FREE-STREAMING LIMIT OF PRE-EQUILIBRIUM DYNAMICS IN HEAVY-ION COLLISIONS

Jia Liu
The Ohio State University
Collaborators: Chun Shen, Ulrich Heinz

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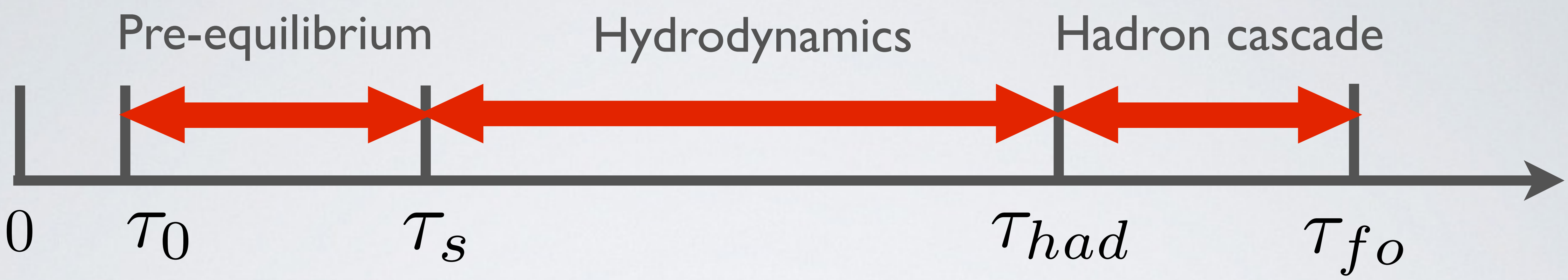
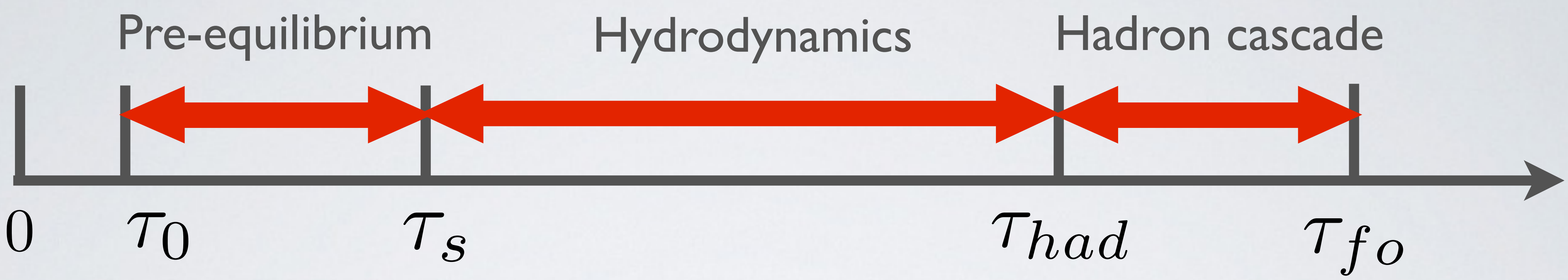
1. Time scales in a heavy-ion collision



2. Pre-equilibrium stage

- Many models:
    - pQCD based parton cascade
    - IP-Glasma
    - Chromo-Weibel instability, … …
- But we are still looking for exact thermalization mechanism.

2. Pre-equilibrium stage (cont'd)



- Compare two extremes
  - Start hydrodynamics from small τ_0
  - No interactions $\longrightarrow$ free-streaming to τ_s
- Solution of collisionless Boltzmann equation:

$$f(\vec{x}_\perp, \tau; \vec{p}_\perp, y - \eta_s) = \boxed{f(\vec{x}_\perp - (\tau - \tau_0)\vec{e}_{p_\perp}, \tau_0; \vec{\mathrm{p}}_\perp, y - \eta_s)}$$

- Energy-momentum tensor:

$$T^{\mu\nu}(\vec{x}_\perp, \tau) = \sum_i \frac{g_i}{(2\pi)^3} \int \frac{d^3p}{E} p^\mu p^\nu f_i(\vec{x}_\perp, \tau; p)$$

3. Landau Matching

- Matching pre-equilibrium to hydrodynamics:

$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^{\mu}u^{\nu}$$

Matching Condition: $$T^{\mu\nu}u_{\nu} = eu^{\mu} \xrightarrow{u^{\mu}u_{\mu} = 1} e,\ u^{\mu}$$

EOS: $$p = p(e)$$

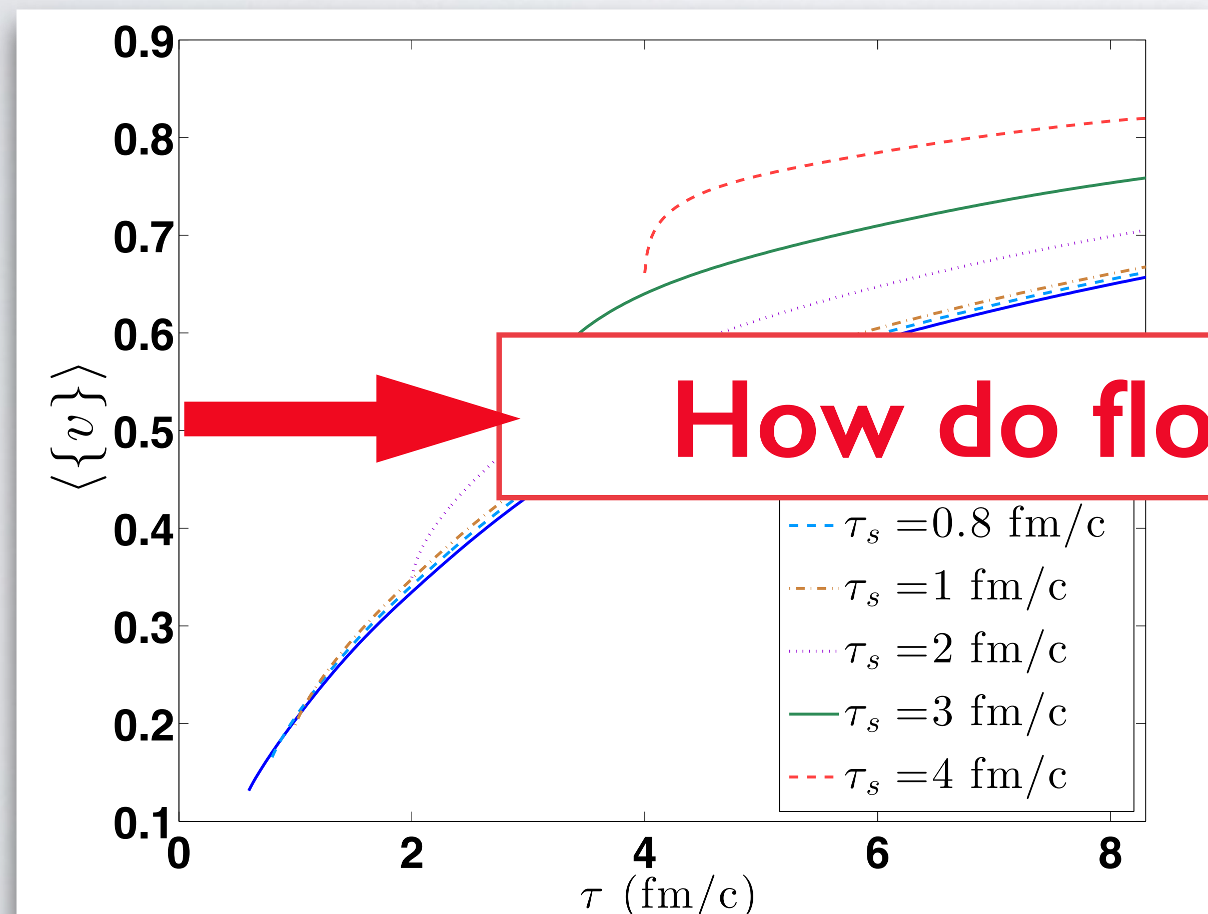
$$\Pi = -\frac{1}{3}\Delta^{\mu\nu}T_{\mu\nu} - p$$

$$\pi^{\mu\nu} = T^{\mu\nu} - eu^{\mu}u^{\nu} + (p + \Pi)\Delta^{\mu\nu}$$

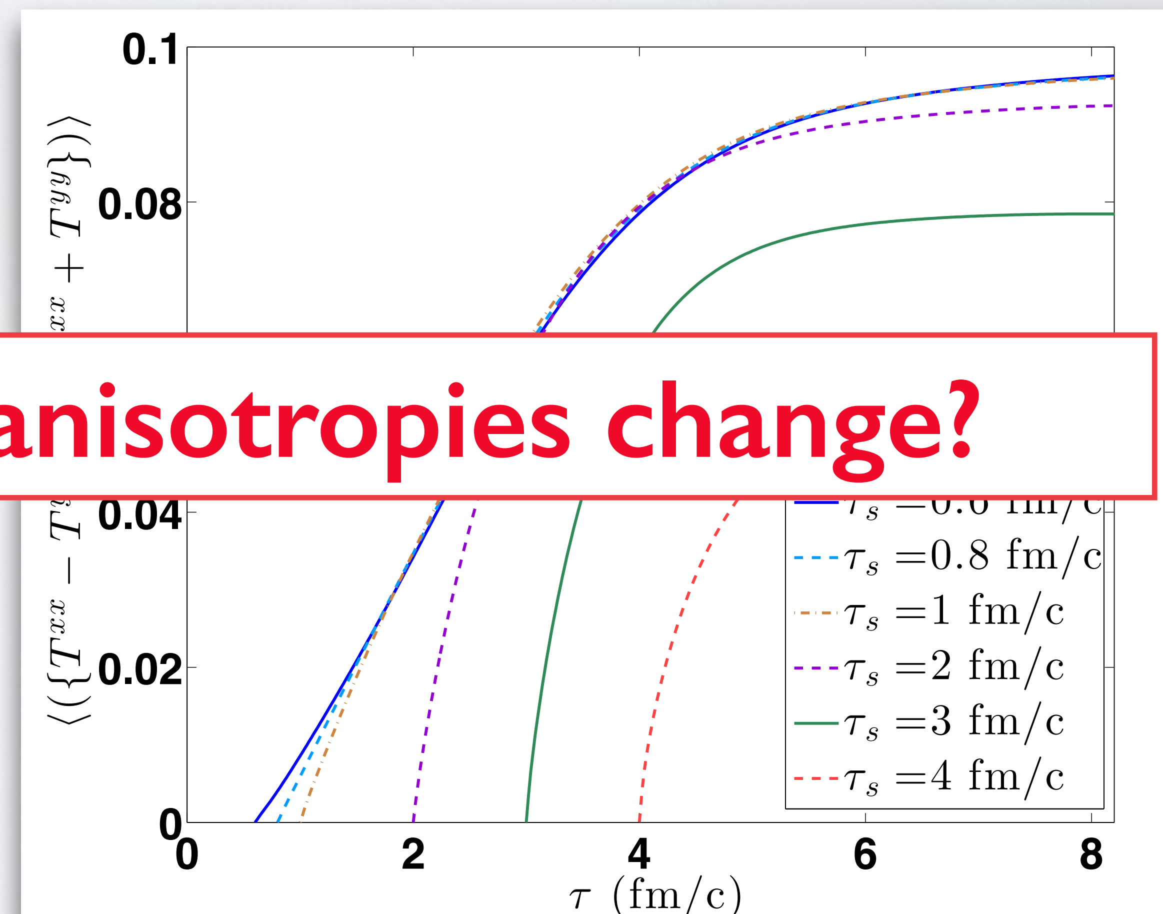
- Note: non-zero flow velocity profile at τ_s .

4. Influence of pre-equilibrium stage (I)

- Simulation setup:
  - Pb-Pb@2760GeV, MC-KLN: centrality 10%~20%
  - Viscous hydro with $\eta/s = 0.2,\ \zeta/s = 0$
  - Rescale initial profiles such that the final dE_T/dy is independent of τ_s



Radial flow

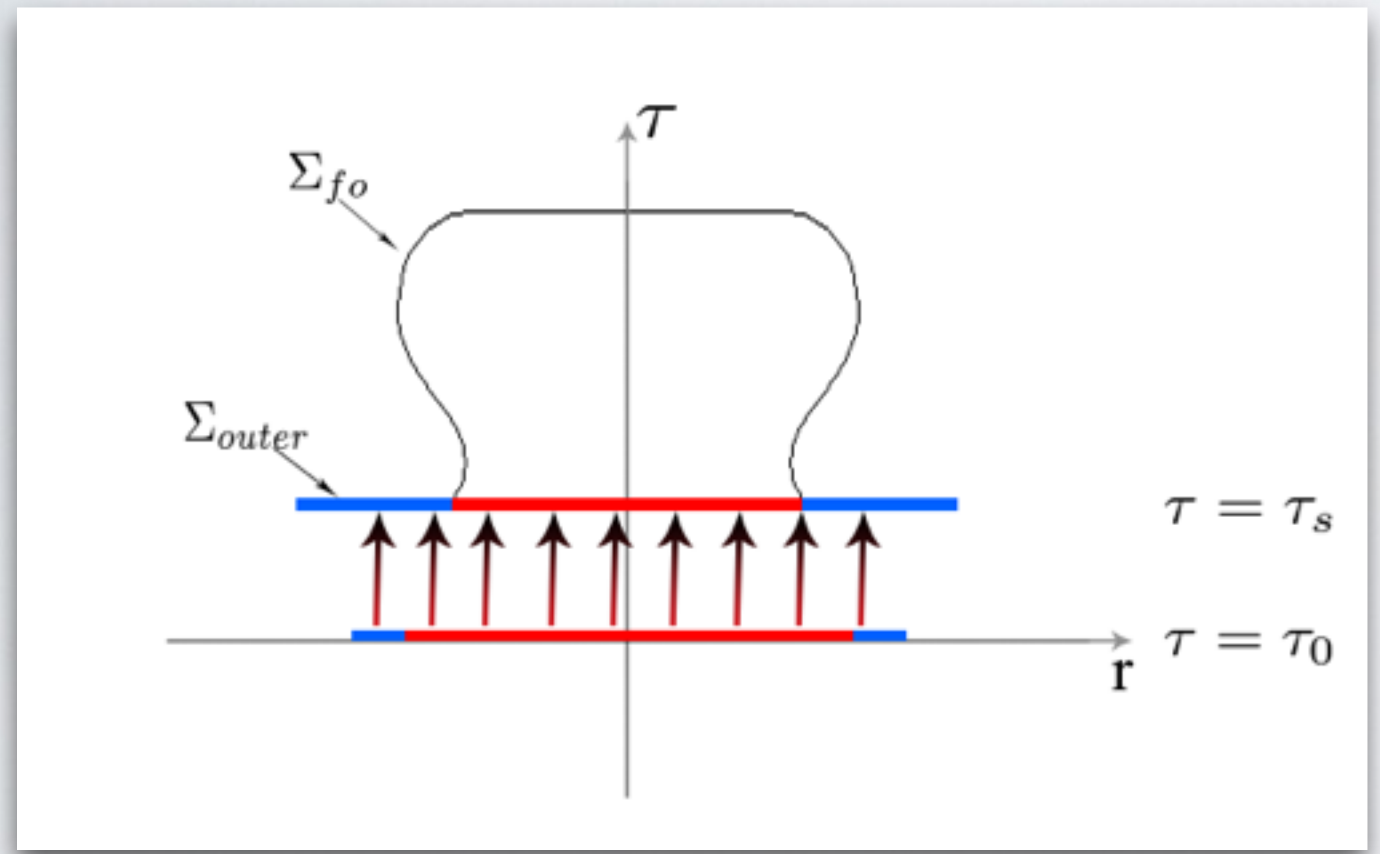


Momentum anisotropy

How do flow anisotropies change?

4. Influence of pre-equilibrium stage (2)

- Difficulty: cells which never thermalize



- Free-streaming dilutes the system.
- Larger switching time → more cells move out of the freeze-out surface.
- Cooper-Frye formula cannot deal with such cells!
- Neither can pQCD-based fragmentation function.

4. Influence of pre-equilibrium stage (3)

- Construct anisotropy from E_T distribution
  - Good news: free-streamed distribution is known

$$\frac{dE_T}{dyd\phi} = \sum_i \frac{g_i}{(2\pi)^3} \int p^0 p_\perp dp_\perp \int_\Sigma p^\mu d^3\sigma_\mu f_i(x,p) \quad \text{(i for parton or hadron species)}$$

  - Apply to freeze-out surface:

$$\left.\frac{dE_T}{dyd\phi}\right|_{\Sigma_{fo}} = \sum_i \frac{g_i}{(2\pi)^3} \int p^0 p_\perp dp_\perp \int_{\Sigma_{fo}} p^\mu d^3\sigma_\mu (f_{i,eq} + \delta f_i)$$

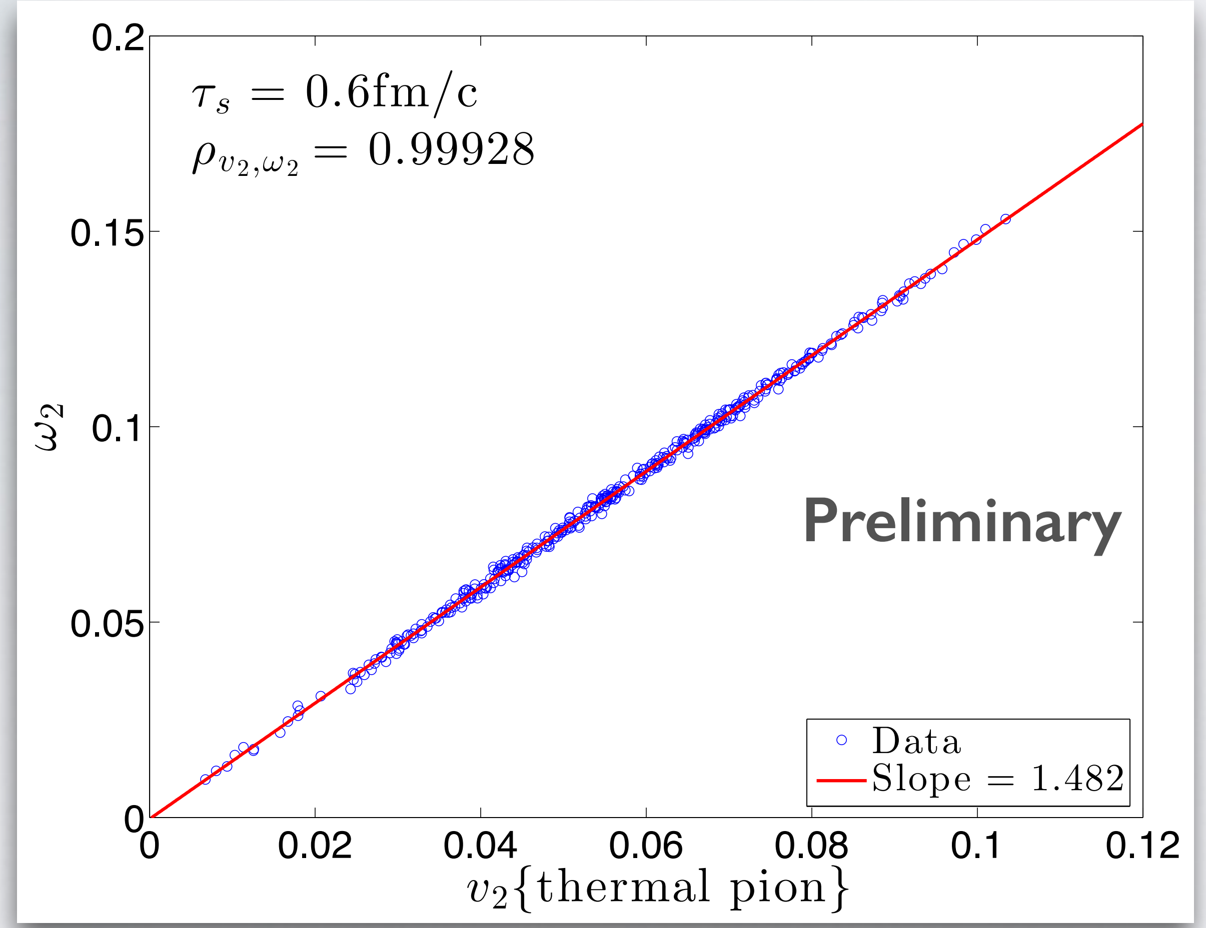
$$\boxed{\omega_n e^{in\tilde{\Psi}_n} = \frac{\int_\Sigma \frac{dE_T}{dyd\phi} e^{in\phi} d\phi}{\int_\Sigma \frac{dE_T}{dyd\phi} d\phi}}$$

  - Apply to outer surface:

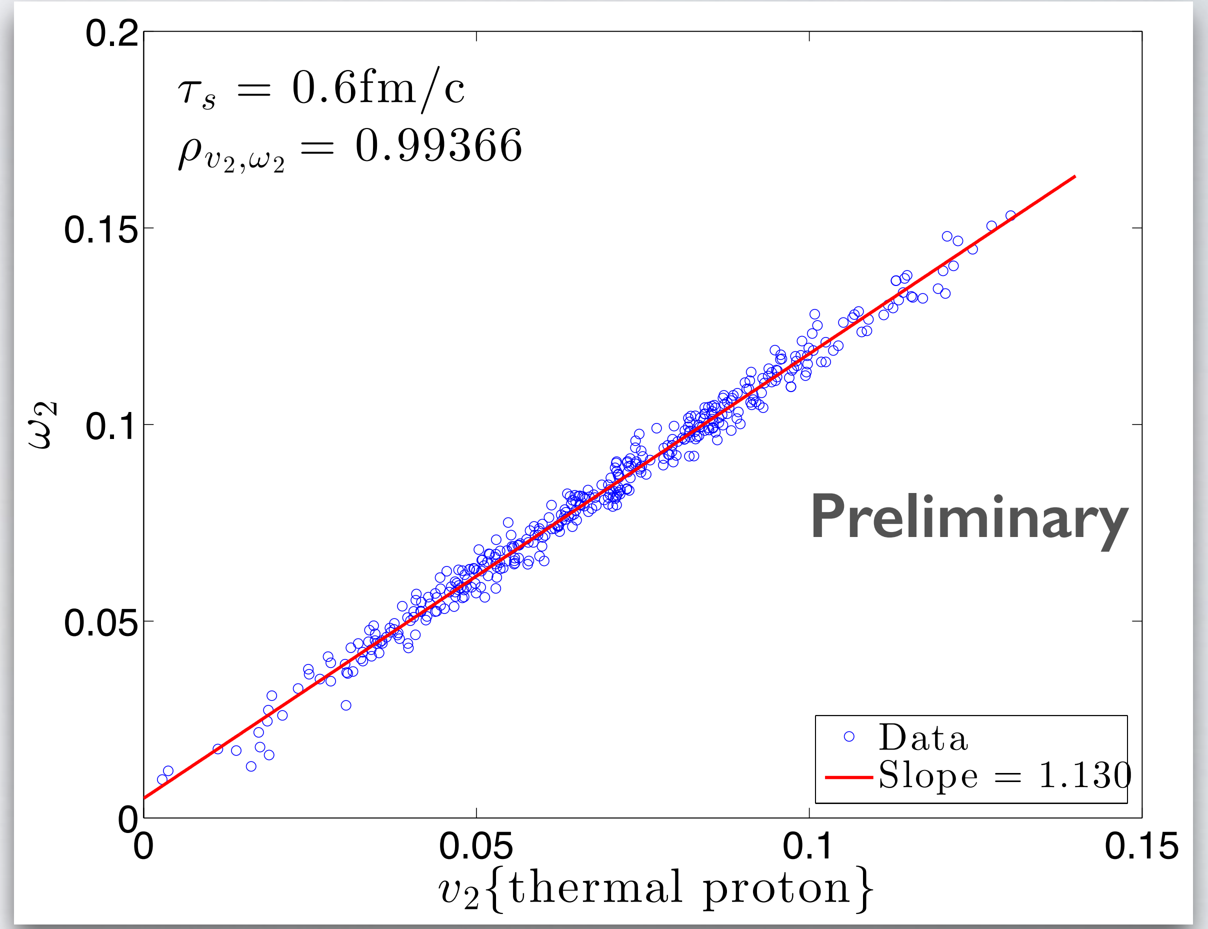
$$\left.\frac{dE_T}{dyd\phi}\right|_{\Sigma_{outer}} = \sum_i \frac{g_i}{(2\pi)^3} \int d^2x_\perp \int p_\perp^2 dp_\perp f_i(x,p)$$

4. Influence of pre-equilibrium stage (4)

- Correlation with flow anisotropy v_2



Pion +

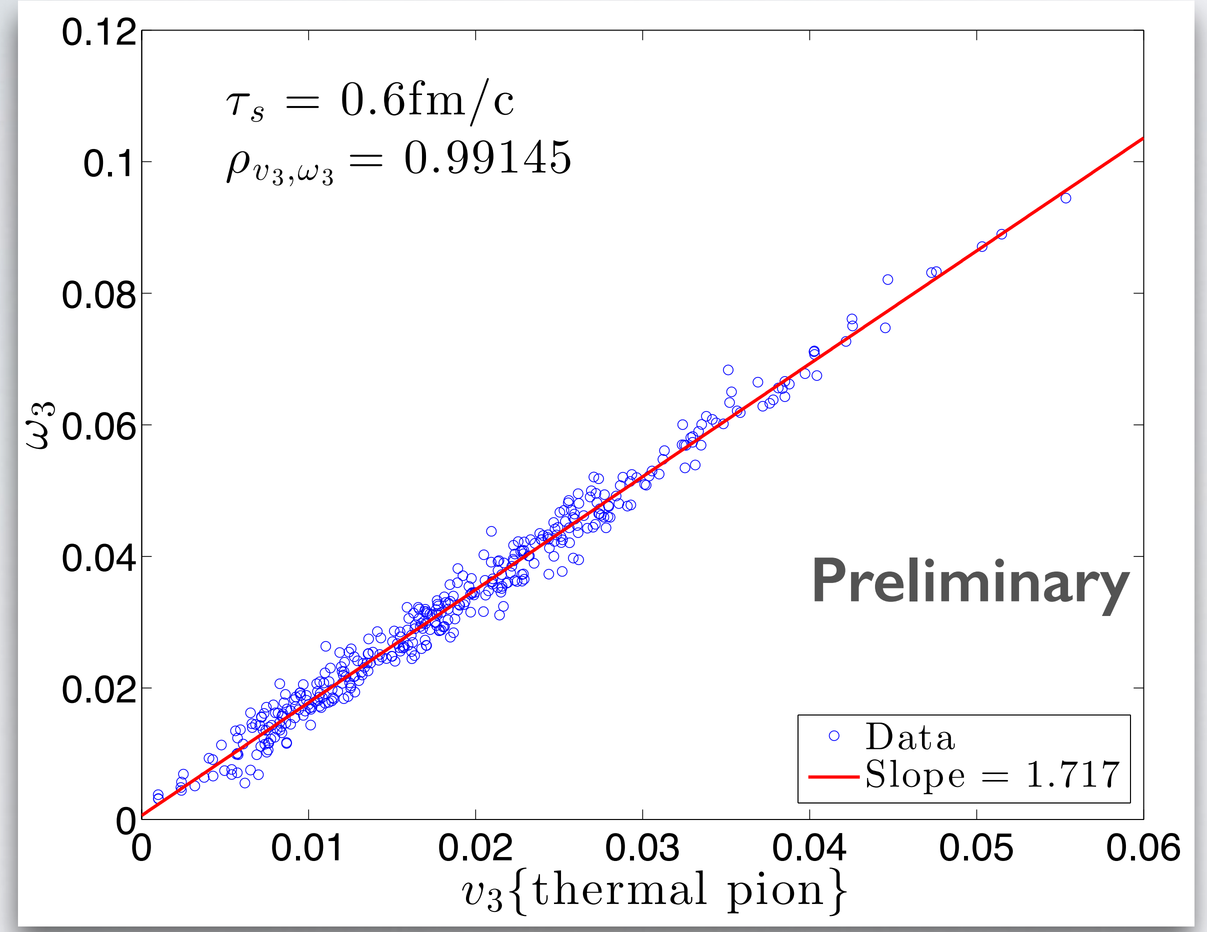


Proton

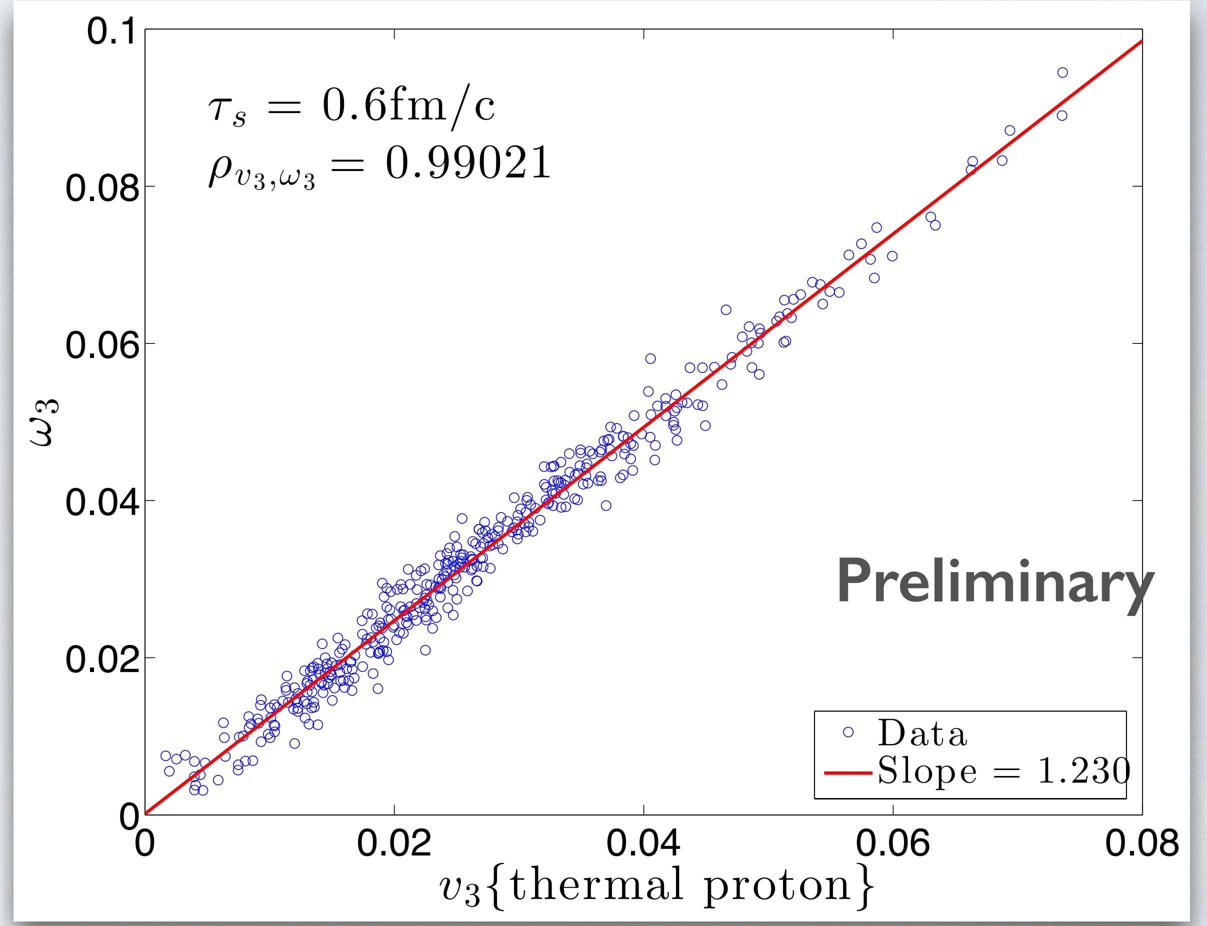
- Early matching time: not so much cells move out
- Strong correlation!

4. Influence of pre-equilibrium stage (4)

- Correlation with flow anisotropy v_3



Pion +

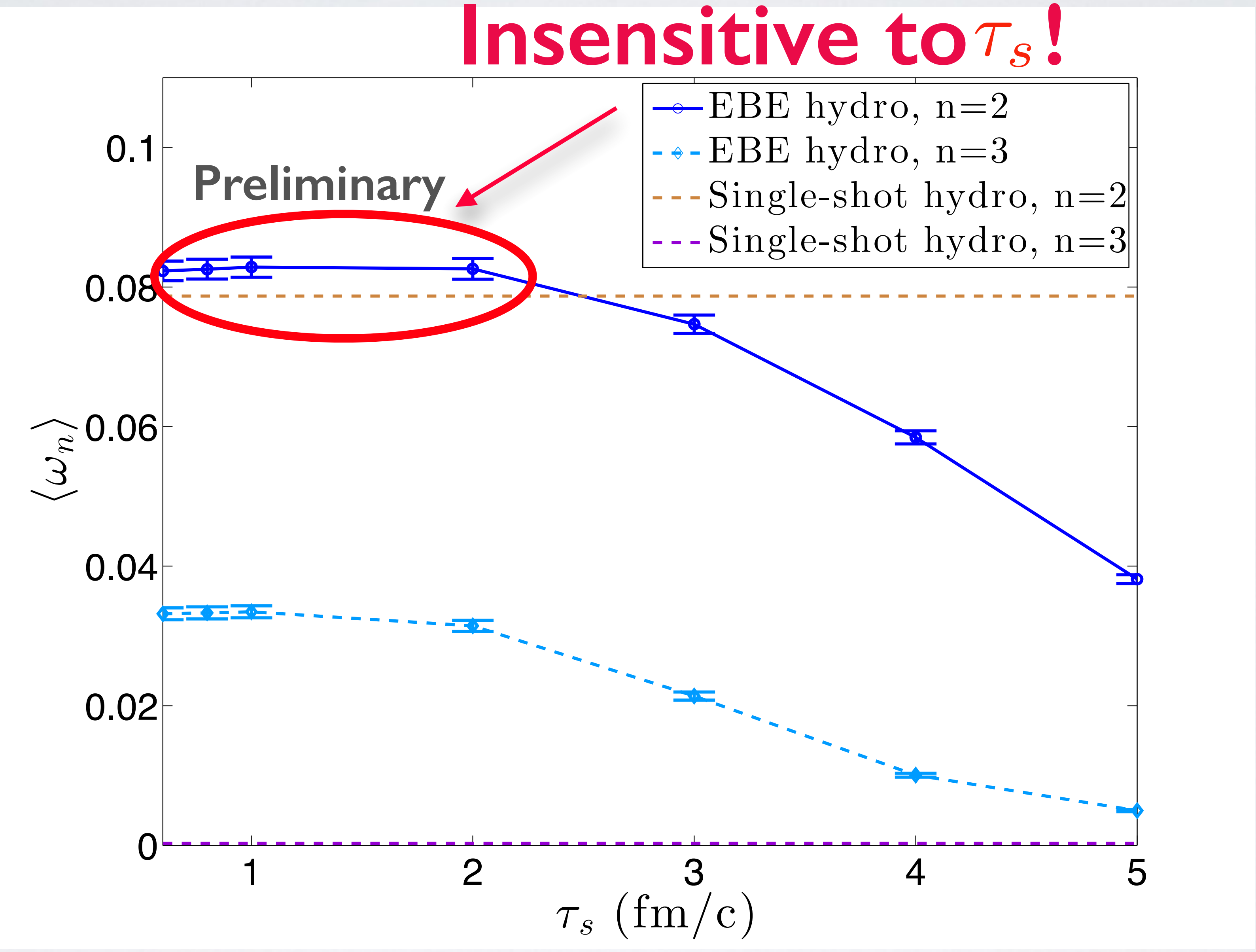


Proton

- Correlation is still good.

4. Influence of pre-equilibrium stage (5)

- Different switching time?



Conclusion

- System is insensitive to τ_s if it is small.
- Energy flow anisotropies can qualify particle flow anisotropies (early switching time).
- Goal: find the upper limit of τ_s.