Toward understanding of Quark-Gluon Plasma in relativistic heavy ion collisions

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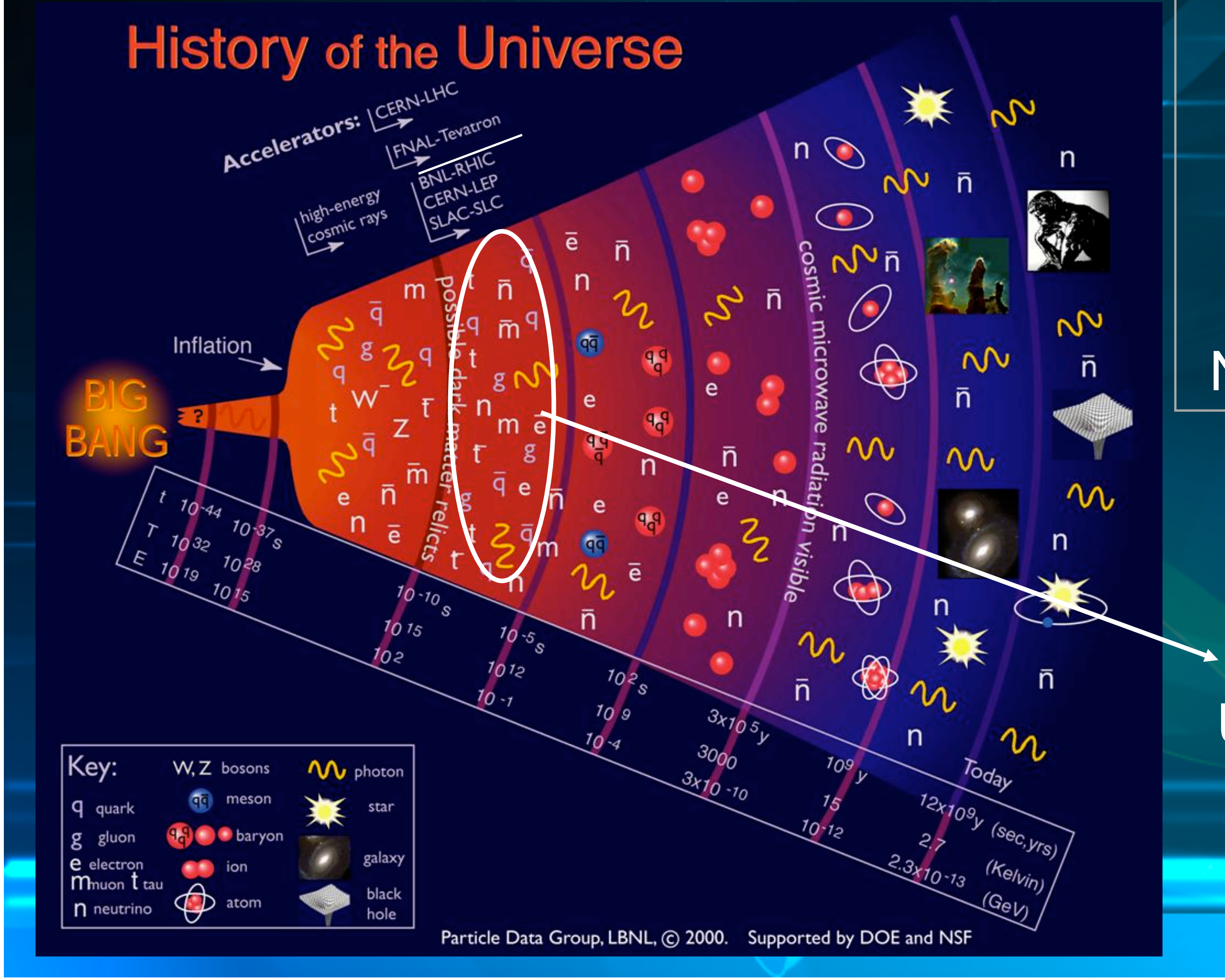
OUTLINE

- Introduction
- Basic Checks
  - Energy density
  - Chemical and kinetic equilibrium
- Dynamics of Heavy Ion Collisions
  - Elliptic flow
  - Jet quenching
- Summary and Outlook
- Discussion

Physics of the QGP

- Matter governed by QCD, not QED
- Frontier of high energy density/ temperature
  - ➔Toward an ultimate matter (Maximum energy density/temperature)
- Understanding the origin of matter which evolves with our universe
- Reproduction of QGP in H.I.C.
  - ➔Reproduction of “early universe” on the Earth

History of the Universe ~ History of Matter



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Quark Gluon Plasma

Hadronization

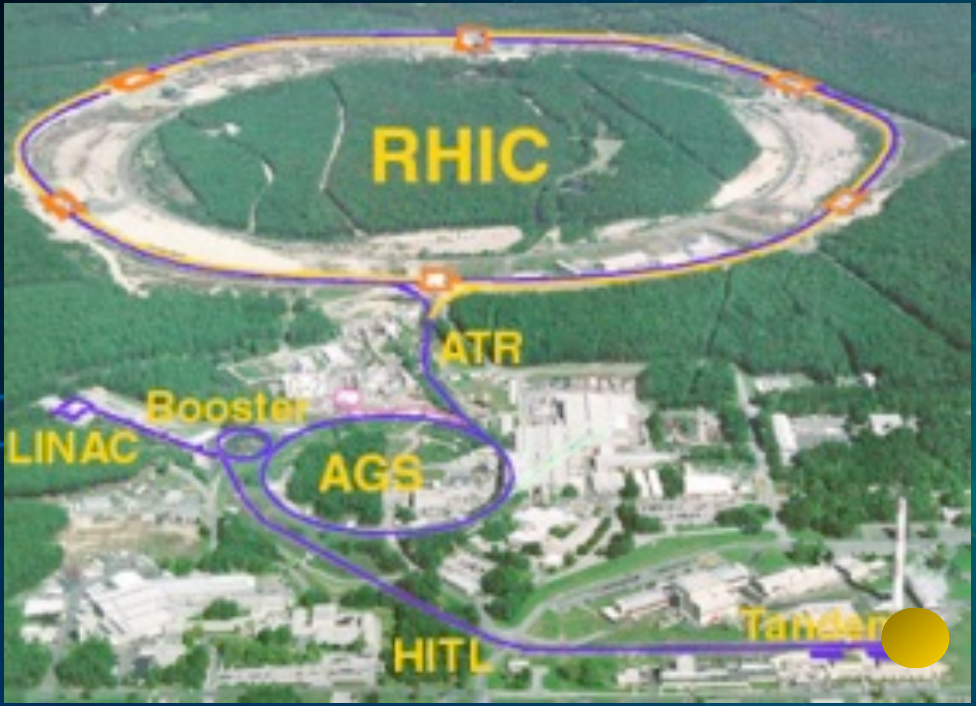
Nucleosynthesis

QGP study

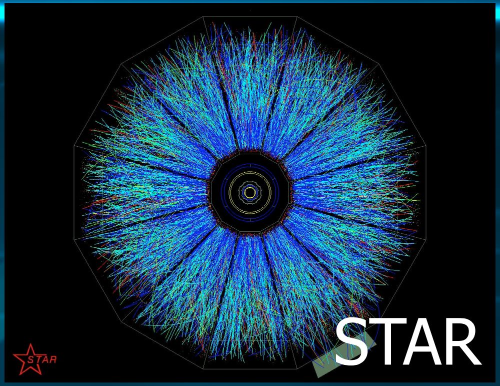
Understanding early universe

Little Bang!

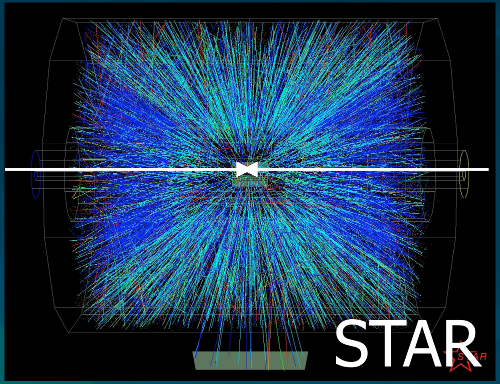
Relativistic Heavy Ion Collider(2000-)
RHIC as a time machine!



100 GeV per nucleon
Au(197×100)+Au(197×100)



front view



side view

Collision energy

⇩

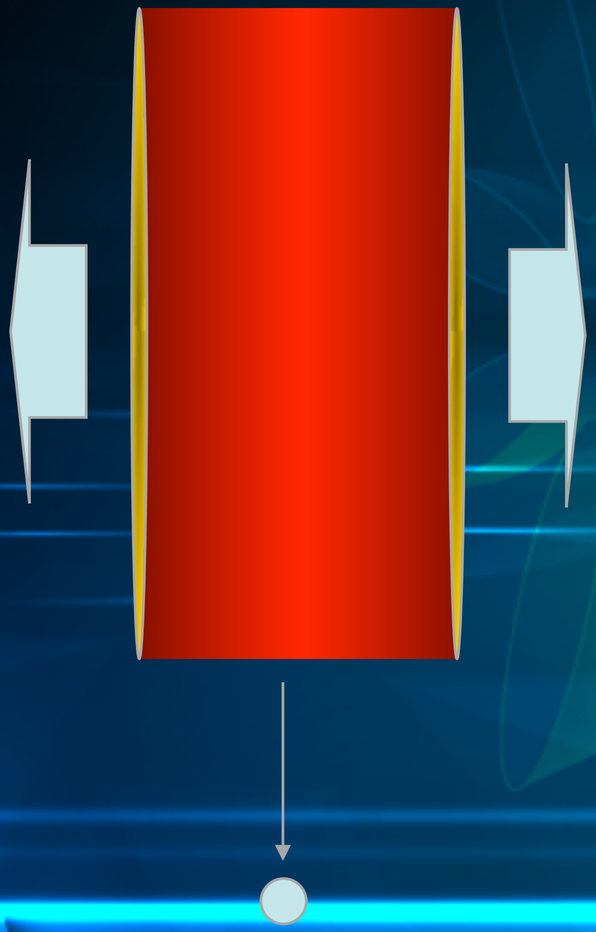
Multiple production
(N~5000)

⇩

Heat

BASIC CHECKS

Basic Checks (I): Energy Density



Bjorken('83)

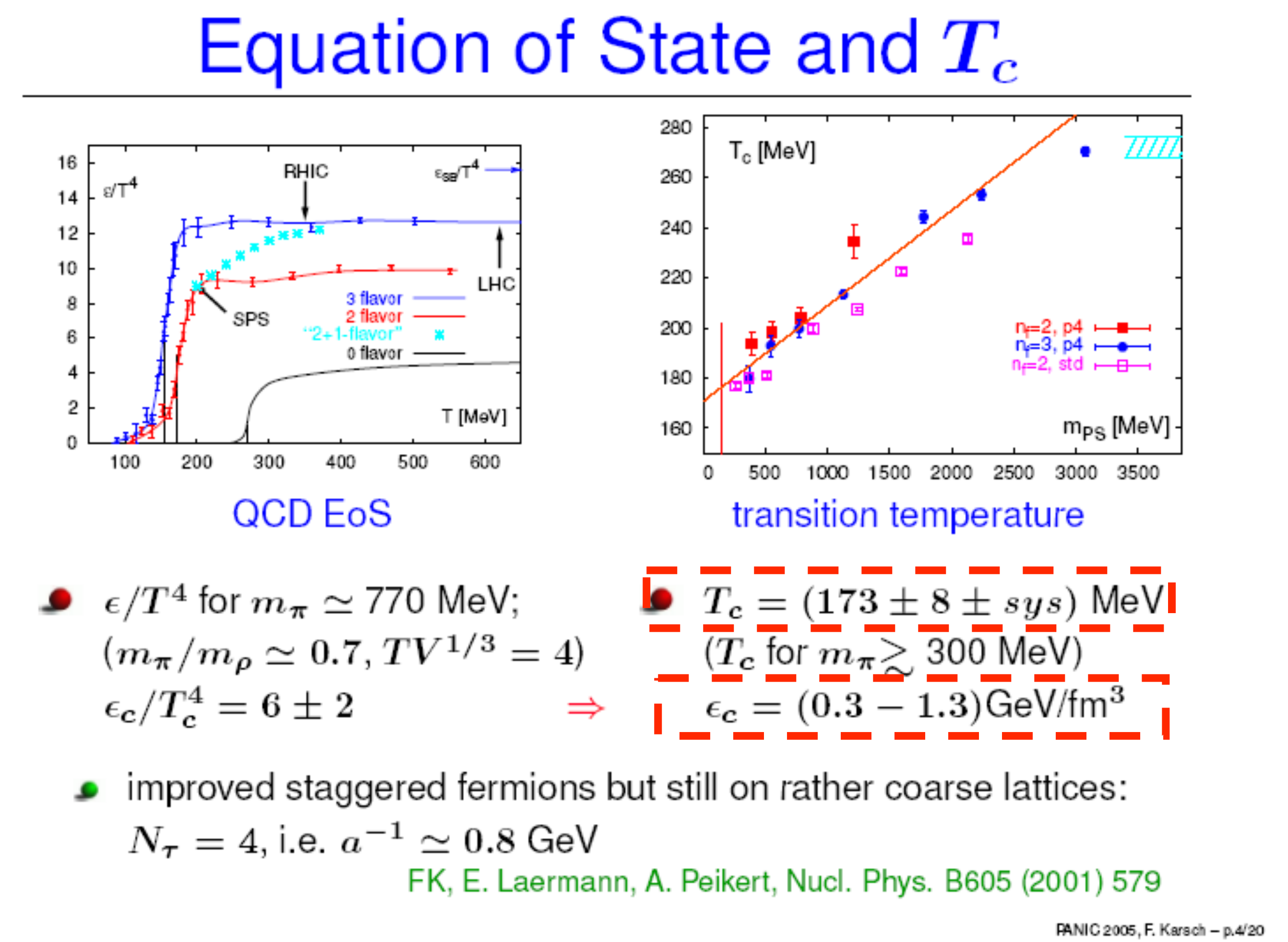
Bjorken energy density

$$\epsilon_{\mathrm{Bj}}(\tau) = \frac{\langle m_T \rangle}{\tau \pi R^2} \frac{dN}{dy}$$

total energy
(observables)

τ: proper time
y: rapidity
R: effective transverse radius
m_T: transverse mass

Critical Energy Density from Lattice



Equation of State and T_c

QCD EoS

transition temperature

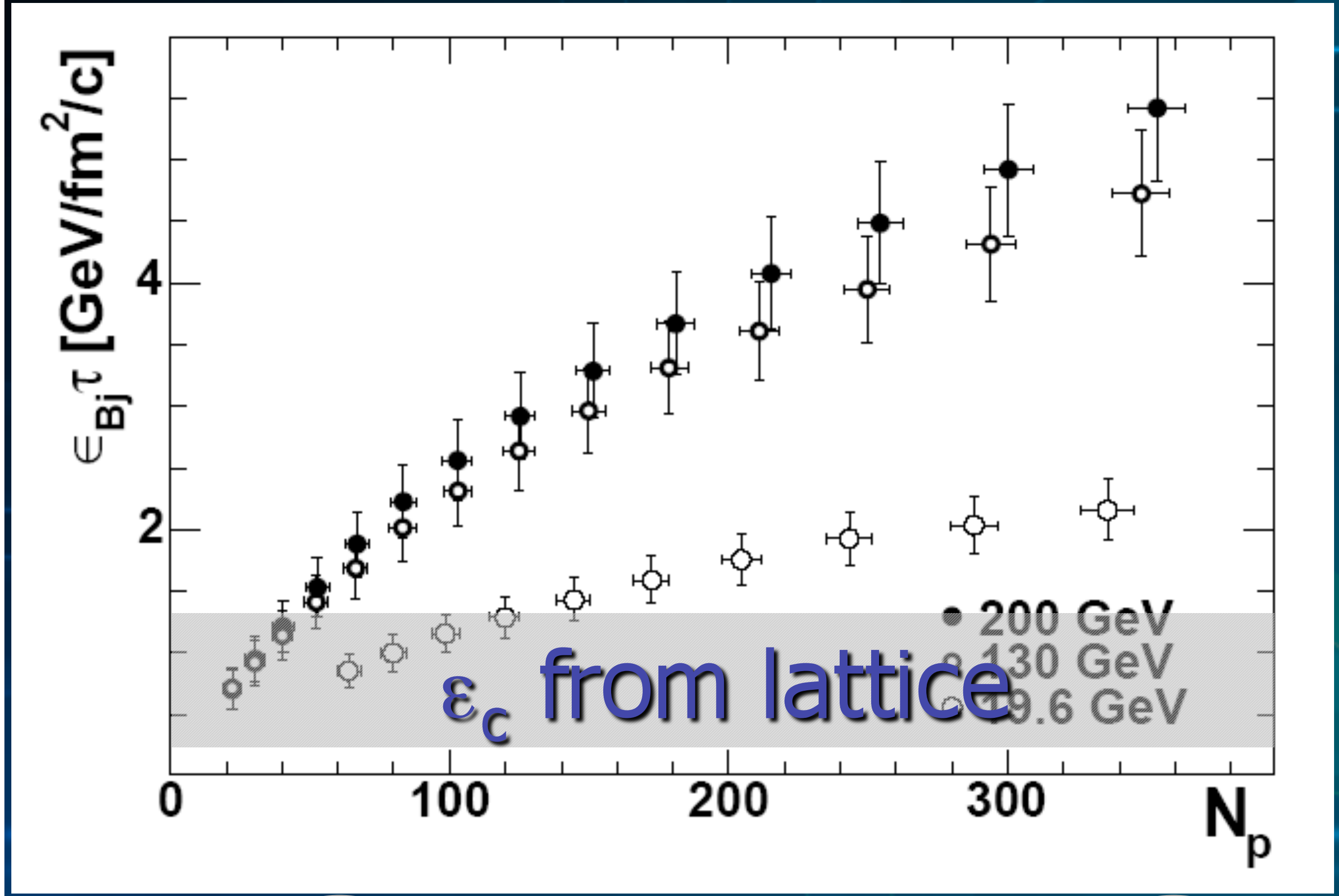
- ϵ/T^4 for $m_\pi \simeq 770$ MeV;
  $(m_\pi/m_\rho \simeq 0.7, TV^{1/3} = 4)$
  $\epsilon_c/T_c^4 = 6 \pm 2$ $\Rightarrow$
- $T_c = (173 \pm 8 \pm sys)$ MeV
  (T_c for $m_\pi \gtrsim 300$ MeV)
  $\epsilon_c = (0.3 - 1.3)\mathrm{GeV/fm}^3$
- improved staggered fermions but still on rather coarse lattices:
  $N_\tau = 4$, i.e. $a^{-1} \simeq 0.8$ GeV

FK, E. Laermann, A. Peikert, Nucl. Phys. B605 (2001) 579

PANIC 2005, F. Karsch – p.4/20

Stolen from Karsch(PANIC05);
Note that recent results seem to be T_c~190MeV

Centrality Dependence of Energy Density



PHENIX('05)

Well above
ε_c from lattice
in central
collision at RHIC,
if assuming
τ=1fm/c.

CAVEATS (I)

- Just a necessary condition in the sense that temperature (or pressure) is not measured.
- How to estimate tau?
- If the system is thermalized, the actual energy density is larger due to pdV work.

Gyulassy, Matsui('84) Ruuskanen('84)

- Boost invariant?
- Averaged over transverse area. Effect of thickness? How to estimate area?

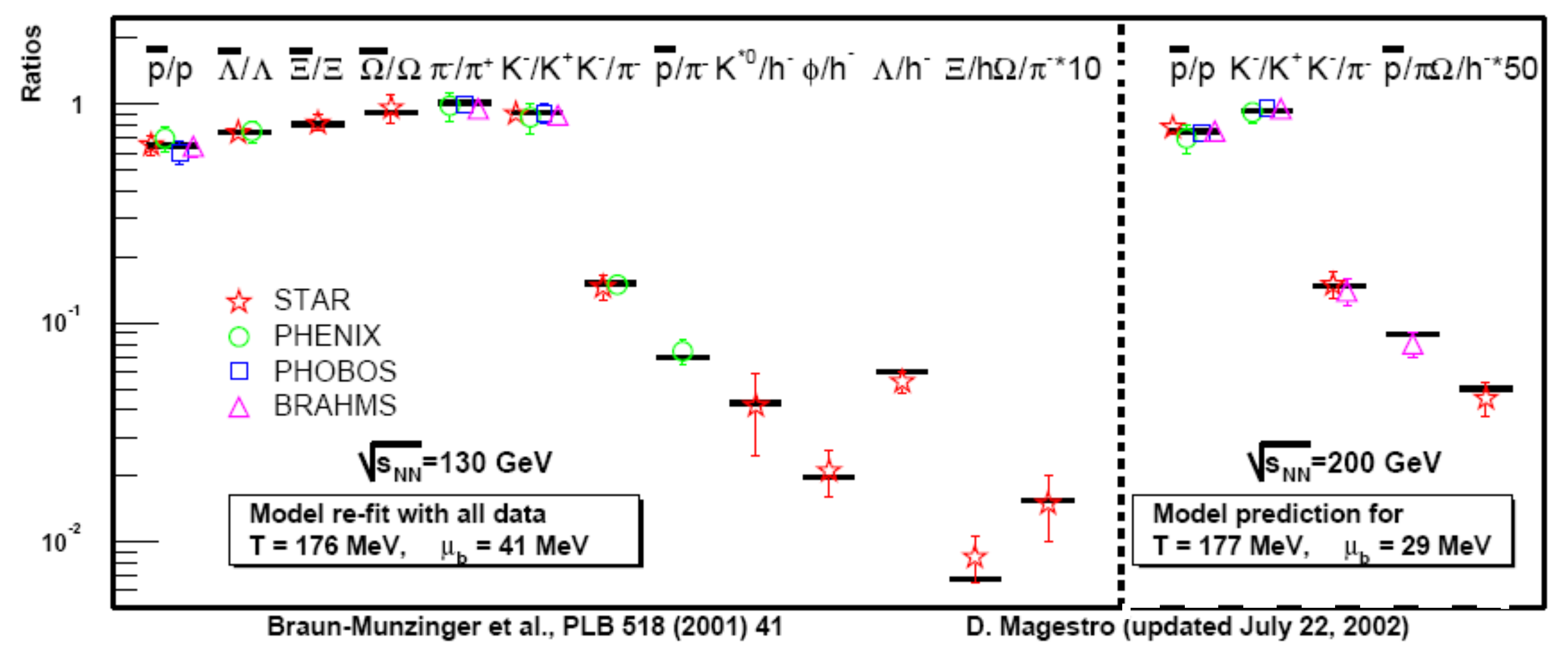
Basic Checks (II): Chemical Eq.

$$n_i(T,\mu) = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2dp}{\exp[(E_i-\mu_i)/T]\pm 1}$$

$$\langle N_i\rangle = V\left[\underbrace{n_i^{\mathrm{th}}(T,\mu)}_{\text{direct}} + \underbrace{\sum_R \Gamma_{R\to i}n_R(T,\mu)}_{\text{Resonance decay}}\right]$$

Two fitting parameters: T_{ch}, μ_B

Amazing fit!



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

D. Magestro (updated July 22, 2002)

T=177MeV, μ_B = 29 MeV

Close to T_c from lattice

CAVEATS (II)

- Even e^+e^- or pp data can be fitted well!

  See, e.g., Becattini&Heinz('97)

- What is the meaning of fitting parameters? See, e.g., Rischke('02),Koch('03)
- Why so close to T_c?

  → No chemical eq. in hadron phase!?

  → Essentially dynamical problem!

Expansion rate ←→ Scattering rate (Process dependent)

$\partial \cdot u(x)$ $\sum_j \langle \sigma_{ij} v_{ij} \rangle \rho_j$

see, e.g., U.Heinz, nucl-th/0407067

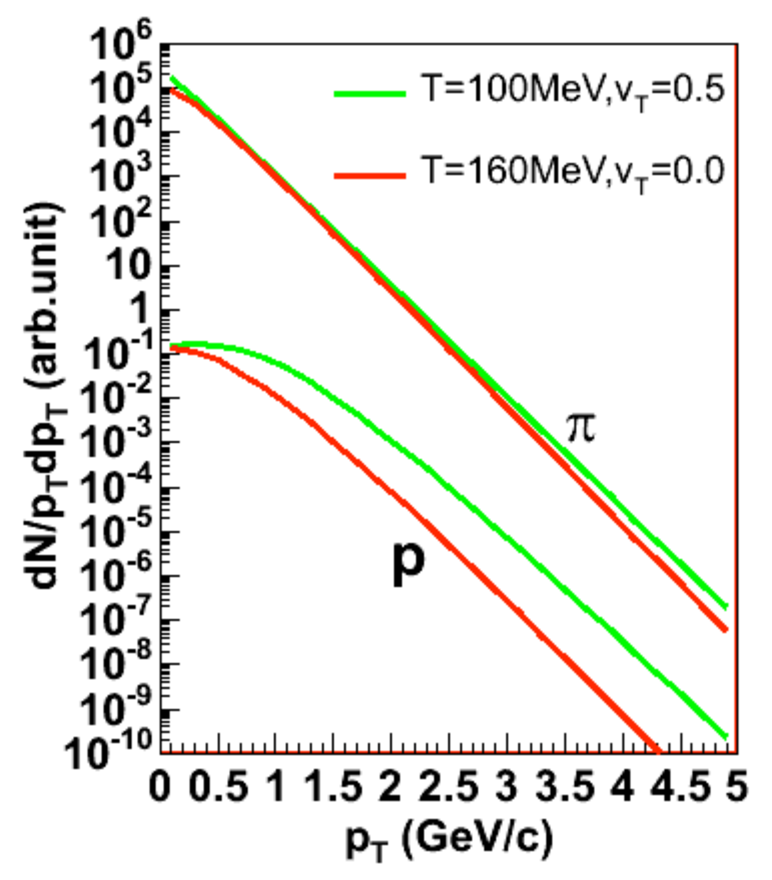
Basic Checks (III): Radial Flow

Driving force of flow
→pressure gradient
Inside: high pressure
Outside: vacuum (*p*=0)

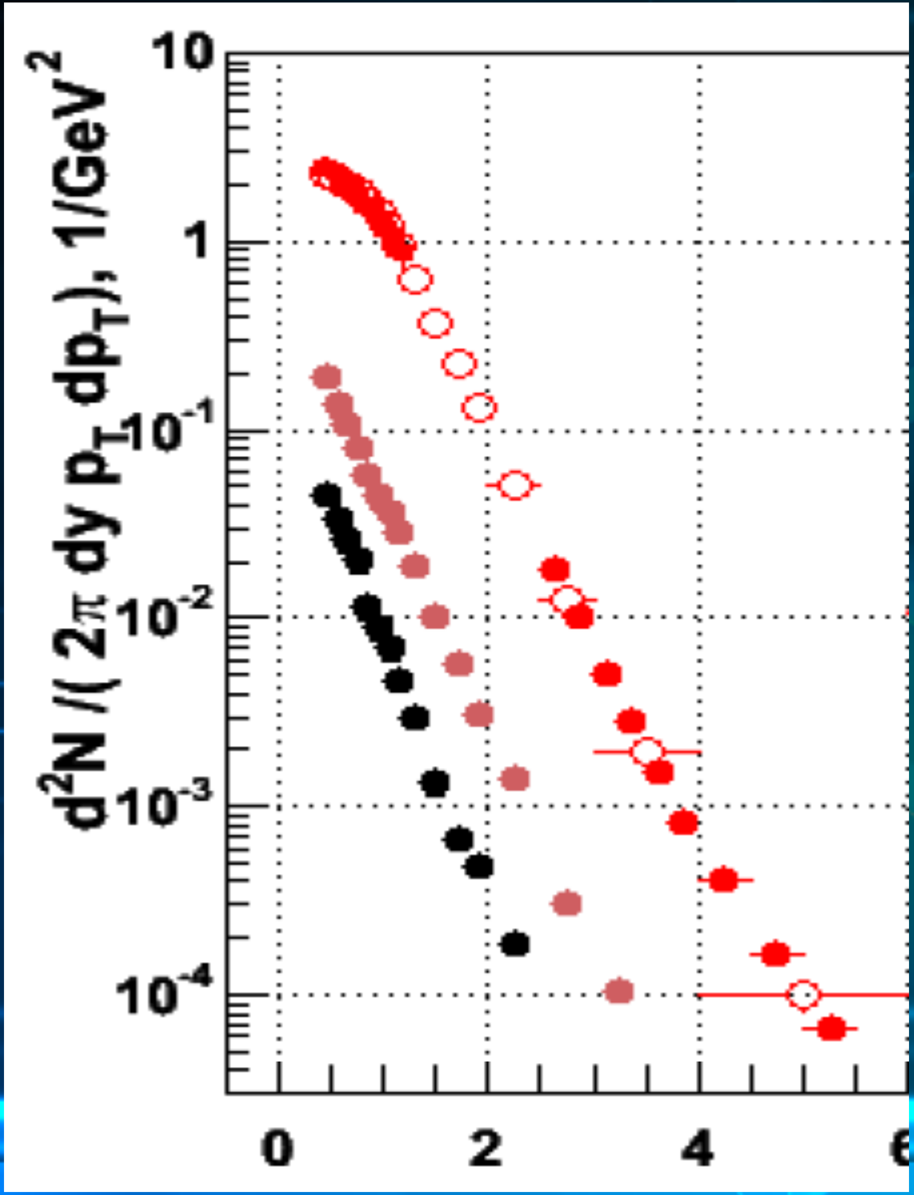
Spectrum for heavier particles
is a good place to see radial flow.

Blast wave model (thermal+boost)
Sollfrank et al.('93)

$$\frac{dN}{p_T dp_T} \propto m_T K_1\left(\frac{\gamma m_T}{T}\right) I_0\left(\frac{\gamma v_T p_T}{T}\right)$$



Spectral change is seen in AA!



O.Barannikova, talk at QM05

Power law in pp & dAu

Convex to Power law in Au+Au

- "Consistent" with thermal + boost picture
- Large pressure could be built up in AA collisions

CAVEATS (III)

- Not necessary to be thermalized completely
  - Results from hadronic cascade models.
- How is radial flow generated dynamically?
- Finite radial flow even in pp collisions?
  - (T,v_T)~(140MeV,0.2)
  - Is blast wave reliable quantitatively?
- Consistency?
  - Chi square minimum located a different point for ϕ and Ω
- Flow profile? Freezeout hypersurface? Sudden freezeout?

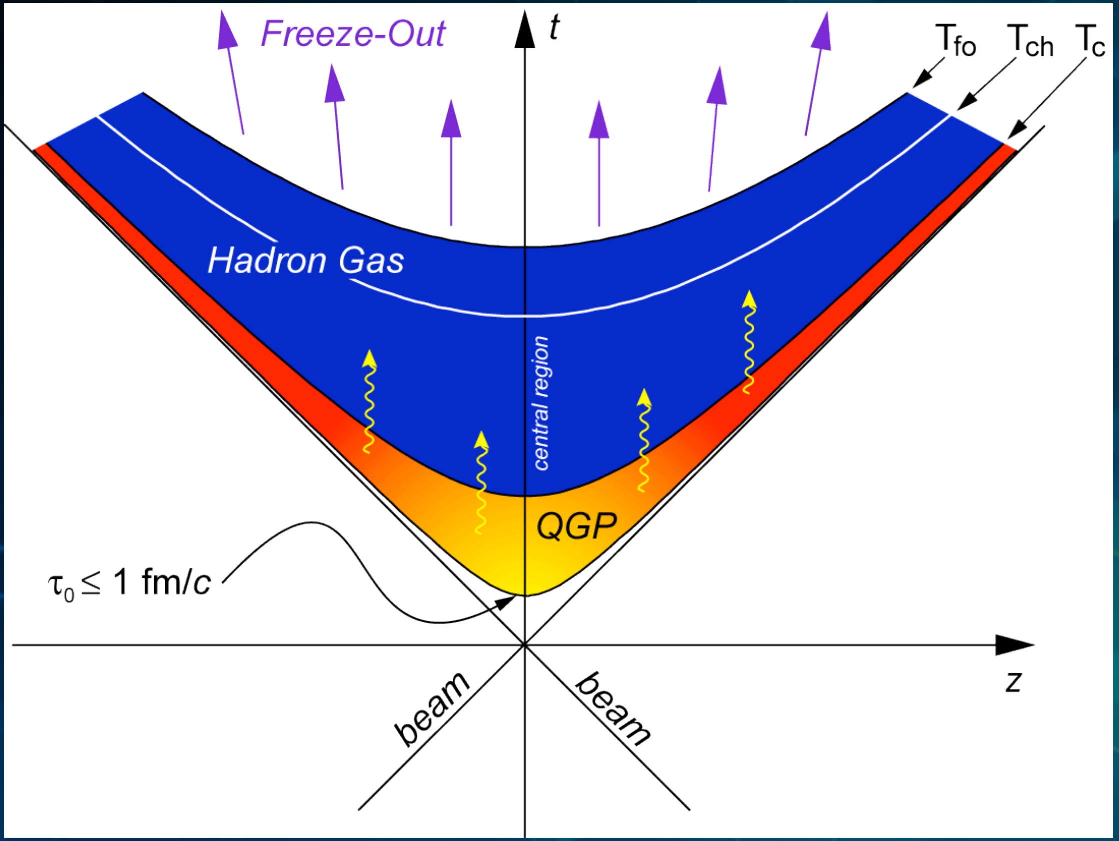
Basic Checks → Necessary Conditions to Study QGP at RHIC

- Energy density can be well above ε_c.
  - Thermalized?
- “Temperature” can be extracted.
  - Why freezeout happens so close to T_c?
- High pressure can be built up.
  - Completely equilibrated?

Importance of systematic study
based on dynamical framework

Dynamics of Heavy Ion Collisions

Dynamics of Heavy Ion Collisions



Freezeout

"Re-confinement"

Expansion, cooling

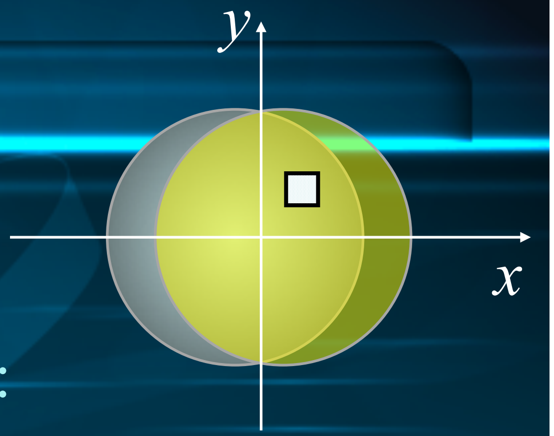
Thermalization

First contact
(two bunches of gluons)

Time scale
10fm/c~10^{-23}sec
<<10^{-4}(early universe)

Temperature scale
100MeV~10^{12}K

N_{coll} & N_{part}



Thickness function:

$$T(\mathbf{r}) = \int dz\,\rho\left(\sqrt{\mathbf{r}^2 + z^2}\right)$$

Woods-Saxon nuclear density:

$$\rho(r) = \frac{\rho_0}{\exp[(r-R)/\delta] + 1}$$

Gold nucleus:

ρ_0=0.17 fm^{-3}

R=1.12$A^{1/3}$-0.86$A^{-1/3}$

d=0.54 fm

of binary collisions

$$T_{AA} = \int d^2\mathbf{r}\,T(\mathbf{r} - \mathbf{b}/2)T(\mathbf{r} + \mathbf{b}/2)$$

$$N_{\text{coll}} = T_{AA}(b)\sigma_{\text{in}}$$

σ_{in} = 42mb @200GeV

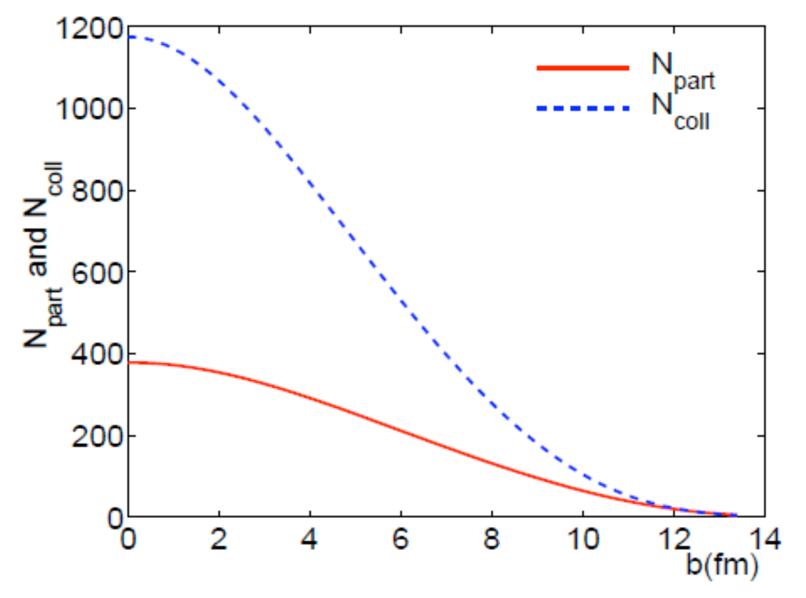
of participants

$$\begin{aligned}
&\frac{d^2N_{\text{part}}}{d^2\mathbf{r}}(\mathbf{r};\mathbf{b}) \\
=\; & T_a\left(\mathbf{r} + \frac{1}{2}\mathbf{b}\right)\left\{1 - \exp\left[-\sigma_{\text{in}}T_b\left(\mathbf{r} - \frac{1}{2}\mathbf{b}\right)\right]\right\} \\
+\; & T_b\left(\mathbf{r} - \frac{1}{2}\mathbf{b}\right)\left\{1 - \exp\left[-\sigma_{\text{in}}T_a\left(\mathbf{r} + \frac{1}{2}\mathbf{b}\right)\right]\right\}
\end{aligned}$$

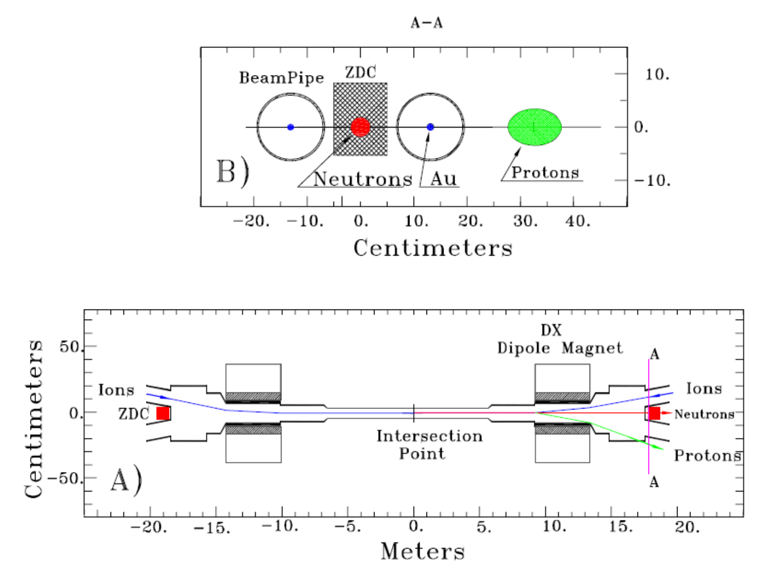
1 − (survival probability)

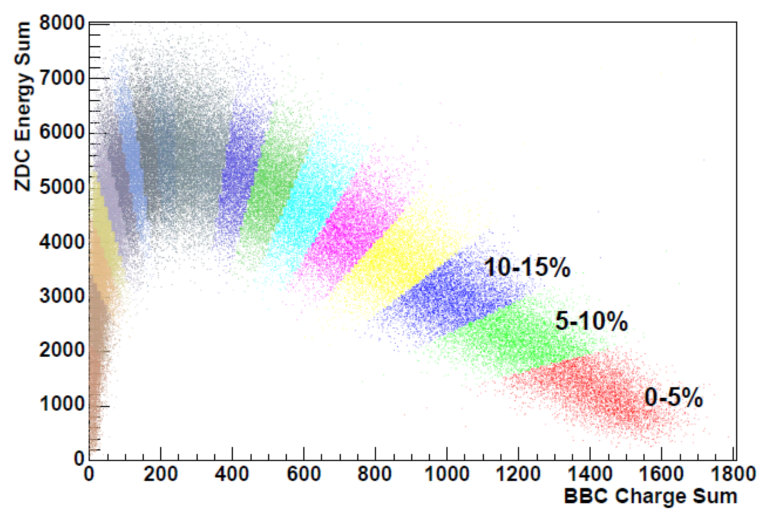
$$N_{\text{part}} = \int d^2\mathbf{r}\,\frac{d^2N_{\text{part}}}{d^2\mathbf{r}}$$

Centrality



N_{part} and N_{coll} as a function of impact parameter





PHENIX: Correlation btw. BBC and ZDC signals

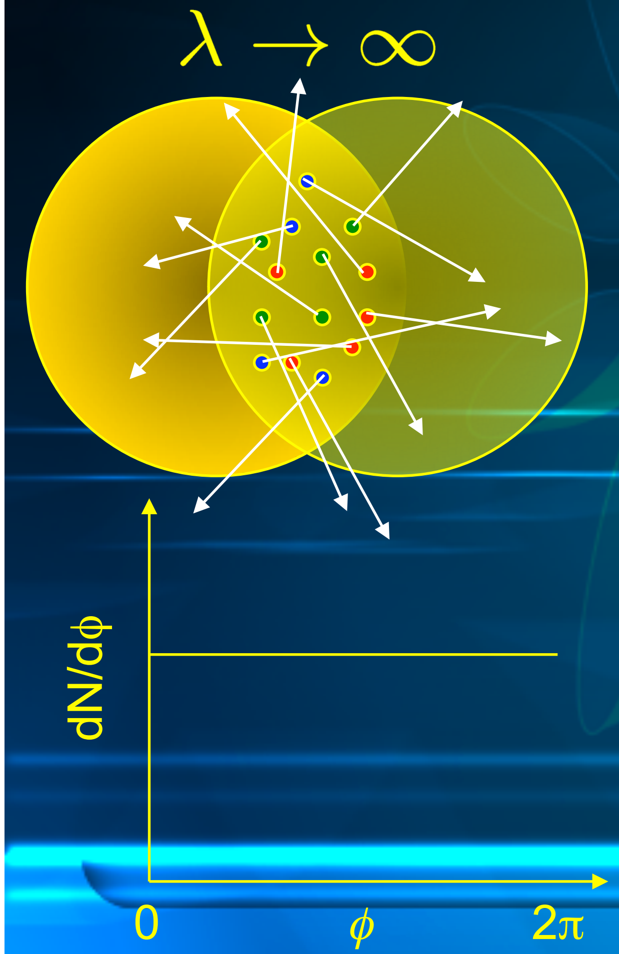
Elliptic Flow

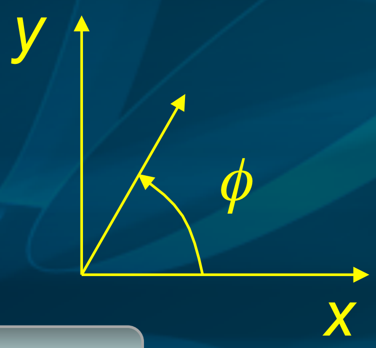
What is Elliptic Flow?

Ollitrault ('92)

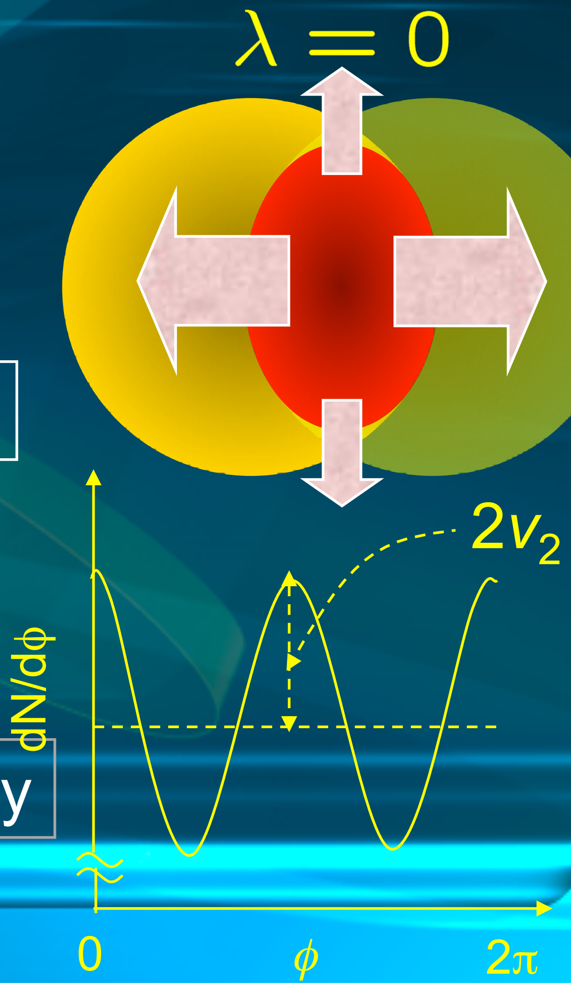
How does the system respond to spatial anisotropy?

No secondary interaction





Hydro behavior



INPUT

Spatial Anisotropy

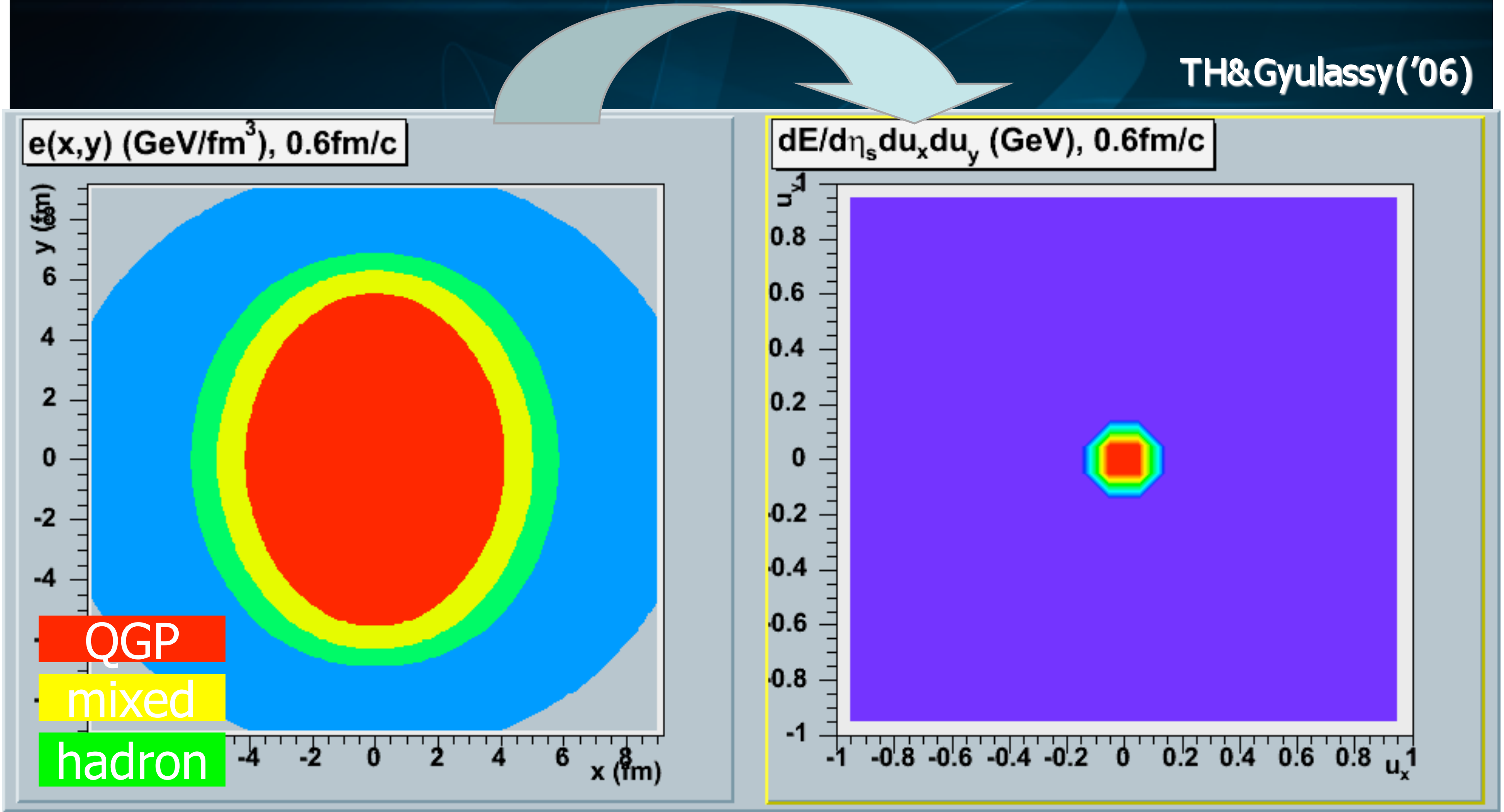
Interaction among produced particles

OUTPUT

Momentum Anisotropy

Time Evolution of a QGP Fluid

TH&Gyulassy('06)



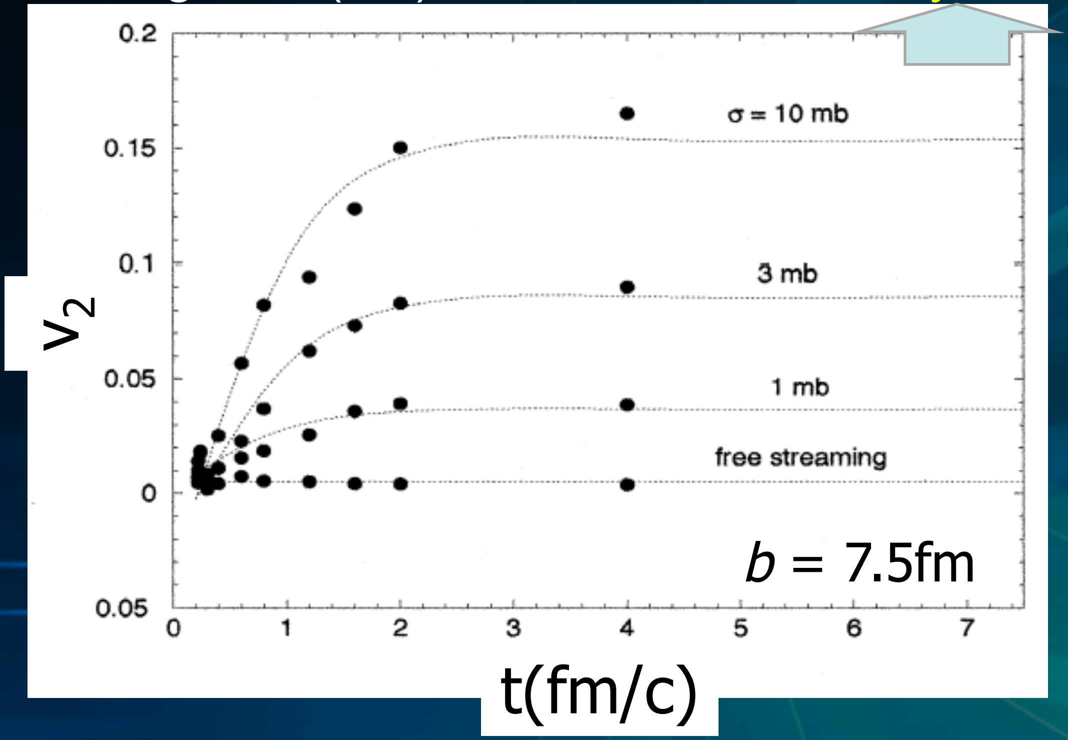
Anisotropy of energy density distribution

→ Anisotropy of "Momentum" distribution

v_2 from a Boltzmann simulation

Zhang et al.('99)

ideal hydro limit



$$\boxed{\lambda = \frac{1}{\sigma\rho} \propto \eta}$$

$\lambda \to 0$: Ideal hydro

$\sigma \to \infty$: strongly interacting system

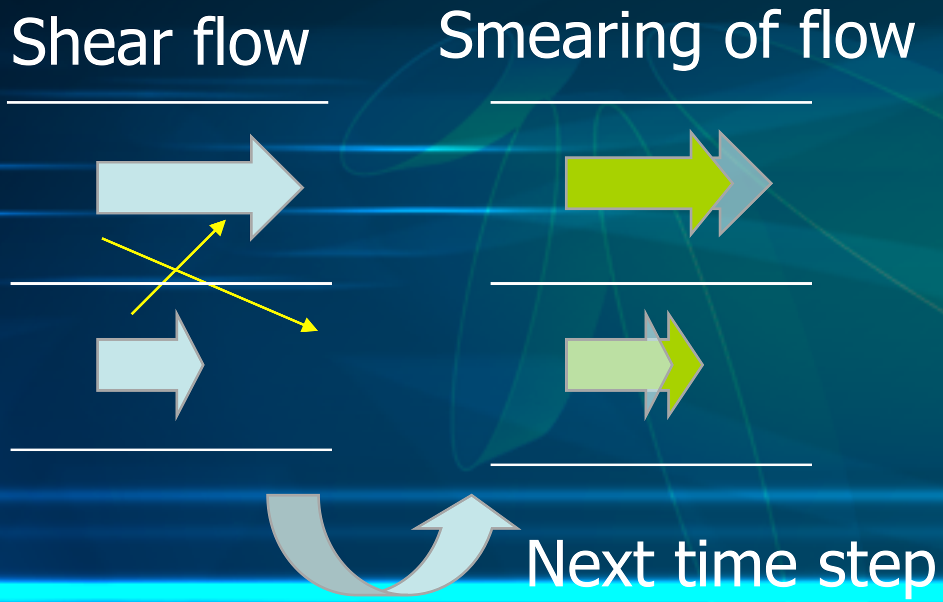
v_2 is
- generated through secondary collisions
- saturated in the early stage
- sensitive to cross section (~1/m.f.p.~1/viscosity)

Schematic Picture of Shear Viscosity

See, e.g. Danielewicz&Gylulassy('85)

Assuming relativistic particles,

$$\eta \approx \frac{4}{15}\sum n_i \langle p \rangle_i \lambda_i$$



Shear flow

Smearing of flow

Next time step

Perfect fluid:
$\lambda = 1/\sigma\rho$ → 0
↓
shear viscosity → 0

Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collic repeatedly smashed the nuclei of gold atoms together with s that their energy briefly generated trillion-degree temperature

科学家称初生宇宙可能是液体状的而非气体状

www.XINHUANET.com 2005年04月20日 07:45:55 来源：新京报

【字体：大 中 小】【打印本稿】【读后感言】【进入论坛】【推荐 Go 】 【关闭】

本报综合报道 4月18日，在美国佛罗里达州坦帕市举行的美国物理协会会议上，有科学家提出，对粒子碰撞的最新研究结果表明，在宇宙诞生的最初百万分之一秒，宇宙可能是液体状的，而不是像过去所认为的那样是炽热的气体状的。

Post

as 'liquid-l

have hot, ng old

Neues aus der Welt der Wissenschaft

[ORF ON Science : News : Wissen und Bildung . Kosmos]

Das Universum war am Anfang "flüssig"

Das Universum war direkt nach dem Urknall vermutlich einem Fluidum ähnlich. Das schließen dänische Forscher aus Experimenten am weltstärksten Kernbeschleuniger RHIC am Brookhaven National Laboratory.

Mit seiner enormen Kollisionsenergie bildet der RHIC rund 1.000 Milliarden Grad Celsius heiße Urmaterie vom Anbeginn der Zeit vor rund 13,7 Milliarden Jahren nach.

Magyar részvétellel fedezték fel az univerzum ősanyagát

Az univerzum keletkezése utáni néhány milliomod másodperc állapotát sikerült modellezniük amerikai és magyar tudósoknak. Az Ősrobbanás utáni anyag forró, sűrű és folyékony lehetett.

Az amerikai Brookhaven Nemzeti Laboratórium (BNL) RHIC gyorsítója (Relativistic Heavy Ion Collider, Relativisztikus Nehézion-Ütköztető) mellett működő négy kísérleti csoport közös bejelentést tett: az ütköztetett nagyenergiás nehéz atommagokból sikerült előállítaniuk az anyagnak egy új, forró és sűrű állapotát. Az anyagnak ez az új formája az atommagok már ismert elemi építőköveiből, kvarkokból és gluonokból áll, viszont tulajdonságai jelentősen eltérnek az elméleti jóslatoktól, és igen figyelemreméltóak mivel a nehézion-ütközésekben keletkezett anyag nem szabad kvarkok és gluonok alkotta ideális gázként, hanem folyadékként viselkedik– olvasható a kfki.hu-n. A négy cikket, amelyeken a RHIC négy nagy nemzetközi kísérleti együttműködése közel egy éve dolgozik, a *Nuclear Physics* folyóirat egyszerre fogja közölni.

aborations, dubbed BRAHMS, 2 and STAR, working at

age: BNL

. When hey e a clear ization arly

社会 asahi.comトップ > 社会 > その他・話題

宇宙の始まりはしずく？ 「クオークは液体」と発表

2005年04月18日23時34分

宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは18日、物質を形づくる究極の基本粒子クオークは超高温でバラバラになるが、気体のように自由に跳び回るのでなく、しずくのような液体状態にあったと考えられる、と発表した。理論的に予想外の発見で、宇宙や物質のなりたちを説明するシナリオに影響を与える可能性がある。

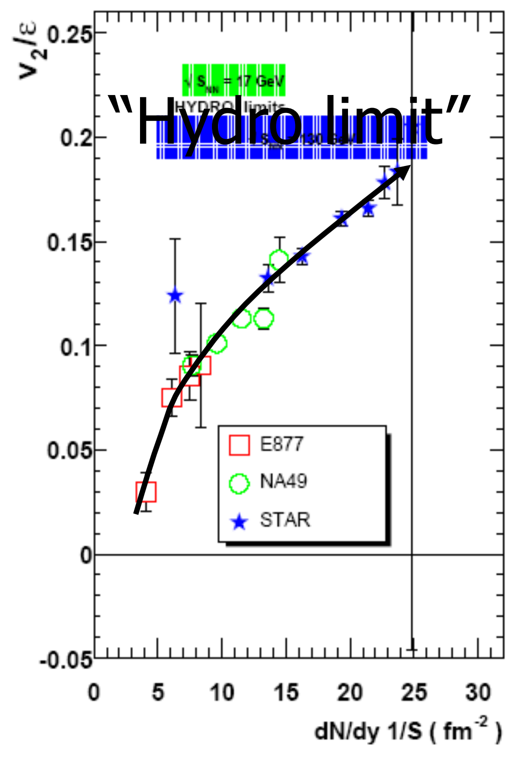
markable than had been predicted. In summarizing the first three years of RHIC findings, t instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions

microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Ans 'Dus Quest Matter as it Was Just After Big Bang

Basis of the Announcement

STAR('02)

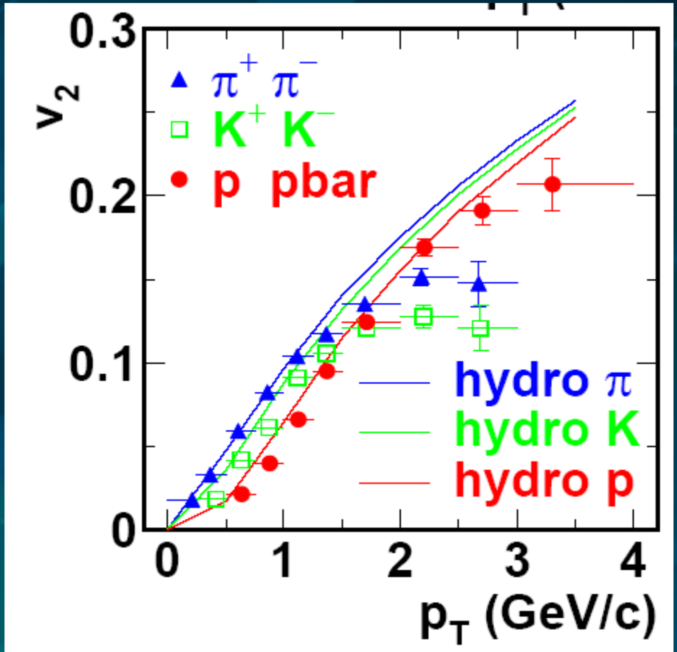


"Hydro limit"

response = (output)/(input)

Multiplicity dependence

PHENIX('03)



p_T dependence
and mass ordering

Hydro results: Huovinen, Kolb, Heinz,…

It is found that they reproduce $v_2(p_T)$ data accidentally.

T.Hirano and M.Gyulassy,Nucl.Phys.**A769** (2006)71.

Recent Hydro Results from Our Group

Bottom-Up approach

- The first principle (QuantumChromo Dynamics)

$$\mathcal{L} = \bar{\psi}_i (i\gamma_\mu D^\mu_{ij} - m\delta_{ij})\psi_j - \frac{1}{4}F_{\mu\nu a}F^{\mu\nu a}$$

- Inputs to phenomenology (lattice QCD)

$$P = P(e, n), \eta, \zeta, \lambda$$

- Phenomenology (hydrodynamics)

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n^\mu = 0$$

$$T^{\mu\nu} = [e + P(e,n)]u^\mu u^\nu - P(e,n)g^{\mu\nu}$$

Complexity

Non-linear interactions of gluons

Strong coupling

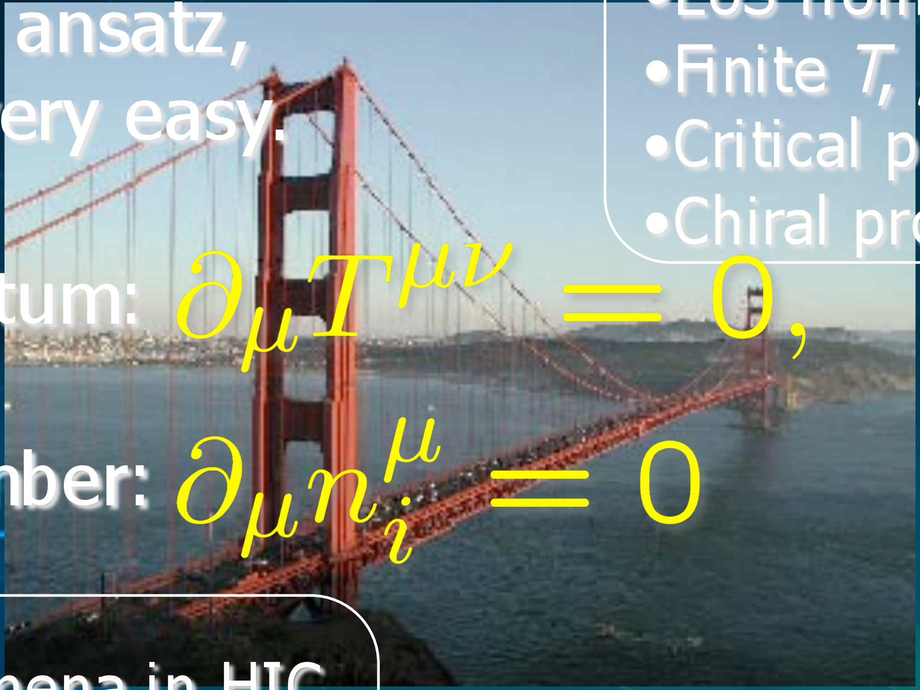
Dynamical many body system

Color confinement

- Experimental data
@ Relativistic Heavy Ion Collider
  ~150 papers from 4 collaborations
  since 2000

Why Hydrodynamics?

Once one accepts local thermalization ansatz, life becomes very easy.



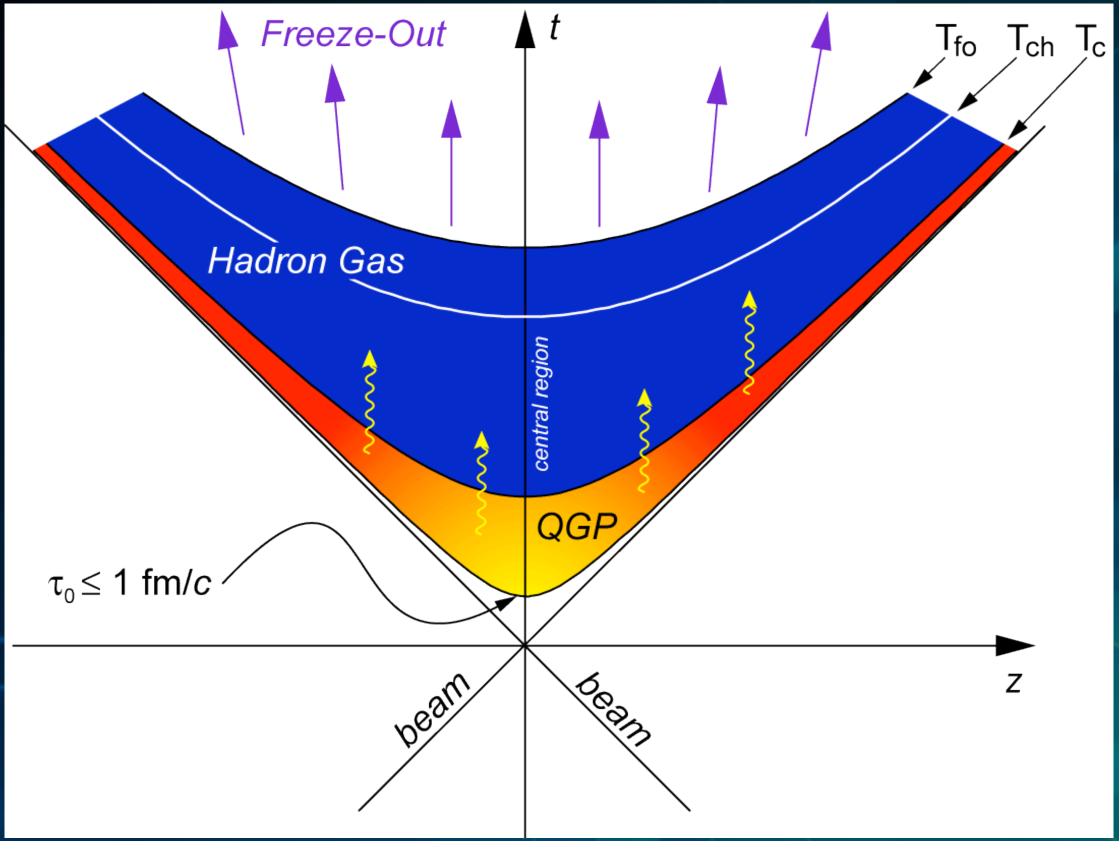
Static
- EoS from Lattice QCD
- Finite T, μ field theory
- Critical phenomena
- Chiral property of hadron

Energy-momentum: $\partial_\mu T^{\mu\nu} = 0,$

Conserved number: $\partial_\mu n_i^\mu = 0$

Dynamic Phenomena in HIC
- Expansion, Flow
- Space-time evolution of thermodynamic variables

Dynamics of Heavy Ion Collisions



Freezeout

"Re-confinement"

Expansion, cooling

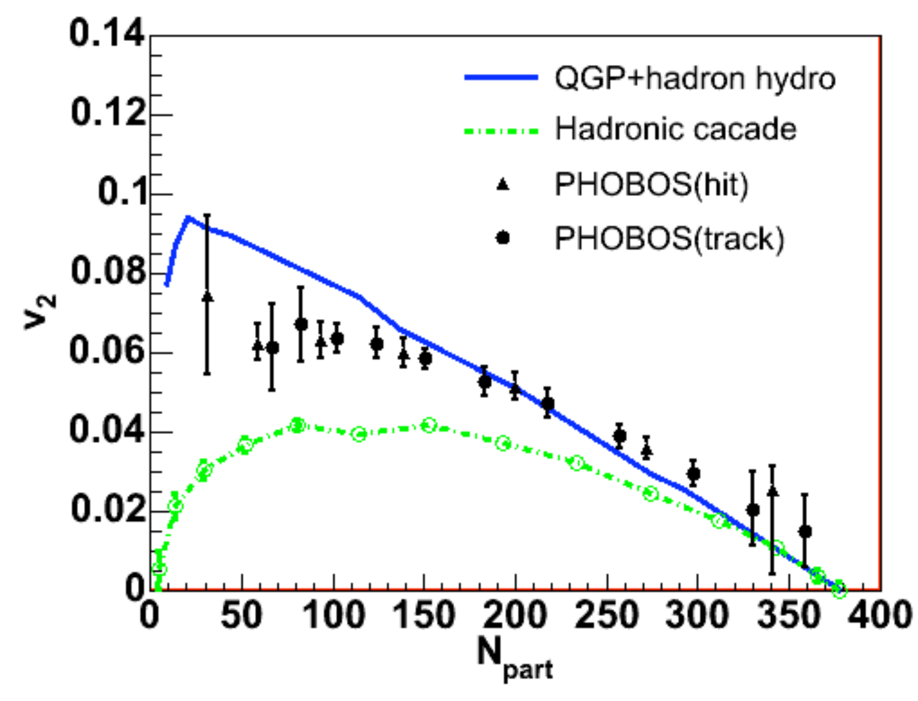
Thermalization

First contact
(two bunches of gluons)

Inputs in hydrodynamic simulations:
- Initial condition
- Equation of state
- Decoupling prescription

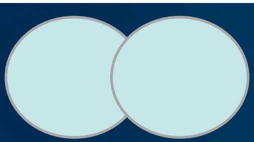
Centrality Dependence of v_2

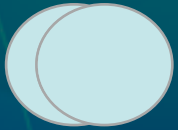
TH et al. ('06).



Discovery of "Large" v_2 at RHIC

- v_2 data are comparable with hydro results.
- Hadronic cascade cannot reproduce data.
- Note that, in v_2 data, there exists eccentricity fluctuation which is not considered in model calculations.

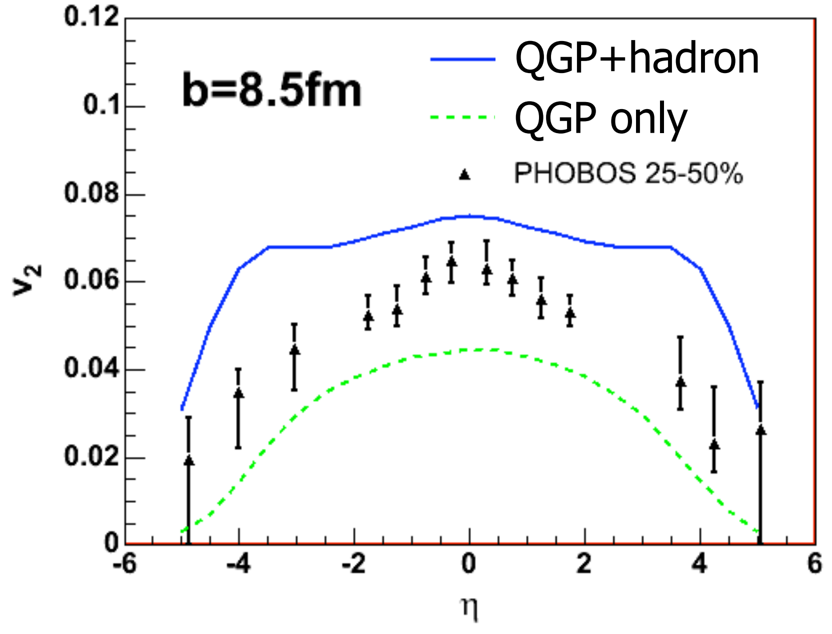


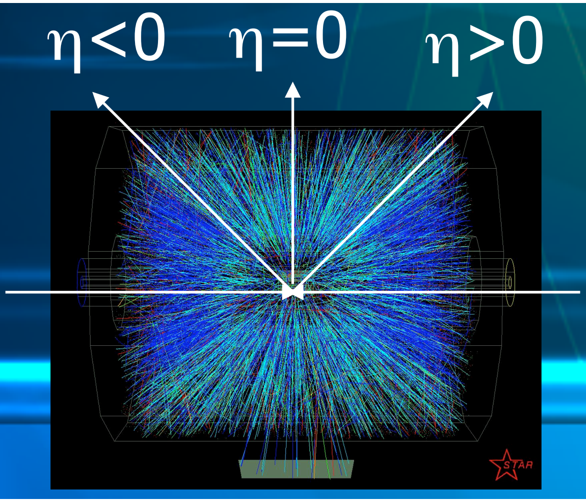


Result from a hadronic cascade (JAM)
(Courtesy of M.Isse)

Pseudorapidity Dependence of v_2

TH('02); TH and K.Tsuda('02);
TH et al. ('06).





- v_2 data are comparable with hydro results again around $\eta=0$
- Not a QGP gas → sQGP
- Nevertheless, large discrepancy in forward/ backward rapidity

→See next slides

Hadron Gas Instead of Hadron Fluid

T.Hirano and M.Gyulassy,Nucl.Phys.**A769** (2006)71.

A QGP fluid surrounded
by hadronic gas

QGP: Liquid (hydro picture)
Hadron: Gas (particle picture)

"Reynolds number"

$$R^{-1} = \frac{4}{3T\tau}\frac{\eta}{s}$$

Matter proper part:

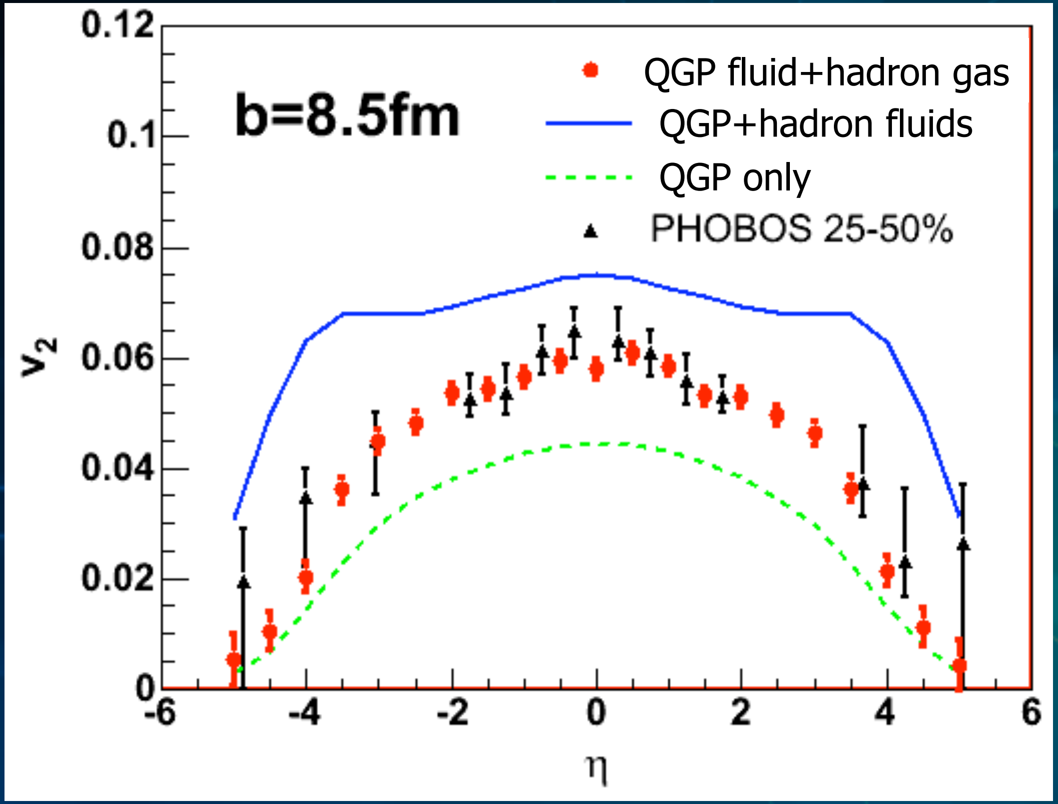
$$\frac{\text{(shear viscosity)}}{\text{(entropy density)}}$$

$$\eta/s$$

big
in Hadron

small
in QGP

Importance of Hadronic "Corona"

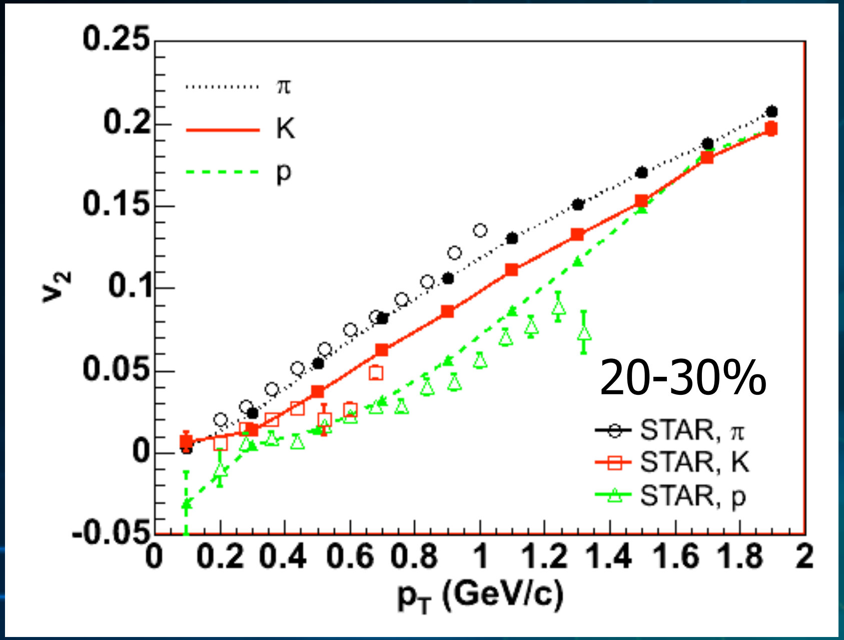


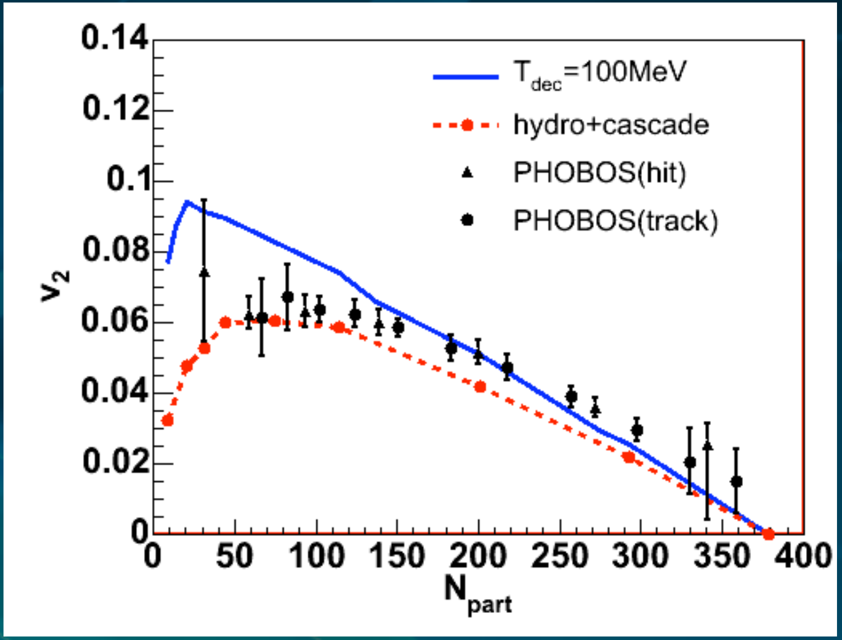
T.Hirano et al.,Phys.Lett.B**636**(2006)299.

- Boltzmann Eq. for hadrons instead of hydrodynamics
- Including viscosity through finite mean free path

- Suggesting rapid increase of entropy density
- Deconfinement makes hydro work at RHIC!?
→ Signal of QGP!?

QGP Liquid + Hadron Gas Picture Works Well



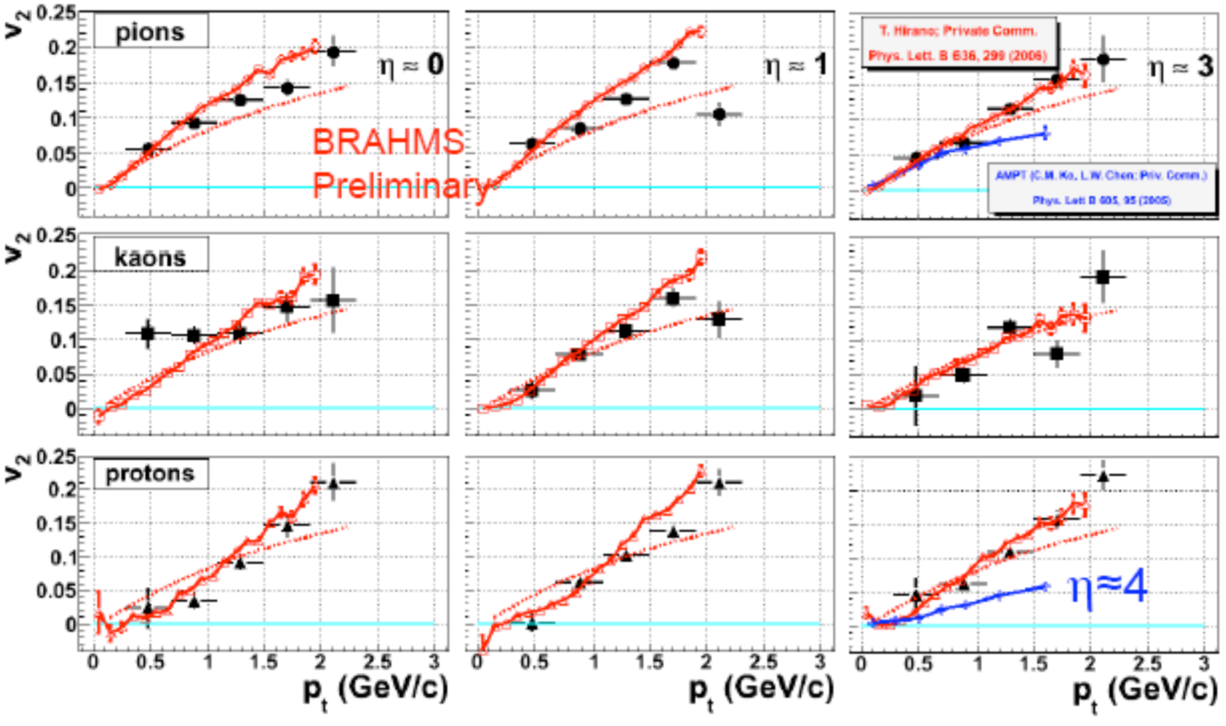


Mass dependence is o.k.
Note: First result was obtained by Teaney et al.

- Centrality dependence is ok
- Large reduction from pure hydro in small multiplicity events

T.Hirano et al.,Phys.Lett.B**636**(2006)299.

QGP Liquid + Hadron Gas Picture Works Well (contd.)



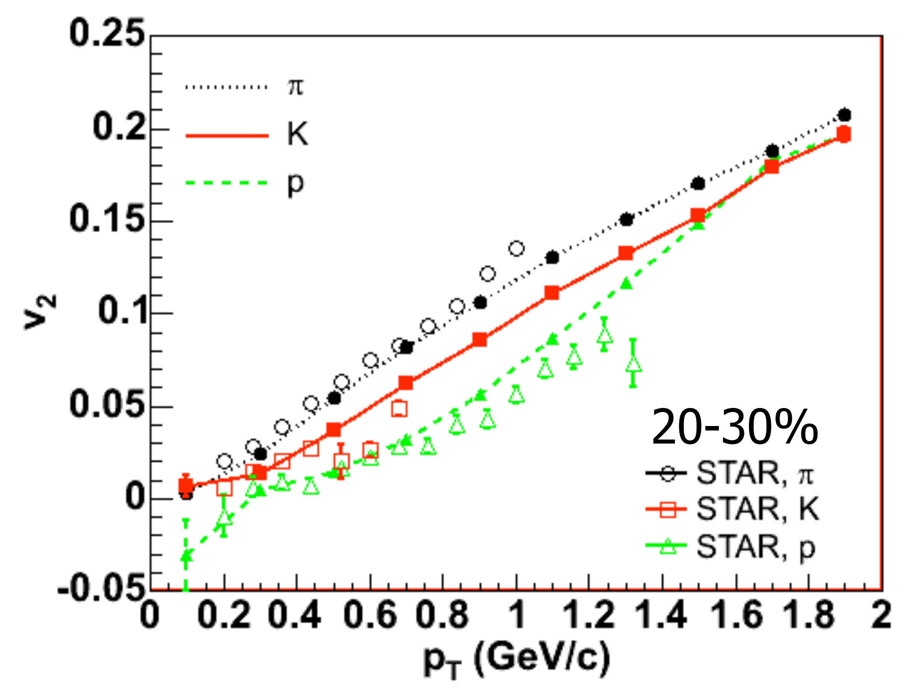
— hybrid model

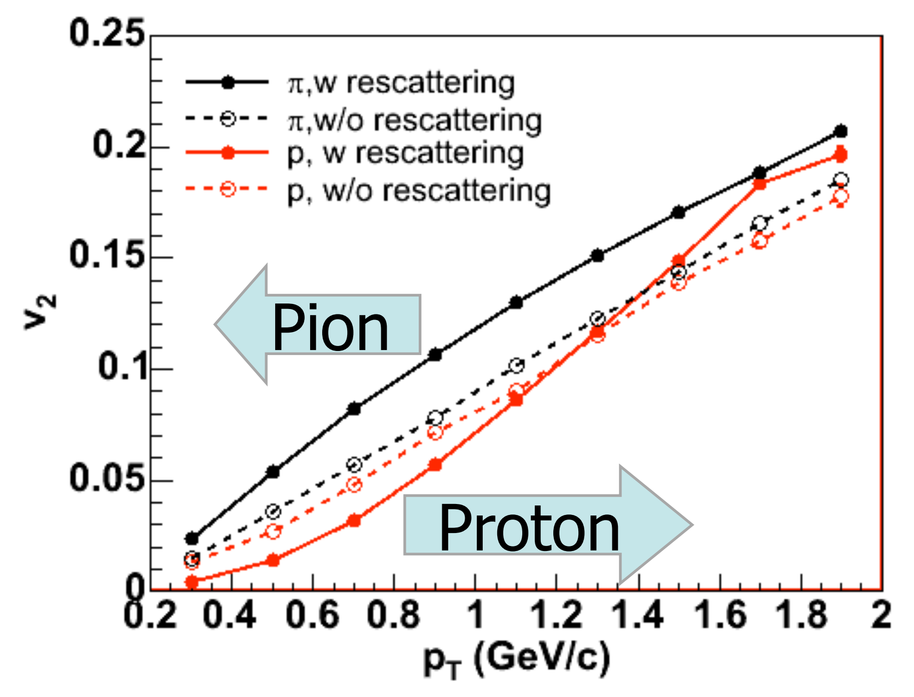
— AMPT

Adopted from S.J.Sanders
(BRAHMS) talk @ QM2006

How Fragile/ Robust the Perfect Fluid Discovery is

1. Is mass ordering for $v_2(p_T)$ a signal of the perfect QGP fluid?



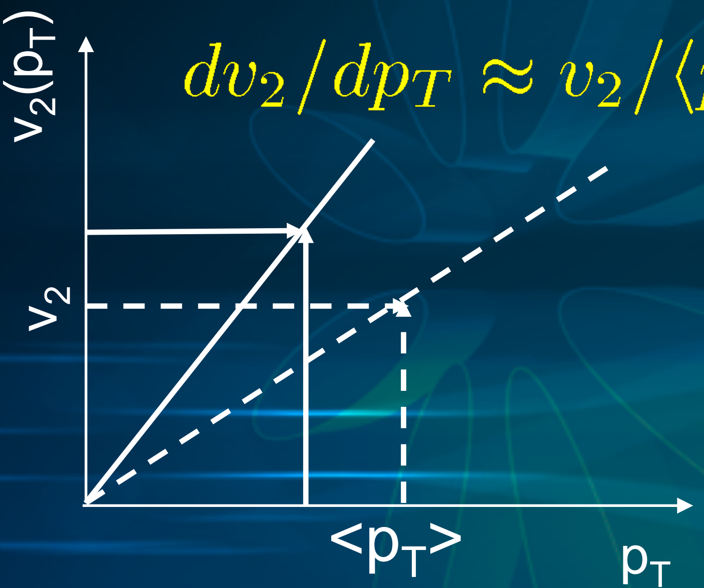


Mass dependence is o.k. from hydro+cascade.

Mass ordering comes from rescattering effect. Interplay btw. radial and elliptic flows
→Not a direct sign of the perfect QGP fluid

Why they shift oppositely?

pions



$$dv_2/dp_T \approx v_2/\langle p_T \rangle$$

$$dE_T/dy \approx \langle m_T \rangle dN/dy$$

must decrease with proper time

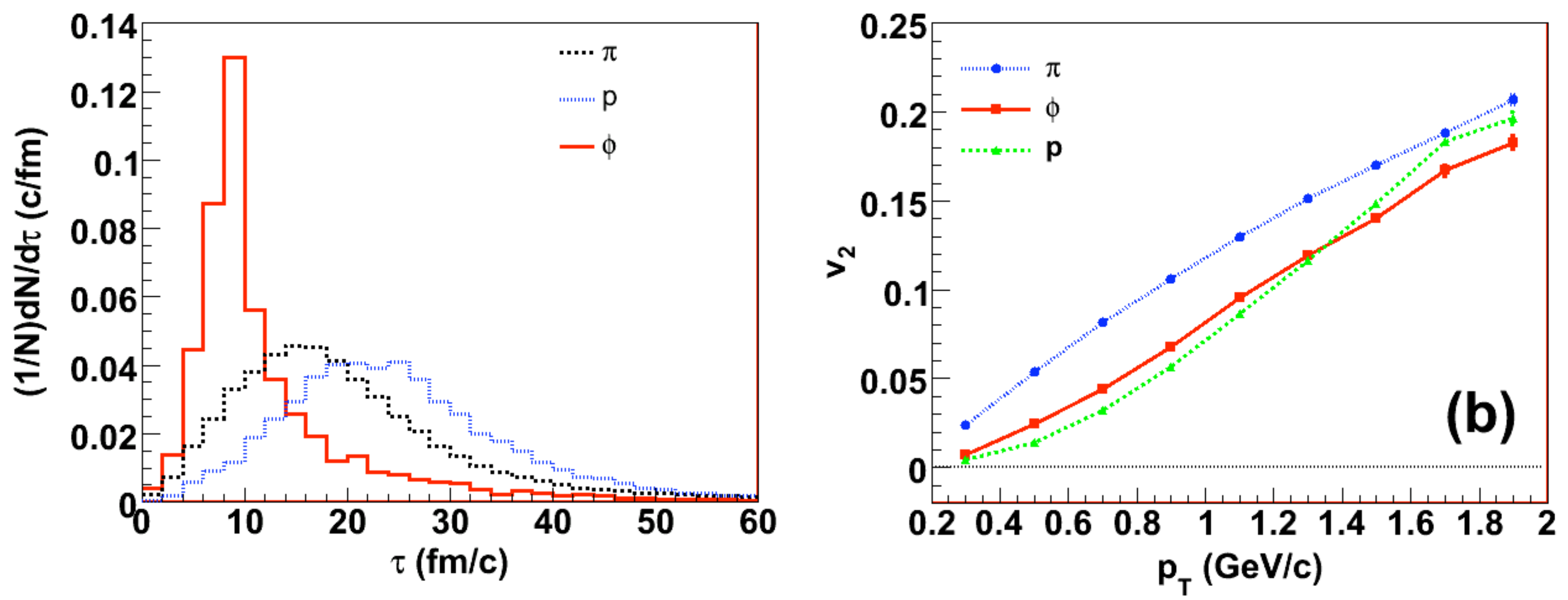
protons

v_2 for protons can be negative even in positive elliptic flow

TH and M.Gyulassy, NPA769,71(06)

P.Huovinen et al.,PLB503,58(01)

Violation of Mass Ordering



Early decoupling from the system for phi mesons
Mass ordering is generated during hadronic evolution.

TH et al., arXiv:0710.5795[nucl-th].

2. Is viscosity really small in QGP?

- 1+1D Bjorken flow Bjorken('83)

Baym('84)Hosoya,Kajantie('85)Danielewicz,Gyulassy('85)Gavin('85)Akase et al.('89)Kouno et al.('90)...

$$\begin{aligned} d\epsilon/d\tau &= -sT/\tau && \text{(Ideal)} \\ &= -(sT/\tau)[1-4(\eta/s)/3T\tau] && \text{(Viscous)} \end{aligned}$$

η : shear viscosity (MeV/fm^2), s : entropy density (1/fm^3)

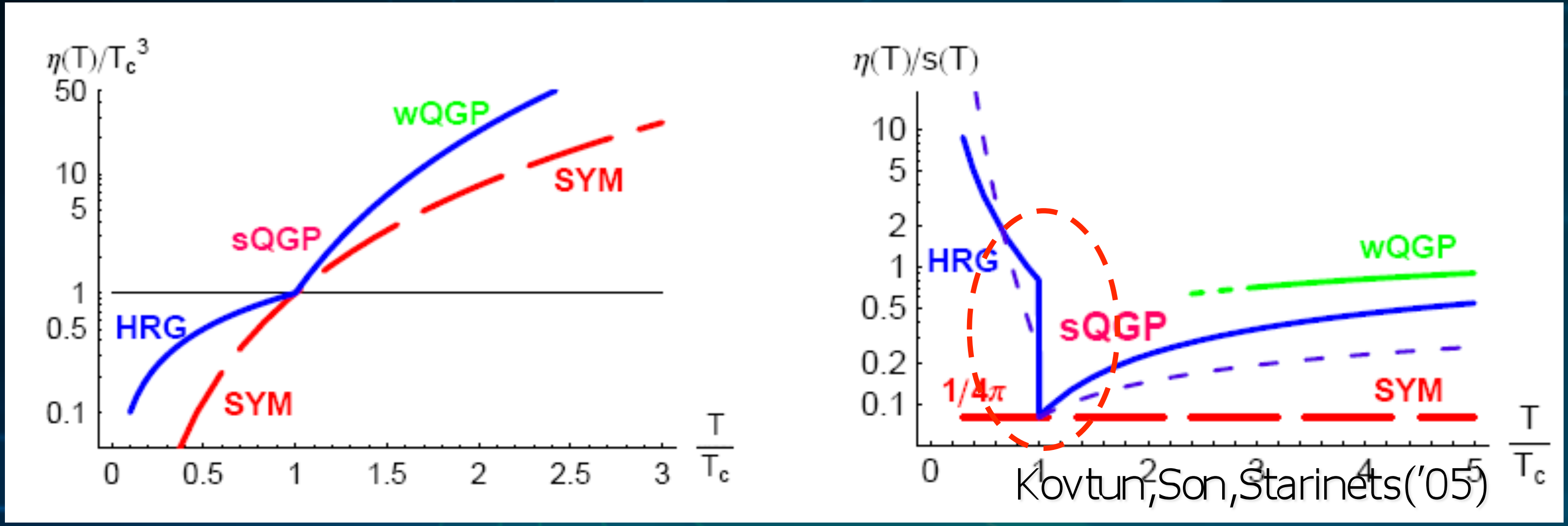
η/s is a good dimensionless measure (in the natural unit) to see viscous effects.

Shear viscosity is small *in comparison with* entropy density!

A Probable Scenario

TH and Gyulassy ('06)

η : shear viscosity, s : entropy density



Kovtun,Son,Starinets('05)

- Absolute value of viscosity
  $\eta(\text{sQGP}) > \eta(\text{hadron})$!
- Its ratio to entropy density
  $\eta/s(\text{sQGP}) \ll \eta/s(\text{hadron})$

Rapid increase of entropy density can make hydro work at RHIC.
Deconfinement Signal?!

Digression

[Pa] = [N/m^2]

(Dynamical) Viscosity η:

~1.0x10^{-3} [Pa s] (Water 20℃)

~1.8x10^{-5} [Pa s] (Air 20℃)

Kinetic Viscosity $\nu=\eta/\rho$:

~1.0x10^{-6} [m^2/s] (Water 20℃)

~1.5x10^{-5} [m^2/s] (Air 20℃)

$$\boxed{\eta_{\mathrm{water}} > \eta_{\mathrm{air}} \quad \text{BUT} \quad \nu_{\mathrm{water}} < \nu_{\mathrm{air}}}$$

Non-relativistic Navier-Stokes eq. (a simple form)

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\vec{\nabla}P + \boxed{\frac{\eta}{\rho}}\nabla^2\vec{u}$$

Neglecting external force and assuming incompressibility.

3. Is η/s enough?

- Reynolds number

Iso, Mori, Namiki ('59)

$$R = \frac{|\Delta_{\mu\nu} T_i^{\mu\nu}|}{|\Delta_{\mu\nu} T_v^{\mu\nu}|},$$

R>>1
→Perfect fluid

$$R \approx (\text{static property}) \otimes (\text{dynamics})$$

- (1+1)D Bjorken solution

$$R^{-1} = \frac{3}{4T\tau}\frac{\eta}{s}$$

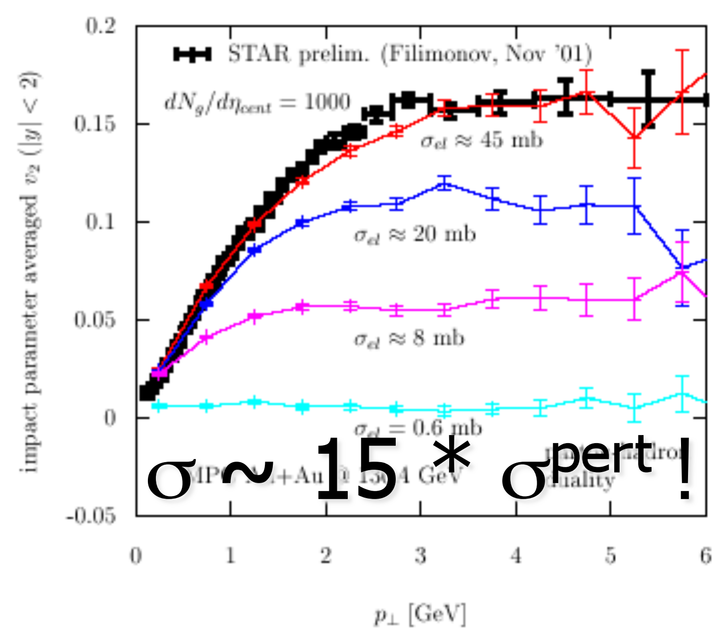
$$1/\tau = \partial_\mu u^\mu : \text{expansion rate in 1+1D}$$

- Need to solve viscous fluid dynamics in (3+1)D

→ Cool! But, tough!
→ Causality problem

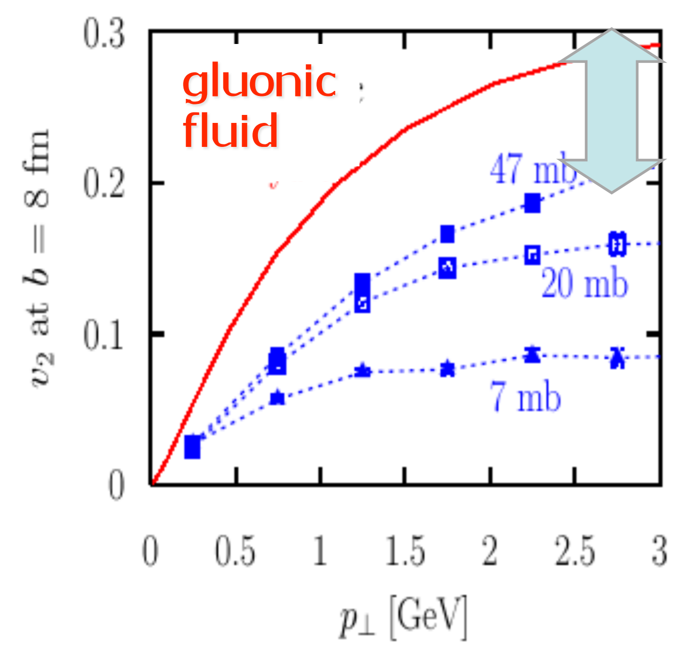
4. Boltzmann at work?

Molnar&Gyulassy('00)



$\sigma \sim 15 * \sigma^{pert}$!

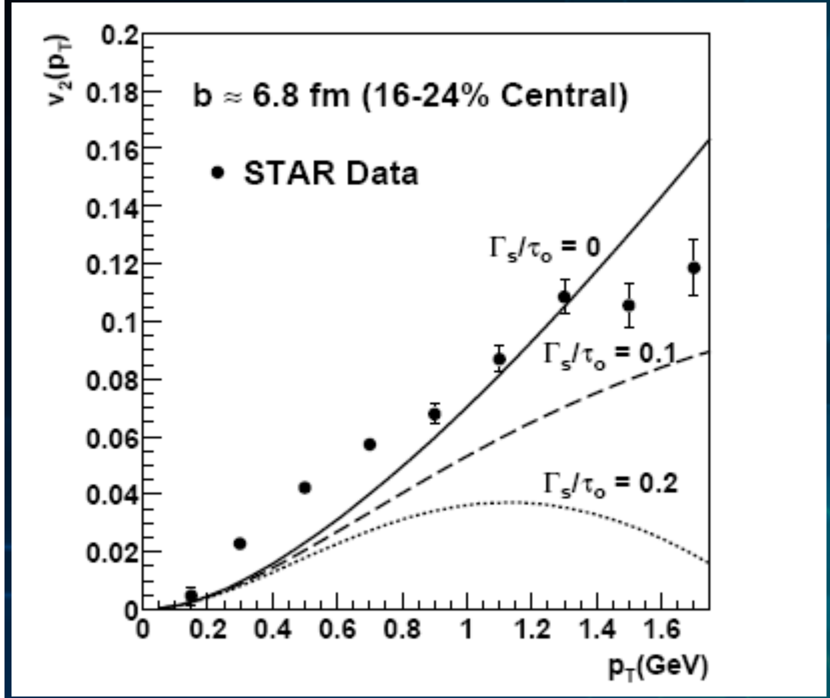
Molnar&Huovinen('04)



25-30% reduction

Caveat 1: Where is the "dilute" approximation in Boltzmann simulation? Is $\lambda \sim 0.1$fm o.k. for the Boltzmann description?
Caveat 2: Differential v_2 is tricky. $dv_2/dp_T \sim v_2/\langle p_T \rangle$.
Difference of v_2 is amplified by the difference of $\langle p_T \rangle$.
Caveat 3: Hadronization/Freezeout are different.

5. Does $v_2(p_T)$ really tell us smallness of η/s in the QGP phase?



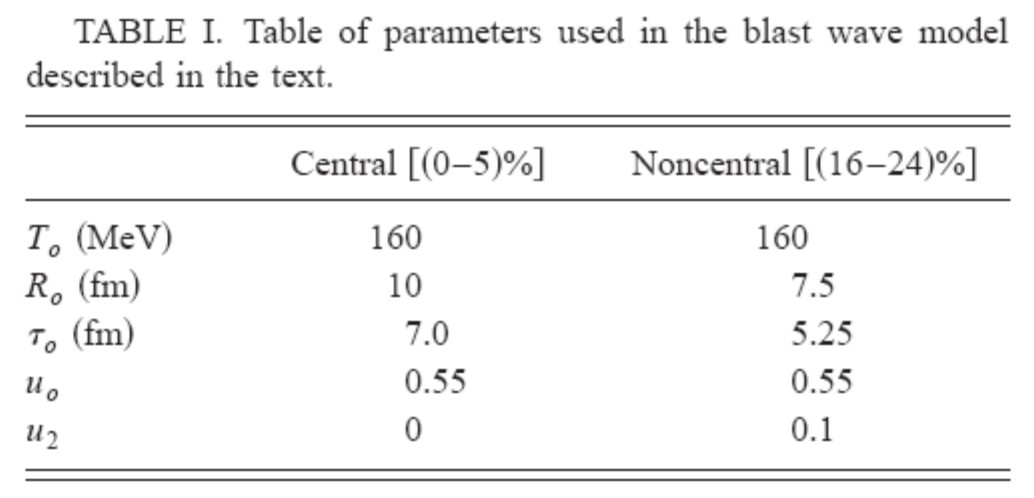


TABLE I. Table of parameters used in the blast wave model described in the text.

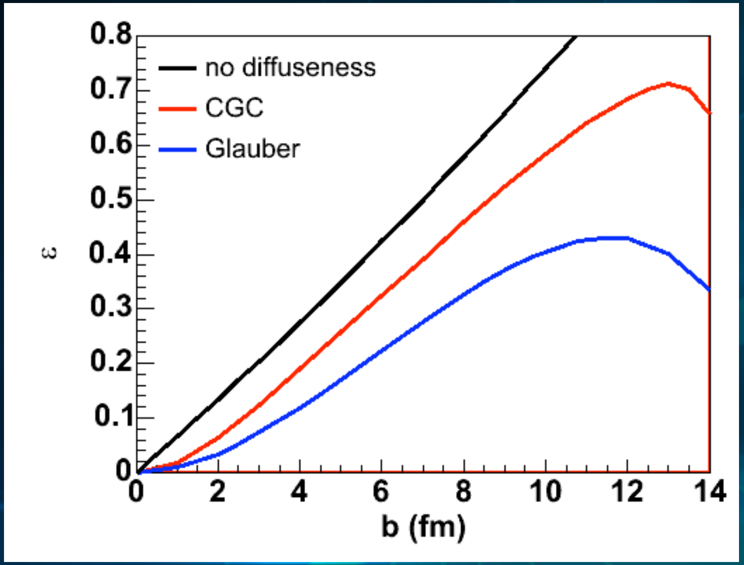
	Central [(0–5)%]	Noncentral [(16–24)%]
T_o (MeV)	160	160
R_o (fm)	10	7.5
τ_o (fm)	7.0	5.25
u_o	0.55	0.55
u_2	0	0.1

D.Teaney('03)

- Not a result from dynamical calculation, but a "fitting" to data.
- No QGP in the model
- τ_0 is not a initial time, but a freeze-out time.
- Γ_s/τ_0 is not equal to η/s, but to $3\eta/4sT_0\tau_0$ (in 1+1D).
- Being smaller T_0 from p_T dist., τ0 should be larger (~10fm/c).

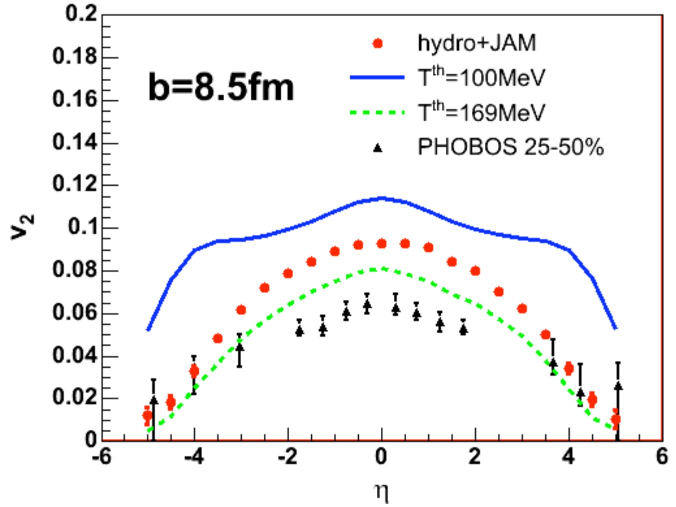
6. Is there model dependence in hydro calculations?

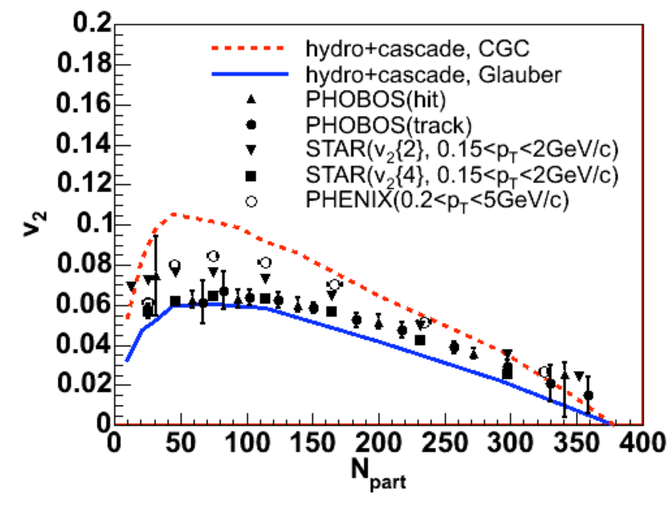
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$



Novel initial conditions from Color Glass Condensate lead to large eccentricity.

Hirano and Nara('04), Hirano et al.('06)
Kuhlman et al.('06), Drescher et al.('06)





Need viscosity and/or softer EoS in the QGP!

Summary

- Agreement btw. hydro and data comes from one particular modeling. (Glauber + ideal QGP fluid + hadron gas)
- IMO, still controversial for discovery of perfect fluid QGP.
- Check model dependences to obtain robust conclusion (and toward comprehensive understanding of the QGP from exp. data).

Heavy Ion Café

http://tkynt2.phys.s.u-tokyo.ac.jp/~hirano/hic/index.html

HEAVY ION CAFÉ

- ホーム
- はじめに
- プログラム
- 世話人
- アドバイザー
- アクセス
- リンク

第6回　Heavy Ion Café

日時：9月8 or 15日(土)　午後1時から
場所：東京大学理学部(本郷)1号館2階大学院講義室(233号室)

申し訳ありませんが、参加を希望される方は事前にご連絡をください。
土曜日で建物が閉まっているため、建物の入り口で担当が待ちます。

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