Quark Matter 2004
Oakland – January 11-17

Hydrodynamic Models of Heavy-Ion Collisions

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Parallel Talks Based on Hydro

Jan. 13

- **<u>H. Niemi</u>,** Photon production from non-equilibrium QGP in heavy-ion collisions
- **<u>M. Csanad</u>**, Indication for quark deconfinement and evidence for a Hubble flow in Au+Au collisions at RHIC

Jan. 15

- **<u>Y. Nara</u>,** CGC, hydrodynamics and the parton energy loss
- **<u>E. Shuryak</u>,** Why does the QGP behaves like a perfect fluid?
- **<u>U. Heinz</u>,** Rapidity dependence of momentum anisotropies in nuclear collisions
- **<u>D. Teaney</u>,** Viscosity and thermalization

Outline

1. Why hydrodynamics?
2. How hydrodynamics works at RHIC
3. Hybrid models based on hydrodynamics
   - Information of the inside (jet quenching , EM probe)
   - Improvement of initial stage
4. Improvement of ideal hydro (viscosity)
5. Summary

1. Why Hydrodynamics?

Once we accept 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

Caveat: Thermalization in HIC is a tough problem like building the Golden Gate Bridge!

1. Why Hydrodynamics (contd.)

Space-time evolution of energy density in
sqrt(s_{NN})=200 GeV Au+Au collision at b=7.2fm

Animation is here in the presentation.
If you need, please ask me (hirano@bnl.gov).

A full 3D hydrodynamic simulation with a CGC initial condition
Talk by Y.Nara

Hydrodynamics provides
us a very intuitive
and simple description of
relativistic heavy ion collisions.

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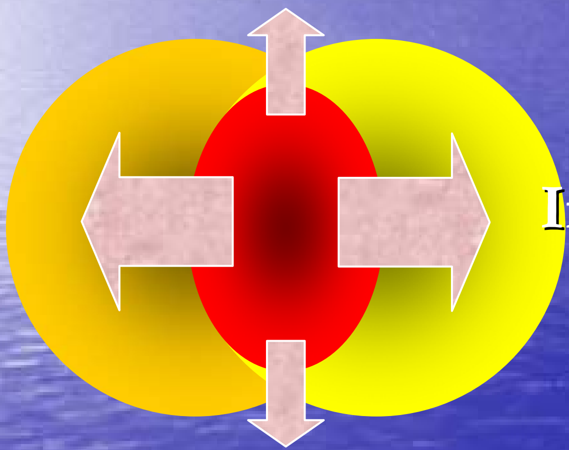
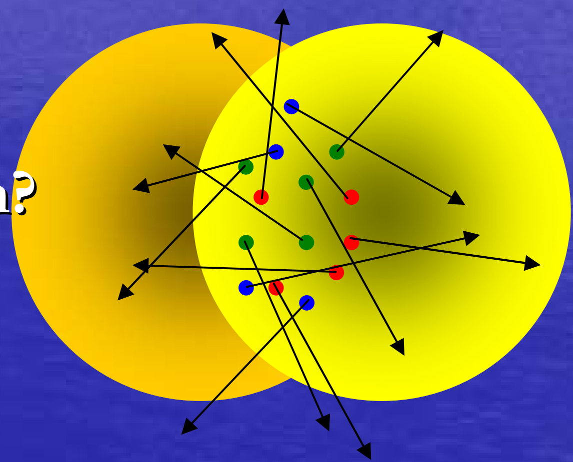
2. How Hydrodynamics Works at RHIC

Elliptic flow (J.-Y.Ollitrault ('92))

How does the system respond to initial spatial anisotropy?



Dense or dilute?
If dense, thermalization?
If thermalized, EoS?



$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}(1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \cdots)$$

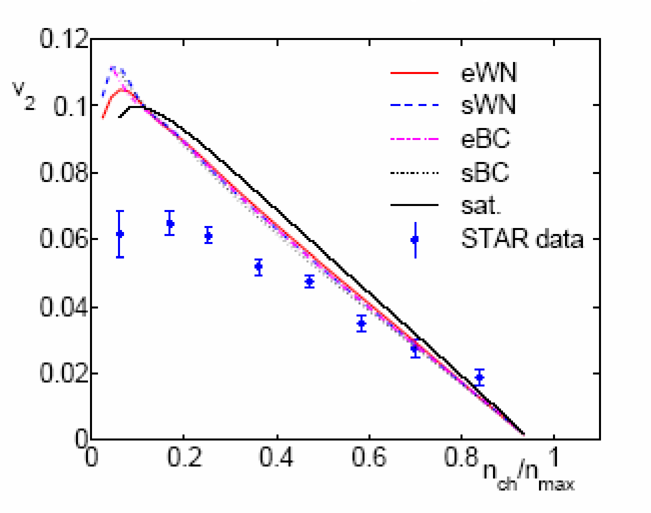
A.Poskanzer & S.Voloshin ('98)

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

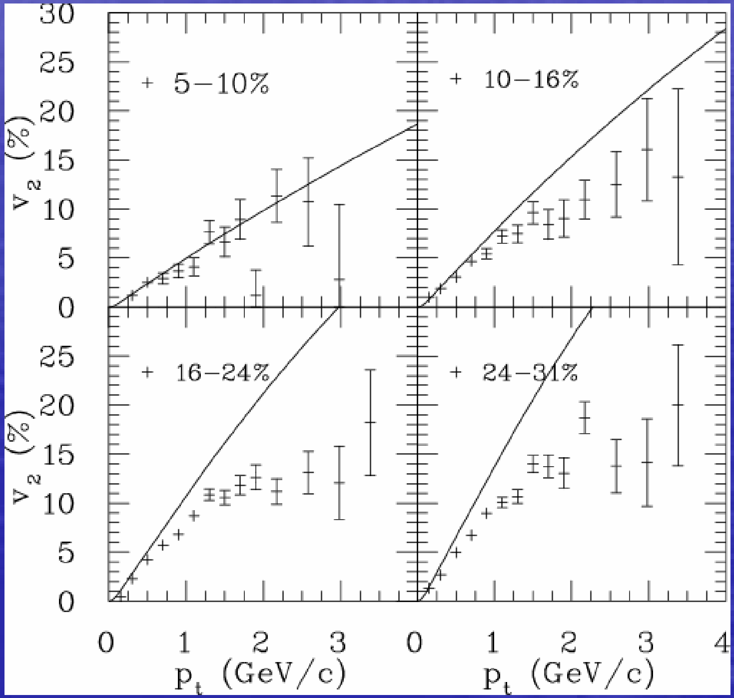
v_4 :P.Kolb('03), talk by A.Poskanzer

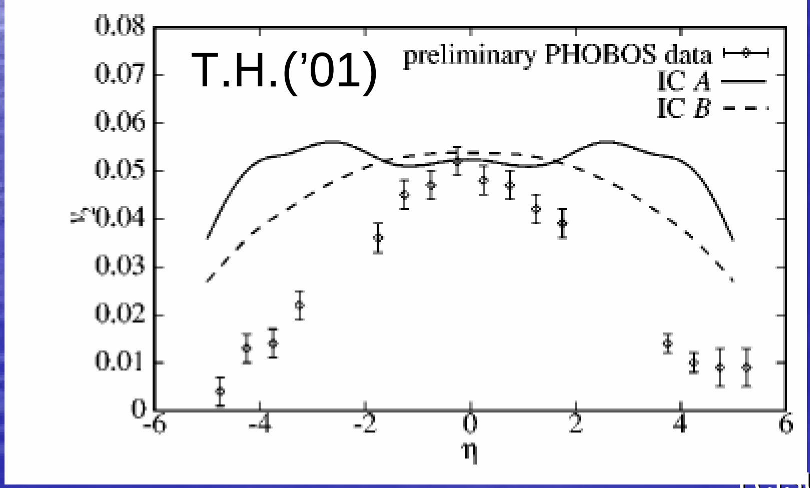
Elliptic Flow of Charged Particles

P.Kolb et al.('01)



P.Huovinen('03)





Roughly speaking,

ideal hydro gives a good description

$$b \lesssim 5 \text{ fm},$$

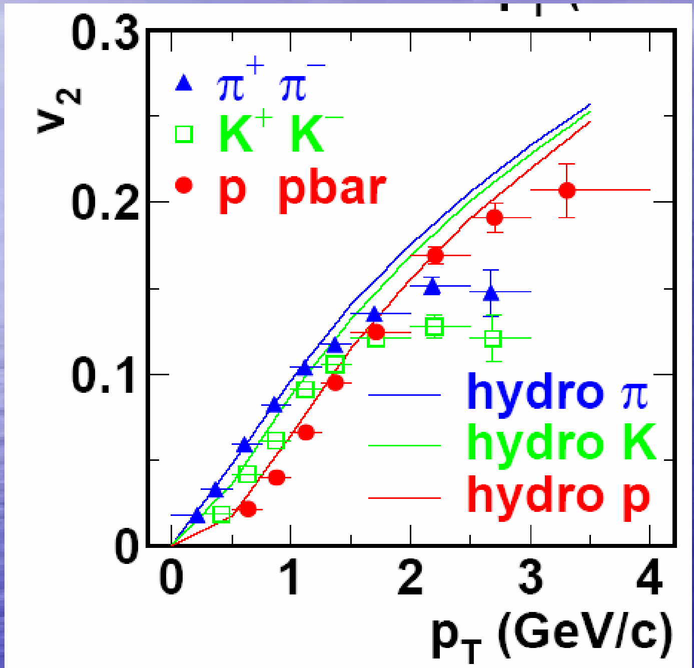
$$p_T \lesssim 1\text{-}1.5 \text{ GeV}/c,$$

$$|\eta| \lesssim 1\text{-}2$$

For improvement of models, talk by U.Heinz

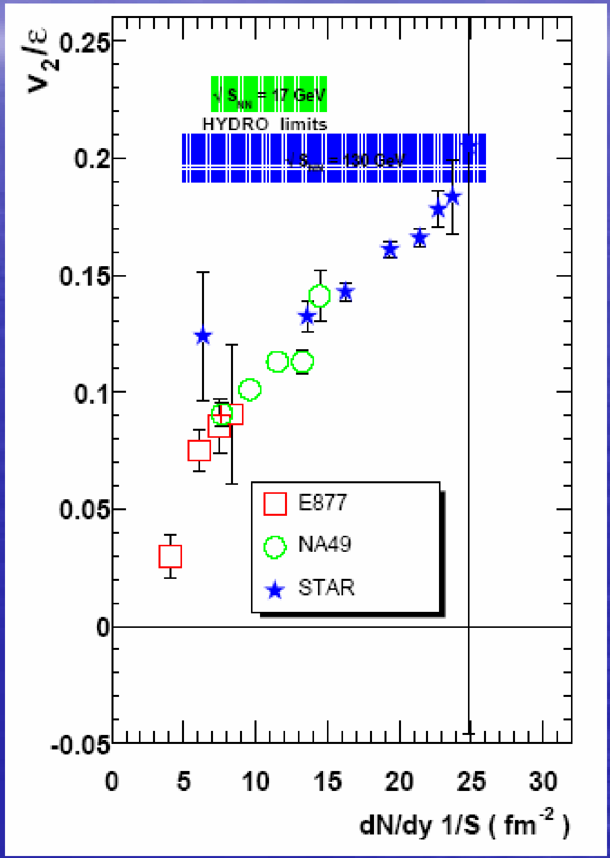
More on Elliptic Flow

PHENIX, PRL91('03)182301.



Hydro: P.Huovinen et al.('01)

STAR, PRC66('02)034904



Hydro: P.Kolb et al.('99)
(Note: Hydro+RQMD gives a better description.
D.Teaney et al.('01))

See recent excellent reviews,

P.Huovinen (QM2002) , nucl-th/0305064;
P.Kolb and U.Heinz, nucl-th/0305084;
E.Shuryak, hep-ph/0312227, today's talk.

Ideal hydro seems to give a good description at RHIC

What's next?

1. ***<u>Making the most use of hydro models to study the RHIC physics</u>***
2. ***<u>Checking how robust the current results are when hydro models are improved</u>***

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1. Why hydrodynamics?
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   - Information inside fluids (jet quenching , EM probe)
   - Improvement of initial stage
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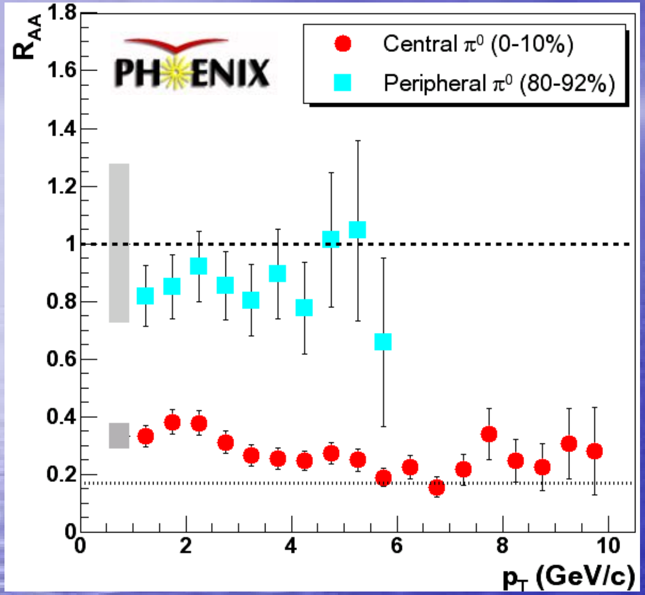
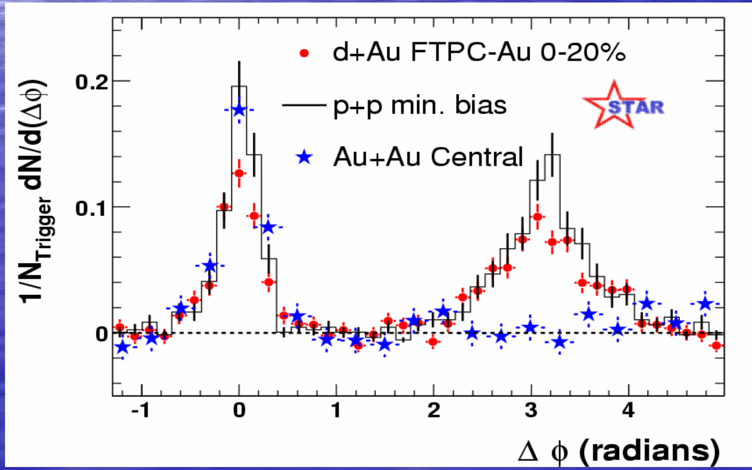
3.1 Information inside fluids





Jet quenching is
a manifestation
of interaction between
matter and partons
(Talks by G.Moore and I.Vitev)

For quantitative analysis,
the information about
the space-time evolution
of matter
is indispensable!

3.1.1 Hydro as a Tool to Analyze Jet Quenching

Jet quenching analysis taking account of (2+1)D hydro results

(M.Gyulassy et al.('02))

Hydro+Jet model (T.H. & Y.Nara ('02))

GLV 1st order formula (M.Gyulassy et al.('00))

$$\Delta E = C \int_{\tau_0} d\tau (\tau - \tau_0) \times \rho(\tau, \mathbf{x}(\tau)) \ln \left(\frac{2 p_0^{\mu} u_{\mu}}{\mu^2 L} \right)$$

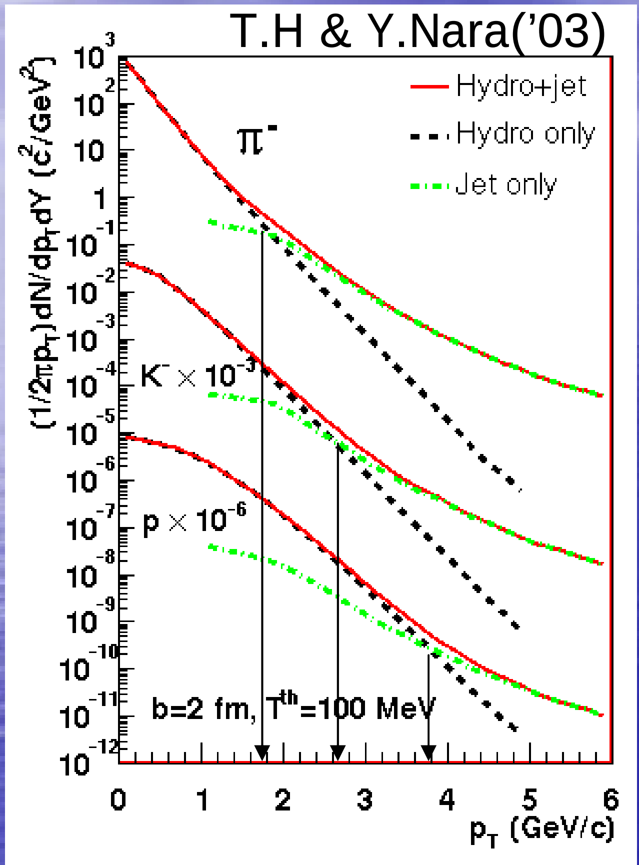
Parton density $\rho(x)$ taken from full 3D hydro simulations

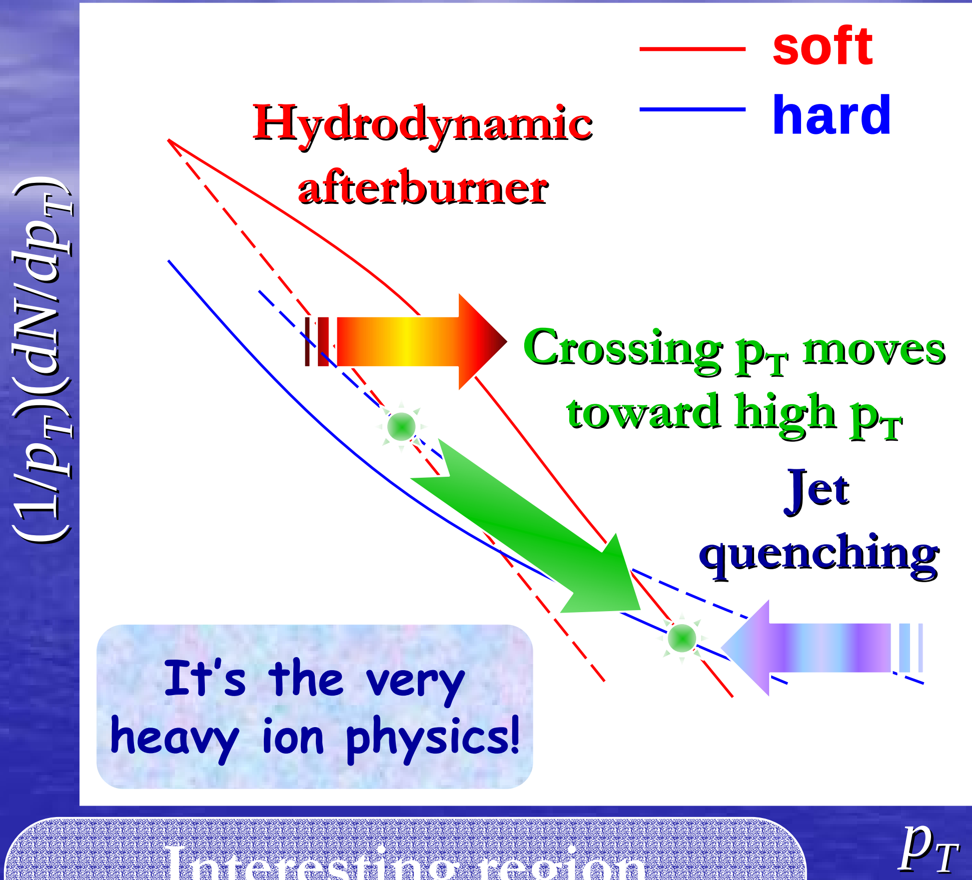
Animation is here in the presentation.
If you need, please ask me
hirano@bnl.gov

Movie and data of $\rho(x)$ are available at
`http://quark.phy.bnl.gov/~hirano/`

Interplay between Soft and Hard

Au+Au at b=2 fm





$N_{SOFT} \sim N_{HARD}$

$p_{T,\mathrm{cross}} \sim$ 1.8 GeV/c for π

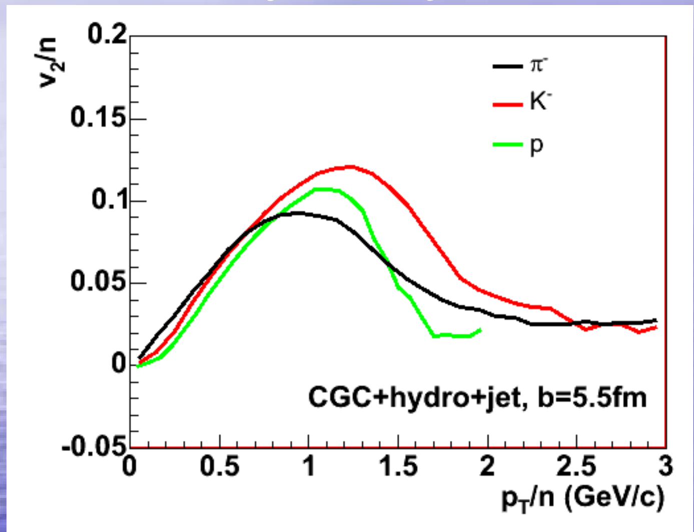
2.7 GeV/c for K

3.7 GeV/c for p

Interesting region
→Intermediate p_T
($2 < p_T < 3.5$ GeV/c)
Pion ←hard, Proton ←soft

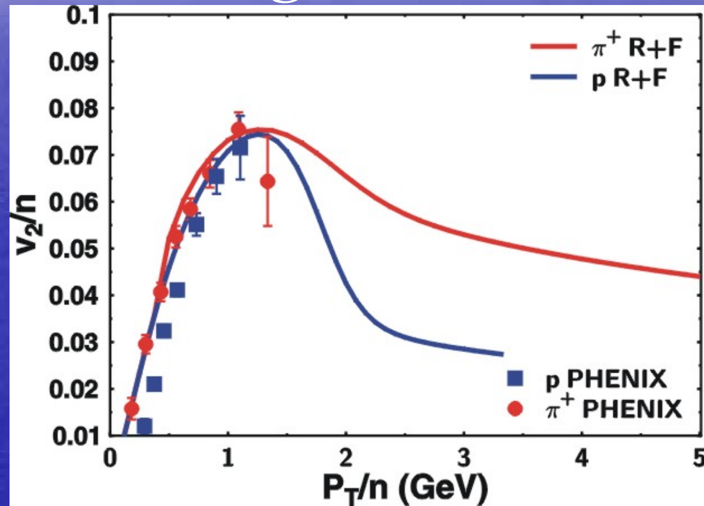
Consequense from hadron species dependent $p_{T,cross}$

Hydro+Jet

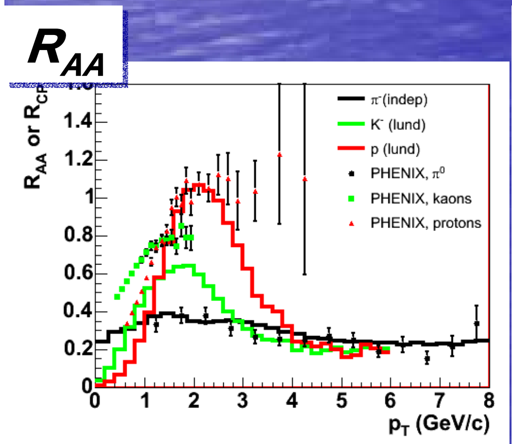


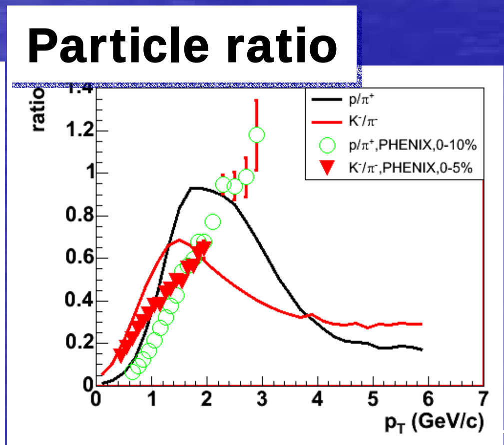
!?

Recombination +Fragmentation



Talk by R.Fries

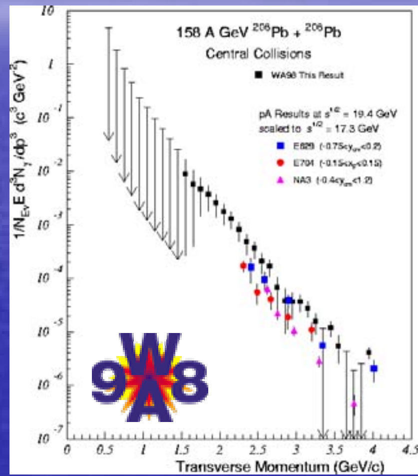




“Scaling v_2”
Interplay between soft and hard?
Recombination mechanism?

3.1.2 Hydro as a Tool to Analyze Electromagnetic Radiation

Thermal photon is a penetrating probe of QGP (E.Shuryak('78))



- **Production rate**

(Number per unit space-time volume)

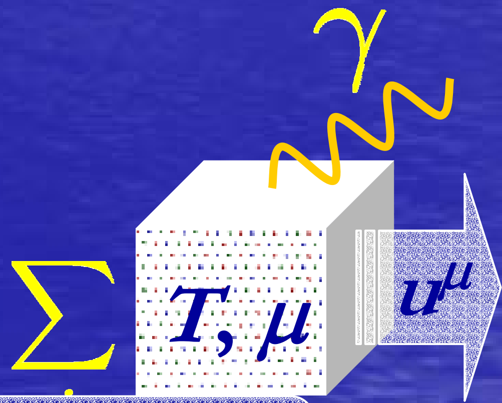
$$E\frac{dR_\gamma}{d^3p}(T,\mu) = \frac{-1}{(2\pi)^3}n(T,\mu)\mathrm{Im}\Pi^{R}{}_{\mu}{}^{\mu}$$

H.A.Weldon ('83), L.McLerran & T.Toimela ('84)
C.Gale & J.Kapusta ('91)
Talk by G.Moore

- **Invariant spectrum of photons**

$$E\frac{dN_\gamma}{d^3p} = \sum_i \Delta V_i \tilde{E}\frac{dR_\gamma}{d^3\tilde{p}}(T(x_i),\mu(x_i),\tilde{E}=p_\mu u^\mu(x_i))$$

D.K.Srivastava & B.Sinha('94), J.Sollfrank et al.('97),
J.Alam et al.('01) and a lot of work



Importance of temperature profile

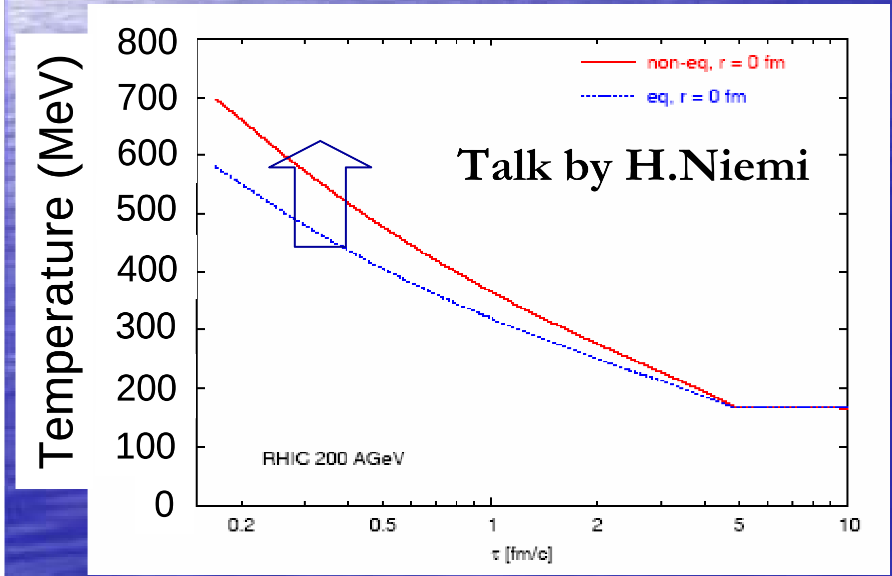
Chemical Non-Equilibrium

QGP phase	"Gluon Plasma (GP)" → QGP
Hadron phase	Chemical freezeout $T^{\mathrm{th}} < T < T^{\mathrm{ch}}$

QGP phase

Hydro + rate eq.

Smaller d.o.f. → Larger initial T



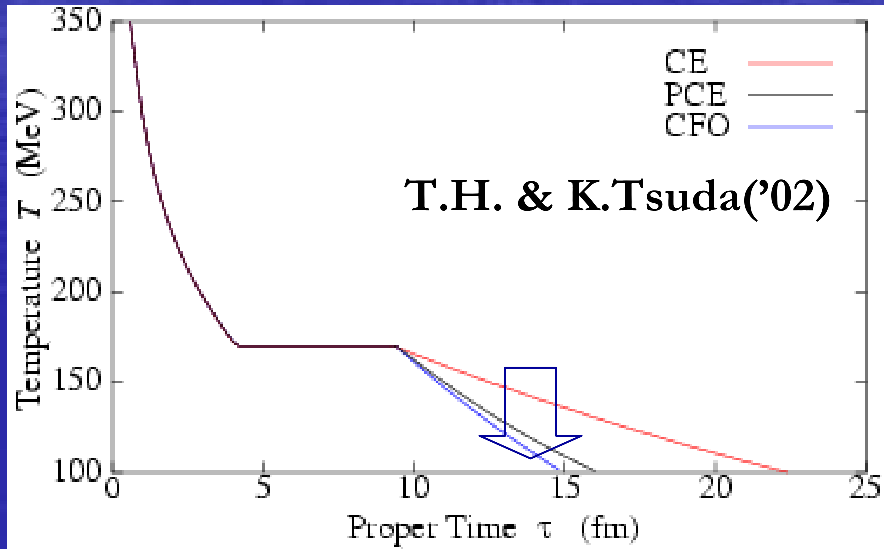
T.S.Biro et al.('93), D.K.Srivastava et al.('97), A.K.Chaudhuri('00), D.M.Elliott & D.Rischke('00)

Hadron phase

Hydro($T^{\mathrm{th}} \neq T^{\mathrm{ch}}$)

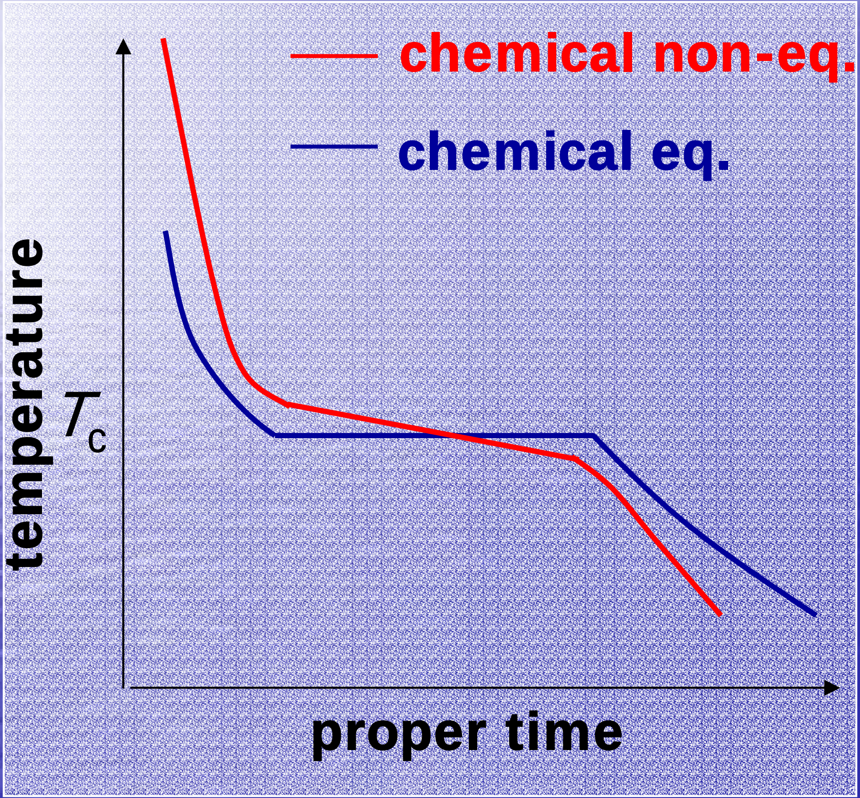
Overpopulation of resonance

→ Rapid cooling



N.Arbex et al.('01), T.H. & K.Tsuda('02), D.Teaney('02), P.Kolb & R.Rapp('03)

Novel Temperature Evolution



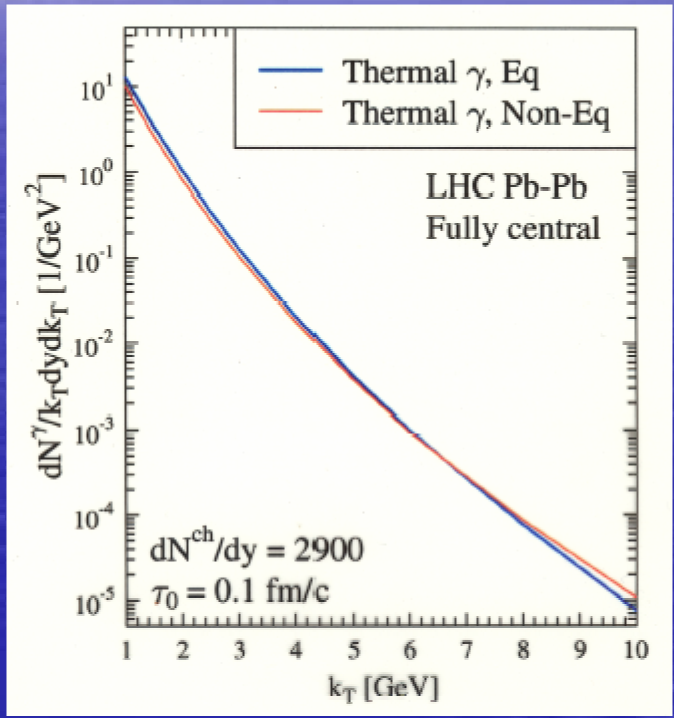
Caveat:
one has to take account of fugacity λ in calculating EM spectra.

- QGP phase: λ<1
- Hadron phase: λ>1

$$n(T, \lambda) \sim \lambda n_0(T)$$

Compensation between T and λ?

Talk by H.Niemi


Thermal γ, Eq
Thermal γ, Non-Eq
LHC Pb-Pb
Fully central
dN^ch/dy = 2900
τ0 = 0.1 fm/c
dN^γ/k_T dy dk_T [1/GeV^2]
k_T [GeV]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1 2 3 4 5 6 7 8 9 10

3.2 Improvement of Initial Condition -Toward an unified model in HIC-

$$e(\tau_0, x), n_B(\tau_0, x), u^\mu(\tau_0, x)$$

Group	Hydro	Initial condition
M.Gyulassy et al.	SHASTA (2+1D, Bjorken)	HIJING, event-by-event
C.Nonaka et al.	Lagrangian hydro (full 3D)	URASiMA, event average
B.Schlei et al.	HYLANDER (2+1D)	VNI, event average
C.E.Aguiar et al.	SPheRIO (full 3D)	NeXus, event-by-event
L.P.Csernai et al.	Particle-in-cell (full 3D)	String ropes, flux tubes, classical YM
K.Eskola et al.	SHASTA (2+1D, Bjorken)	pQCD + final state saturation
T.H. & Y.Nara	τ–η coordinate (full 3D)	CGC, $\phi(k_T^2,x)$ a la Kharzeev & Levin
…	…	…

*Smoothed Particle hydrodynamical evolution of Relativistic heavy IOn collisions (Sao Paulo & Rio de Janeiro)

3.2.1 SPheRIO*

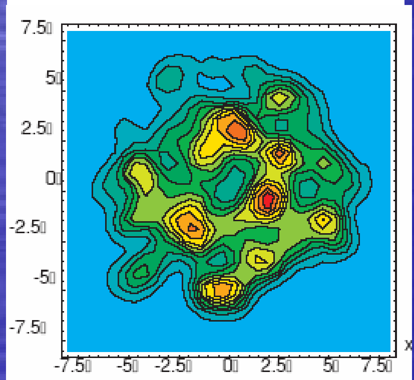
C.E.Aguiar, R.Andrade, F.Grassi, Y.Hama, T.Kodama, T.Osada, O.Socolowski Jr.…
Poster by F.Grassi

Main features:

- "Particle" method (a kind of Lagrangian hydro)
- Numerical cost cheaper than conventional finite grids method (Even in 3+1 D, any geometry)
- Event-by-event physics (NeXus + SPheRIO=NeXSPheRIO)
  (NeXus: parton based Gribov-Regge theory)

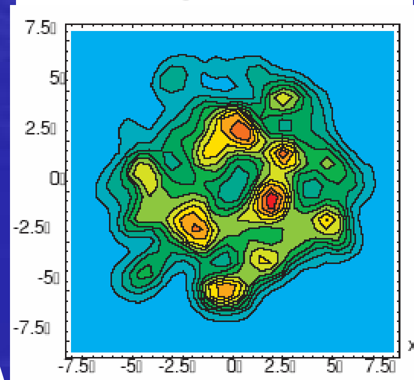
SPheRIO | **Conventional approach**

Spectra from ⟨ Energy density of single event ⟩



=?=

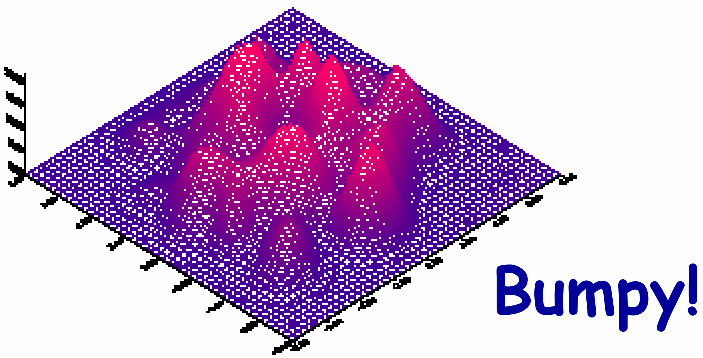
Spectra from ⟨ Energy density of single event ⟩



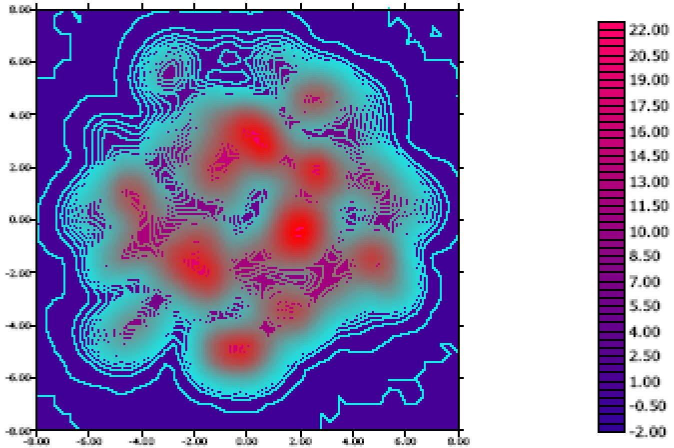
Similar approach based on HIJING:
M.Gyulassy et al.('97)

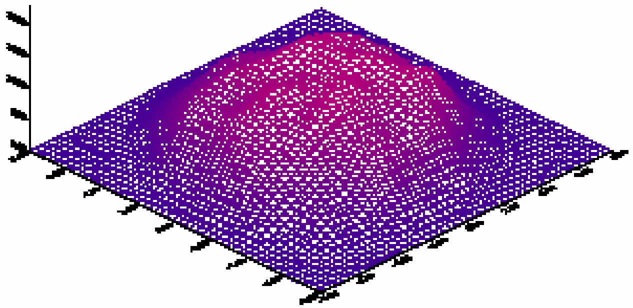
Initial Conditions in NeXSPheRIO

Energy density in the transverse plane (z=0)

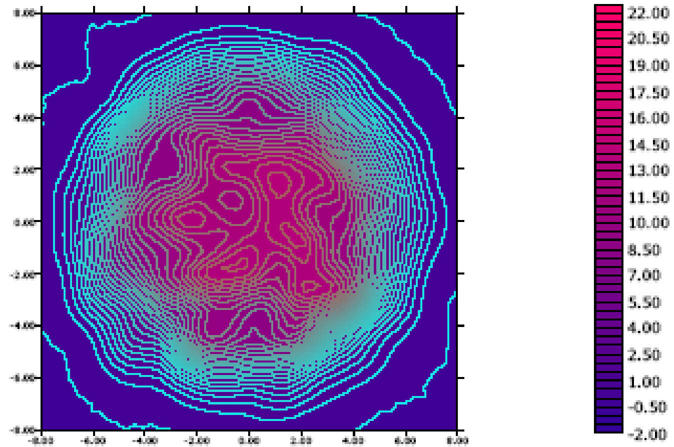


Single event (b=0fm)



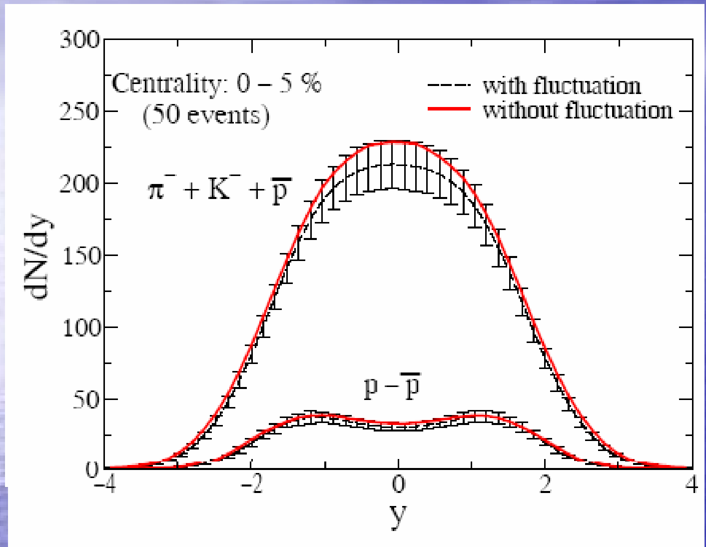


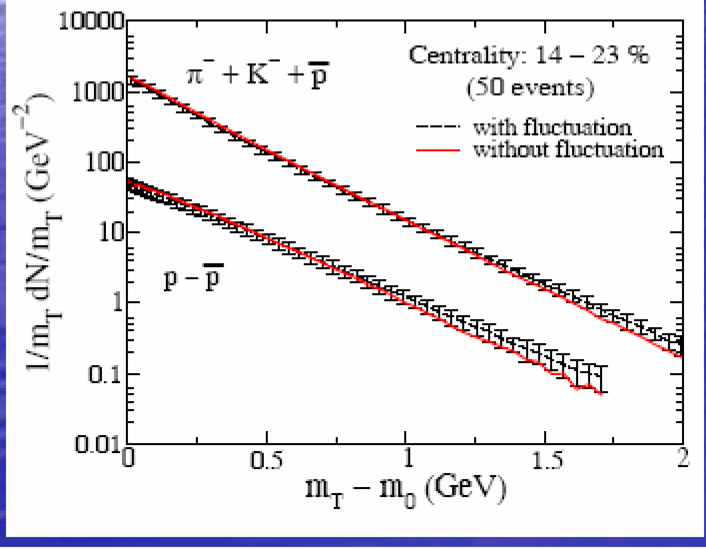
Average over 30 events (b=0fm)



Results from NeXSPheRIO

Pb+Pb 17.3A GeV





Effect of ***initial energy density*** fluctuation (simple EoS case):

$$\langle \cdots \rangle = \frac{1}{N} \sum_i \cdots$$:(event average)

$$\langle S \rangle_{\text{final}} \sim \langle S \rangle_{\text{initial}} \left[1 - \alpha \frac{\langle \Delta E^2 \rangle}{\langle E \rangle^2} \right]$$

Negative!

Multiplicity is reduced by ~10%!

p_T slope is not affected largely.
→ $v_2(p_T)$ and its fluctuation?

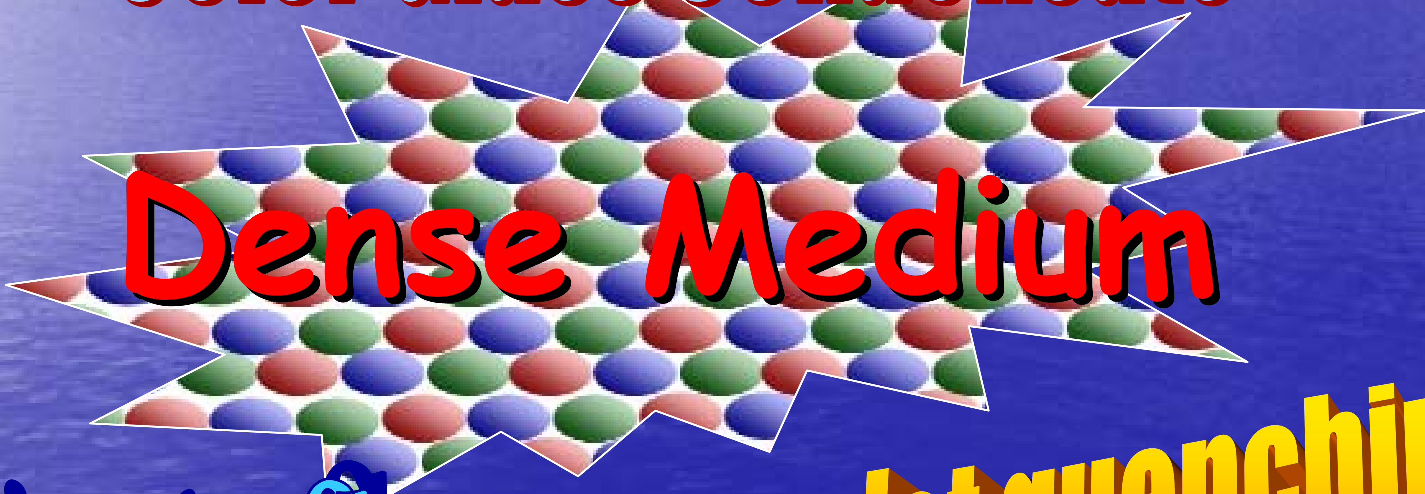
Now the hydro simulation becomes close to experimental situations like event-generators!

3.2.2 CGC+Hydro+Jet Model

T.H. & Y.Nara
Talk by Y.Nara

Color Glass Condensate

Talk by
J.Jalilian-Marian



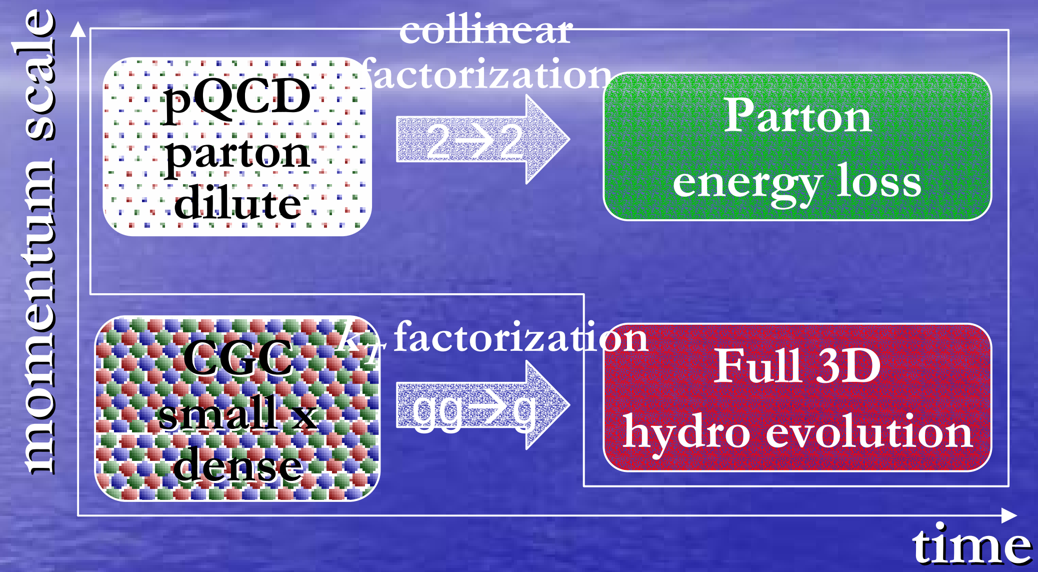
Elliptic flow

Jet quenching

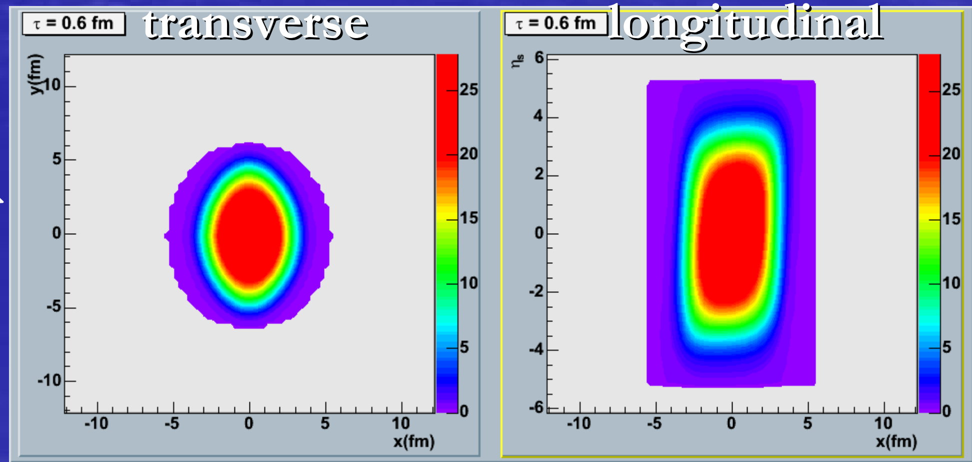
Talk by
I.Vitev

These three physics closely related with each other!

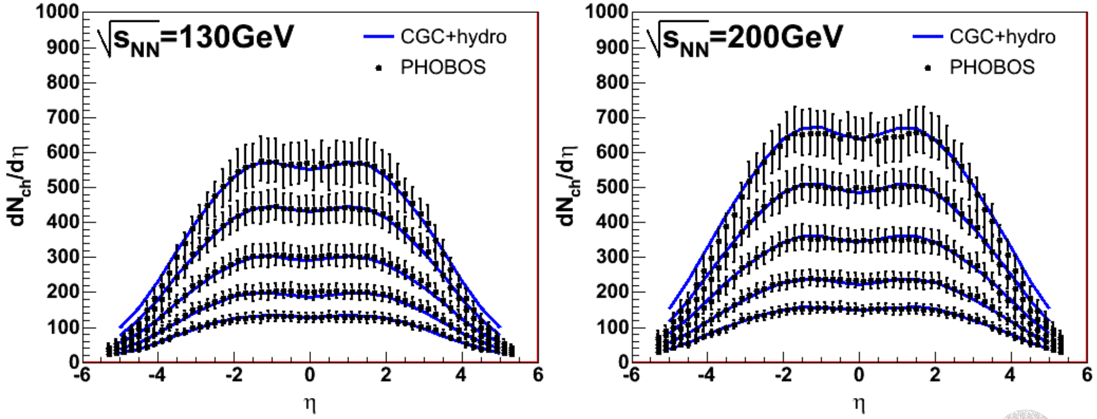
CGC+Hydro+Jet Model (contd.)



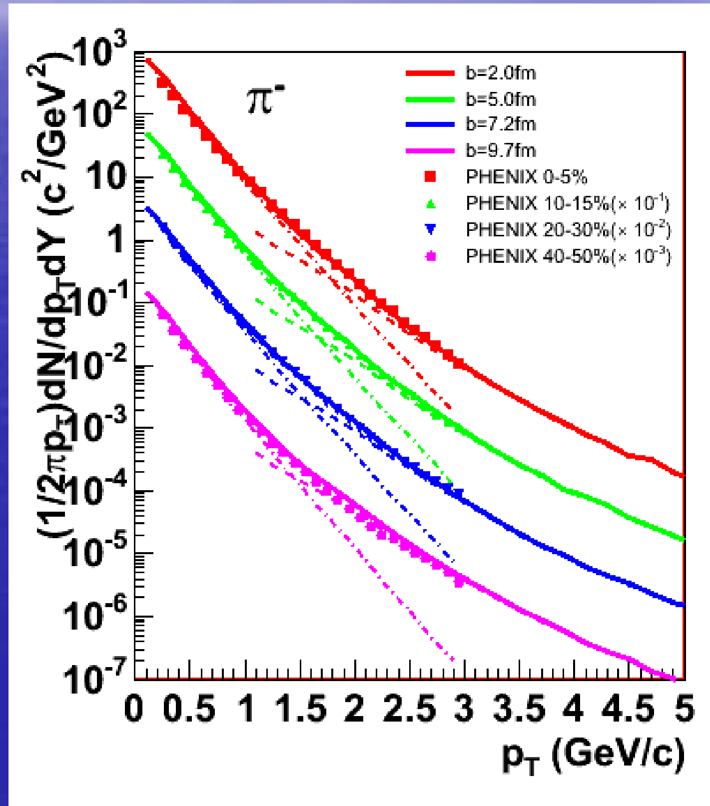
Initial condition of energy density from CGC
Au+Au 200AGeV
b=7.2fm, τ_0 =0.6fm



Results from CGC+hydro+jet



Au+Au sqrt(s_{NN}) = 200 GeV



CGC initial condition
works very well!
(Energy, rapidity, centrality
dependences)

For details, talk by Y.Nara

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4. Viscosity

Talks by E.Shuryak and D.Teaney

Change not only the equations of motion but the local thermal distribution function

A.Dumitru('02), D.Teaney('03)

- Blast wave model + dist. fn. with viscous correction

1st order correction to dist. fn.:

$$\delta f \propto \frac{\Gamma_s}{T^2} f_0(1+f_0)p^\mu p^\nu X_{\mu\nu}$$

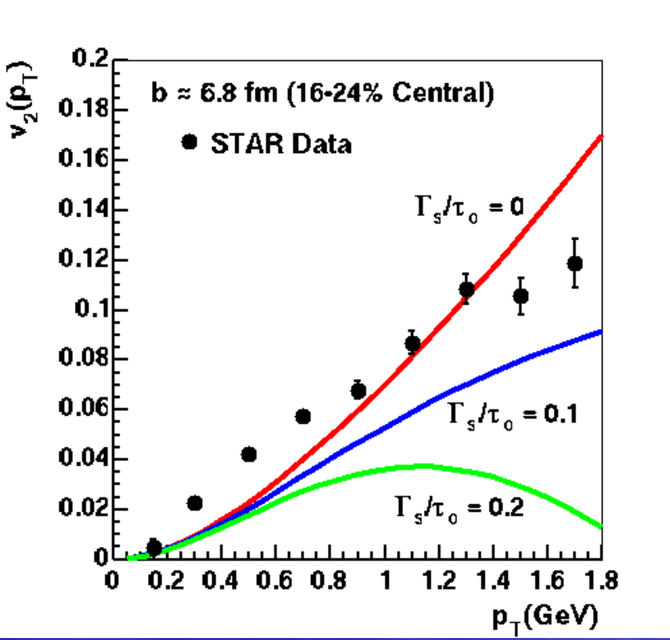
Γ_s :Sound attenuation length

$X_{\mu\nu}$:Tensor part of thermodynamic force

Reynolds number in Bjorken flow

$$R^{-1} \approx \Gamma_s/\tau$$

Nearly ideal hydro !?



D.Teaney('03)

Break Down of Naive Navier-Stokes Eq. and a Relaxation Method

• Non-relativistic case (Based on discussion by Cattaneo (1948))

Balance eq.: $\dot{T} = -\vec{\nabla} \cdot \vec{q}$

Constitutive eq.: $\tau \dot{\vec{q}} + \vec{q} = -\kappa \vec{\nabla} T$ $\quad$ $\tau \rightarrow 0$: Fourier's law

$$\tau \ddot{T} + \dot{T} = \kappa \triangle T, \quad c = \sqrt{\kappa / \tau}$$

τ : "relaxation time"

Parabolic equation (heat equation)

ACAUSAL!!

↓ Finite τ

Hyperbolic equation (telegraph equation)

Talk by D.Teaney

See also, A.Muronga ('02)

5. Summary

Hydrodynamics is one of the valuable tools at RHIC energies

- Open our mind !
  Hydrodynamics can be used even for "high p_T physics in HIC".
  - Jet tomography
  - EM probe
  - (J/Ψ suppression)
  - …
- Keep in mind !
  How robust is the current agreement of hydro?:
  - Chemical non-eq.?
  - Initial fluctuation?
  - Viscosity?
  - Thermalization?
  - EoS?
  - (Freeze-out?)