Dynamical freeze-out in event-by-event hydrodynamics

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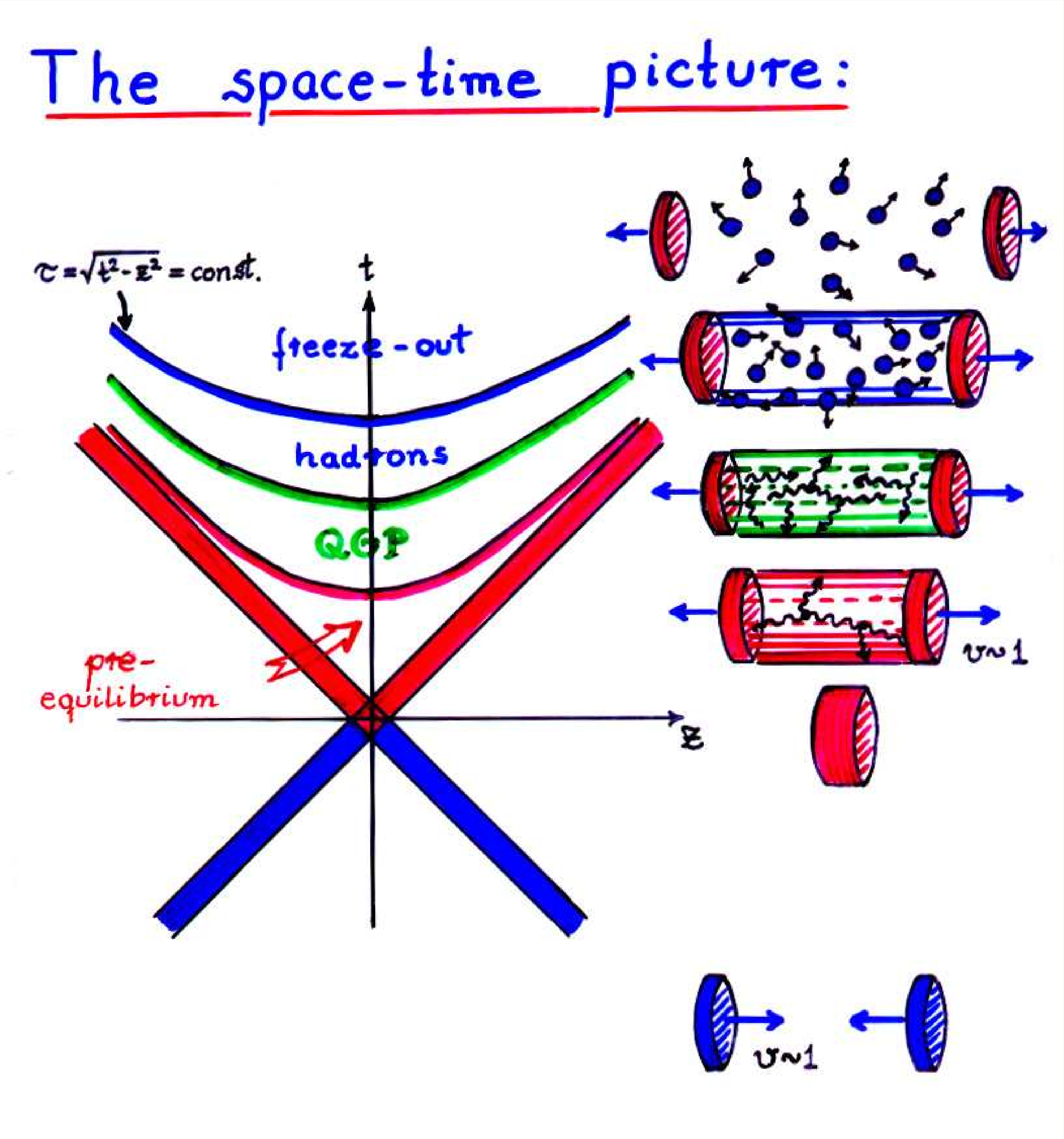

The space-time picture:
$\tau = \sqrt{t^2 - z^2}$ = const.
t
freeze-out
hadrons
QGP
pre-
equilibrium
z
v~1
v~1

Freeze-out

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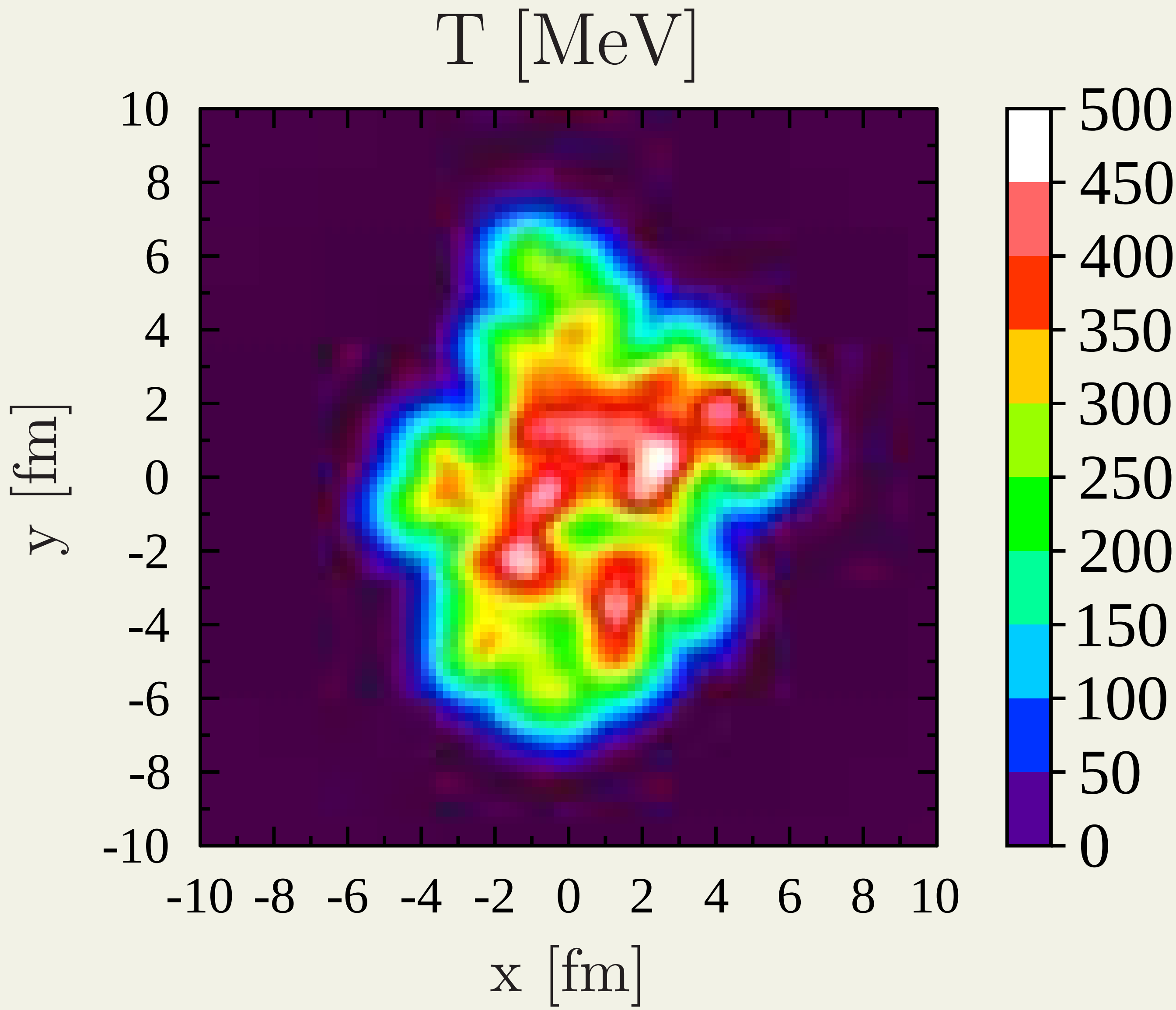
- $\tau_{\mathrm{scat}}^{-1} \propto T^4 \rightarrow$ rapid transition to free streaming
- **Approximation:** decoupling takes place on constant temperature hypersurface $T = T_{\mathrm{fo}}$



fluctuating initial state $\Longrightarrow$ large gradients

Dynamical criterion

- **need to evaluate**

$$\frac{1}{K_n} = \frac{\tau_{\text{scat}}^{-1}}{\partial_\mu u^\mu}$$

- $\partial_\mu u^\mu$ **known from hydro**
- τ_{scat}^{-1}**?**

Dynamical criterion

- need to evaluate

$$\frac{1}{K_n} = \frac{\tau_{\rm scat}^{-1}}{\partial_\mu u^\mu}$$

- $\partial_\mu u^\mu$ known from hydro
- $\tau_{\rm scat}^{-1}$?
  - Prakash *et al.*, Phys. Rept. 227, 321 (1993):

    Parametrization: Daghigh & Kapusta, Phys. Rev. D 65, 064028 (2002)

$$\tau_{\pi\pi}^{-1}(T) \approx 16 \left(\frac{T}{100\ \rm MeV}\right)^4 \rm MeV$$

- pions only, chemical equilibrium

Scattering rate

- **evaluate scattering rate of pions in thermal hadron gas**
  - **number of scatterings:** $N = F_1 N_2 \sigma_{12} = n_1 |\vec{v}_{12}| N_2 \sigma_{12}$
  - $|\vec{v}_{12}| = \sqrt{(s-s_a)(s-s_b)}/(2E_a E_b)$
    where $s_a = (m_1 + m_2)^2$ **and** $s_b = (m_1 - m_2)^2$
  - **fold over thermal distributions**
  - **sum over all scattering partners**
  - **scatterings per pion $\rightarrow$ divide by pion density**

$$\tau_{\mathrm{scat}}^{-1} = \frac{1}{n_\pi(T,\mu_\pi)} \sum_i \int \mathrm{d}^3 p_\pi \, \mathrm{d}^3 p_i \, f_\pi(T,\mu_\pi) f_i(T,\mu_\pi) \frac{\sqrt{(s-s_a)(s-s_b)}}{2E_\pi E_i} \sigma_{\pi i}(s)$$

- **what is $\sigma_{\pi i}$?**

Cross sections

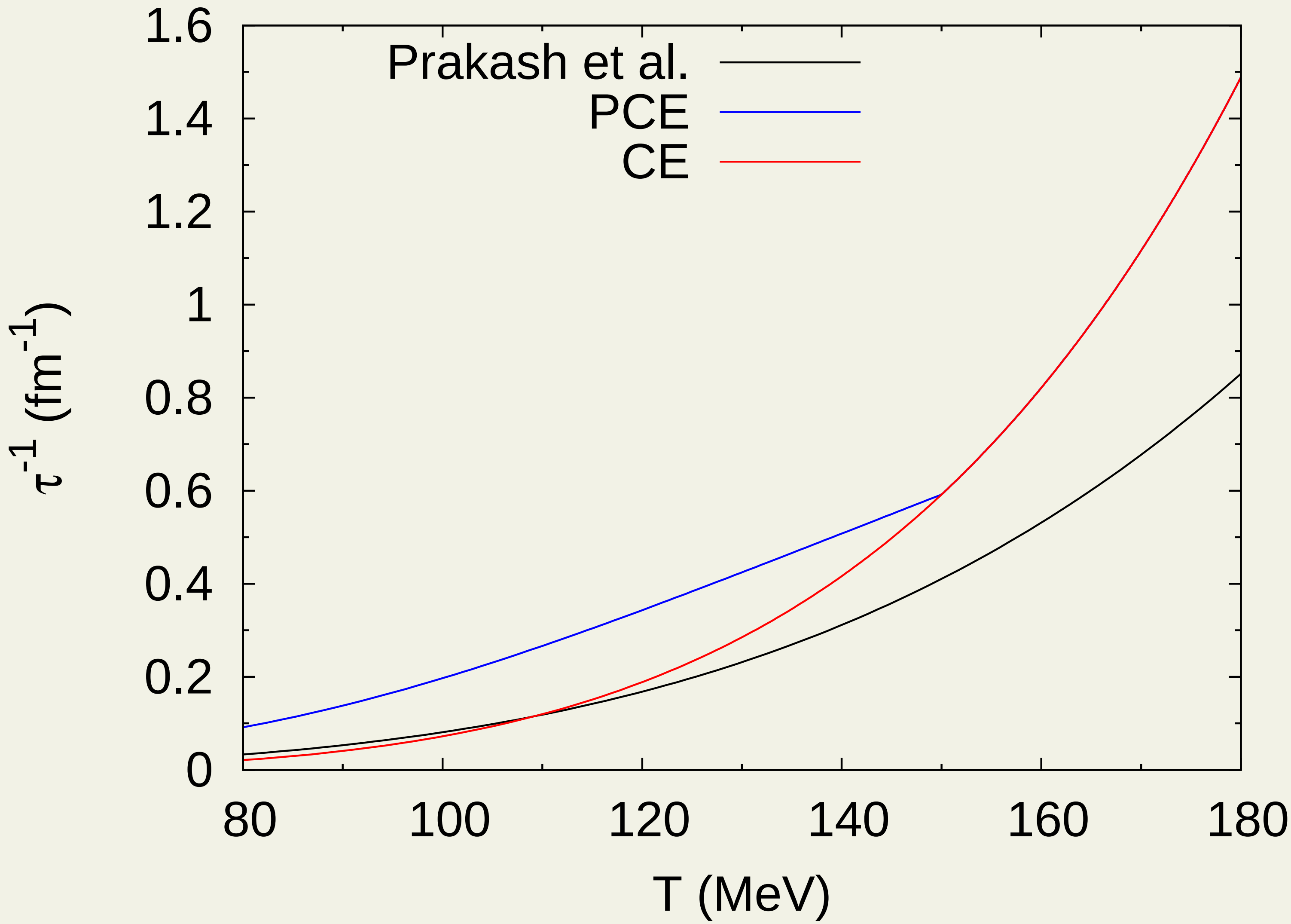
- as in UrQMD:
  - $\sigma_{\pi i}(s)$ for resonance formation using Breit-Wigner

$$\sigma_{\pi i}(s) = \sum_{R} \sigma_{\pi i \to R}(s)$$

  - estimate $\sigma_{\pi m}(s)$ for elastic π-meson scattering

$\Rightarrow$ check that the result fits the cross section data

Scattering rate

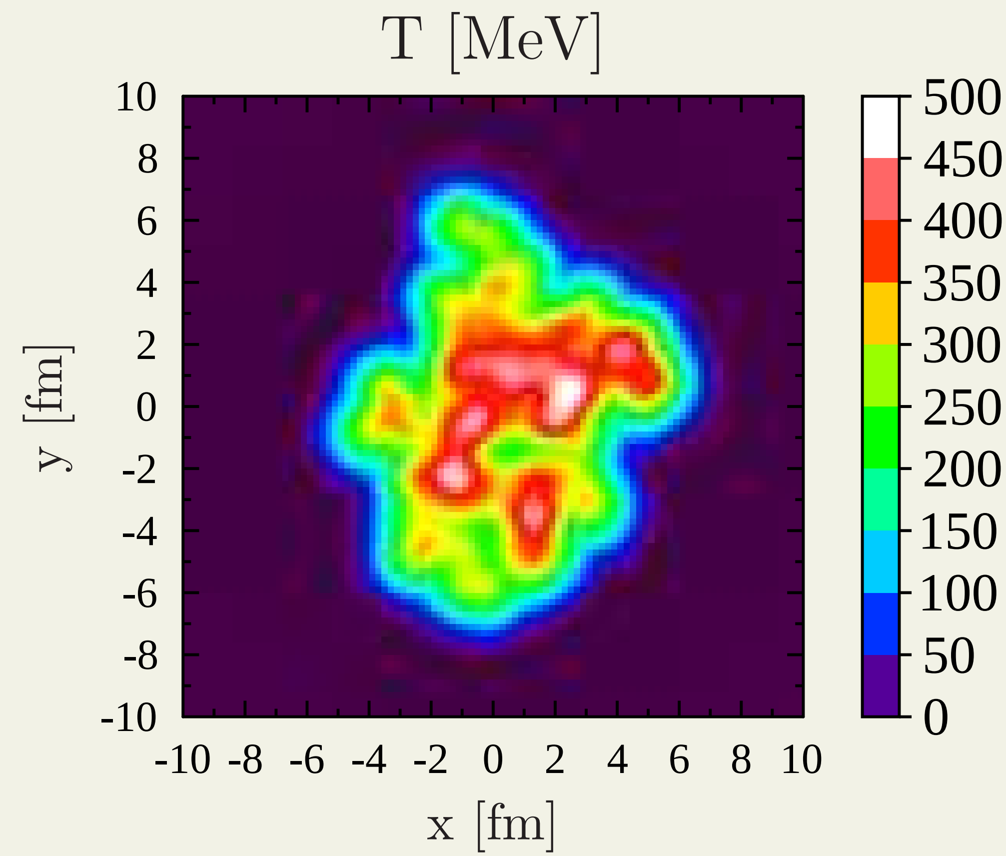


Hydro

- **ideal**
- **boost-invariant, 2+1D**
- **lattice based EoS, $s95p$-PCE-v1**
- $T_{\mathrm{chem}} = 150$ **MeV**
- **Au+Au at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV**

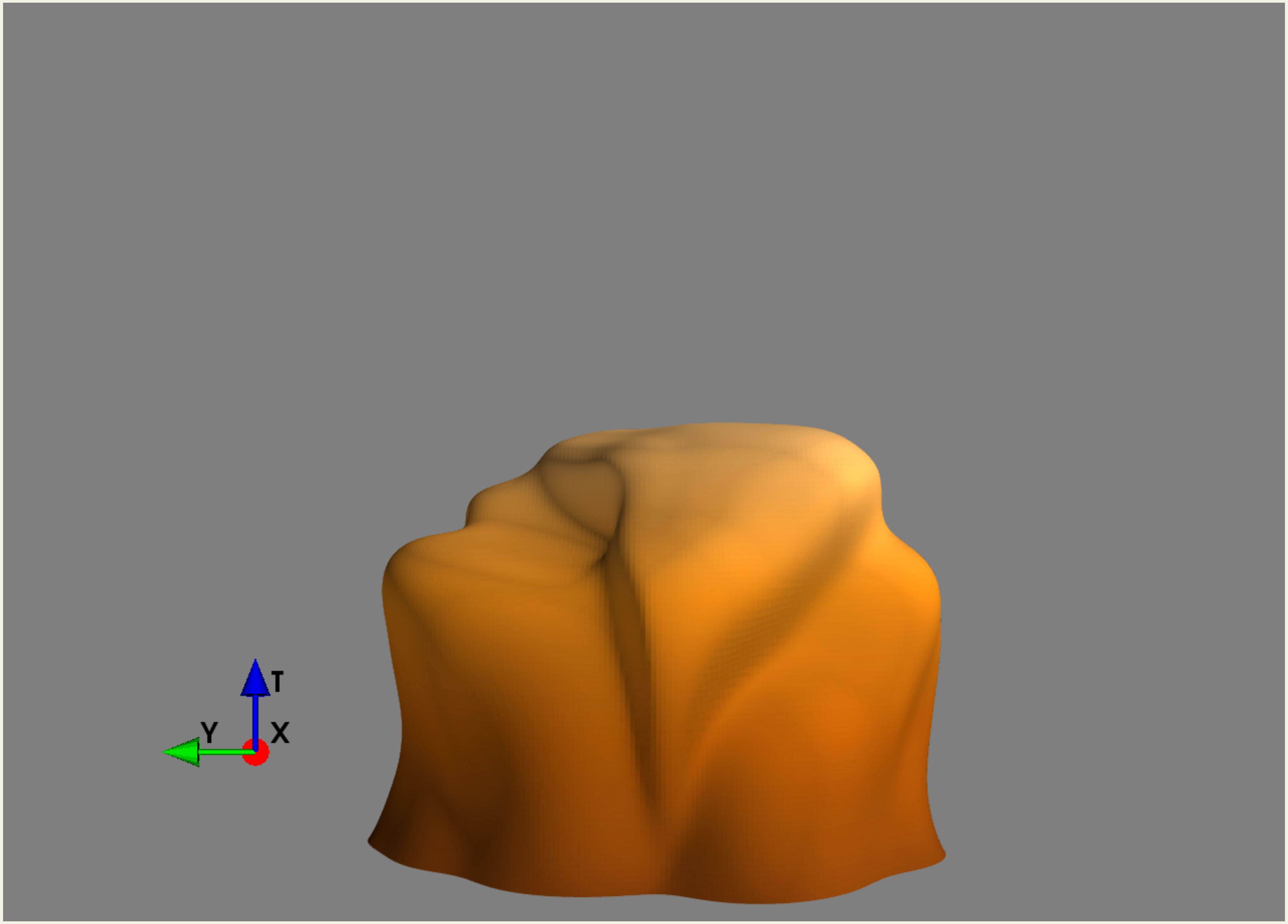
Fluctuating initial state

- **Monte Carlo Glauber**
- **Entropy density is distributed around the positions of WN and BC**
- **When distributing entropy we use Gaussian smearing:**

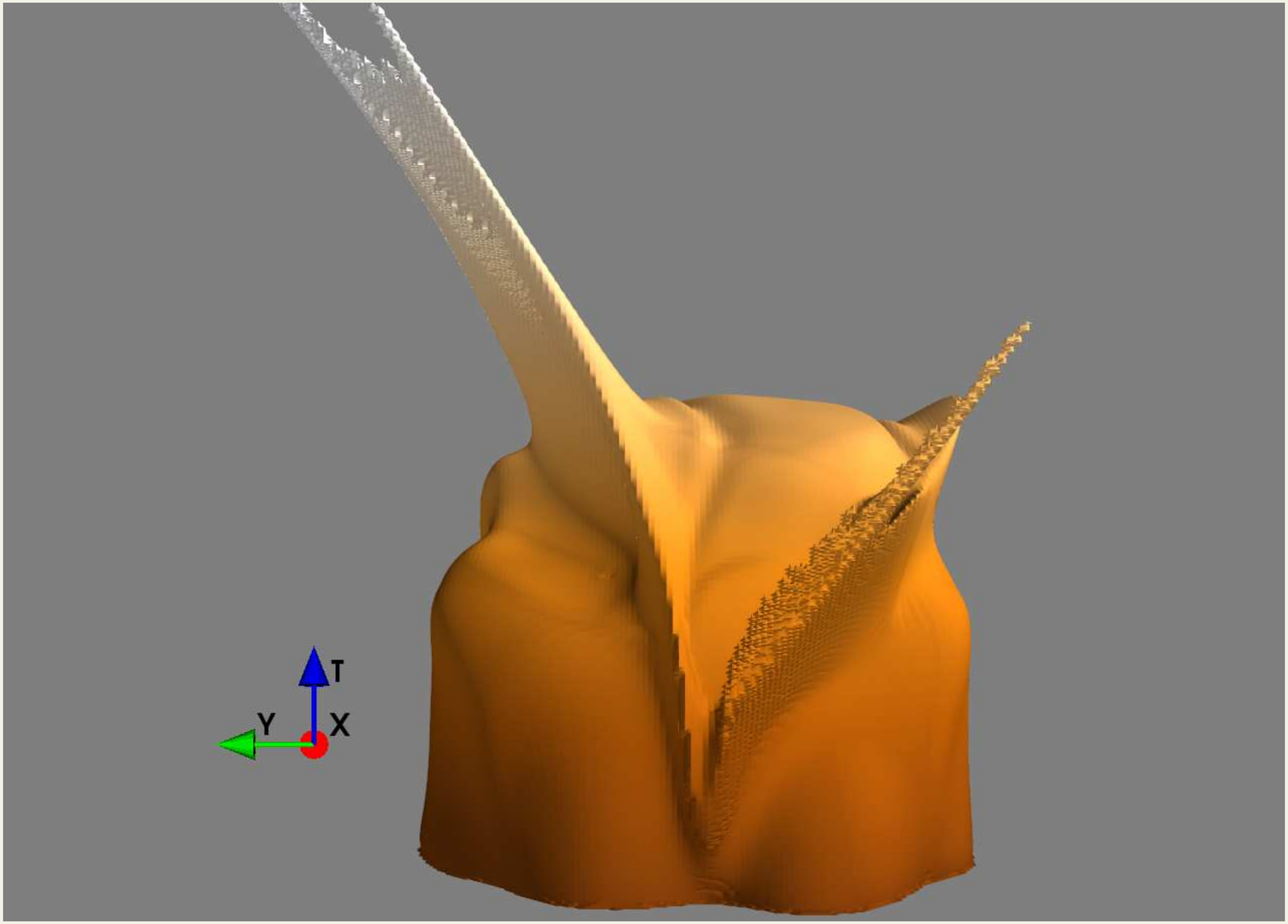


$$s(x,y) = \text{const.} \sum_{\text{wn,bc}} \frac{1}{2\pi\sigma^2} \exp\left[-\frac{(x-x_i)^2 + (y-y_i)^2}{2\sigma^2} \right]$$

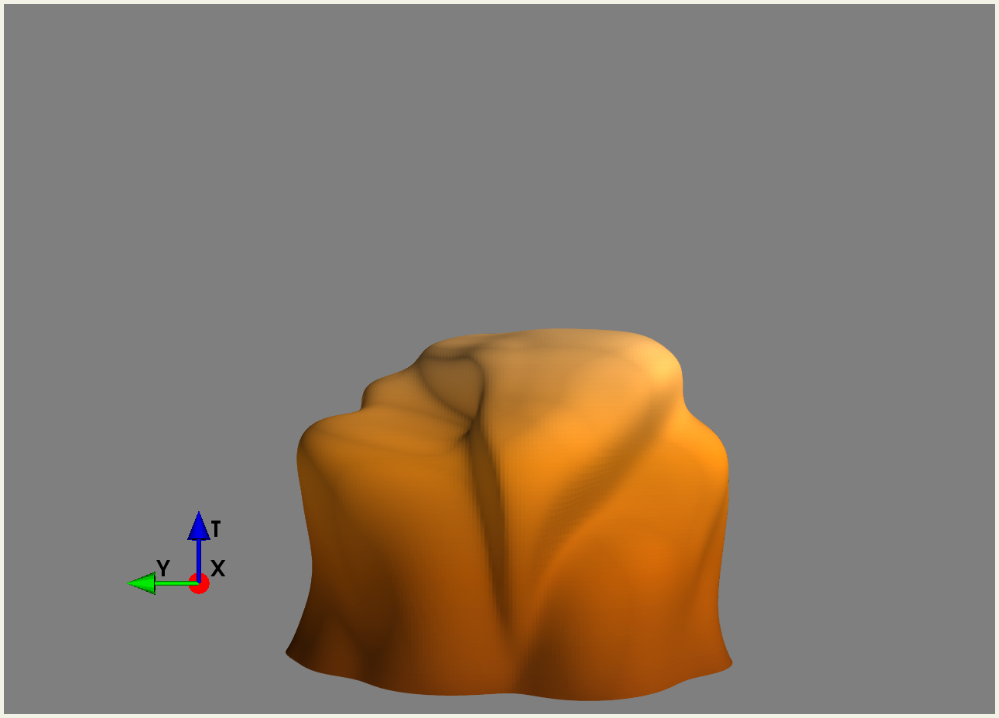
Constant temperature surface

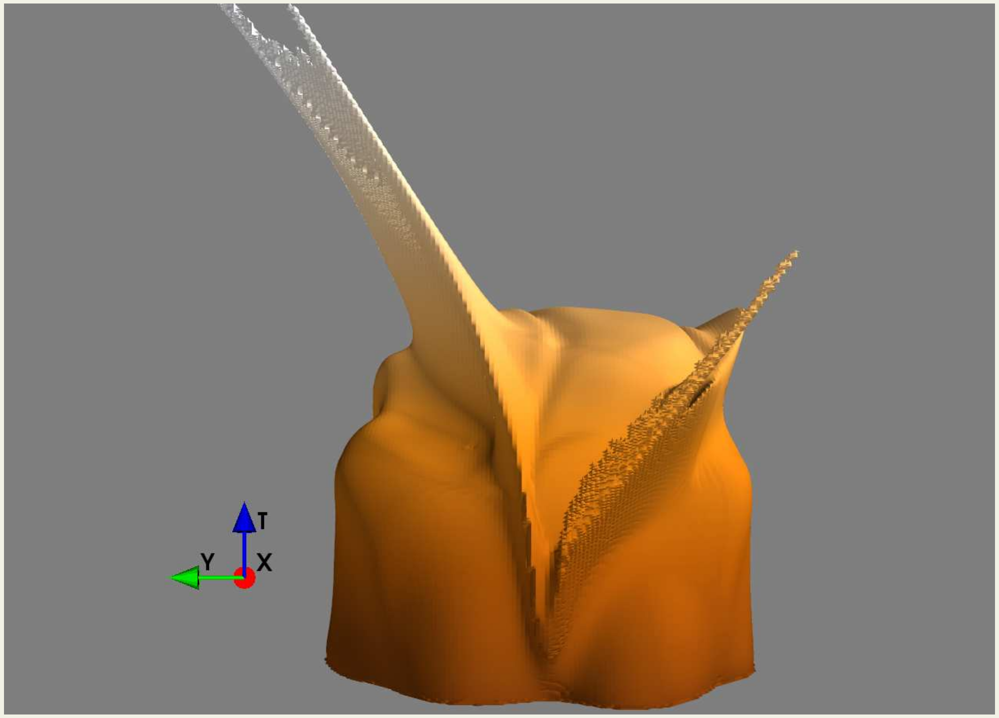


Constant K_n surface

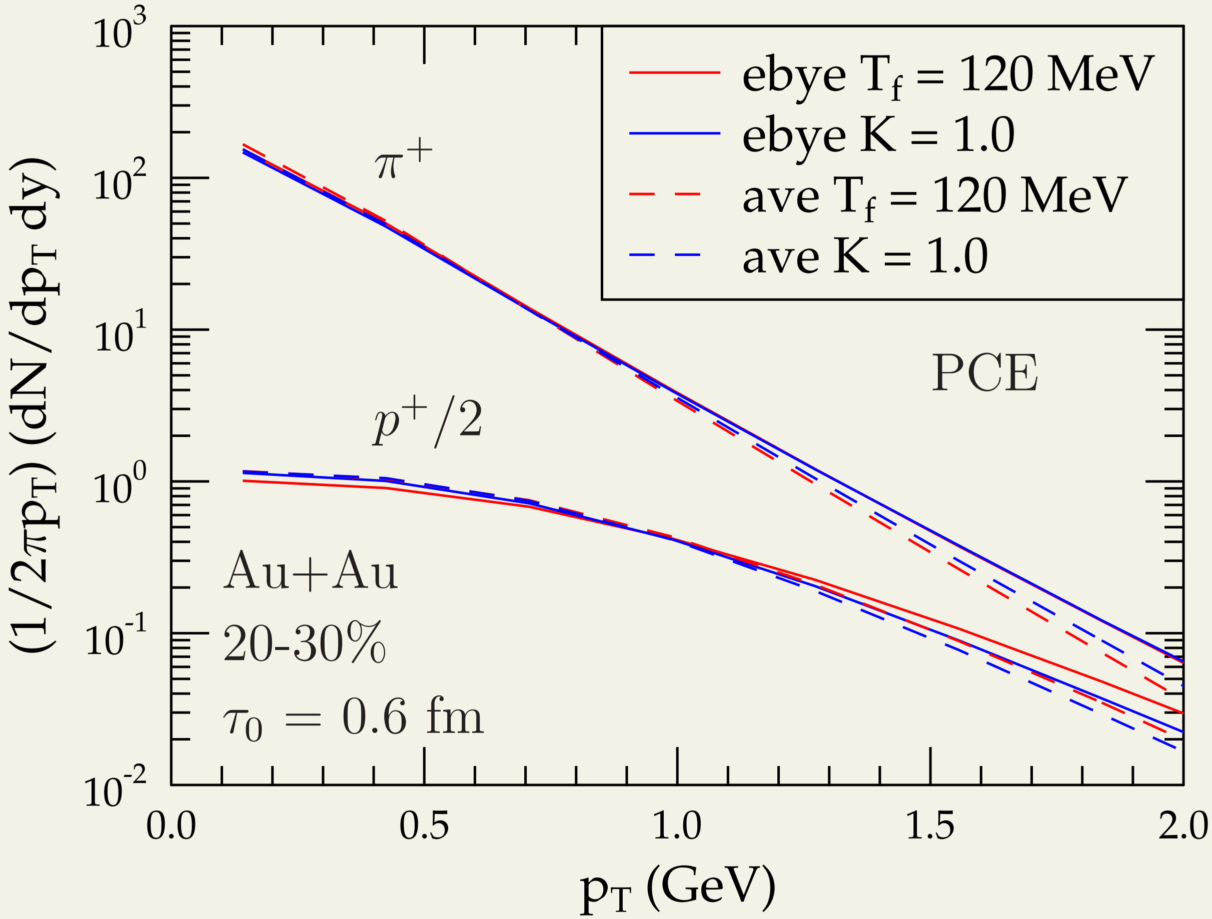


Constant T vs. constant K_n





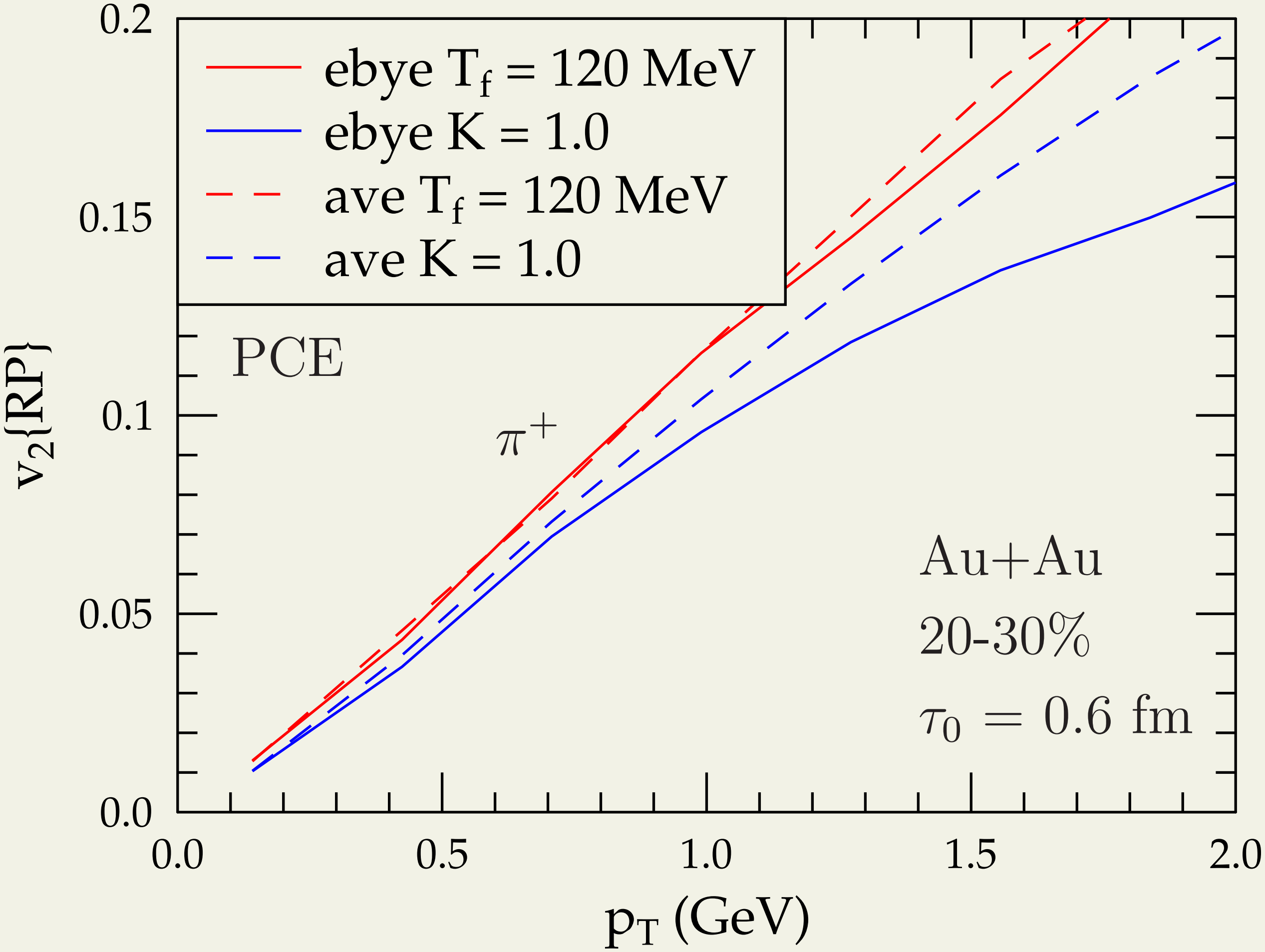
p_T spectra



Main effect:

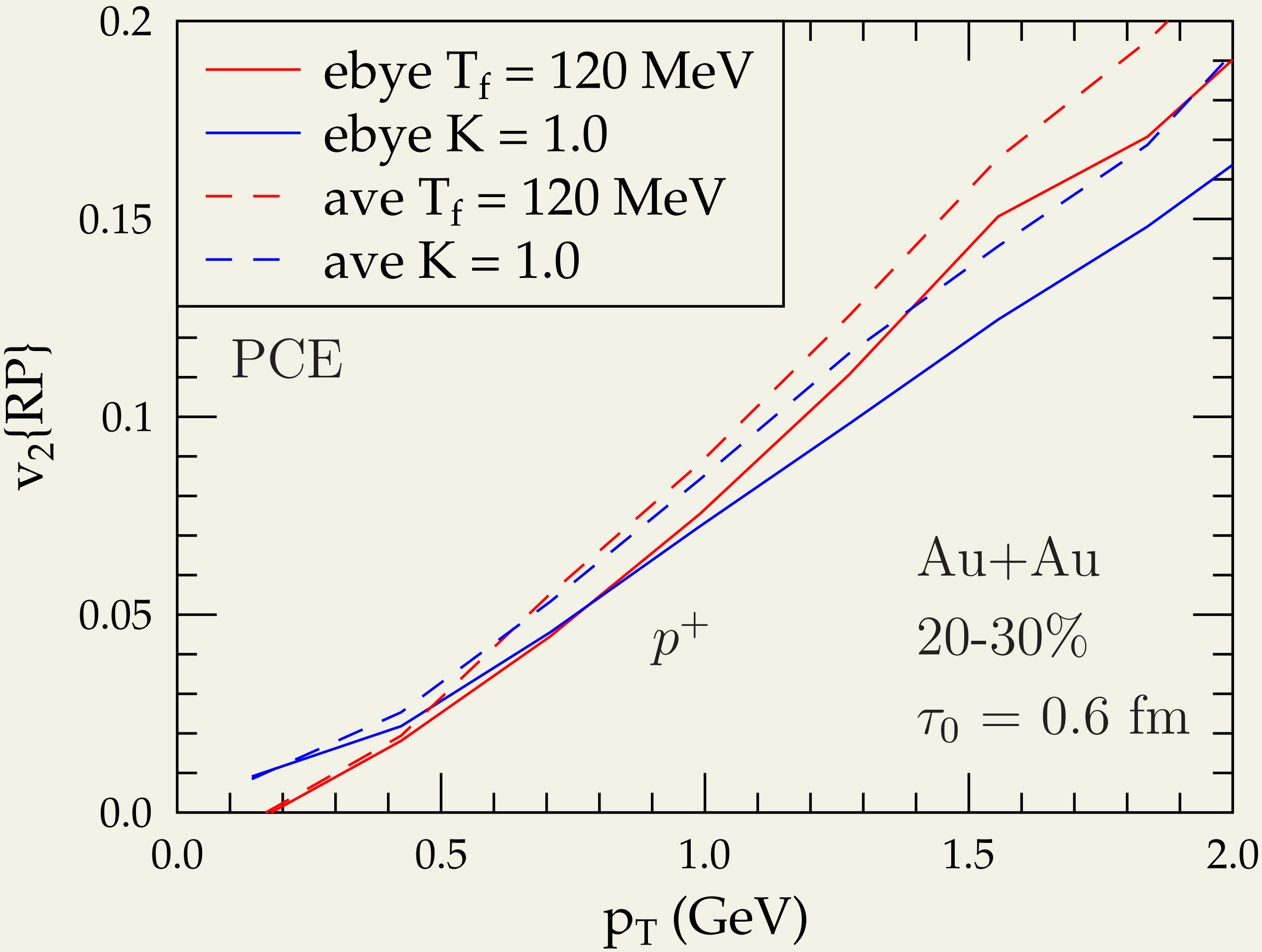
- **pions: fluctuations**
- **protons: both**

pion $v_2(p_T)$



- **~10% reduction**
- **sensitive to fluctuations**

proton $v_2(p_T)$



- **sensitive at small and large p_T**
- **fluctuations have larger effect**

Conclusions

- constant T freeze-out is an oversimplification
  - pion $v_2(p_T)$ decreases by 10%
  - sensitivity to fluctuations increases