Heavy Ion Physics from RHIC to LHC

Joe Kapusta

University of Minnesota

University of Seoul
19 April 2008

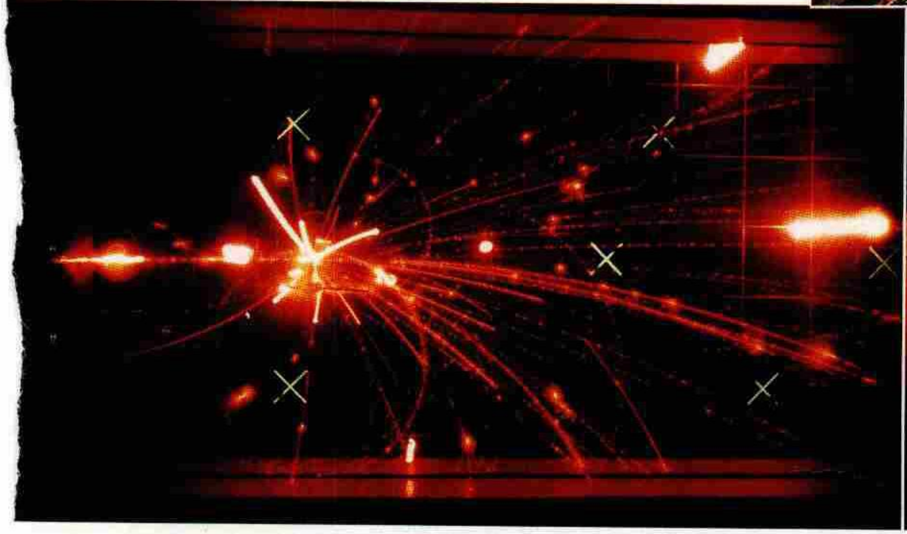
Bevatron + SuperHILAC = Bevalac

Purpose: Create dense nuclear matter
in the laboratory for a brief moment.

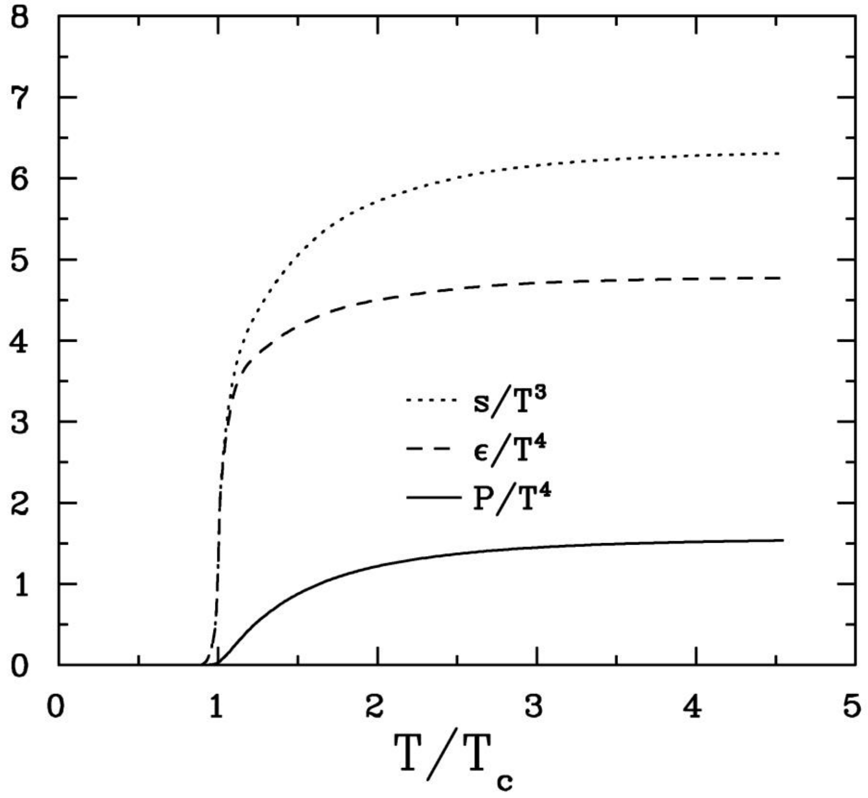
- 1974-75: Beams of carbon and oxygen accelerated to 2.1 GeV/nucleon.
- 1981-82: Upgraded to accelerate beams up to uranium at 1 GeV/nucleon.
- 1993: Turned off for the last time, being eclipsed by the higher energies available at the AGS at BNL and at the SPS at CERN.

In the early 1970s Tsung Dao Lee and Gian-Carlo Wick discussed the possibility that a new phase of nuclear matter might exist at high density, and that this new phase of matter might lie lower in energy than the more common type of matter in a nucleus. The Bevalac seemed to be the ideal instrument with which to make and discover this new matter: If it existed and was more stable than ordinary matter, it would accrete ordinary matter and grow. Eventually it would become so massive that it would fall to the floor of the experimental hall and be easily observed. But what would stop it from eating the Earth? Knowledge of dense nuclear matter was so poor at that time that the possibility of this disaster was taken seriously. Meetings were held behind closed doors to decide whether or not the proposed experiments should be aborted.

Experiments were eventually performed, and fortunately no such disaster has yet occurred. The behavior of nuclear matter in heavy-ion collisions turns out to be very different from this early picture.



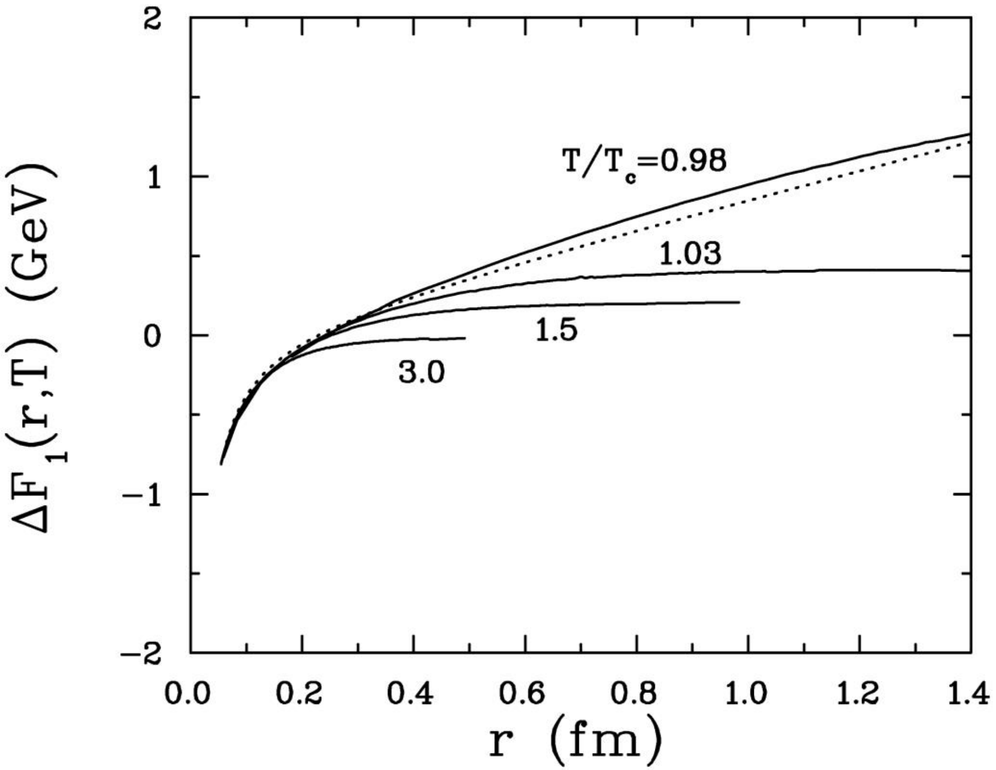
Lattice Gauge Theory w/o Dynamical Quarks

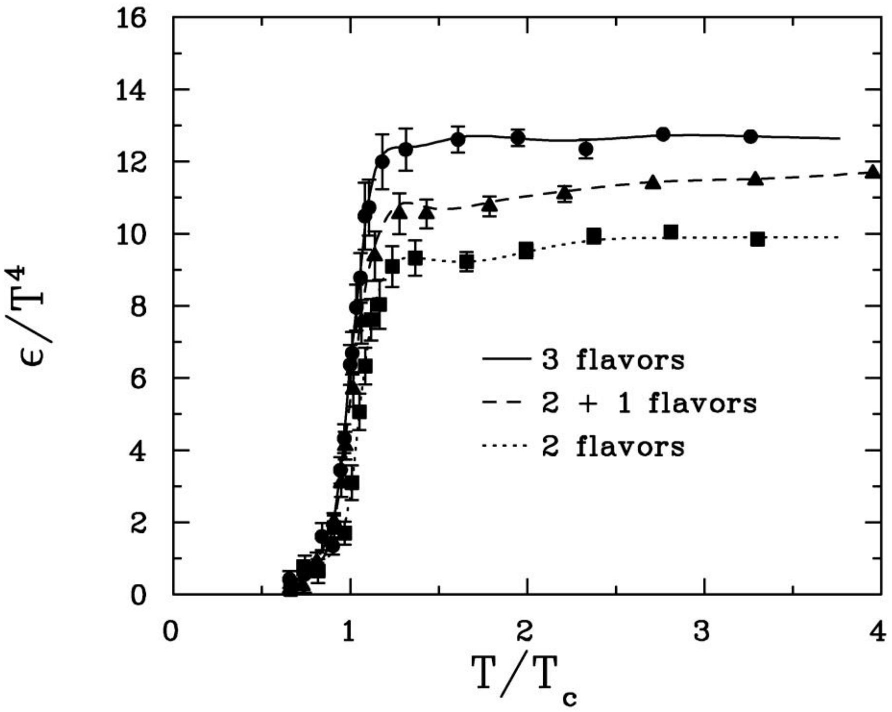


Equation of state exhibits first order phase transition

Calculations by Bielefeld group.

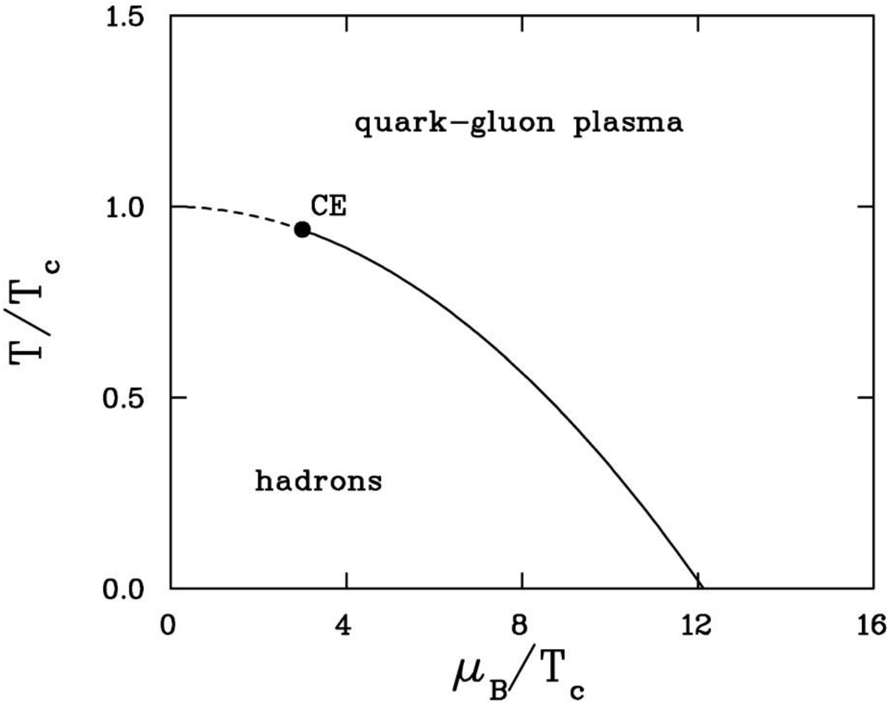
Heavy quarks are deconfined beyond the transition temperature





For realistic quark masses there may be a line of 1st order transition terminating at a critical point.

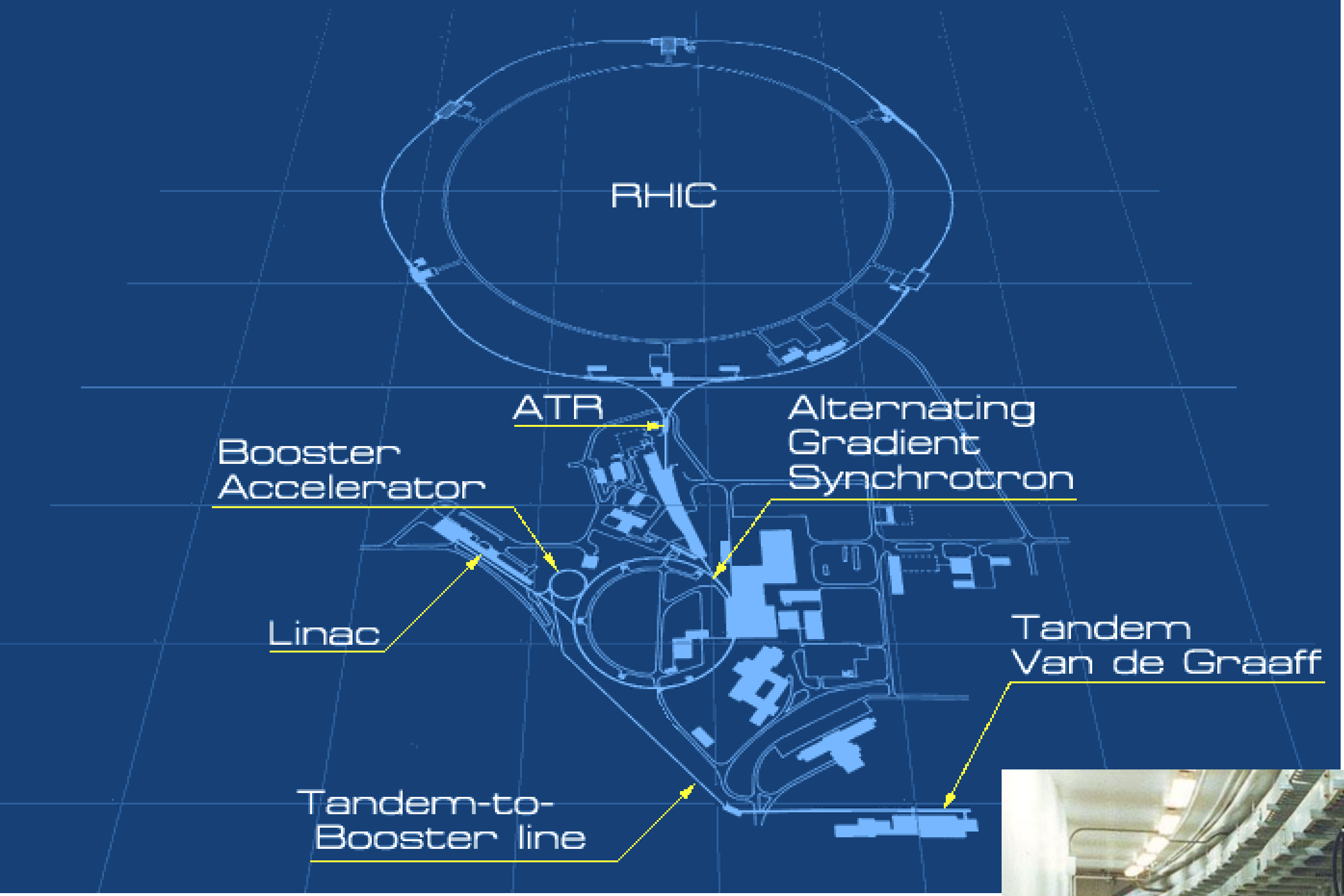
de Forcrand, Philipsen



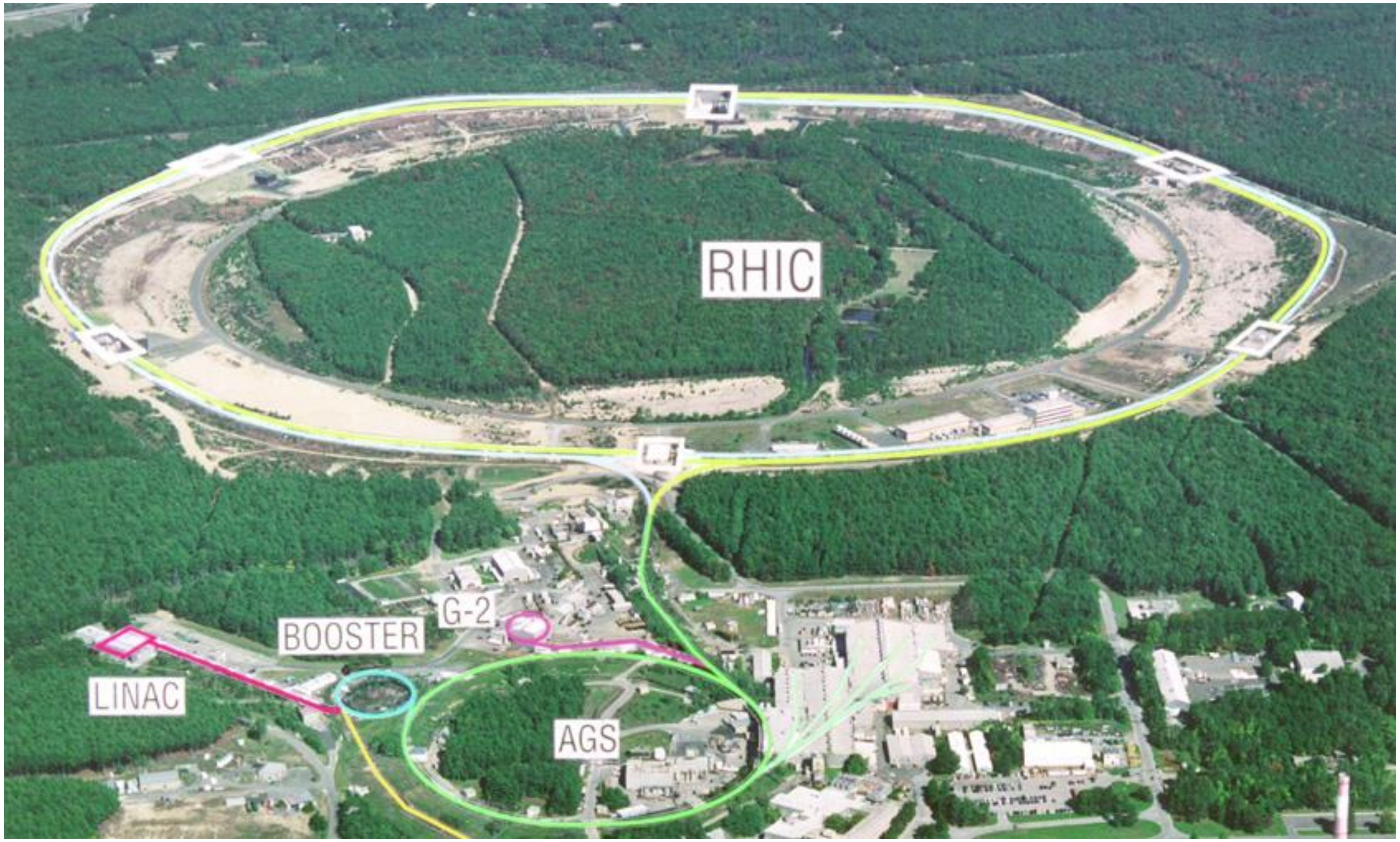
The phase transition is 2nd order for 2 massless flavors and 1st order for 3, otherwise a rapid crossover.

Karsch, Laermann, Peikert

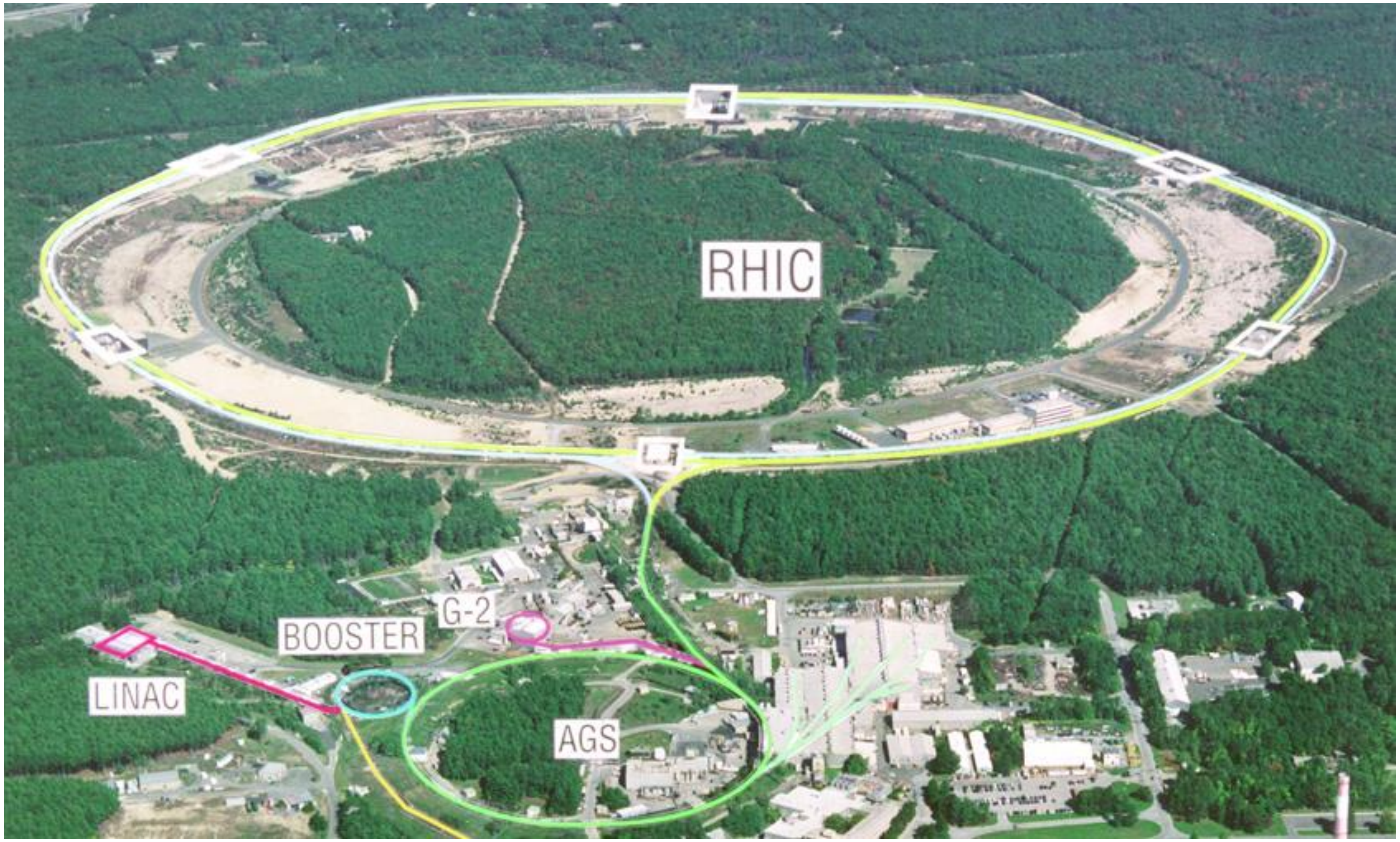
Colliding beams
of
100 GeV/nucleon
gold nuclei to
create
quark-gluon
plasma.



What has RHIC told us about the equation of state?



How does RHIC connect to other fields like cosmology and condensed matter physics?



Pictorial of a Heavy Ion Collision

Hard parton scattering & jets

Strong classical fields

Quark-Gluon Plasma

Hydrodynamic flow

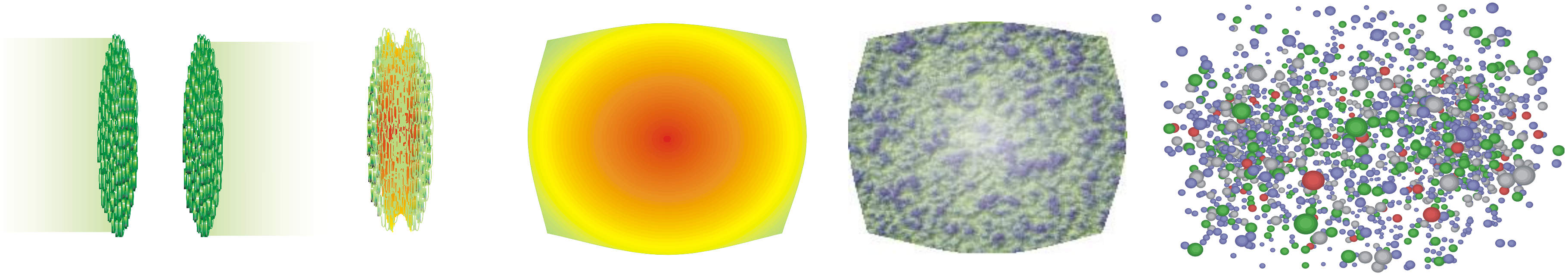
Hadronization

Hadronic rescattering

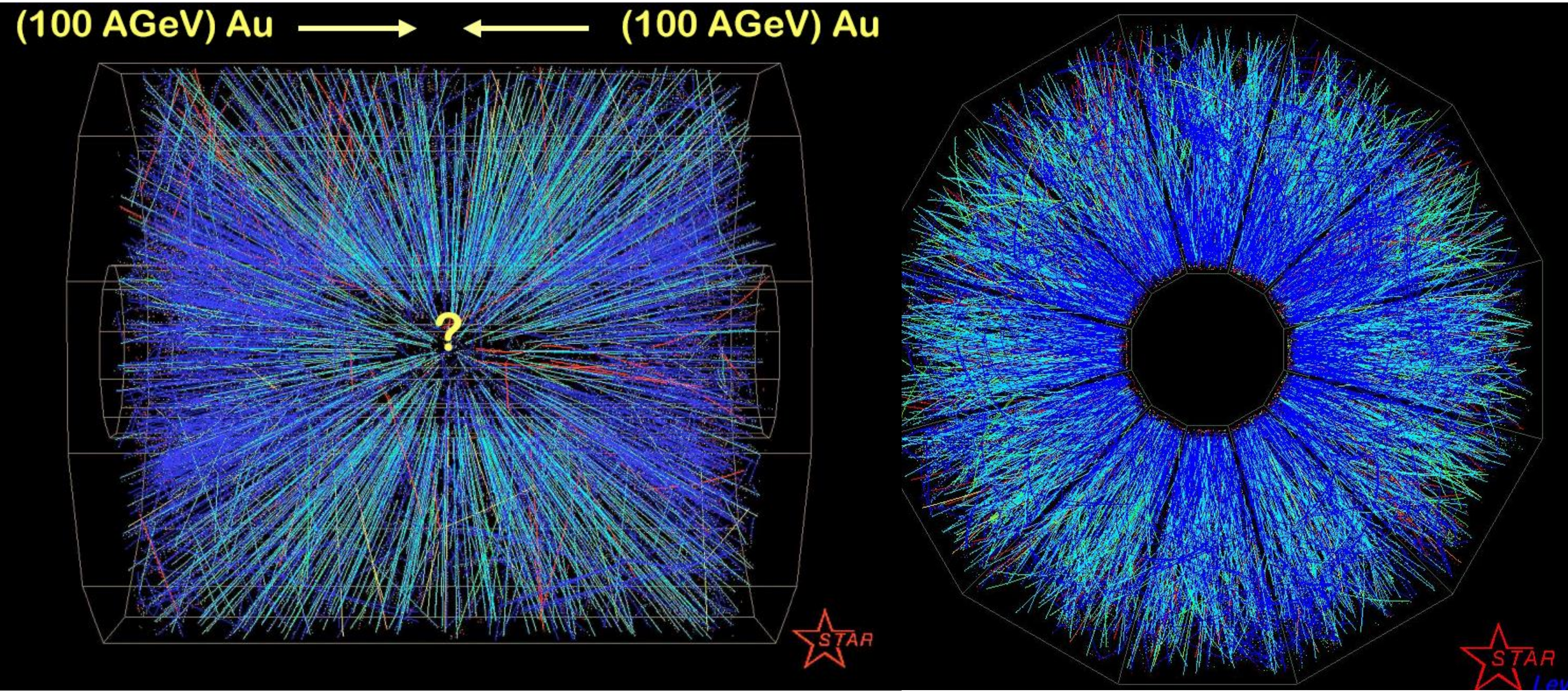
< 1fm/c

~ 10 fm/c

Time



Au+Au Collisions



Thousands of particles created!

Are collisions at RHIC just superpositions of nucleon-nucleon collsions?

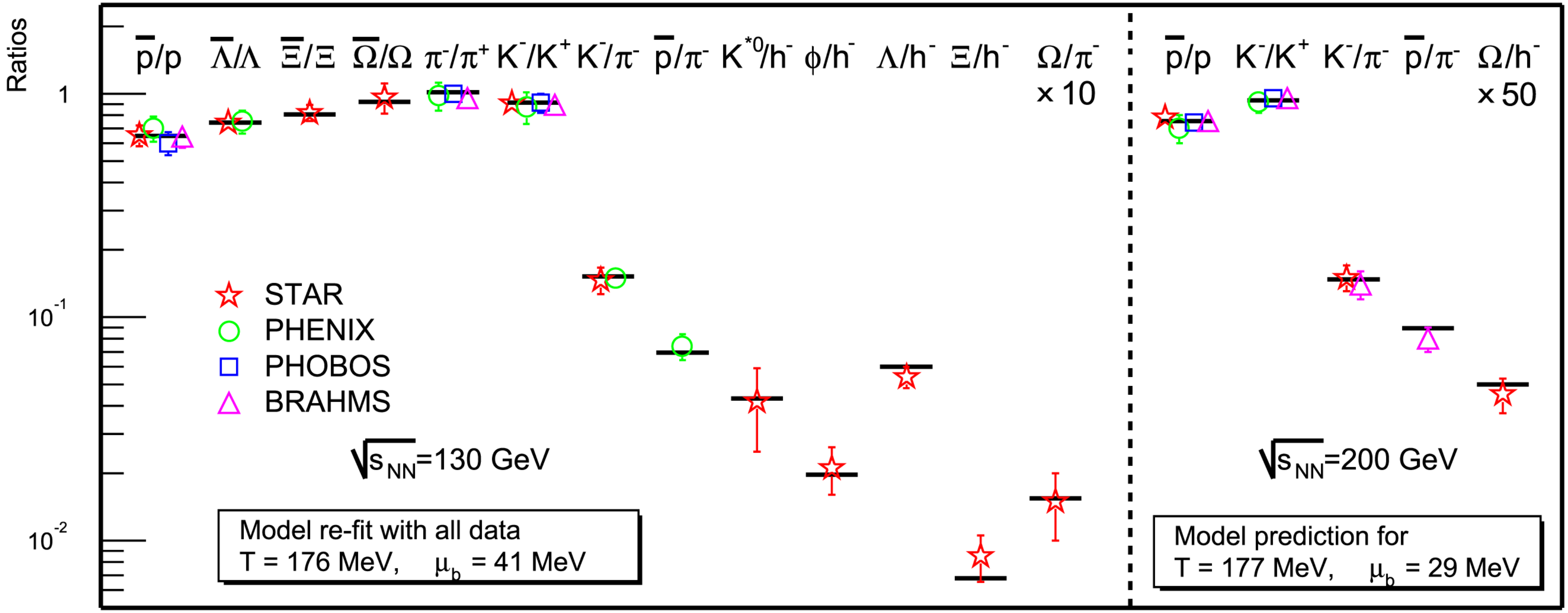
Are collisions at RHIC just superpositions of nucleon-nucleon collsions?

Absolutely not!

Temperature

- Hadron ratios:

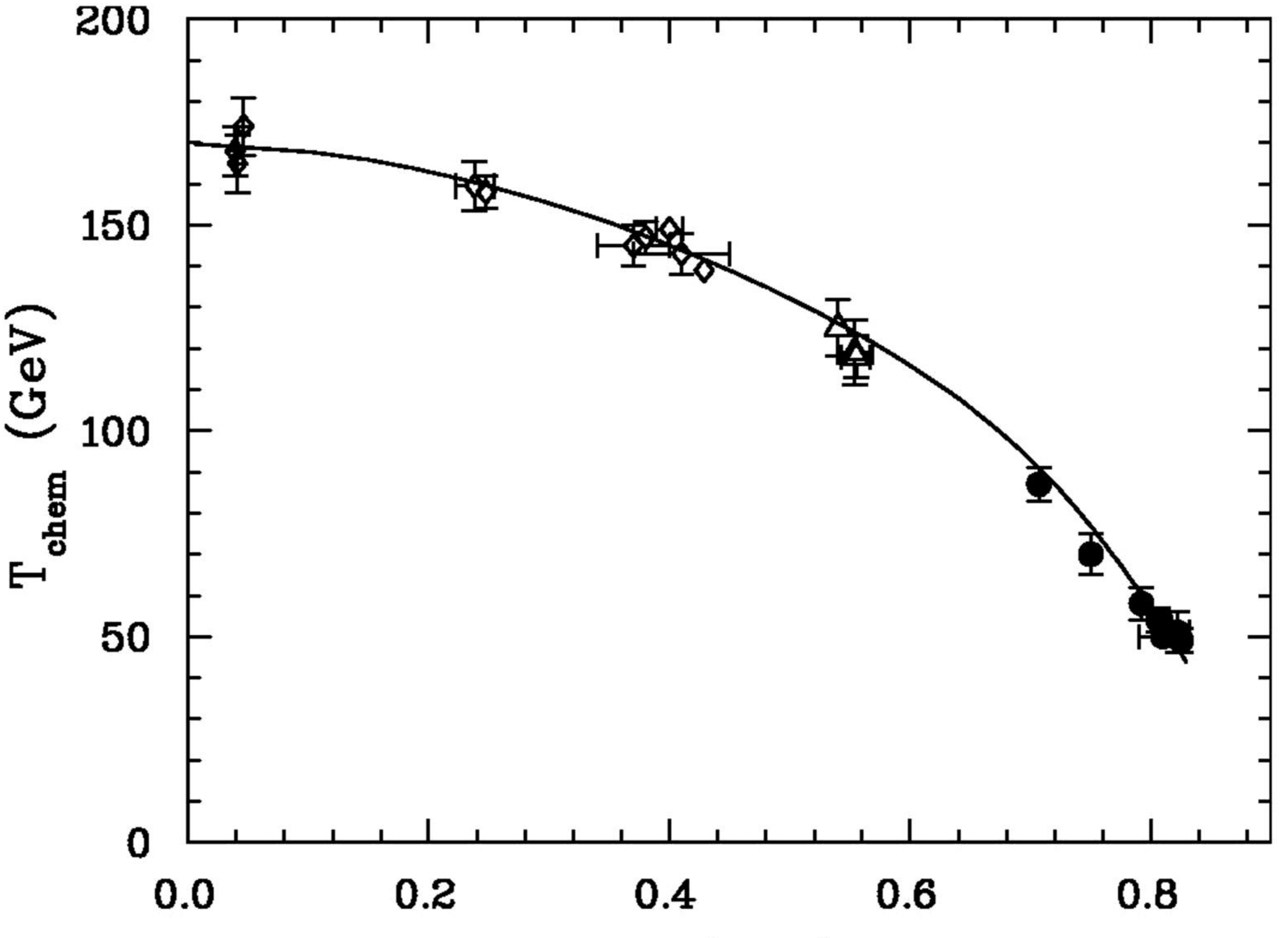
$$n_i(T,\mu) = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{e^{(E_i-\mu_i B_i-\mu_s S_i)/T}\pm 1}$$



Braun-Munzinger et al., PLB 518 (2001) 41

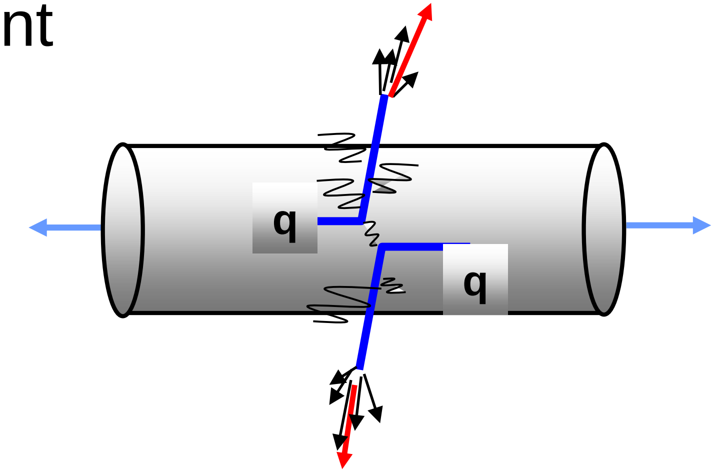
D. Magestro (updated July 22, 2002)

Compilation of freezeout conditions from the SIS, AGS, SPS and RHIC.



Hard Probes

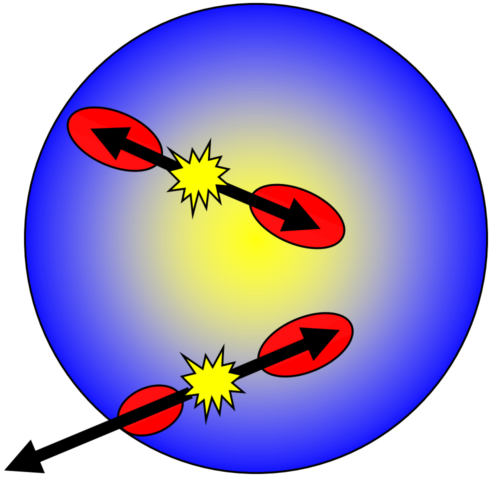
- Use hard processes as plasma probes
  - hard processes ⇨ jet production, photons, etc.
  - Calibration under control
    - perturbative calculations
    - p+p baseline experiment

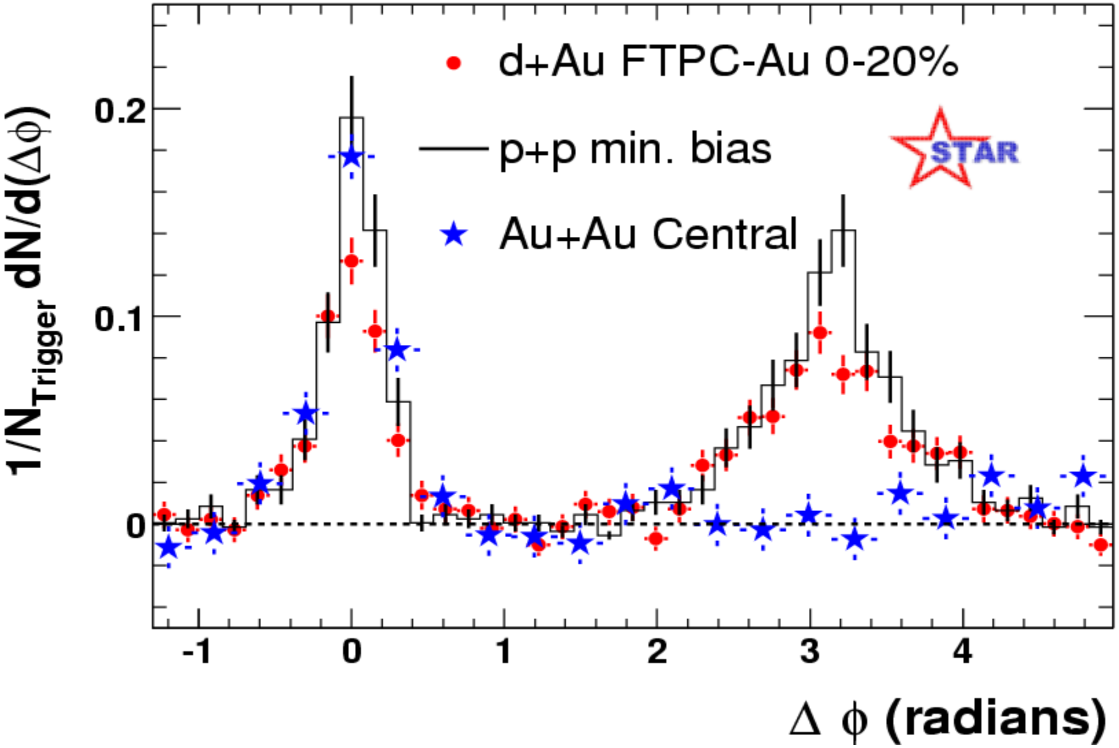


- Strong final state interactions for jets
  - Energy loss of fast quarks/gluons traveling through the plasma ⇨ jet quenching

Jet Quenching

- Away-side jets vanish
  - Trigger on a high p_T hadron and look for associated hadron as a function of relative azimuthal angle and rapidity

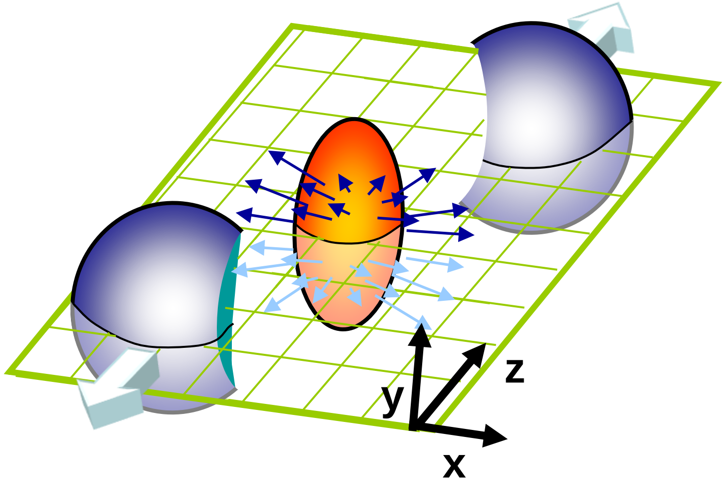




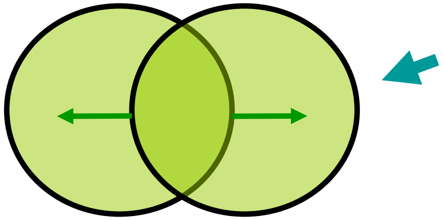
The away side jet is absorbed in the medium

Elliptic Flow

- Finite impact parameter *b* > 0:
  - Spatial anisotropy in the initial state
  - Momentum anisotropy in the final state



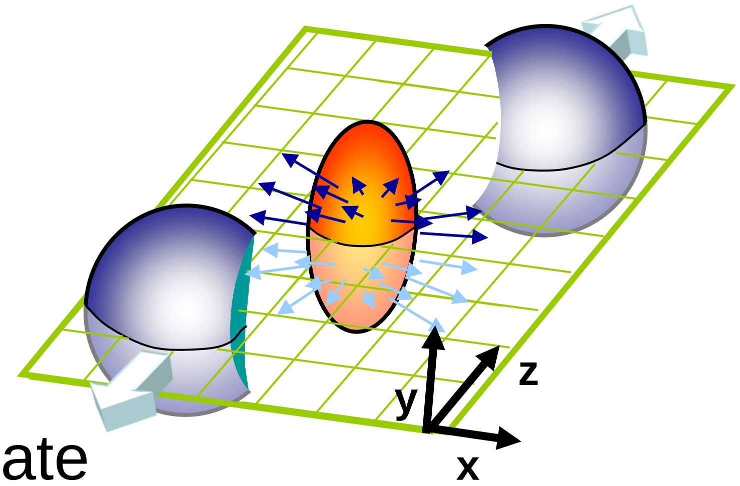
- coordinate space ↔ momentum space



Infer equation of state of the system?

$$Force = -\nabla P$$

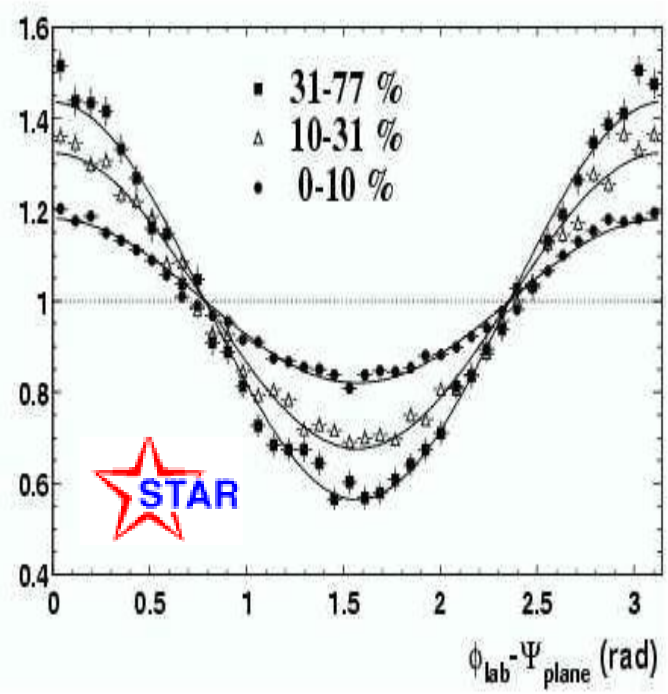
Elliptic Flow



- Nonzero impact parameter *b* > 0:
  - – Spatial anisotropy in the initial state
  - – Momentum anisotropy in the final state
- coordinate space ↔ momentum space
- Fourier analysis

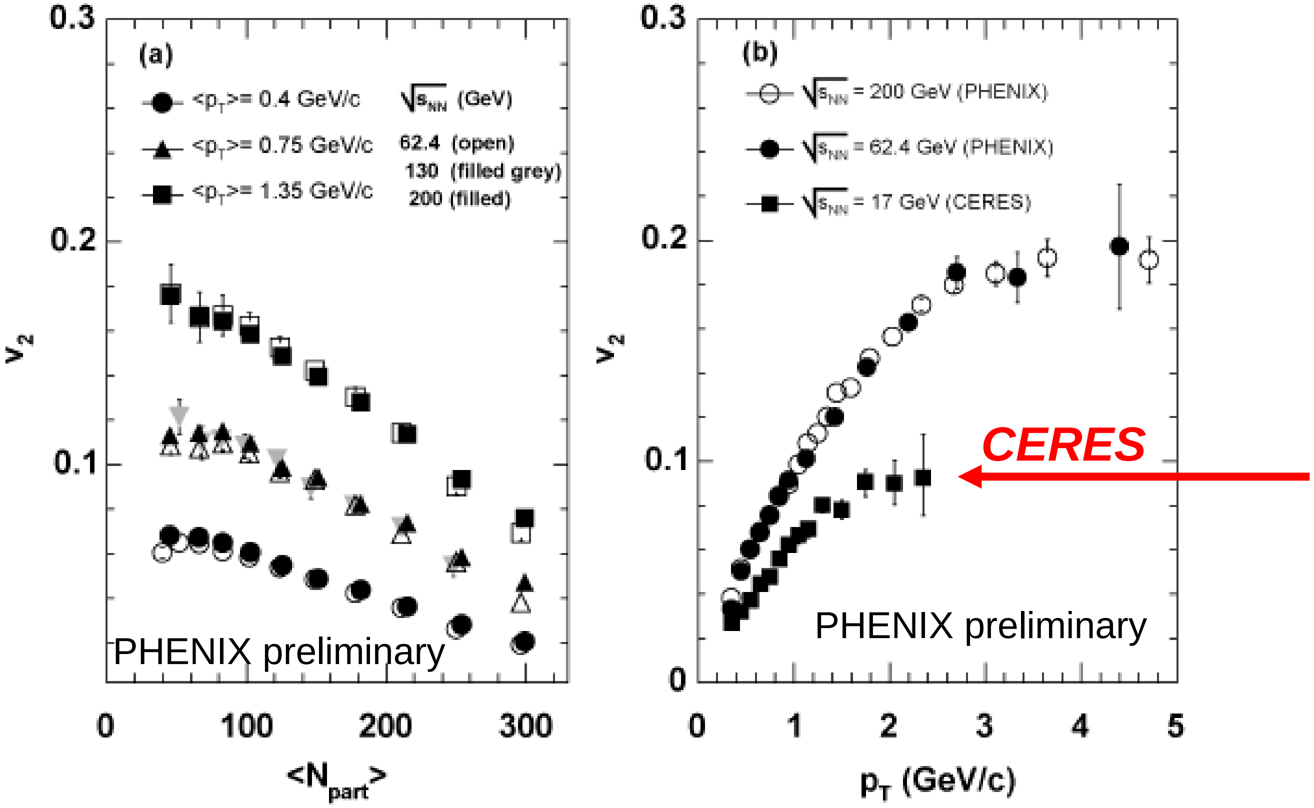
  => v_2 = elliptic flow

$$\frac{dN}{P_T dP_T d\varphi} = \frac{dN}{2\pi P_T dP_T}\left[1 + 2\sum_n v_n(P_T)\cos(n\varphi)\right]$$



How special is this matter?

$\sqrt{s_{NN}} = 17.2, 62.4,\ 130\ \&\ 200\ \text{GeV}$



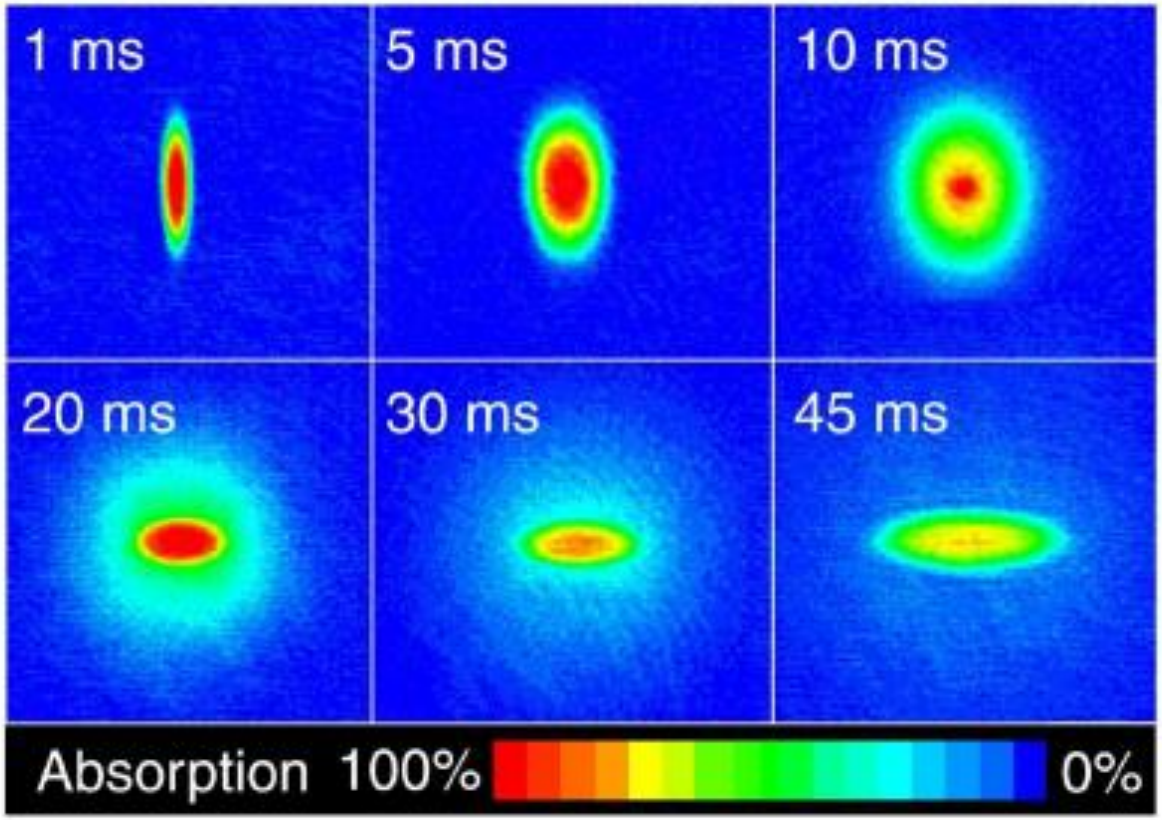
Results are strikingly similar for $\sqrt{s_{NN}} = 62.4,\ 130\ \&\ 200\ \text{GeV}$

V_2 decreases by ~ 50% from RHIC to SPS

Significantly larger pressure (gradients) developed at RHIC

^{23}Na atoms

Ketterle group, MIT



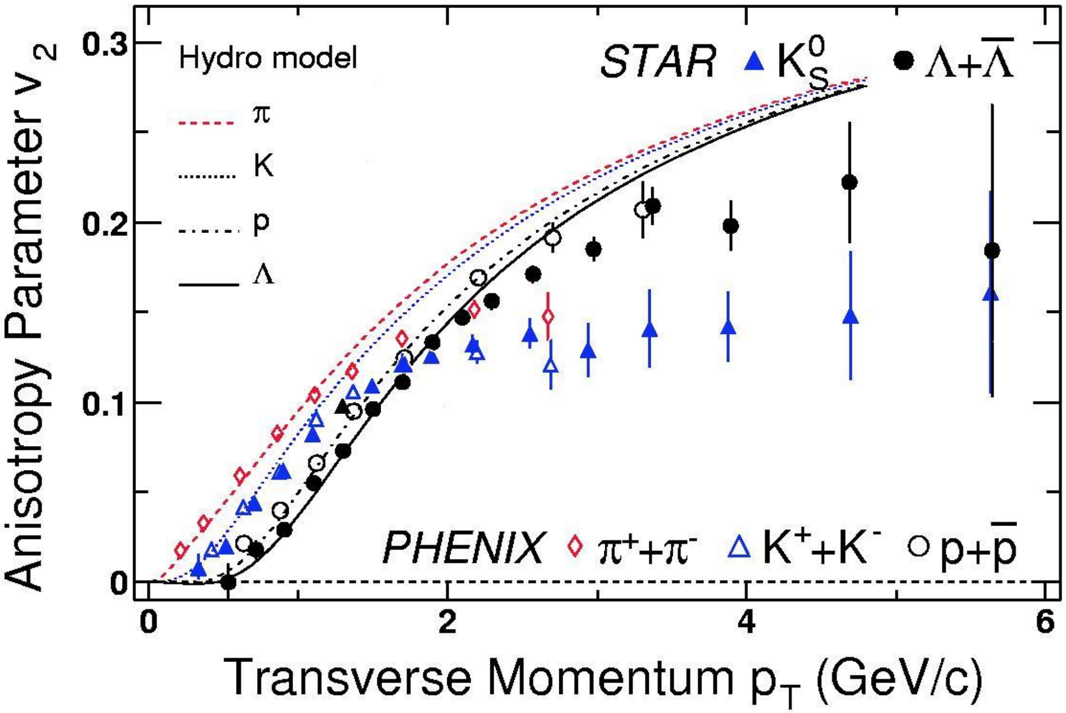
Anisotropic expansion of a Bose-Einstein condensate

Numerical Hydrodynamics

(Huovinen, Kolb, Heinz, Hirano, Teaney, Shuryak, Hama, Morita, Nonaka, Bass)

Assume thermalization between 0.15 and 1 fm/c.

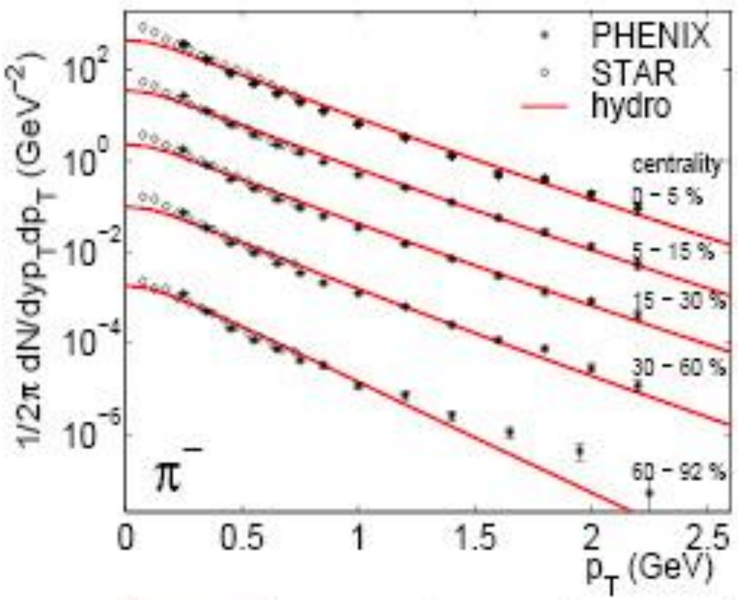
Agreement provides strong indication for early thermalization and collective flow.

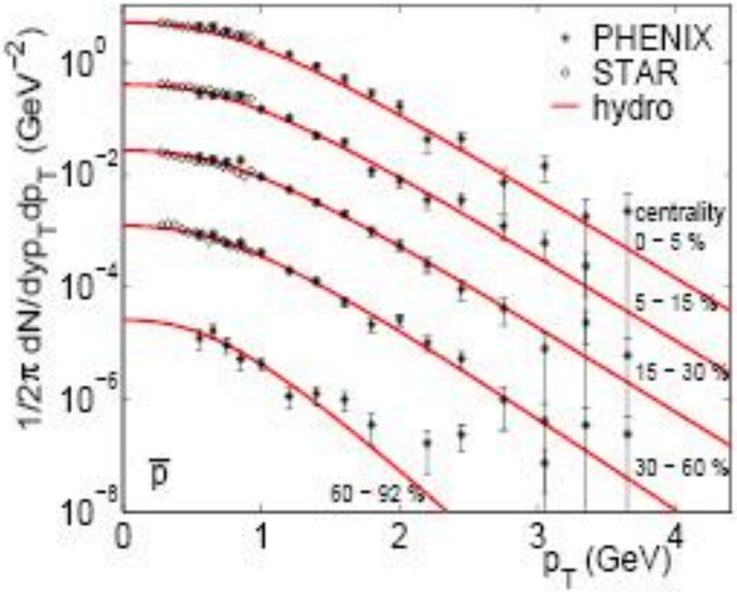


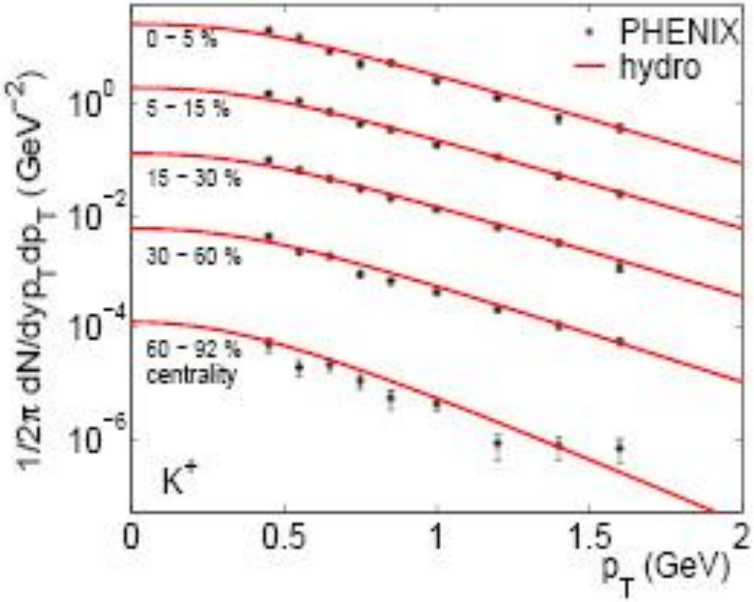
Numerical Hydrodynamics

Model parameters fixed by π and $\bar{p}$ at $b = 0$, the rest are predictions (Heinz and Kolb)

$$\boxed{H_{\text{RHIC}} / H_{\text{Universe}} = 2\times 10^{40}}$$







Big Theoretical Motivation!

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

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

Using the Kubo formula $\eta = \frac{1}{20} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x \, e^{i\omega t} \left\langle \left[T^{ij}_{\text{traceless}}(x), T^{ij}_{\text{traceless}}(0) \right] \right\rangle$

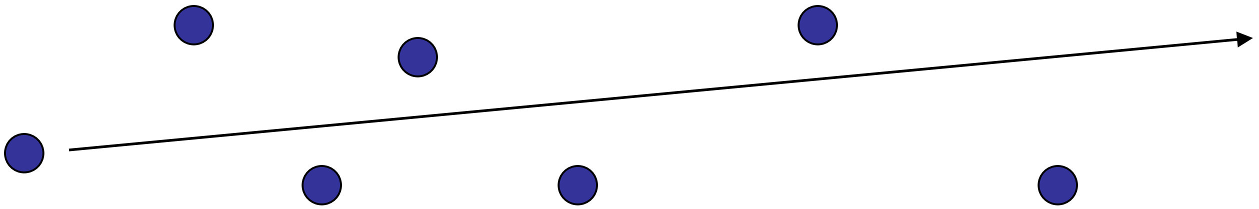
the low energy absorption cross section for gravitons on black holes, and the black hole entropy formula they found that

$\eta / s = 1/4\pi$ and conjectured that this is a universal lower bound.

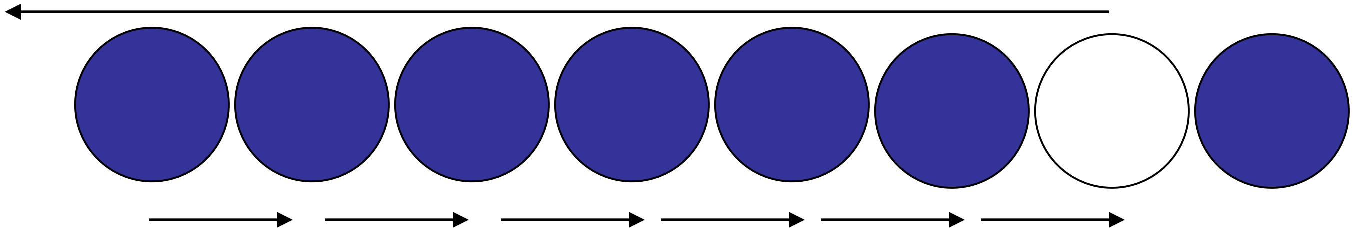
Atomic and Molecular Systems

In classical transport theory $\frac{\eta}{s} \sim T l_{\text{free}} \bar{v}$ and $l_{\text{free}} \sim \frac{1}{n\sigma}$

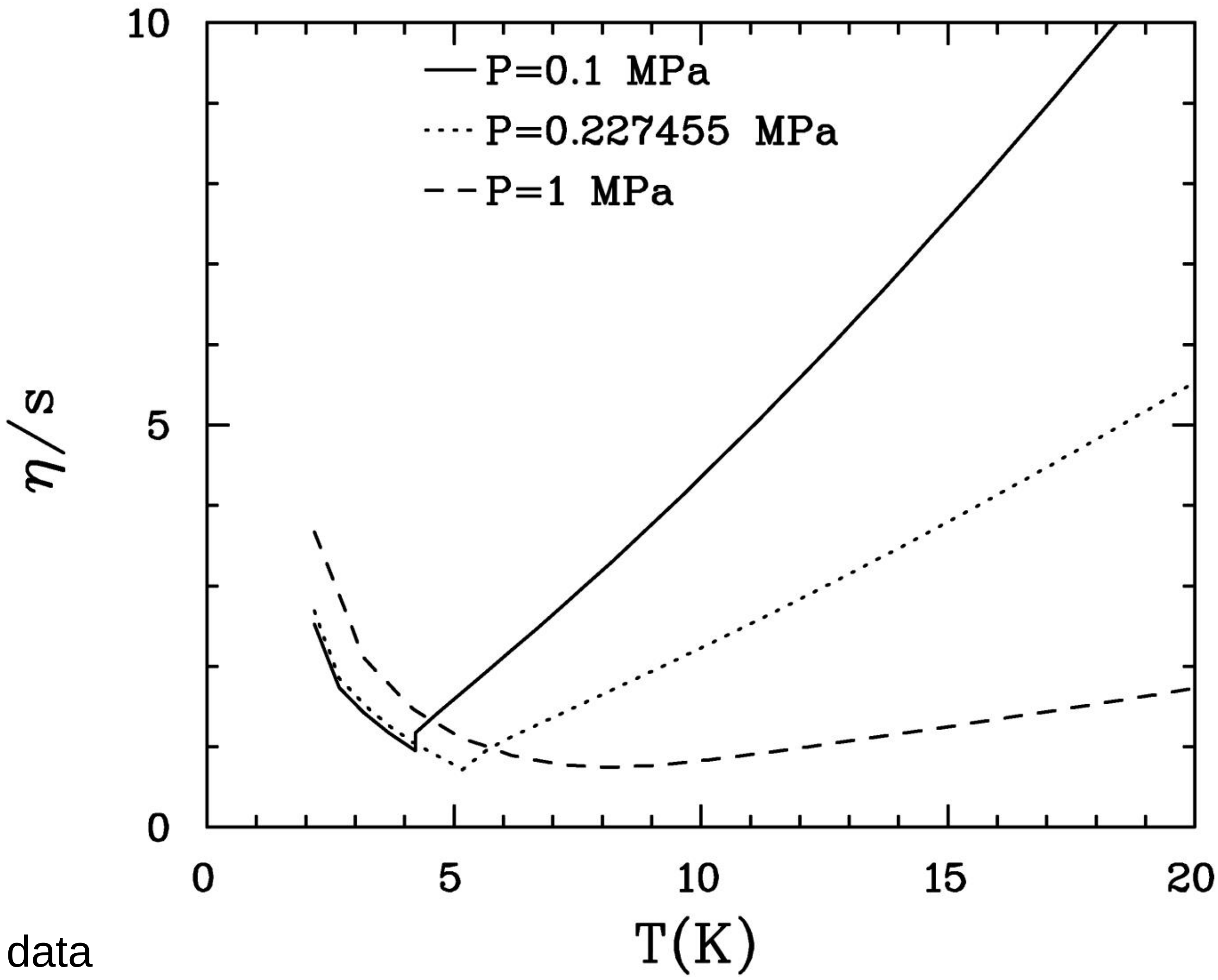
so that as the density and/or cross section is reduced (dilute gas limit) the ratio gets larger.



In a liquid the particles are strongly correlated. Momentum transport can be thought of as being carried by voids instead of by particles (Enskog) and the ratio gets larger.

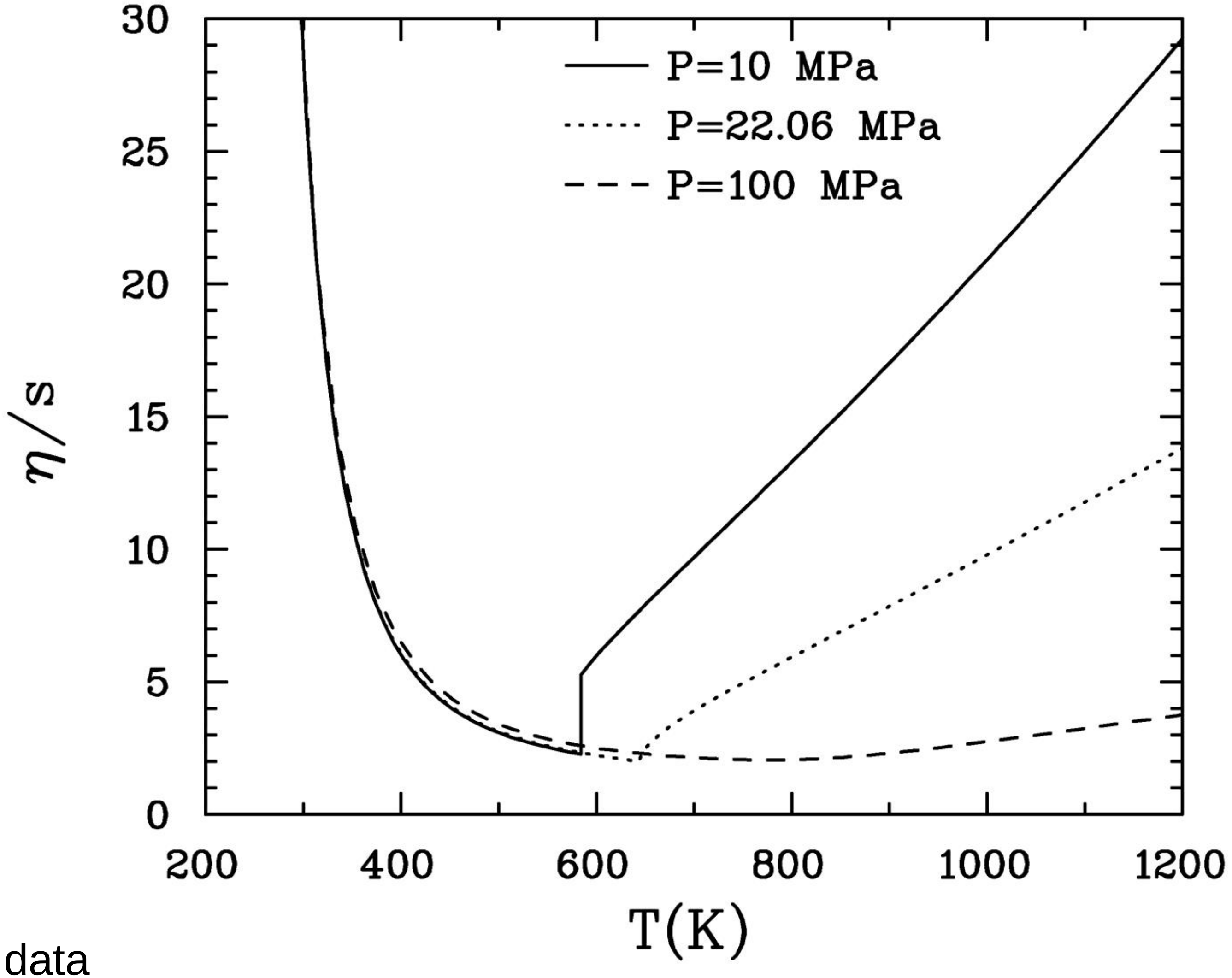


Helium

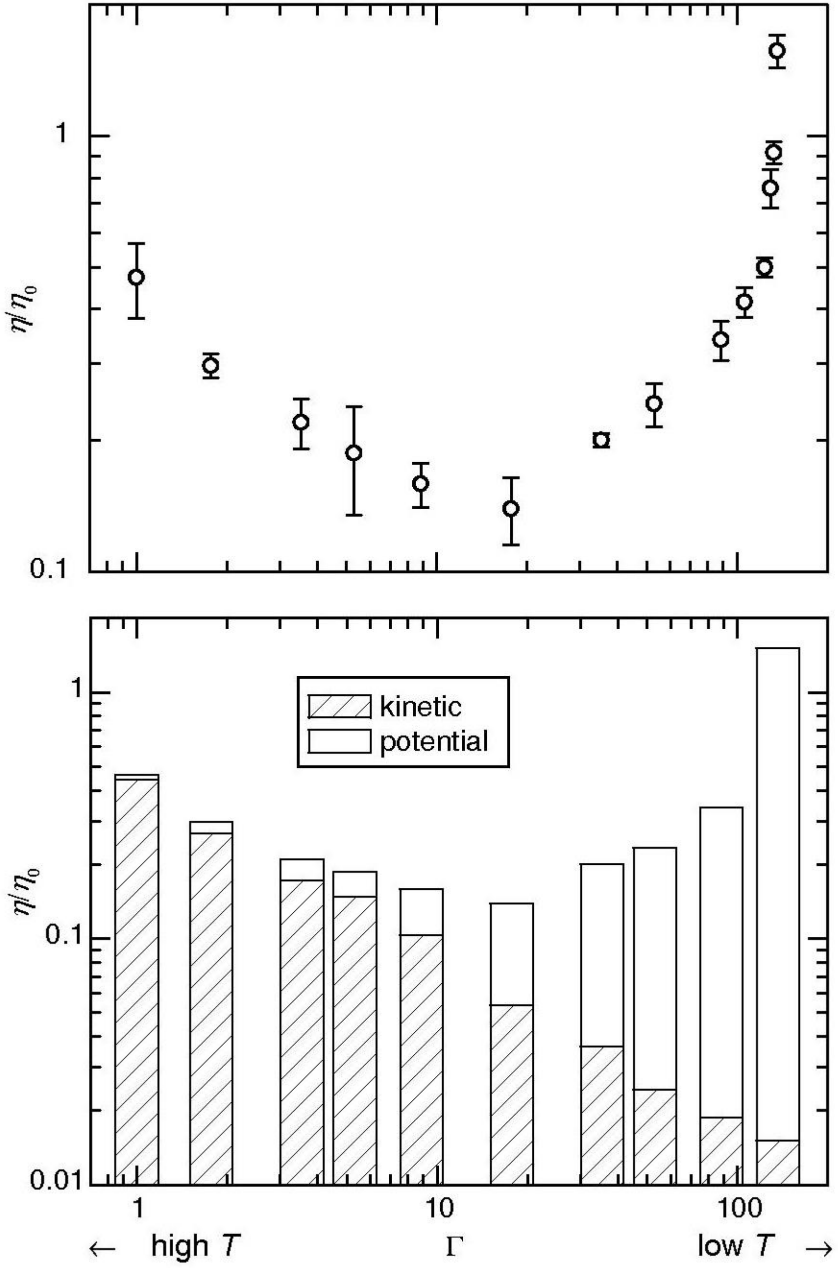


NIST data

H_2O



NIST data



2D Yukawa Systems in the Liquid State

Minimum located at

$$\Gamma = \frac{Q^2}{aT} = \text{Coulomb coupling parameter} \approx 17$$

$$a^2 = \frac{1}{\pi n} = \text{Wigner-Seitz radius}$$

Applications to dusty-plasmas and many other 2D condensed matter systems.

Liu & Goree

QCD

- Chiral perturbation theory at low T (Prakash *et al*.): grows with decreasing T.

$$\frac{\eta}{s} = \frac{15}{16\pi}\frac{f_\pi^4}{T^4}$$

- Quark-gluon plasma at high T (Arnold, Moore, Yaffe): grows with increasing T.

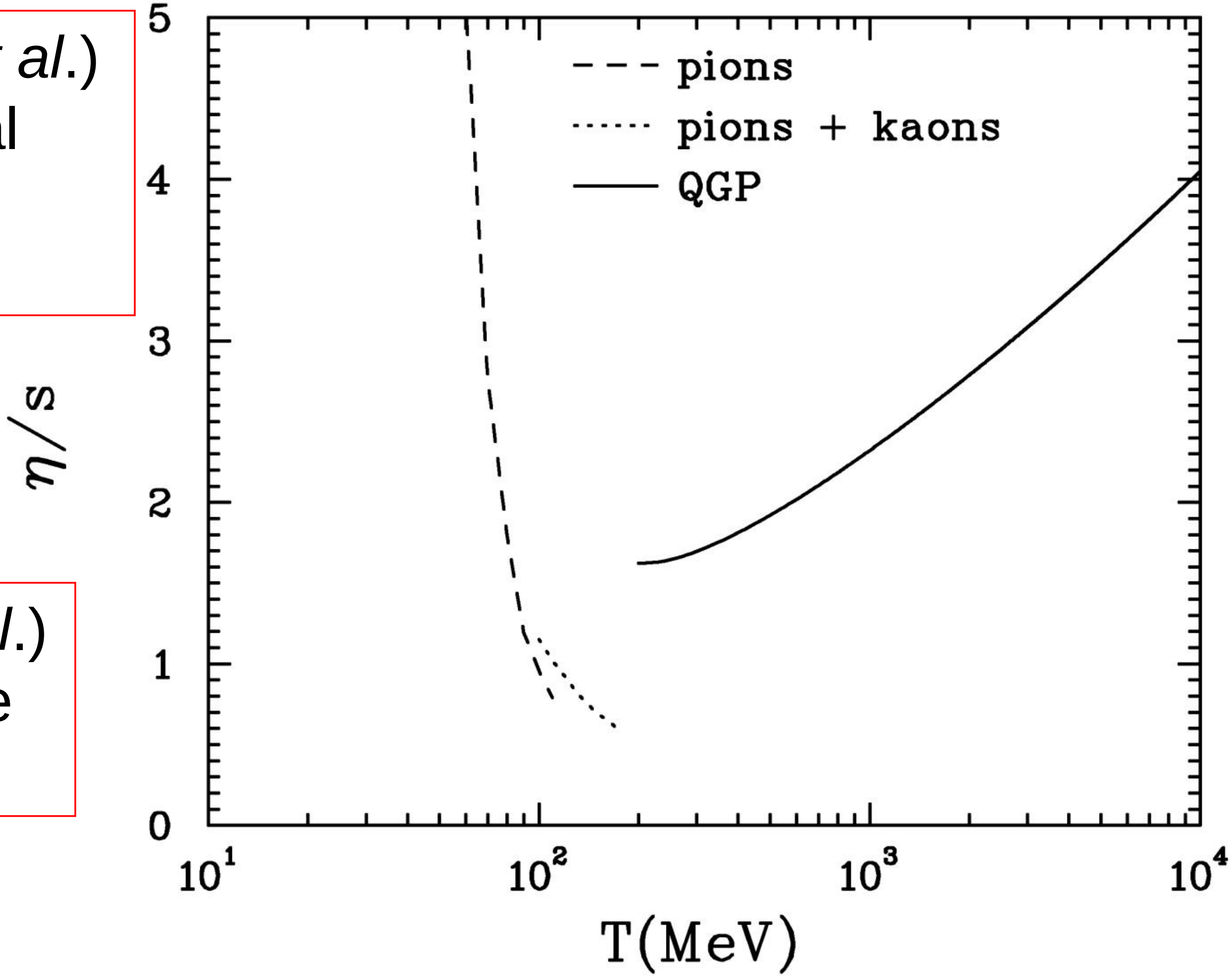
$$\frac{\eta}{s} = \frac{5.12}{g^4 \ln(2.42/g)}$$

$$\frac{1}{g^2(T)} = \frac{9}{8\pi^2}\ln\left(\frac{T}{\Lambda_T}\right) + \frac{4}{9\pi^2}\ln\left(2\ln\left(\frac{T}{\Lambda_T}\right)\right) \qquad \Lambda_T = 30\,\mathrm{MeV}$$

QCD

Low T (*Prakash et al*.) using experimental data for 2-body interactions.

High T (Yaffe *et al*.) using perturbative QCD.



η/s≈1/2 just above T_c
from lattice (Nakamura, Sakai)
and classical quasiparticle model (Gelman, Shuryak, Zahed)

Relativistic Dissipative Fluid Dynamics

$$\boxed{\begin{aligned} &T^{\mu\nu} = -Pg^{\mu\nu} + wu^{\mu}u^{\nu} + \Delta T^{\mu\nu} \\ &J_B^{\mu} = n_B u^{\mu} + \Delta J_B^{\mu} \end{aligned}}$$

In the Landau-Lifshitz approach u is the velocity of energy transport.

$$\boxed{\Delta T^{\mu\nu} = \eta\left(\Delta^{\mu}u^{\nu} + \Delta^{\nu}u^{\mu}\right) + \left(\tfrac{2}{3}\eta - \zeta\right)H^{\mu\nu}\partial_{\rho}u^{\rho}}$$

$$H^{\mu\nu} \equiv u^{\mu}u^{\nu} - g^{\mu\nu}, \quad \Delta_{\mu} \equiv \partial_{\mu} - u_{\mu}u^{\beta}\partial_{\beta}, \quad Q_{\alpha} \equiv \partial_{\alpha}T - Tu^{\rho}\partial_{\rho}u_{\alpha}$$

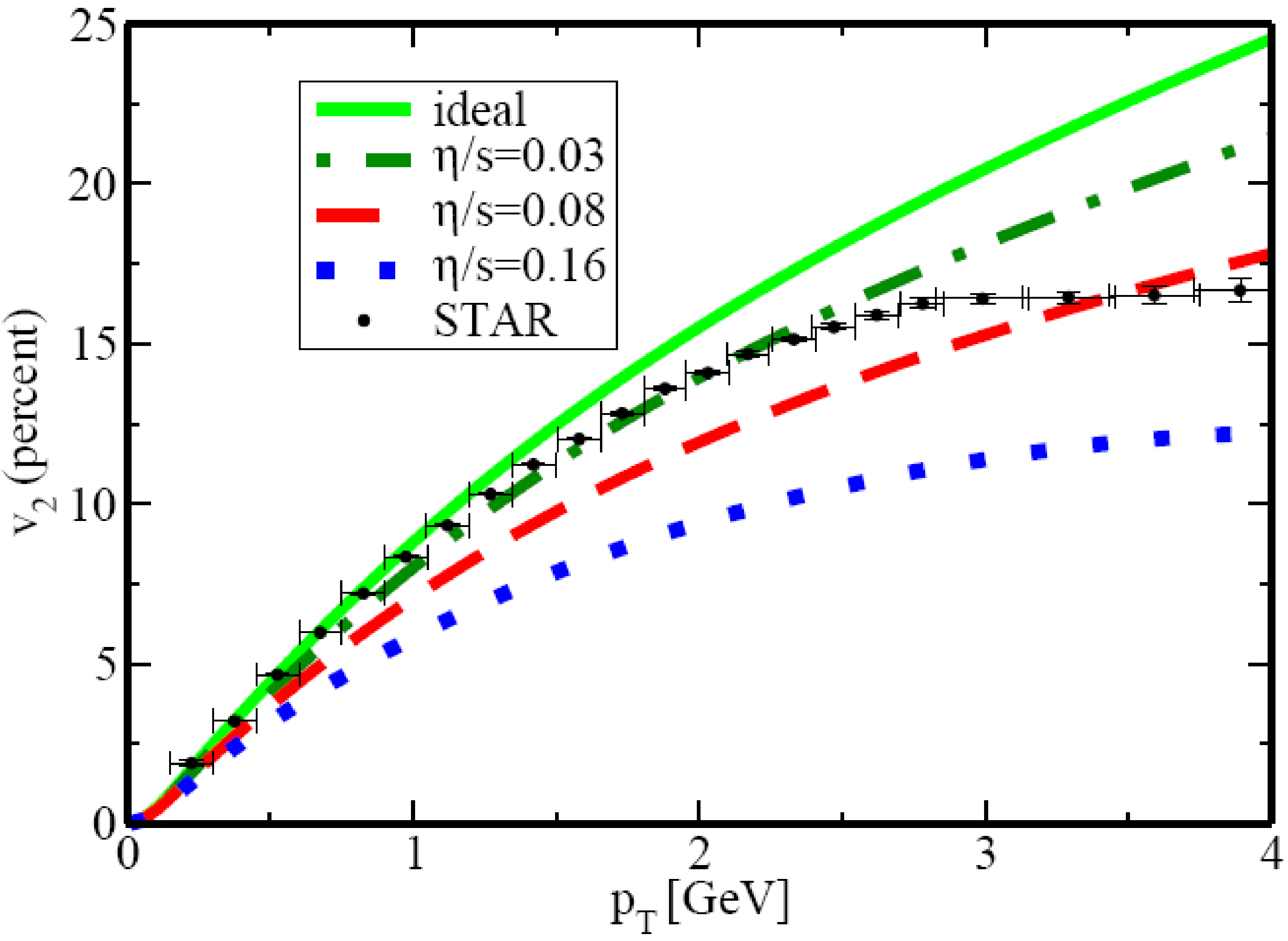
$$\Delta J_B^{\mu} = \chi\left(\frac{n_B T}{w}\right)^2 \Delta^{\mu}\left(\frac{\mu_B}{T}\right), \quad s^{\mu} = su^{\mu} - \frac{\mu_B}{T}\Delta J_B^{\mu}$$

$$\boxed{\partial_{\mu}s^{\mu} = \frac{\eta}{2T}\left(\partial_i u^j + \partial_j u^i - \tfrac{2}{3}\delta^{ij}\partial_k u^k\right)^2 + \frac{\zeta}{T}\left(\partial_k u^k\right)^2 + \frac{\chi}{T^2}\left(\partial_k T + T\dot{u}_k\right)^2}$$

Extracting η/s from RHIC/LHC data

- Elliptic flow
- Hanbury Brown & Twiss interferometry
- Momentum spectra
- Momentum fluctuations
- Photon & dilepton spectra
- Jet quenching

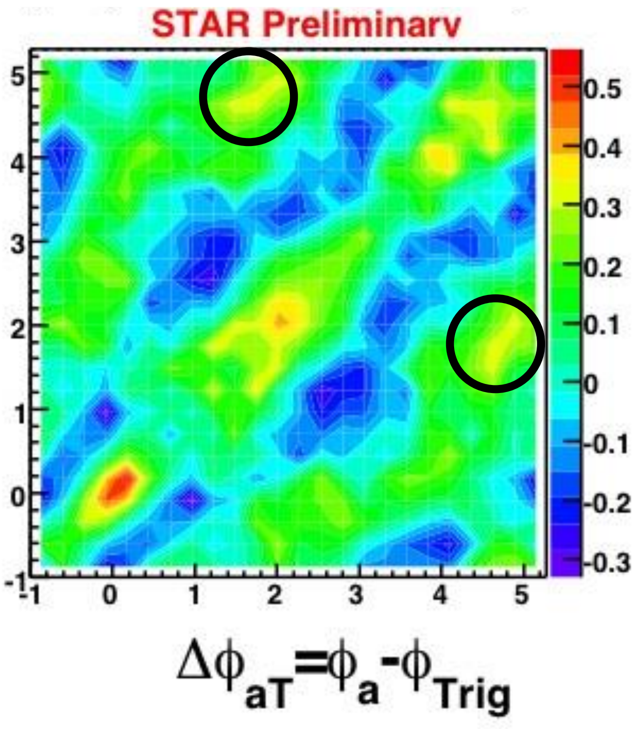
Dependence of v_2 on viscosity.

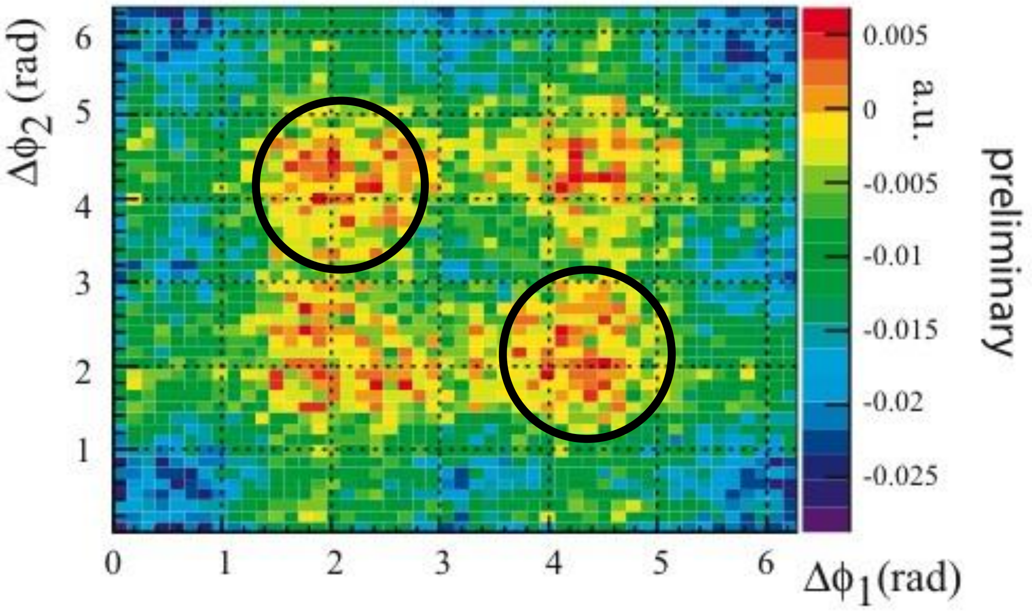


Romatschke & Romatschke 2007/2008

Is QGP physics at RHIC and SPS the same or different?

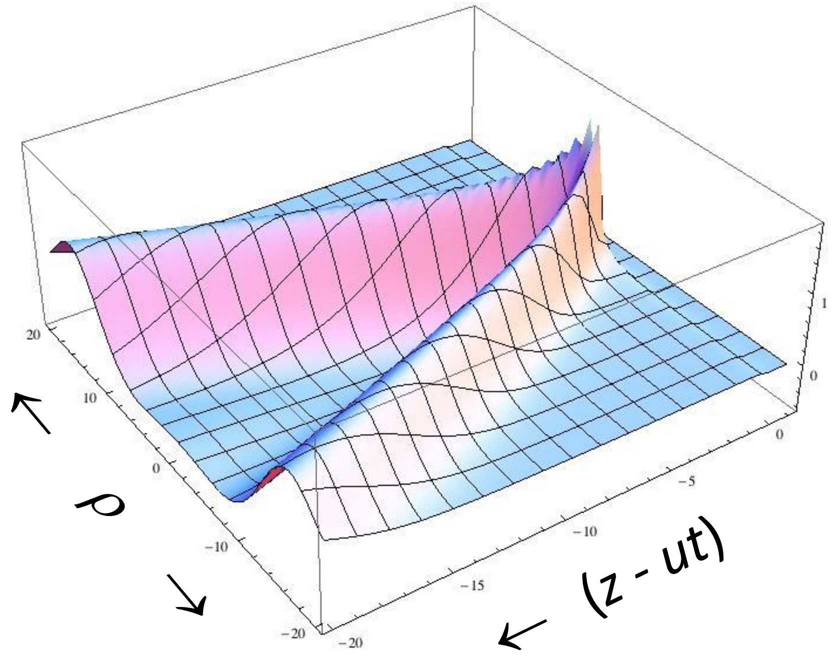
3-particle correlations - is there a Mach cone?



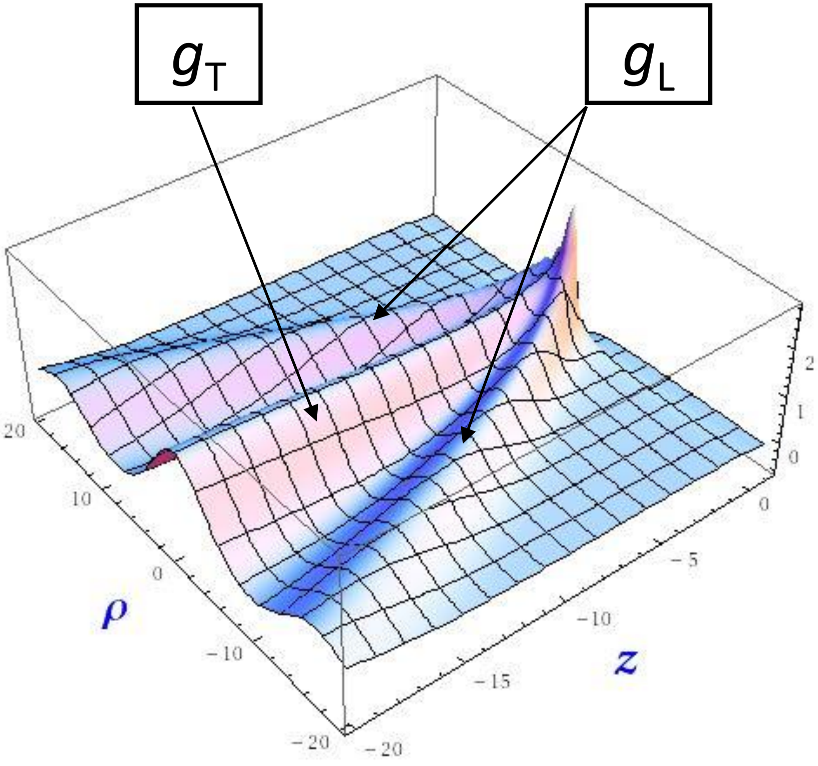


The Mach cone generated by a high energy parton in the plasma

Asakaw, Mueller, Neufeld, Nonaka, Ruppert



Energy density



Momentum density

An approach to model the collisions from first impact until the last hadronic scattering.

Duke (Bass, Muller) Nagoya (Nonaka)
Texas A&M (Fries) Iowa (Li)
Minnesota (Kapusta)

Theory Outline

1. Hard parton scattering and jet production.
2. Generation of classical gluon field by large momentum partons that have not scattered (color glass condensate).
3. Decay of classical gluon fields via particle production.
4. Matching to relativistic viscous fluid dynamics in 3+1 dimensions.
5. Phase transition or crossover from quarks and gluons to hadrons.
6. Rescattering of hadrons followed by freestreaming to the detectors.

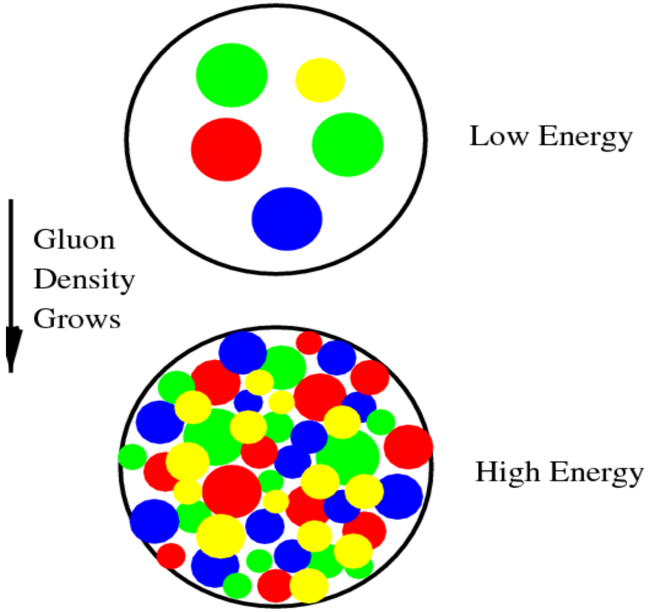
Color Glass

- Start from a large nucleus.
  - How does it look in the limit $p^+ \rightarrow \infty$ and Bjorken-x << 1?

- Gluon density reaches saturation
  - Gluon density sets a scale

$$\boxed{Q_s^2 = \alpha_s \frac{G\left(x, Q_s^2\right)}{\pi R_A^2} \sim A^{1/3}}$$

  - High density limit of QCD (Mueller & Qiu, McLerran & Venugopalan, Weigert, McLerran & Kovner, …)

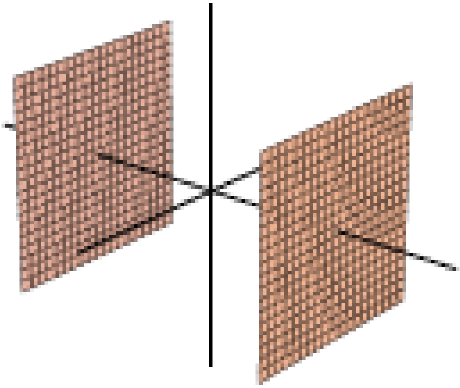


- Large number of gluons in the wave function: classical description of the gluon field

Color Glass: Two Nuclei

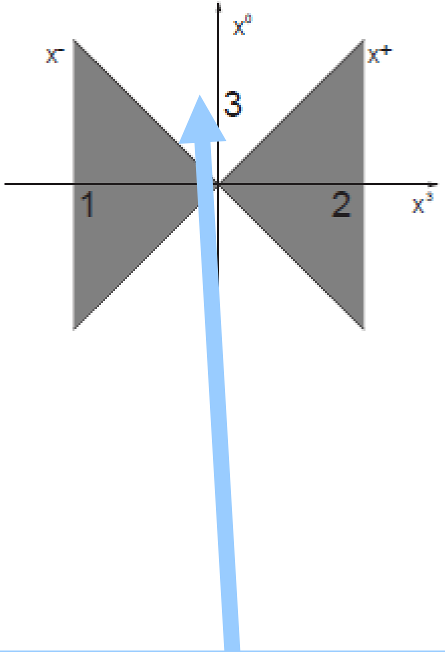
- Gauge potential:
  - In sectors 1 and 2 single nucleus solutions are valid
  - In sector 3 (forward light cone):

Coarse-grain color charges in 2d sheets



$$A^{\pm} = \pm x^{\pm}\alpha(\tau, x_\perp)$$

$$A^{i} = \alpha_3^{i}(\tau, x_\perp)$$



- YM in forward direction:
  - Set of non-linear differential equations
  - Boundary conditions given by the fields in the single nuclei

$$\frac{1}{\tau^3}\partial_\tau \tau^3 \partial_\tau \alpha - \left[D^i,\left[D^i,\alpha\right]\right] = 0$$

$$\frac{1}{\tau}\left[D^i, \partial_\tau \alpha_3^i\right] - ig\tau\left[\alpha, \partial_\tau \alpha\right] = 0$$

$$\frac{1}{\tau}\partial_\tau \tau \partial_\tau \alpha_3^i - ig\tau^2\left[\alpha,\left[D^i,\alpha\right]\right] - \left[D^j, F^{ji}\right] = 0$$

Initial Energy Density at RHIC

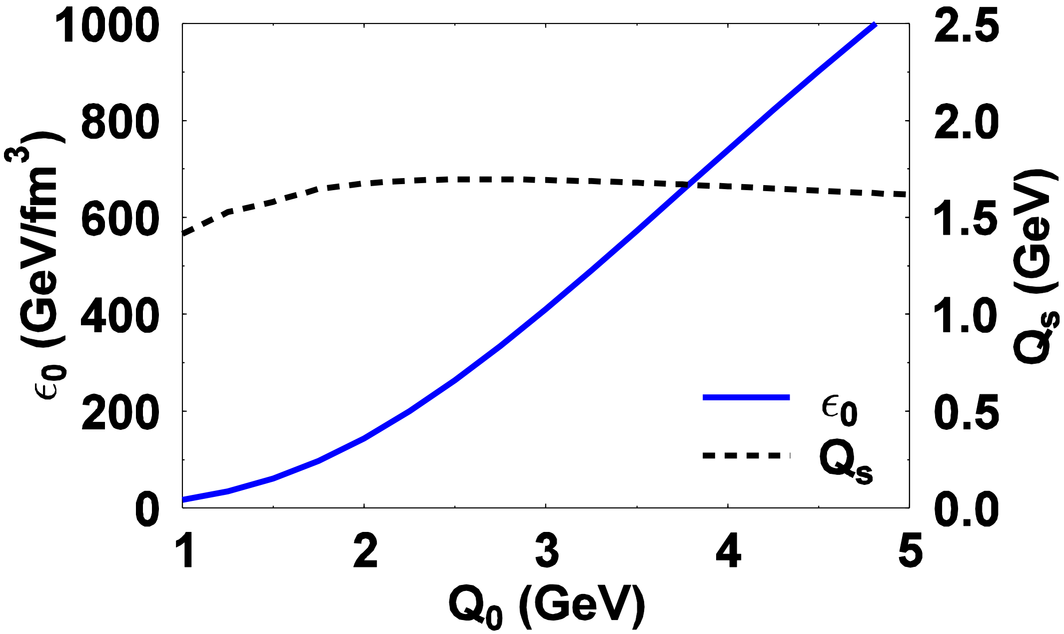
$$\langle \varepsilon_E \rangle = \langle \varepsilon_M \rangle \approx \frac{\pi \alpha_s^3}{N_c} \sigma_1 \sigma_2 \ln^2\left(1 + 0.42 \frac{Q_0^2}{Q_s^2}\right) + \text{energy from jets/minijets}\,(Q_0)$$

σ = quarks+antiquarks+(C_A/C_F)gluons per unit area

Q_0 = cutoff between IR and UV

$Q_s^2 = \alpha_s \sigma$ = saturation scale

From IR only →



Why LHC?

SPS: 8.6 GeV/nucleon Pb-Pb in cm
RHIC: 100 GeV/nucleon Au-Au in cm
LHC: 2700 GeV/nucleon Pb-Pb in cm

- Jets played no role at SPS, an important role at RHIC, and will dominate at LHC.

- The Z^0 will provide a standard candle as reference for all other hard perturbative processes at LHC.

- The much greater volumes, energy densities, temperatures and lifetimes of produced matter at LHC will provide the lever arm to infer the equation of state and transport coefficients which is necessary due to the space-time expansion of the system.

Conclusion

- RHIC/LHC are thermometers (hadron ratios, photon and lepton pair production)
- RHIC/LHC are barometers (elliptic flow, transverse flow)
- RHIC/LHC are viscometers (deviations from ideal fluid flow)
- There is plenty of work for theorists (and experimentalists)!

Finite-Temperature Field Theory

Principles and Applications

Joseph Kapusta and Charles Gale

1. Review of quantum statistical mechanics
2. Functional integral representation of the partition function
3. Interactions and diagrammatic techniques
4. Renormalization
5. Quantum electrodynamics
6. Linear response theory
7. Spontaneous symmetry breaking and restoration
8. Quantum chromodynamics
9. Resummation and hard thermal loops
10. Lattice gauge theory
11. Dense nuclear matter
12. Hot hadronic matter
13. Nucleation theory
14. Heavy ion collisions
15. Weak interactions
16. Astrophysics and cosmology

Conclusion

Appendix

CAMBRIDGE
UNIVERSITY PRESS