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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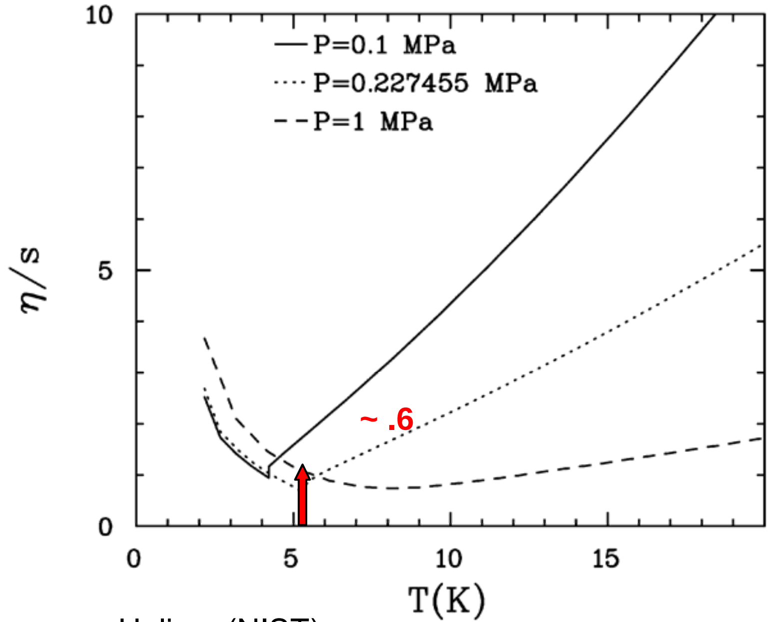
E o S (Quarkyonic M.)

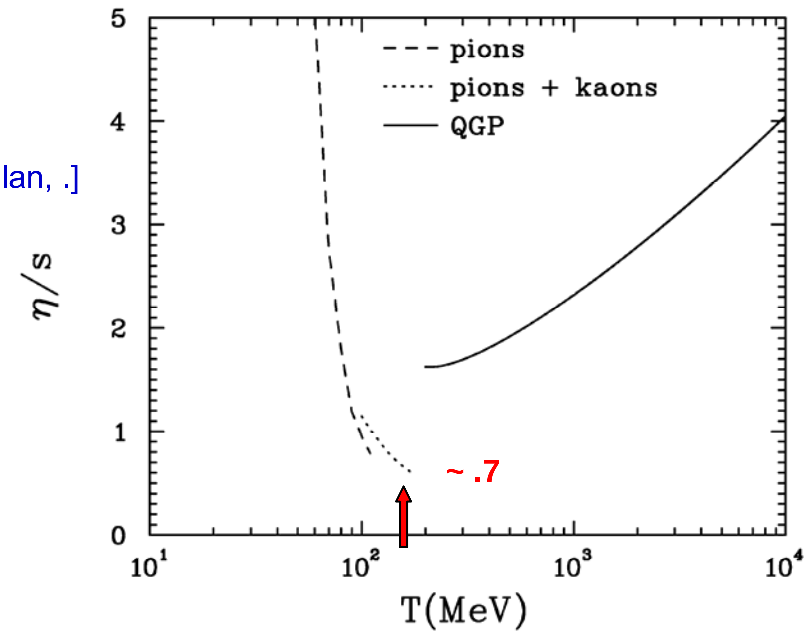
Transport properties

Fluid Dynamics



Helium (NIST)

[Prakash, Venugopalan, .]

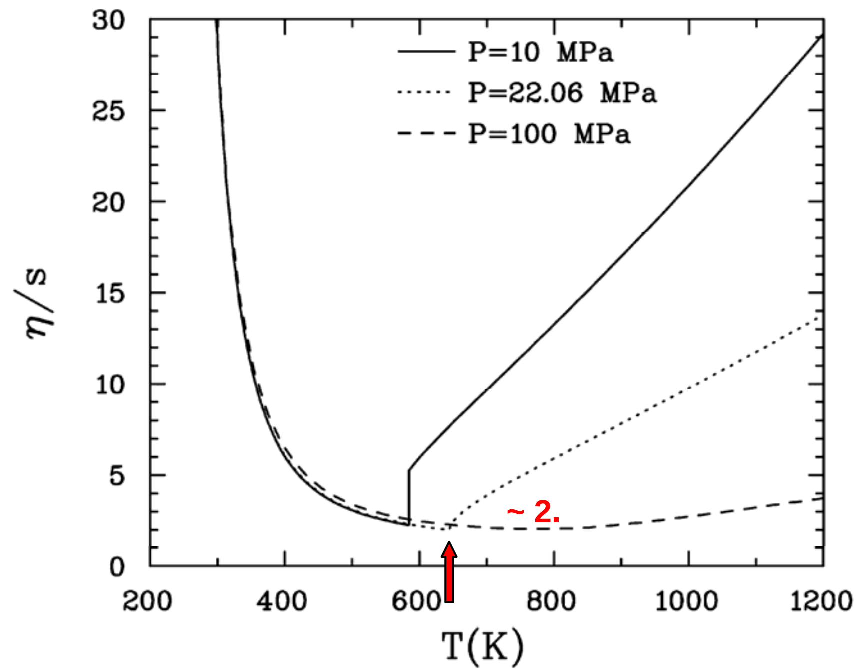


QGP (Arnold, Moore, Yaffe)

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

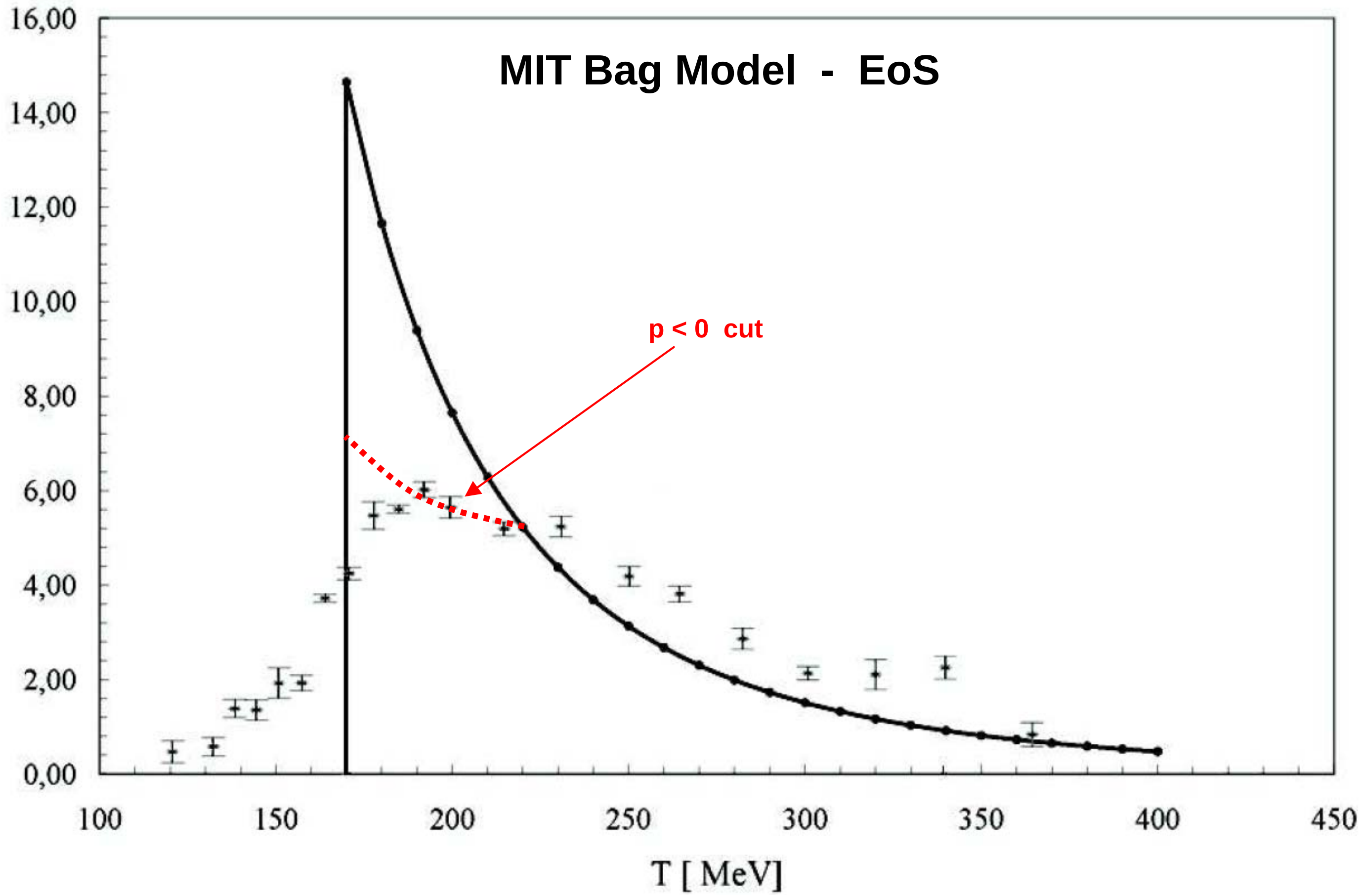
η can be determined from (i) fluctuation of flow parameters and from (ii) scaling properties of flow parameters.

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



Water (NIST)

Interaction Measure



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

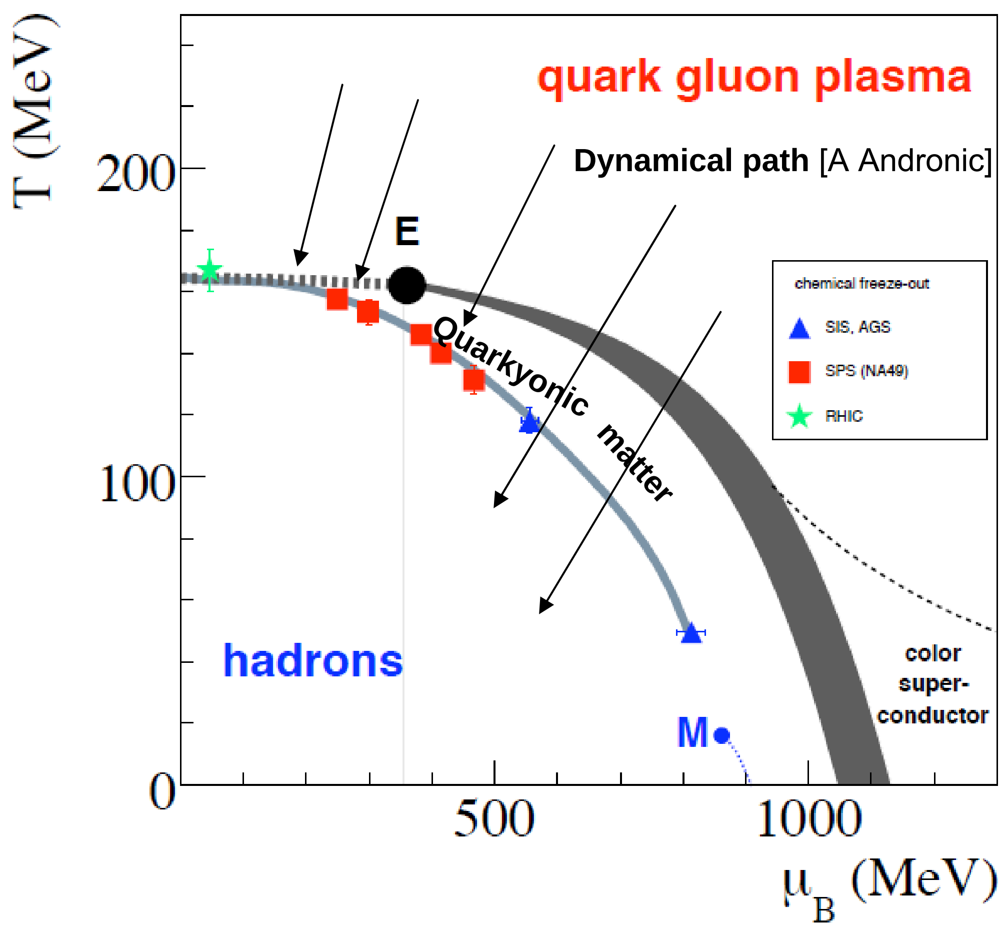
Dynamical viscous pressure ~ bulk stress → p<0 → cavitation ~ bubble / droplet formation [Rajogapal, Tripuraneni 2009]

Interaction measure, (e-3p)/T4 , from the MIT Bag model and from Lattice QCD [MILC]. The bag model is acceptable above T=200MeV. The bag model behaviour around Tc with a fix B leads **to negative pressure**.

Fluid Dynamics

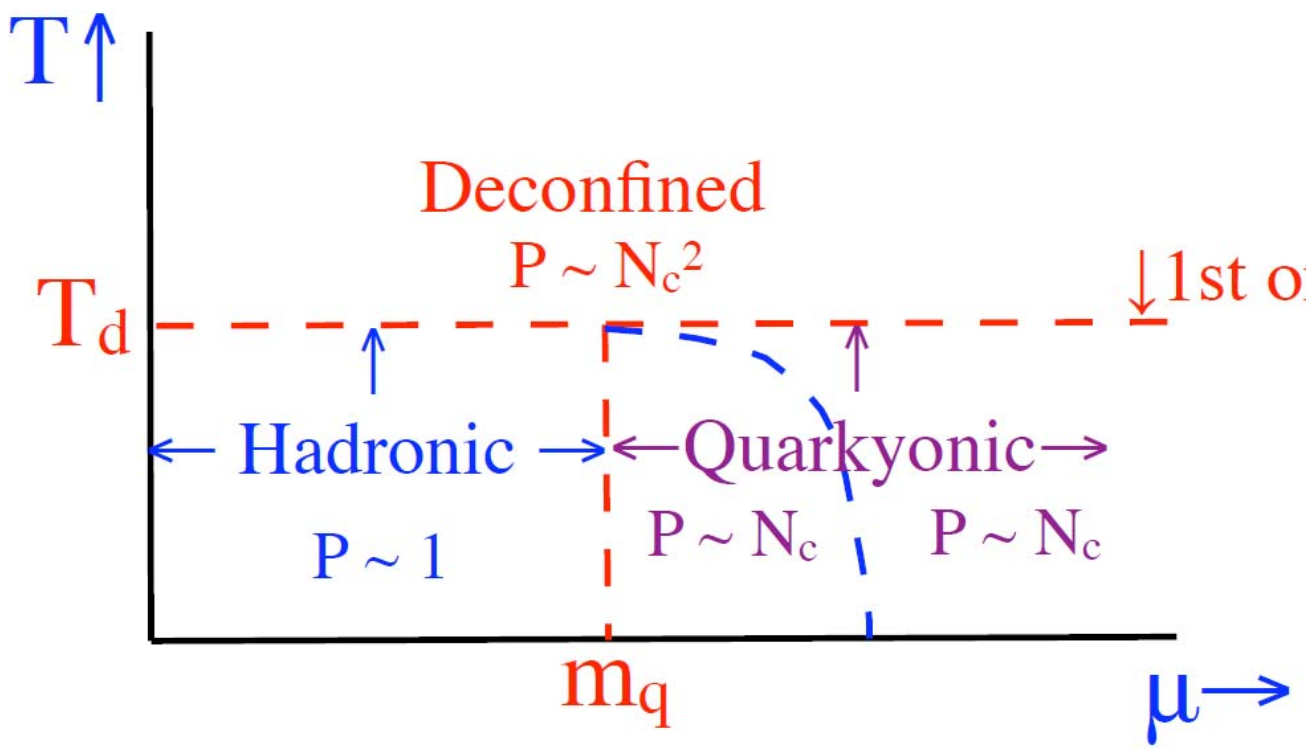
↔

Equation of State & Transport Properties



Quarkyonic Matter [McLerran, Pisarski]

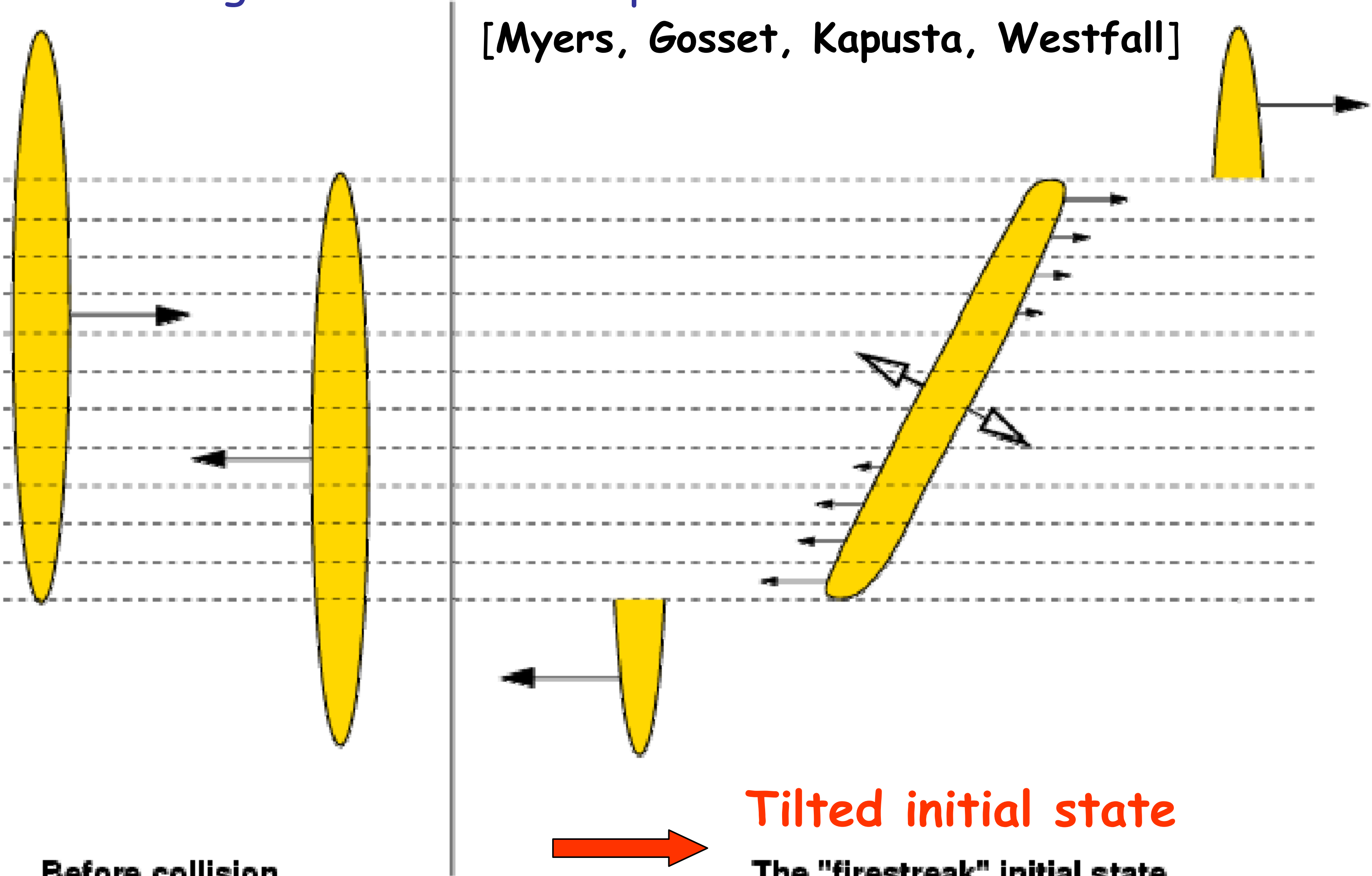
Quarks exist, gaining mass, gluons are absorbed



YM – Flux tubes ← → String ropes

At low energies – fire streak picture

[Myers, Gosset, Kapusta, Westfall]

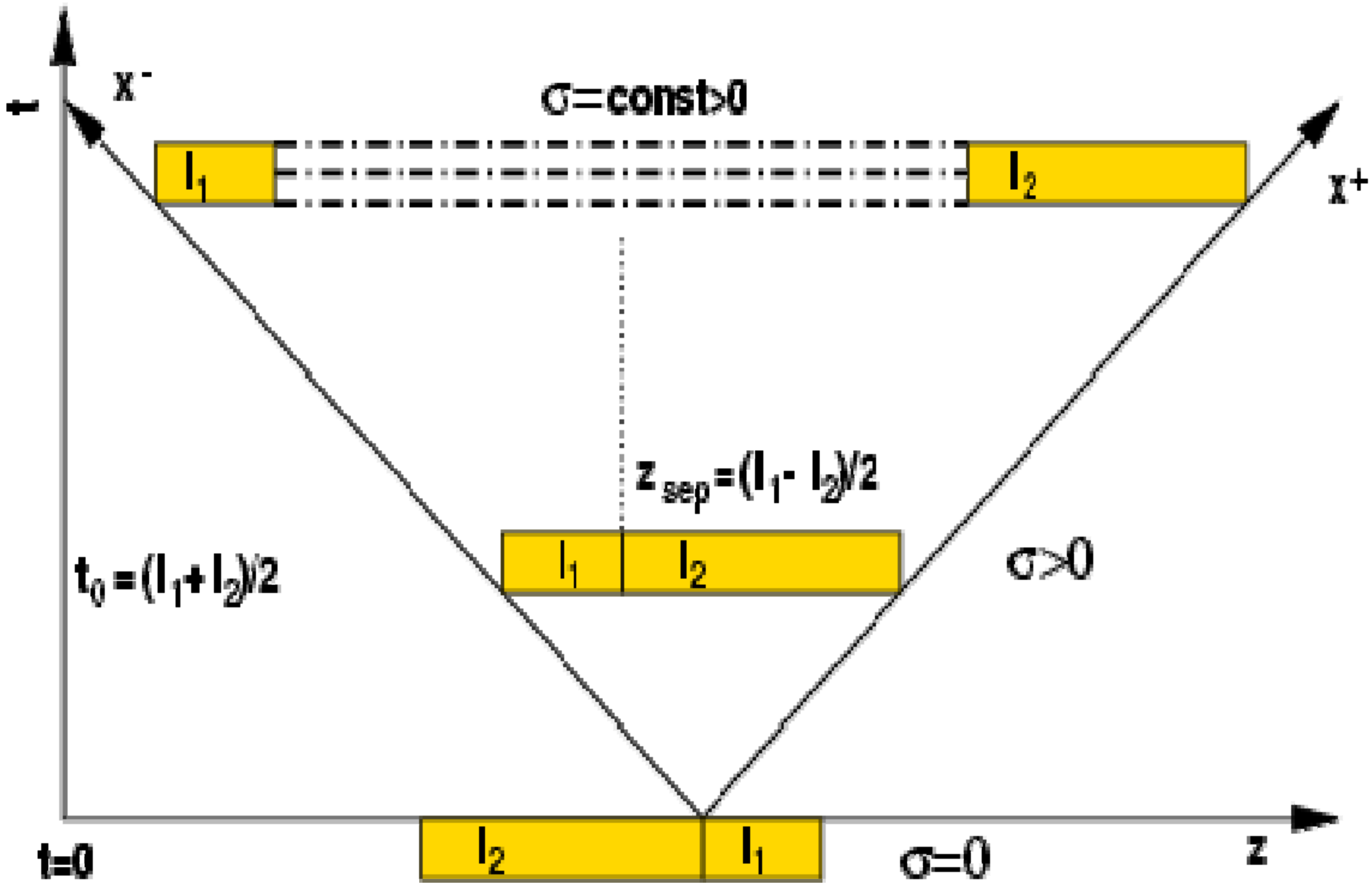


Tilted initial state

Before collision

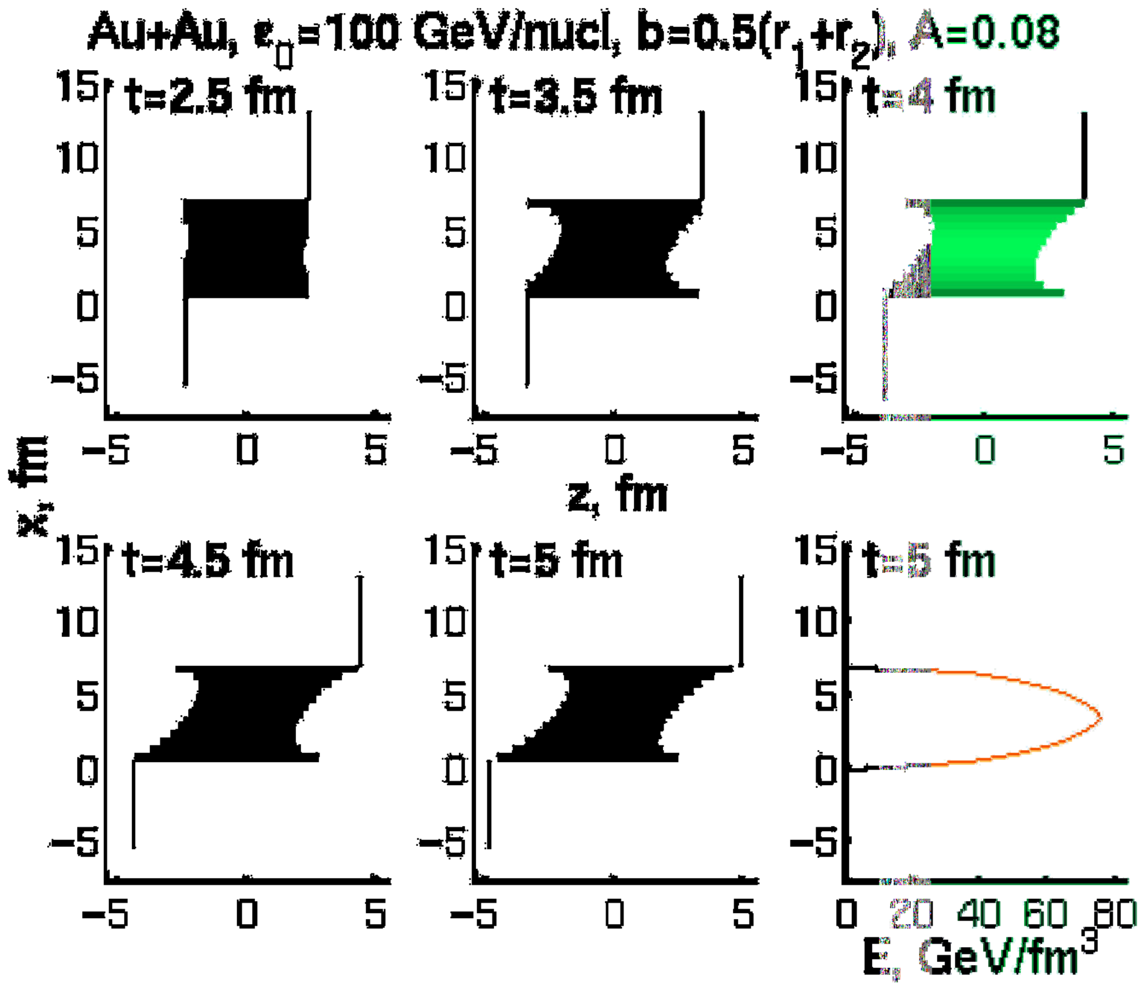
The "firestreak" initial state

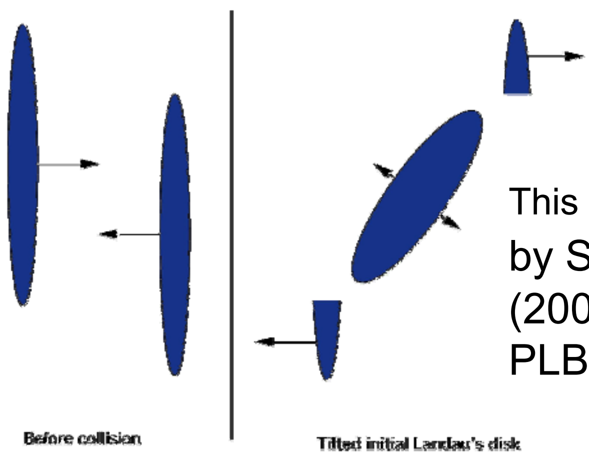
String rope --- Flux tube --- Coherent YM field



Baryon charge & energy are uniformly distributed within each streak.

Initial State

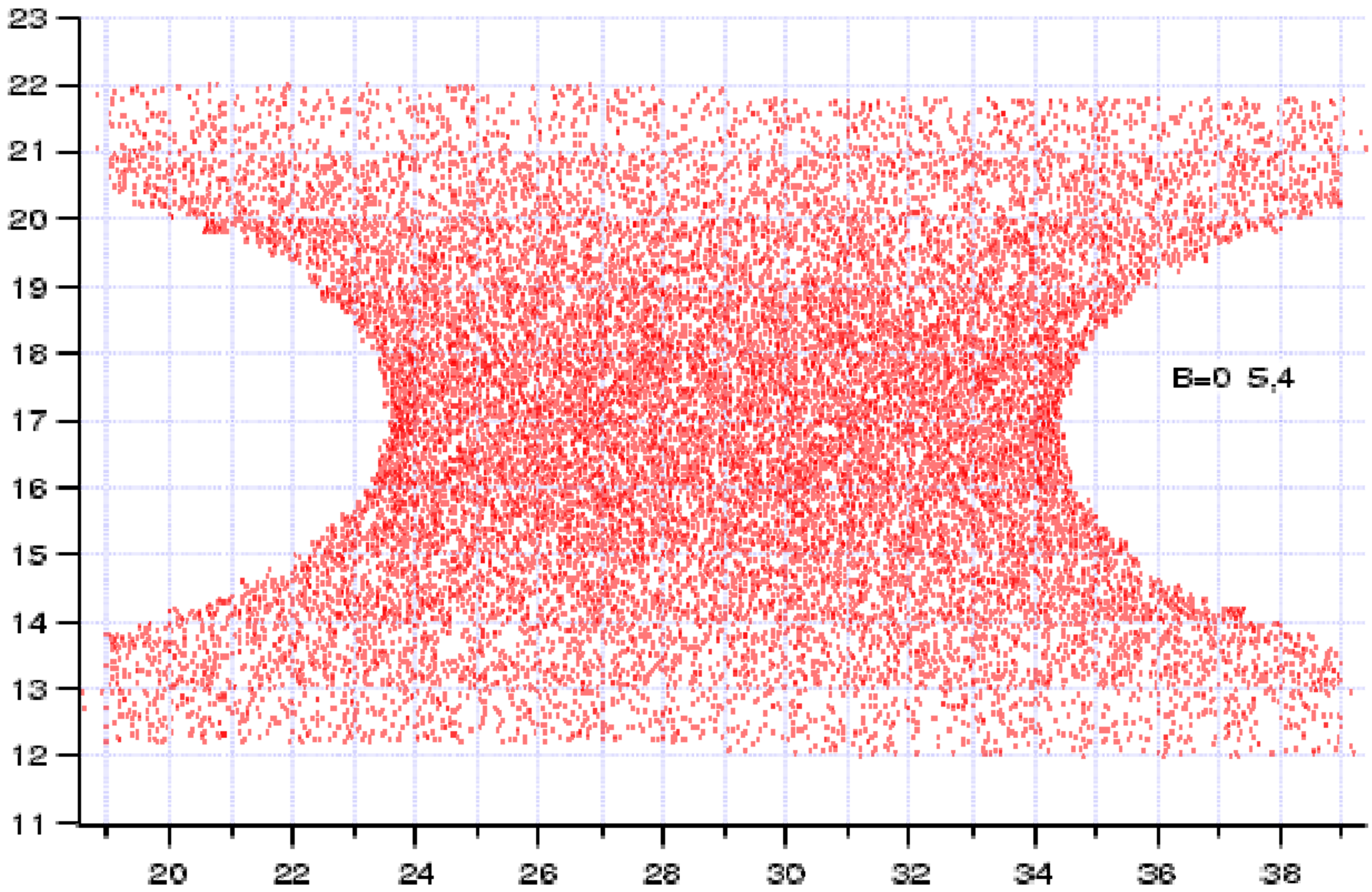




This shape is confirmed by STAR HBT: PLB496 (2000) 1; & M.Lisa &al. PLB 489 (2000) 287.

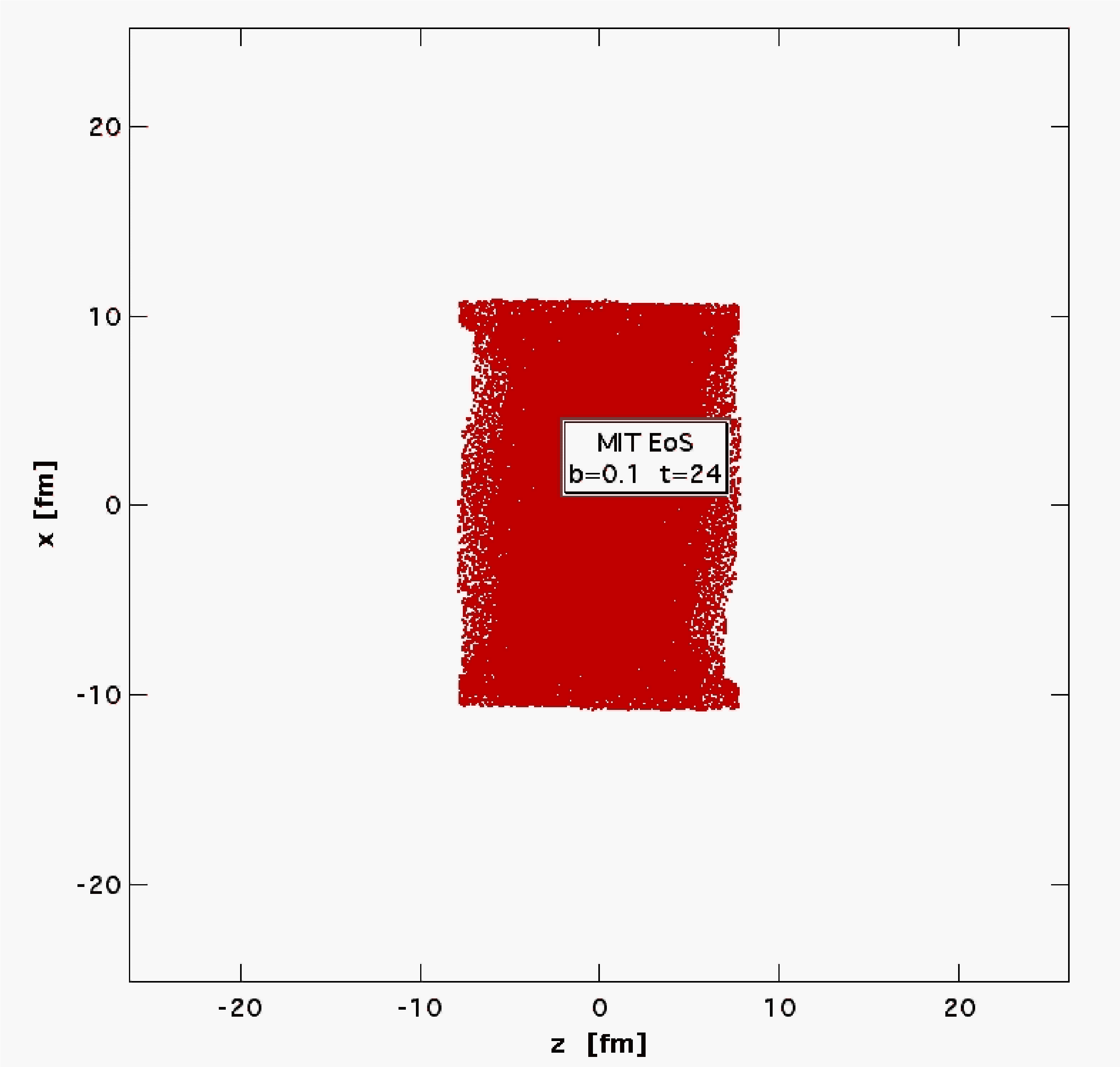
3rd flow component

3-Dim Hydro for RHIC (PIC)



M2

Dan Strottman

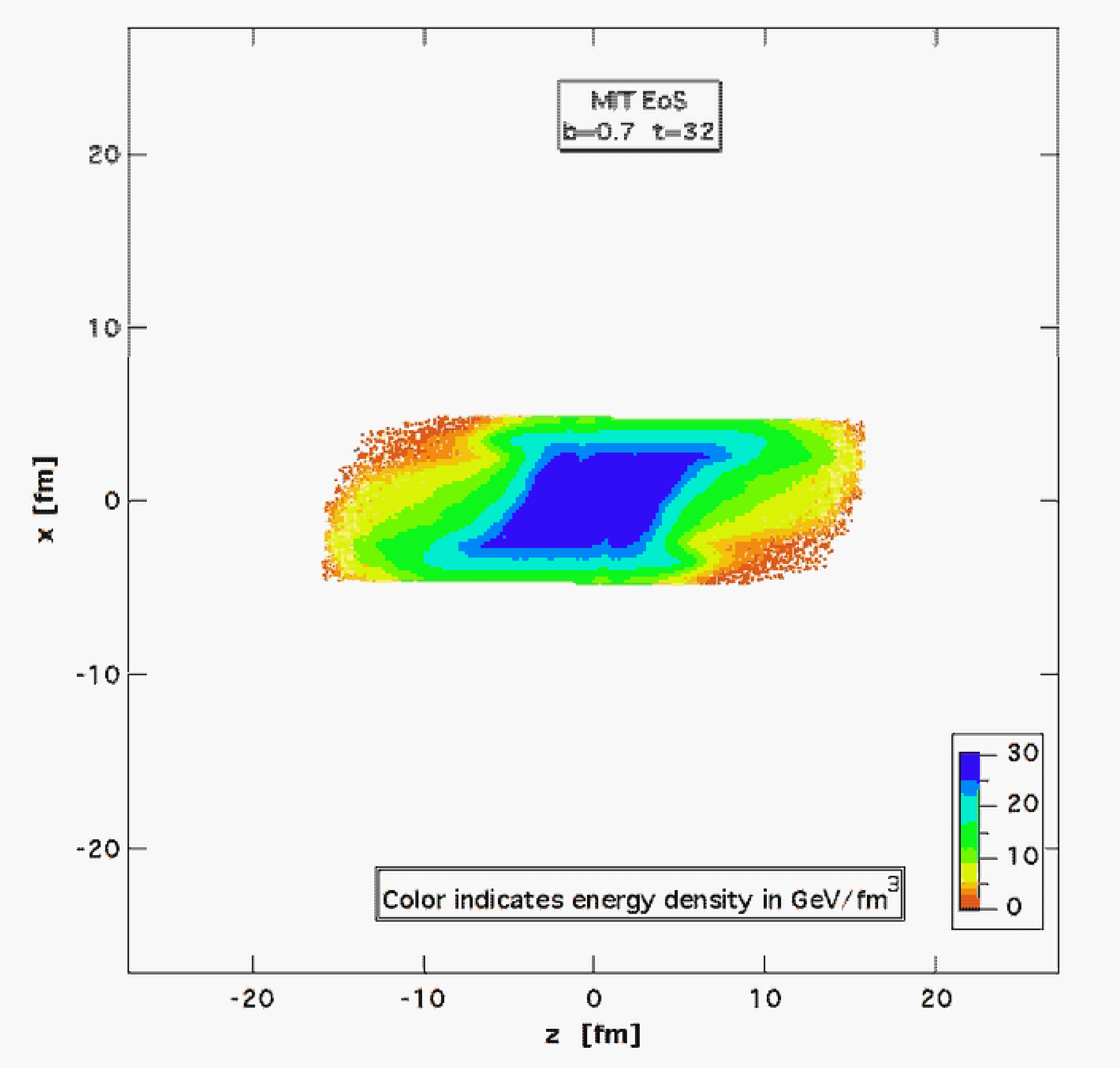


Au+Au at
65+65 A GEV,
b= 0.1 (R_p + R_t)

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

Cell resolution
tnc = 24

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



Au+Au 65+65 A GeV, b= 70 % of b_max

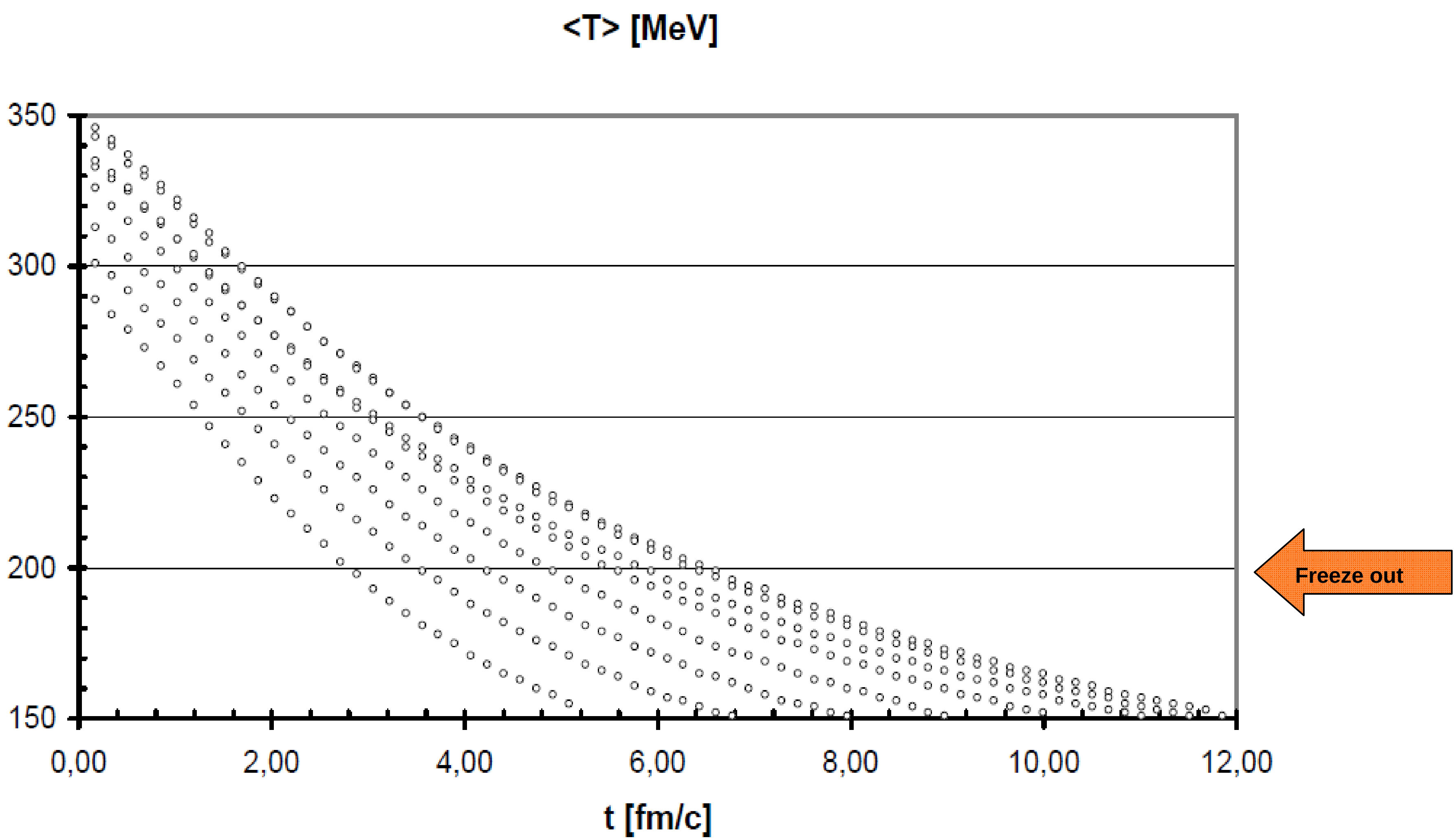
Lagrangian fluid cells, moving, ~ 5 mill.

MIT Bag m. EoS

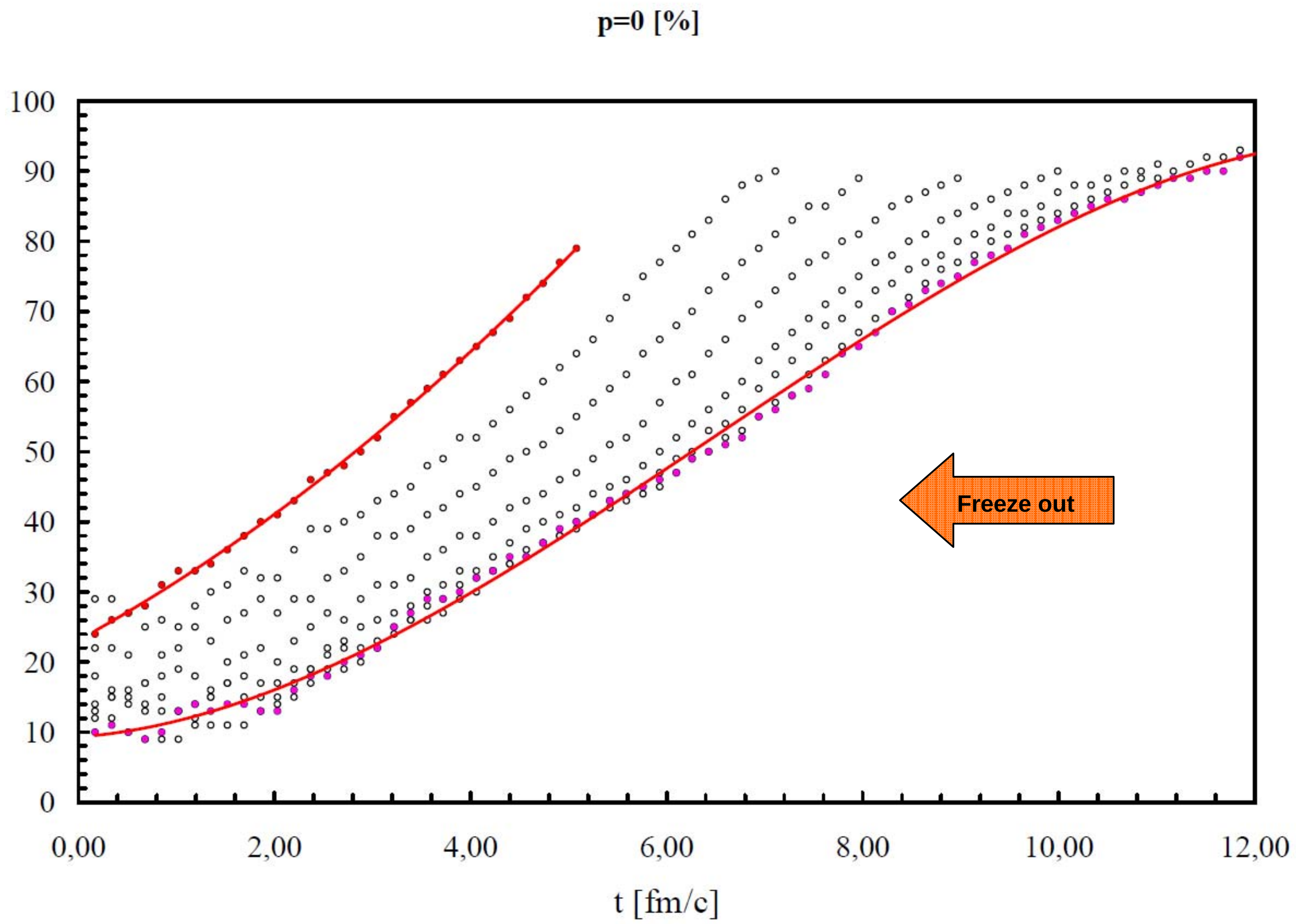
FO at T ~ 200 MeV, but calculated much longer, until pressure is zero for 90% of the cells.

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

Spatially tilted at FO, 3rd Flow component!

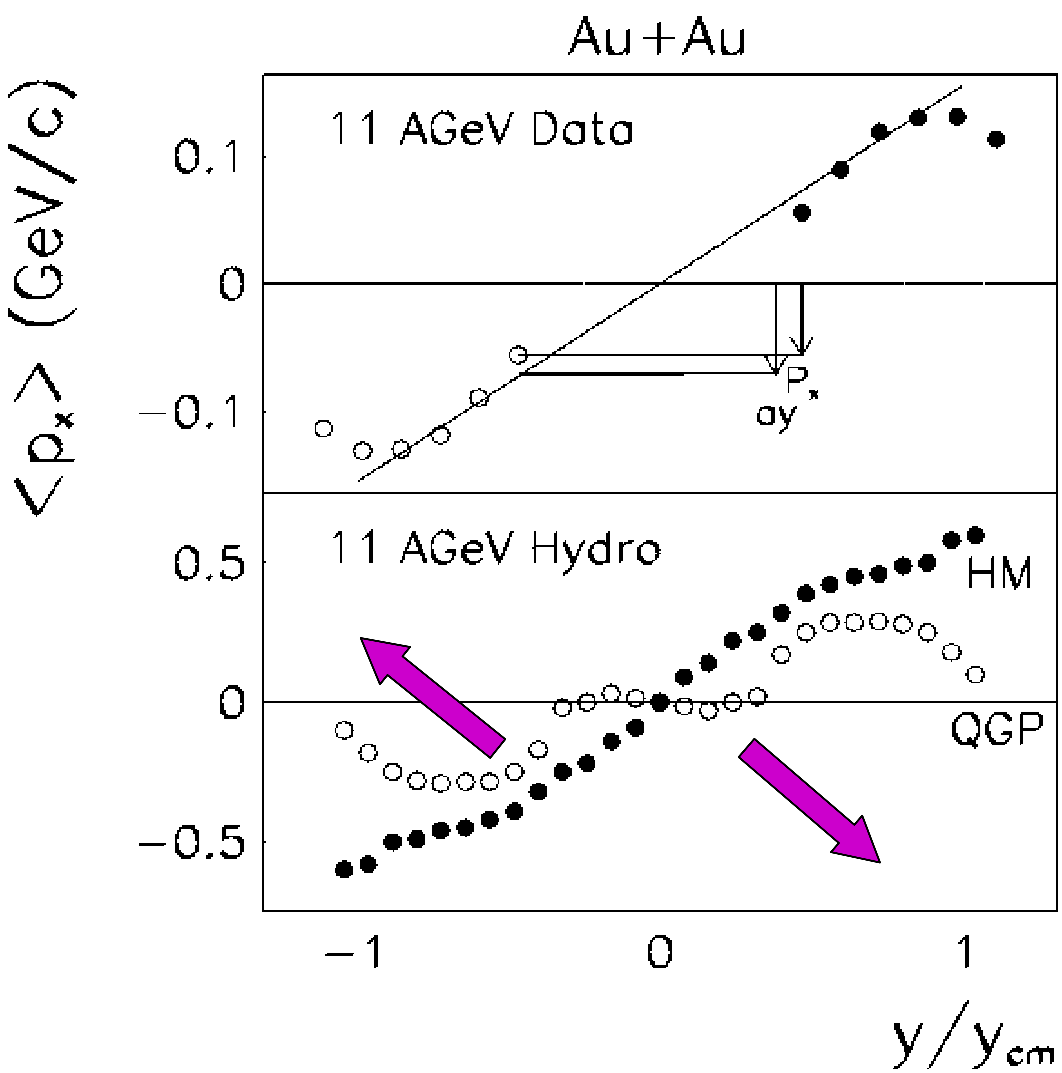


Average temperature versus time in Au+Au collisions at 65+65 AGeV, for impact parameters, b = 0, 0.1, 0.2, … 0.7 b_max from the top (0.00) down (0.7).



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, … 0.7 b_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



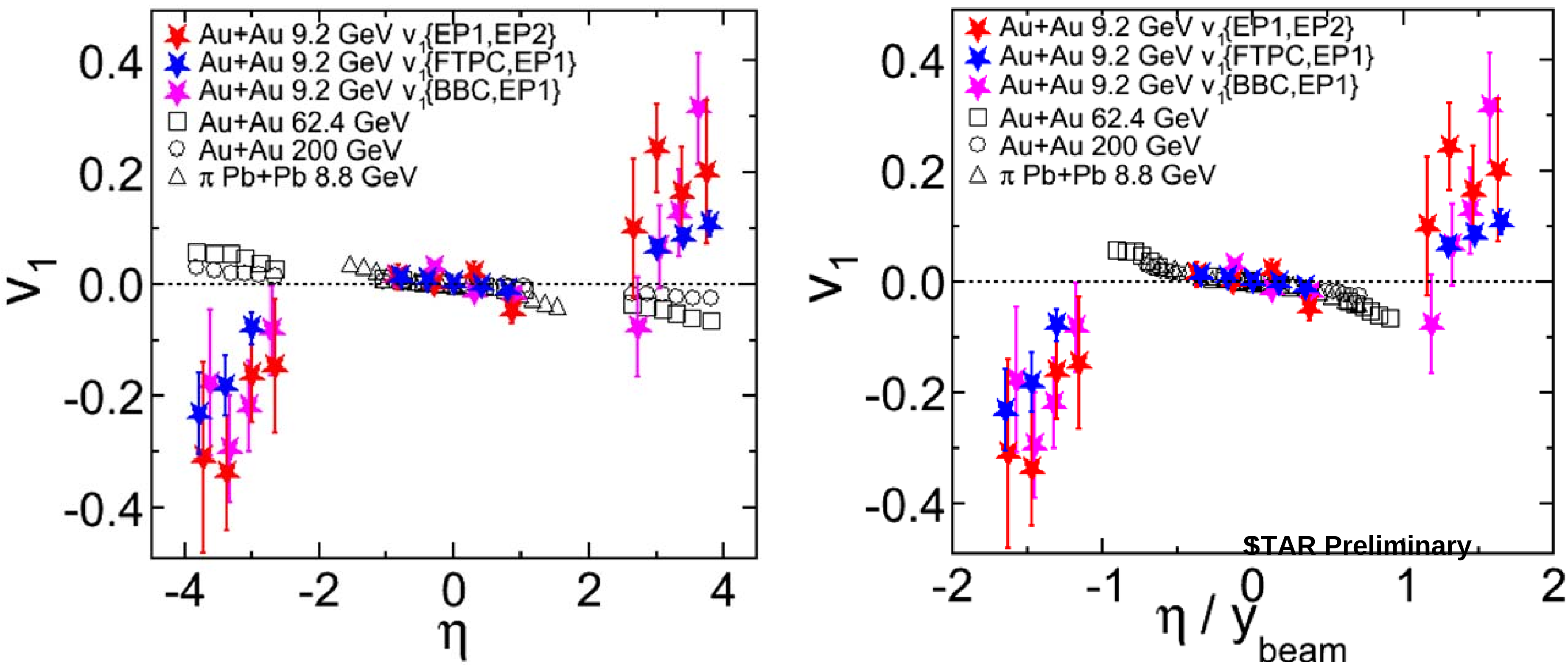
Csernai & Röhrich

[Phys.Lett. B458 **(99)** 454]

Hydro

[Csernai, HIPAGS ’93]

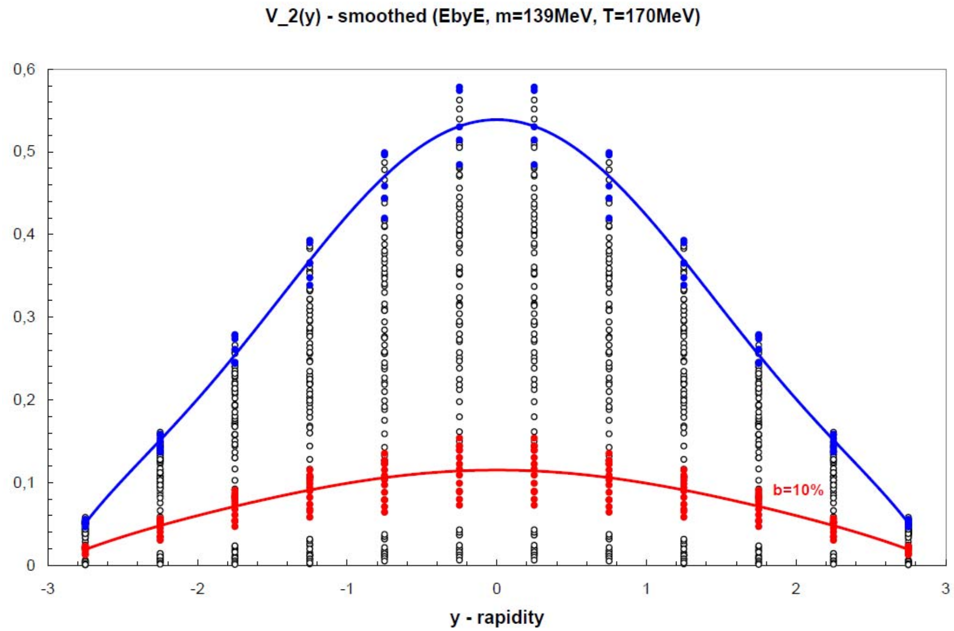
Directed Flow v_1

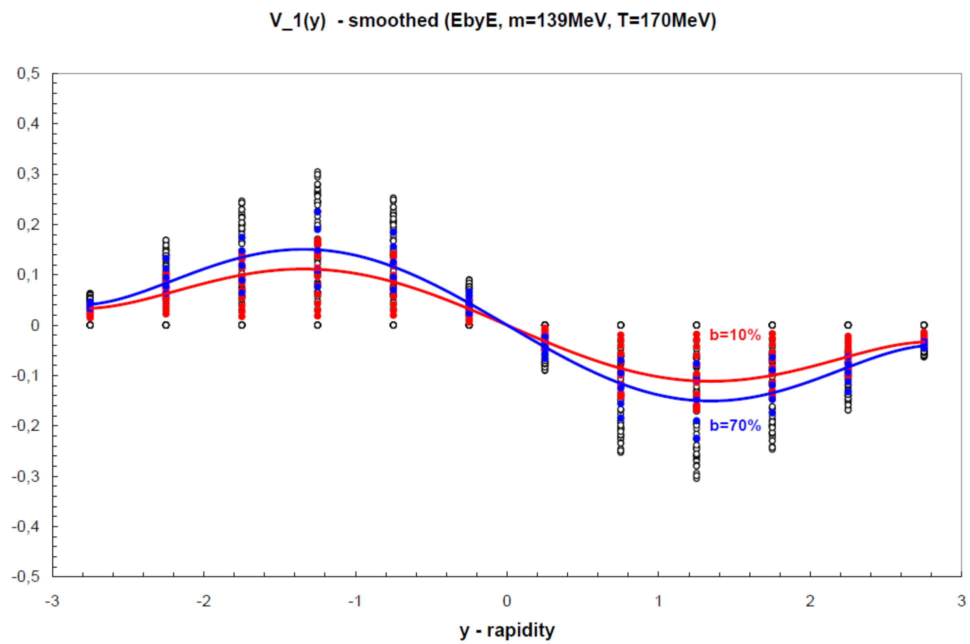


- At mid-rapidity, all the results have comparable values. At forward rapidity, the trend of v_1 from low energy is different from high energies. This is due to early longitudinal collision dynamics.
- V_1 values lie on a common trend.

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

Freeze Out



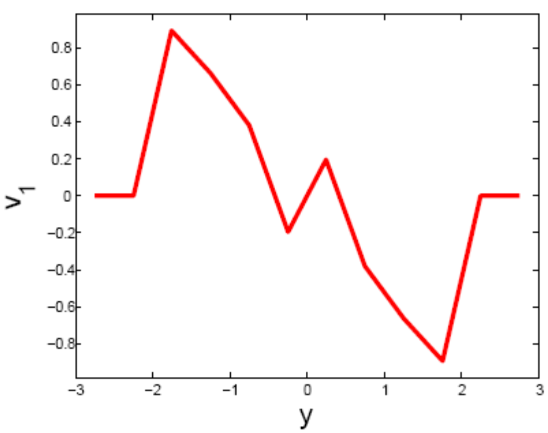


Pre FO:
V_1 and V_2 versus y from PIC hydro ,

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

For different impact parameters, b = 10% (70%) of b_max = R_p + R_t

Before Cooper Frye FO with 'thermal' distributions, (with m_cq, T_cq)!



NCQ - Importance of Initial State

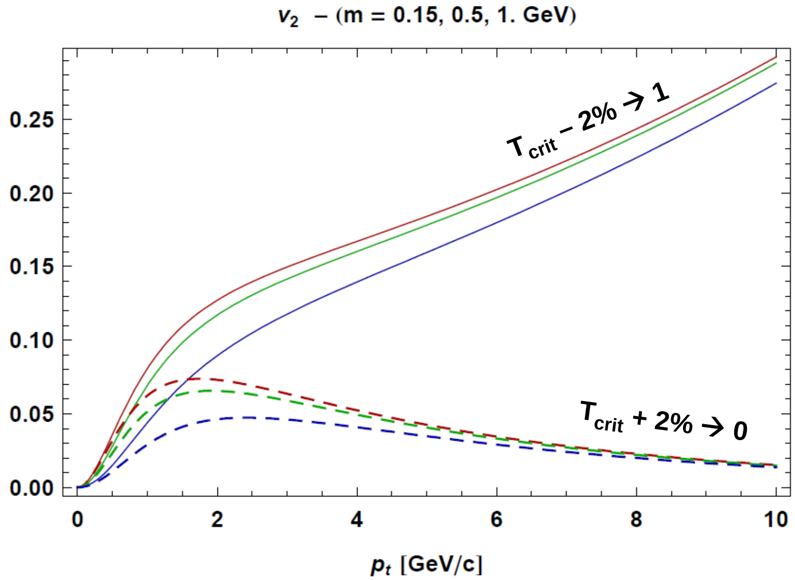
CF FO
[w/Mishustin]

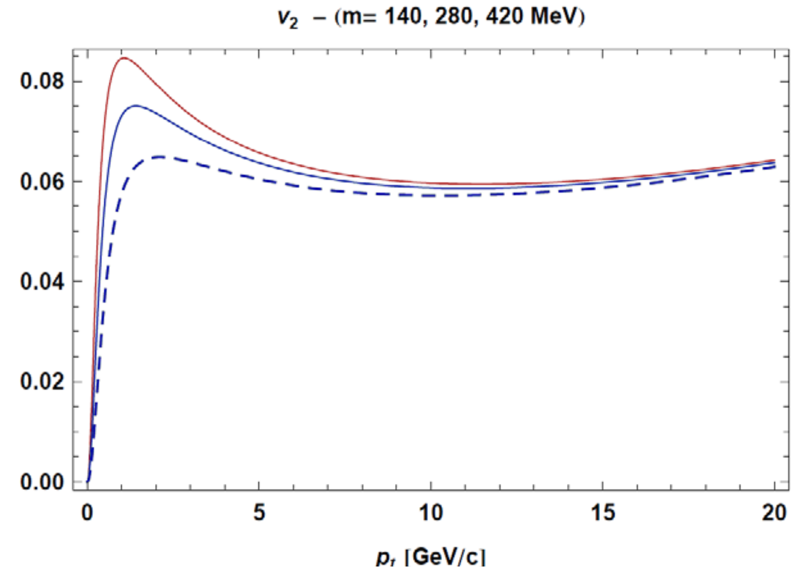
V_2 from few source models [Huovinen et al. 2001] v_2 (p_t) rises linearly at high p_t (Bjorken Model)

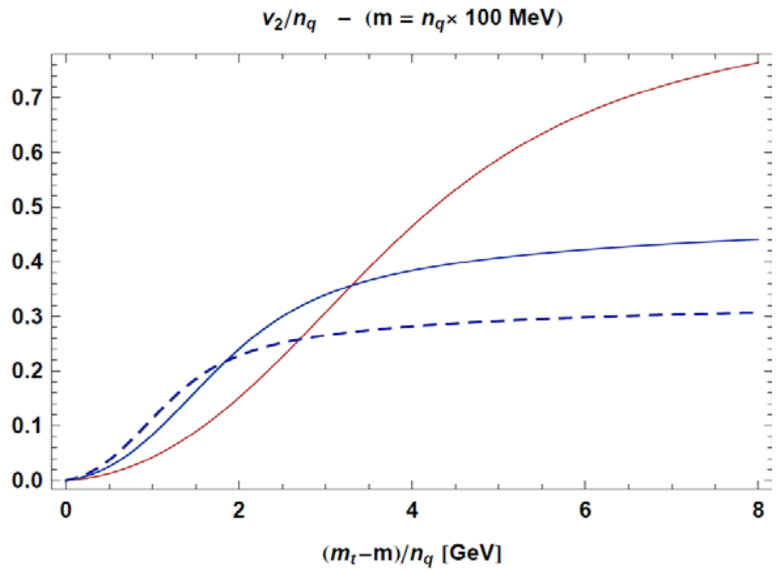
As Ac=
50 100

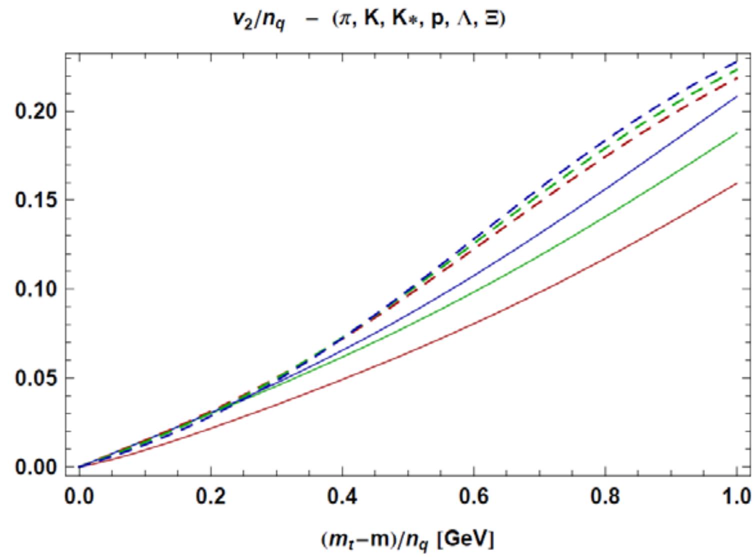
Ts=100
vx=0.2

Tcr=122









T (x) ←
→ u(x)

Hadron flow does not show NCQ scaling !!

Freeze Out

Rapid and simultaneous FO and "hadronization"

- **Improved Cooper-Frye FO**:
- \- Conservation Laws: $\left[T^{\mu\upsilon}\Lambda_\upsilon\right]=0, \quad \left[N^\upsilon\Lambda_\upsilon\right]=0$
- \- Post FO distribution: $\Theta(p^\upsilon\Lambda_\upsilon)\ f(p) > 0$

[L.P. Csernai, Sov. JETP, 65 (l987) 216.]

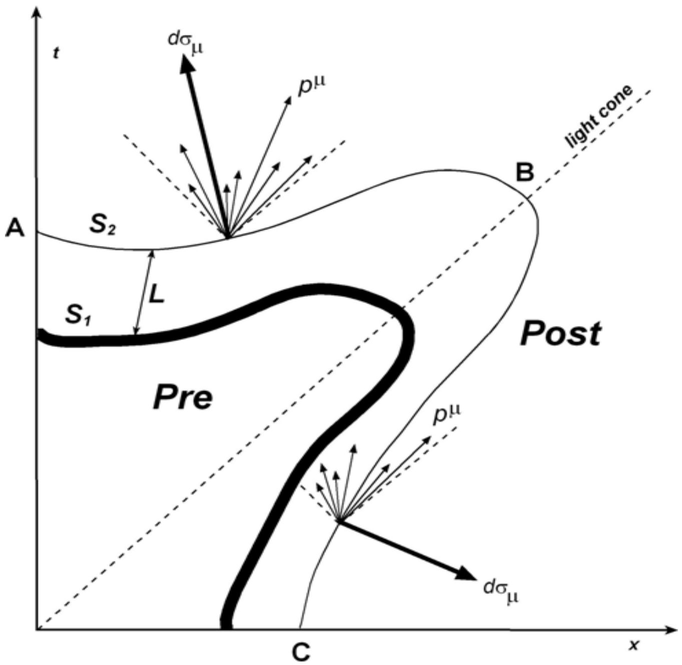
[Cancelling Juttner or Cut Juttner distributions.]

- **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:

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

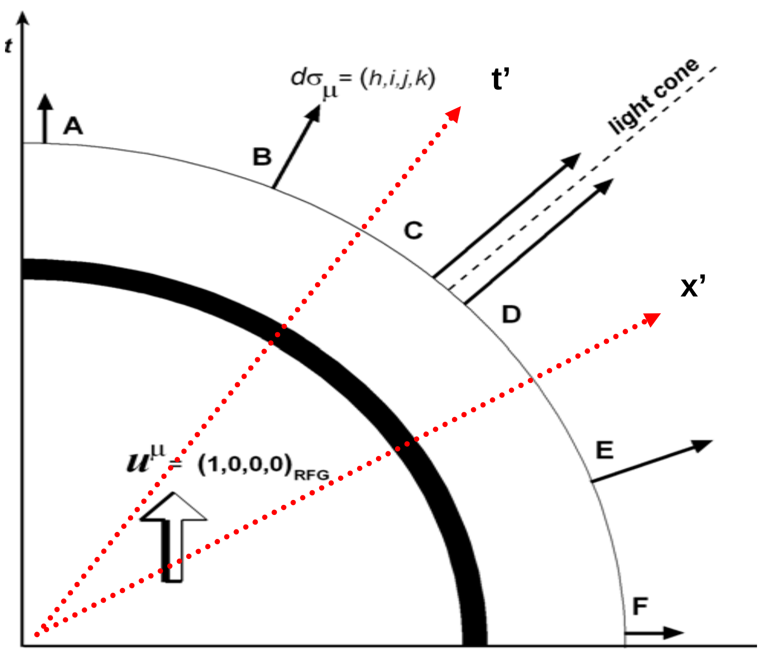
$$\begin{aligned} f_f(x,p) &= f_J(p) - f_i(x,p) \\ &= f_J(p)\left[1 - \left(\frac{L-s}{L}\right)^{\frac{L}{\lambda}\left(\frac{p^s}{p^\mu u_\mu}\right)\Theta(p^s)}\right] \\ &\xrightarrow{s\rightarrow L} \boxed{f_J(p)\Theta(p^s)} \end{aligned}$$

[**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.]

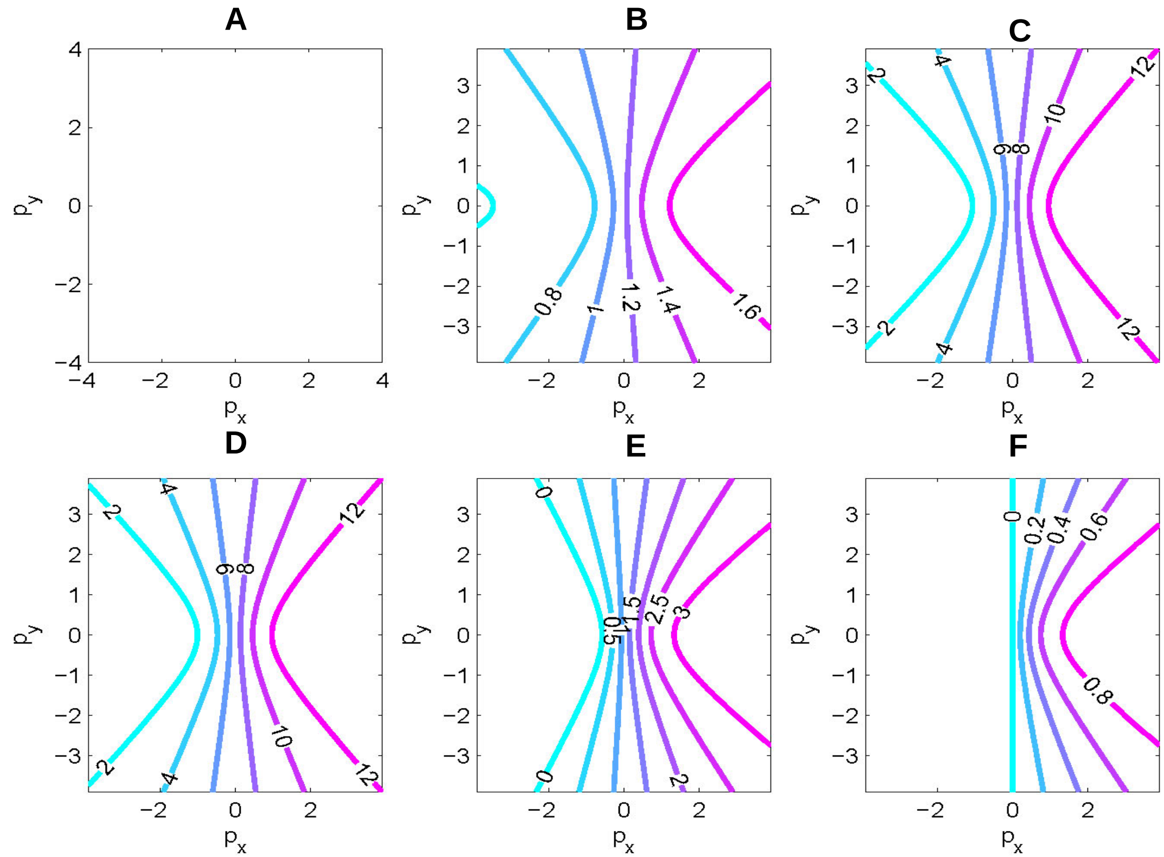
$f_J(p)\Theta(p_x)$	$f_J(p)$
Space-like	Time-like

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

The invariant " Escape" probability

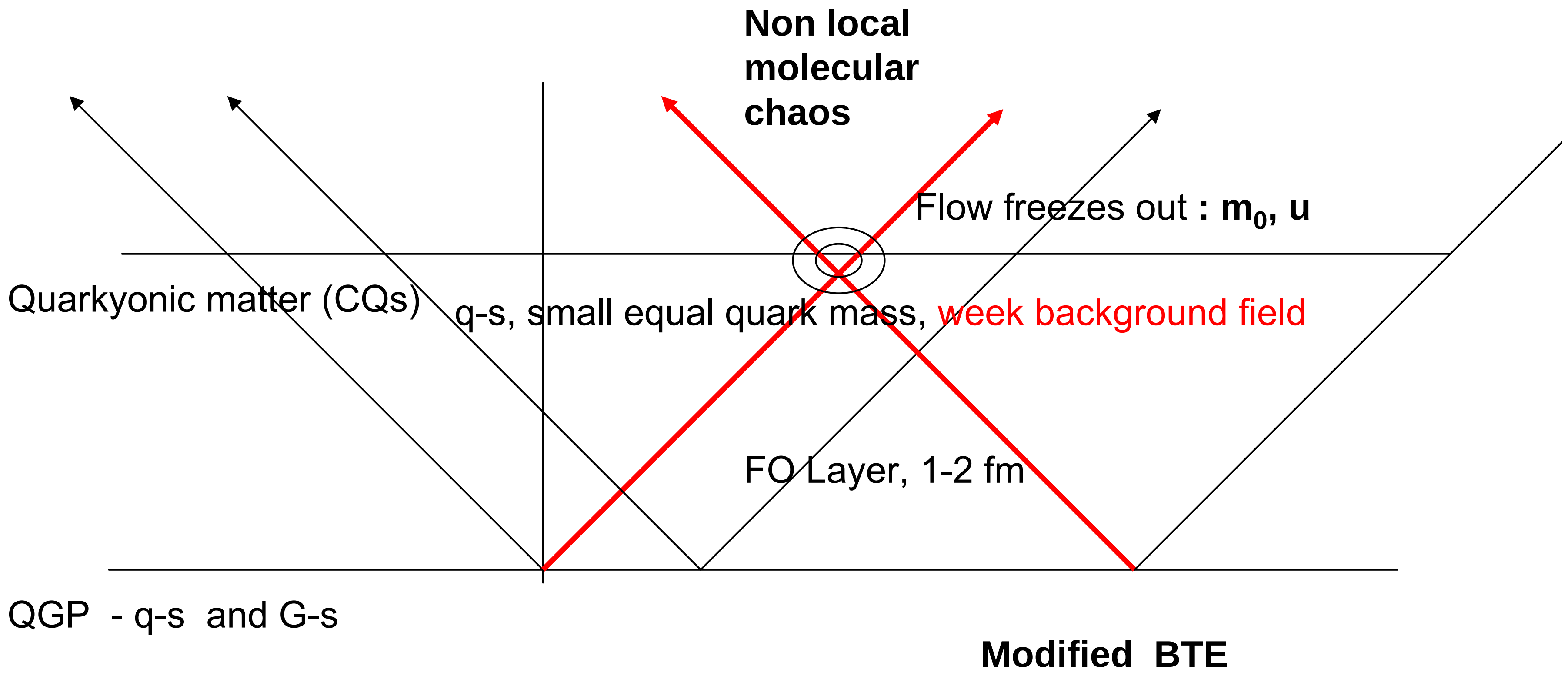


[RFG]



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_o . 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.

2nd step: $p_t / n_q \rightarrow KE_T / n_q = m_o (\sqrt{(1+u^2)} - 1) / n_q$

$\Rightarrow u \ll 1 : \; m_o u_T^2 / 2$

$\Rightarrow u \gg 1 : \; m_o u_T$

Thus, **NCQ scaling** of flow indicates dependence (equilibration) of transverse energy**:** flow velocity **u** and constituent quark mass, $\mathbf{m_o}$, 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 from 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 $v_2(p_t)$:

v1(p_t), v_2(y), v_1(y), Mach cone vs. p_t

SUMMARY

- **Initial state** is decisive and can be tested by v1 & v2
- v1: semi-central collisions, position depends on b, σ, Tf , NCQ ??
- v2 : 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** ← → **u**
- Numerical viscosity should be taken in correction
- **F.O.** : entropy condition
- → space like FO is weak at RHIC / LHC - important at FAIR
- → bulk viscosity causes negative pressure in expansion → rapid FO & H

The END