Collective flow and QGP properties
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Freeze-out and elliptic anisotropy

Pasi Huovinen
University of Jyväskylä

Freeze-out

- When/where particles scatter the last time
- Loosely speaking: "when mean free path is larger than system size"
- Mean free path depends strongly on temperature $\longrightarrow$ simple approximation: freeze-out at constant temperature/energy density
- Dynamical criterion (Bondorf *et al.* NPA296 (1978)): Freeze-out when expansion rate equals scattering rate:

$$\xi = \frac{\tau_{exp}}{\tau_{scat}} \approx 1$$

- Expansion time:

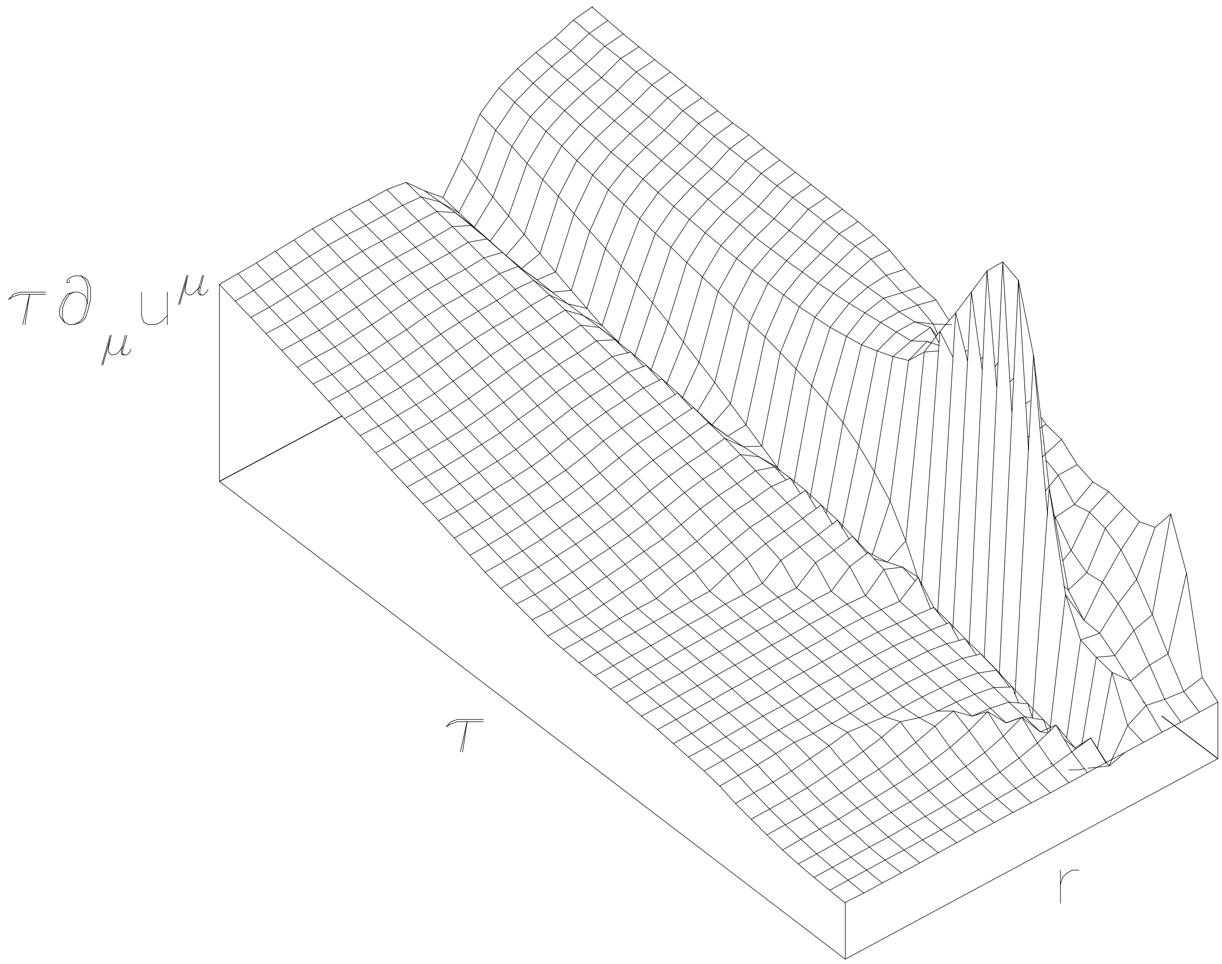
$$\tau_{exp} = \frac{1}{\partial_\mu u^\mu}$$

- Scattering rate of pions from Prakash *et al.* Phys. Rep. 227 (1993).

$$\tau_{\pi\pi}^{-1} \approx 16 \left(\frac{T}{100\,\mathrm{Me}V} \right)^4 \mathrm{Me}V$$

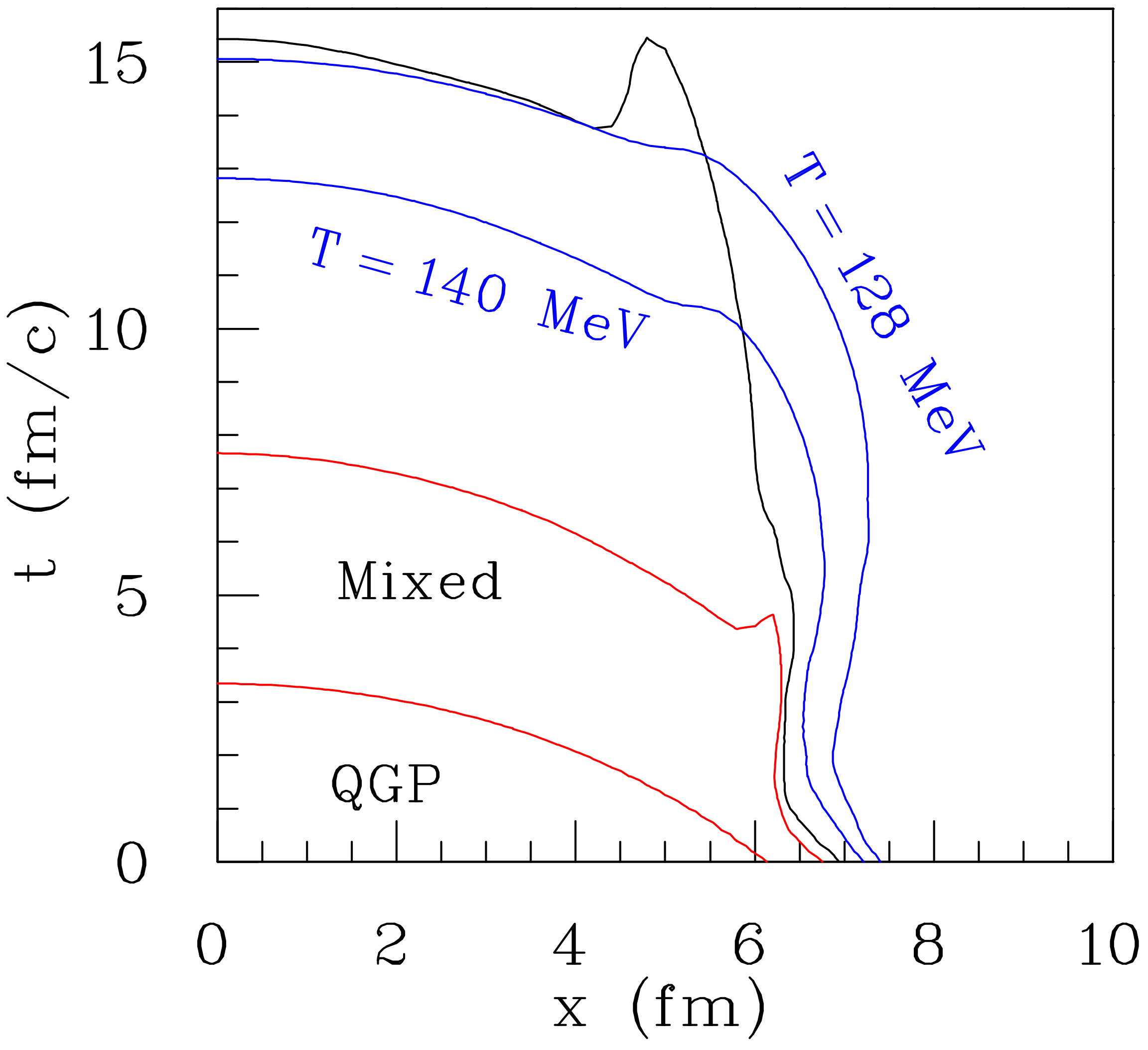
Parametrization by Daghigh & Kapusta, PRD65 (2002)

Expansion rate in almost central collision



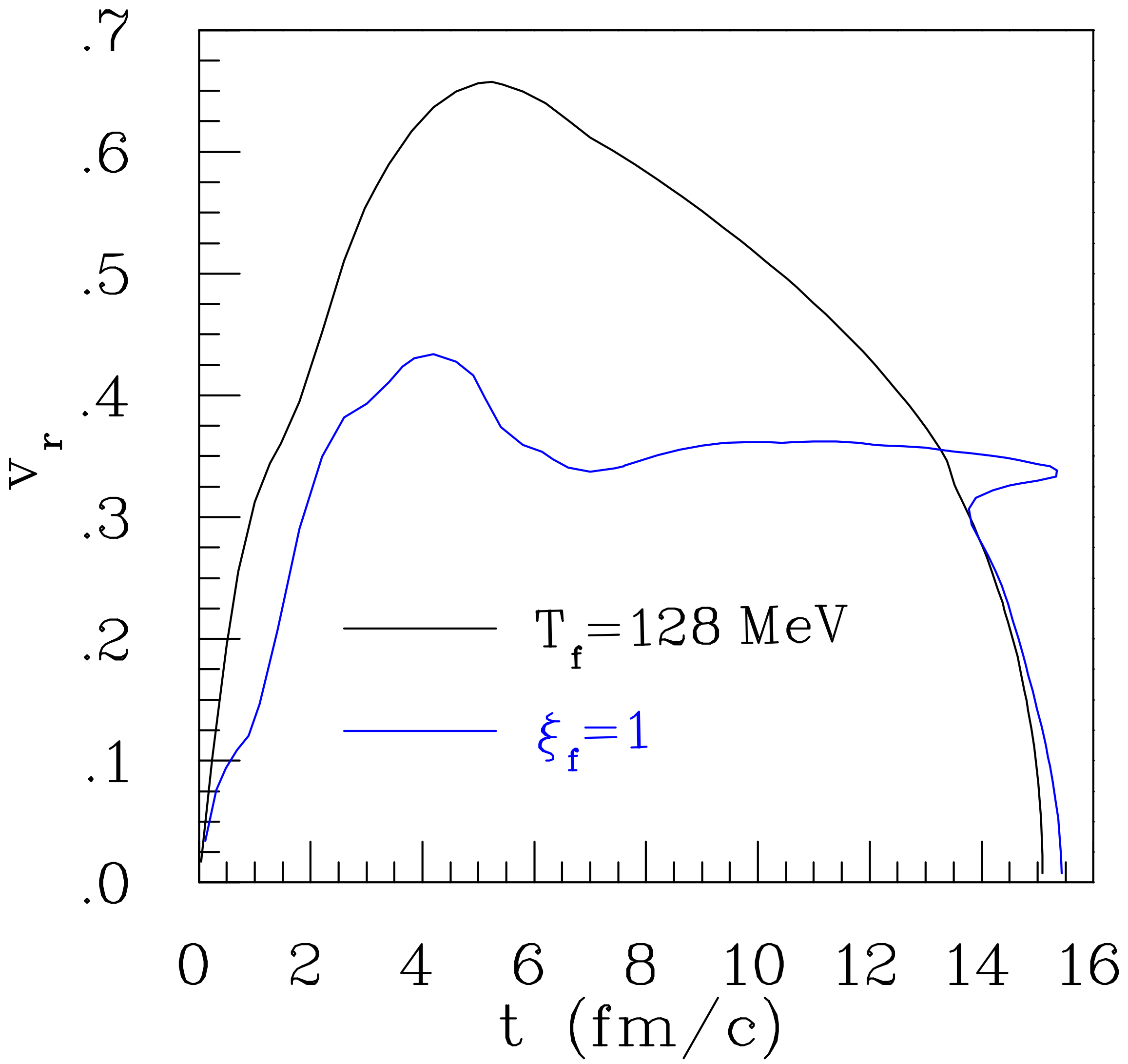
- Expansion rate $\partial_\mu u^\mu$ multiplied by time to remove "trivial" longitudinal expansion
- Rarefaction shock wave in the early stage
- "Valley of slow expansion" has its origin in mixed phase but it even after the system is completely hadronized

Freeze-out and constant temperature surfaces in *xt*-plane



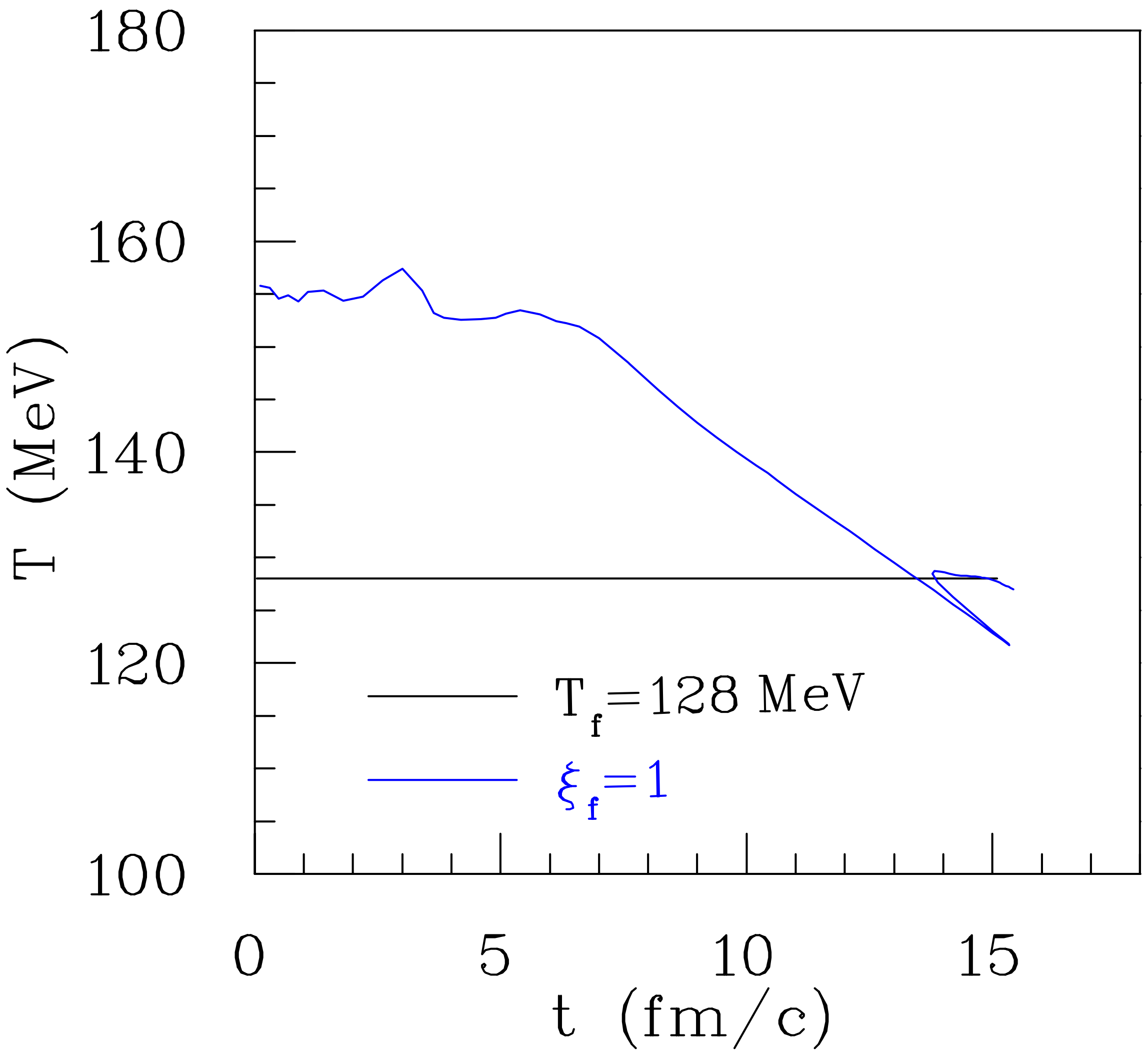
- Change in size small
- Most particles emitted in almost constant temperature

Transverse flow velocity on freeze-out surface as function of time



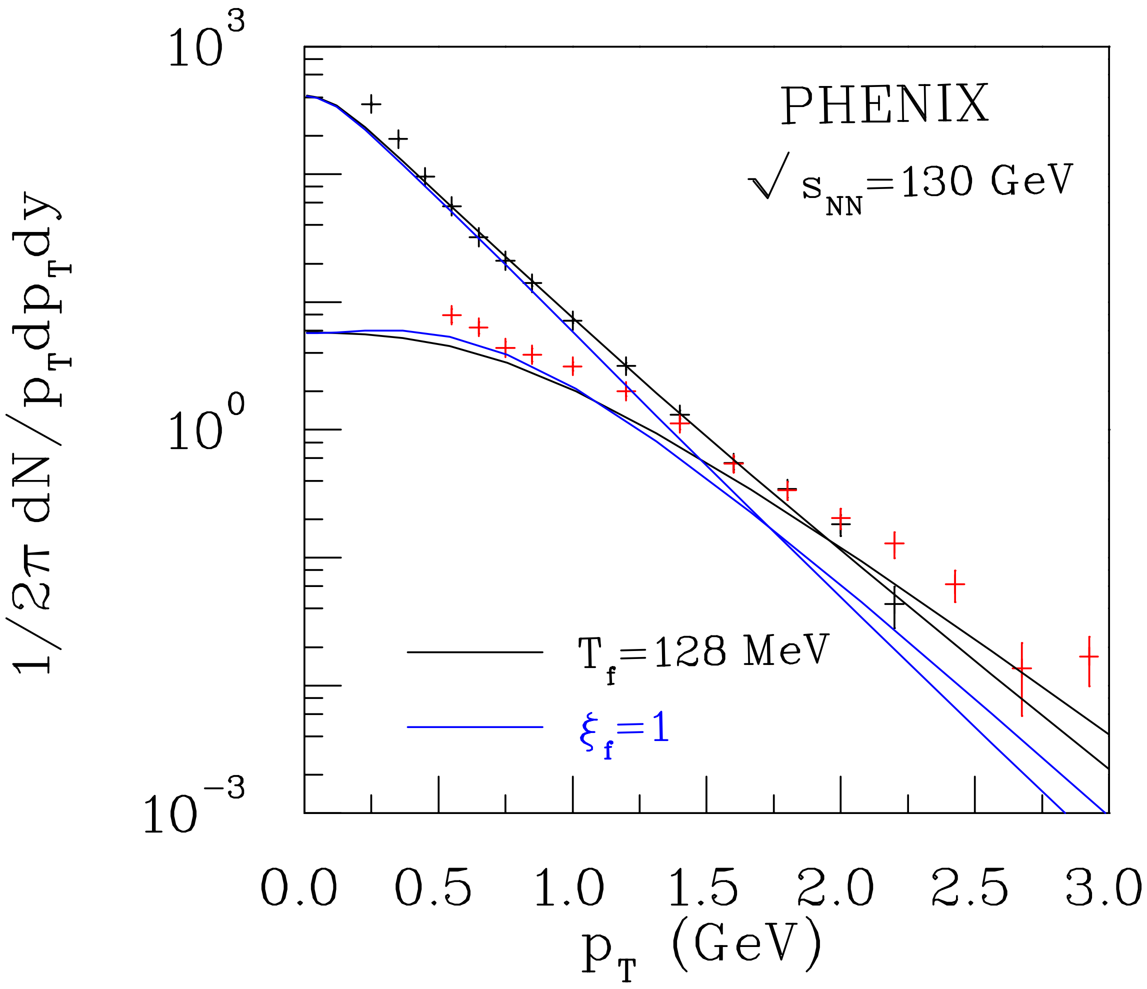
- Maximum flow velocity cut by almost a factor of two!

Temperature on freeze-out surface as function of time

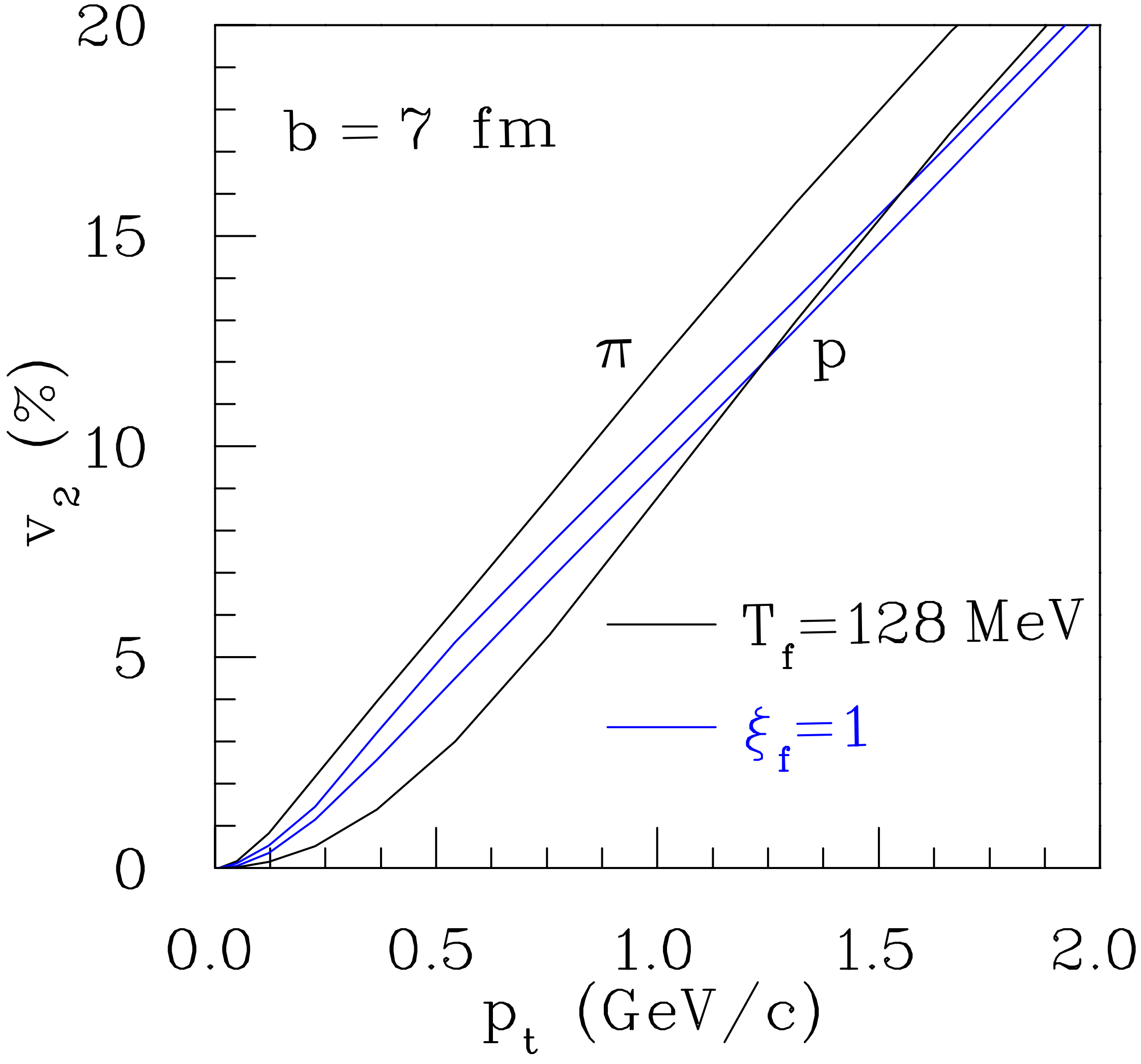


- Average temperature $\sim$ 140 MeV

Pion and antiproton p_T spectra for most central collisions

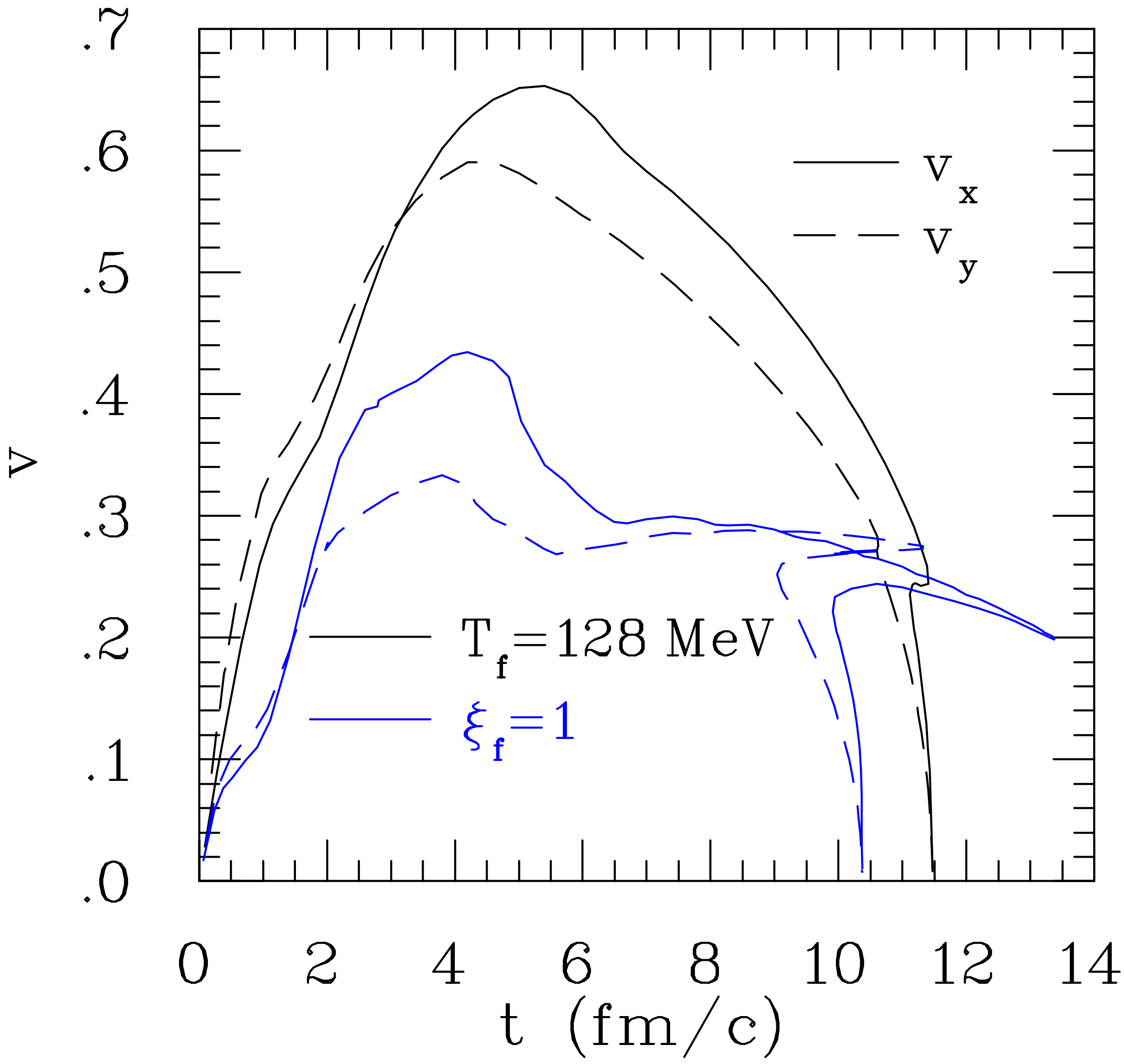


Pions and protons $v_2(p_t)$ in $b = 7$ fm collision



- Pion and proton v_2 close!
- Sign of shape, not flow anisotropy

Transverse flow velocity in in-plane and out-of plane directions

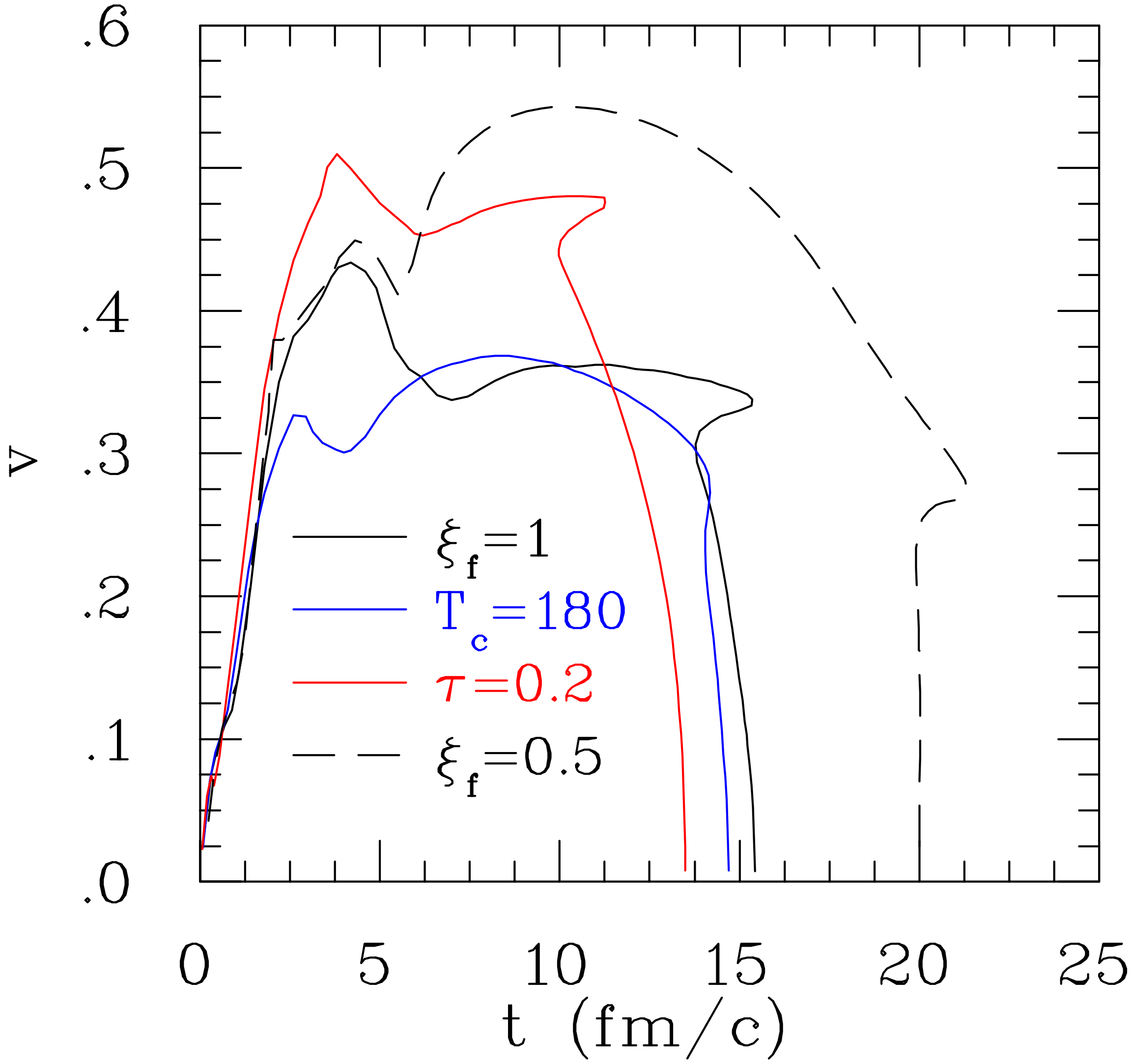


- Flow velocity in-plane and out-pf-plane almost similar after hadronization shock disappears

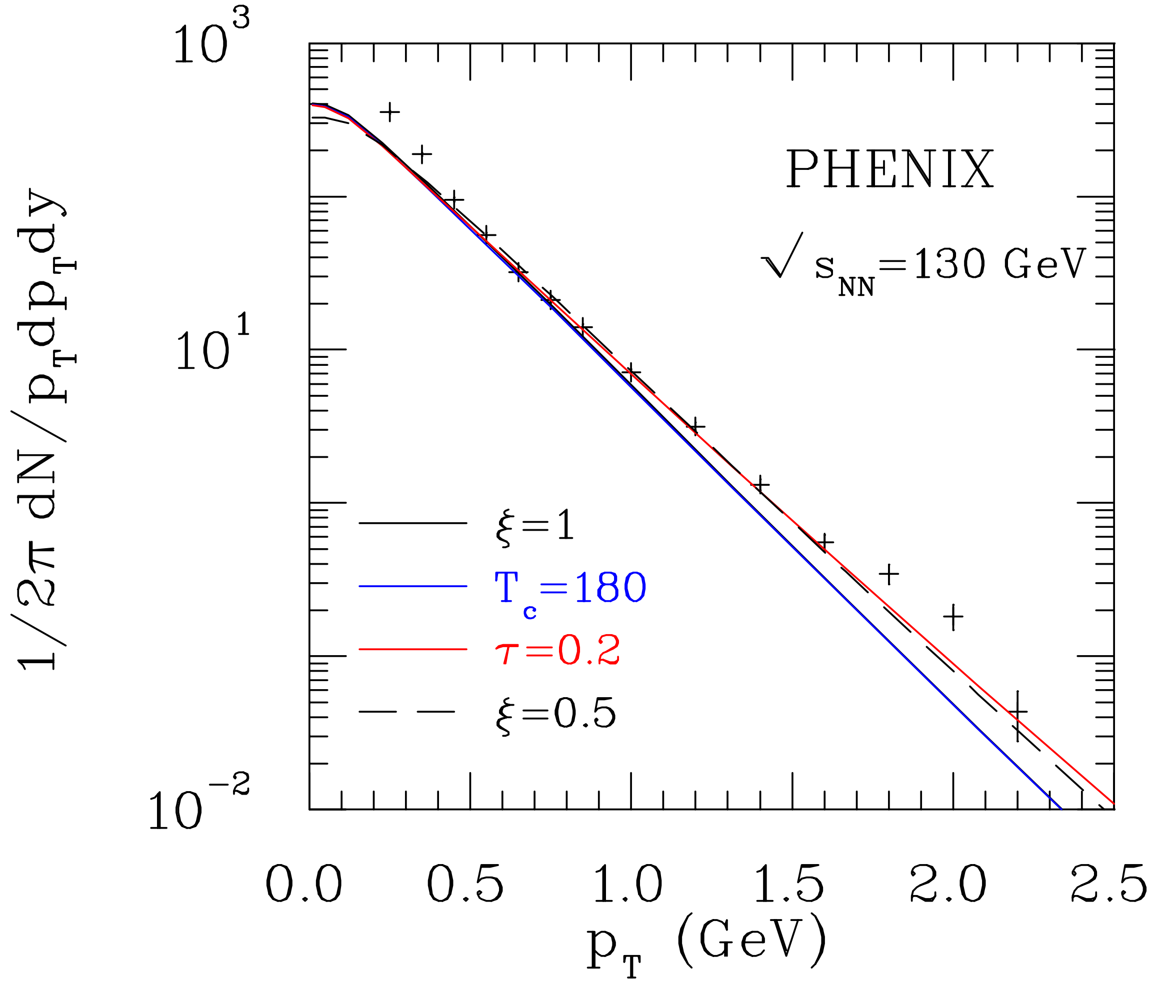
How to create more flow?

- Stiffer EoS
  - higher $T_c \to T_c = 180$ MeV instead of 165 MeV
- Steeper initial gradients
  - Participant vs. binary collisions scaling
- Shorter initial time
  - $\tau_0 = 0.2$ fm/c instead of 0.6 fm/c
- Later freeze-out
  - $\xi = 0.5$ instead of 1

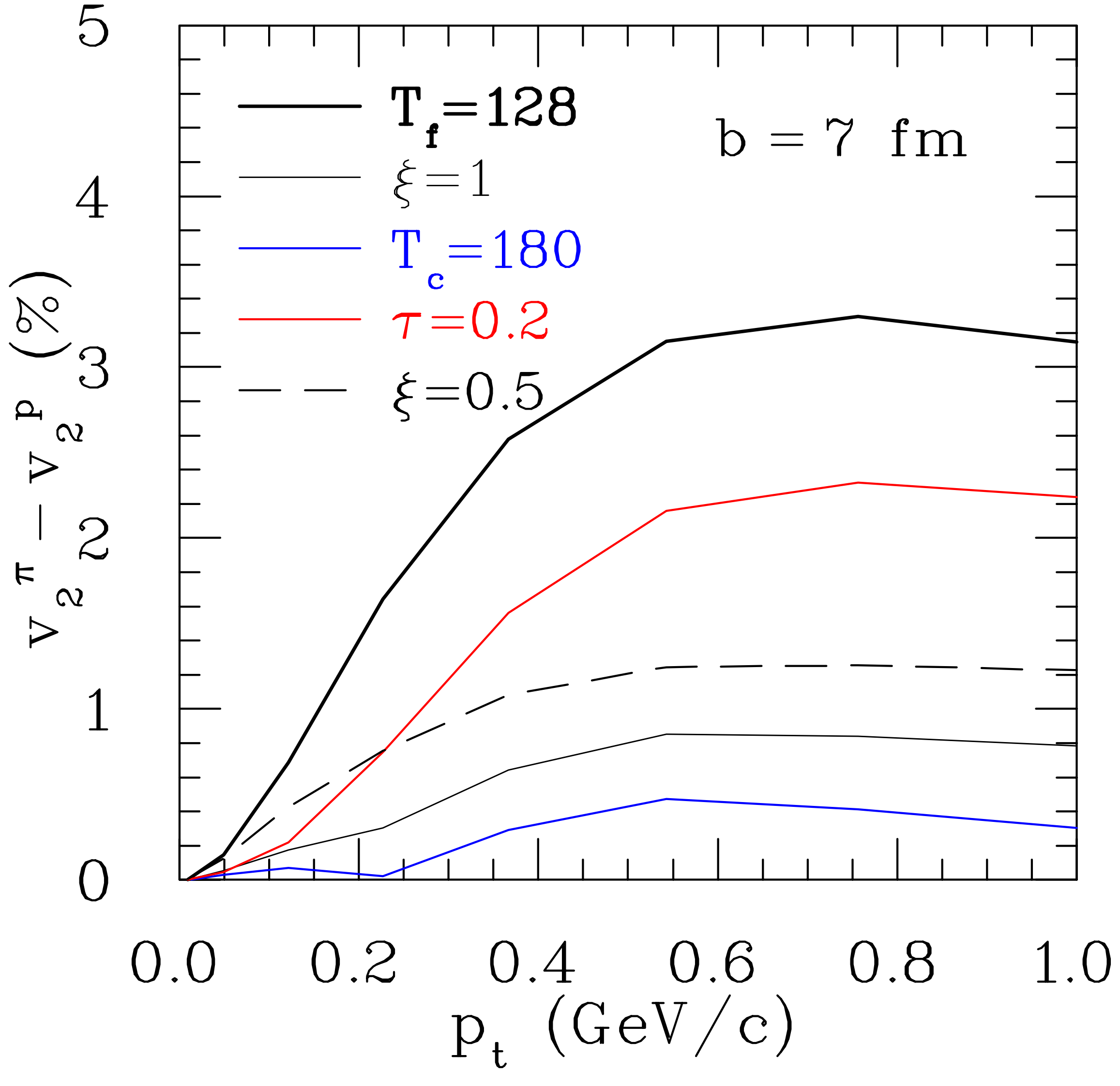
The effect of EoS, initial state and ξ_f on transverse flow velocity



The effect of EoS, initial state and ξ_f on pion p_T spectrum



Difference between pion and proton $v_2(p_T)$



Summary

- Freeze-out at constant temperature/density is over-idealization
- But freeze-out where expansion and scattering rates are equal does not fit the data!
  - seem to need larger scattering rates in hadron gas
- Possible solutions
  - scattering rate wrong?
  - EoS with smooth crossover $\longrightarrow$ no shock $\longrightarrow$ smoother expansion?
  - EoS with smaller T_c?
  - Continuous freeze-out from 4-volume?