Dynamical Modeling of Relativistic Heavy Ion Collisions

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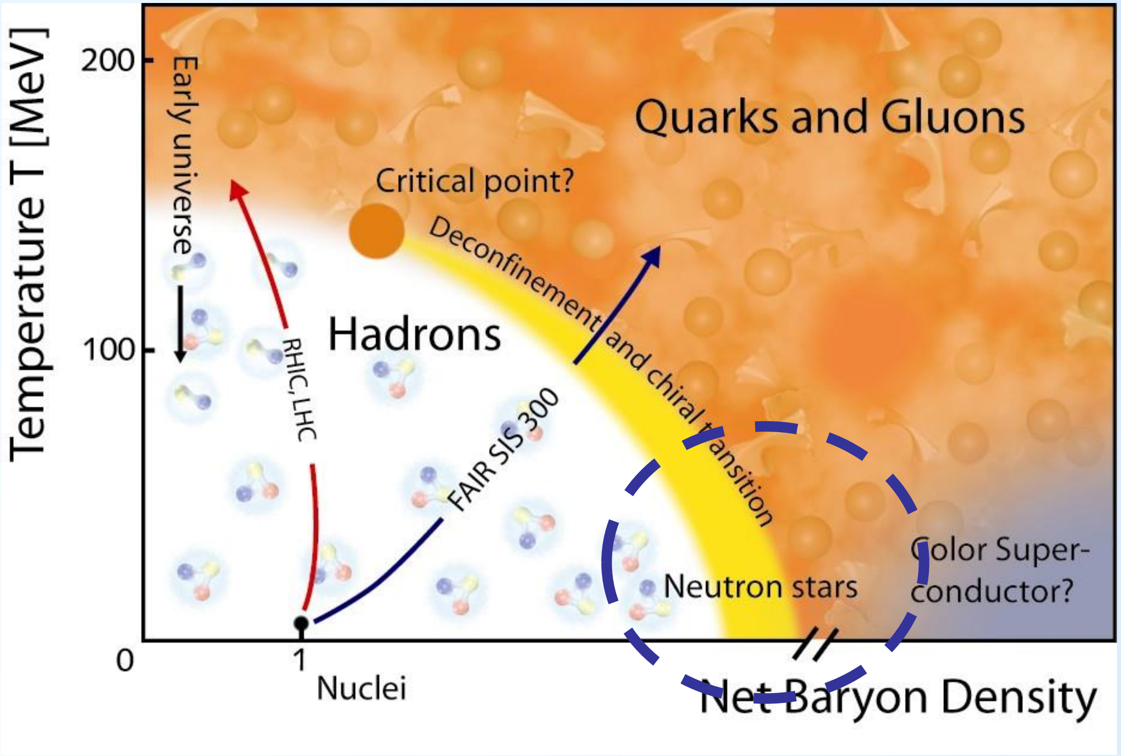
Oct.19-20, 2007

Outline

- Introduction
- Dynamical modeling of heavy ion collisions
- Bulk
- Hard/rare probes and interplay btw. soft and hard
- Summary and Outlook

Phase Diagram of QCD

Understanding of phase diagram and EOS is one of the main topics in modern nuclear physics.



Taken from http://theory.gsi.de/~friman/trento_06.html

Constraint of EOS from Observation of Compact Stars

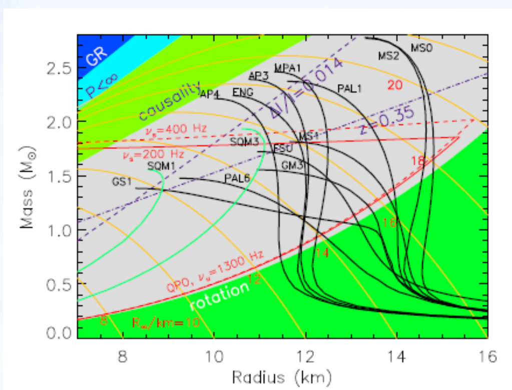
Model EOS $P(\rho)$: Pressure as a function of mass-energy density

Tolman-Oppenheimer-Volkov eq. (Hydrostatic equilibrium)

$$\frac{dP}{dr} = -\frac{G[m(r) + 4\pi r^3 P(\rho)/c^2][\rho + P(\rho)/c^2]}{r(r - 2Gm(r)/c^2)}$$

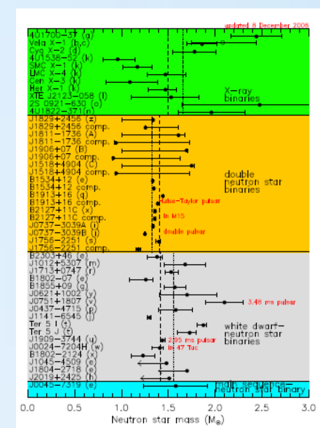
$$\frac{dm(r)}{dr} = 4\pi r^2 \rho$$

Mass-Radius relation



Taken from Lattimer, Prakash('06)

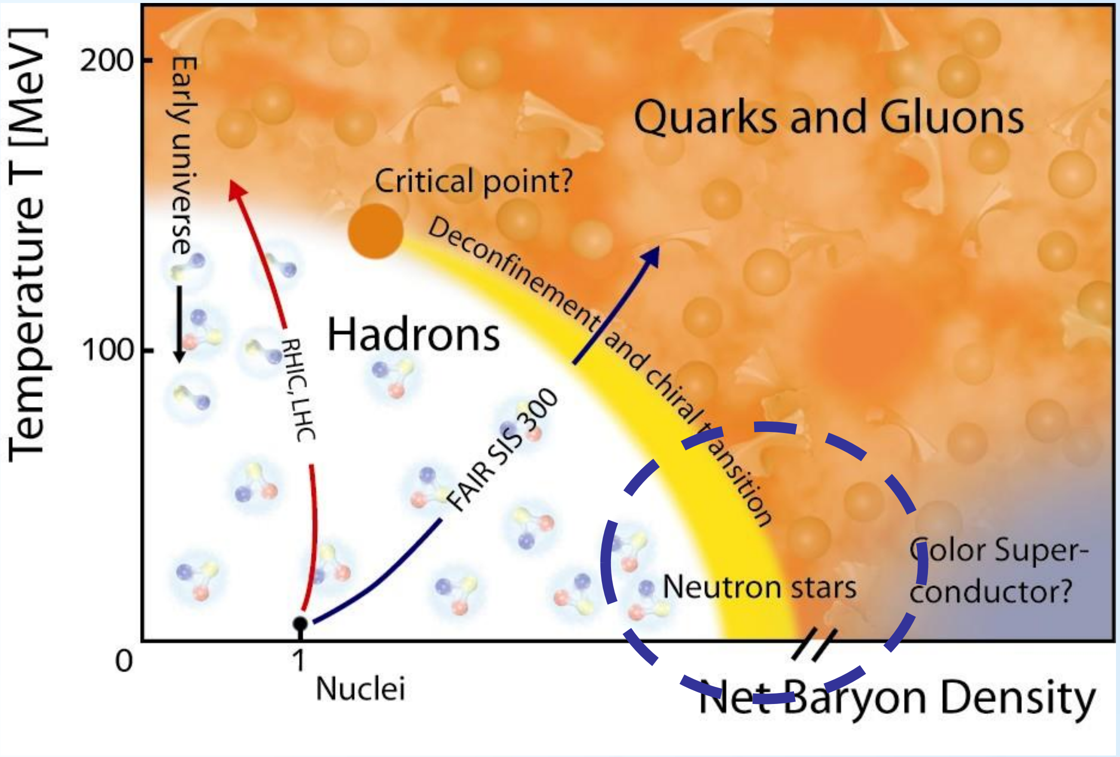
Observation of compact star mass



Taken from Lattimer, Prakash('06)

TOV eq. plays an important role in understanding of EOS

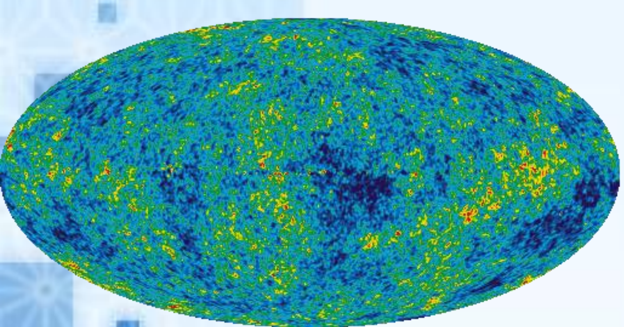
Phase Diagram of QCD



Taken from http://theory.gsi.de/~friman/trento_06.html

Constraint of Cosmological Parameters from CMB

Observation
COBE, WMAP,…



Taken from
http://lambda.gsfc.nasa.gov/

CMB tools:
CMBFAST, CAMB,
…

"Best" cosmological parameters
C.L.Bennett et al.,Ap.J.Suppl('03)

Table 3. "Best" Cosmological Parameters

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	-0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

[a]from *COBE* (Mather et al. 1999)

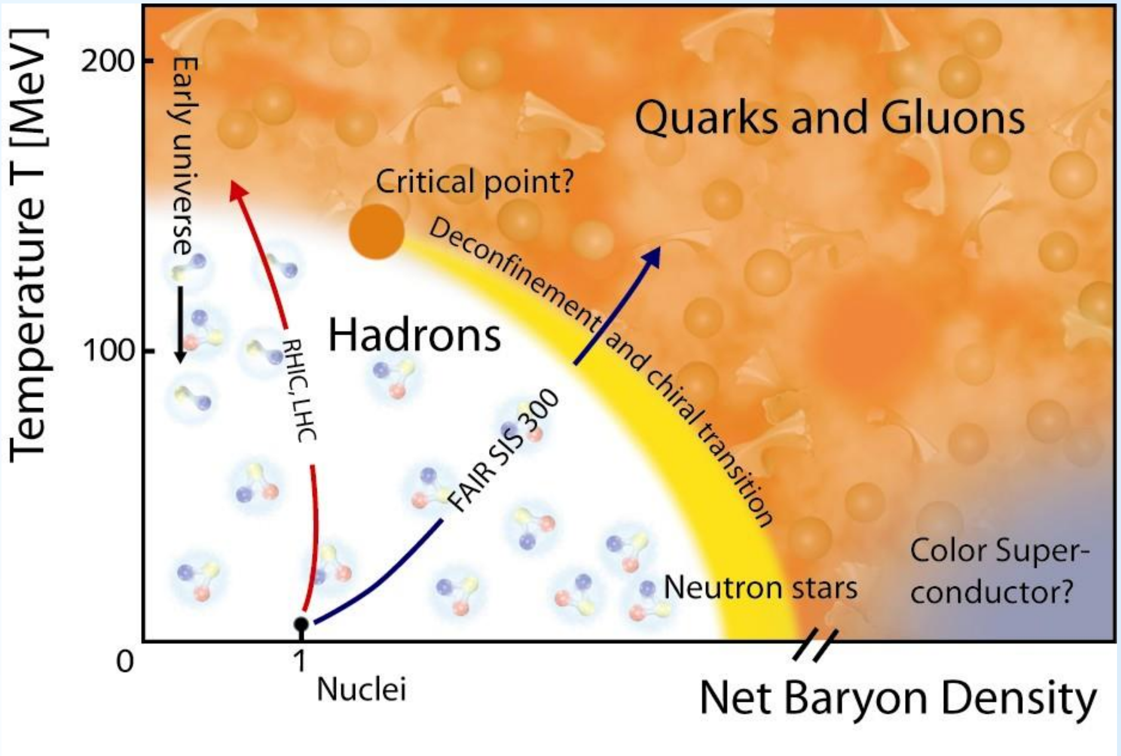
[b]derived from *COBE* (Mather et al. 1999)

[c]$l_{eff} \approx 700$

[d]$\ell_A \equiv \pi \theta_A^{-1}$ $\quad \theta_A \equiv r_s\, d_a^{-1}$

Analysis codes play a major role in precision physics.

Phase Diagram of QCD



Taken from http://theory.gsi.de/~friman/trento_06.html

"Mind The Gap"

- The first principle (QuantumChromo Dynamics)

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

ex.)QCDOC

- Inputs to phenomenology (lattice QCD)

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

Complexity

Non-linear interactions of gluons

Strong coupling

Dynamical many body system

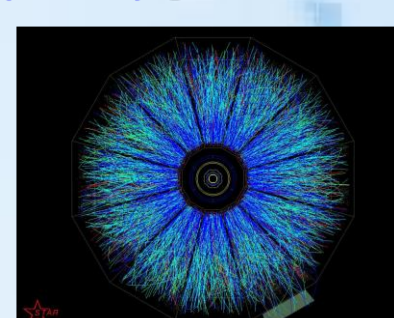
Color confinement

- Phenomenology (hydrodynamics)

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

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

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



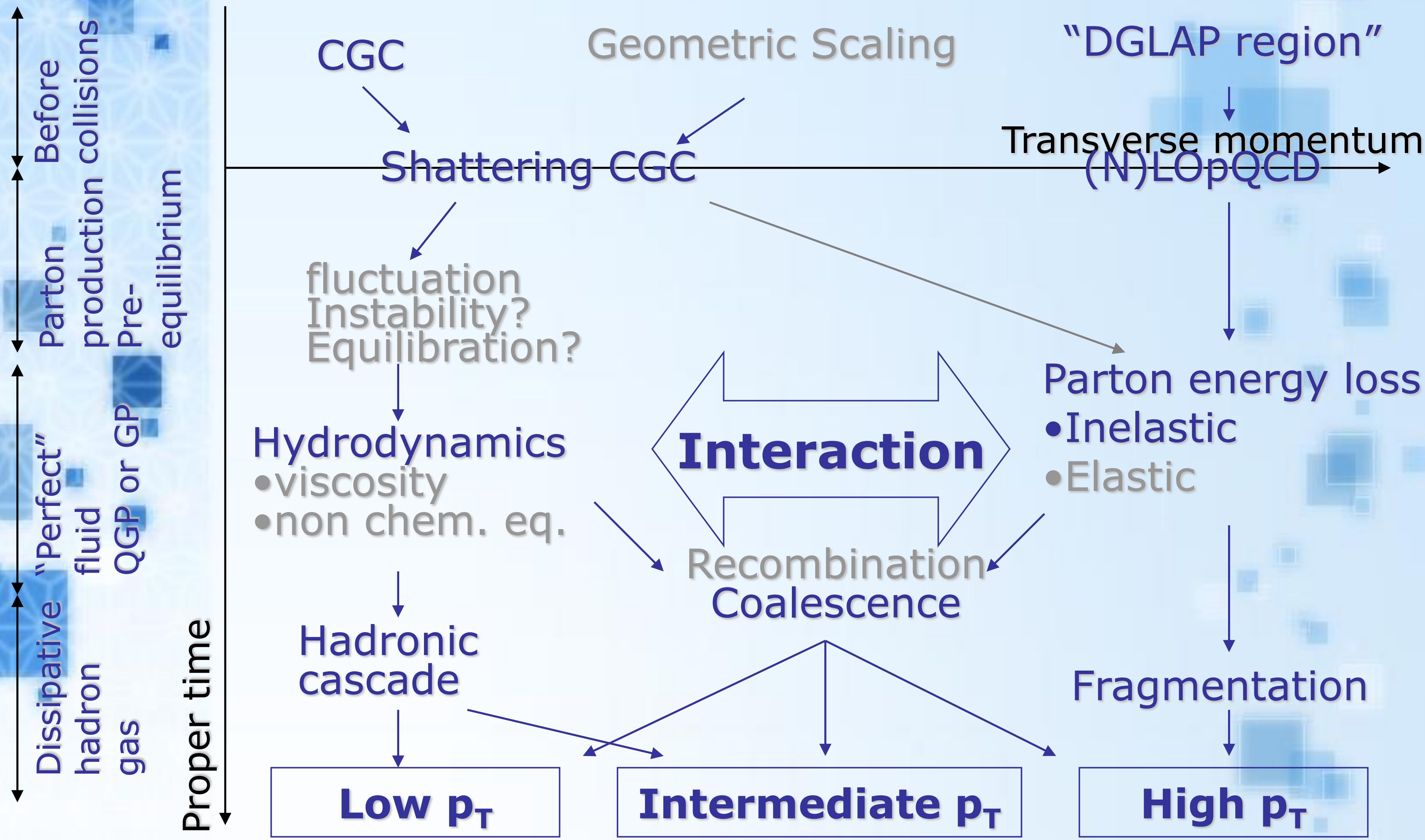
Lessons from Other Fields

- Necessity of collaborative activity in more extended community
- Necessity of analysis tool(s) in R.H.I.C. physics
- Toward establishment of the "observational QGP physics"

Dynamical Modeling Based on 3D Ideal Hydrodynamics

T.Hirano and Y.Nara('02-)

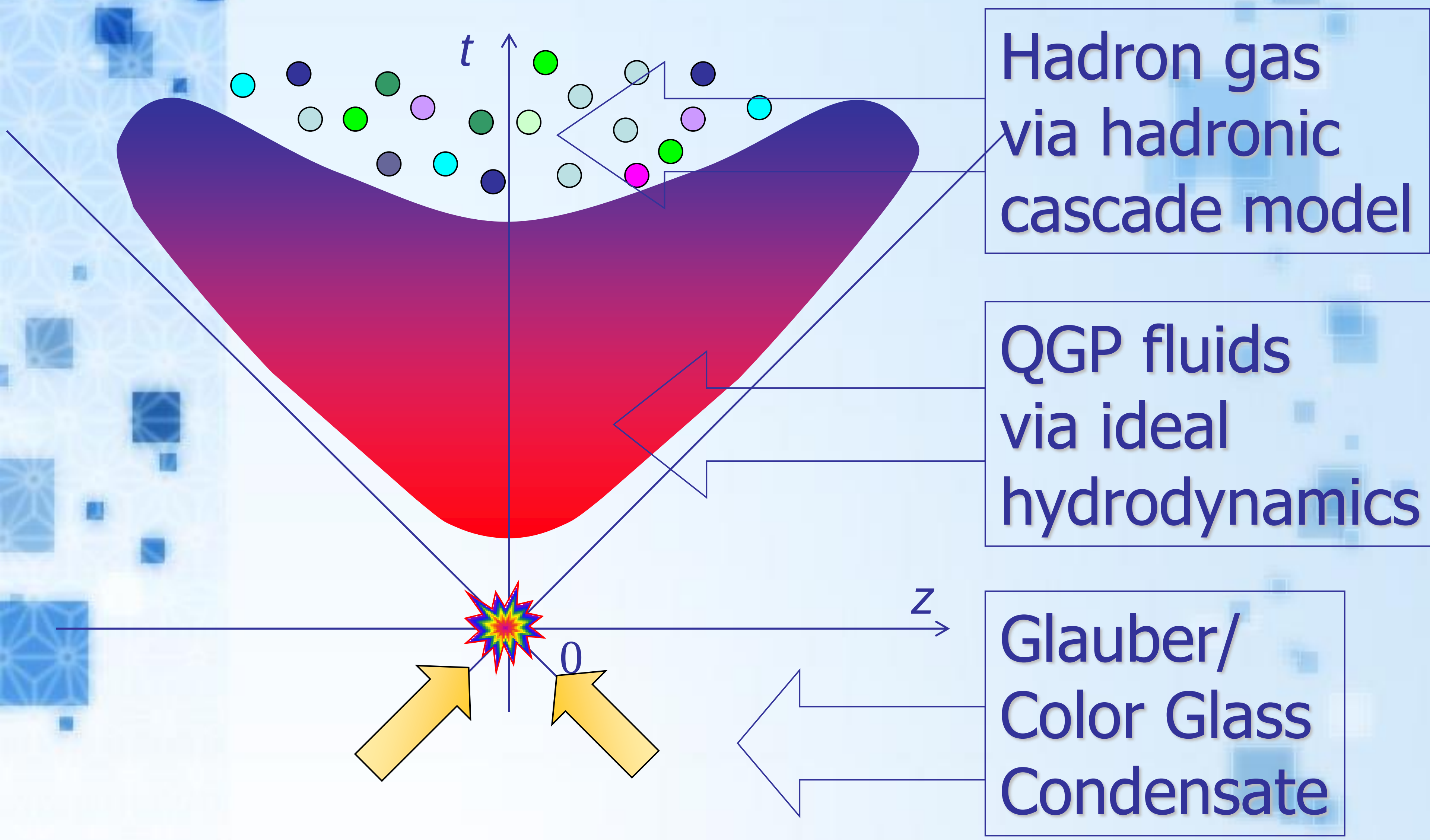
Current Status of Dynamical Modeling in H.I.C.



BULK

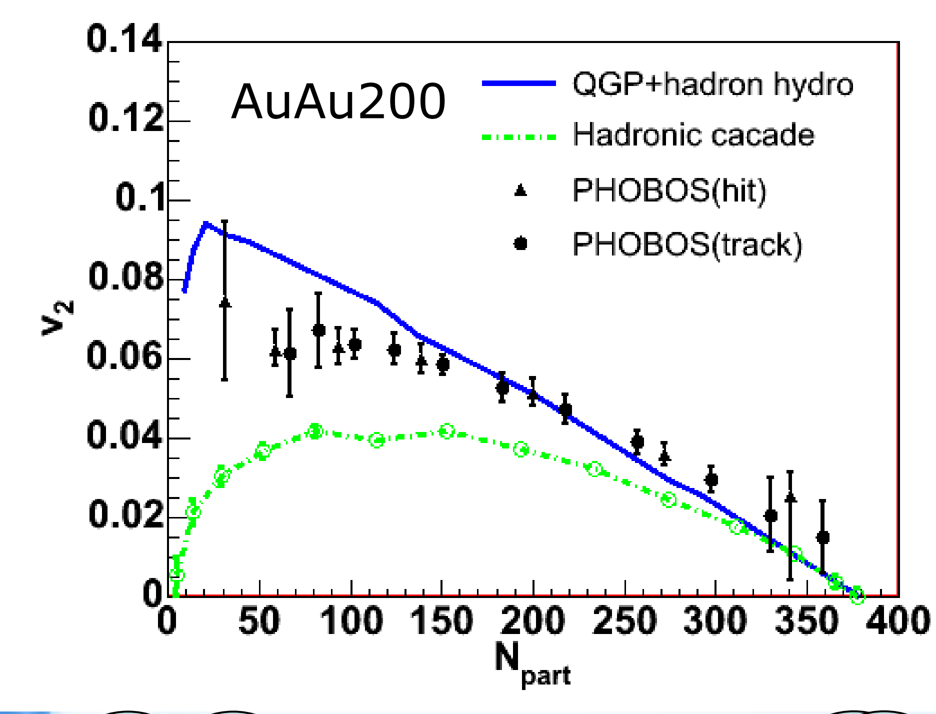
- 3D Hydro
- 3D Hydro+Cascade
- CGC initial conditions

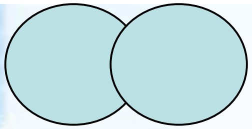
Full 3D Hydro+Cascade Model

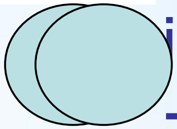


TH et al. ('06).

Centrality Dependence of v_2







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

<u>Discovery of "large" v_2 at RHIC</u>

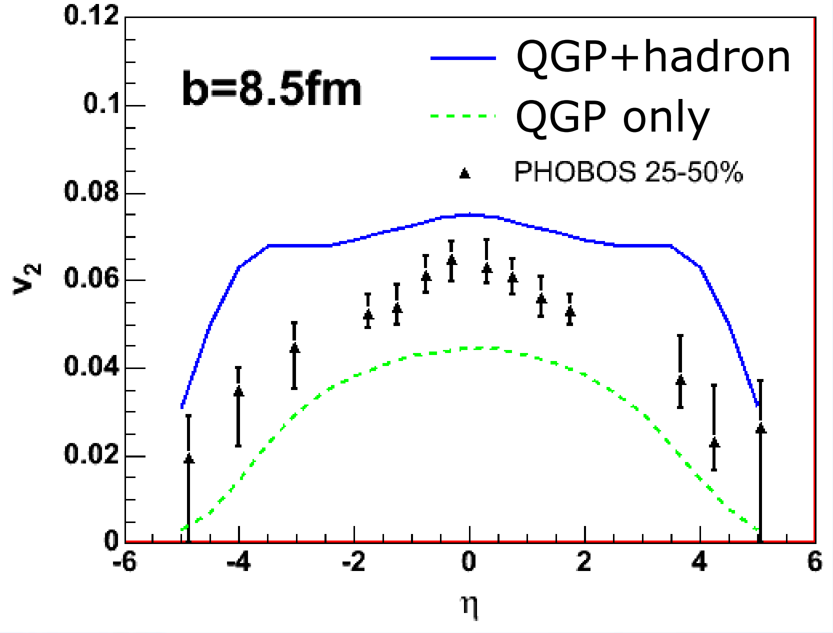
- v_2 data are comparable with hydro results for the first time.
- Hadronic cascade models cannot reproduce data.

This is the first time for ideal hydro at work in H.I.C.
→ Strong motivation to develop hydro-based tools.

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

Pseudorapidity Dependence of v_2

AuAu200

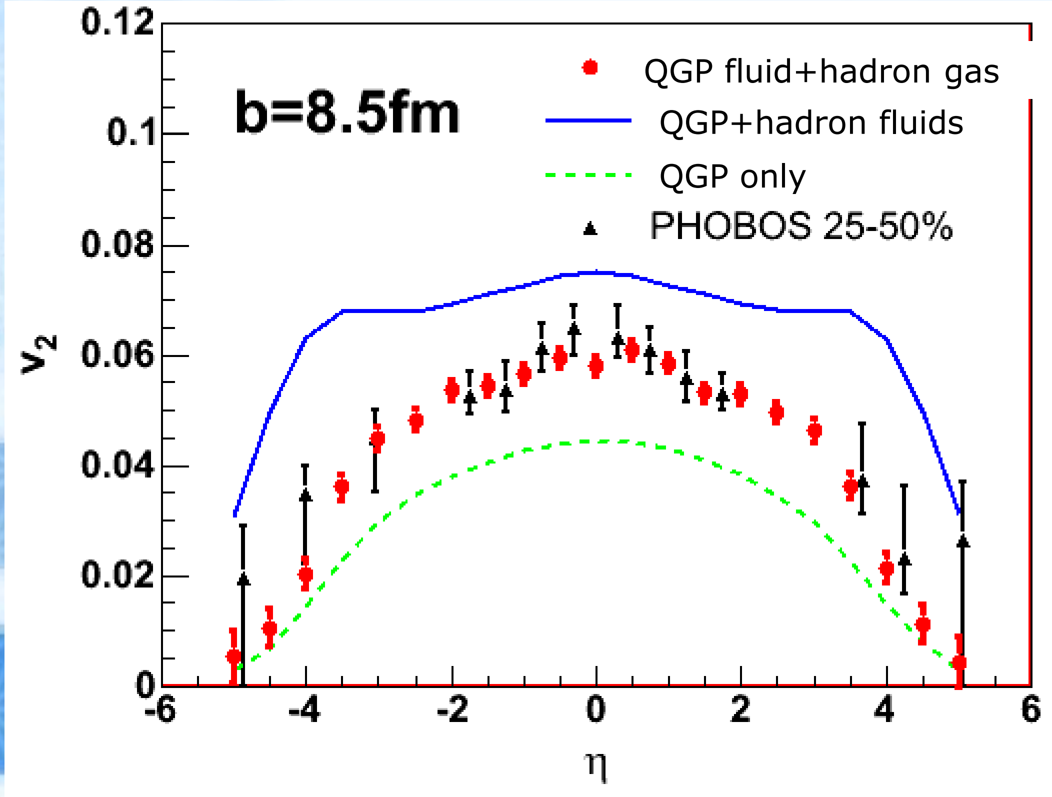


- v_2 data are comparable with 3D hydro results again around h=0
- Not a QGP gas → sQGP
- Nevertheless, large discrepancy in forward/backward rapidity

→ See next slides

Importance of Hadronic "Corona"

AuAu200



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

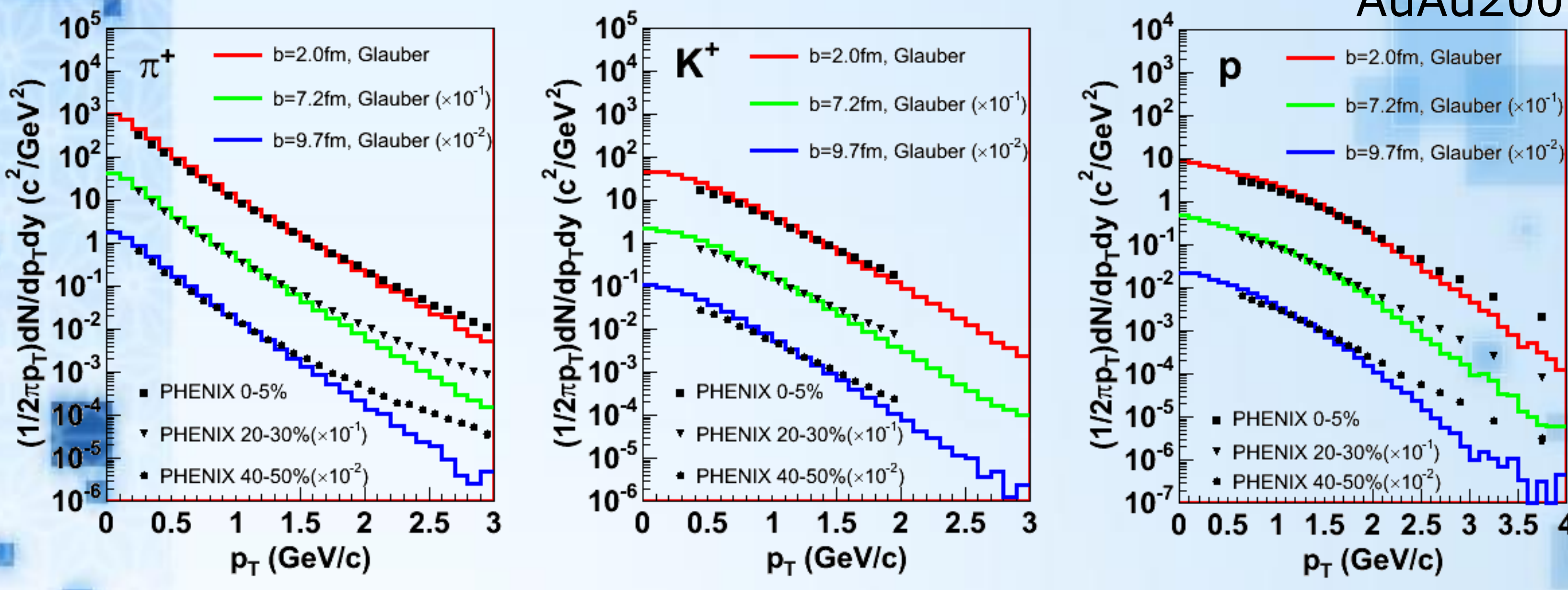
- Boltzmann Eq. for hadrons instead of hydrodynamics
- Including viscosity through finite mean free path

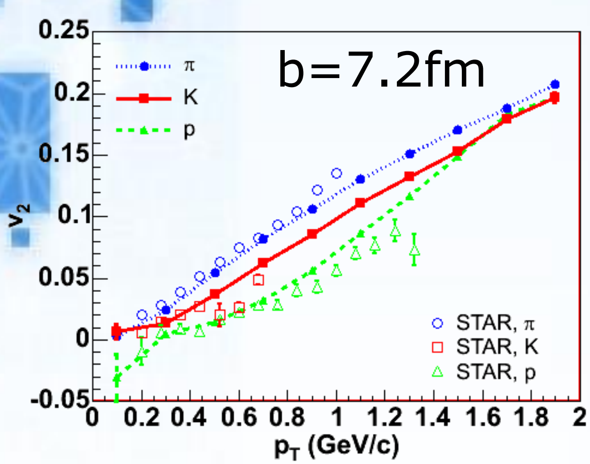
Perfect fluid QGP core
+
Dissipative hadronic corona

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

Highlights from a QGP Hydro + Hadronic Cascade Model

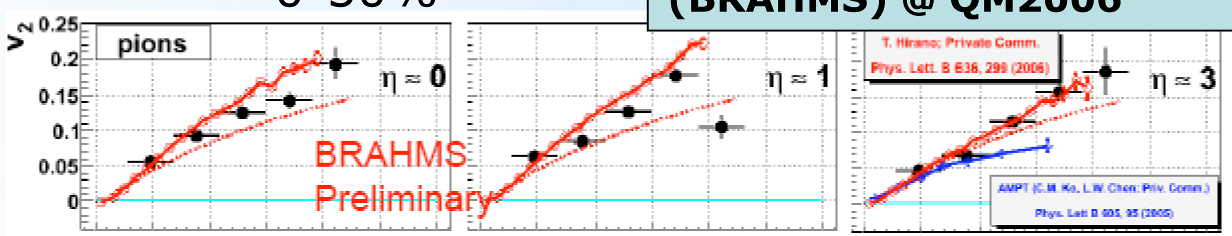
AuAu200





0-50%

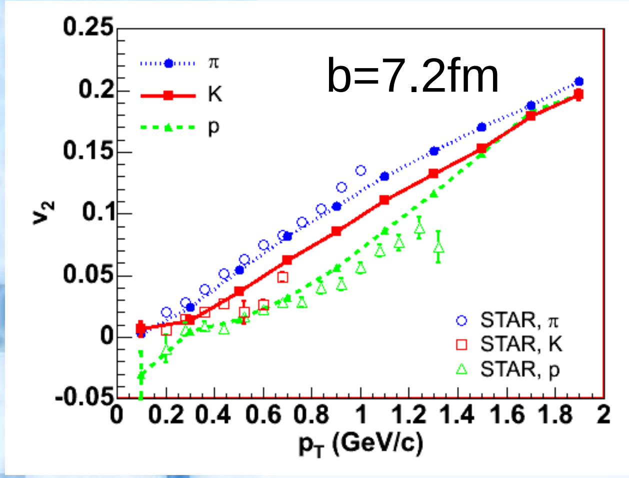
Adapted from S.J.Sanders (BRAHMS) @ QM2006

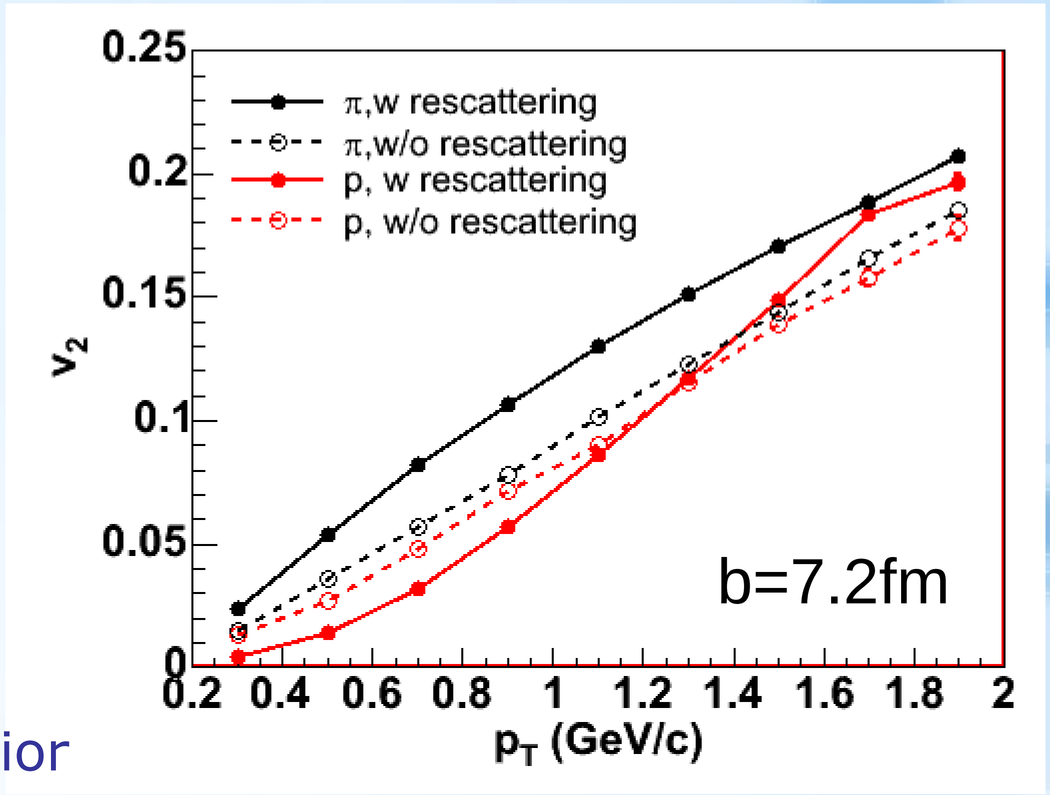


Works quite well!

TH et al. (in preparation).

Origin of Mass Ordering





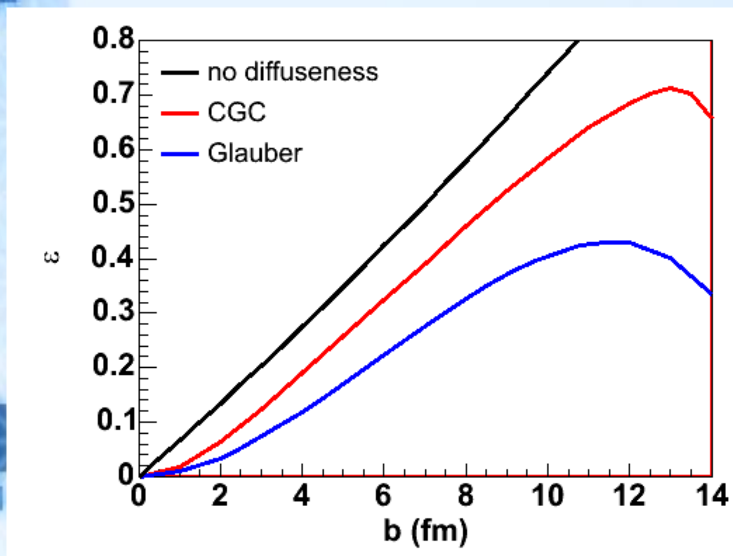
Mass ordering behavior comes from hadronic rescattering.

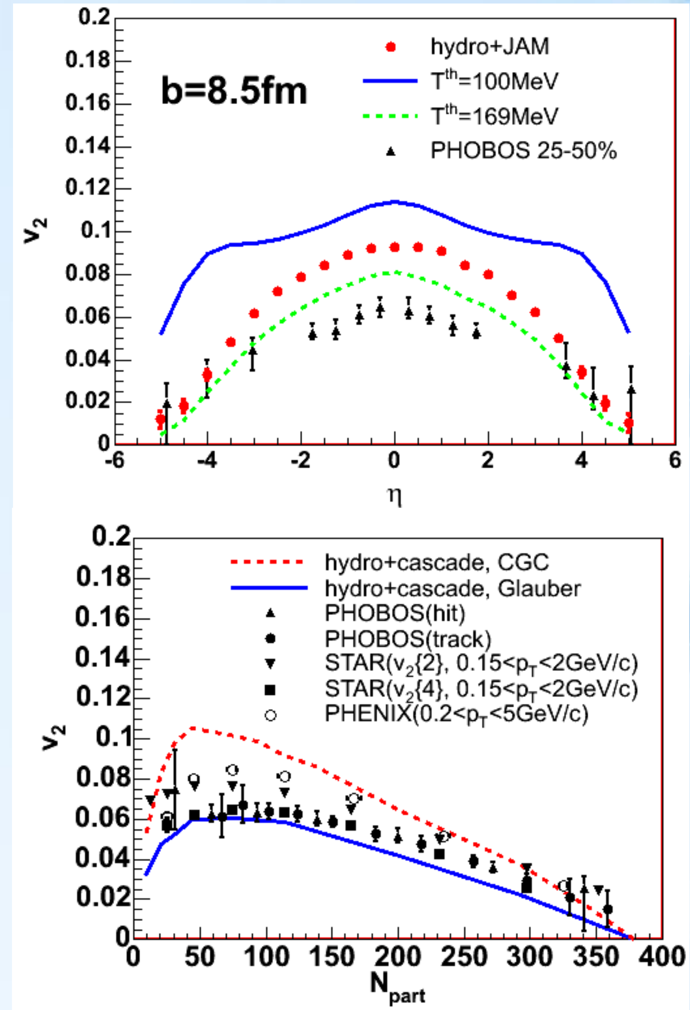
→ Not a direct signal of “perfect fluid QGP”

→ Interplay btw. QGP fluid and hadron gas

Sensitivity to Initial Conditions

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



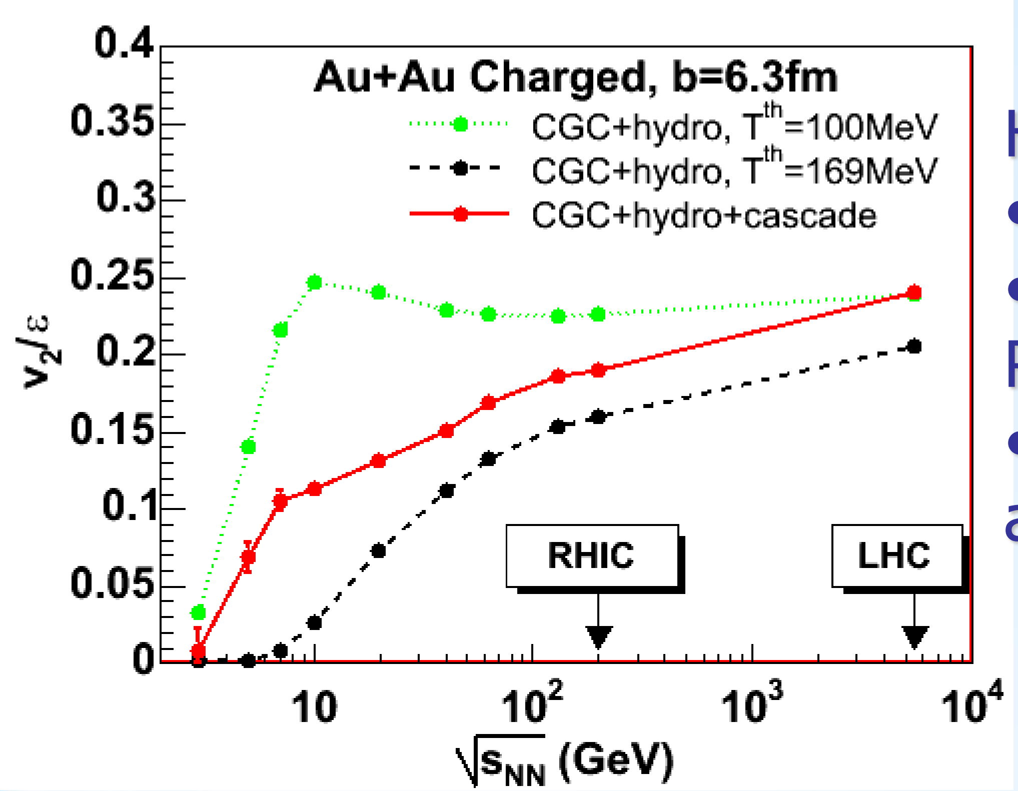


Novel initial conditions from "Color Glass Condensate" lead to large eccentricity.

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

Need viscosity/soft EOS in QGP!

Excitation Function of v_2



Hadronic Dissipation

- is huge at SPS.
- still affects v_2 at RHIC.
- is almost negligible at LHC.

HARD/RARE PROBES

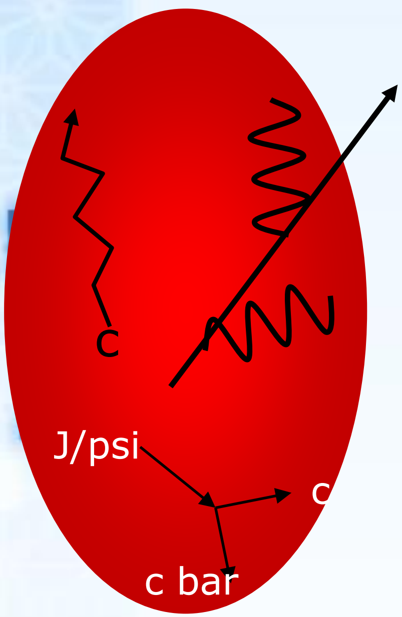
- Hydro+Jet model
- Hydro+J/Y model

Interplay btw. soft and hard

- Jet-fluid string formation

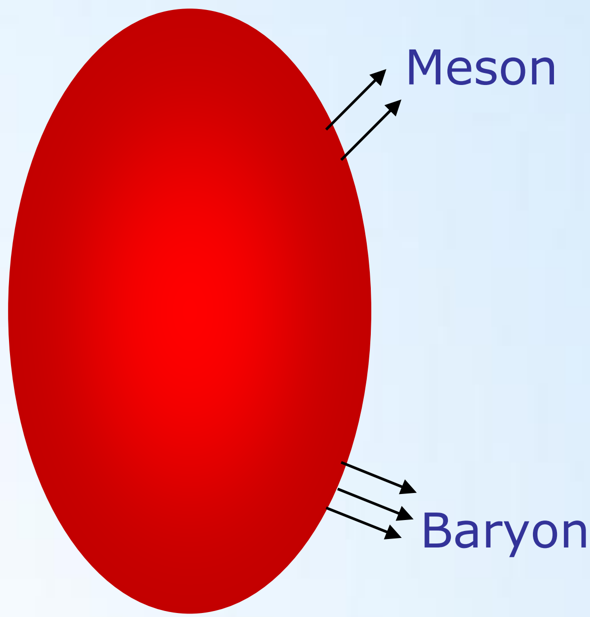
Utilization of Hydro Results

Jet quenching
J/psi suppression
charm diffusion



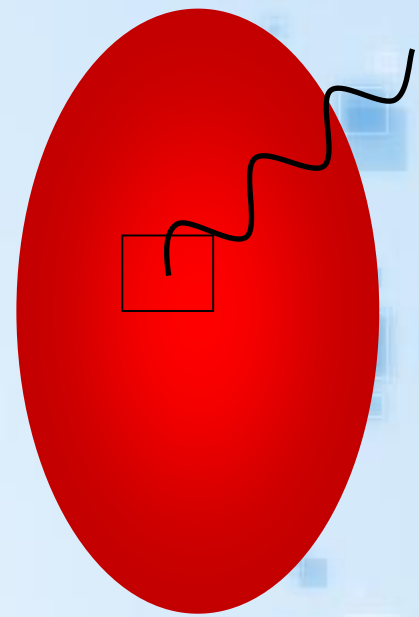
Information
along a path

Recombination
Coalescence



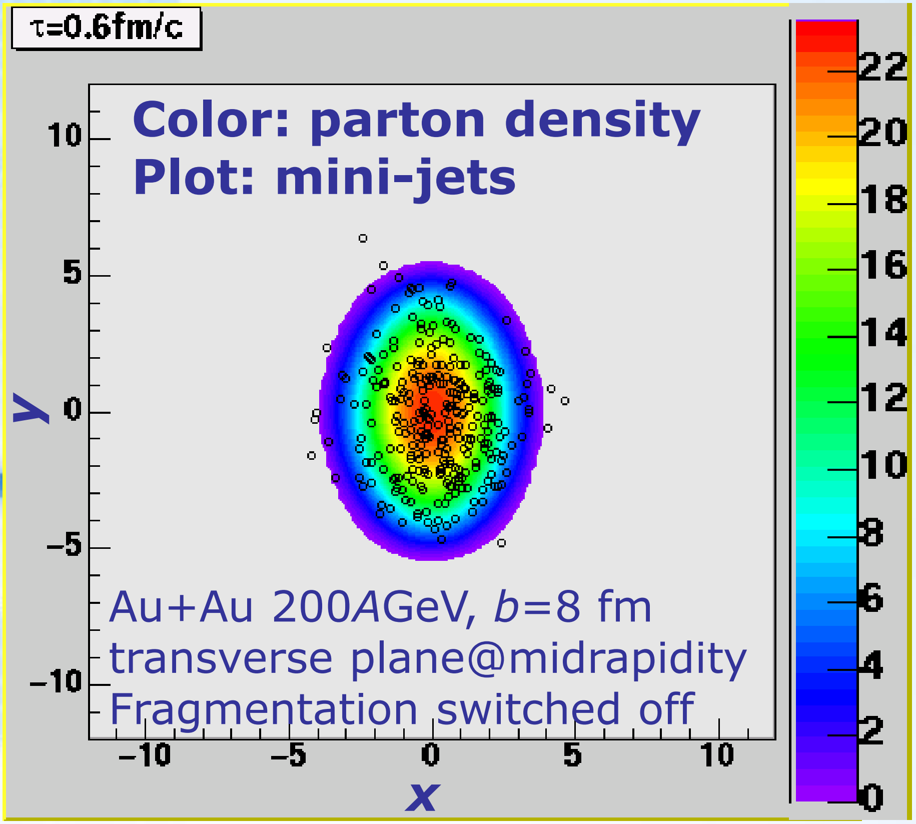
Information
on surface

Thermal
radiation
(photon/dilepton)



Information
inside medium

Jet Propagation through a QGP Fluid



hydro+jet model

T.Hirano and Y.Nara ('02-)

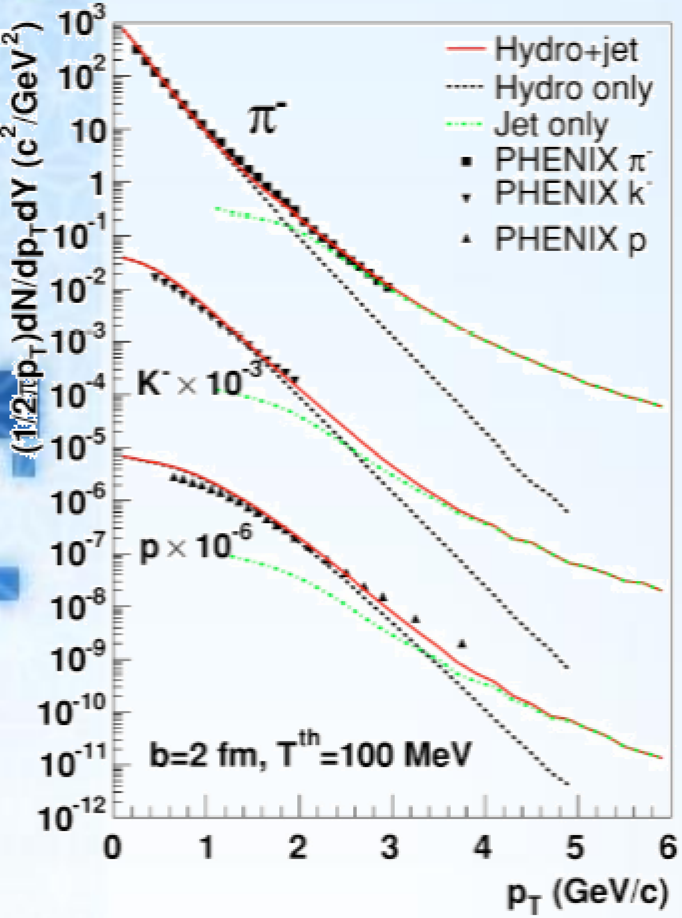
Full 3D ideal hydrodynamics

+

PYTHIA
Parton distribution fn.
pQCD 2→2 processes
Fragmentation

Gyulassy-Levai-Vitev formula
Inelastic energy loss

p_T Distribution from Hydro+Jet Model

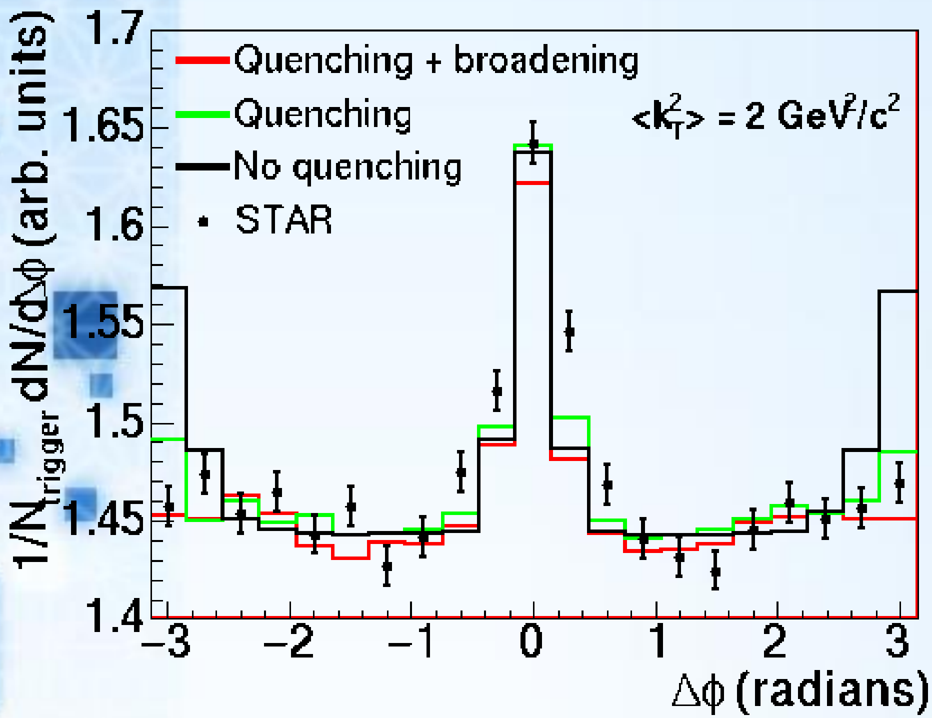


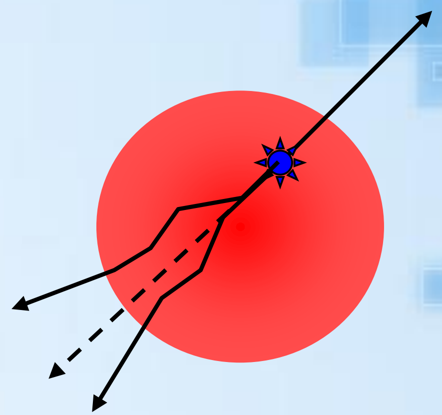
Soft + Quenched Hard picture works reasonably well
→Re/Co components may be needed for a better description

Note: Hadronic cascade is switched off in the bulk

T.Hirano and Y.Nara, Phys.Rev.C**69**,034908(2004).

Back-To-Back Correlation





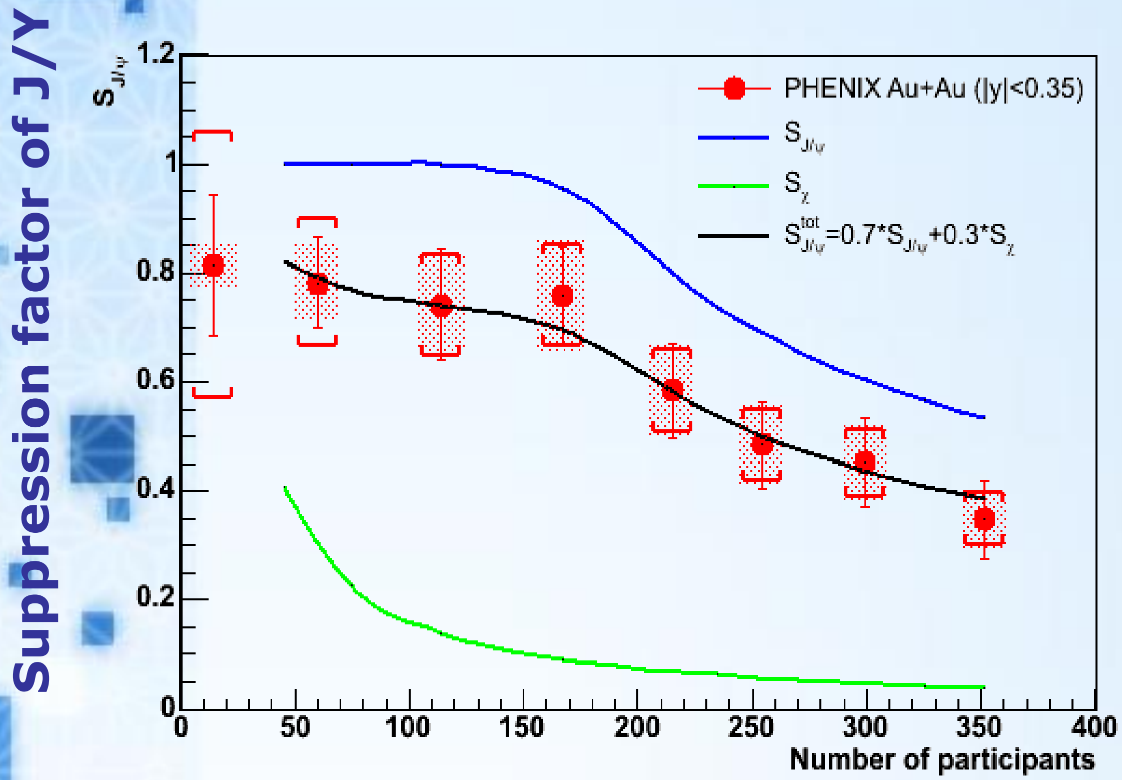
Not only energy loss but also deflection are found to be important.

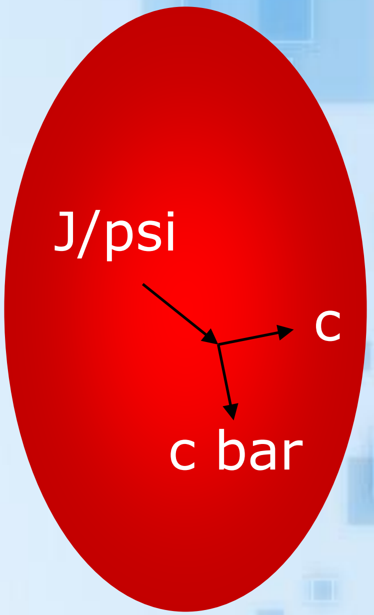
T.Hirano and Y.Nara, Phys.Rev.Lett.**91**,082301(2003).

Gunji, Hamagaki, Hatsuda, Hirano, PRC (in press)

Onset of J/Ψ Melting in a QGP Fluid

Hydro+J/Y model

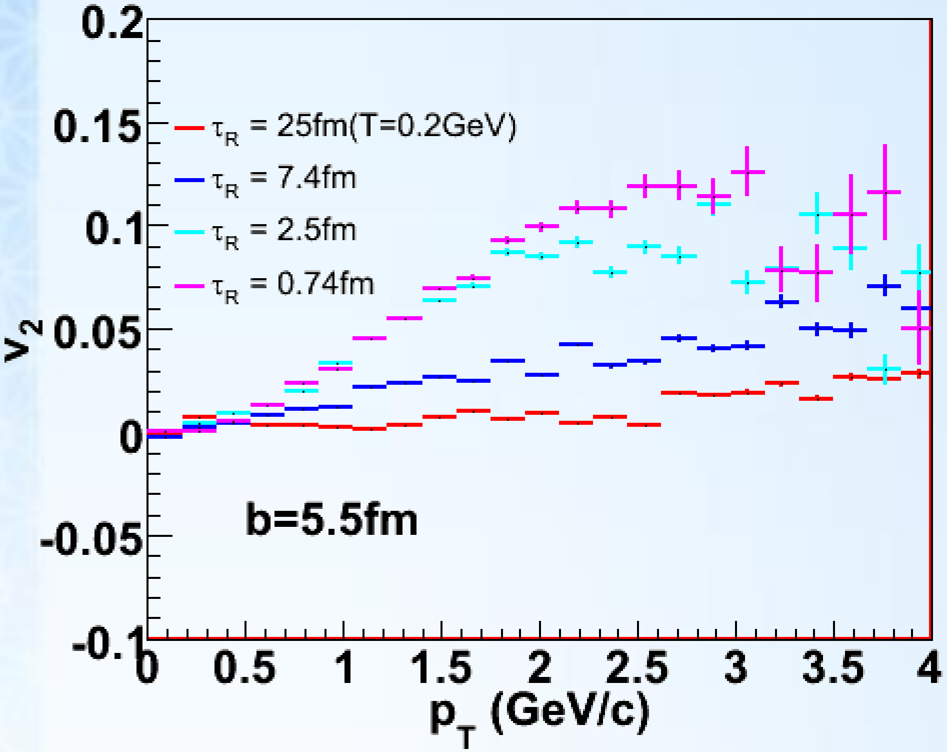


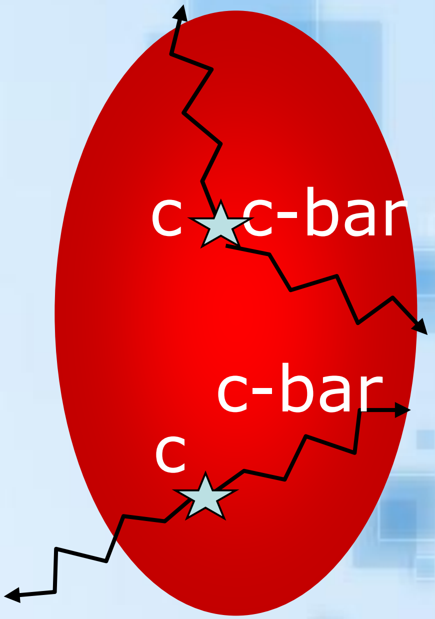


J/Y is assumed to melt away above $T_{J/y} \sim 2T_c$

Local temperature from full 3D hydro simulations

Heavy Quark Diffusion in a QGP Fluid



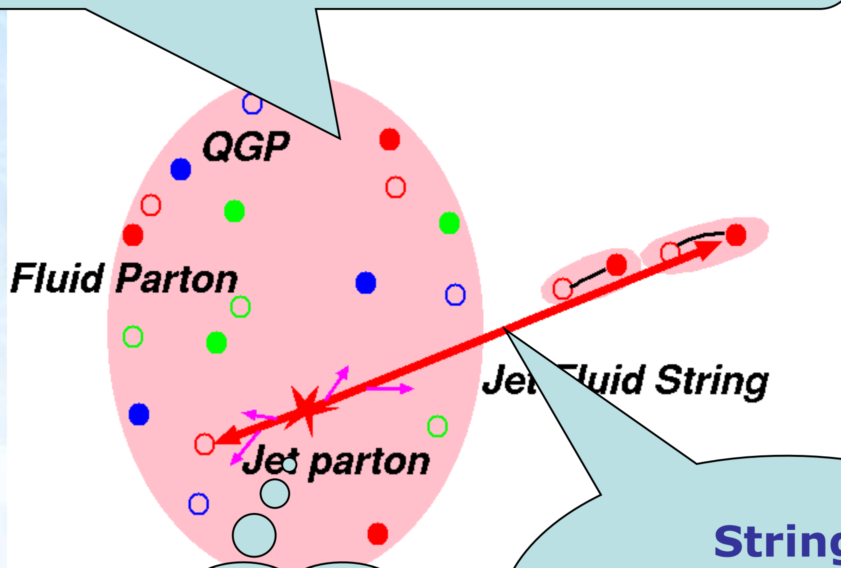


v_2 is sensitive to relaxation time for heavy quarks in QGP.
Toward comprehensive understanding of transport properties of QGP

Talk by Akamatsu at KPS meeting yesterday
Akamatsu, Hatsuda, Hirano (work in progress)

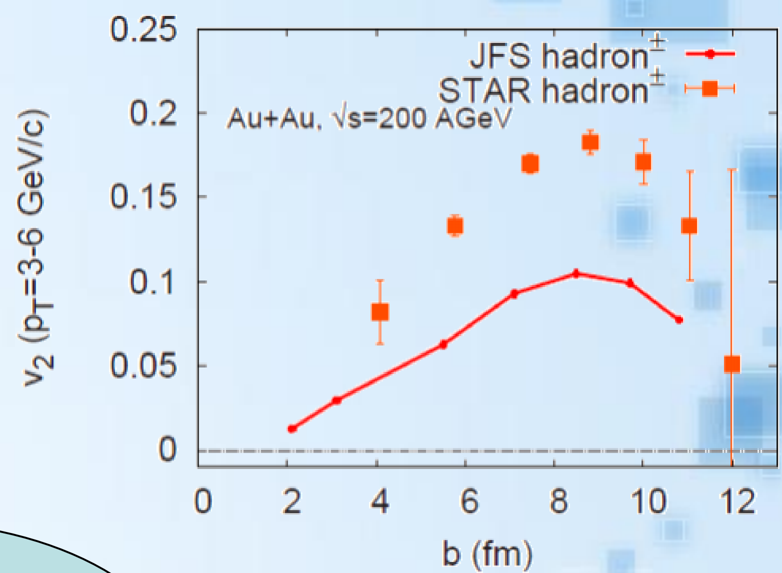
Hadronization through Jet-Fluid String Formation

Space-time evolution of the QGP fluid → *Open data table*



Energy loss
→ GLV 1st order

String Fragmentation
→ PYTHIA
(Lund)



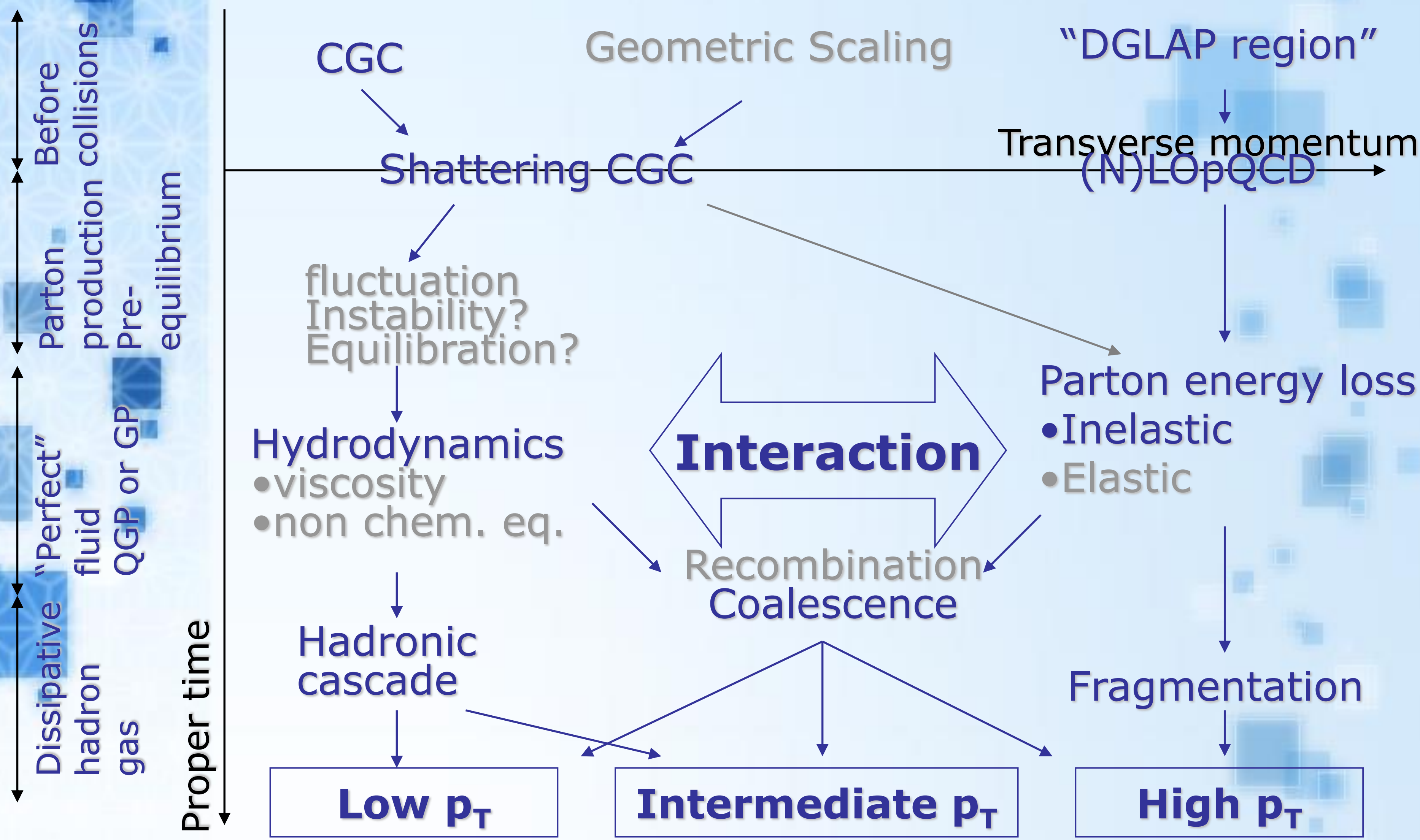
Hirano, Isse, Nara, Ohnishi, Yoshino, Mizukawa, nucl-th/0702068; (work in progress)

Summary & Outlook

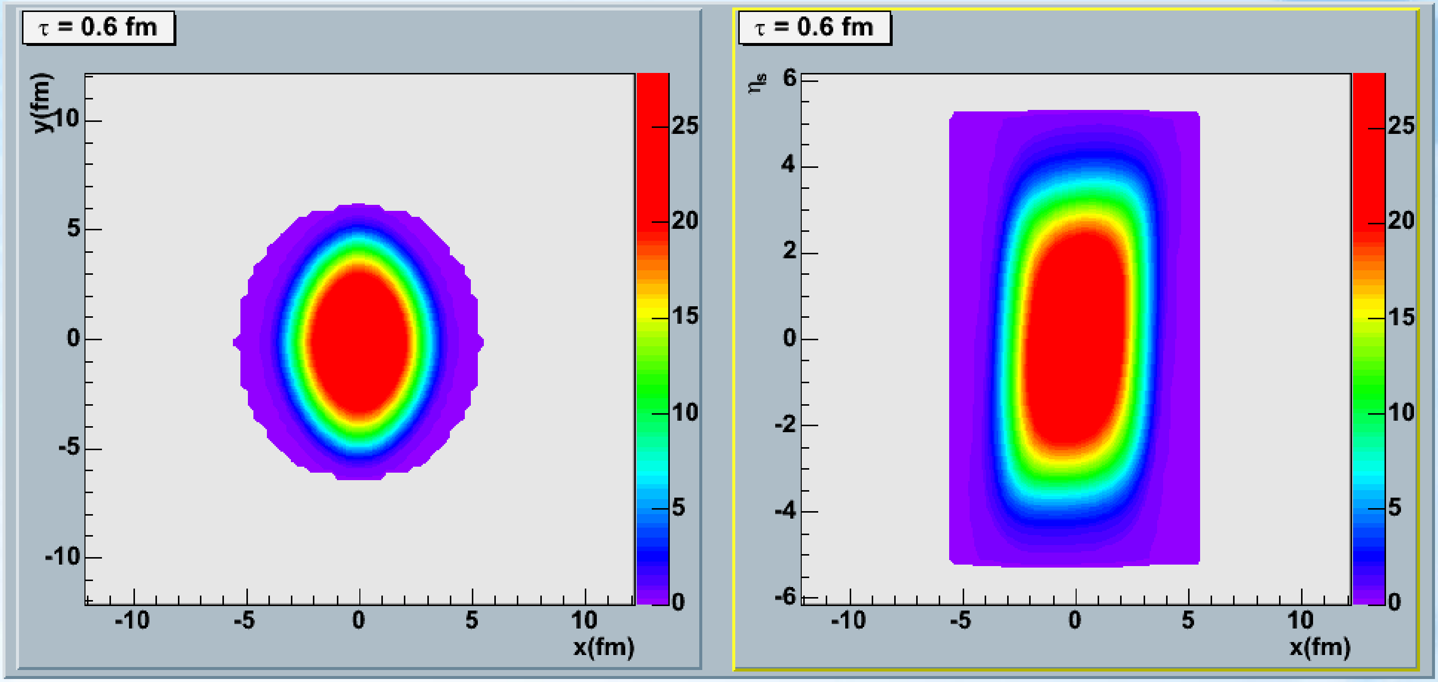
- Development of an analysis code in H.I.C.
  - QGP fluid + hadronic gas picture works well
  - Sensitivity to initial conditions in hydro
  - EOS dependence (not discussed in this talk)
- Application of hydro results
  - Single- and di-hadron distributions at high p_T
  - J/Ψ suppression
  - Jet-Fluid String formation
  - (EM probes)
- Toward an open and standard tool in H.I.C. (like PYTHIA, CMBFAST, …)

T.Hirano and Y.Nara('02-)

Current Status of Dynamical Modeling in H.I.C.



Thanks!


τ = 0.6 fm
y(fm)
10
5
0
-5
-10
-10
-5
0
5
10
x(fm)
25
20
15
10
5
0
τ = 0.6 fm
η_s
6
4
2
0
-2
-4
-6
-10
-5
0
5
10
x(fm)
25
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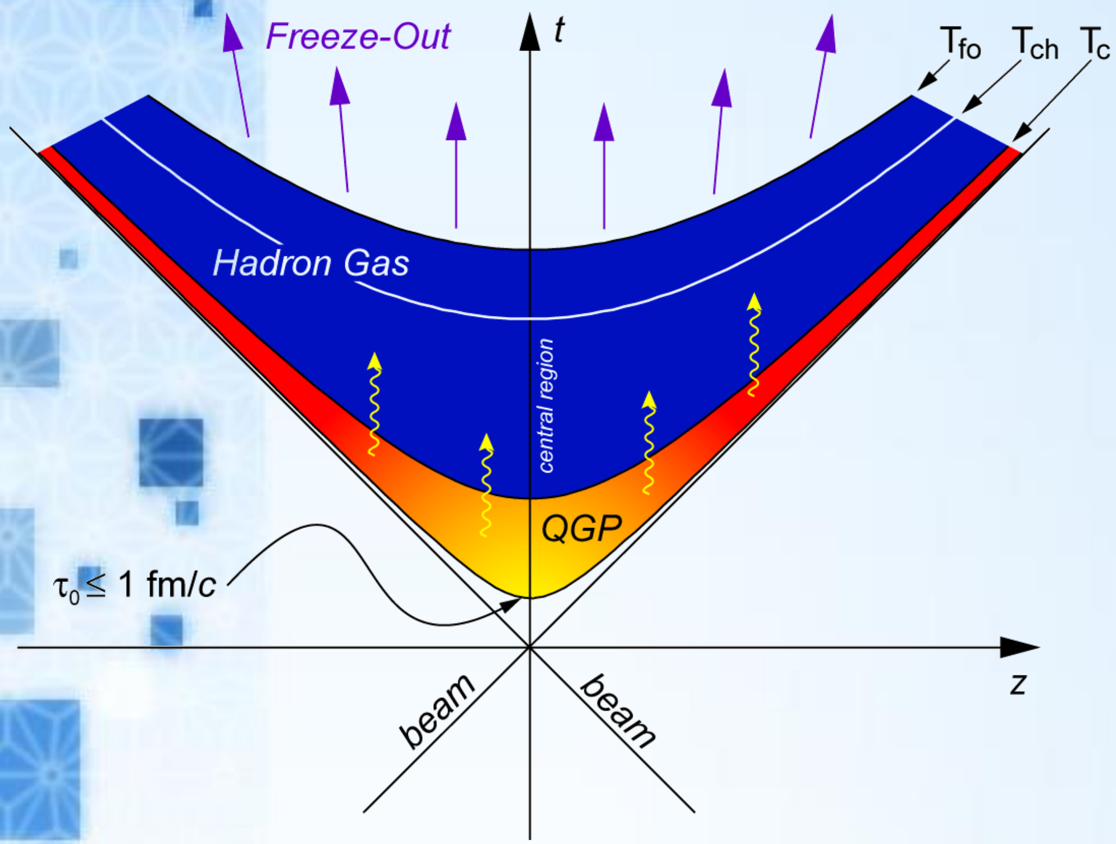
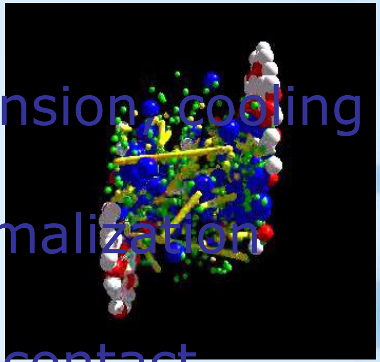
15
10
5
0

Dynamics of Heavy Ion Collisions



Freezeout

“Re-confinement”



Expansion, cooling

Thermalization

First contact
(two bunches of gluons)

Time scale
10fm/c~10^{-23}sec

Temperature scale
100MeV~10^{12}K

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

Hadron Gas Instead of Hadron Fluid

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:

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

$$\eta/s$$

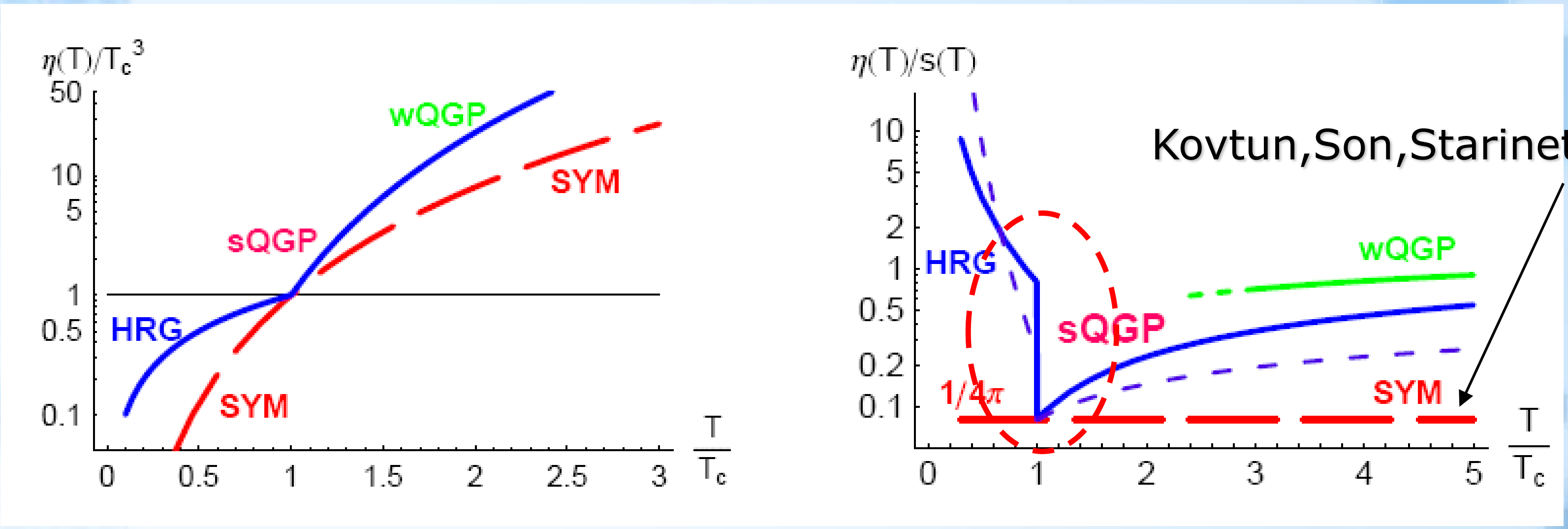
big in Hadron

small in QGP

TH and Gyulassy ('06)

A Probable Scenario

h : shear viscosity, *s* : entropy density



- Absolute value of viscosity

$\eta(\text{sQGP}) > \eta(\text{hadron})$!

- Its ratio to entropy density

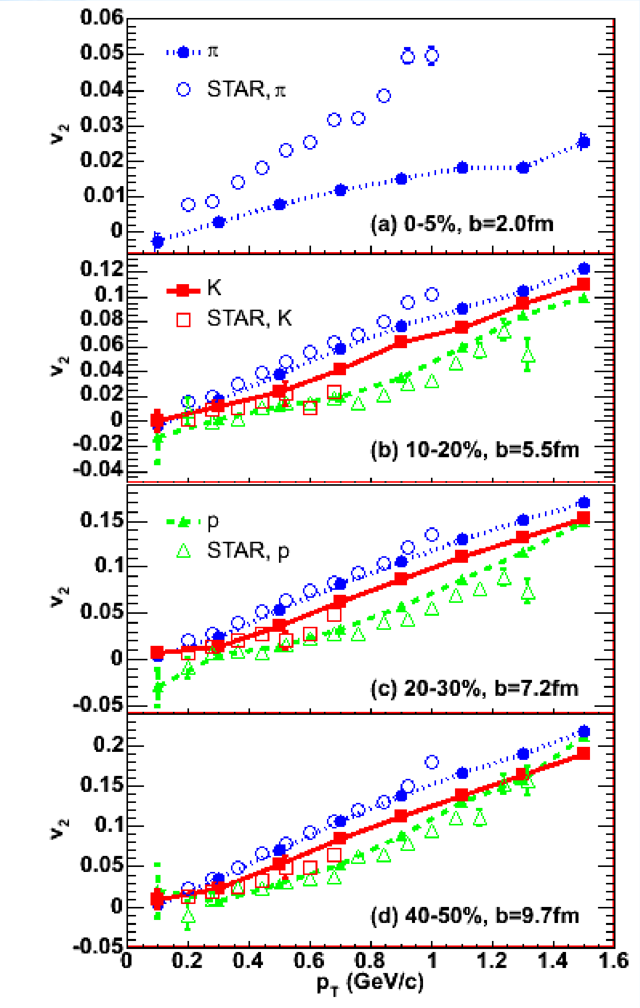
$\eta/s(\text{sQGP}) \ll \eta/s(\text{hadron})$

QGP fluid at work!

→ Rapid increase of entropy density?!

→ Deconfinement Signal?!

$v_2(p_T)$ for pi, K, and p



← Due to fluctuation of geometry

OK!

TH et al. (in preparation).