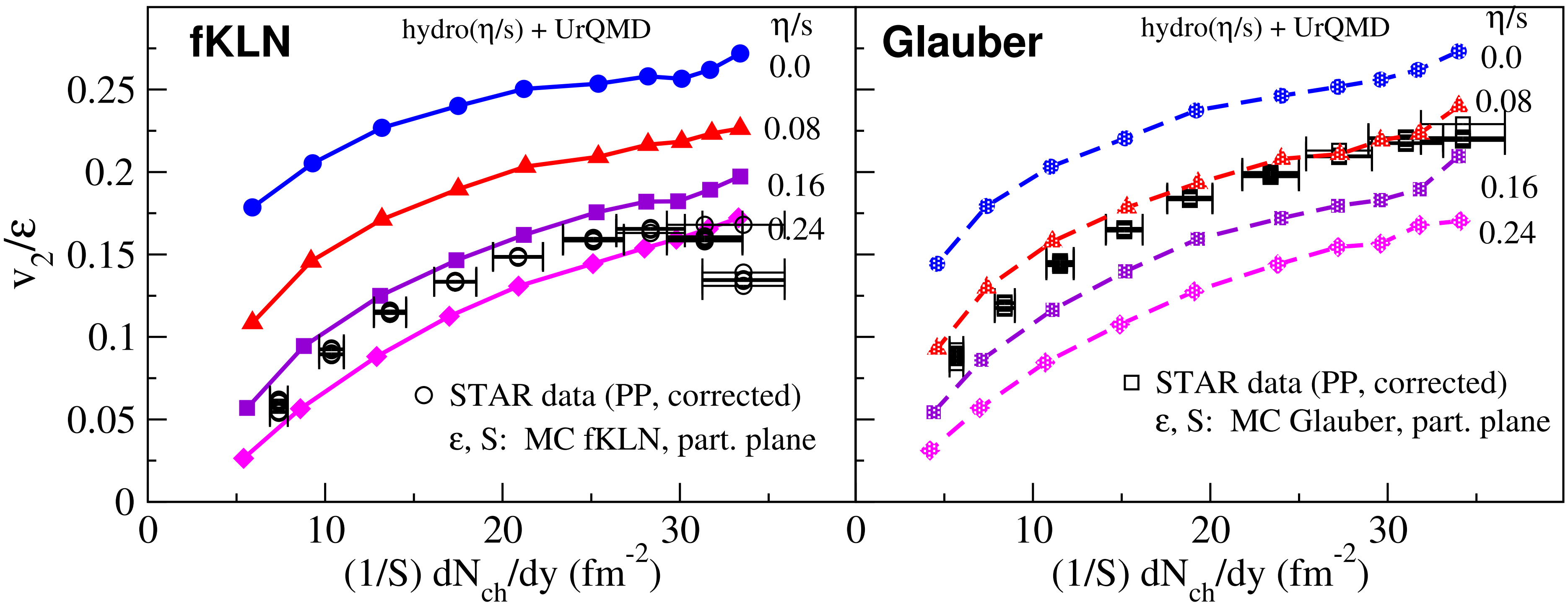




- viscous hydro for QGP with constant $\frac{\eta}{s}$ coupled to UrQMD at $T_{\rm sw} = 160\,$MeV
- use latest lattice EOS matched to PCE hadron resonance gas (s95p-PCE (Huovinen))
- UrQMD handles chemical and kinetic freeze-out of all hadrons automatically by solving coupled Boltzmann equations
- Initial conditions include event-by-event eccentricity fluctuations
- v_2/ε vs. $(1/S)dN_{\rm ch}/dy$ is "universal", i.e. independent of which model is used to calculate ε and S, as long as $dN_{\rm ch}/dy$ vs. $N_{\rm part}$ is approx. correctly reproduced

Extracting η/s from RHIC data: VISH2+1 $\oplus$ UrQMD

(H. Song, S. Bass, UH, T. Hirano, C. Shen, in preparation)



- VISH2+1 + UrQMD correctly describes centrality dependence of scaled elliptic flow
- First quantitative extraction of $\frac{\eta}{s}$ with a model that incorporates all essential physics
- Slope cannot distinguish between Glauber and CGC-fKLN model
- 30% uncertainty in initial eccentricity causes 100% uncerainty in $\frac{\eta}{s}$

$$1 < 4\pi(\eta/s)_{\mathrm{QGP}} < 2.5$$

Moving towards a quantitative characterization of the QGP

Questions:

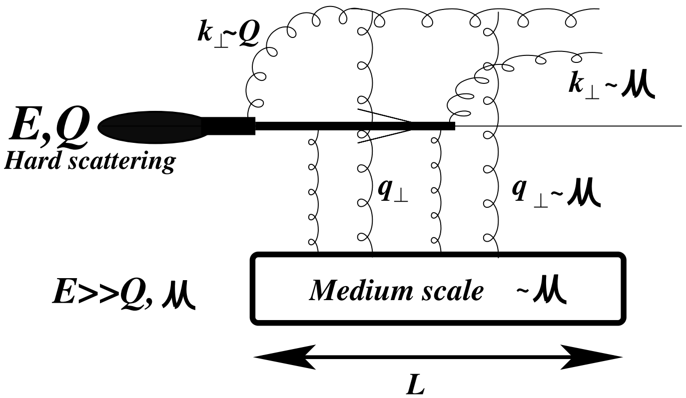
- How large (or rather, small) is the QGP viscosity, exactly?
- How large is the energy loss dE/dx of a fast parton, exactly?
- How different is it for quarks and gluons, is it the same for heavy and light quarks?
- How large is the initial fireball temperature and density, exactly?
- When, exactly, does the medium reach local thermal equilibrium, if at all? When does it break down again? How long does the QGP live?
- How accurately can pQCD describe (i) the fireball medium? (ii) the interaction of hard probes with the medium?
- Do we need help from superstring theorists?!

Parton energy loss dE/dx

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

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

Baier, Dokshitzer, Mueller, Peigne, Schiff ('96), Zakharov ('97), Wiedemann ('00), Gyulassy, Levai, Vitev ('00), . . . :



4 formulations of radiative energy loss:

- ASW (Armesto-Salgado-Wiedemann)
- AMY (Arnold-Moore-Yaffe)
- HT (Higher Twist, Majumder-Wang)
- WHDG (Wicks-Horowitz-Djordjevic-Gyulassy)

Non-abelian radiative energy loss controlled by "transport coefficient" $\hat{q} = \frac{d(\Delta p_\perp)^2}{dt}$

$(= \mu_D^2/\lambda$ in pQCD medium).

Additionally, elastic collisions: transport coefficients $\hat{e} = \frac{dE}{dt}$ (elastic energy loss) and $\hat{e}_2 = \frac{d(\Delta E)^2}{dt}$

(diffusion in elastic energy transfer)

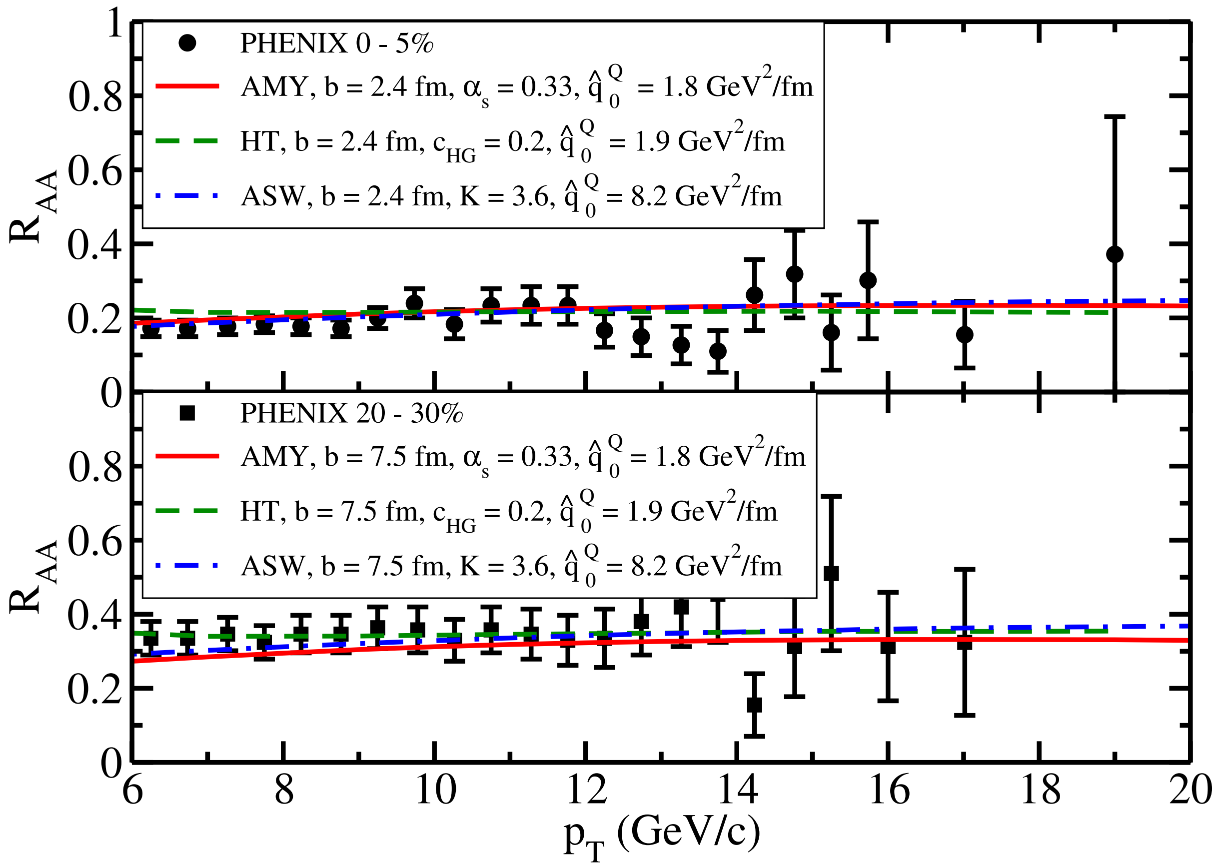
In thermal medium:

Isotropy, fluctuation-dissipation theorem $\Longrightarrow \frac{d(\Delta p_\perp)^2}{dt} \approx 2\frac{d(\Delta p_z)^2}{dt} \approx 2\frac{T}{|v|}\frac{dp_z}{dt} \quad (\hat{q} \approx 2\hat{e}_2 \approx 2\frac{T}{|v|}\hat{e})$

The "$\hat{q}$ problem"

Different formulations of radiative energy loss, using expanding thermalized pQCD medium, give wildly different $\hat{q}$ for same set of R_{AA} data:

(S. A. Bass et al., PRC 79 (2009) 024901)



Centrality dependence of R_{AA} cannot distinguish between formulations.

What is the origin of these large differences in $\hat{q}$?

Breakdown of soft radiation approximation (I)

Horowitz & Cole, 0910.1823:

Systematic comparison of ASW and WHDG implementations of the Gyulassy-Lévai-Vitev opacity expansion. To first order in opacity

$$x\frac{dN_g}{dx} = \int_0^{k_{\max}} \mathcal{K}(x, k_\perp; q_{\max})$$

Kernel $\mathcal{K}(x, k_\perp; q_{\max})$ derived in the collinear limit $k_\perp \ll xE$, by neglecting terms $\sim \frac{k_\perp}{xE}$.

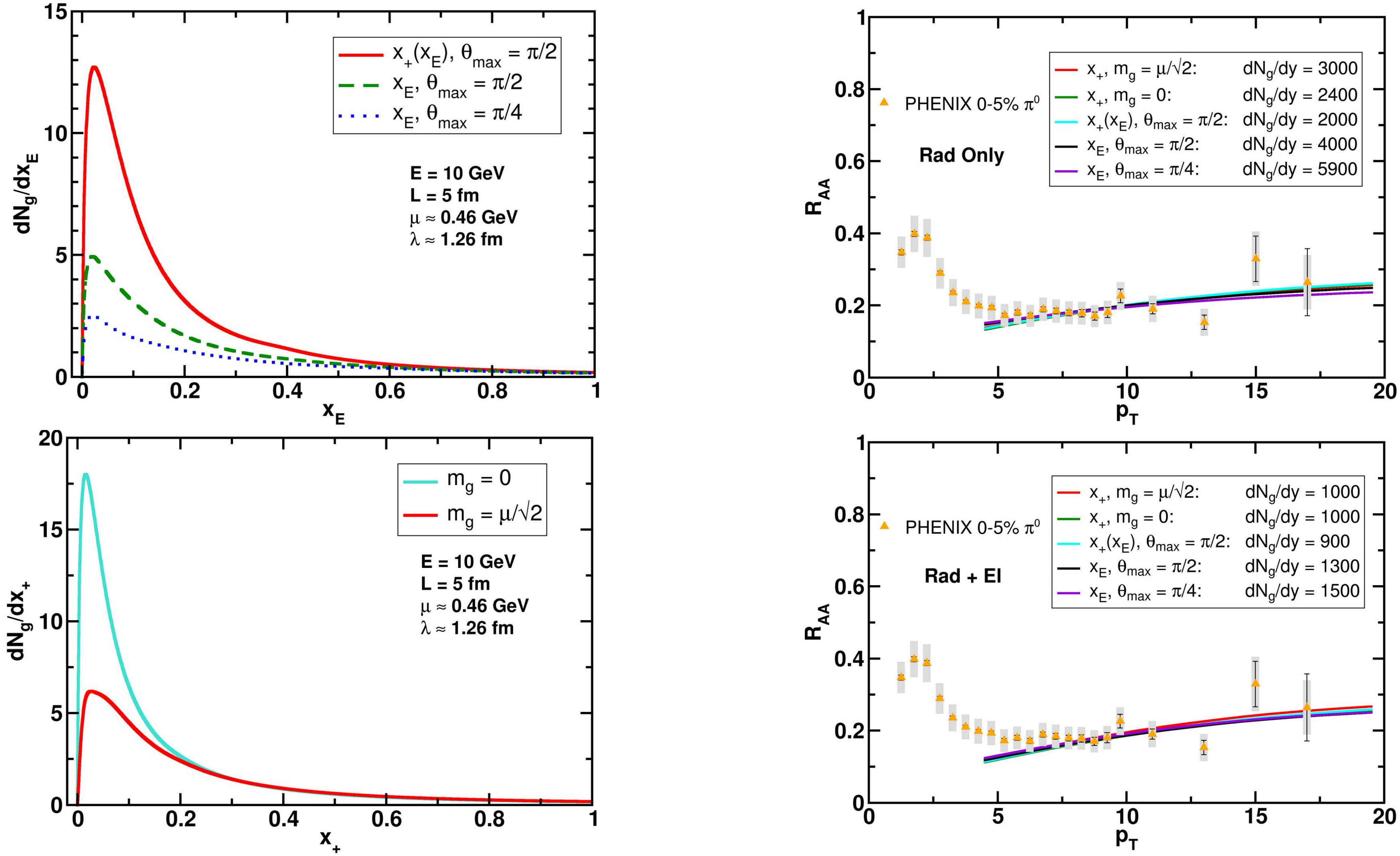
Collinear approximation breaks down badly near kinematic limit $k_{\max}$.
Radiated gluon spectrum and parton energy loss are very sensitive to

- the interpretation of x ($x = x_E \equiv \frac{k^0}{E}$ vs. $x = x_+ \equiv \frac{k^+}{E^+} = \frac{k^0+k_z}{k^0-k_z}$)
- the cutoff $\theta_{\max}$ for the opening angle for emitted radiation (related to $k_{\max}$)
- the thermal gluon mass ($m = 0$ vs. $m = \mu_D/\sqrt{2}$)

These sensitivities persist for $E \to \infty$!

Breakdown of soft radiation approximation (II)

W. Horowitz & B. Cole, arXiv:0910.1823



$\Longrightarrow$ For controlled parton energy loss calculations, need radiation kernel for large-angle emission, matched to small-angle emission kernel.

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Parton energy loss: perturbative or not? (I)

3 possibilities:

(1) pQCD (e.g. LO-HTL) medium probed by weakly interacting hard probe

(2) strongly coupled medium probed by weakly interacting hard probe

(3) strongly coupled medium probed by strongly coupled hard probe

New tool: Use of AdS/CFT correspondence to calculate energy loss in strongly coupled limit.

Comes in 2 flavors:

1. Liu, Rajagopal, Wiedemann:
   Weakly coupled probe ploughing through strongly coupled medium

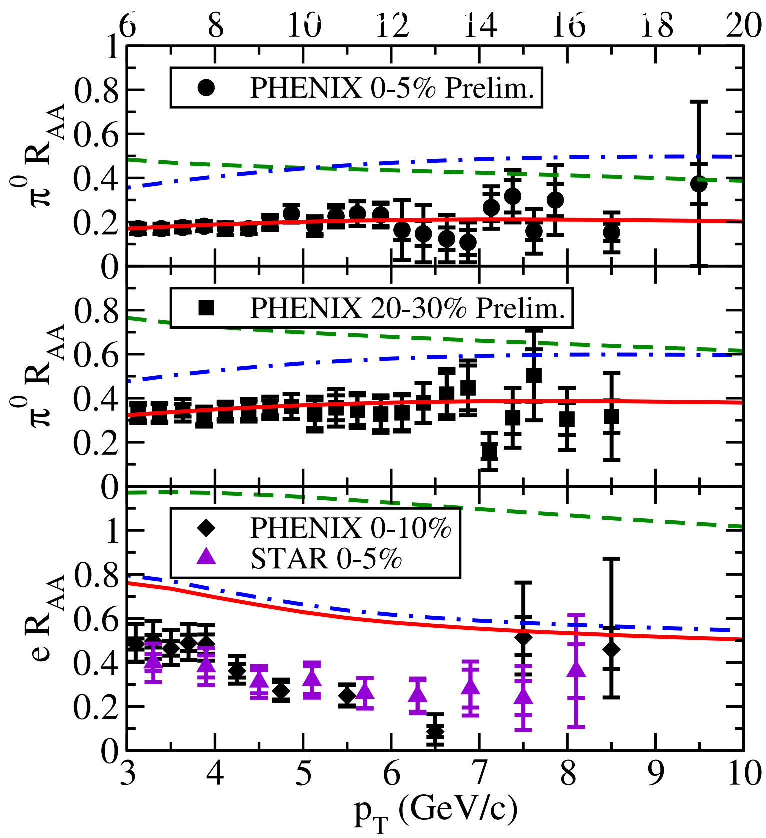
2. Gubser, Herzog, Chesler, Yaffe, . . . :
   Strongly coupled string moving through strongly coupled medium

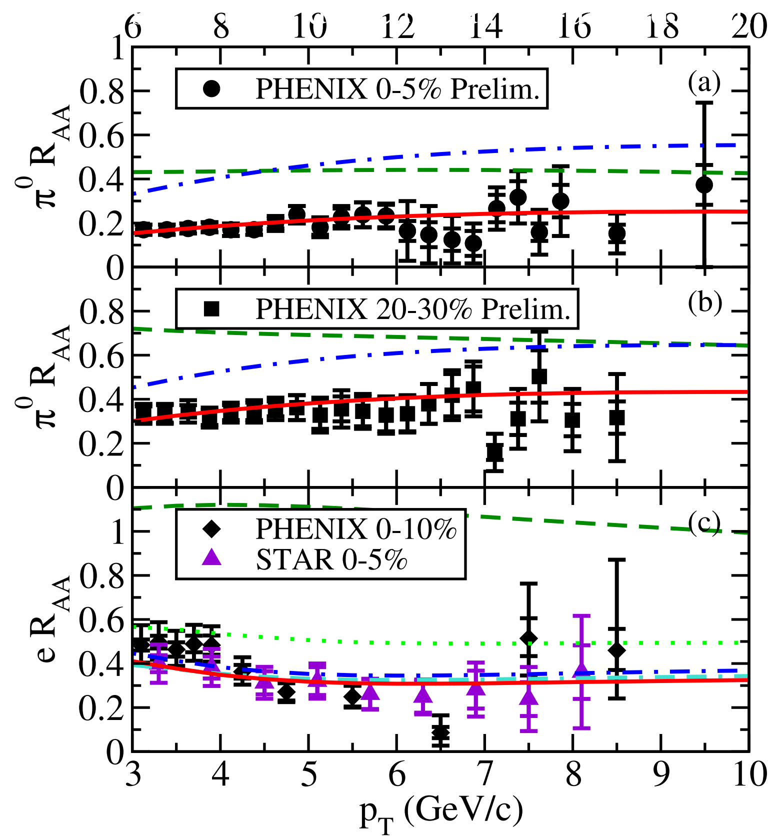
Parton energy loss: perturbative or not? (II)

Use pQCD probe within HT formalism to compute R_{AA} for light and heavy flavors, but parametrize $\hat{q} = 2\hat{e}_2 = (2T/|v|)\hat{e}$ nonperturbatively ($\hat{q} = CT^3$, C = nonperturbative constant).

Allow for flavor dependent $\hat{q}$, $C_q \neq C_c \neq C_b$. Best fit: $\hat{q}_q \approx 0.9\hat{q}_c \approx 0.6\hat{q}_b$.

G.-Y. Qin & A. Majumder, arXiv:0910.xxxx





$\hat{q}_q^{\rm HTL} = C_R \alpha_s m_D^2 T \ln[4ET/m_D^2]$ $\qquad$ $\hat{q}_Q = CT^3 (= 2\,\mathrm{GeV}^2/\mathrm{fm}\ @\ T = 400\,\mathrm{MeV})$

- Observed heavy quark energy loss too strong for a weakly coupled LO-HTL medium
- Non-perturbative parametrization of $\hat{q}$ provides simultaneous successful description of both R_{AA} and v_2 for both π^0 and heavy flavor decay e.
- **No need (yet) to doubt weak interaction between probe and medium!**

Summary:

RHIC data provide evidence for

- fast thermalization $(\tau_{\rm therm} < 1\,\text{fm}/c)$
  at high initial density and temperature $(e_0 > 10\,e_{\rm cr},\ T_0 \sim 2\,T_{\rm cr})$.
- almost perfect fluidity (very low viscosity)
- dynamical deconfined quark degrees of freedom
- statistical hadronization through a phase transition at $T_{\rm cr} \approx 170\,\text{MeV}$
- strong opacity to colored probes
- strong collective coupling among plasma constituents

Turning these into precise quantitative statements is hard work.
The state of the art is:

- The specific shear viscosity of the QGP at RHIC temperatures is $1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$.
- The quark energy loss parameter is presently uncertain by about a factor 10, $\hat{q}/T^3 \sim 3-25$. Improved radiation kernel and consistent inclusion of elastic energy loss needed to narrow this down.
- There are indications that the transport parameters describing the collective dynamics of the QGP and its action on hard probes may be non-perturbative in nature while its interaction with hard probes remains perturbative $\Longrightarrow$ good news for the JET program.

Supplements

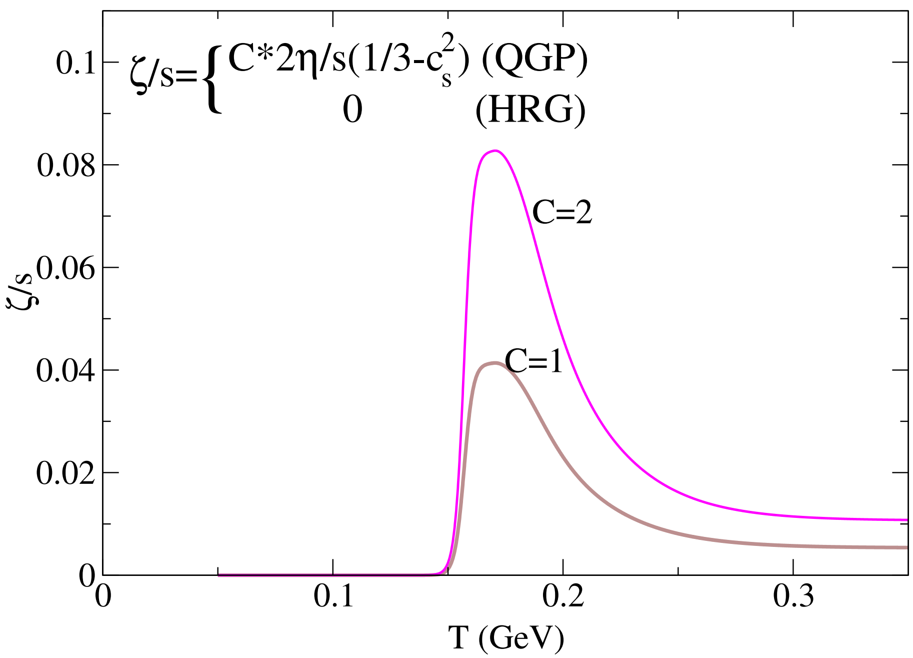
Bulk viscosity as a contaminant in extracting η/s from v_2

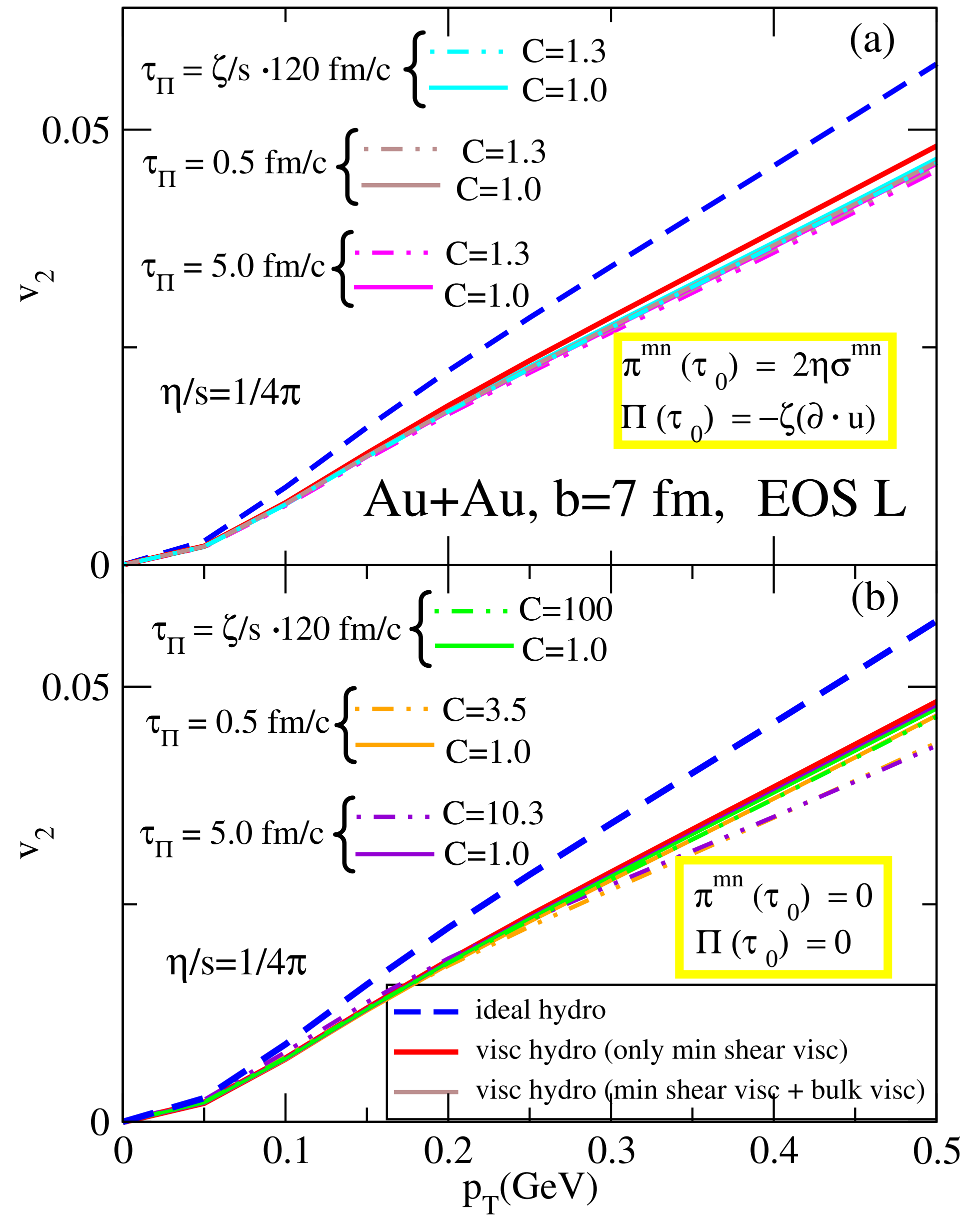
H. Song, UH, 0909.1549

$$p \rightarrow p + \Pi$$

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left(\Pi + \zeta \nabla\cdot u\right) + 2^{\rm nd} \text{ order}$$

ζ/s and τ_Π peak near T_c!



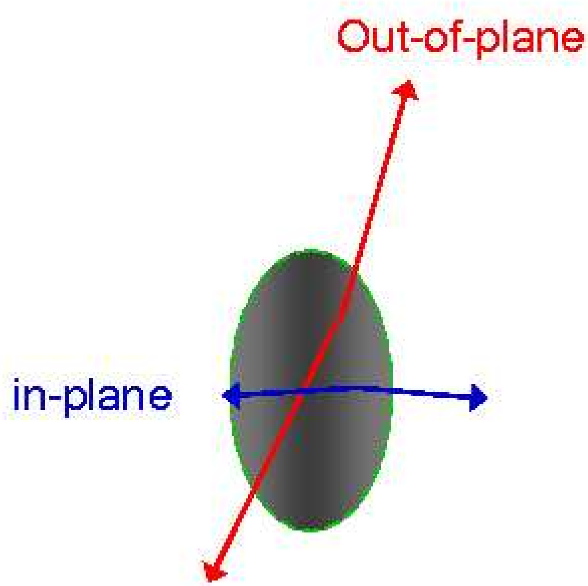


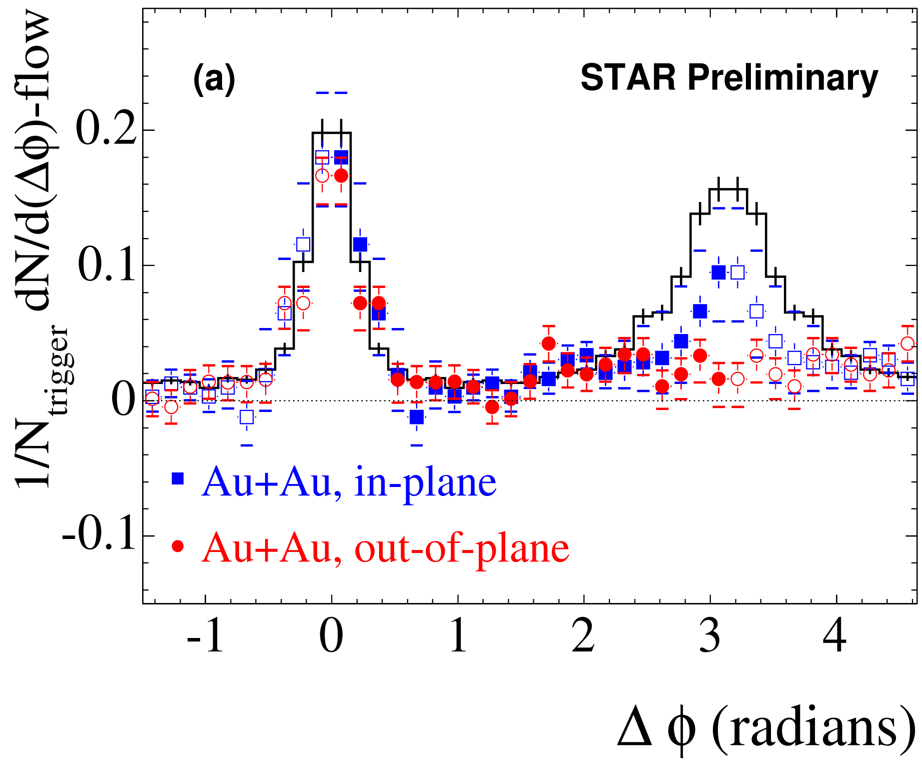
- bulk viscosity reduces both radial and elliptic flow
- even for $\eta/s \sim 1/4\pi$, bulk viscous effects on v_2 are $< 15-20\%$ of shear viscous suppression (relief!)

Path length dependence of parton energy loss:

STAR Coll., nucl-ex/0403018, Quark Matter 2004

Emission angle dependence:



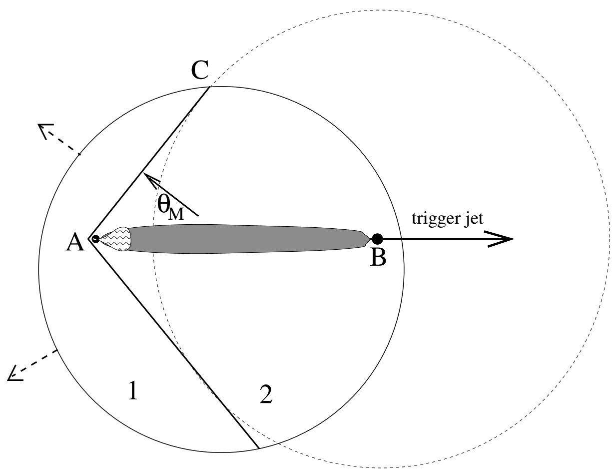


- medium opaque for colored particles
- energy loss increases strongly with path length

Mach cones from quenching jets?

Evidence for a "sonic boom"?!

Shuryak et al., hep-ph/0411315



Away-side jet creates Mach cone at $\cos\theta_M = \frac{c_s}{c}$

$\Longrightarrow$ $\theta_M \approx 63^\circ \approx 1.1\,\text{rad}$

PHENIX Coll., PRL 97 (2006) 052301 (fig. courtesy W.A.Zajc)