Hydrodynamic attractors in ultrarelativistic nuclear collisions

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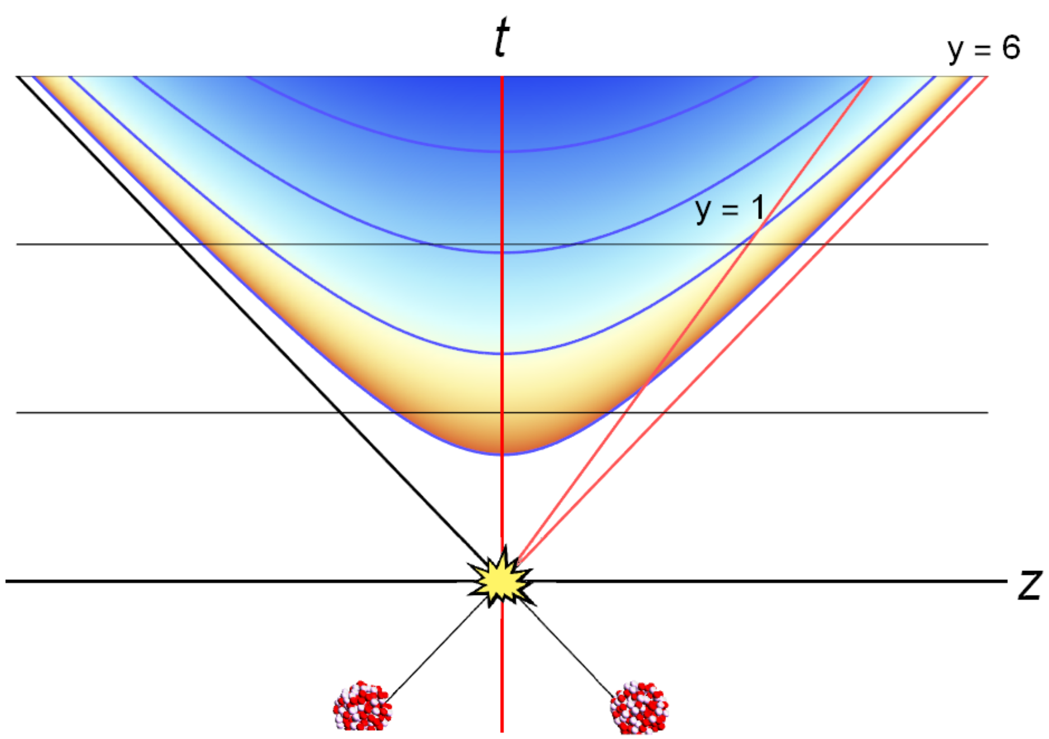
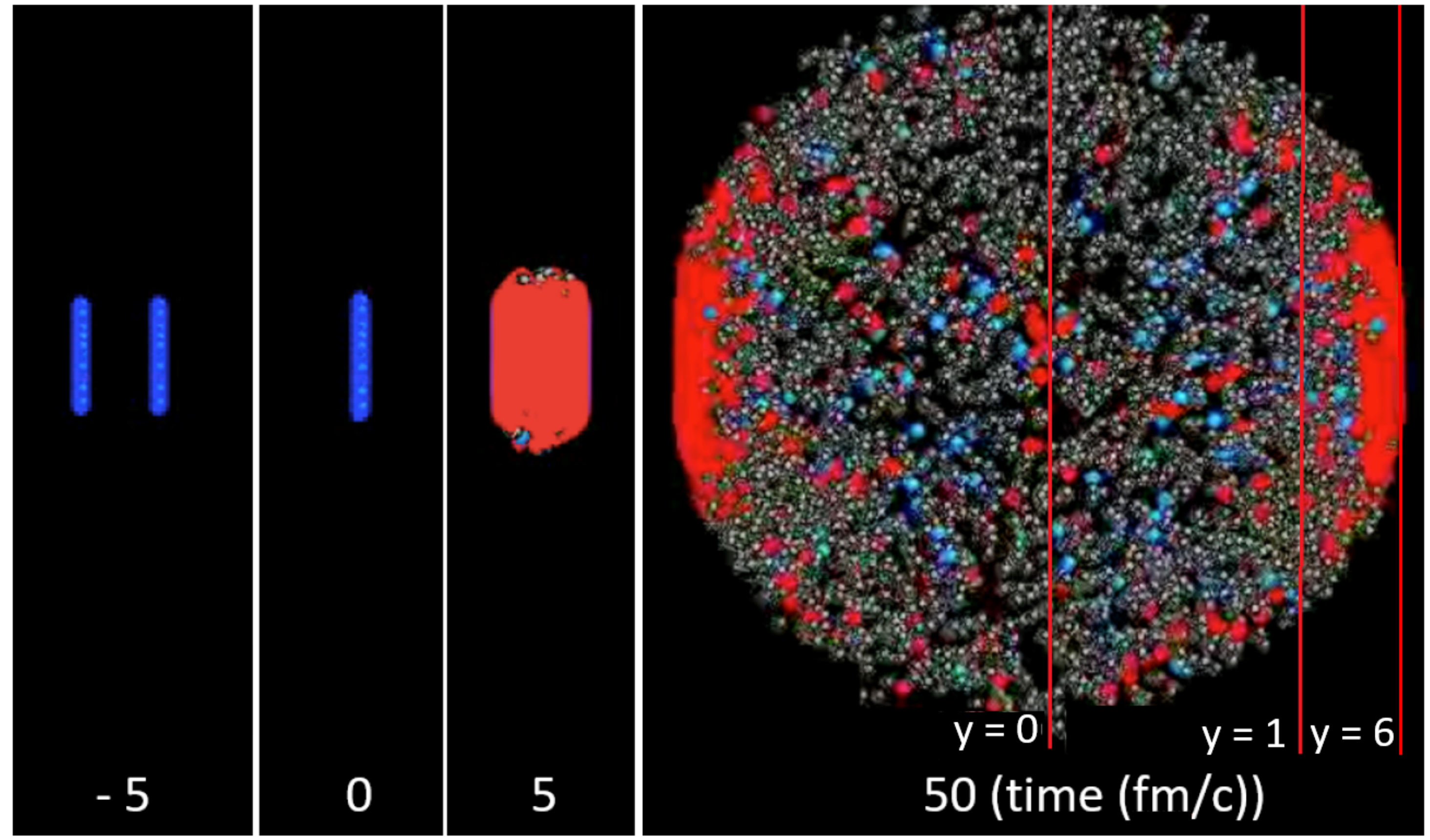
Heavy-ion collisions
Spacetime picture





Busza et al. 1802.04801

1. Initial stages
2. Hydrodynamic evolution
    - effective description of a small set of observables
    - early thermalisation puzzle
3. Hadronisation

Relativistic hydrodynamics
as an effective description

Effective description of the energy-momentum tensor

$$\langle \hat{T}^{\mu\nu} \rangle \equiv T^{\mu\nu} = (\mathscr{E} + \mathscr{P}) u^\mu u^\nu + \mathscr{P} \eta^{\mu\nu} + \pi^{\mu\nu}$$

for which we have the conservation law

$$\partial_\alpha T^{\alpha\beta} = 0$$

This is a statement of fact at the microscopic level and an equation of motion in hydrodynamic models such as MIS theory

$$\tau_\pi D \pi^{\mu\nu} + \pi^{\mu\nu} = -2\eta\sigma^{\mu\nu} + \ldots$$

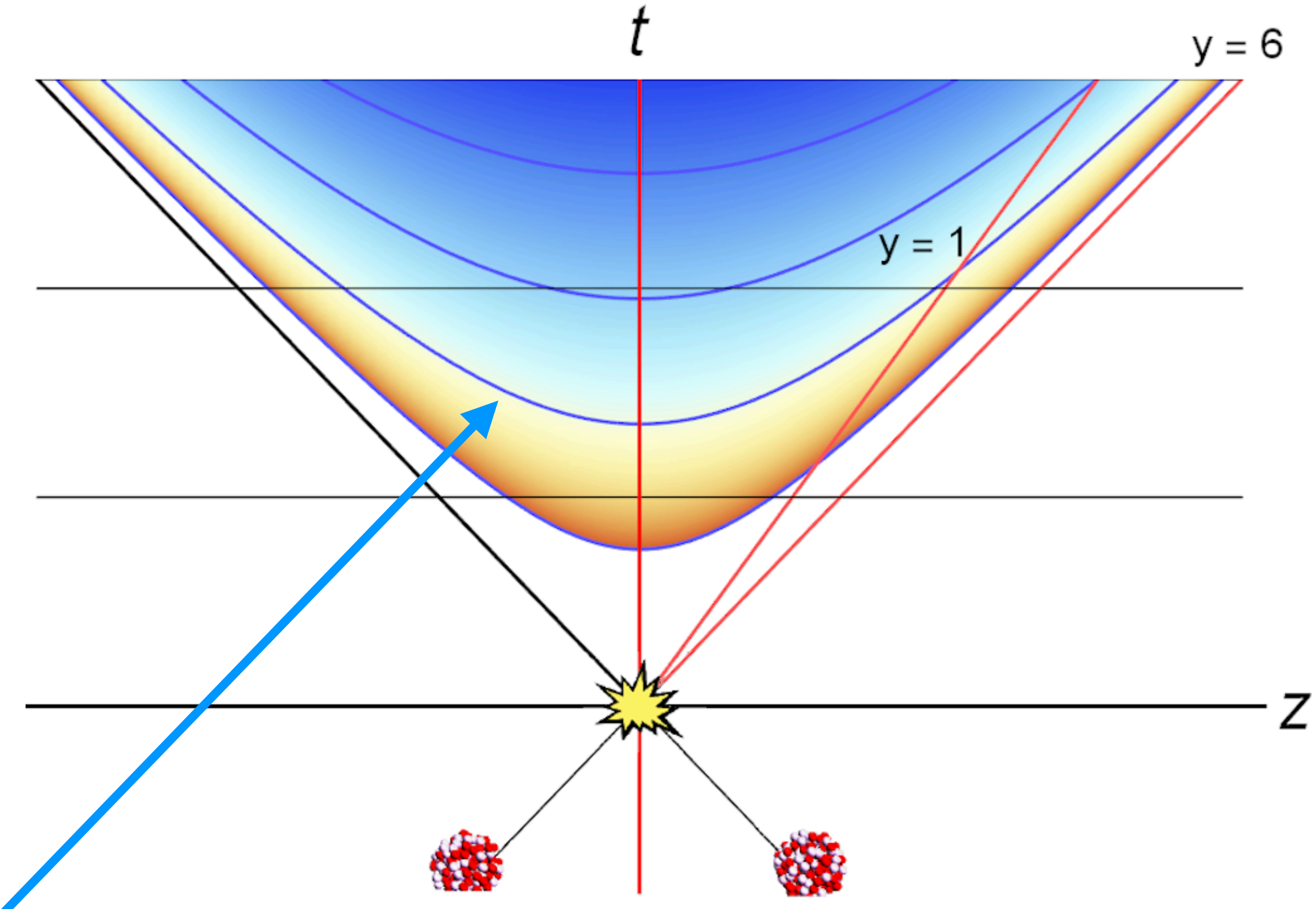
The gradient expansion: asymptotics “near" equilibrium

$$\pi^{\mu\nu} = -2\eta\sigma^{\mu\nu} + \ldots$$

Opens the way to matching to microscopic theories.

Bjorken flow

as a model of hydrodynamization



$$(T^{\mu\nu}) = \mathrm{diag}(\mathcal{E}, \mathcal{P}_L, \mathcal{P}_T, \mathcal{P}_T)$$

Everything expressed in terms of a single function

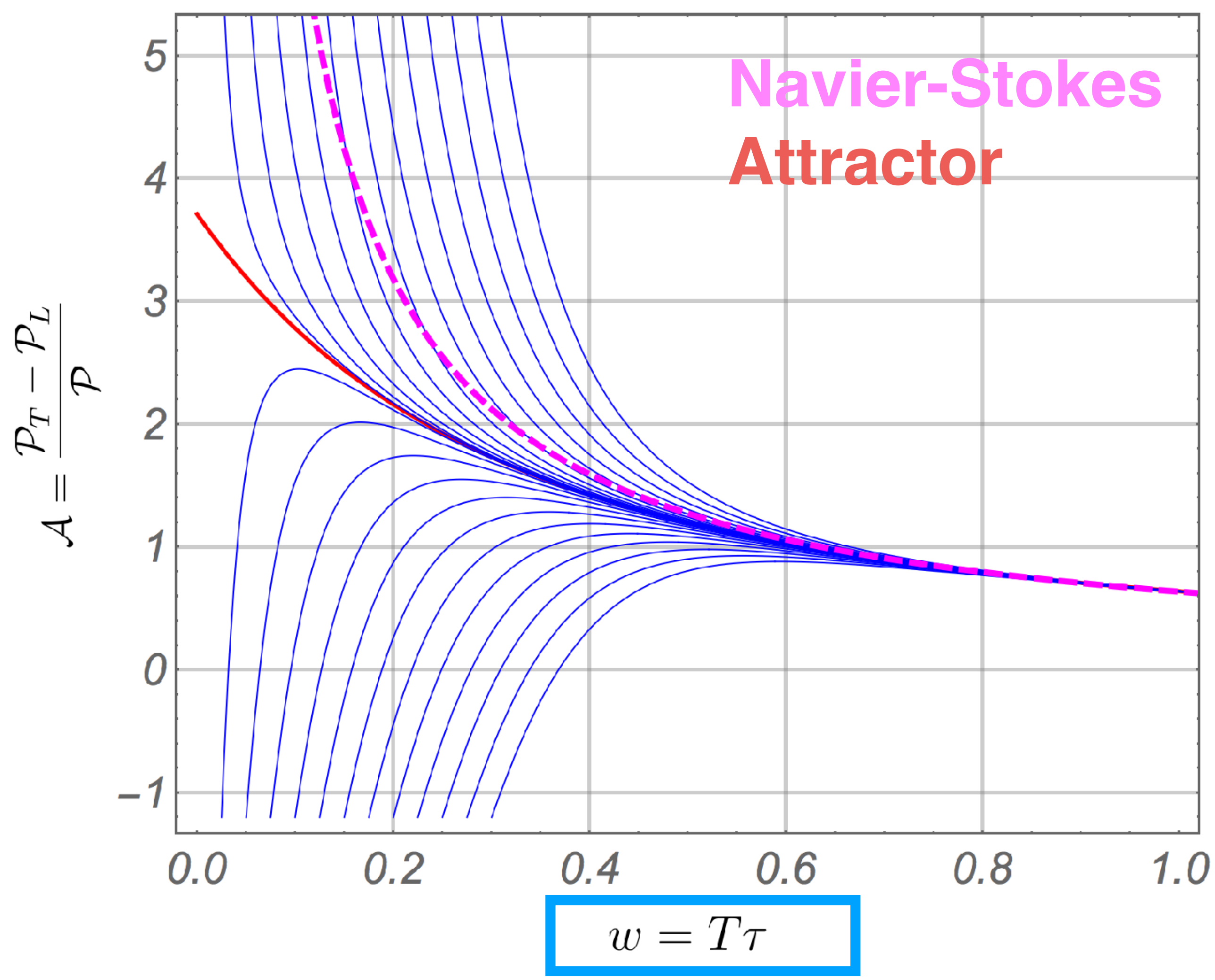
$$\mathcal{E}(\tau) \sim T(\tau)^4$$

Bjorken flow: the dynamics depends only on the proper-time

$$\mathcal{A} \equiv \frac{\mathcal{P}_T - \mathcal{P}_L}{\mathcal{P}}$$

Bjorken flow in MIS theory

and hydrodynamic attractors



$$\mathscr{E} = \mathscr{E}_0 \exp\left(4 \int_{w_0}^{w} \frac{dx}{x} \frac{\mathscr{A}(x) - 6}{\mathscr{A}(x) + 12}\right)$$

Dimensionless transport coefficients

$$C_\tau \left(1 + \frac{\mathscr{A}}{12}\right) \mathscr{A}' + \frac{C_\tau}{3w} \mathscr{A}^2 = \frac{3}{2}\left(\frac{8C_\eta}{w} - \mathscr{A}\right)$$

Information about initial conditions is exponentially "dissipated"

Asymptotic solution at late time

$$\mathscr{A} = \underbrace{\frac{8C_\eta}{w}}_{\text{Navier–Stokes}} + \underbrace{\frac{16C_\eta C_\tau}{3w^2}}_{\text{2nd order}} + \ldots = \underbrace{\sum_{n>0} \frac{a_n^{(0)}}{w^n}}_{\text{gradient expansion}} + \underbrace{\left(\sigma\, w^{\frac{C_\eta}{C_\tau}} e^{-\frac{3}{2C_\tau} w}\right) \sum_{n\geq 0} \frac{a_n^{(1)}}{w^n}}_{\text{transseries sectors}} + \ldots$$

Work published in 2021

- Convergence of hydrodynamic modes: insights from kinetic theory and holography
  M. P. Heller, A.Serantes, MS, V. Svensson, B.Withers
  SciPost Phys. 10 (2021) 6, 123

- Transseries for causal diffusive systems
  M. P. Heller, A.Serantes, MS, V. Svensson, B.Withers
  JHEP 04 (2021) 192

- Hydrodynamic gradient expansion in linear response theory
  M. P. Heller, A.Serantes, MS, V. Svensson, B.Withers
  Phys.Rev.D 104 (2021) 6, 066002

- Constraining the initial stages of ultrarelativistic nuclear collisions
  J. Jankowski, S.Kamata, M.Martinez, MS
  Phys.Rev.D 104 (2021) 7, 074012

Constraining the initial stages …

J. Jankowski, S.Kamata, M.Martinez, MS

Early time attractor is due to boost-invariant expansion connected with scaling behaviour of the energy density $\mathscr{E} \sim \tau^{\beta}$

Assuming that the attractor takes over "right away"

$$\frac{dN}{dy} = \boxed{\tau_0^{\frac{2\beta}{4-\beta}} h(\beta)} \int d^2\mathbf{x}_\perp \mathscr{E}(\tau_0, \mathbf{x}_\perp)^{\frac{2}{4-\beta}}$$

Note: the initial energy profile depends on event centrality.

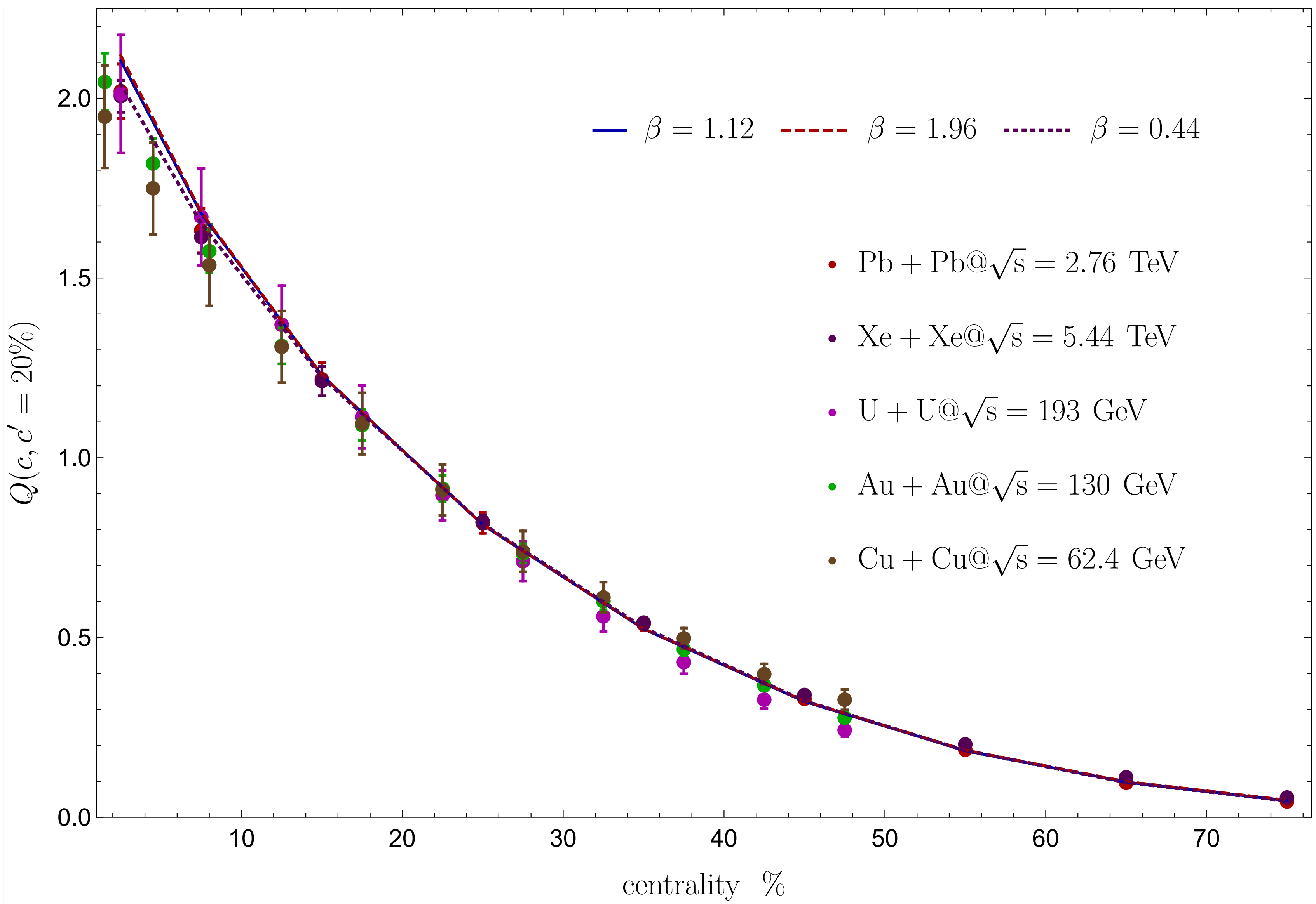
Unknown factors cancel in the ratio

$$Q(c, c') \equiv \frac{\langle dN/dy \rangle_c}{\langle dN/dy \rangle_{c'}}$$

where the average is over MC generated events based a specific initial state model (we looked at three).

Constraining the initial stages …

J. Jankowski, S.Kamata, M.Martinez, MS



Found strong dependence of prehydrodynamic flow on the choice of initial state model. This has implication for Bayesian analyses which assume free-streaming at early times.

Closing remarks

- The study of QGP dynamics is an interdisciplinary endeavour
- Relativistic hydrodynamics plays a pivotal role
- Hydrodynamic attractors are a new paradigm for understanding the early thermalisation puzzle
- Challenges for the near future
    - Nature of the gradient expansion and the future of matching
    - New hydrodynamic models involving more transient modes?
    - Identifing attractors beyond the simplest settings?
    - Use attractors in simulation pipelines?