

# Quarkyonic Matter and Constituent Quark Number Scaling

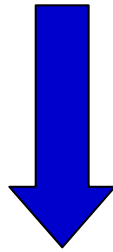
Flow and dissipation in ultrarelativistic Heavy Ion Collisions  
ECT\*/HICforFAIR/CATHIE/Nikhef workshop at ECT\* Trento  
Monday September 14 - Friday September 18, 2009

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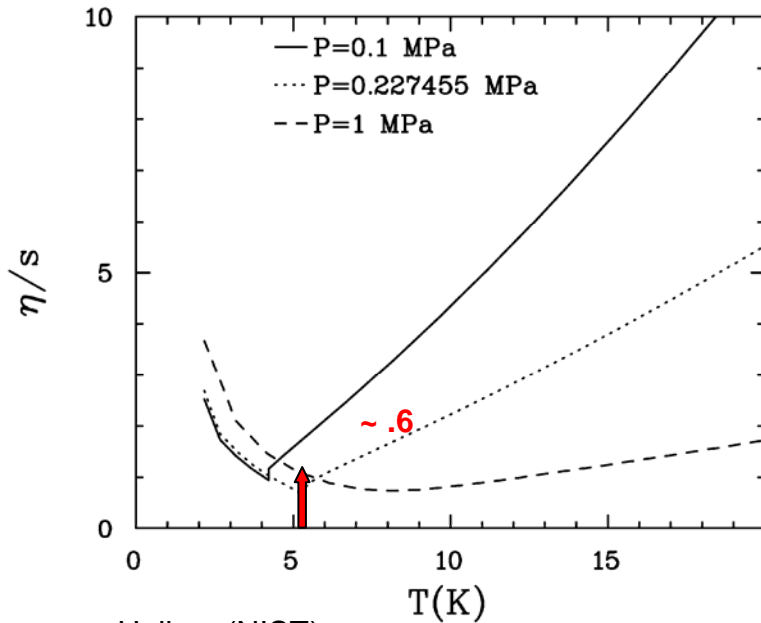


**E o S (Quarkyonic M.)**

**Transport properties**



**Fluid Dynamics**



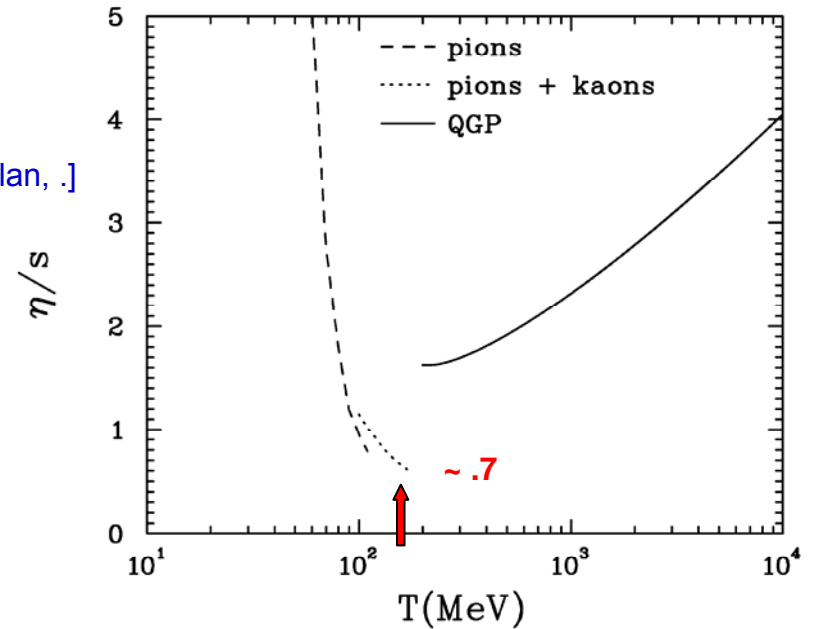
Helium (NIST)

**This phenomenon can help us to detect experimentally the critical point!**

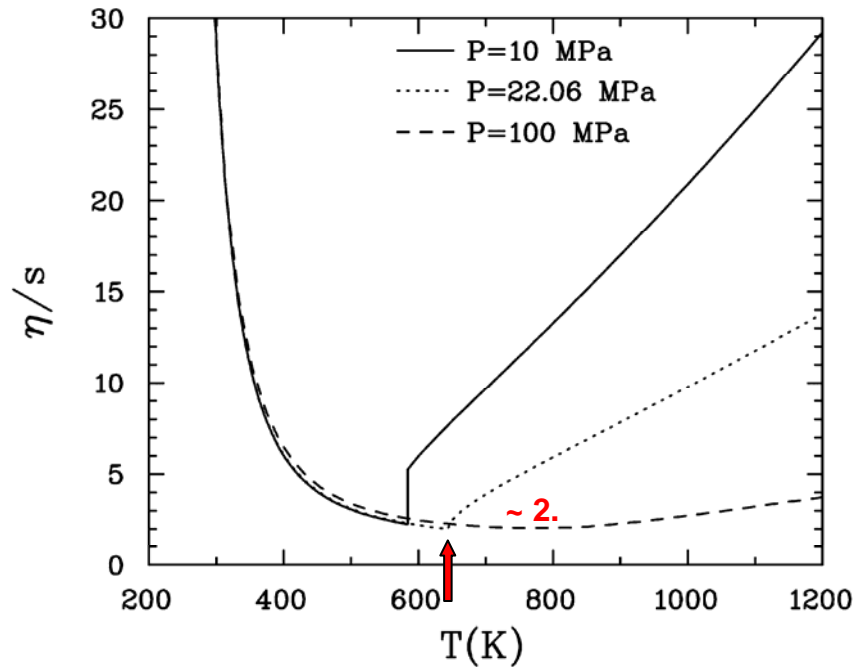
$\eta$  can be determined from (i) fluctuation of flow parameters and from (ii) scaling properties of flow parameters.

[L.P. Csernai, J.I. Kapusta, and L.D. McLerran, PRL **97**, 152303 (2006)]

[Prakash, Venugopalan, .]

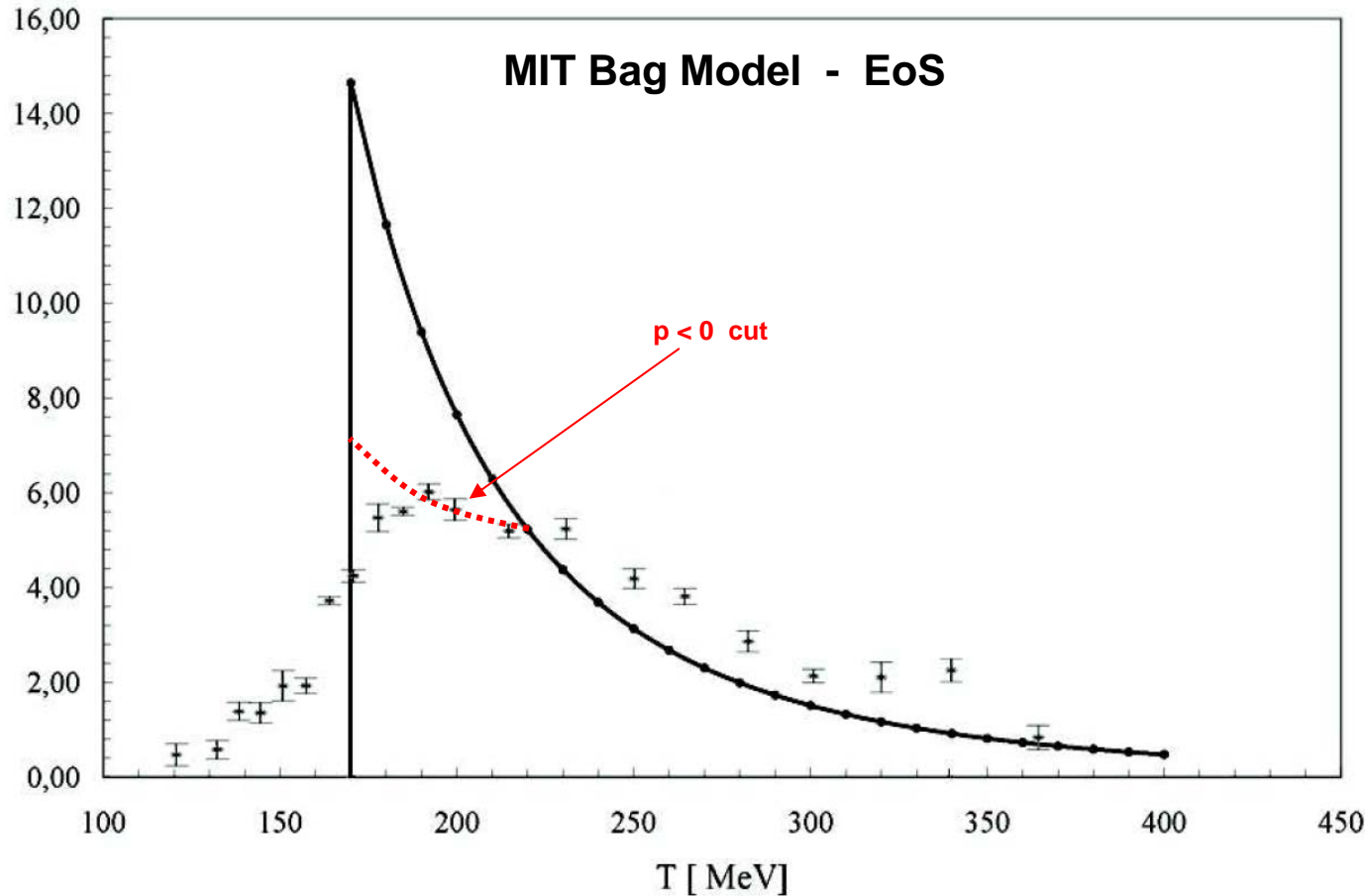


QGP (Arnold, Moore, Yaffe)



Water (NIST)

## Interaction Measure



Clusterization in QGP due to dynamical stretching of the plasma  
[Mishustin, CPOD 2007]

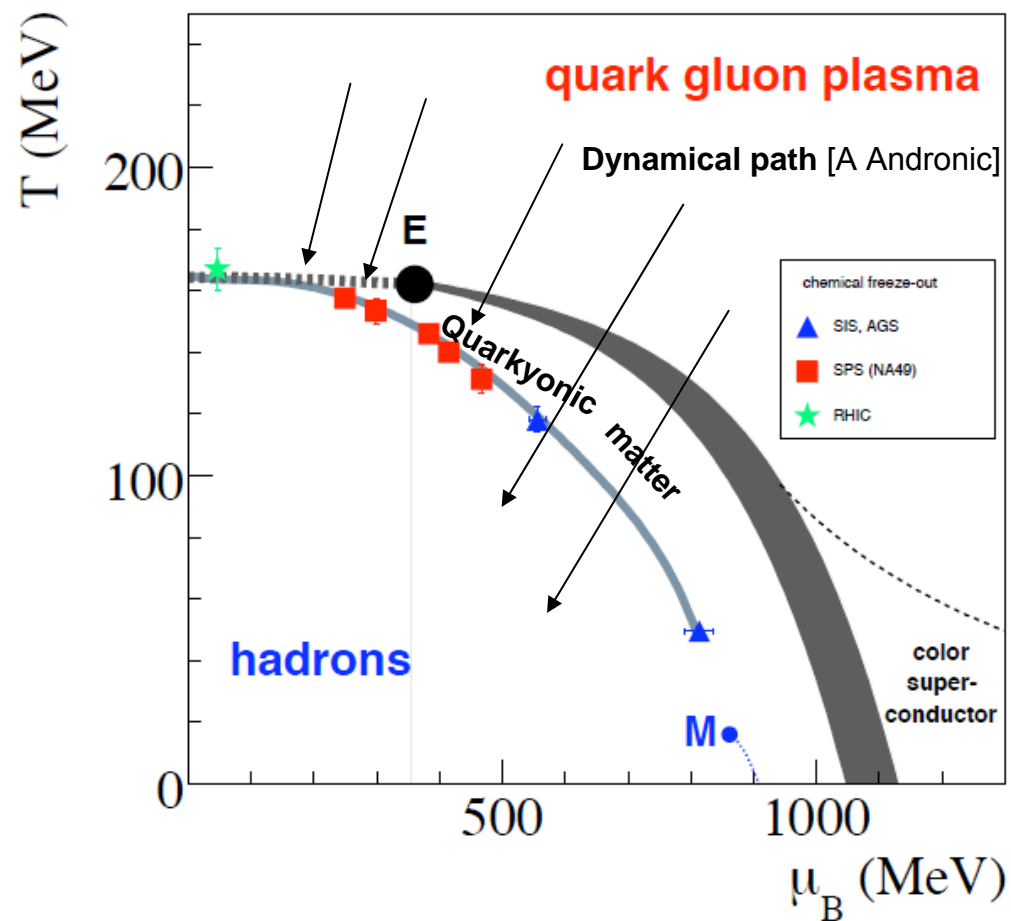
Dynamical viscous pressure  
~ bulk stress →  
 $p < 0$  → cavitation  
~ bubble / droplet formation  
[Rajogopal, Tripuraneni 2009]

Interaction measure,  $(e-3p)/T^4$ , from the MIT Bag model and from Lattice QCD [MILC].  
The bag model is acceptable above  $T=200\text{MeV}$ . The bag model behaviour around  $T_c$  with a fix  $B$  leads to **negative pressure**.

# Fluid Dynamics

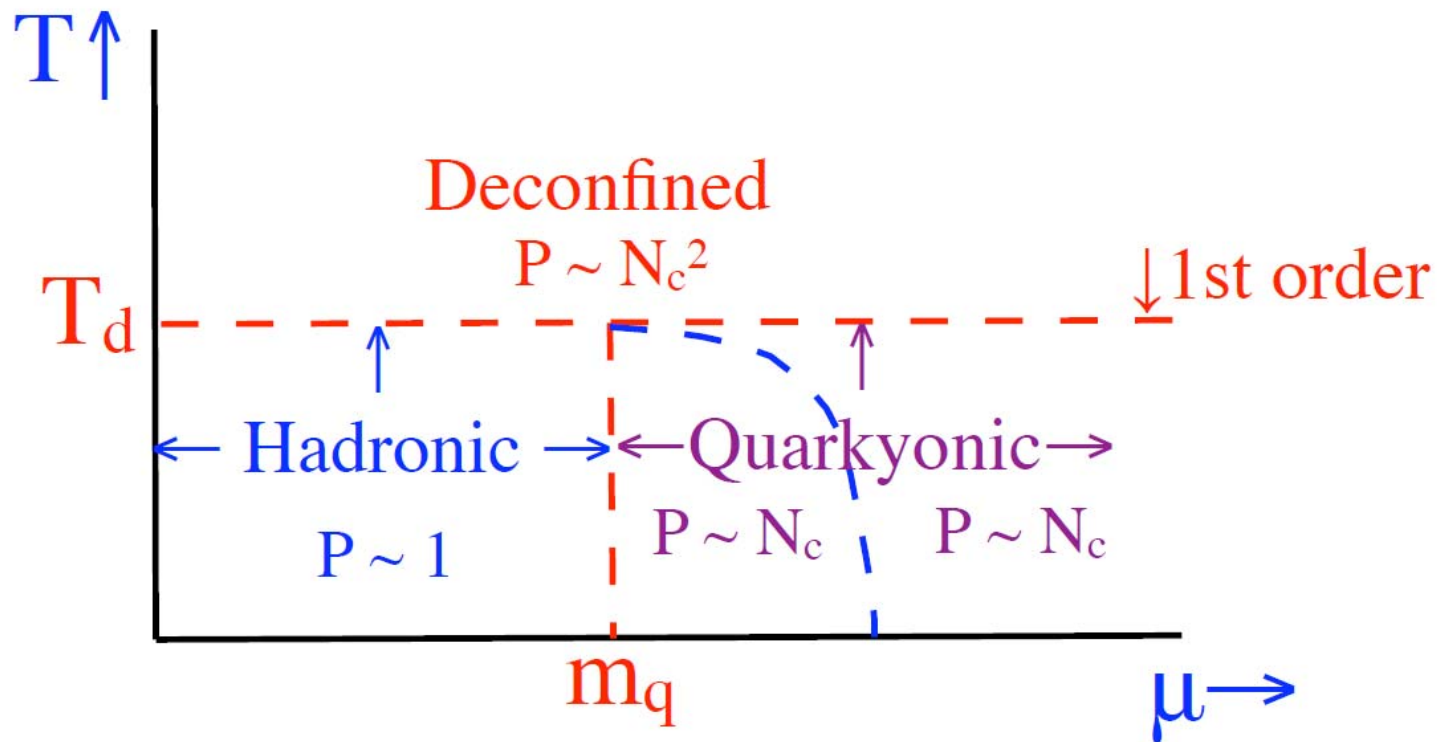


## Equation of State & Transport Properties



## Quarkyonic Matter [McLerran, Pisarski]

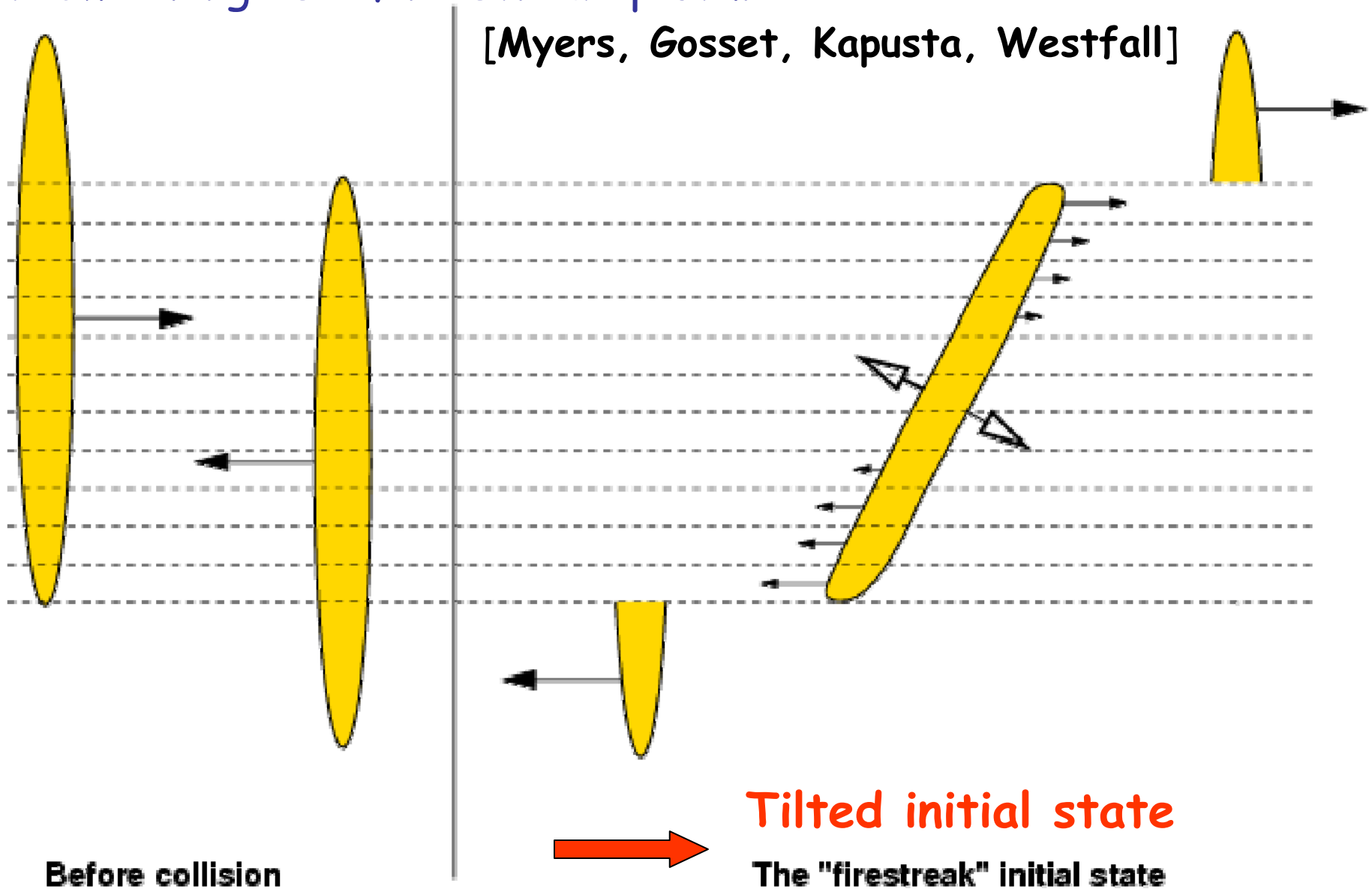
Quarks exist, gaining mass, gluons are absorbed



# YM – Flux tubes $\leftrightarrow$ String ropes

At low energies – fire streak picture

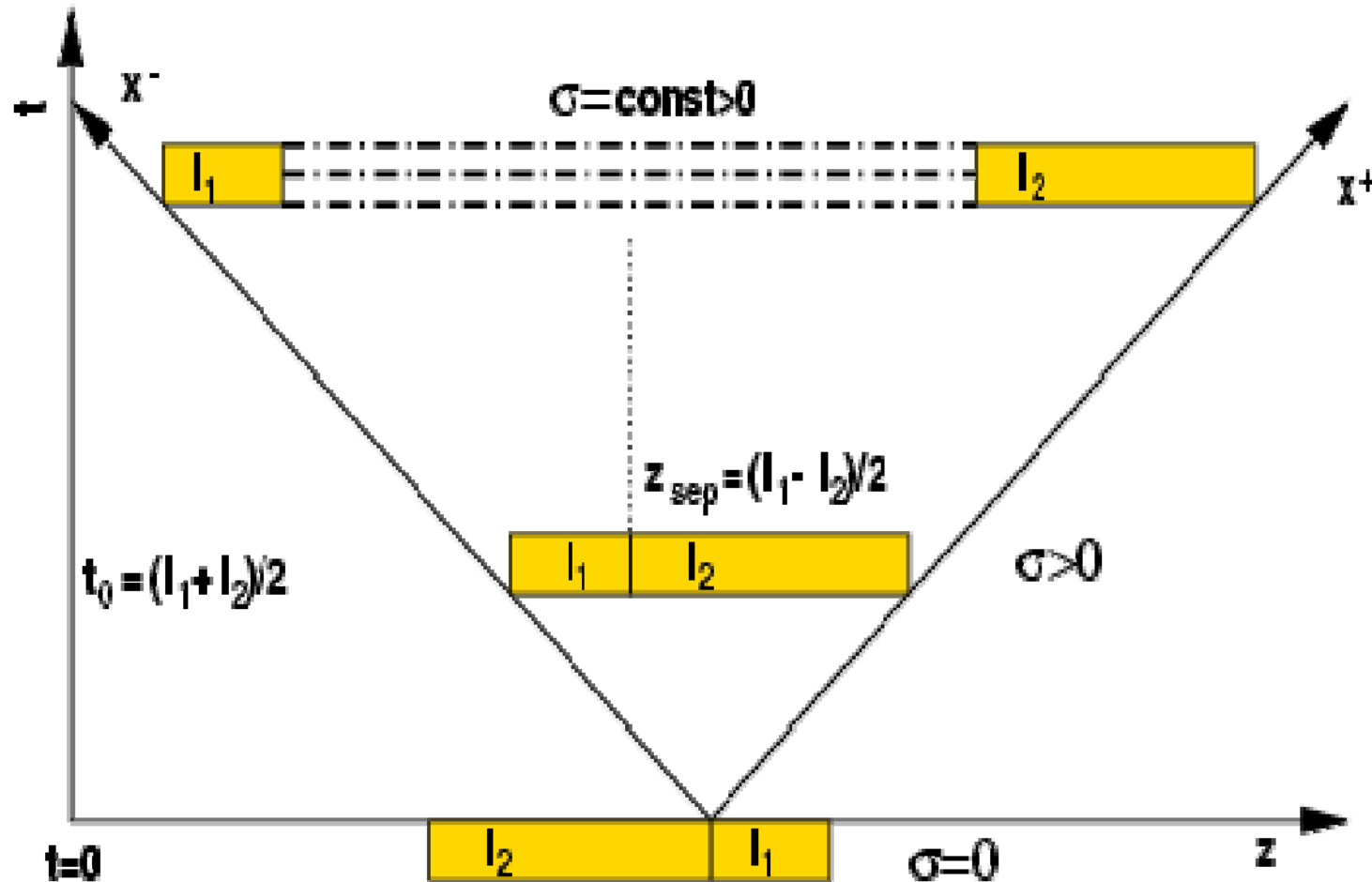
[Myers, Gosset, Kapusta, Westfall]



Before collision

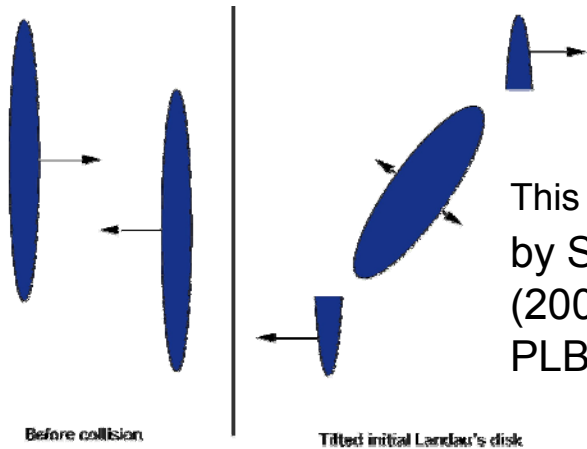
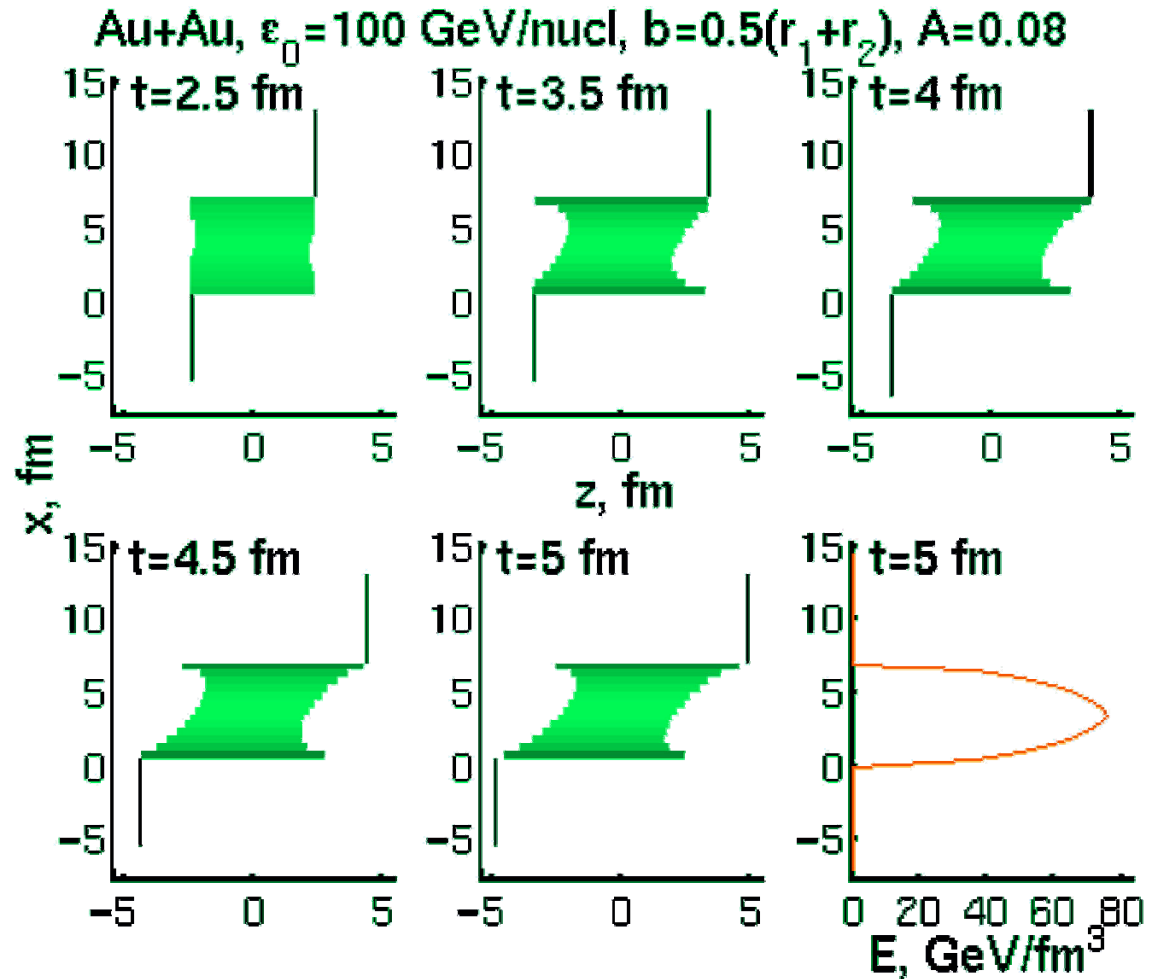
Tilted initial state  
The "firestreak" initial state

# String rope --- Flux tube --- Coherent YM field



Baryon charge & energy are uniformly distributed within each streak.

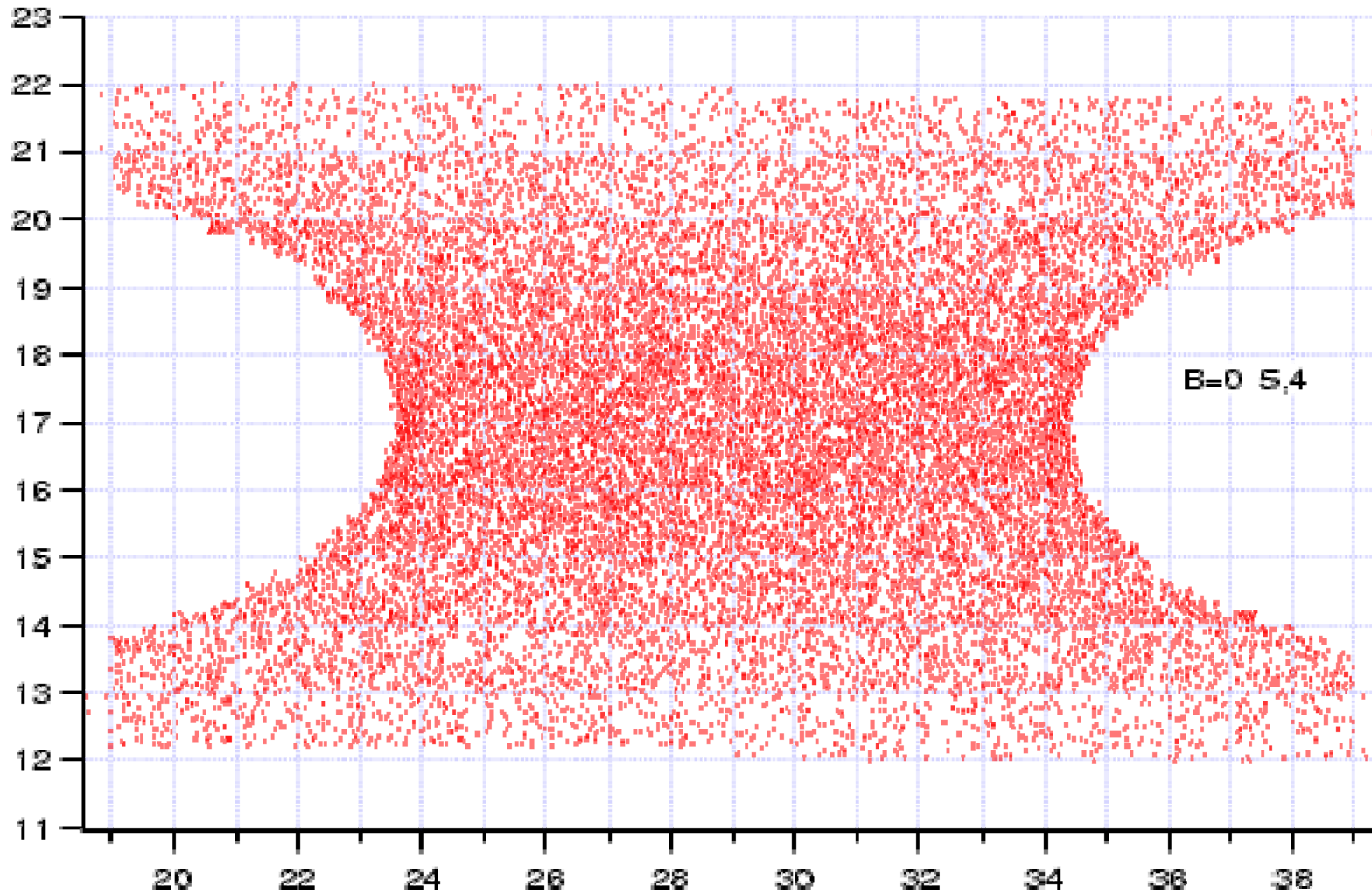
# Initial State



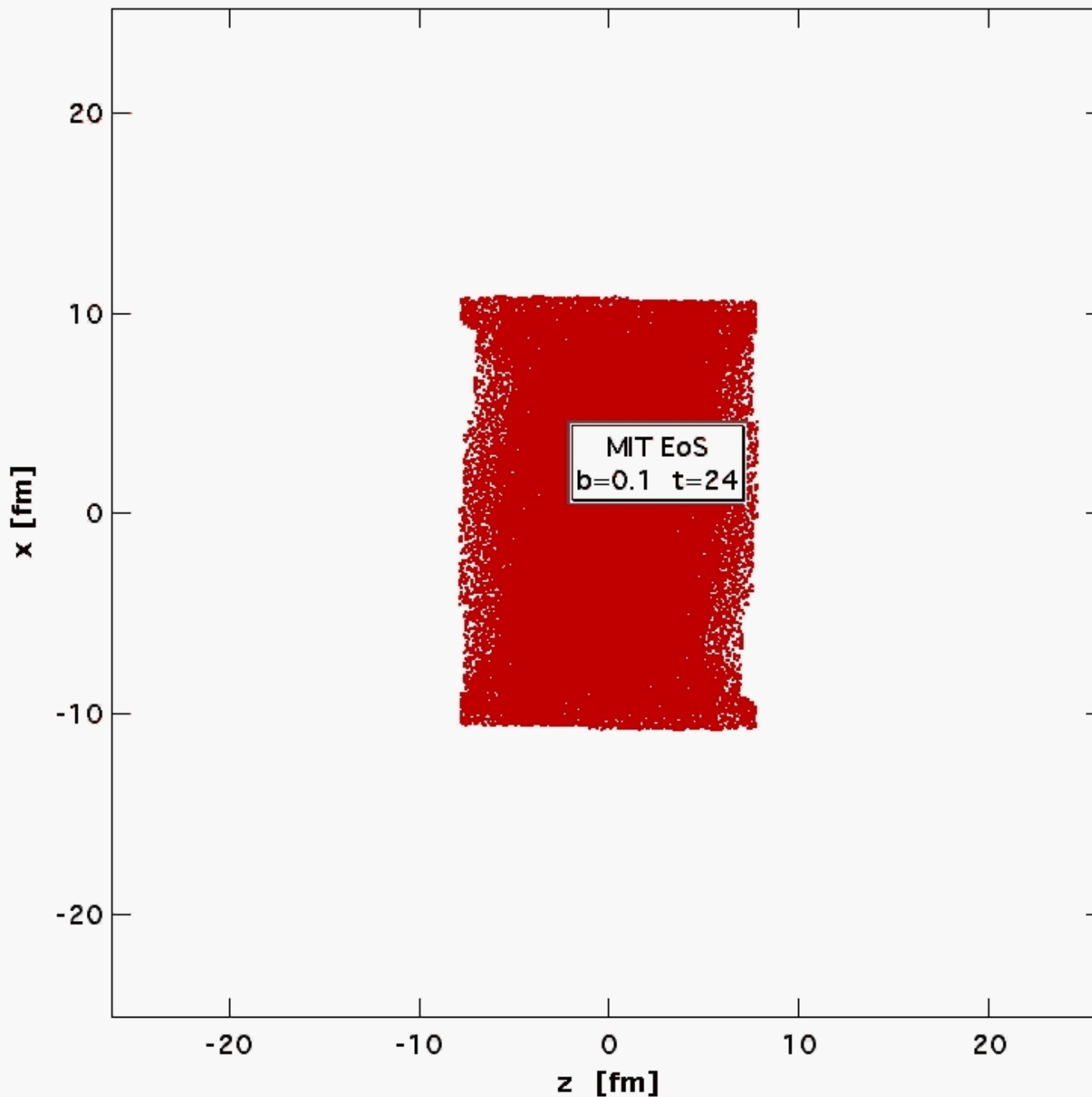
This shape is confirmed by STAR HBT: PLB496 (2000) 1; & M.Lisa & al. PLB 489 (2000) 287.

**3<sup>rd</sup> flow component**

# ***3-Dim Hydro for RHIC (PIC)***



**M2**

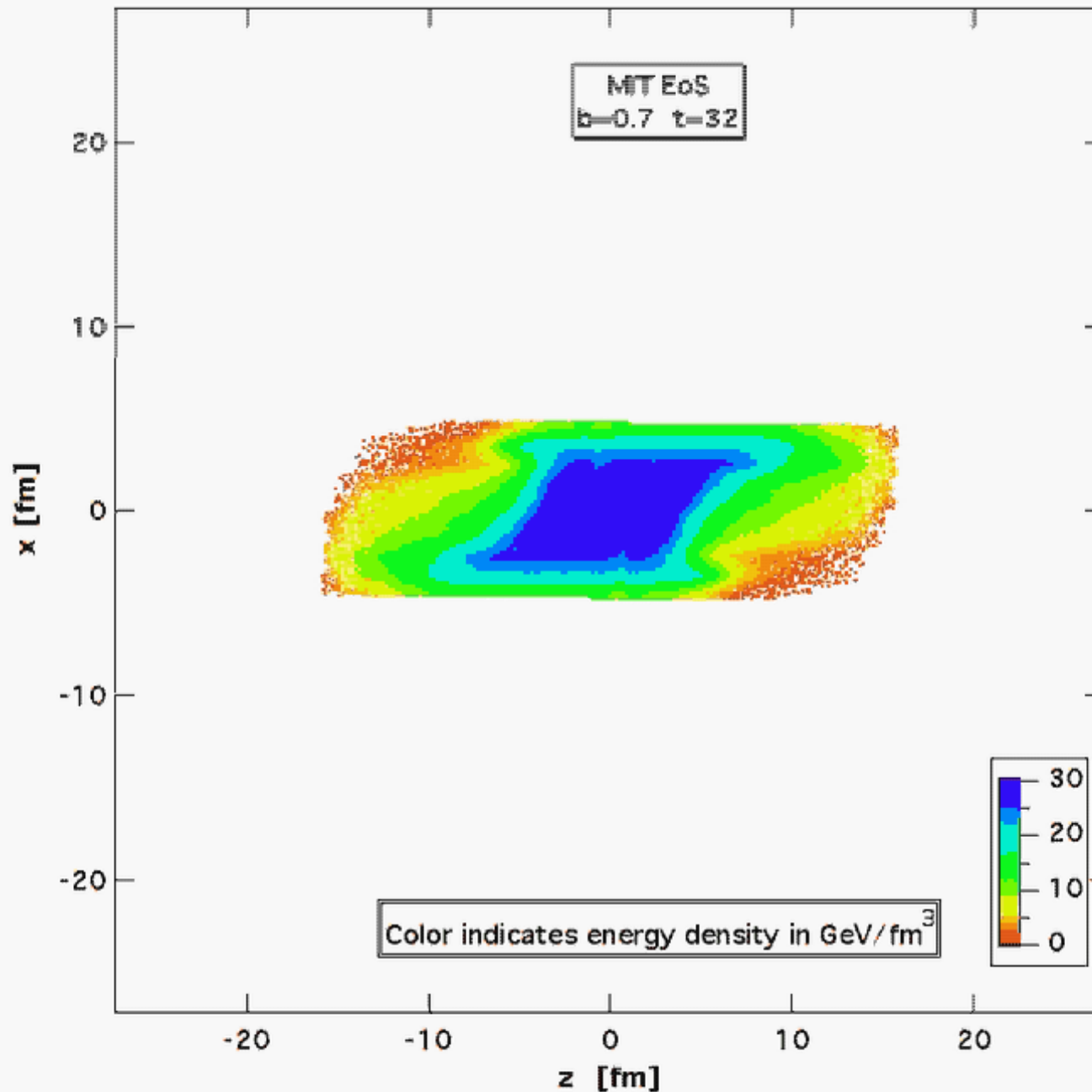


Au+Au at  
65+65 A GEV,  
 $b = 0.1 (R_p + R_t)$

Plotted: positions of  
the lagrangian fluid  
cells, marker particles  
of the PIC method.

Cell resolution  
 $t_{nc} = 24$

The initial structure is  
maintained in the  
expansion due to low  
(numerical) viscosity.



Au+Au 65+65 A GeV,  
 $b=70\%$  of  $b_{\text{max}}$

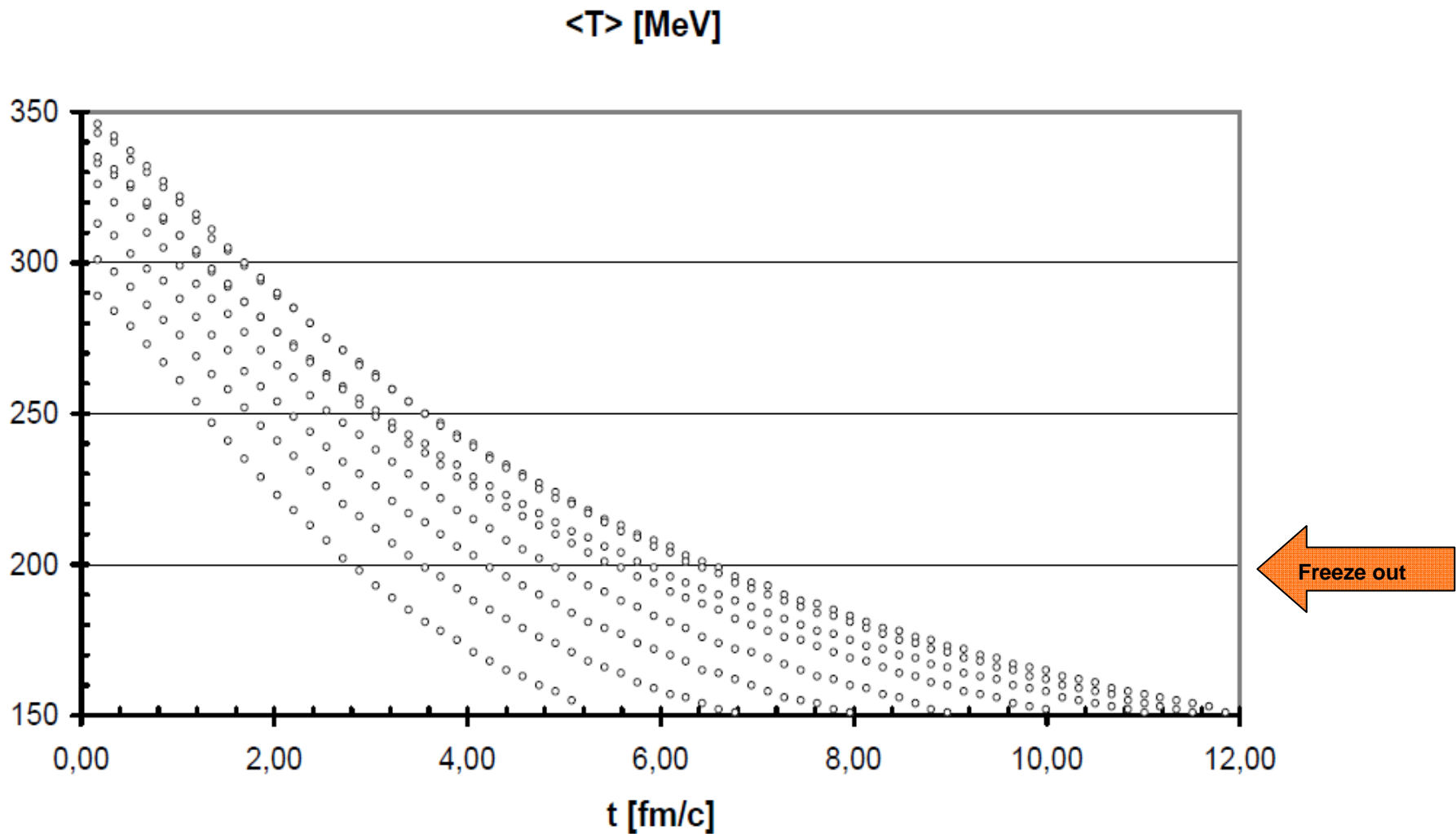
Lagrangian fluid cells,  
moving,  $\sim 5$  mill.

MIT Bag m. EoS

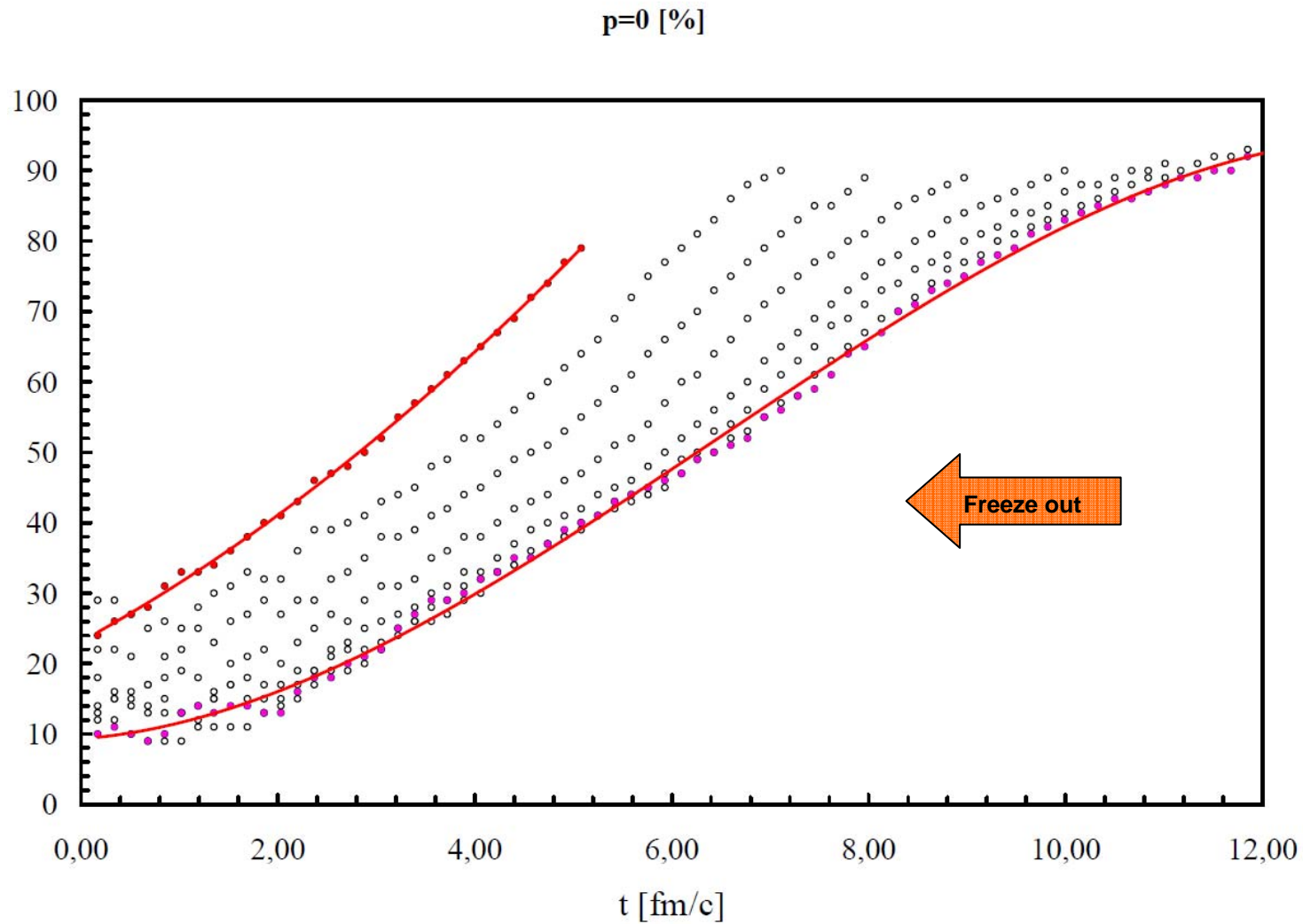
FO at  $T \sim 200$  MeV,  
but calculated much  
longer, until pressure  
is zero for 90% of the  
cells.

Structure and  
asymmetries of init.  
state are maintained  
in nearly perfect  
expansion.

Spatially tilted at FO,  
3<sup>rd</sup> Flow component!

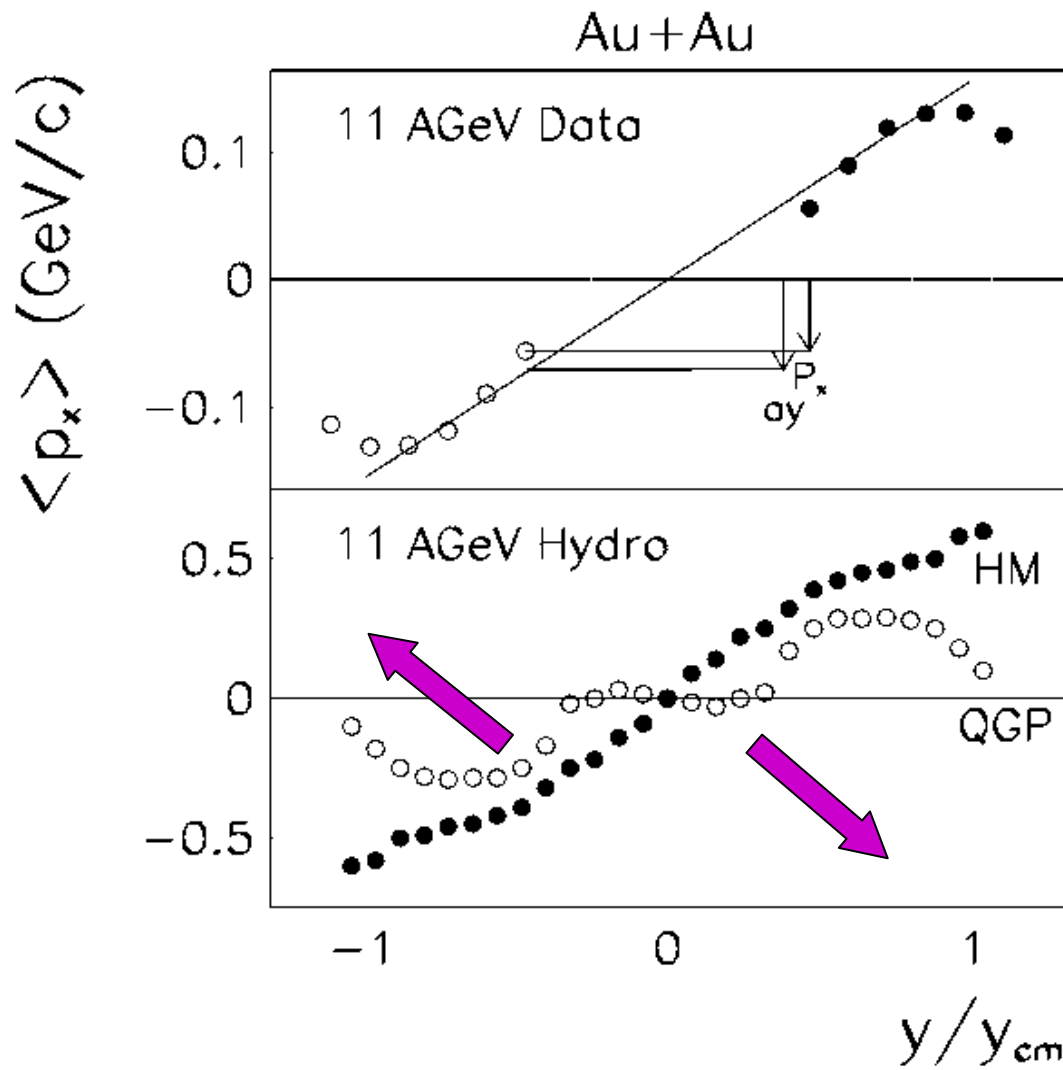


Average temperature versus time in Au+Au collisions at 65+65 AGeV, for impact parameters,  $b = 0, 0.1, 0.2, \dots, 0.7 b_{\text{max}}$  from the top (0.00) down (0.7).



Percentage of the cells with vanishing pressure ( $P=0$ ) versus time in Au+Au collisions at 65+65 AGeV, for impact parameters,  $b = 0, 0.1, 0.2, \dots 0.7 b_{\text{max}}$ . The most peripheral collision at the top ( $b=0.7$ ) and the most central one ( $b=0.00$ ) are indicated in red with a trend line.

# „3rd flow” component



Csernai & Röhrich

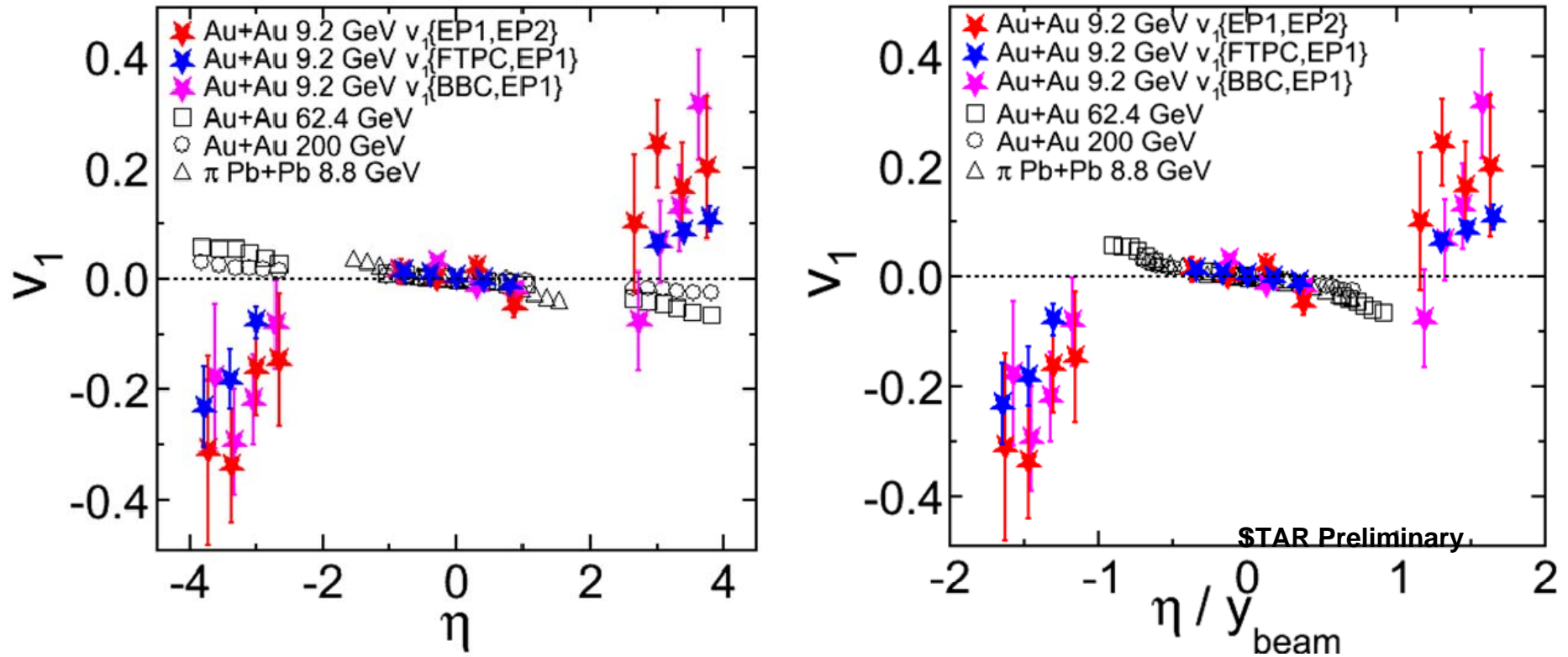
[Phys.Lett. B458 (99) 454]



Hydro

[Csernai, HIPAGS '93]

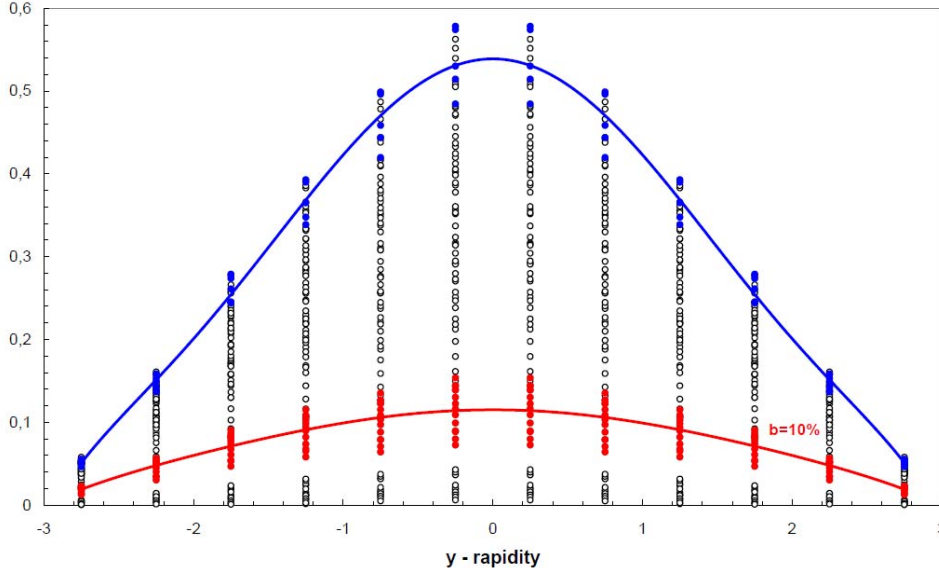
# Directed Flow $v_1$



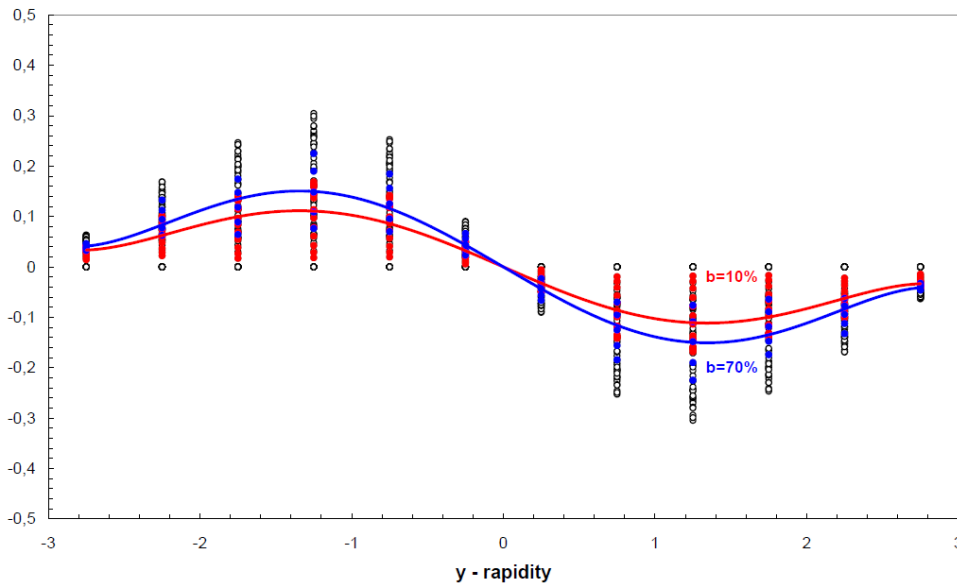
- At mid-rapidity, all the results have comparable values. At forward rapidity, the trend of  $v_1$  from low energy is different from high energies. This is due to early longitudinal collision dynamics.
- $V_1$  values lie on a common trend.

STAR : PRL 92 (2004) 062301  
PRL101 (2008) 252301  
NA49: PRC68(2003)034903

V<sub>2</sub>(y) - smoothed (EbyE, m=139MeV, T=170MeV)



V<sub>1</sub>(y) - smoothed (EbyE, m=139MeV, T=170MeV)



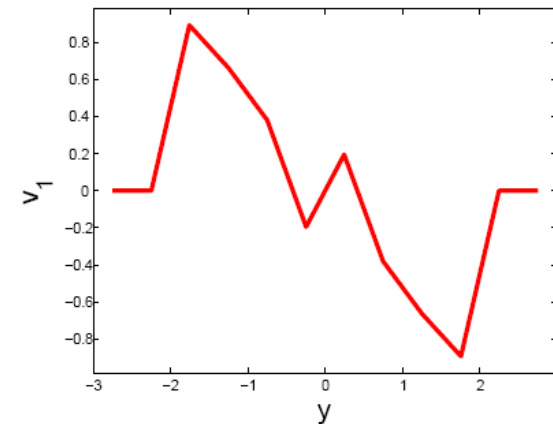
# Freeze Out

Pre FO:  
V<sub>1</sub> and V<sub>2</sub> versus y from PIC hydro ,

after smoothing in an FO layer considering Modified BTE with parameters, **m & T.**

For different impact parameters, **b = 10% (70%)** of **b<sub>max</sub> = R<sub>p</sub> + R<sub>t</sub>**

Before Cooper Frye FO with 'thermal' distributions, (with **m<sub>cq</sub>, T<sub>cq</sub>**)!

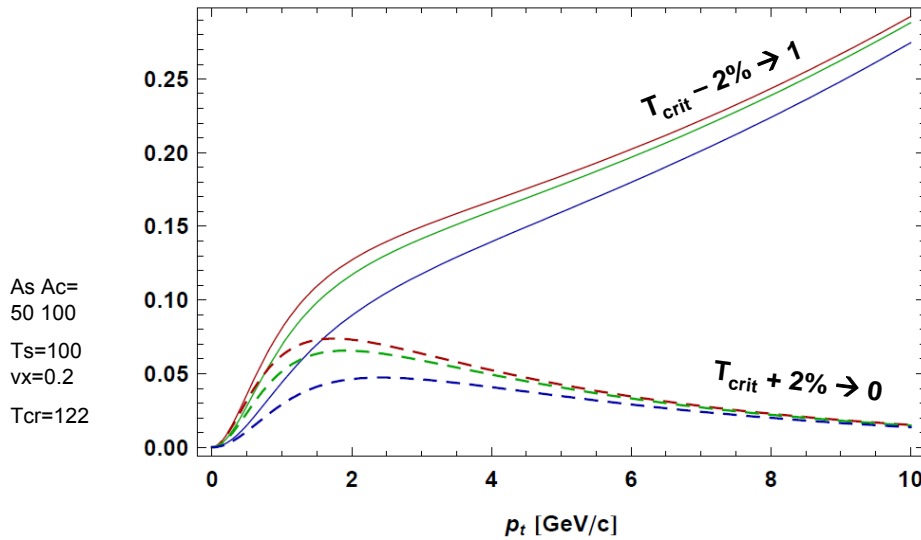


# NCQ - Importance of Initial State

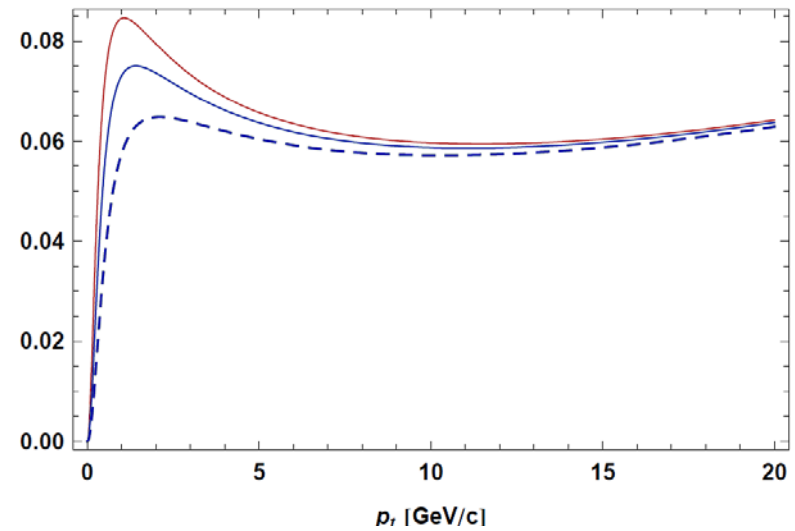
CF FO  
[w/Mishustin]

$V_2$  from few source models [Huovinen et al. 2001]  $v_2(p_t)$  rises linearly at high  $p_t$  (Bjorken Model)

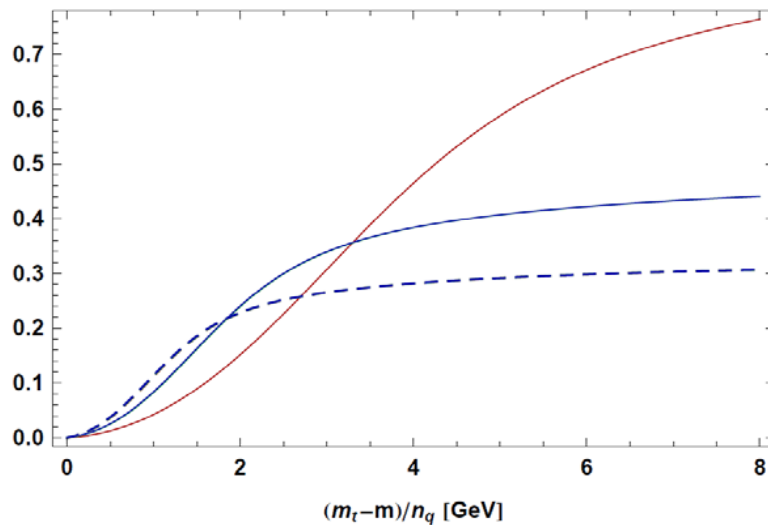
$v_2 - (m = 0.15, 0.5, 1. \text{ GeV})$



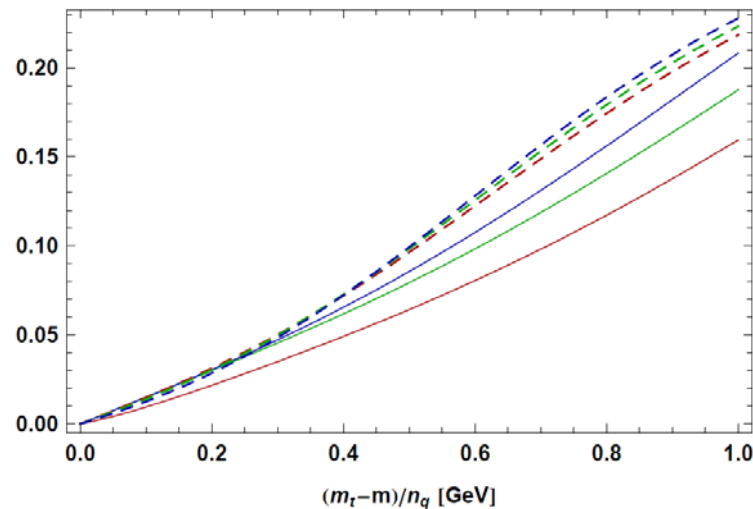
$v_2 - (m = 140, 280, 420 \text{ MeV})$



$v_2/n_q - (m = n_q \times 100 \text{ MeV})$



$v_2/n_q - (\pi, K, K^*, p, \Lambda, \Xi)$



$T(x) \leftarrow$   
 $\rightarrow u(x)$

Hadron flow does not show NCQ scaling !!

# Freeze Out

## Rapid and simultaneous FO and “hadronization”

- **Improved Cooper-Frye FO:**

- - Conservation Laws:  $[T^{\mu\nu}\Lambda_\nu]=0, [N^\nu\Lambda_\nu]=0$

- - Post FO distribution:  $\Theta(p^\nu\Lambda_\nu) f(p) > 0$

[L.P. Csernai,  
Sov. JETP, 65 (1987) 216.]

[Cancelling Juttner or  
Cut Juttner distributions.]

- **Hadronization ~ CQ-s**

- - Pre FO: Current  $q$  and  $\bar{q}$ , QGP

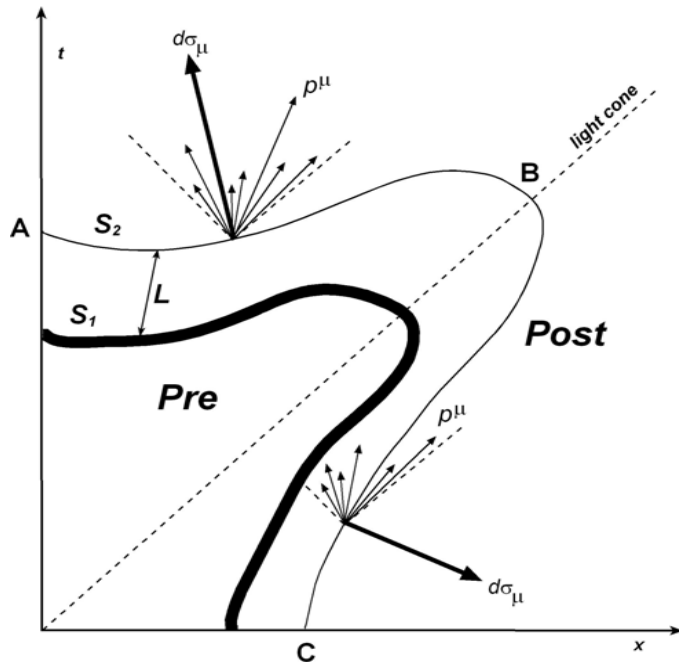
- - Post FO: Constituent  $q$  and  $\bar{q}$

- -  $N_q$  and  $N_{\bar{q}}$  are conserved in FO!!!

- **Choice of F.O. hyper-surface / layer**

**M3**

# Freeze out in a finite layer



- The corresponding equations for both space-like and time-like freeze out /wo re-thermalization

$$\partial_s f_i ds = - \left( \frac{L}{L-s} \right) \left( \frac{p^s}{p^\mu u_\mu} \right) \Theta(p^s) f_i \frac{ds}{\lambda}$$

$$\partial_s f_f ds = \left( \frac{L}{L-s} \right) \left( \frac{p^s}{p^\mu u_\mu} \right) \Theta(p^s) f_i \frac{ds}{\lambda}$$

- The solution:

$$f_i(x, p) = f_J(p) \left( \frac{L-s}{L} \right)^{\frac{L}{\lambda}} \left( \frac{p^s}{p^\mu u_\mu} \right) \Theta(p^s)$$

$$f_f(x, p) = f_J(p) - f_i(x, p)$$

$$= f_J(p) \left[ 1 - \left( \frac{L-s}{L} \right)^{\frac{L}{\lambda}} \left( \frac{p^s}{p^\mu u_\mu} \right) \Theta(p^s) \right]$$

$$\xrightarrow{s \rightarrow L} \boxed{f_J(p) \Theta(p^s)}$$

Space-like

$$f_J(p) \Theta(p_x)$$

Time-like

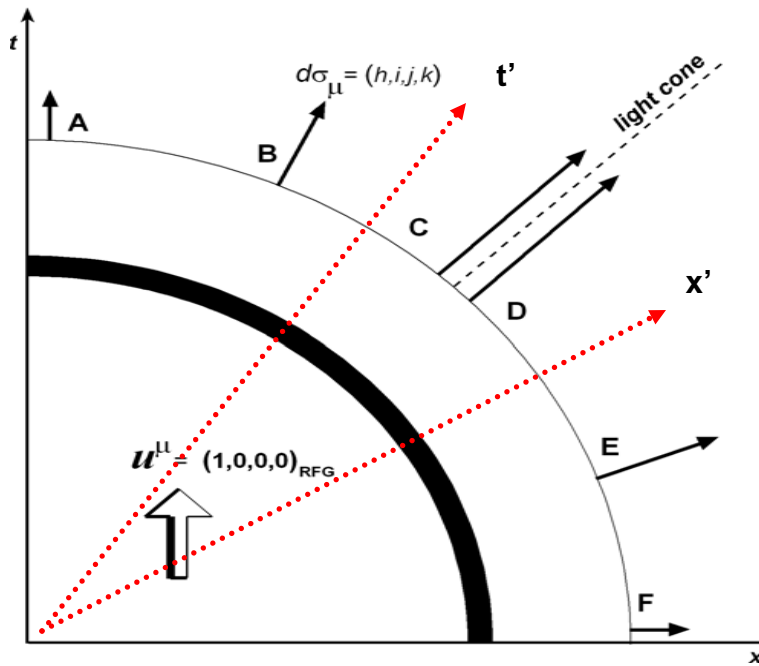
$$f_J(p)$$

[ E. Molnar, et al., J.Phys.G34 (2007) 1901; Phys.Rev.C74 (2006) 024907; Acta Phys.Hung. A27 (2006) 359; V.K. Magas, et al., Acta Phys. Hung.A27 (2006) 351. ]

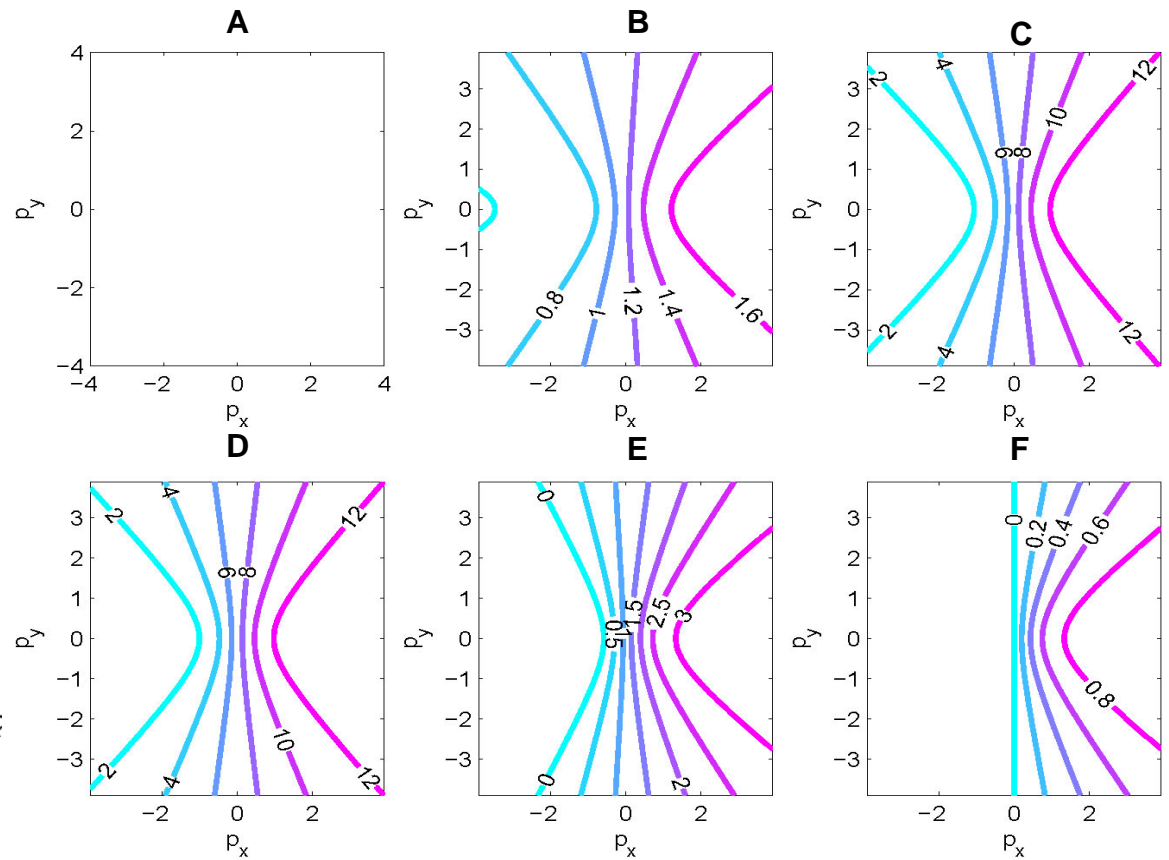


This should be supplemented with a **recombination** process into hadrons / constituent quarks.

# The invariant "Escape" probability

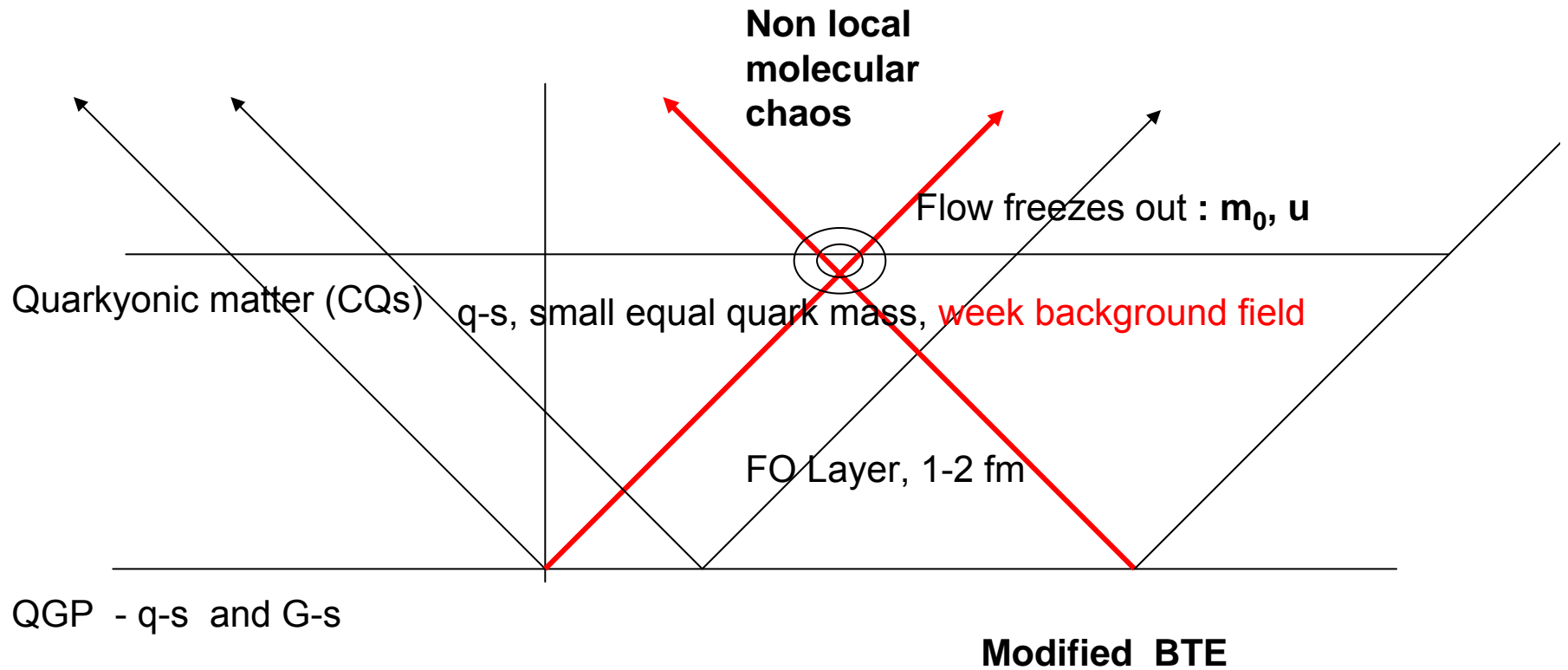


[RFG]



Escape probability factors for different points on FO hypersurface, in the RFG. Momentum values are in units of  $[mc]$

$$P(p) = \frac{p^\mu d\sigma_\mu}{p^\mu u_\mu} \Theta(p^\mu d\sigma_\mu)$$



In the FO layer the main free path increases, local molecular chaos assumption does not hold, (large effective viscosity)

Current quarks are gaining mass, while gluons are absorbed, forming constituent quarks (CQs) with mass,  $m_0$ . Final flow develops with joint flow velocity,  $u$ , for all CQs.

These then gain mass and recombine to hadrons, but the  $u$ -distribution per NCQ does not change.

$$\begin{aligned}
 \text{2nd step: } p_t / n_q &\rightarrow K E_T / n_q = m_o (\sqrt{1+u^2} - 1) / n_q \\
 &\rightarrow u \ll 1 : m_o u_T^2 / 2 \\
 &\rightarrow u \gg 1 : m_o u_T
 \end{aligned}$$

Thus, **NCQ scaling** of flow indicates dependence (equilibration) of transverse energy: flow velocity  $u$  and constituent quark mass,  $m_o$ , at the **FO of flow**. Then final hadrons develop, their masses change but flow angular distribution of  $u$  and **NCQ** remains the same.

In **CONCLUSION** the FO and hadronization is a gradual process, where (i) first constituent quarks form and gain nearly equal masses, (ii) and flow asymmetry freezes out, (iii) finally constituent quarks locally recombine into hadrons, gaining mass, by equating the transverse energy, but not changing the flow pattern or NCQ.

**PROOF:** If all flow patterns, follow the same principle as  $v_2(p_t)$  :  
 $v_1(p_t), v_2(y), v_1(y)$ , **Mach cone vs.  $p_t$**

## **SUMMARY**

- **Initial state** is decisive and can be tested by  $v_1$  &  $v_2$
- $v_1$ : semi-central collisions, position depends on  $b$ ,  $\sigma$ ,  $T_f$ , NCQ ??
- $v_2$ : more peripheral collisions, NCQ scaling Quarkyonic m. !
- Mach cone around jets – tests hydro properties, NCQ ??
- **Viscosity** is important both in hydro and in the initial dynamics:  $T \leftrightarrow u$
- Numerical viscosity should be taken in correction
- **F.O.**: entropy condition
- $\rightarrow$  space like FO is weak at RHIC / LHC - important at FAIR
- $\rightarrow$  bulk viscosity causes negative pressure in expansion  $\rightarrow$  rapid FO & H

*The END*