The Quest for the Quark-Gluon-Plasma:
from Discovery to Quantitative Exploration

Steffen A. Bass
Duke University

- Introduction: QCD
- Jet Energy-Loss
- Near-Ideal Fluids & Elliptic Flow
- Shear-Viscosity of QCD Matter
- Hadronization: Parton Recombination
- η/s of a Hadron Gas
- Global Quantitative Analysis

work supported through grants by

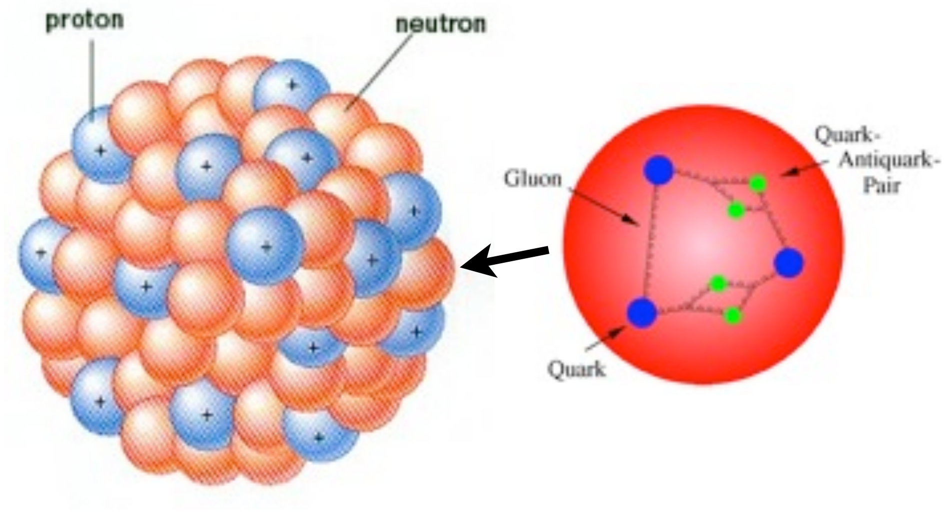
Introduction:

- QCD Matter
- Discoveries at RHIC

Strong Interaction Force: QCD

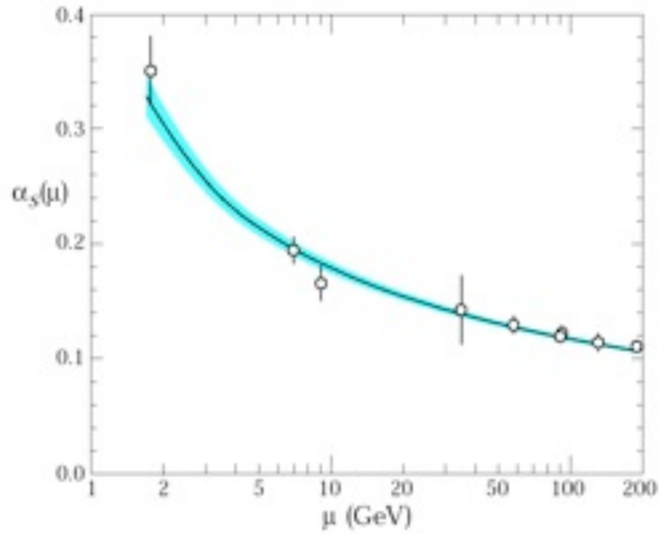
Quantum-Chromo-Dynamics (QCD):

- one of the four basic forces of nature
- holds protons and neutrons together in atomic nuclei
- basic constituents of matter: quarks and gluons
- is responsible for most of the mass of ordinary matter



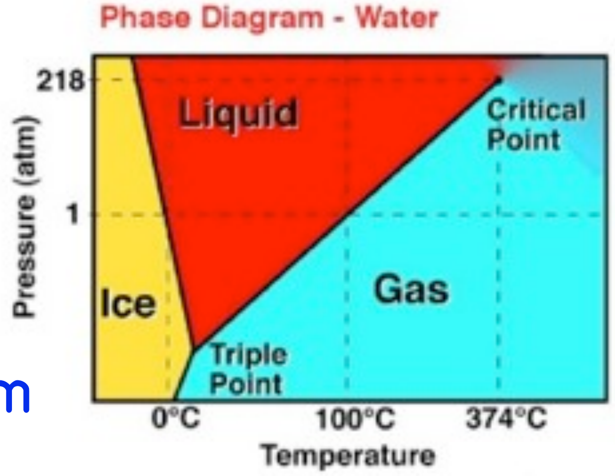
Confinement & Asymptotic Freedom:

- quarks and gluons carry color charge (RGB)
- only color-neutral bound states are observed
- coupling diverges as large distances / small Q^2
- at small distances / large Q^2 q's and g's roam freely
- 2004 Nobel Prize to D. Gross, D. Politzer & F. Wilczek



ordinary matter:

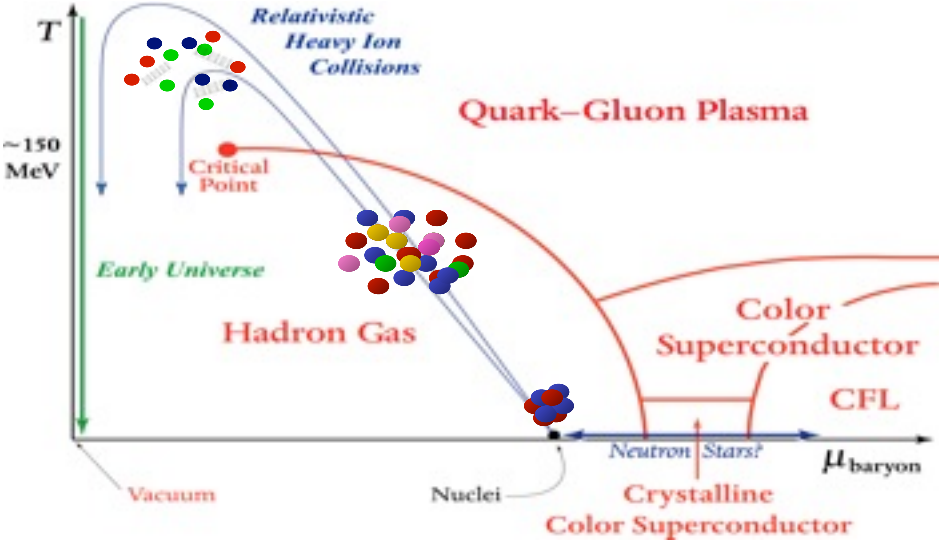
- phases determined by (EM) interaction
- apply heat & pressure to study phase-diagram



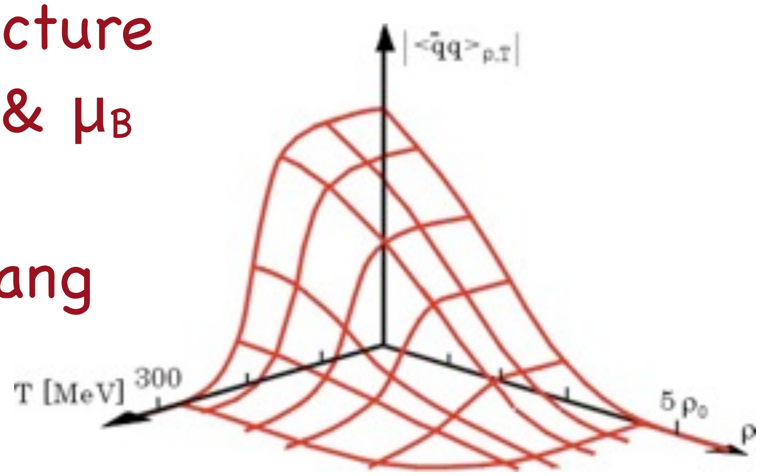
Phases of QCD matter:

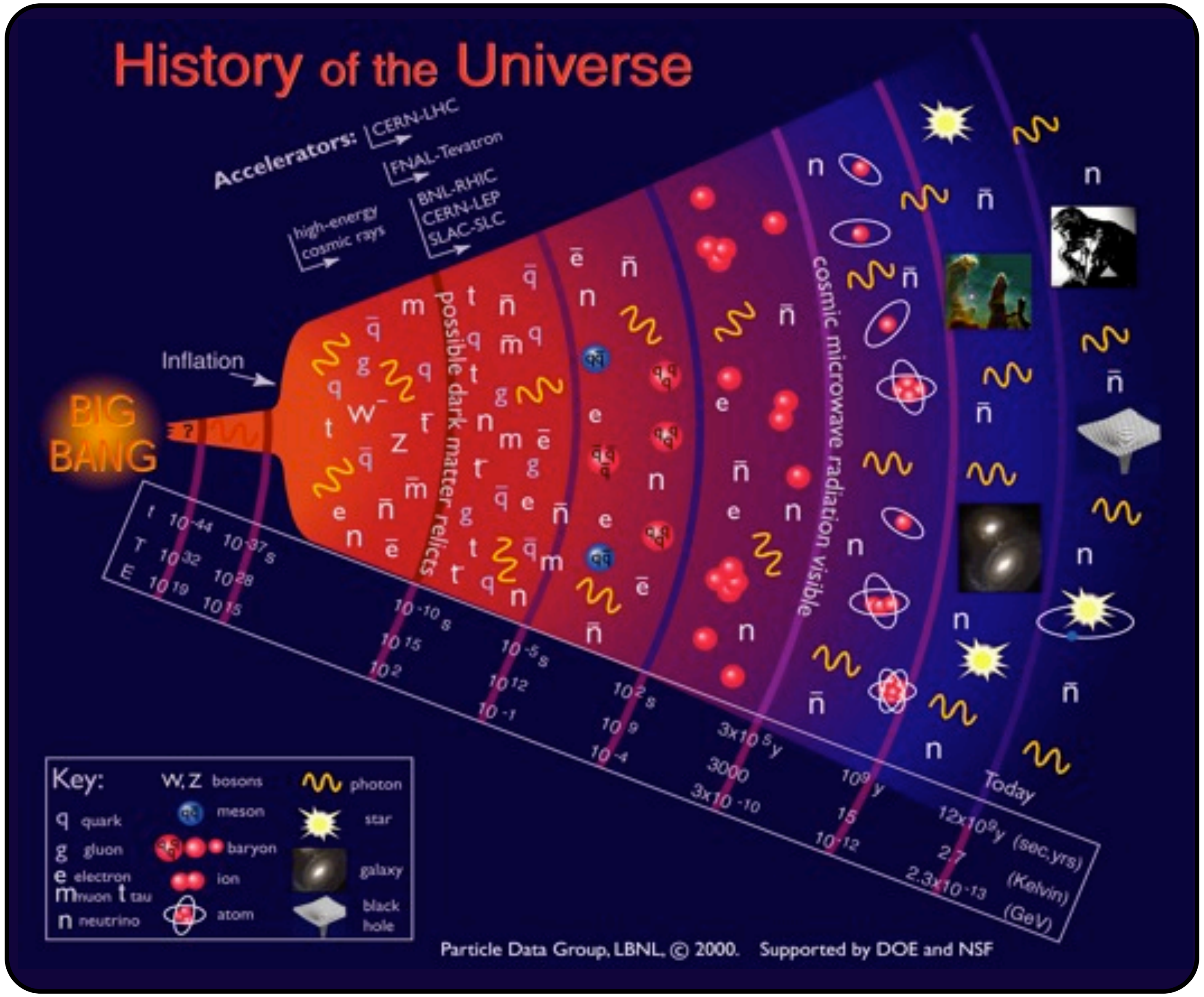
- how to heat & compress QCD matter?
  - collide heavy atomic nuclei
- numerical simulations:
  - solve partition function (Lattice QCD)

The many sides of QCD Matter



- QCD has a rich phase-structure
- "easier" to solve at high T & μ_B
- QGP state thought to have existed shortly after Big Bang





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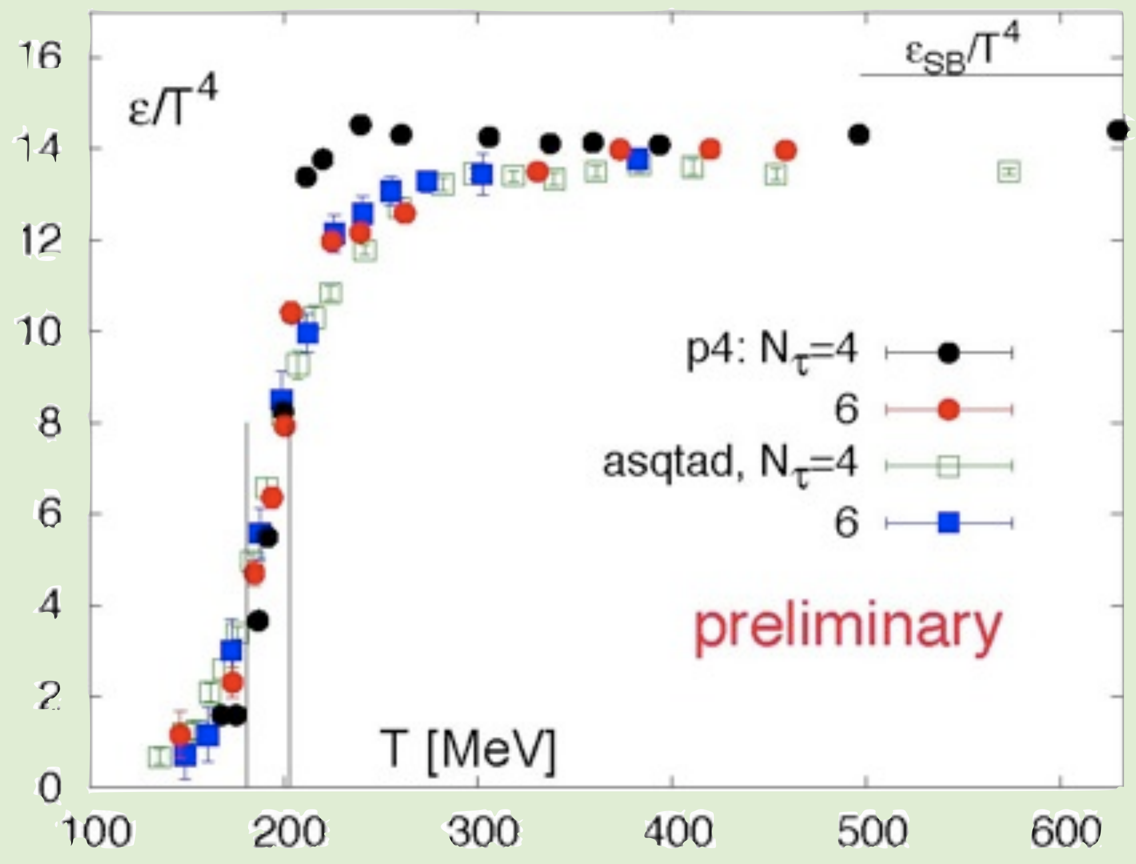
Lattice QCD predictions:



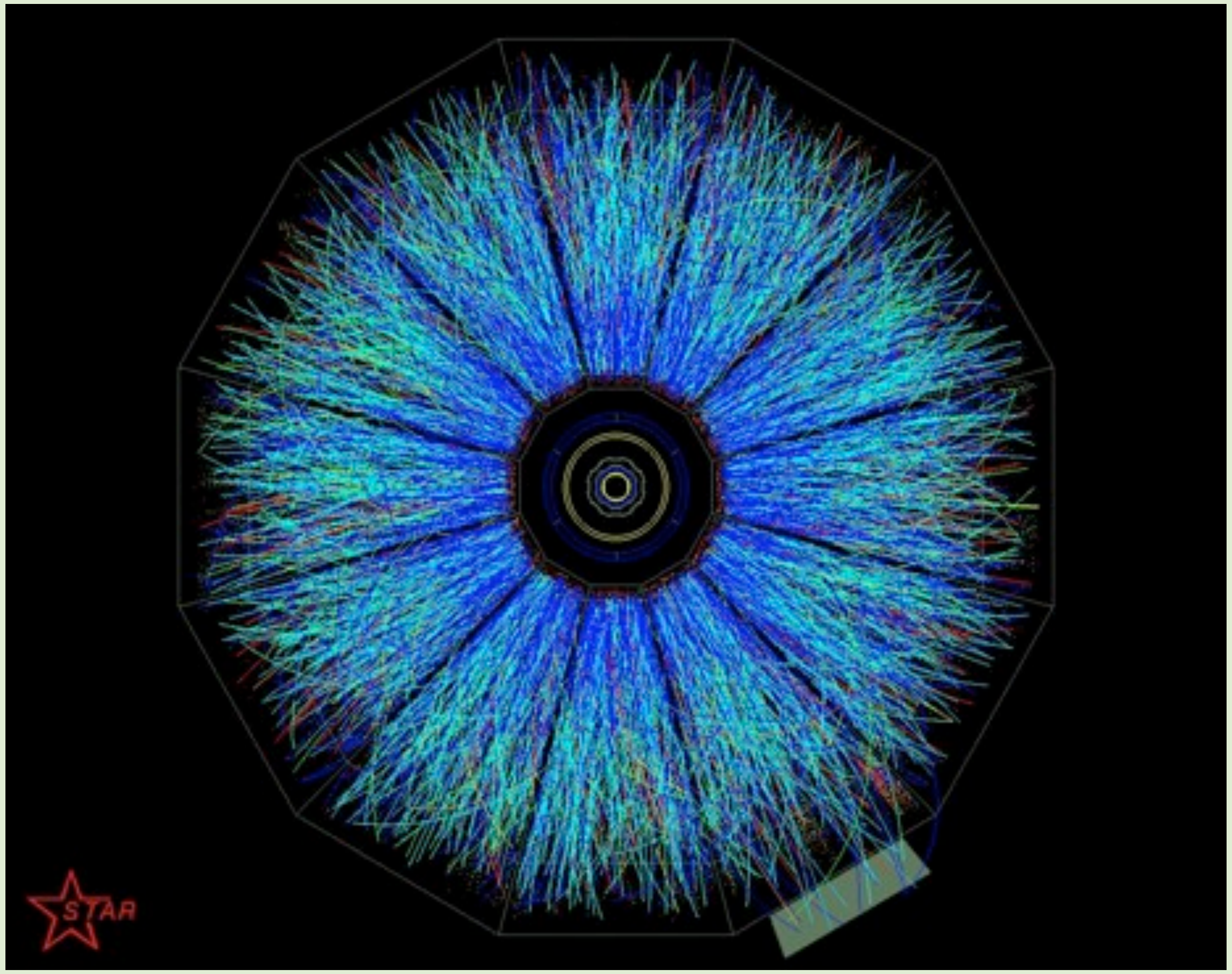
EoS of a gas of massless bosons:

$$\varepsilon = \frac{\pi^2}{30} g_{\mathrm{DOF}} T^4$$

Heating & Compressing QCD Matter

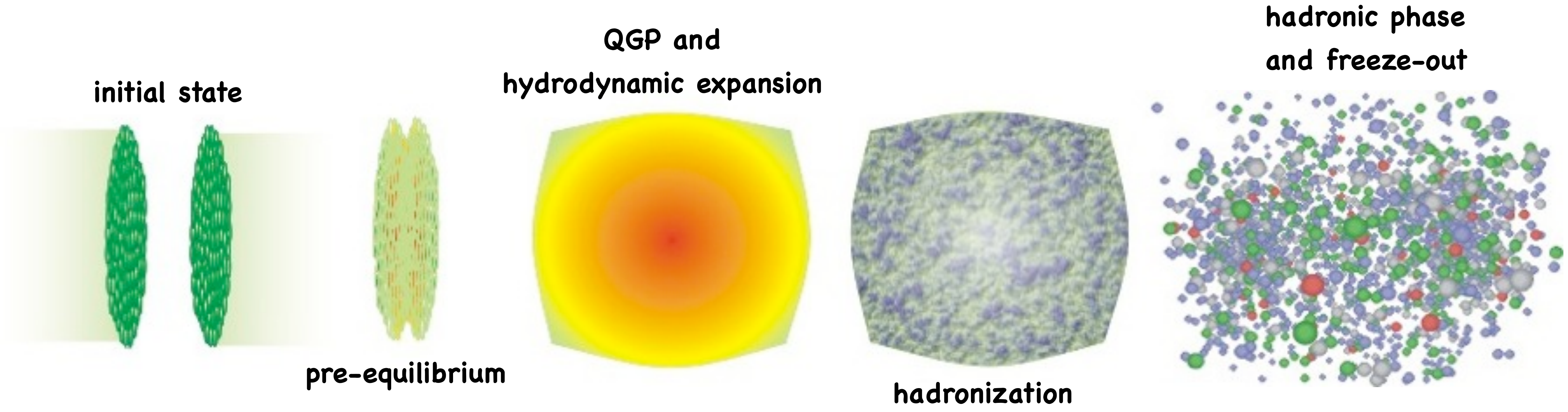
Brookhaven National Laboratory: Relativistic Heavy-Ion Collider

- 2 large experiments (STAR, PHENIX)
- 2 small experiments (PHOBOS, BRAHMS)
- 1200+ scientists from 80+ institutions



- typical collision @ RHIC: 1000s of tracks
- task: reconstruction of final state to characterize matter created in collision

Probing QCD in Heavy-Ion Collisions



Challenges:

- time-scale of the collision process: 10^{-24} seconds! [too short to resolve]
- characteristic length scale: 10^{-15} meters! [too small to resolve]
- confinement: quarks & gluons form bound states @ hadronization, experiments don't observe them directly

Experiments:

- observe only the final state
- rely on QGP signatures predicted by Theory

Lattice QCD:

- rigorous calculation of QCD properties in equilibrium

Transport-Models:

- full description of collision dynamics
- connect intermediate state to measurements & lattice

Transport Models for RHIC

microscopic transport models based on the **Boltzmann Equation**:

- transport of a system of microscopic particles
- all interactions are based on binary scattering

$$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E} \times \frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p},\vec{r},t) = \sum_{processes} C(\vec{p},\vec{r},t)$$

diffusive transport models based on the **Langevin Equation**:

- transport of a system of microscopic particles in a thermal medium
- interactions contain a drag term related to the properties of the medium and a noise term representing random collisions

$$\vec{p}(t+\Delta t) = \vec{p}(t) - \frac{\kappa}{2T}\vec{v}\cdot\Delta t + \vec{\xi}(t)\Delta t$$

(viscous) relativistic fluid dynamics:

- transport of macroscopic degrees of freedom
- based on conservation laws:

$$\partial_\mu T^{\mu\nu} = 0$$

$$\begin{aligned} T_{ik} &= \varepsilon u_i u_k + P\left(\delta_{ik} + u_i u_k\right) \\ &- \eta\left(\nabla_i u_k + \nabla_k u_i - \frac{2}{3}\delta_{ik}\nabla\cdot u\right) \\ &+ \varsigma\,\delta_{ik}\nabla\cdot u \end{aligned}$$

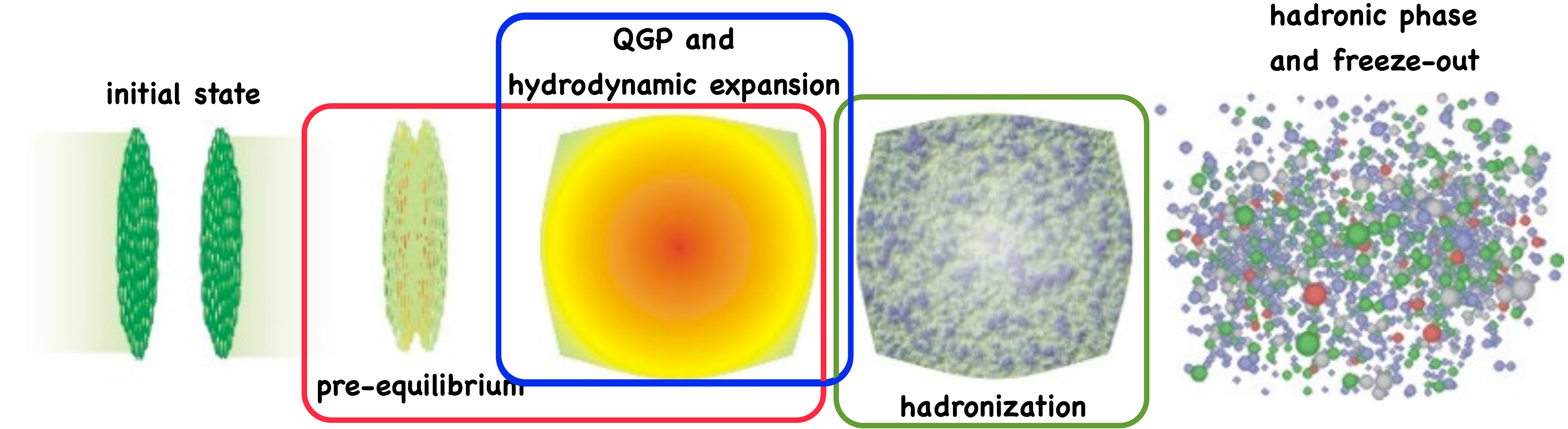
(plus an additional 9 eqns. for dissipative flows)

hybrid transport models:

- combine microscopic & macroscopic degrees of freedom
- current state of the art for RHIC modeling

Each transport model relies on roughly a dozen physics parameters to describe the time-evolution of the collision and its final state. These physics parameters act as a representation of the information we wish to extract from RHIC.

The Case for the QGP: RHIC Discoveries



initial state

pre-equilibrium

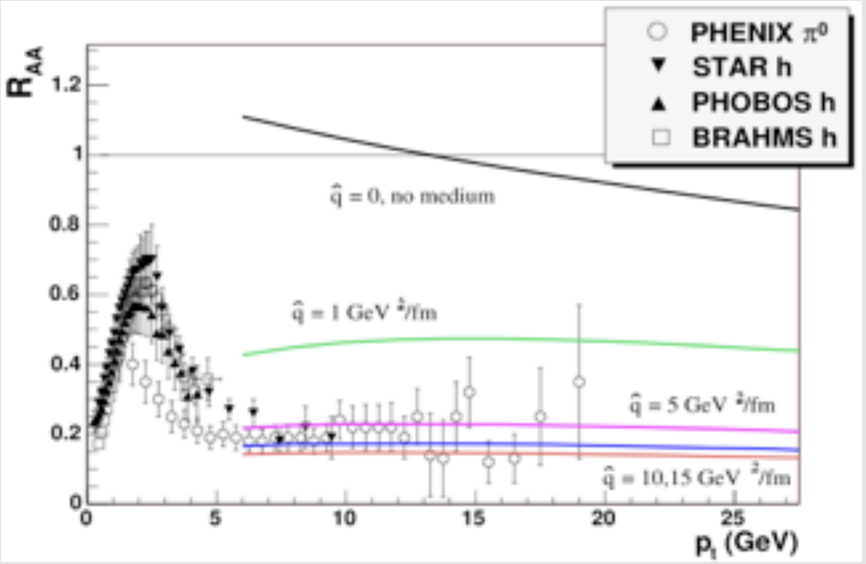
QGP and hydrodynamic expansion

hadronization

hadronic phase and freeze-out

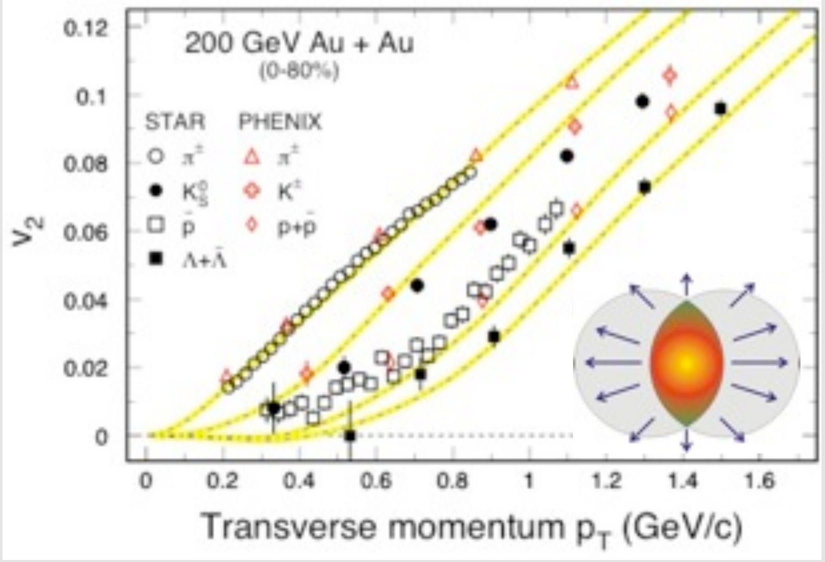
Jet Energy-Loss

- medium exhibits large opacity for a hard parton traversing it
- suppression of high-pt hadrons



Elliptic Flow

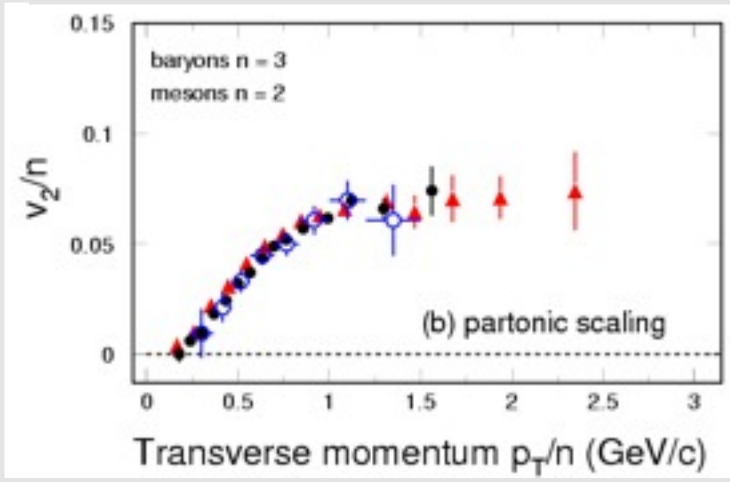
- early time phenomenon
- conversion of spatial to momentum anisotropy due to hydrodynamic flow

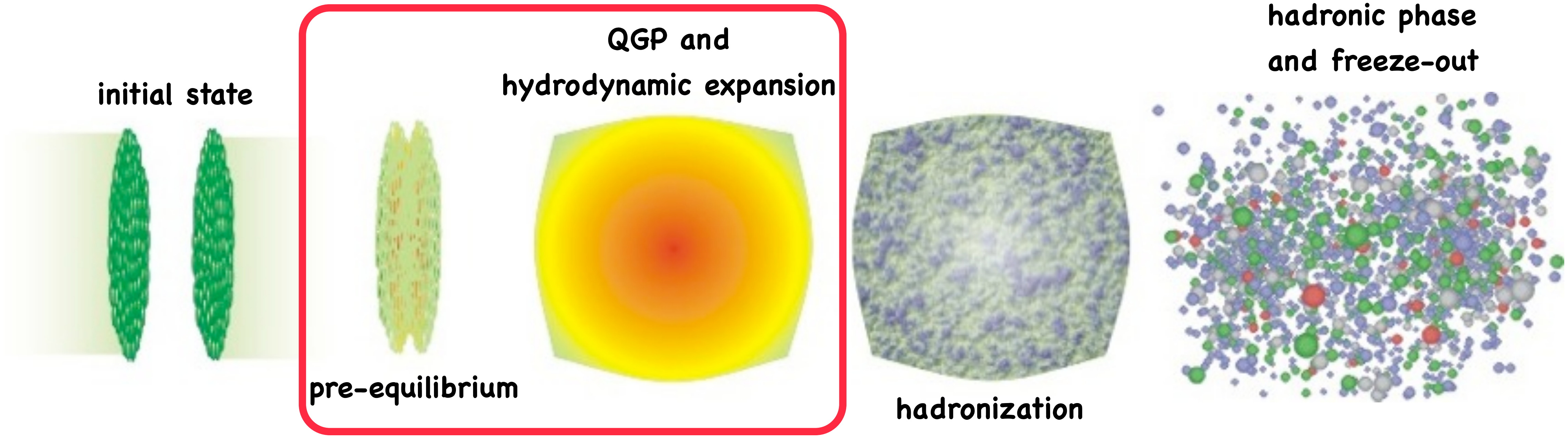


Parton Recombination

- partons form hadrons via recombination
- manifest in quark number scaling laws

$$v_2^M(p_t) \approx 2v_2^p\left(\frac{p_t}{2}\right) \wedge v_2^B(p_t) \approx 3v_2^p\left(\frac{p_t}{3}\right)$$



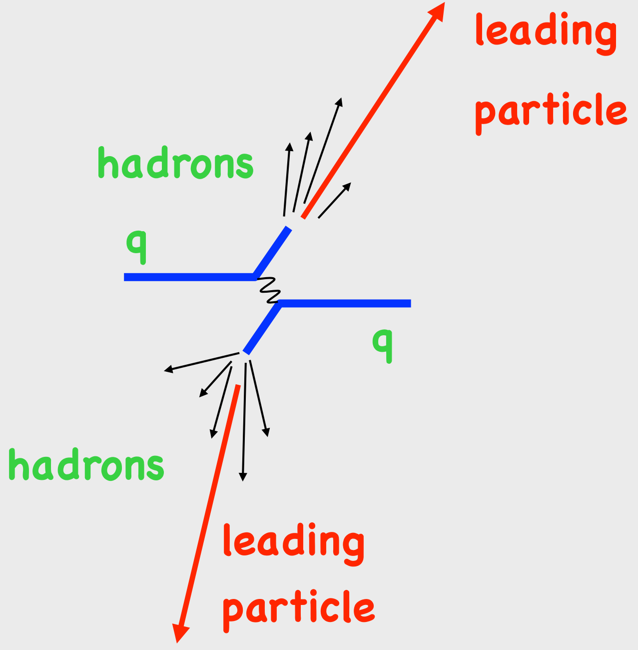


Jet Energy-Loss

Renk, Ruppert, Nonaka & Bass: Phys. Rev. **C75** (2007) 031902
Majumder, Nonaka & Bass: Phys. Rev. **C76** (2007) 041902
Qin, Ruppert, Turbide, Gale, Nonaka & Bass: Phys. Rev. **C76** (2007) 064907
Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert: Phys. Rev. **C79** (2009) 024901

Jet-Quenching: Basic Idea

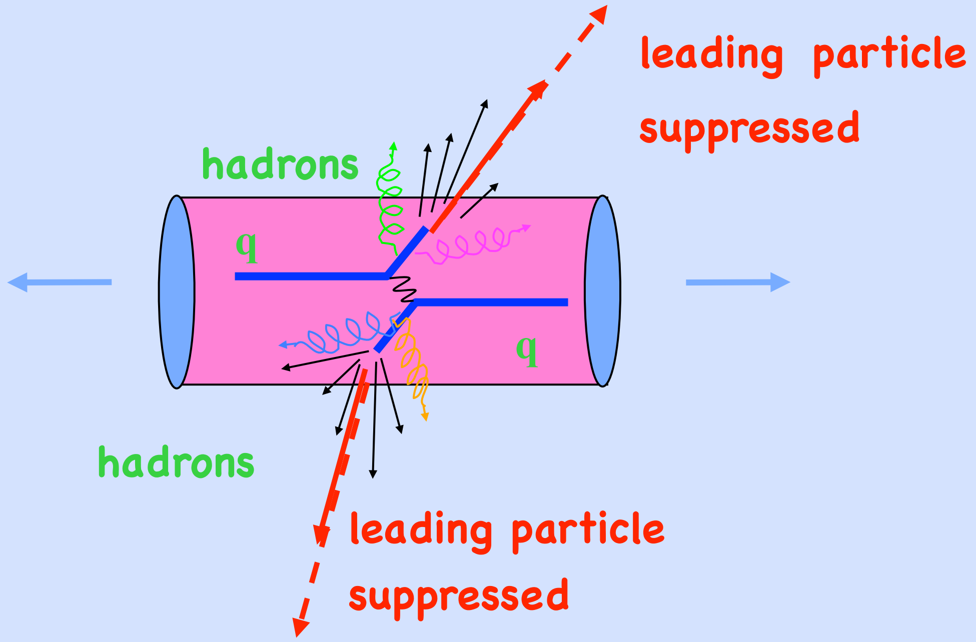
What is a jet?



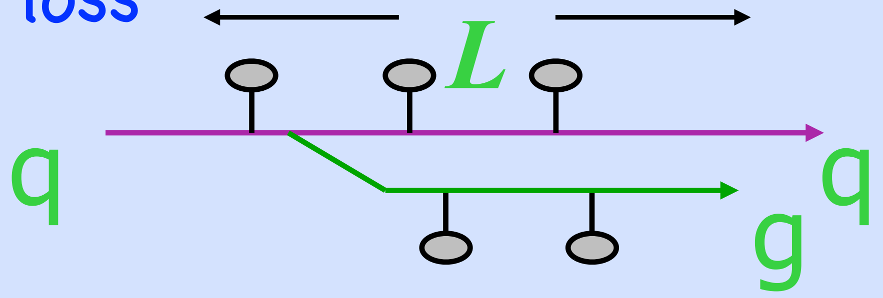
- fragmentation of hard scattered partons into collimated “jets” of hadrons

➢ p+p reactions provide a calibrated probe, well described by pQCD

➢ what happens if partons traverse a high energy density colored medium?



- partons lose energy and/or fragment differently than in the vacuum: radiative energy loss



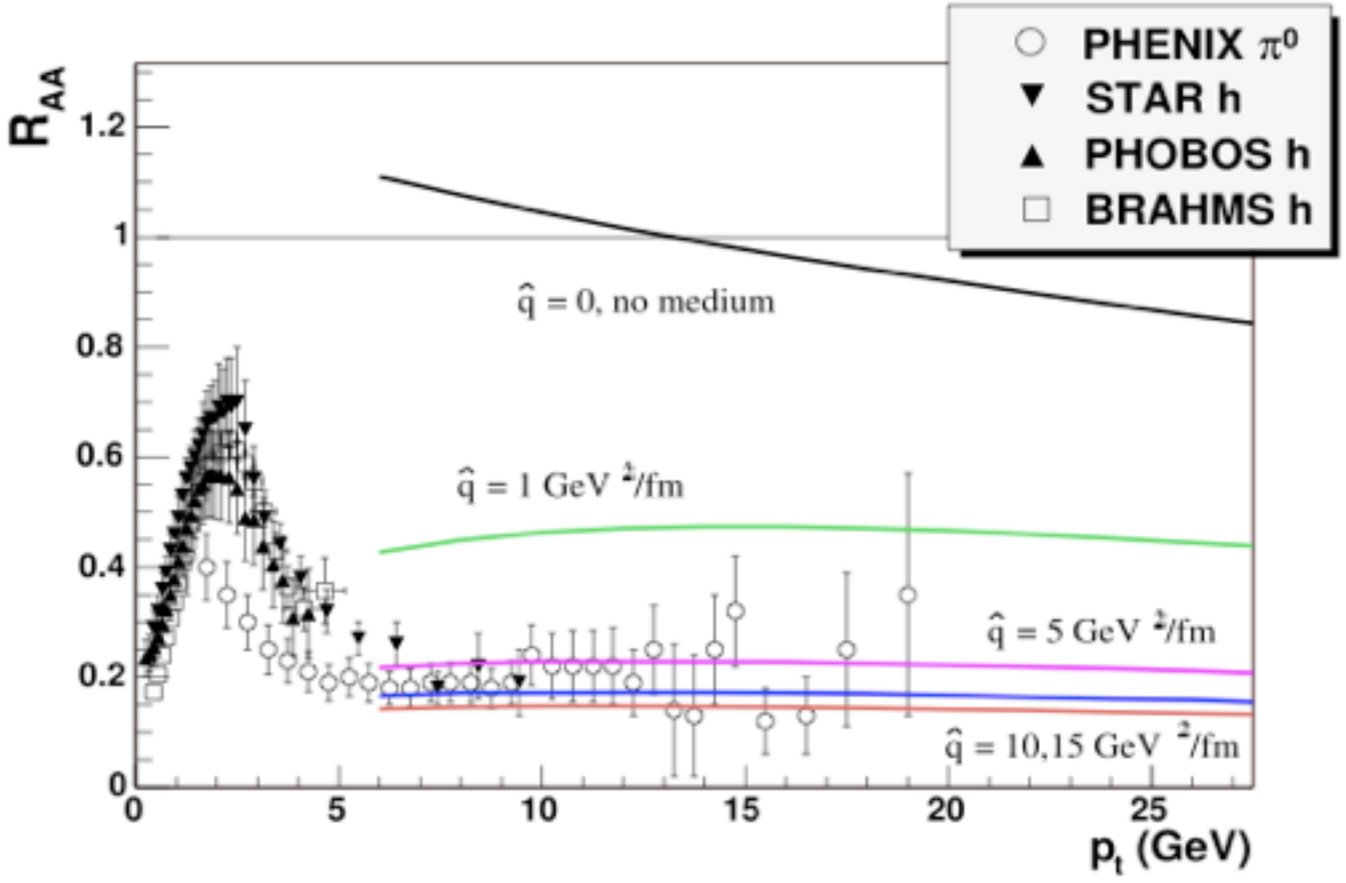
$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho\sigma \left\langle k_T^2 \right\rangle = \frac{\mu^2}{\lambda_f}$$

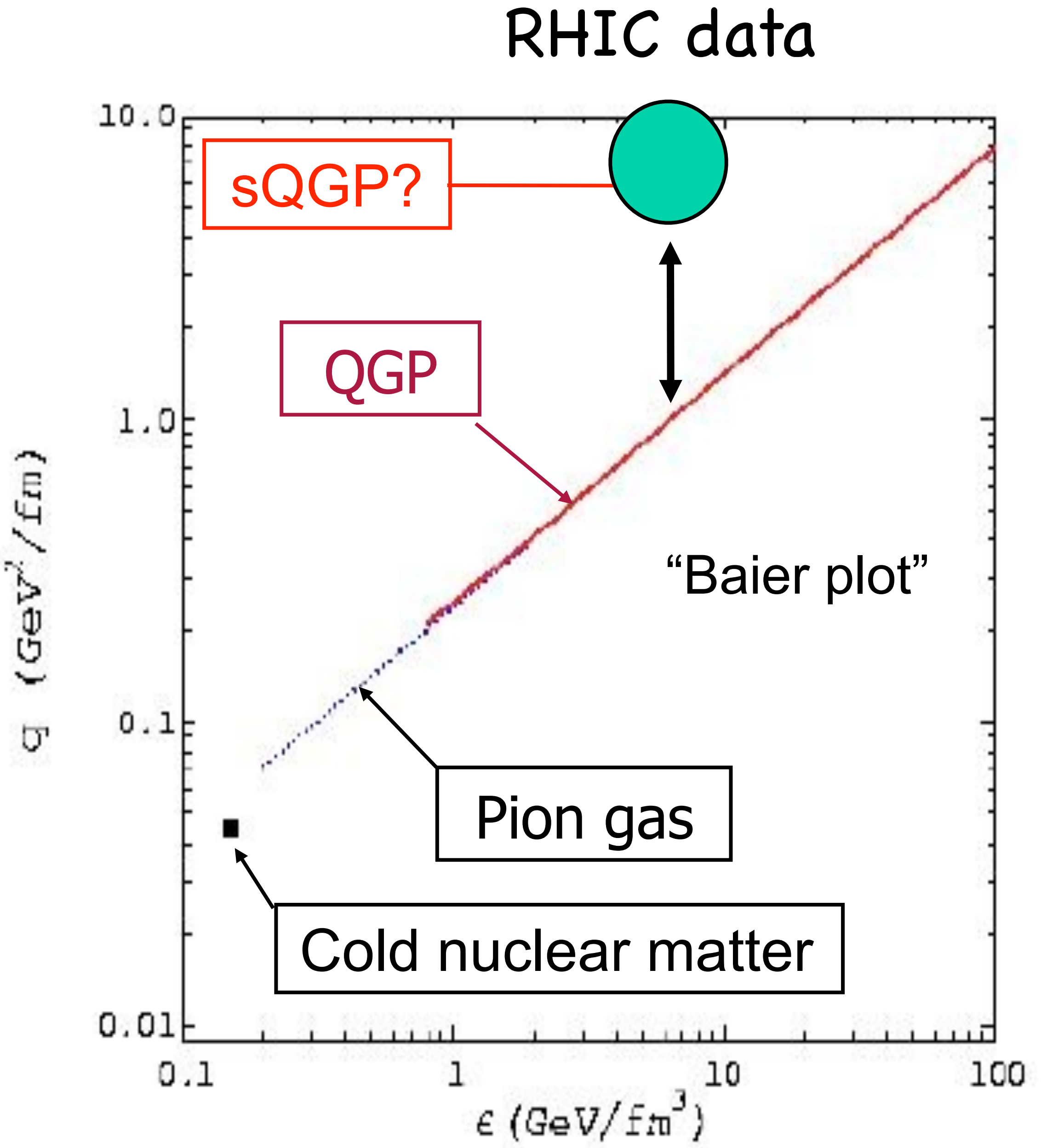
➢ transport coefficient q is sensitive to density of (colored) charges

q-hat at RHIC

- suppression can be experimentally quantified in terms of R_{AA} ratio:

$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_\perp}{d^2N^{pp}/dydp_\perp \times \langle N_{coll}^{AA} \rangle}$$





- ➢ RHIC data shows values for q-hat far larger than expected even for a QGP!

Jet Energy-Loss Schemes

Armesto, Salgado, Wiedemann (ASW):

- medium of heavy static scattering centers w/ Yukawa-like potentials
- path integral over multiple scatterings in the medium

Higher Twist (HT):

- calculates modification of n-hadron FF due to mult. scattering in medium
- scattering encoded as HT gluon-gluon field strength: can be expanded twist-by-twist or resummed for multiple scattering

Arnold, Moore, Yaffe (AMY):

- thermalized partonic medium in HTL approx. ($T\to\infty$ and $g\to 0$)
- resummation over multiple scatterings and absorptions

Gyulassy, Levai, Vitev (GLV):

- medium of heavy static scattering centers w/ Yukawa-like potentials
- operator formalism that sums order by order in opacity $n=L/\lambda_g$

- all approaches make assumptions about the underlying medium and its evolution
- example: 3D hydrodynamic evolution provides ε, T, γ and Γ_{QGP} as function of (τ,x,y,η)
- how does the assumed QGP structure and medium evolution affect the analysis?

Energy-Loss Implementation in 3D RFD

3D hydrodynamic evolution provides ε, T, γ and Γ_{QGP} as function of (τ,x,y,η)

BDMPS/ASW:

- define local transport coefficient along trajectory ξ (K as parameter to fix transport coefficient of medium): $\hat{q}(\xi) = K \cdot 2 \cdot \varepsilon^{\frac{3}{4}}(\xi)$

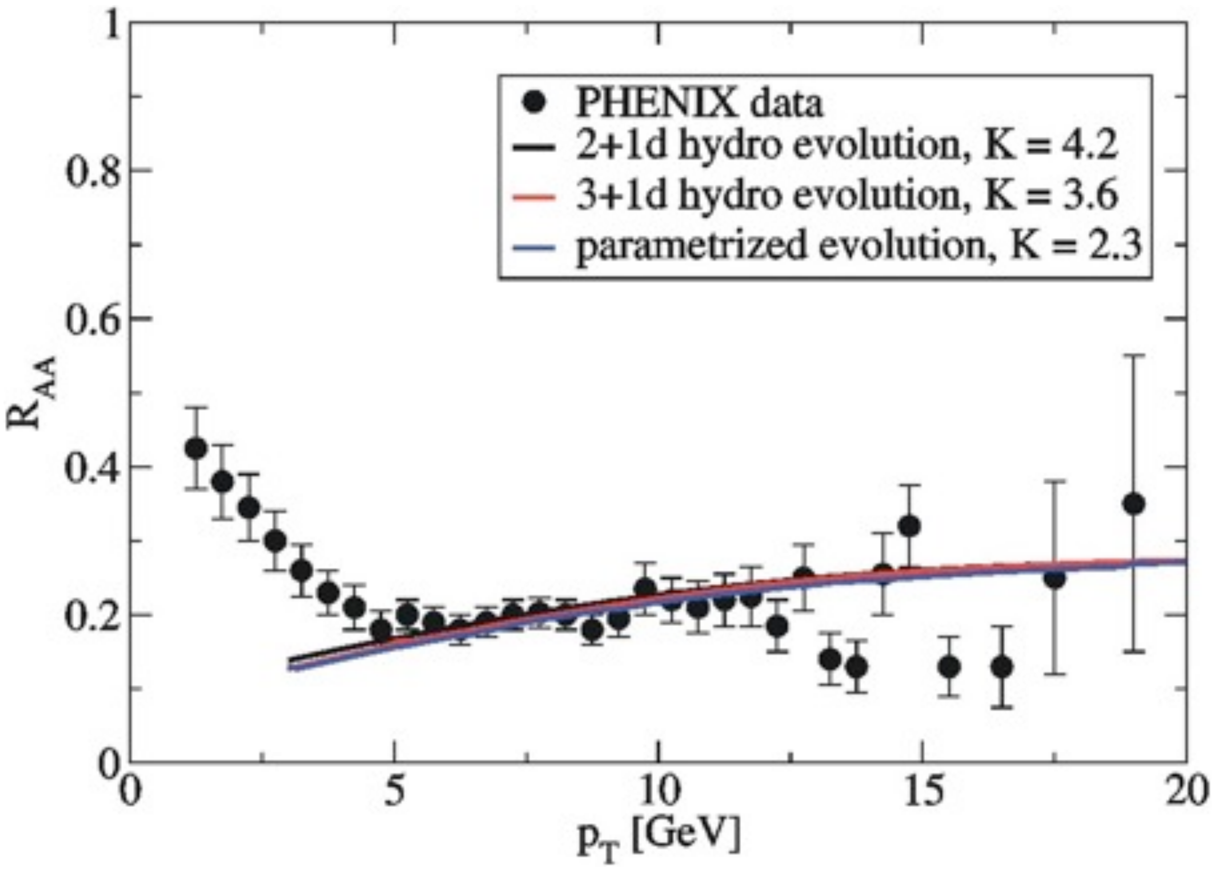
Higher Twist:

- fix starting value of q; hadronic phase can be taken into account via coefficient c_{HG}: $\hat{q}(\vec{r},\tau) = \hat{q}_0 \frac{\gamma(\vec{r},\tau) T^3(\vec{r},\tau)}{T_0^3} \left[\Gamma_{QGP}(\vec{r},\tau) + c_{HG}\left(1 - \Gamma_{QGP}(\vec{r},\tau)\right)\right]$

AMY:

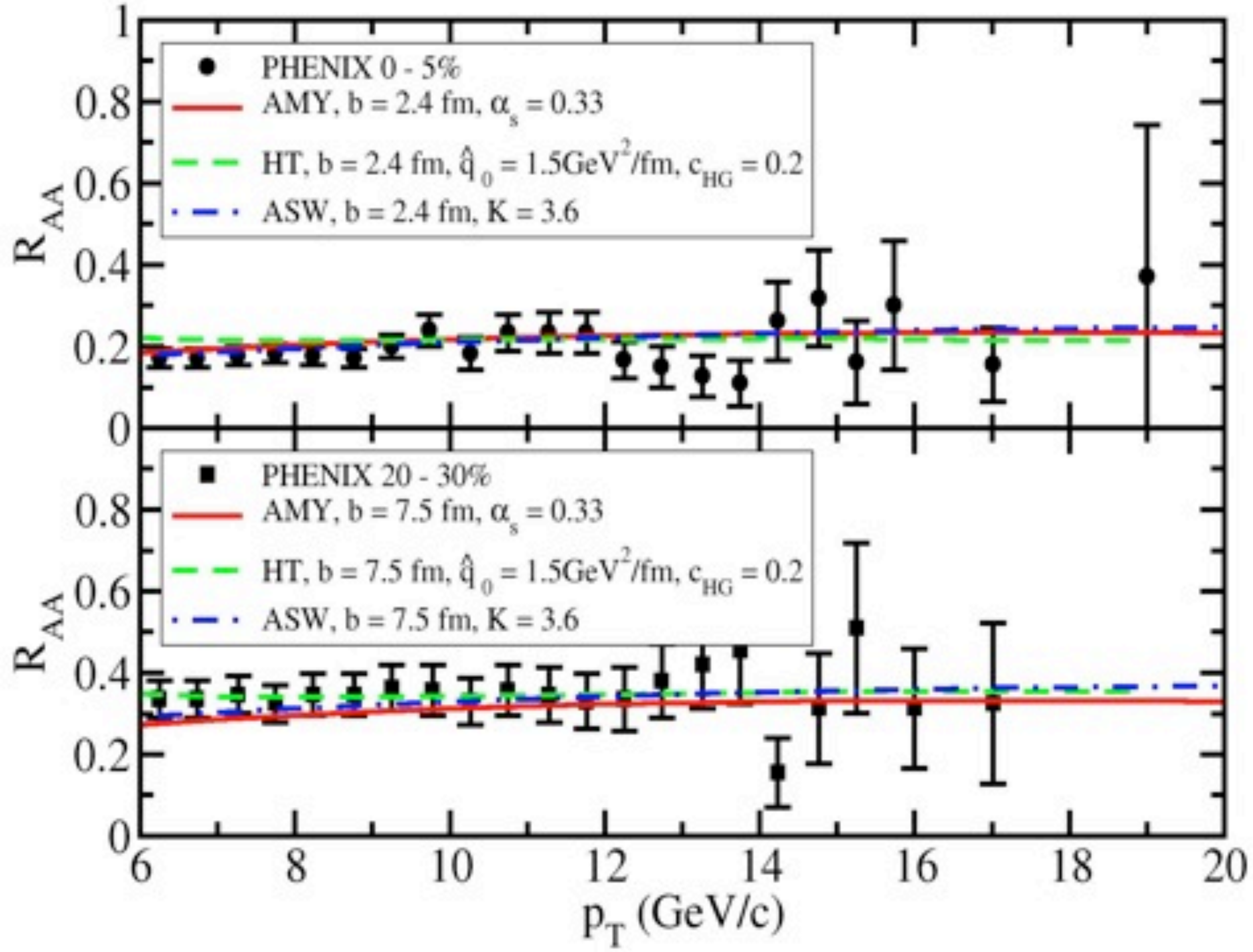
- evolution of jet-momentum distribution is obtained by solving set of coupled rate eqns, with transition rates depending on the coupling constant α_s, local temperature T and flow velocity γ ($q \sim T^3$)

Jet-Tomography: Medium vs. Scheme Dependence



same jet energy-loss scheme and medium assumption:

- ➢ 50% sys. error in tomography analysis due to different evolution descriptions
- ➢ need standard model for evolution to gain predictive and discriminative power



same 3D-hydro medium, 3 different schemes:

- ➢ R_{AA} in (semi-)central collisions is well described by all jet energy-loss schemes
- ➢ parameters reflect response of medium structure hard-wired into schemes
- ➢ large variation in extracted q-hat: 4-18!!

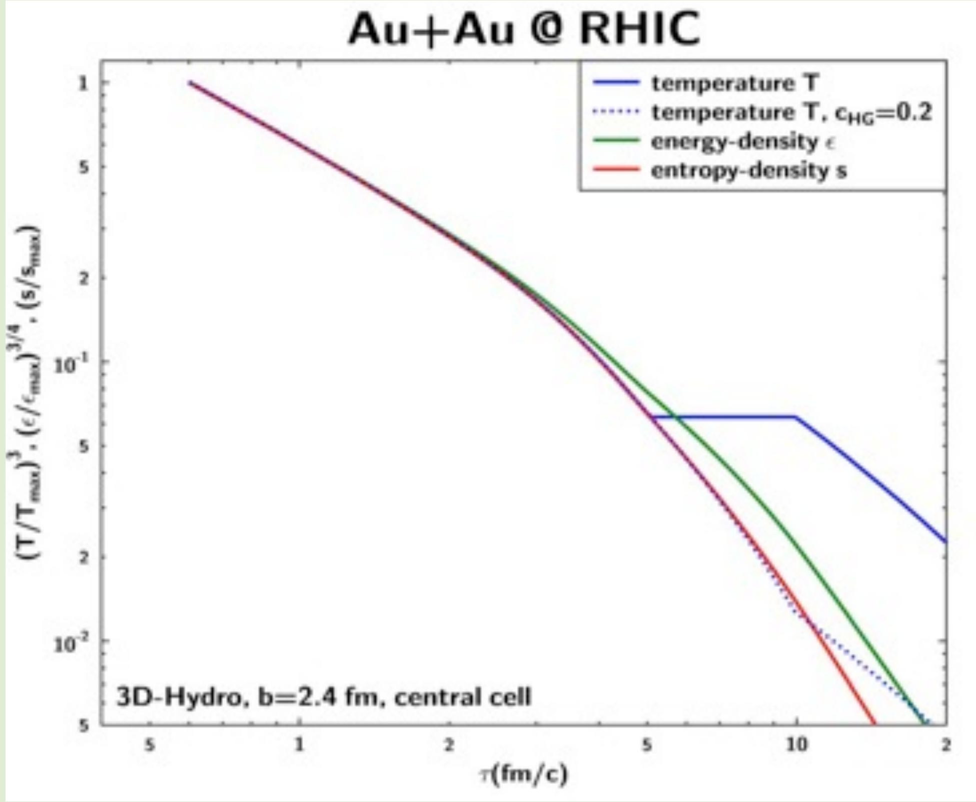
Medium Scaling & Quantitative Comparison:

How does the transport coefficient scale with the thermodynamic properties of the medium? Does the choice of T, ε or s matter?

- EoS for ideal QGP (ideal gas of ultrarelativistic bosons): $\varepsilon = \frac{\pi^2}{30} g_{DOF} T^4$
- common choices for scaling:

$$\hat{q} \sim T^3 \qquad \hat{q} \sim \varepsilon^{3/4} \qquad \hat{q} \sim s$$

➢ identical results only for ideal QGP



(choice of c_{HG}=0.2 mimics scaling with entropy-density s)

- for non-ideal EoS, value of q will be affected by choice of scaling variable:

q_0 [GeV^2/fm]	ASW	HT	AMY
T	10	2.3	4.1
ε	18.5	4.5	X
s		4.3	X

- different medium scaling can affect q-hat by a factor of 2!
- systematic differences in q-hat values extracted by the three schemes remain, even when corrected for medium scaling and are due to differing assumptions on the structure of the medium

‣ need higher precision data and theory advances to provide guidance

Energy Loss vs. In-Medium Shower

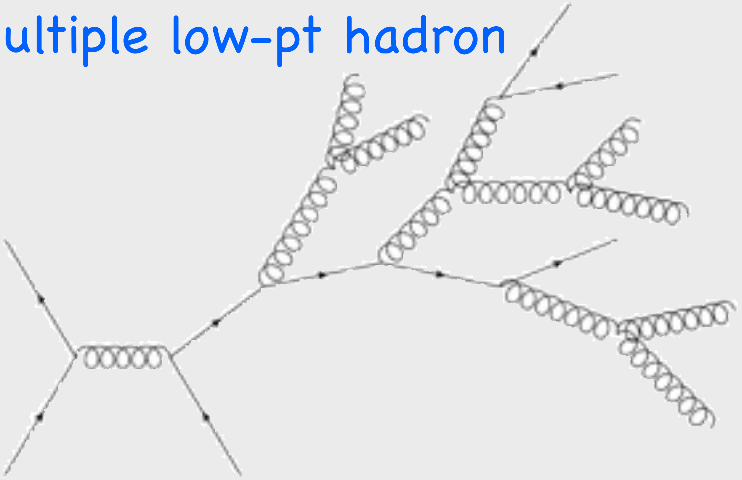
leading particle energy-loss:

- energy loss only describes leading or next-to-leading partons
- information reduction: only small fraction of what happens during shower evolution in medium is utilized
- single and two-particle observables may lack sensitivity to discriminate between the medium assumptions and transport properties inherent in the different energy loss schemes

  - enhance sensitivity/efficiency of the analysis by looking at full shower evolution

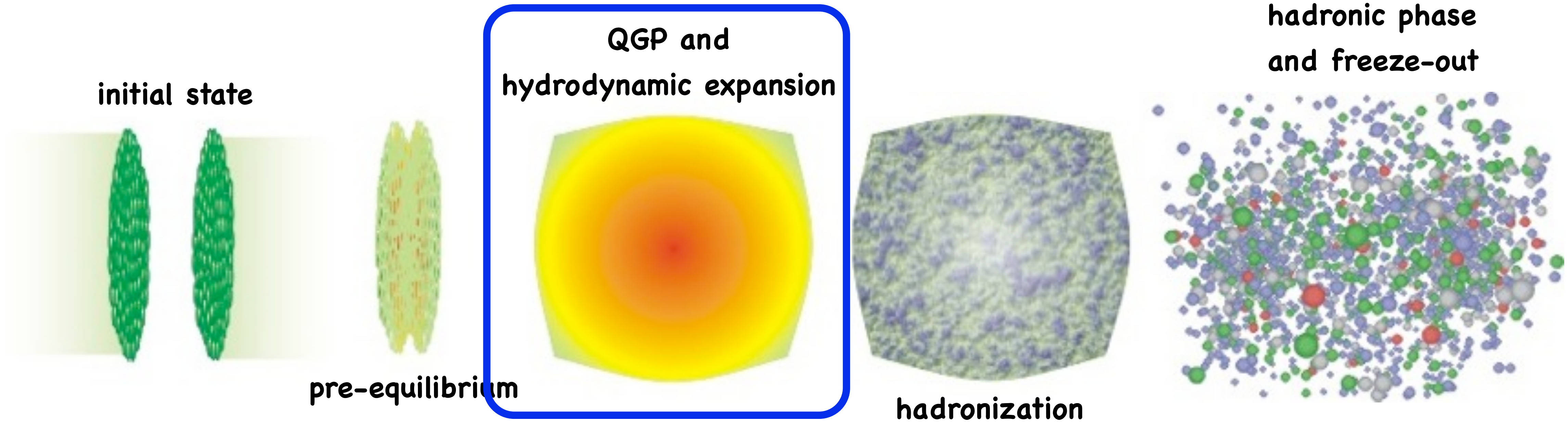
in-medium shower:

- includes dynamics of all partons emitted by shower in medium
- provides full accounting of energy deposited into medium
- describes multiple low-pt hadron production



current state of the art:

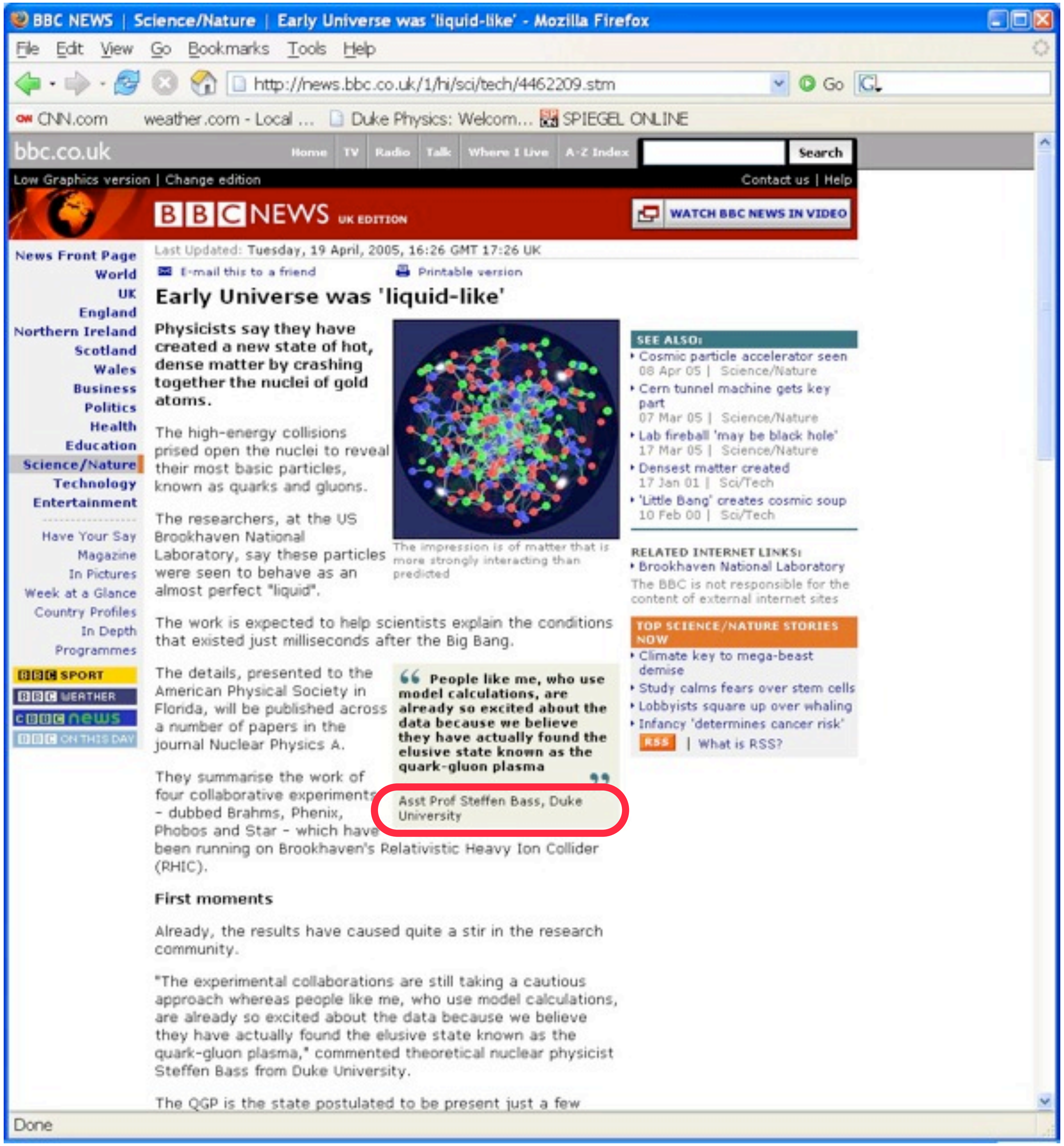
- Monte-Carlo generators with in-medium shower evolution: JEWEL, YaYEM, Q-PYTHIA, Q-HERWIG, MARTINI
- caveat: no real transport!
  - medium response not being calculated
  - no space-time evolution of system
- solution: do full transport:
  - **Parton Cascade Models**



Near-Ideal Fluids & Elliptic Flow

S.A. Bass & A. Dumitru, Phys. Rev **C61** (2000) 064909
D. Teaney et al, nucl-th/0110037
T. Hirano et al. Phys. Lett. **B636** (2006) 299
C. Nonaka & S.A. Bass, Phys. Rev. **C75** (2006) 014902

RHIC in the press: Perfect Liquid



Last Updated: Tuesday, 19 April, 2005, 16:26 GMT 17:26 UK

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The impression is of matter that is more strongly interacting than predicted

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's Relativistic Heavy Ion Collider (RHIC).

> **People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma**
>
> Asst Prof Steffen Bass, Duke University

First moments

Already, the results have caused quite a stir in the research community.

"The experimental collaborations are still taking a cautious approach whereas people like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma," commented theoretical nuclear physicist Steffen Bass from Duke University.

The QGP is the state postulated to be present just a few

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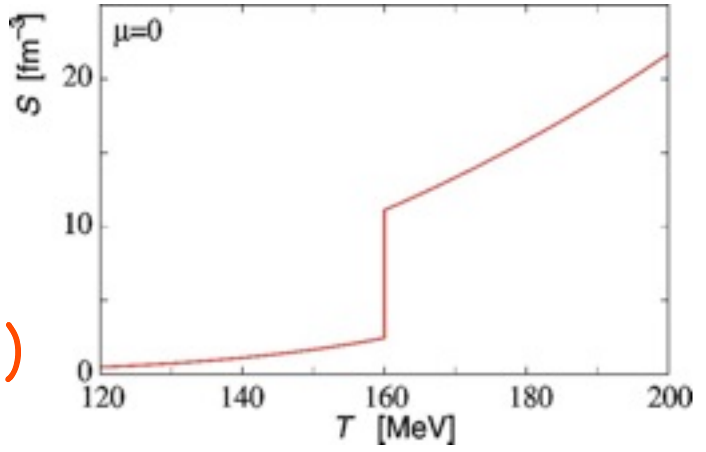
RSS | What is RSS?

- on April 18th, 2005, BNL announced in a press release that RHIC had created a new state of hot and dense matter which behaves like a nearly perfect liquid.
- how does one measure/ calculate the properties of a near ideal liquid?
- are there any other near ideal liquid systems found in nature?

Relativistic Fluid Dynamics (RFD)

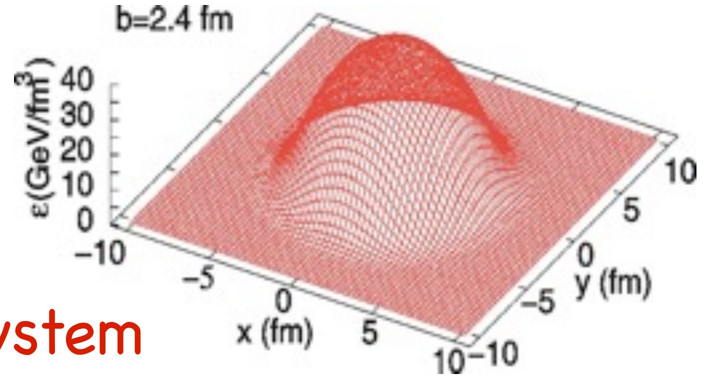
- transport of macroscopic degrees of freedom
- based on conservation laws: $\partial_\mu T^{\mu\nu}=0$ $\partial_\mu j^\mu=0$
- for ideal fluid: $T^{\mu\nu}= (\varepsilon+p)\, u^\mu\, u^\nu - p\, g^{\mu\nu}$ and $j_i^\mu = \rho_i\, u^\mu$
- **Equation of State** needed to close system of PDE's: $p=p(T,\rho_i)$

➢ connection to Lattice QCD calculation of EoS



- initial conditions (i.e. thermalized QGP) required for calculation
- assumes local thermal equilibrium, vanishing viscosity

➢ applicability of hydro is a strong signature for a thermalized system



Viscosity:

- shear and bulk viscosity are defined as the coefficients in the expansion of the stress tensor in terms of the velocity fields:

$$T_{ik} = \varepsilon u_i u_k + P\left(\delta_{ik} + u_i u_k\right) - \eta \left(\nabla_i u_k + \nabla_k u_i - \frac{2}{3}\delta_{ik} \nabla \cdot u \right) + \varsigma\, \delta_{ik} \nabla \cdot u$$

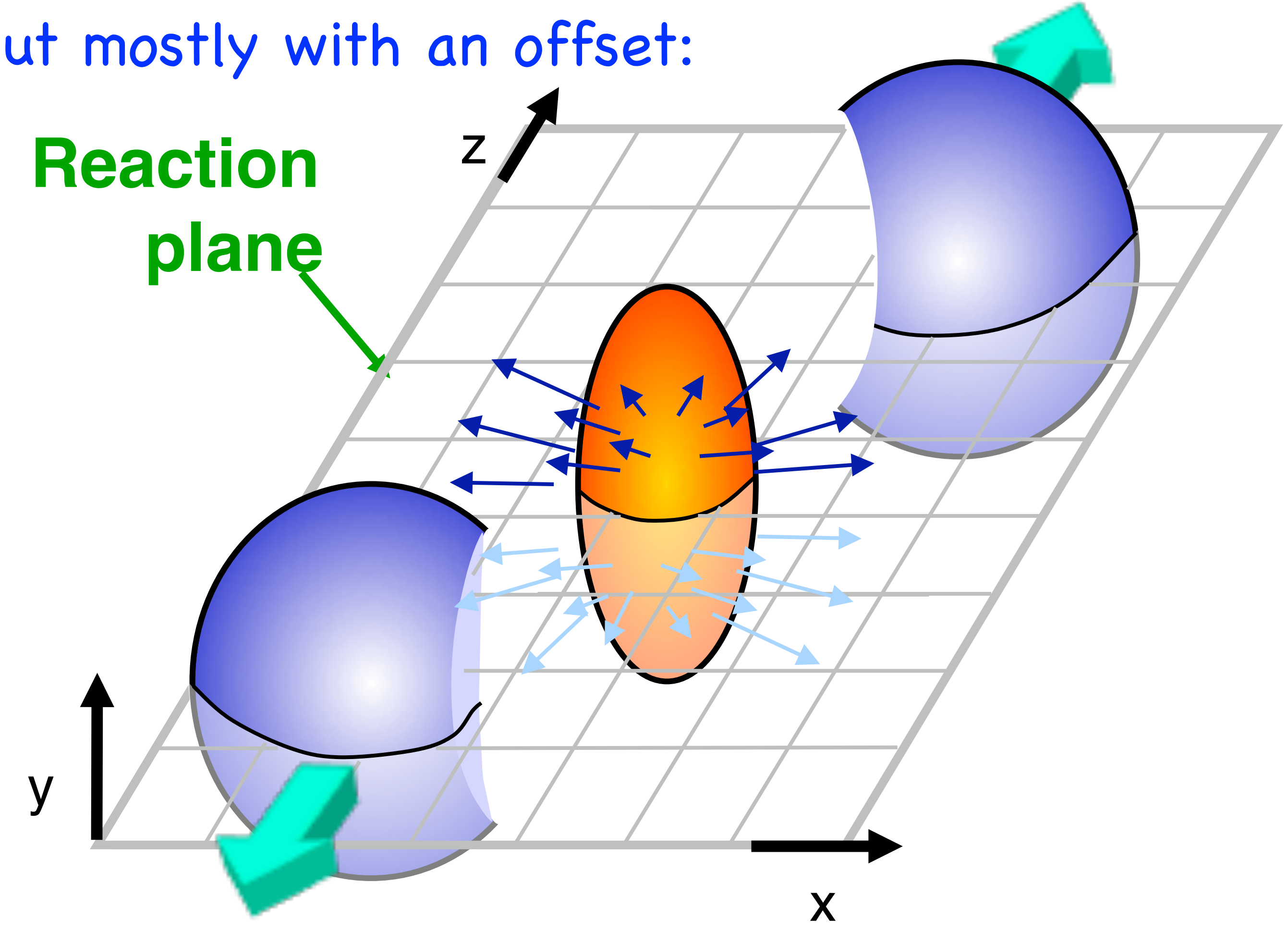
- viscous RFD requires solving an additional 9 eqns. for the dissipative flows

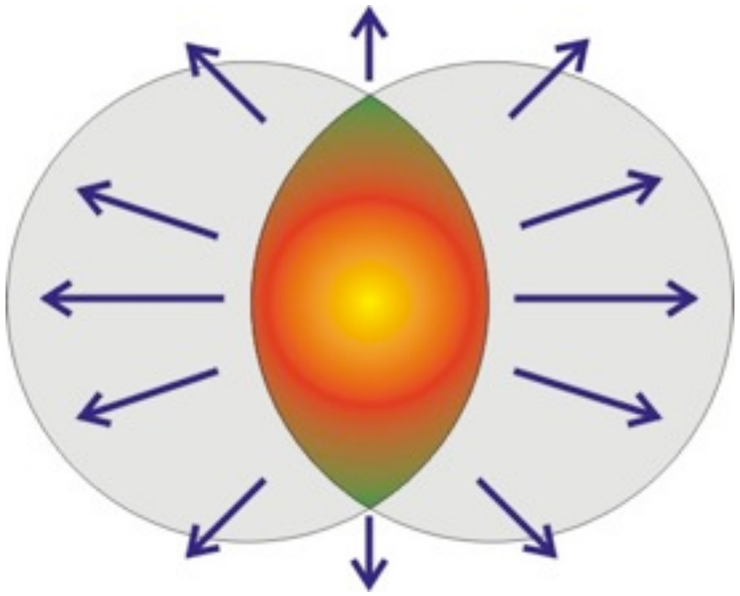
Note:

- for quasi-particulate matter, viscosity decreases with increasing cross section
- for viscous RFD, the microscopic origin of viscosity is not relevant!

Collision Geometry: Elliptic Flow

- two nuclei collide rarely head-on, but mostly with an offset:



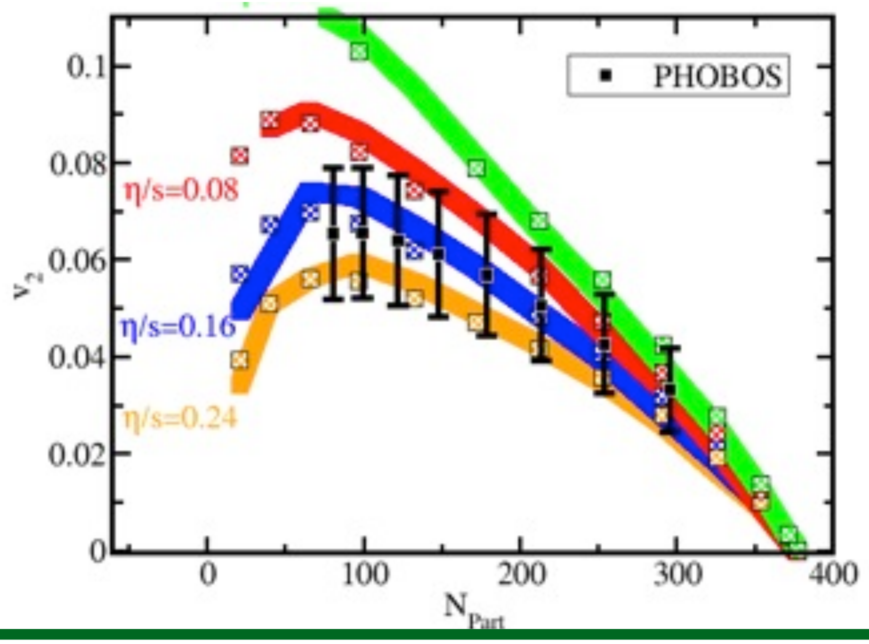


only matter in the overlap area gets compressed and heated up

elliptic flow (v_2):

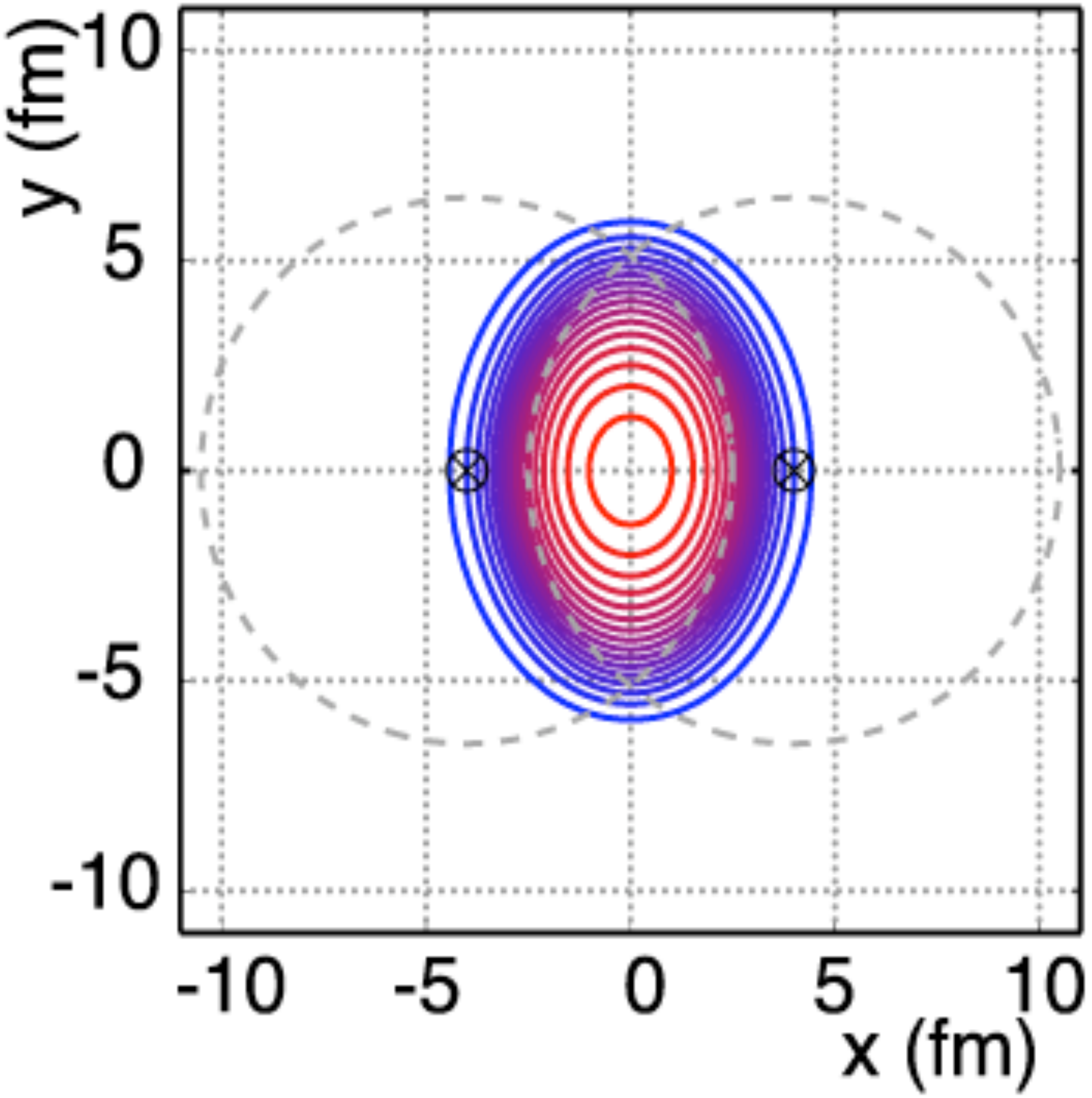
- gradients of almond-shape surface will lead to preferential emission in the reaction plane
- asymmetry out- vs. in-plane emission is quantified by 2nd Fourier coefficient of angular distribution: v_2

➢ vRFD: good agreement with data for very small η/s



Elliptic flow: early creation

initial energy density distribution:

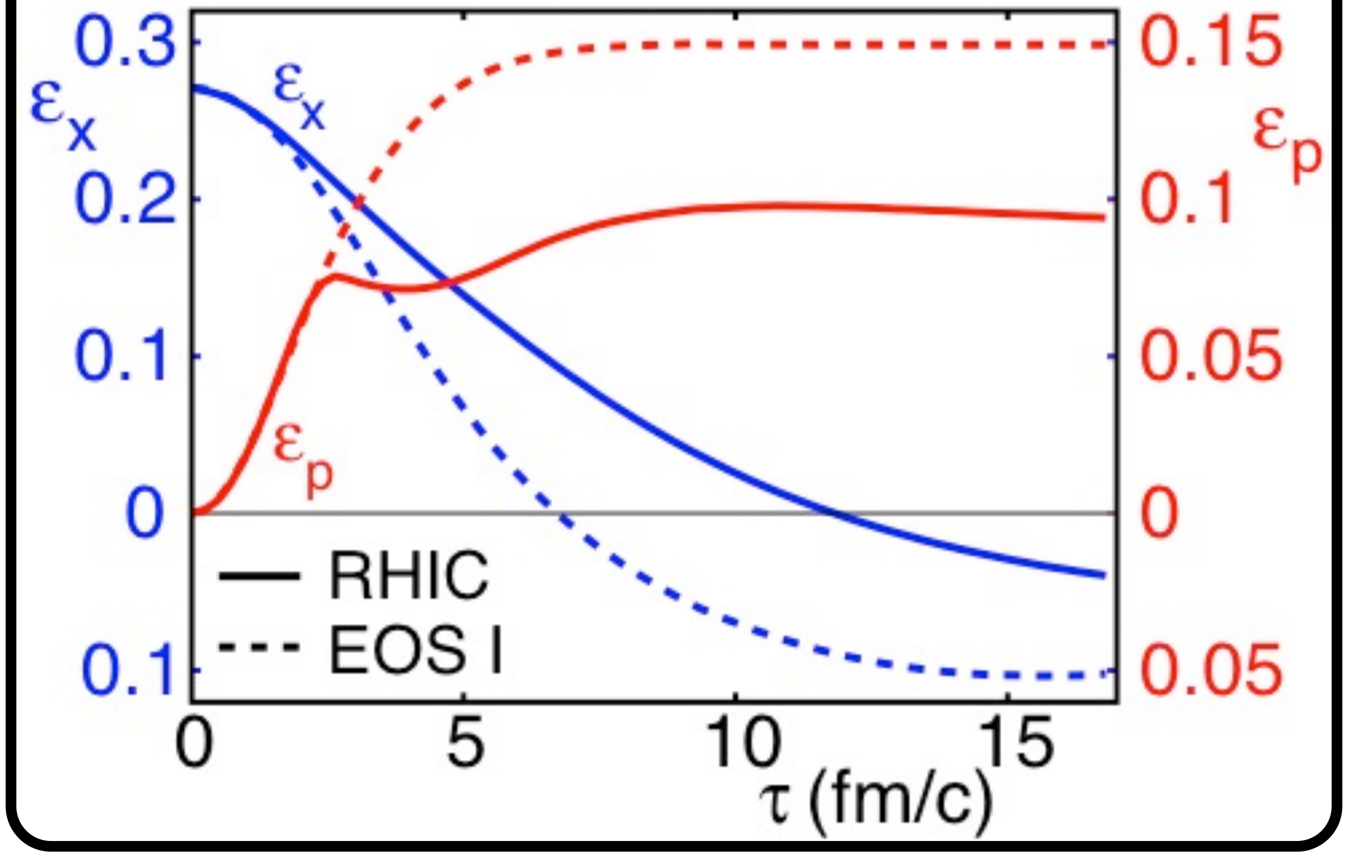


spatial eccentricity

$$\epsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

momentum anisotropy

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



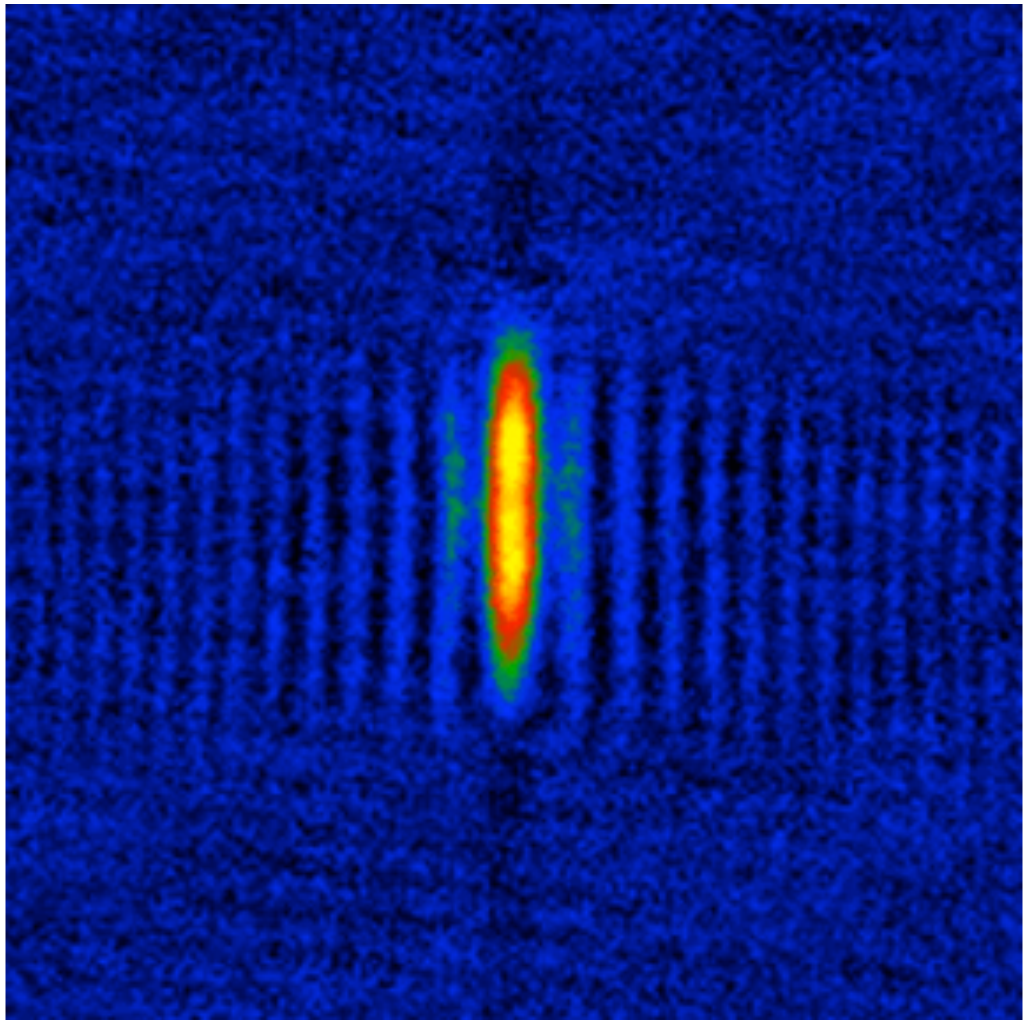
Most model calculations suggest that flow anisotropies are generated at the earliest stages of the expansion, on a **timescale of ~ 5 fm/c** if a QGP EoS is assumed.

P. Kolb, J. Sollfrank and U.Heinz, PRC 62 (2000) 054909

Elliptic flow: ultra-cold Fermi-Gas

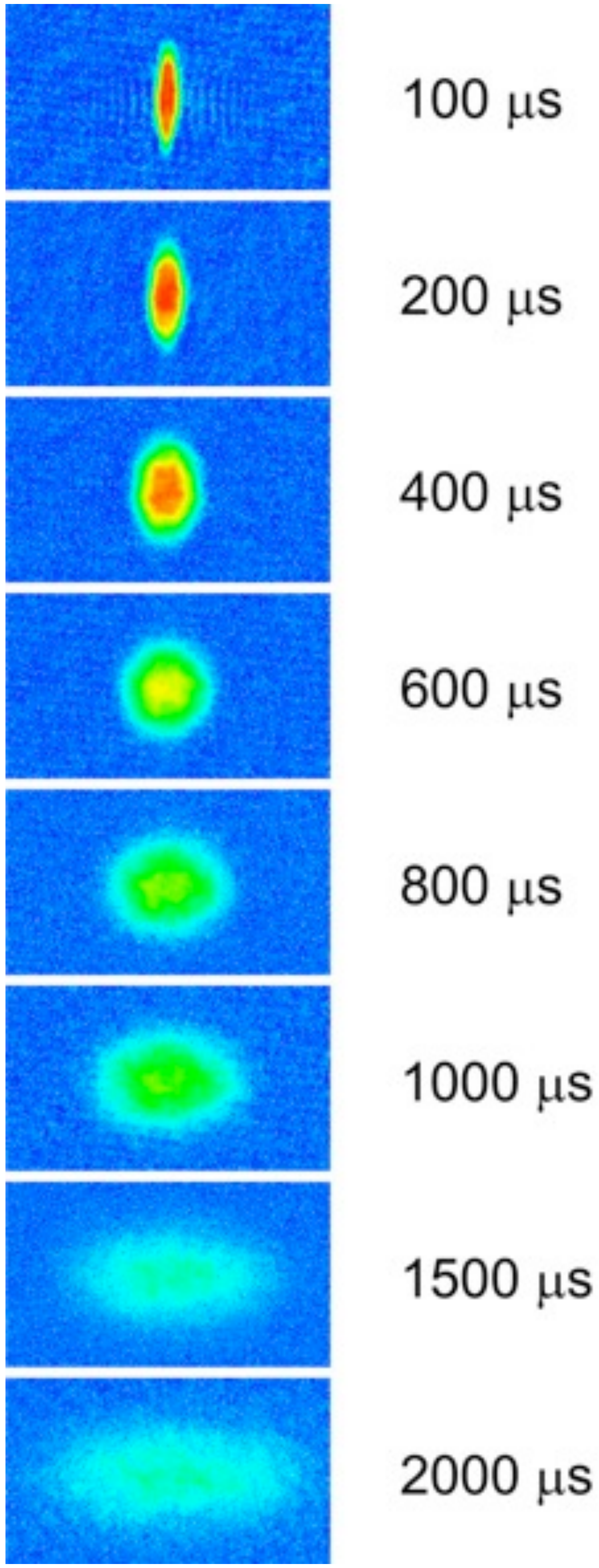
Li atoms at release
from an optical trap:

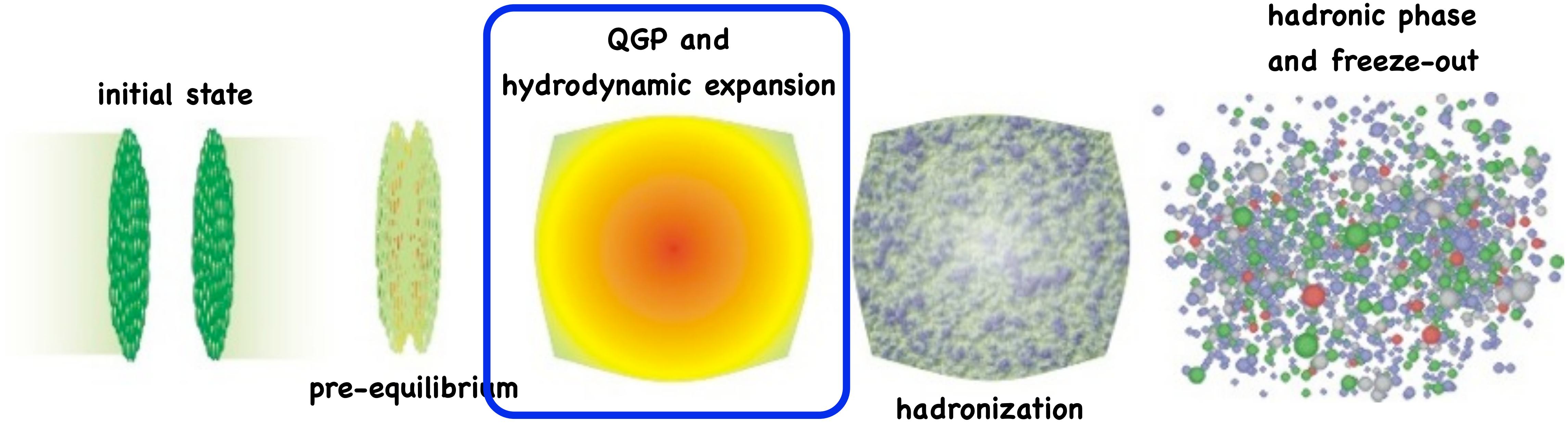
- initial almond shape, similar to interaction area in heavy-ion collision



- Li-atoms released from an optical trap exhibit elliptic flow analogous to what is observed in ultra-relativistic heavy-ion collisions
- Elliptic flow is a general feature of strongly interacting systems!

K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, J. E. Thomas:
Science **298** (2002) 2179





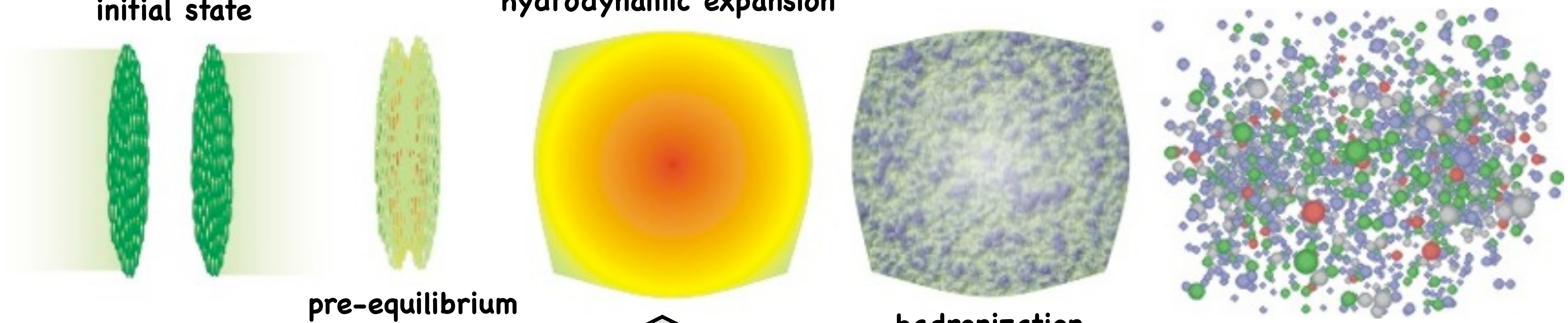
shear-viscosity of QCD matter

- quantifying q-hat is still a challenge
- can we do better with η or η/s?

M. Asakawa, S.A. Bass & B. Mueller: Phys. Rev. Lett. **96** (2006) 252301

M. Asakawa, S.A. Bass & B. Mueller: Prog. Theo. Phys. **116** (2006) 725

Viscosity at RHIC



initial state

pre-equilibrium

QGP and
hydrodynamic expansion

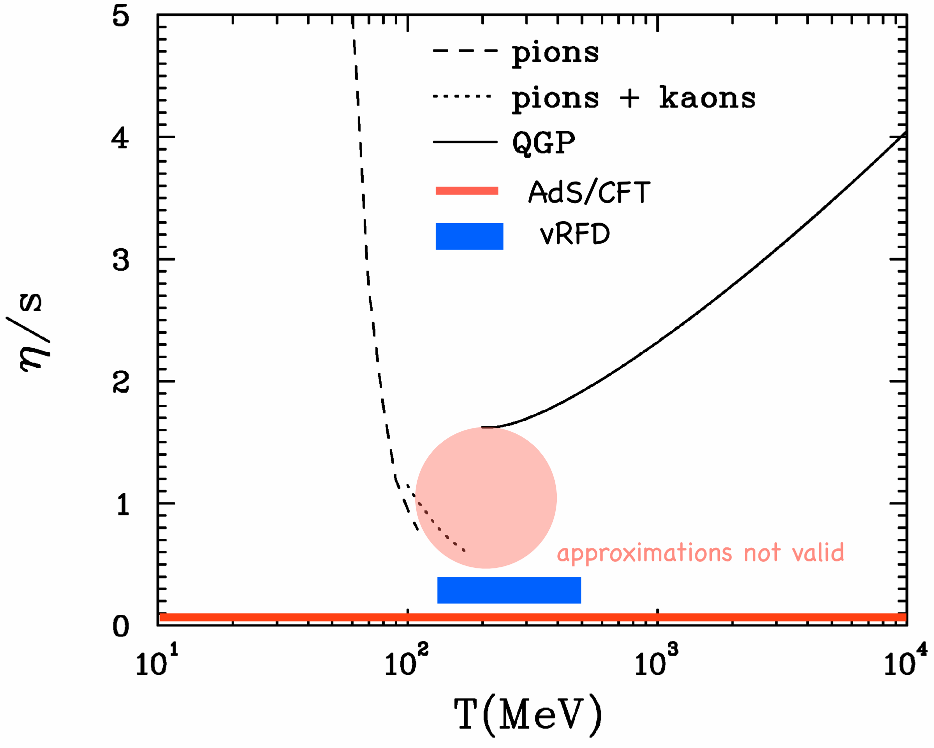
hadronization

hadronic phase
and freeze-out

large elliptic flow:
near ideal fluid w/
small viscosity

parton
recombination:
quasi-particle
d.o.f.

expanding hadron gas
w/ increasing m.f.p.:
large viscosity



- viscosity of QCD matter @ RHIC changes strongly with temperature & phase
- how can we learn more about the viscosity of QCD matter?

L.P. Csernai, J.I. Kapusta & L. McLerran: Phys. Rev. Lett. **97**: 152303 (2006)
M. Prakash, M. Prakash, R. Venugopalan & G. Welke: Phys. Rept. **227**, 321 (1993)
P. Arnold, G.D. Moore & L.D. Yaffe: JHEP **05**: 051 (2003)

η/s from Lattice QCD

The confines of the Euklidian Formulation:

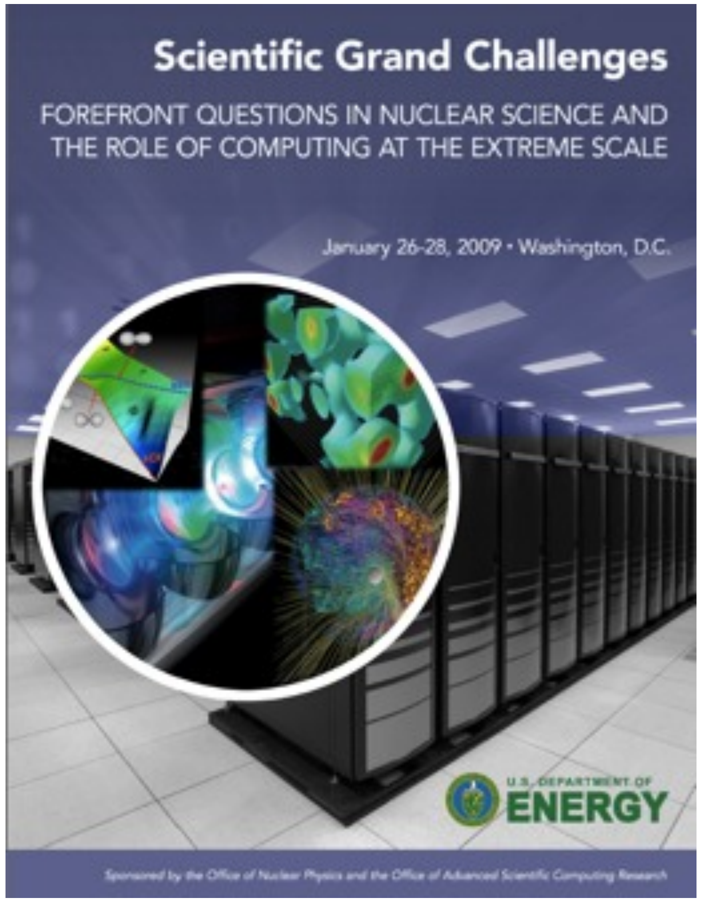
- extracting η/s formally requires taking the zero momentum limit in an infinite spatial volume, which is numerically not possible...

preliminary estimates:

caution:

systematic errors are O(1)!

T	1.58 T_C	2.32 T_C
η/s	0.2	0.26



Scientific Grand Challenges

FOREFRONT QUESTIONS IN NUCLEAR SCIENCE AND THE ROLE OF COMPUTING AT THE EXTREME SCALE

January 26-28, 2009 • Washington, D.C.

U.S. DEPARTMENT OF ENERGY

Sponsored by the Office of Nuclear Physics and the Office of Advanced Scientific Computing Research

- calculating QCD transport coefficients on the Lattice has been identified as a Priority Research Direction by the DOE Office of Nuclear Physics and the Office of Advanced Scientific Computing Research (ASCR) in their report on Extreme-Scale Computing

Harvey B. Meyer: Phys.Rev.**D79**: 011502, 2009

Harvey B. Meyer: **arXiv:0809.5202** [hep-lat]

AdS/CFT correspondence

- calculating viscosity and viscosity/entropy ratio too difficult in full QCD
- quantities are calculable in a related theory using string theory methods

model for QCD:

$N = 4$ Super-Yang-Mills theory ↔ a string theory in 5d AdS

finite temperature ↔ black hole in AdS_5

large N_C and strong coupling limit ↔ classical gravity limit

- YM observables at infinite N_C and infinite coupling can be computed using classical gravity
- technique can be applied to dynamical and thermodynamic observables
- in all theories with gravity-duals one finds: $\frac{\eta}{s} = \frac{\hbar}{4\pi}$ (very small number!)

Caution:

- N=4 SUSY YM is not QCD!
- no information on how low η/s is microscopically generated

J. Maldacena: Adv. Theor. Math. Phys. 2 (1998) 231
E. Witten: Adv. Theor. Math. Phys. 2 (1998) 505
S.S. Gubser, I.R. Klebanov & M. Polyakov: Nucl.Phys. B636 (2002)

The sQGP Challenge: do quasi-particles drive η/s?

- the success of near ideal hydrodynamics has led the community to equate low viscosity with a vanishing mean free path and thus large parton cross sections: **strongly interacting QGP (sQGP)**

- does a small viscosity have to imply that matter is strongly interacting?
- consider effects of (turbulent) color fields?

Anomalous Viscosity: (see e.g. in Plasma-, Astro-, Biophysics)

- any contribution to the shear viscosity not explicitly resulting from momentum transport via a transport cross section

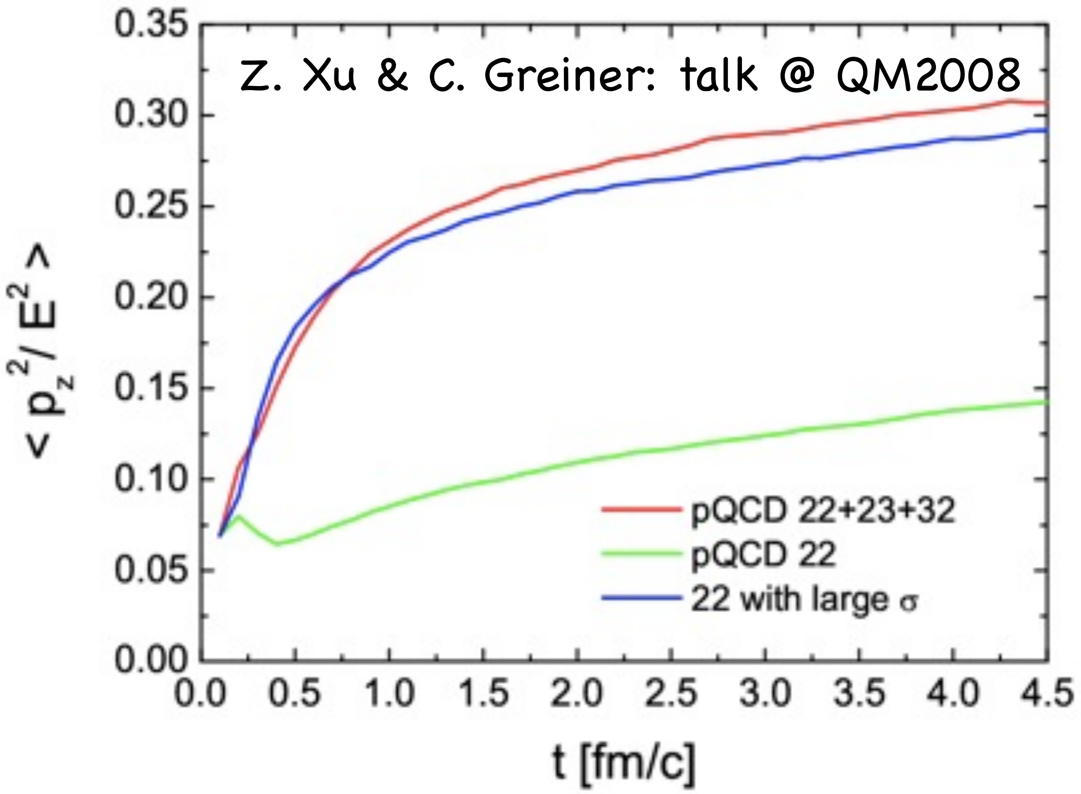
- can the QGP viscosity be anomalous?
  - soft, turbulent color fields generate anomalous transport coefficients, which may give the medium the character of a nearly perfect fluid even at moderately weak coupling.

microscopic kinetic theory:

η is given by the rate of momentum transport:

$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f = \frac{\bar{p}}{3\sigma_{\mathrm{tr}}}$$

- microscopic transport with parton d.o.f. requires either unphysically large cross sections or a very specific implementation of the LPM effect to thermalize & create elliptic flow


Z. Xu & C. Greiner: talk @ QM2008

Hard Thermal Loops: Instabilities

Nonabelian Vlasov equations describe interaction of "hard" (i.e. particle) and "soft" color field modes and generate the "hard-thermal loop" effective theory:

$$\frac{dp^\mu}{d\tau} = gQ^a\, F^{a\mu\nu}\, u_\nu \qquad \frac{dQ^a}{d\tau} = g f_{abc} A^{b\nu}\, u_\nu\, Q^c \qquad D_\mu F^{\mu\nu} = gJ^\nu$$

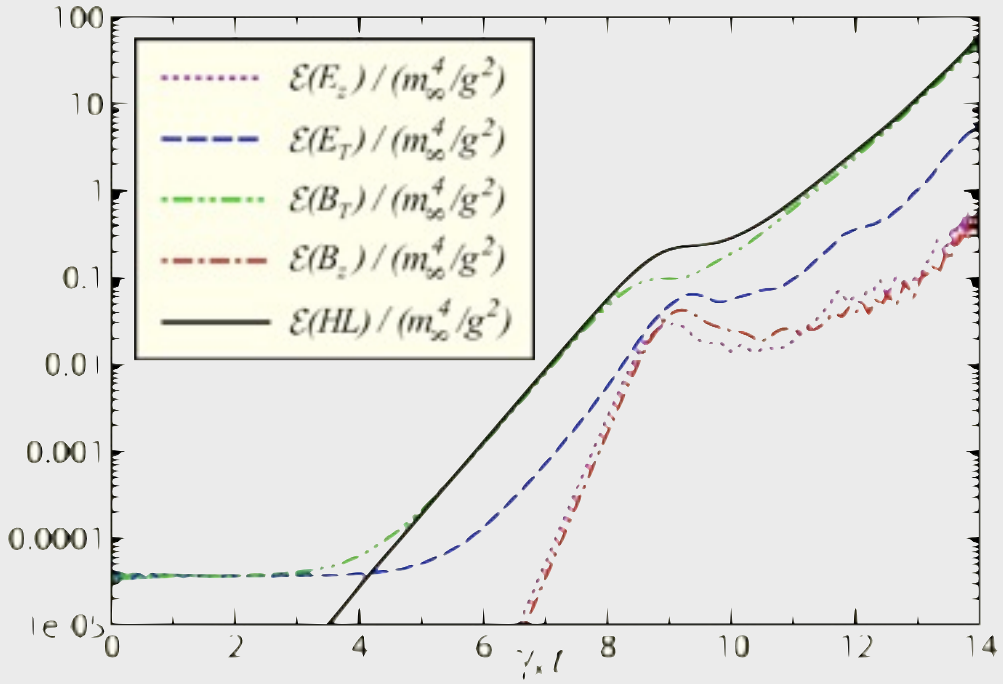
with $J^\nu(x) = \sum_i \int d\tau\, Q_i(\tau)\, u_i^\nu(\tau)\, \delta\left(x - x_i(\tau)\right)$

Effective HTL theory permits systematic study of instabilities of "soft" color fields

find HTL modes for anisotropic distribution:

$$f(\vec{p}, \vec{r}) \approx \left(e^{\beta u\cdot p - f_1(\vec{p},\vec{r})} \mp 1\right)^{-1}$$

- for most $f_1 \neq 0$ there exist unstable modes
- energy-density and growth rate of unstable modes can be calculated:



P. Romatschke & M. Strickland, PRD **68**: 036004 (2003)

P. Arnold, J. Lenaghan & G.D. Moore, JHEP **0308**, 002 (2003)

S. Mrowczynski, PLB **314**, 118 (1993)

Anomalous Viscosity Derivation: Sketch

- linear Response: connect η with momentum anisotropy Δ:

$$\eta = -\frac{1}{15T}\int \frac{d^3p}{(2\pi)^3}\frac{\vec{p}^4}{E_P^2}\bar{\Delta}(p)\frac{\partial f_0}{\partial E_p}$$

with $f(\vec{p},\vec{r}) \approx \left(e^{\beta u\cdot p - f_1(\vec{p},\vec{r})} \mp 1\right)^{-1}$

and $f_1(\vec{p},\vec{r}) = -\frac{\bar{\Delta}(p)}{E_p T^2} p_i p_j (\nabla u)_{ij}$

- use color Vlasov-Boltzmann Eqn. to solve for f and Δ:

$$v^\mu \frac{\partial}{\partial x^\mu} f(\vec{r},\vec{p},t) + g\mathbf{F}^a \cdot \nabla_p f^a(\vec{r},\vec{p},t) + C[f] = 0$$

with

$$\mathbf{F}^a = \mathcal{E}^a + \mathbf{v}\times\mathcal{B}^a$$

- turbulent color field assumption:
  - ensemble average over fields:

$$\langle \mathcal{B}_i^a(x) U_{ab}(x,x') \mathcal{B}_j^b(x')\rangle = \langle \mathcal{B}_i^a \mathcal{B}_j^a\rangle\, \Phi_\tau^{(\mathrm{mag})}(|t-t'|)\; \tilde{\Phi}_\sigma^{(\mathrm{mag})}(|\mathbf{x}-\mathbf{x}'|)$$

➢ diffusive Vlasov-Boltzmann Eqn: $v^\mu \frac{\partial}{\partial x^\mu}\bar{f} - \nabla_p \cdot D \cdot \nabla_p \bar{f} + C[\bar{f}] = 0$

- example: anomalous viscosity in case of transverse magnetic fields

$$\eta_A^{(g)} = \frac{16\zeta(6)(N_c^2-1)^2}{\pi^2 N_c}\frac{T^6}{g^2\langle\mathcal{B}^2\rangle\,\tau_{\mathrm{m}}^{\mathrm{mag}}} \qquad \eta_A^{(q)} = \frac{62\zeta(6)N_c^2 N_f}{\pi^2}\frac{T^6}{g^2\langle\mathcal{B}^2\rangle\,\tau_{\mathrm{m}}^{\mathrm{mag}}}$$

Anomalous vs. Collisional Viscosity

collisional viscosity:

- derived in HTL weak coupling limit

$$\frac{\eta_C}{s} \approx \frac{5}{g^4 \ln g^{-1}}$$

anomalous viscosity:

- induced by turbulent color fields, due to momentum-space anisotropy

$$\frac{\eta_A}{s} = \mathcal{O}(1) \frac{(N_c^2 - 1)}{N_c} \frac{T^6}{g^2 \langle \mathcal{B}^2 \rangle \, \tau_{\mathrm{m}}} \quad \Rightarrow \quad \frac{\eta_A}{s} \sim \frac{1}{\langle B^2 \rangle}$$

- with ansatz for fields:

$$\frac{\eta_A}{s} = \bar{c}_0 \left(\frac{T}{g^2 |\nabla u|} \right)^{3/5}$$

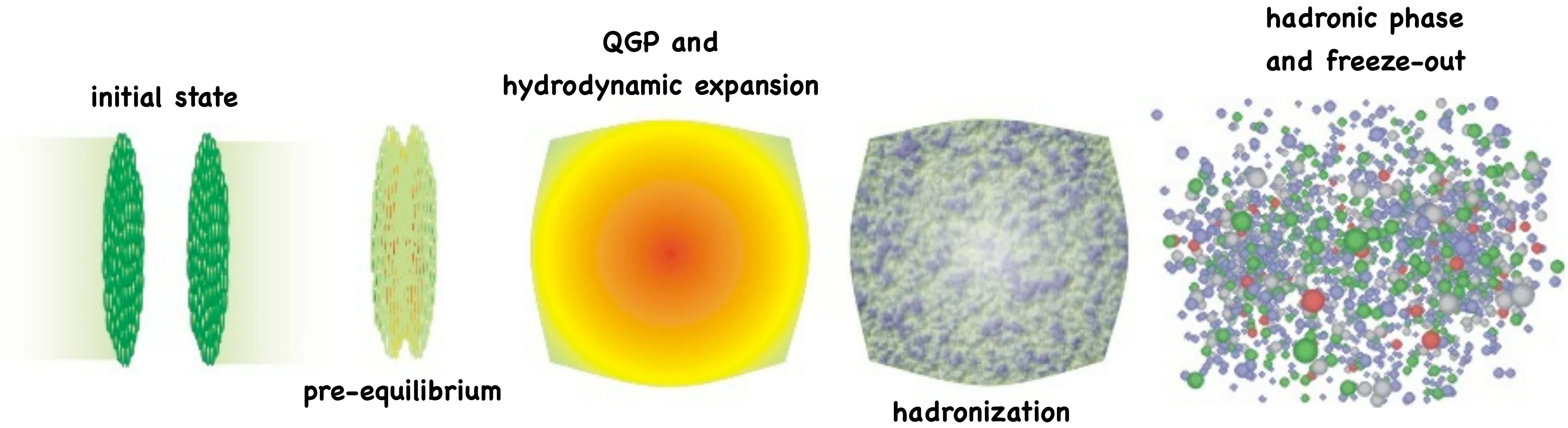
- for reasonable values of g: $\eta_A < \eta_C$

- sum-rule for system w/ 2 viscosities: (derived from variational principle)

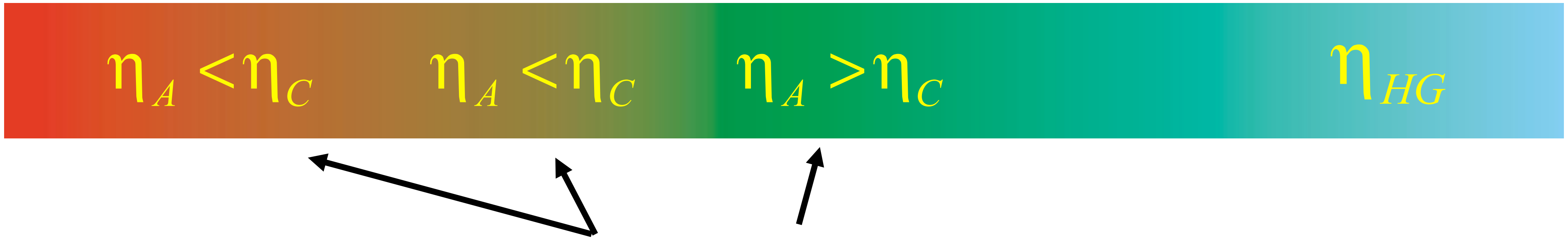
$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

- total viscosity dominated by η_A

Collisional vs. Anomalous Viscosity



temperature evolution:

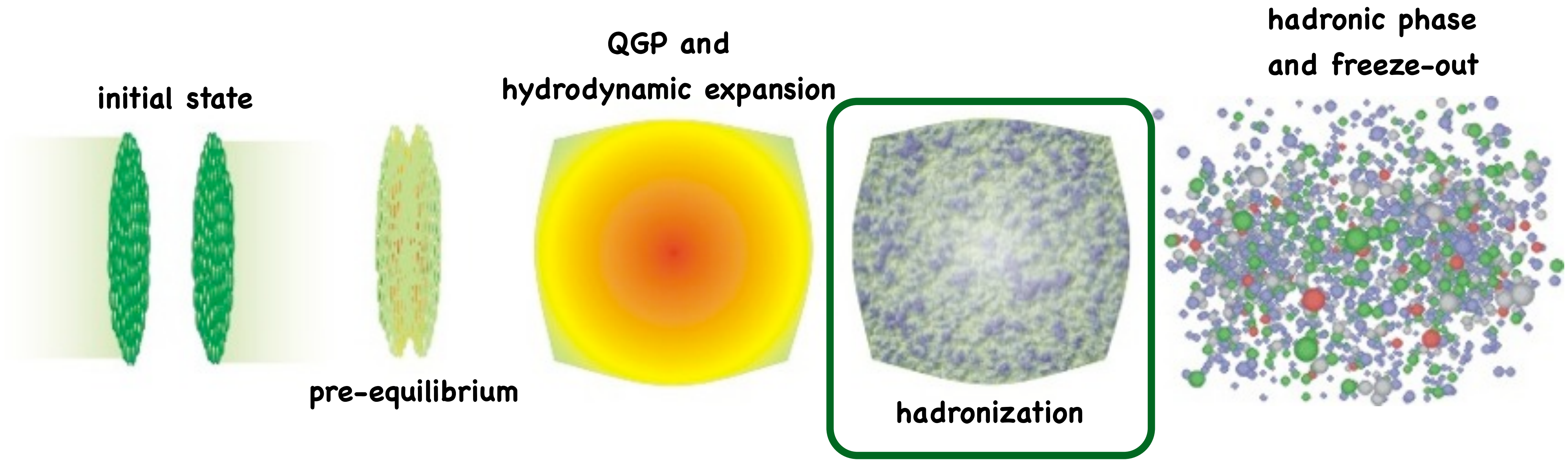


$\eta_A < \eta_C$ $\eta_A < \eta_C$ $\eta_A > \eta_C$ η_{HG}

$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

- smaller viscosity dominates in system w/ 2 viscosities!

- anomalous viscosity dominates total shear viscosity during early QGP evolution
- a small viscosity does not necessarily imply strongly interacting matter!



Intermezzo @ Hadronization:

- Parton Recombination

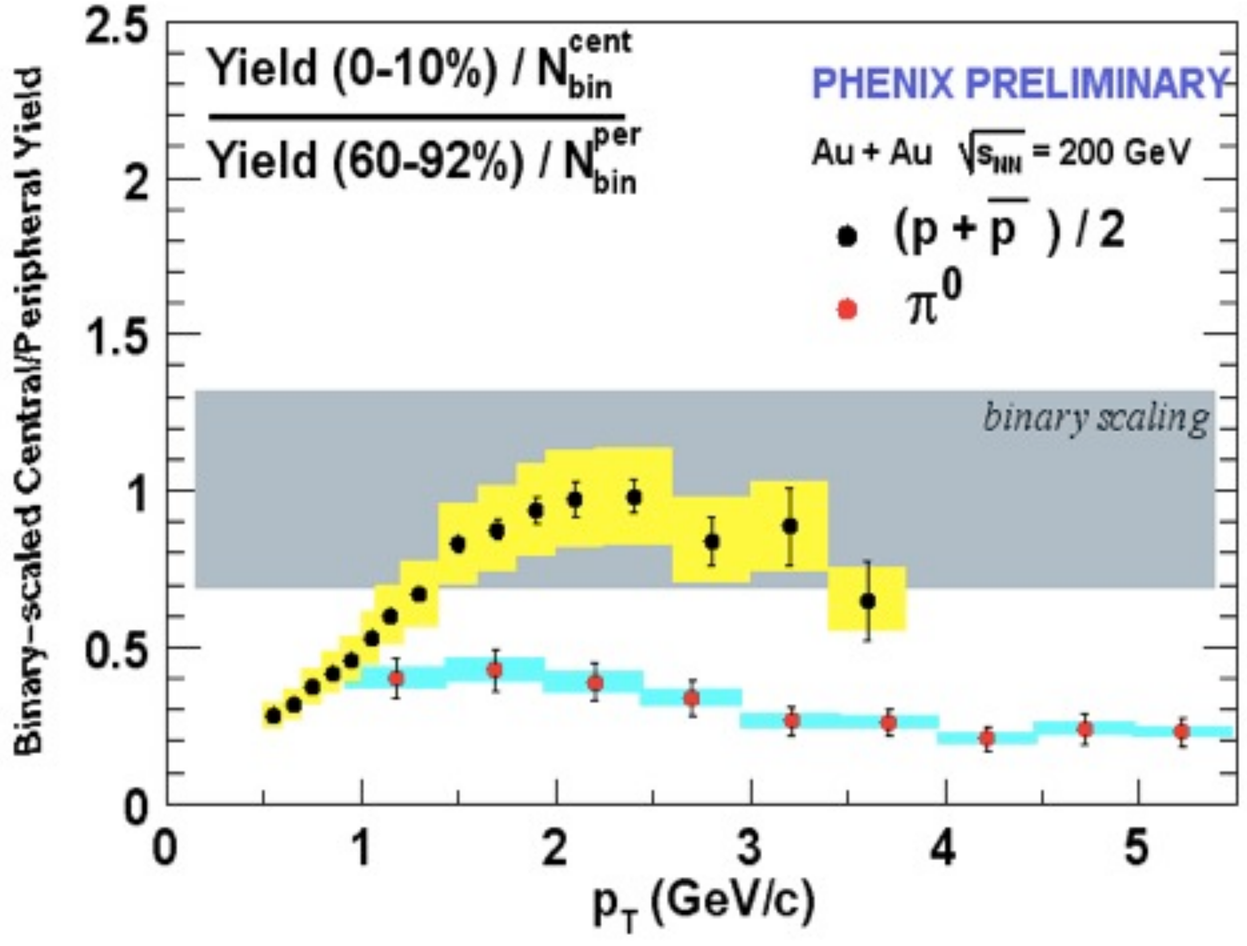
featured in Thompson ESI:
Fast Moving Fronts March 2005

2004 JNS publication prize for
Young Nuclear Theorists awarded
to C. Nonaka

850+ citations since January 2003

R.J. Fries, C. Nonaka, B. Mueller & S.A. Bass, PRL **90** (2003) 202303
R.J. Fries, C. Nonaka, B. Mueller & S.A. Bass, PRC **68** (2003) 044902
C. Nonaka, R.J. Fries & S.A. Bass, Phys. Lett. B **583** (2004) 73
R. J. Fries, S.A. Bass & B. Mueller, PRL **94** (2005) 122301

The baryon puzzle @ RHIC

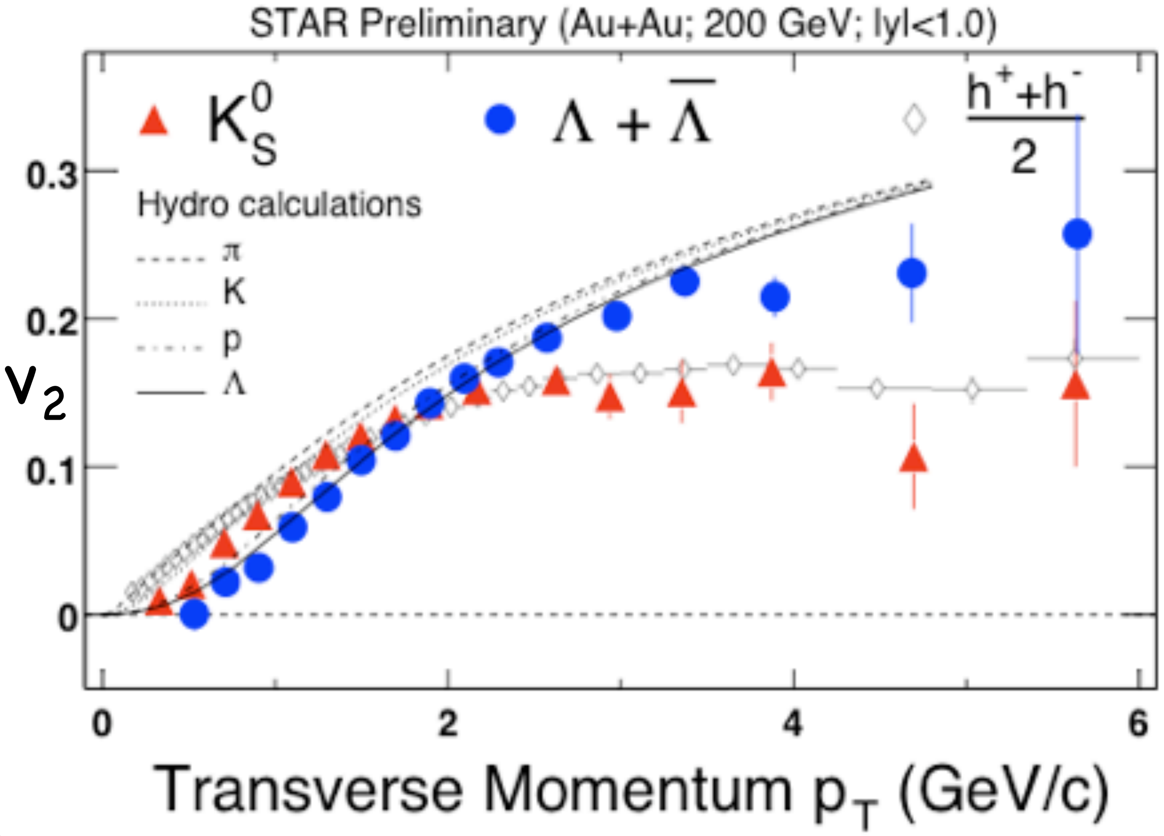


- why do protons not exhibit the same jet- suppression as pions?

➢ fragmentation starts with a single fast parton: energy loss affects pions and protons in the same way!

species dependence of v_2 saturation:

- RFD distributions scale by mass, not Meson/Baryon Number: why does RFD fail at intermediate momenta?
- why do baryons overtake mesons?



what drives the physics that makes intermediate p_t physics dependent on Meson/Baryon Number?

Recombination+Fragmentation Model

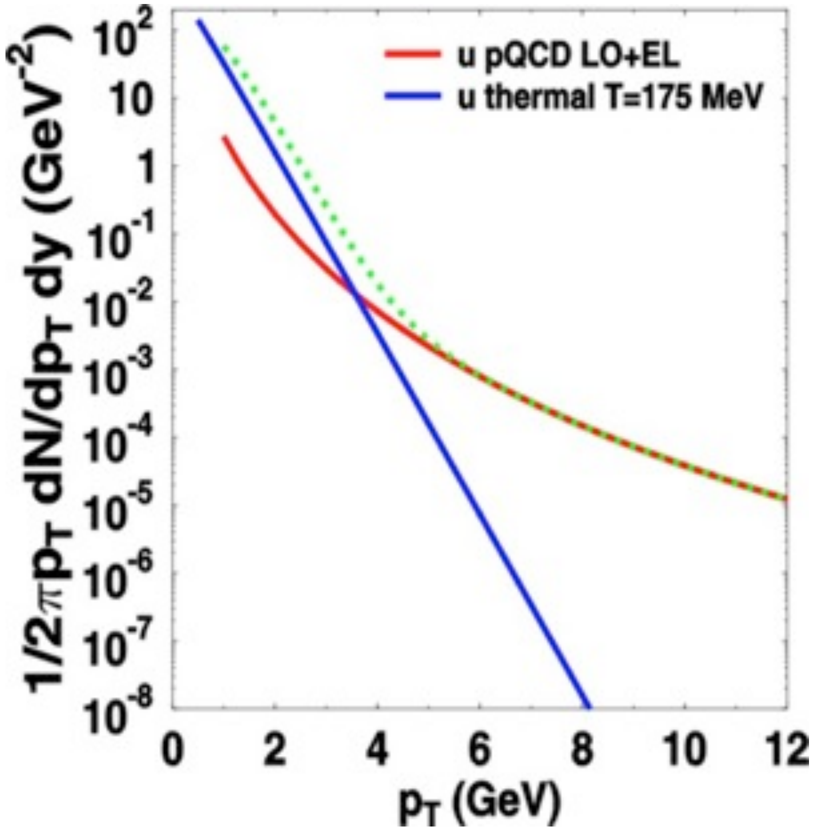
basic assumptions:

- at low p_t, the quark- and antiquark spectrum is thermal and they recombine into hadrons locally "at an instant":

$$\frac{dN_M}{d^3P} = C_M \frac{V}{(2\pi)^3}\int \frac{d^3q}{(2\pi)^3} w\left(\tfrac{1}{2}P - q\right) w\left(\tfrac{1}{2}P + q\right)\left|\hat{\varphi}_M(q)\right|^2$$

- at high p_t, the parton spectrum is given by a pQCD power law, partons suffer jet energy loss and hadrons are formed via fragmentation of quarks and gluons:

$$E\frac{dN_h}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3}\int_0^1 \frac{dz}{z^2}\sum_\alpha w_\alpha\left(R,\tfrac{1}{z}P\right) D_{\alpha\to h}(z)$$



- Reco: baryons shifted to higher p_t than mesons, for same quark distribution
- shape of spectrum determines if reco or fragmentation is more effective:
  - for thermal distribution recombination yield dominates fragmentation yield
  - vice versa for pQCD power law distribution

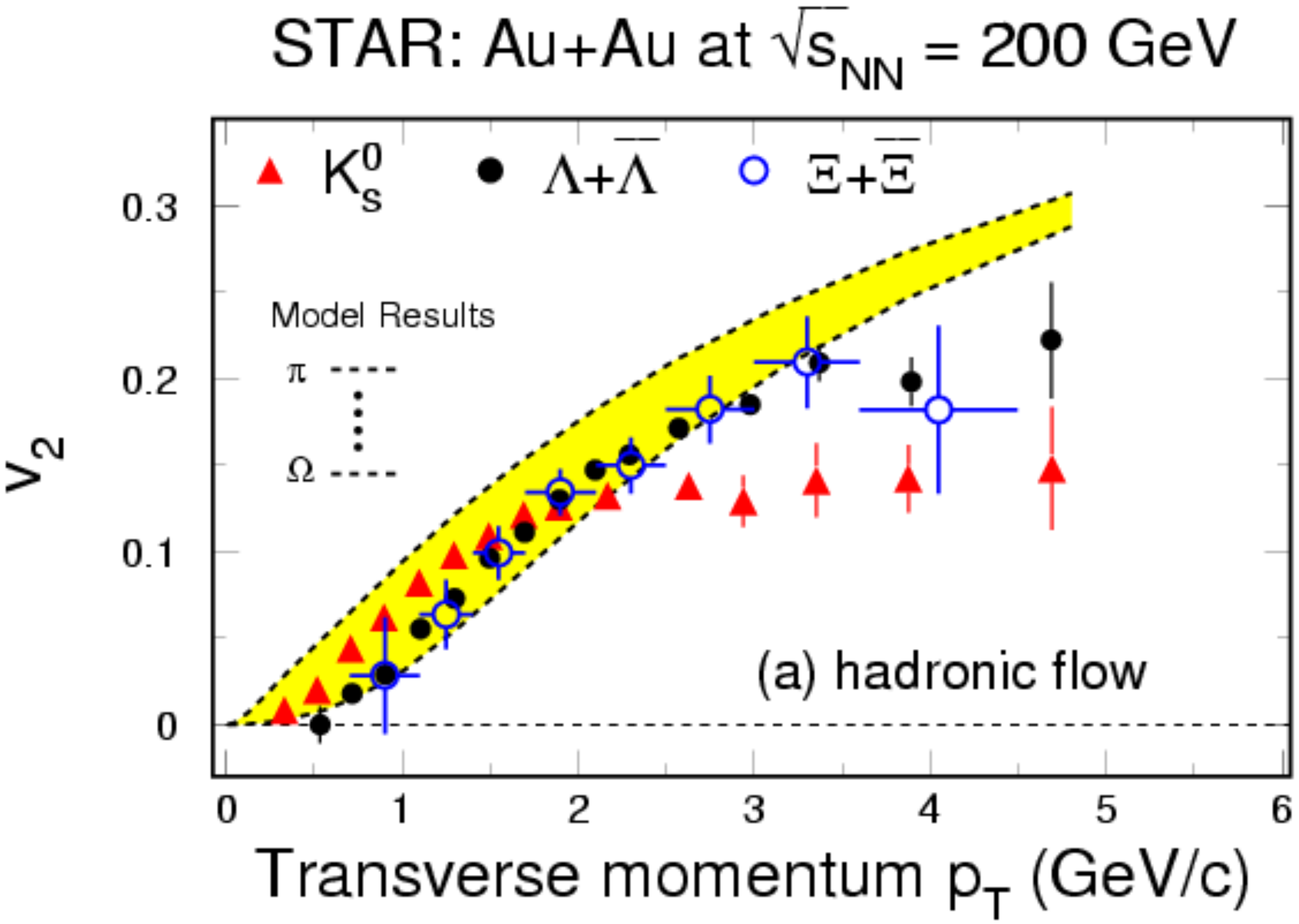
➢ understand behavior of baryons, since jet-quenching is strictly high-p_t!

Quasiparticles at T_C: Parton Recombination

The parton recombination model predicts that the elliptic flow of a hadron as a function of p_t scales with the number of its constituent quarks:

$$v_2^M(p_t) = \frac{2\, v_2^p\left(\frac{p_t}{2}\right)}{1 + 2\left(v_2^p\left(\frac{p_t}{2}\right)\right)^2}$$

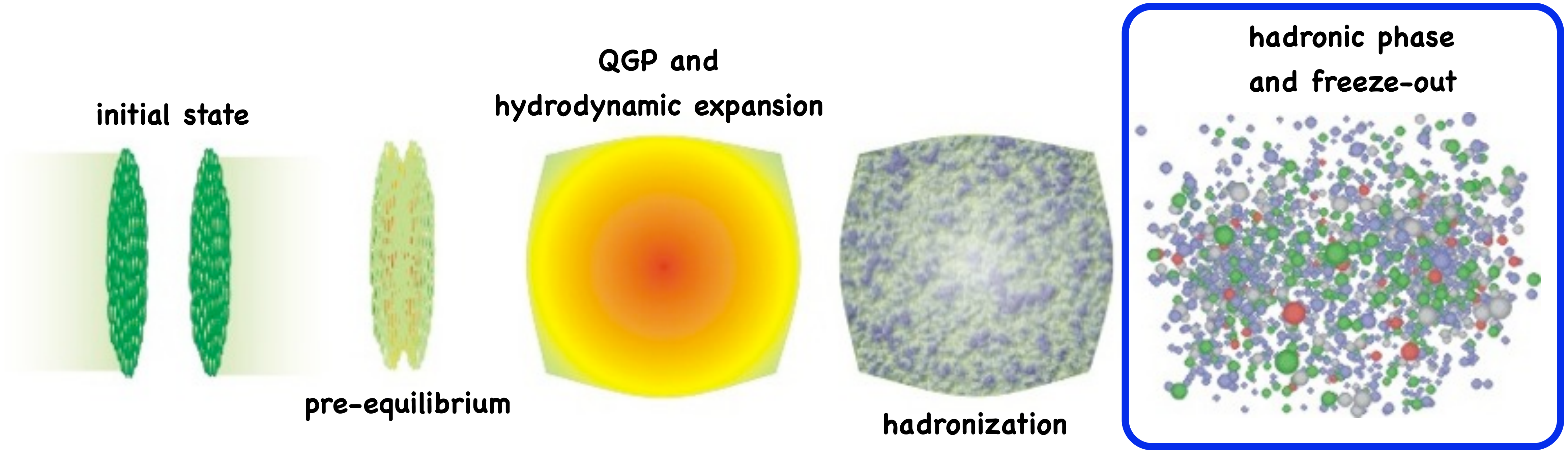
$$v_2^B(p_t) = \frac{3\, v_2^p\left(\frac{p_t}{3}\right) + 3\left(v_2^p\left(\frac{p_t}{3}\right)\right)^3}{1 + 6\left(v_2^p\left(\frac{p_t}{3}\right)\right)^2}$$



Lessons from Constituent-Quark-Scaling:

- as the system evolves towards T_C, the DoF of the QGP become quasi-particles
- at hadronization, constituent quarks are most likely the dominant DoF

‣ **most direct evidence for the creation of a QGP to date!**



initial state

pre-equilibrium

QGP and
hydrodynamic expansion

hadronization

hadronic phase
and freeze-out

η/s of a Hadron Gas

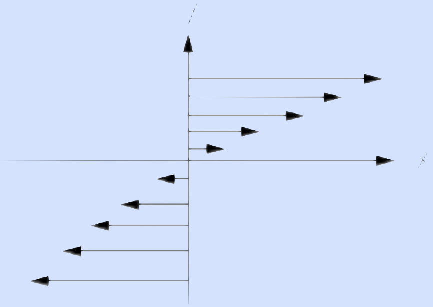
N. Demir & S.A. Bass: Phys. Rev. Lett. **102**, 172302 (2009)

Shear Viscosity: Linear Transport Equation & Green - Kubo Formalism

Mechanical definition of shear viscosity:

- application of a shear force to a system gives rise to a non-zero value of the xy-component of the pressure tensor P_{xy}. P_{xy} is then related to the velocity flow field via the shear viscosity coefficient η:

$$P_{xy} = -\eta \frac{\partial v_x}{\partial y}$$



- a similar linear transport equation can be defined for other transport coefficients: thermal conductivity, diffusion …

- using linear-response theory, the **Green-Kubo relations** for the shear viscosity can be derived, expressing η as an integral of an near-equilibrium time correlation function of the stress-energy tensor:

$$\eta = \frac{1}{T} \int d^3r \int_0^\infty dt \left\langle \pi^{xy}(\vec{0},0)\, \pi^{xy}(\vec{r},t) \right\rangle_{\text{equil}}$$

with the stress-energy tensor: $\pi^{\mu\nu}(\vec{r},t) = \int d^3p \frac{p^\mu p^\nu}{p^0} f(x,p)$

Microscopic Transport: η/s of a Hadron Gas

- for particles in a fixed volume, the stress energy tensor discretizes

$$\pi^{xy} = \frac{1}{V} \sum_{j=1}^{\mathrm{N_{part}}} \frac{p^x(j) p^y(j)}{p^0(j)}$$

- and the Green-Kubo formula reads:

$$\eta = \frac{V}{T} \int_0^\infty dt \, \langle \pi^{xy}(0) \, \pi^{xy}(t) \rangle$$

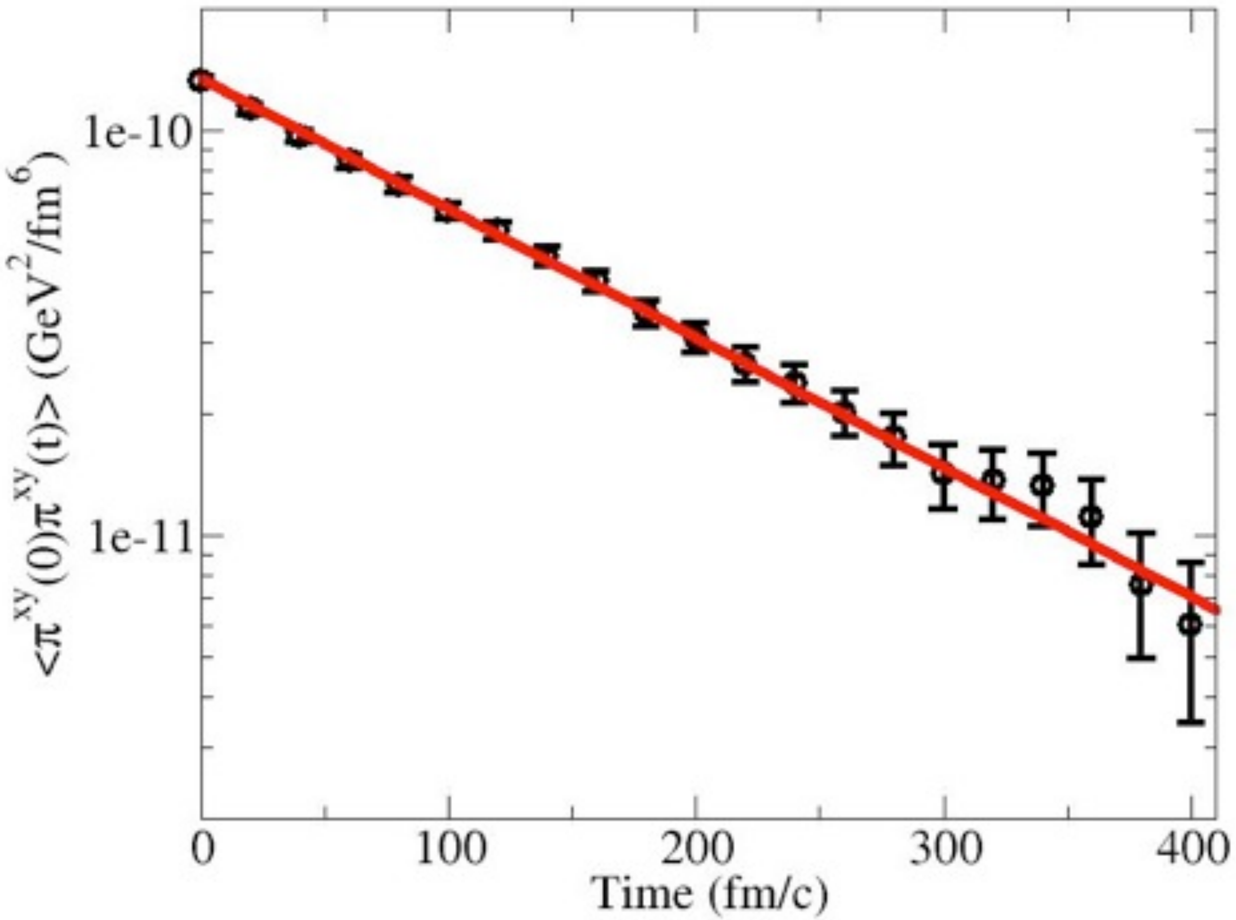
Entropy:

- extract thermodynamic quantities via:

$$P = \frac{1}{3V} \sum_{j=1}^{\mathrm{N_{part}}} \frac{|\vec{p}|^2(j)}{p^0(j)} \qquad \epsilon = \frac{1}{V} \sum_{j=1}^{\mathrm{N_{part}}} p^0(j)$$

- use Gibbs relation (with chem. pot. extratced via SM)

$$s_{\mathrm{Gibbs}} = \left(\frac{\epsilon + P - \mu_i \rho_i}{T} \right)$$



- evaluating the correlator numerically, e.g. in UrQMD one empirically finds an exponential decay as function of time
- using the following ansatz, one can extract the relaxation time τ_π:

$$\langle \pi^{xy}(0) \, \pi^{xy}(t) \rangle \propto \exp\left(-\frac{t}{\tau_\pi} \right)$$

- the shear viscosity then can be calculated from known/extracted quantities:

$$\eta = \tau_\pi \frac{V}{T} \left\langle \pi^{xy}(0)^2 \right\rangle$$

A. Muronga: Phys. Rev. **C69**: 044901, 2004

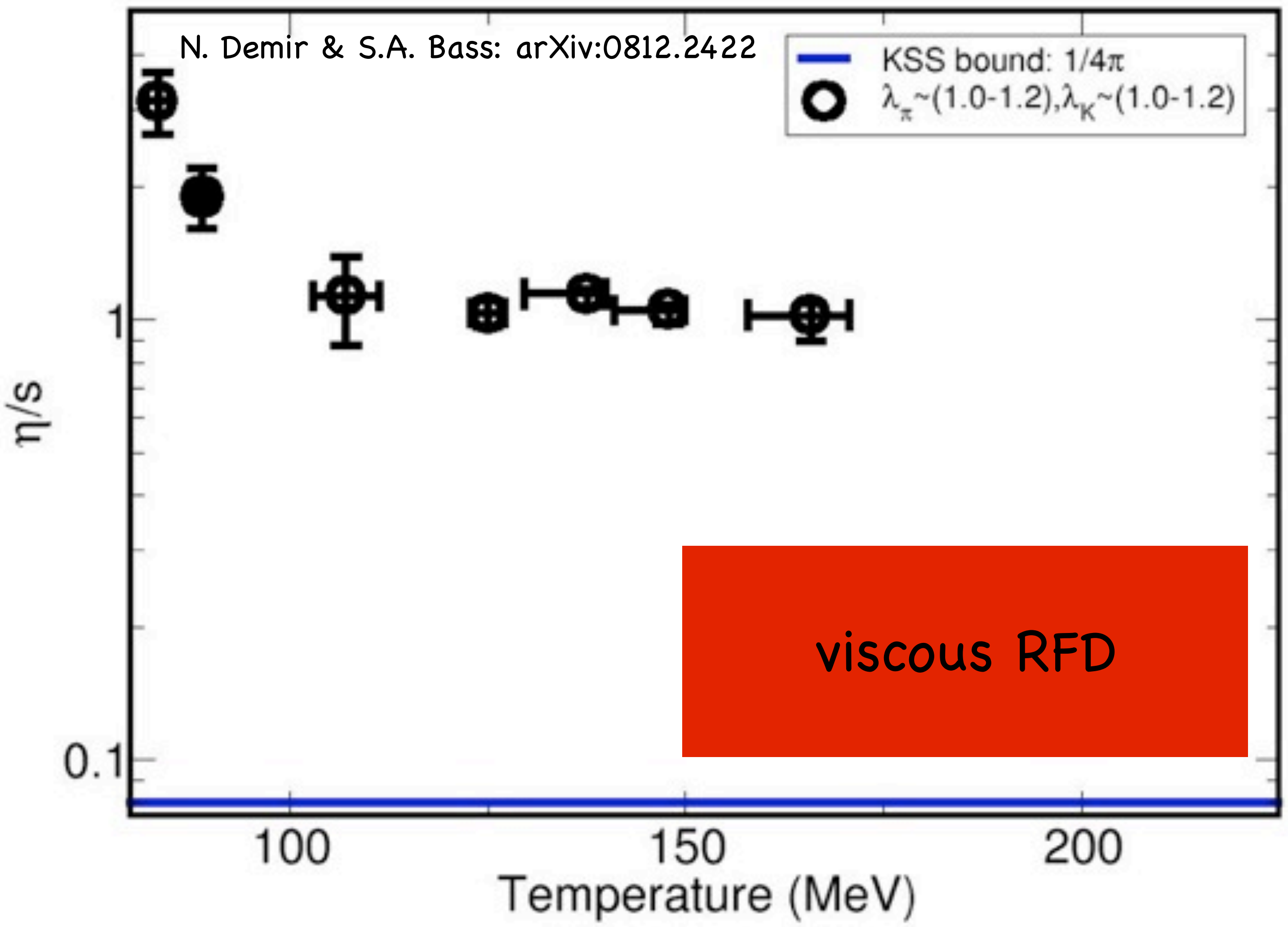
η/s of a Hadron Gas in & out of Equilibrium

first reliable calculation of of η/s for a full hadron gas including baryons and anti-baryons:

- breakdown of vRFD in the hadronic phase?
- what are the consequences for η/s in the deconfined phase?

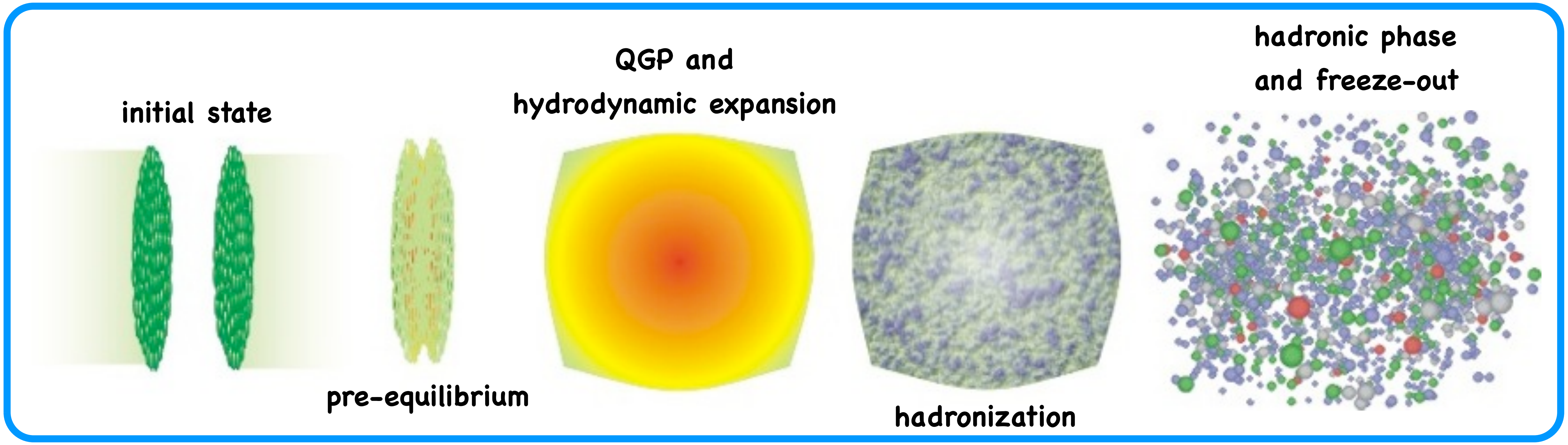
- RFD freeze-out temperature to reproduce spectral shapes: ~110 MeV
- Statistical Model temperature fits to hadron yields/ratios: ~160 MeV
  - separation of chemical and kinetic freeze-out in the hadronic phase!
  - confirmed by hybrid models
  - implies non-unit species-dependent fugacities in RFD

- non-unit fugacities reduce η/s by a factor of two to η/s≈0.5
  - **improved constraint:** η/s needs to be significantly lower in deconfined phase for vRFD to reproduce elliptic flow!


N. Demir & S.A. Bass: arXiv:0812.2422

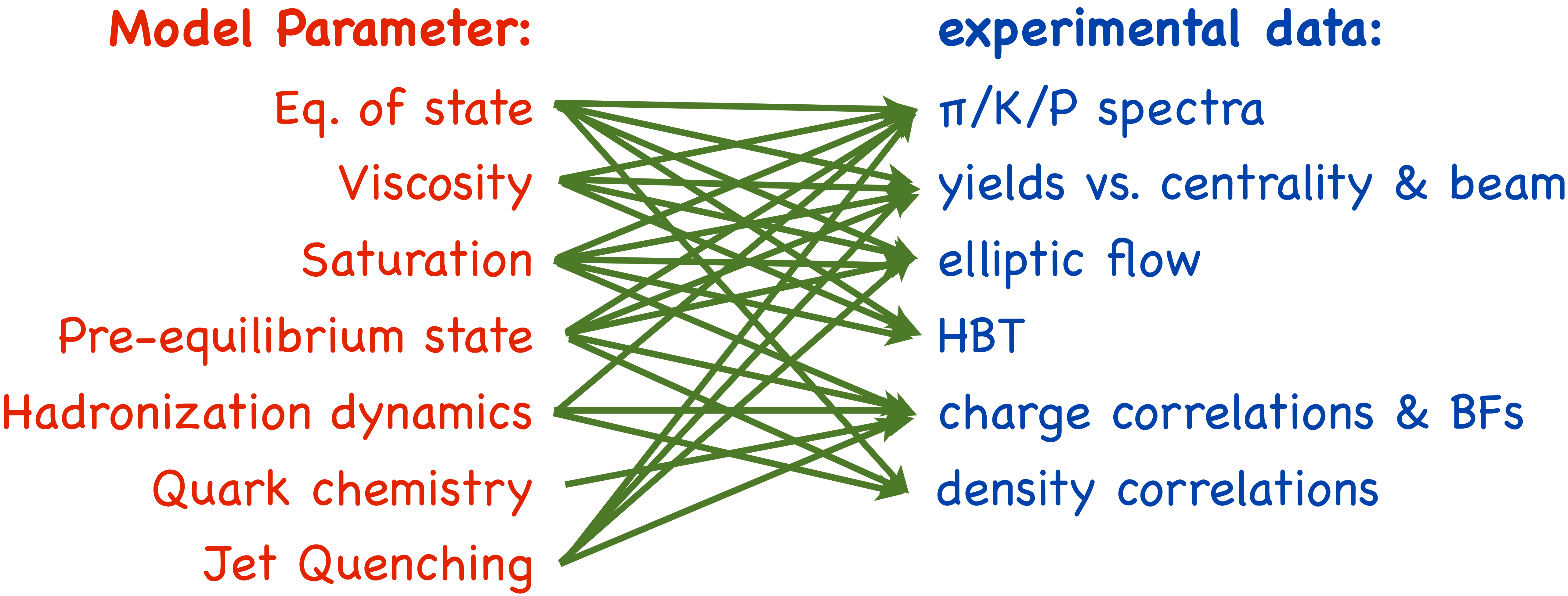
T. Hirano & K. Tsuda: Nucl. Phys. **A715**, 821 (2003)

P.F. Kolb & R. Rapp: Phys. Rev. **C67**, 044903 (2003)



Global Quantitative Analysis

The Challenge of a Rigorous Model to Data Comparison



Model Parameter:

Eq. of state
Viscosity
Saturation
Pre-equilibrium state
Hadronization dynamics
Quark chemistry
Jet Quenching

experimental data:

π/K/P spectra
yields vs. centrality & beam
elliptic flow
HBT
charge correlations & BFs
density correlations

- large number of interconnected parameters w/ non-factorizable data dependencies
- data have correlated uncertainties
- develop novel optimization techniques: Bayesian Statistics and MCMC methods
- transport models require too much CPU: need new techniques based on emulators
- general problem, not restricted to RHIC Physics

→**seek help/collaboration from Statistical Sciences**

MaDAI Collaboration:
Models and Data Analysis Initiative

a multi-institutional and multi-disciplinary collaboration to develop next generation tools for complex model-to-data knowledge extraction

Michigan State University

RHIC Physics: Scott Pratt
Supernova: Wolfgang Bauer
Astrophysics: Brian O'Shea and Mark Voit
Atmospheric Modeling: Sharon Zhong
Statistics: Dan Dougherty

Duke University

RHIC Physics: Steffen A. Bass and Berndt Müller
Statistics: Robert Wolpert

UNC & RENCI

Visualization: Xunlei Wu and Russell M. Taylor

Funded by NSF CDI program (Cyber-Enabled Discovery Initiative)

- US$ 1,800,000 over 4 years

CDI: Extracting Science from Data & Models

- develop a comprehensive transport model (or set of consistent interlocking transport approaches), capable of describing the full time-evolution of a heavy-ion collision at RHIC, starting from the coherent glue-field dominated initial state up to the hadronic final state

- identify the relevant physics parameters (EoS, QCD transport coefficients, matrix elements etc.) which are sensitive to the observables measured at RHIC

- conduct a systematic study in that multi-dimensional parameter-space and via comparison to data to determine the properties of the QCD medium created at RHIC

Conclusion & Outlook: RHIC

Heavy-Ion collisions at RHIC have produced a state of matter which can be called the **Quark-Gluon-Plasma:**

- the properties of the QGP can be characterized by its transport coefficients, such as η/s and q-hat
  - large opacity: values of q-hat beyond the pQCD expectation
  - near ideal fluidity: the smallest value of η/s observed in nature

Transition from Discovery Phase to Exploratory Phase and onwards to Precision Spectroscopy of the QGP:

- establish the physics driving the small value of η/s (e.g. particles vs. fields) and its dependence on temperature and fugacities
- determine proper structure of the QGP to use in jet energy-loss calculations for a precision measurement of q-hat
- explore medium response to jets and heavy quarks and develop a unified picture on the nature of the QGP


Thank you!
Any questions?

The End