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HYDRODYNAMIC SIMULATION FOR THE EIC FIXED-TARGET PROGRAM

2026 RHIC/AGS ANNUAL USERS' MEETING

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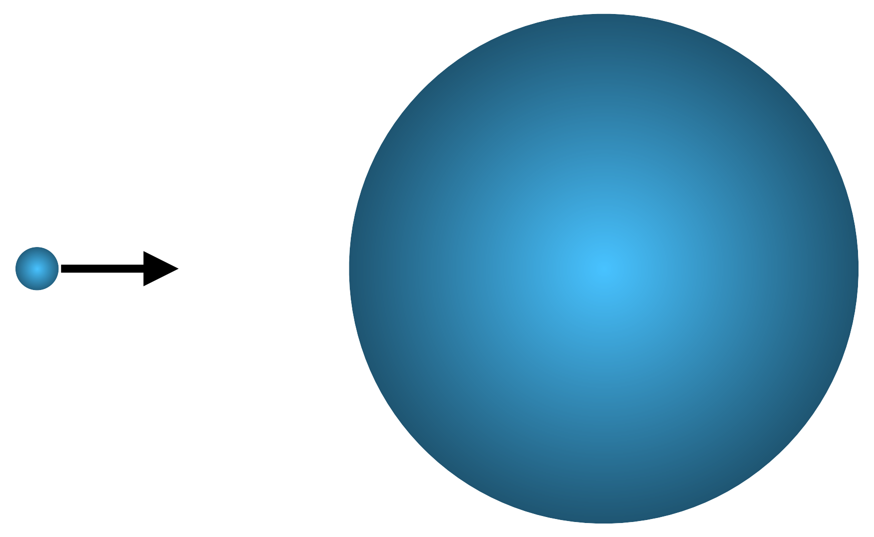
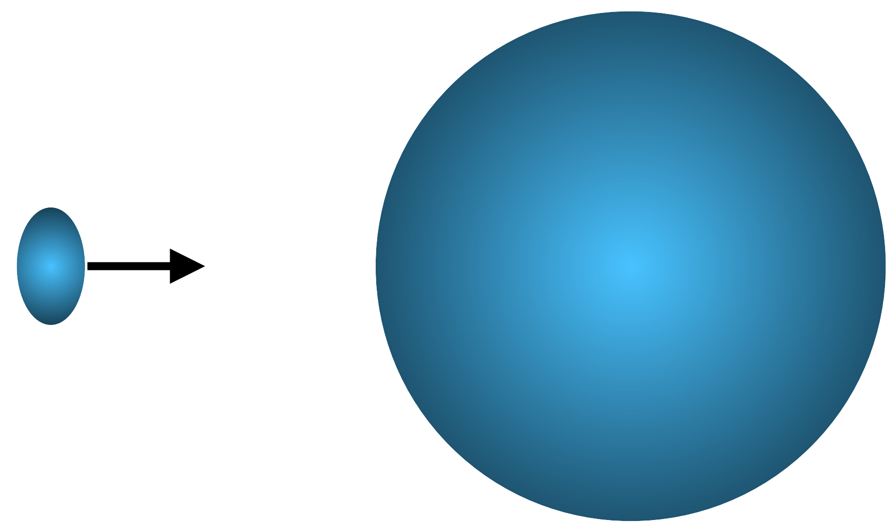
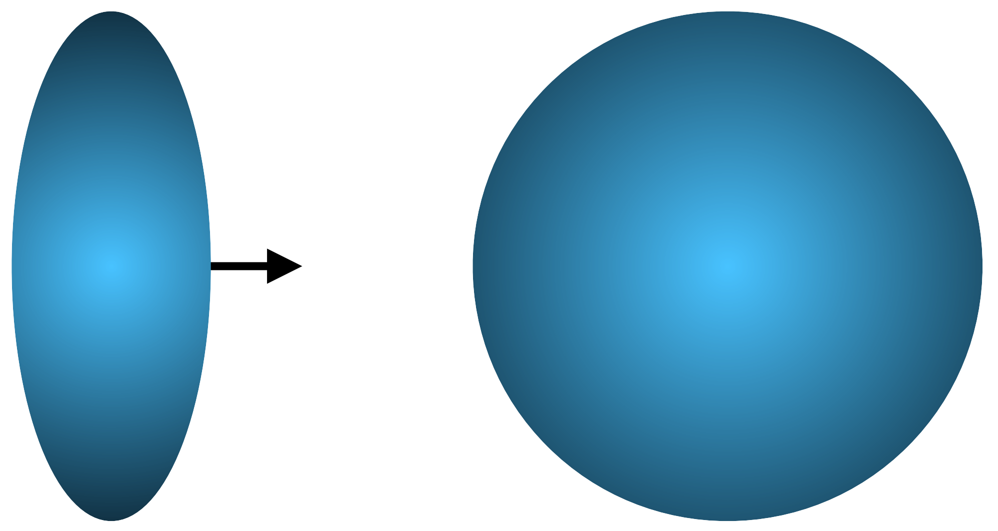
C.-J. Naïm, A. Sorensen, D. Brown, D. Cebra, R. Corliss, J. M. Durham, and R. Vogt, 2603.00265;

L. Du, A. Sorensen and M. Stephanov, Int.J.Mod.Phys.E 33 (2024) 07, 2430008

EIC fixed-target program: from cold nuclei to dense QCD matter







$e + A$

- nuclear structure,
- nPDFs,
- cold nuclear matter.

$p + A$

- cold nuclear matter,
- baryon stopping,
- hadronization,
- small-system correlations.

$A + A$

- dense matter,
- hydrodynamics,
- phase diagram,
- critical fluctuations.

C.-J. Naïm, A. Sorensen, D. Brown, D. Cebra, R. Corliss, J. M. Durham, and R. Vogt, 2603.00265

What do we want to extract from low-energy A+A?

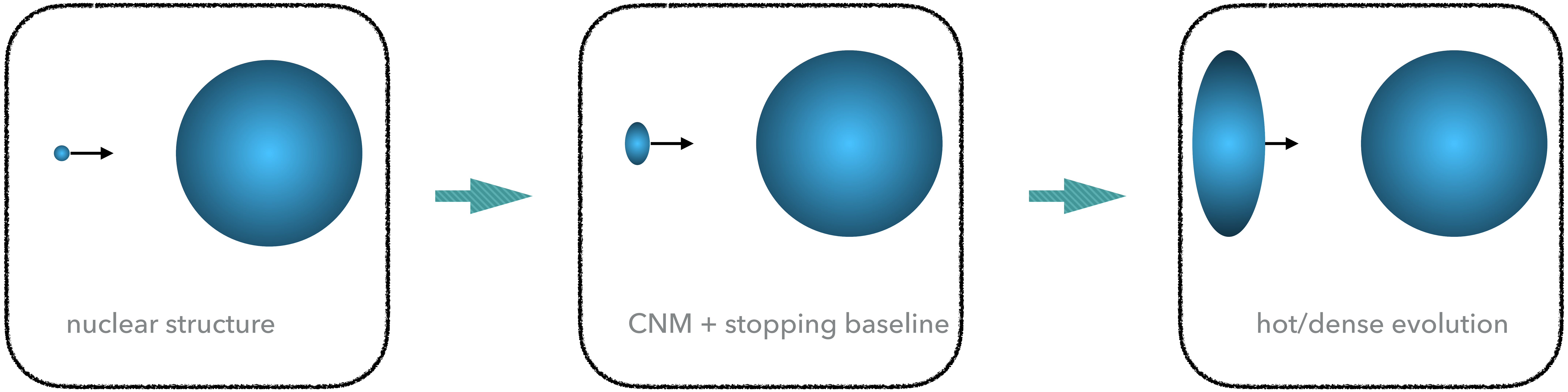
- Goal: use A+A collisions to constrain properties of dense QCD matter.
- Key physics targets:
  - onset of collective behavior and possible deconfinement
  - baryon stopping and conserved-charge transport
  - finite-density EoS and transport coefficients
  - role of hadronic evolution and spectators
  - non-critical baselines and possible critical fluctuations
- Challenge: Measured observables contain entangled contributions from

CNM + baryon stopping + hydrodynamic response + hadronic transport + possible phase-structure effects

$p+A$ as a calibration system for $A+A$

$$(A+A) - \text{prefactor} \cdot (p+A) \neq \text{QGP}$$

- $p+A$ is not a direct subtraction for $A+A$
- Instead, $p+A$ calibrates the non-QGP ingredients: CNM effects, baryon stopping, hadronization in nuclear matter, small-system correlations.
- A consistent model should describe $p+A$ before using $A+A$ to extract dense-medium properties.



Top RHIC and LHC energies

- hydrodynamic simulations benefit from:
  - $n_B \approx 0$ near mid-rapidity,
  - approximate boost invariance,
  - short pre-equilibrium stage,
  - and QGP-dominated evolution.

Low-energy fixed-target collisions

- these simplifications break down:
  - $n_B \neq 0$,
  - strong longitudinal structure,
  - finite nuclear crossing time,
  - hadronic and spectator effects,
  - and possible critical effects.

- At high energy, a common minimal framework evolves

$$\partial_\mu T^{\mu\nu} = 0$$

- At finite density, the hydrodynamic system must include conserved-charge currents:

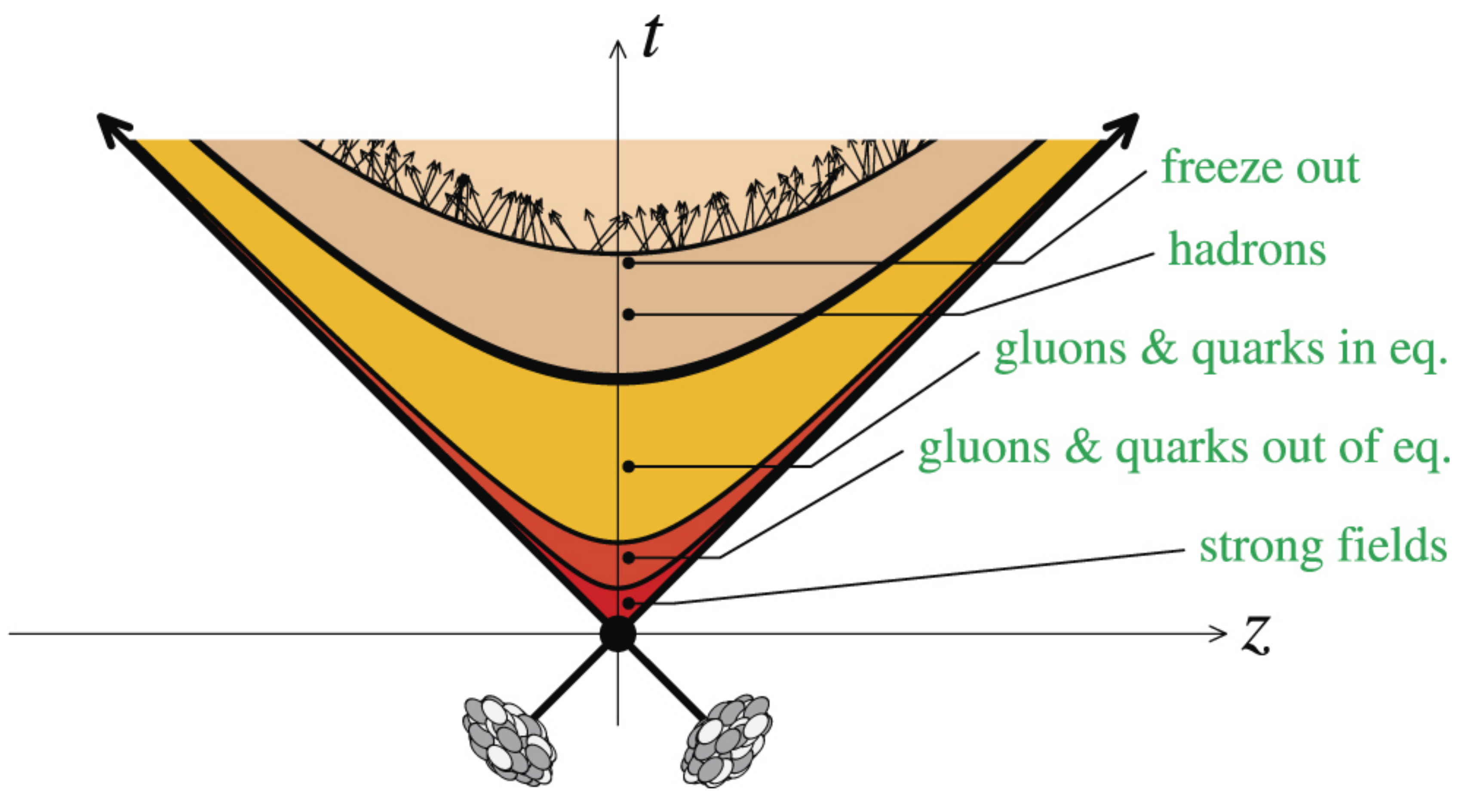
$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu N_q^\mu = 0\,, \quad N_q^\mu = n_q u^\mu + V_q^\mu\,, \quad q \in \{B, Q, S\}$$

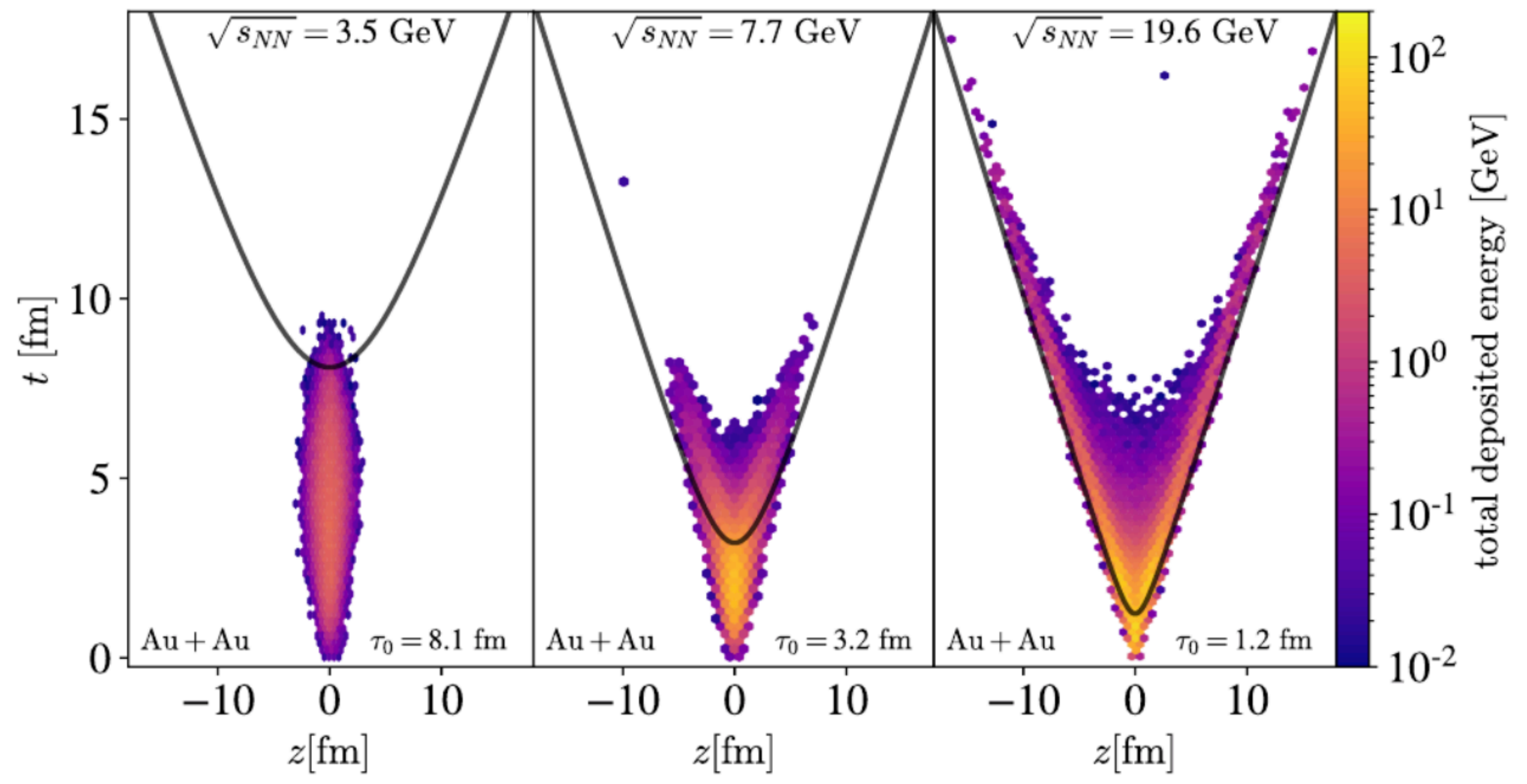
- Additionally, the simulation requires

EoS + transport coefficients + initial condition + particlization.

Non-boost-invariant 3+1D evolution



Ultra-relativistic heavy-ion collisions



Low energy heavy-ion collisions Góes-Hirayama, Egger, Paulínyová, Karpenko, Elfner, 2507.19389

- At high energy, Milne coordinates are often natural: $\tau = \sqrt{t^2 - z^2}$, $\eta_s = \frac{1}{2} \ln \frac{t+z}{t-z}$
- At low fixed-target energies, the evolution is not naturally organized by constant proper time: finite nuclear crossing time matters; baryon deposition is rapidity dependent,
- Full 3+1D evolution, often in Cartesian coordinates, becomes essential.

Dynamical initialization

- At high energy, one often uses $T^{\mu\nu}(\tau_0, x, y)$ at $\eta_s = 0$ as an initial condition.
- At low energies, energy, momentum, and charges may be deposited gradually:

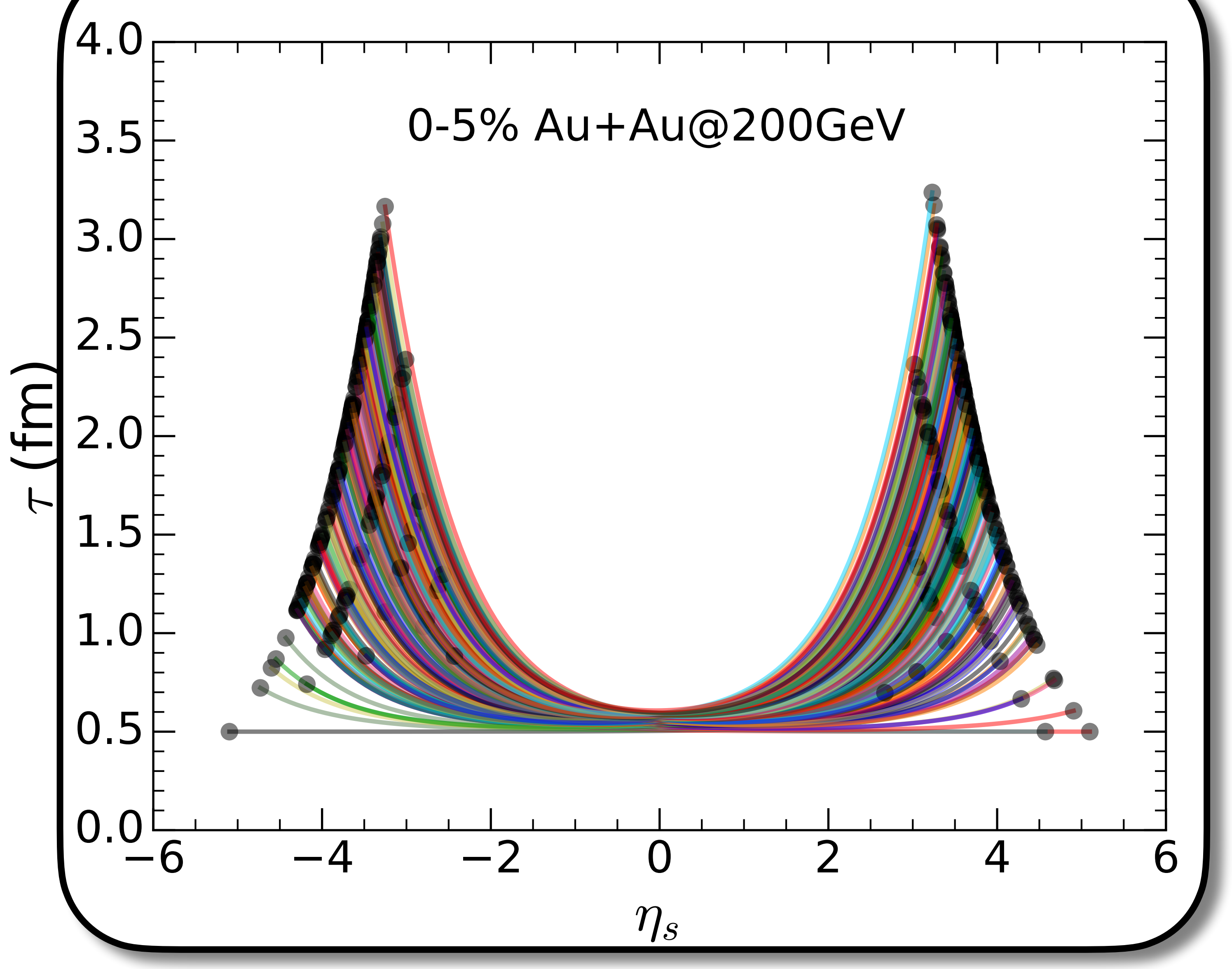
$$\partial_\mu T^{\mu\nu}_{\rm total} = \partial_\mu (T^{\mu\nu}_{\rm fluid} + T^{\mu\nu}_{\rm source}) = 0 \to \partial_\mu T^{\mu\nu}_{\rm fluid} = J^\nu_{\rm source} = -\partial_\mu T^{\mu\nu}_{\rm source},$$

$$\partial_\mu N^{\mu}_{\rm total} = \partial_\mu (N^{\mu}_{\rm fluid} + N^{\mu}_{\rm source}) = 0 \to \partial_\mu N^{\mu}_{\rm fluid} = J_{\rm source} = -\partial_\mu N^{\mu}_{\rm source}\,,$$

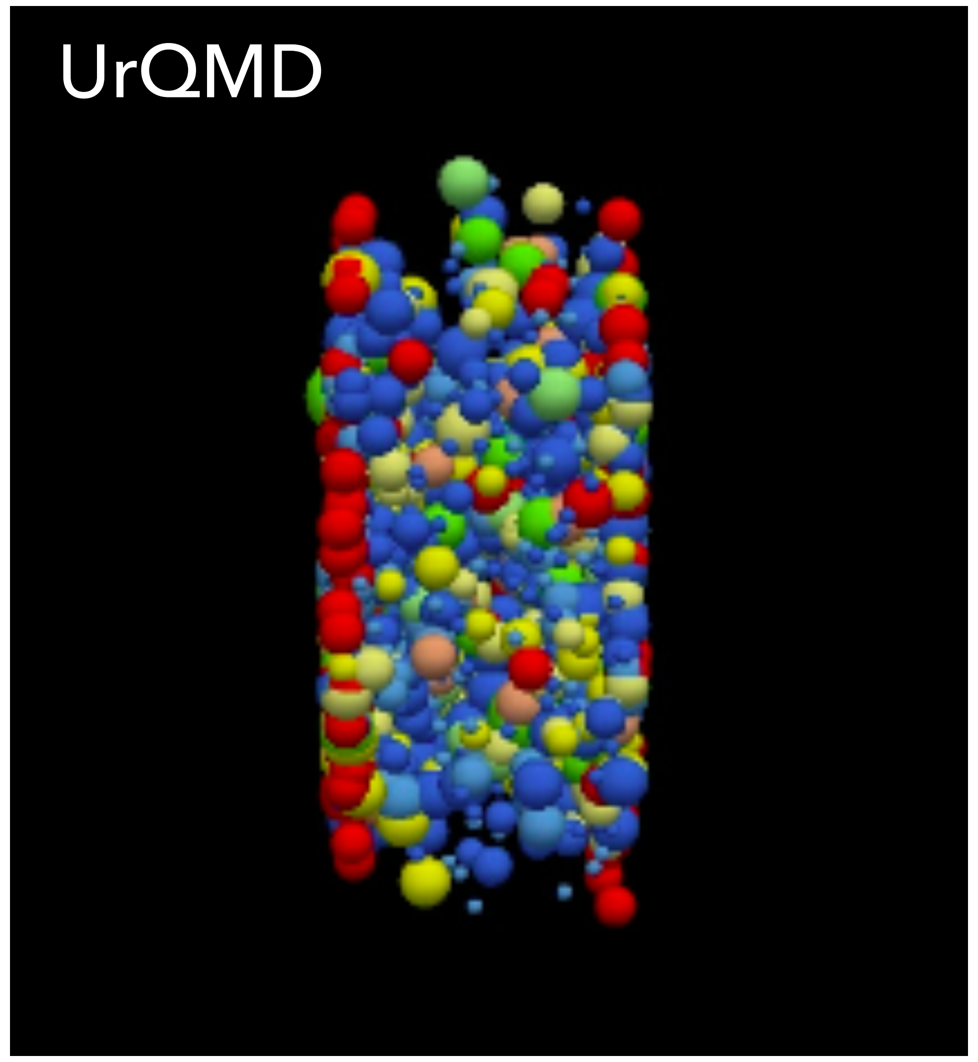
- Hydrodynamization can be local, partial, and time dependent.
- The central challenge is to obtain

$$J^\nu_{\rm source}(t, \boldsymbol{x}) = -\partial_\mu T^{\mu\nu}_{\rm source} \quad \text{and} \quad J_{\rm source}(t, \boldsymbol{x}) = -\partial_\mu N^{\mu}_{\rm source}\,.$$

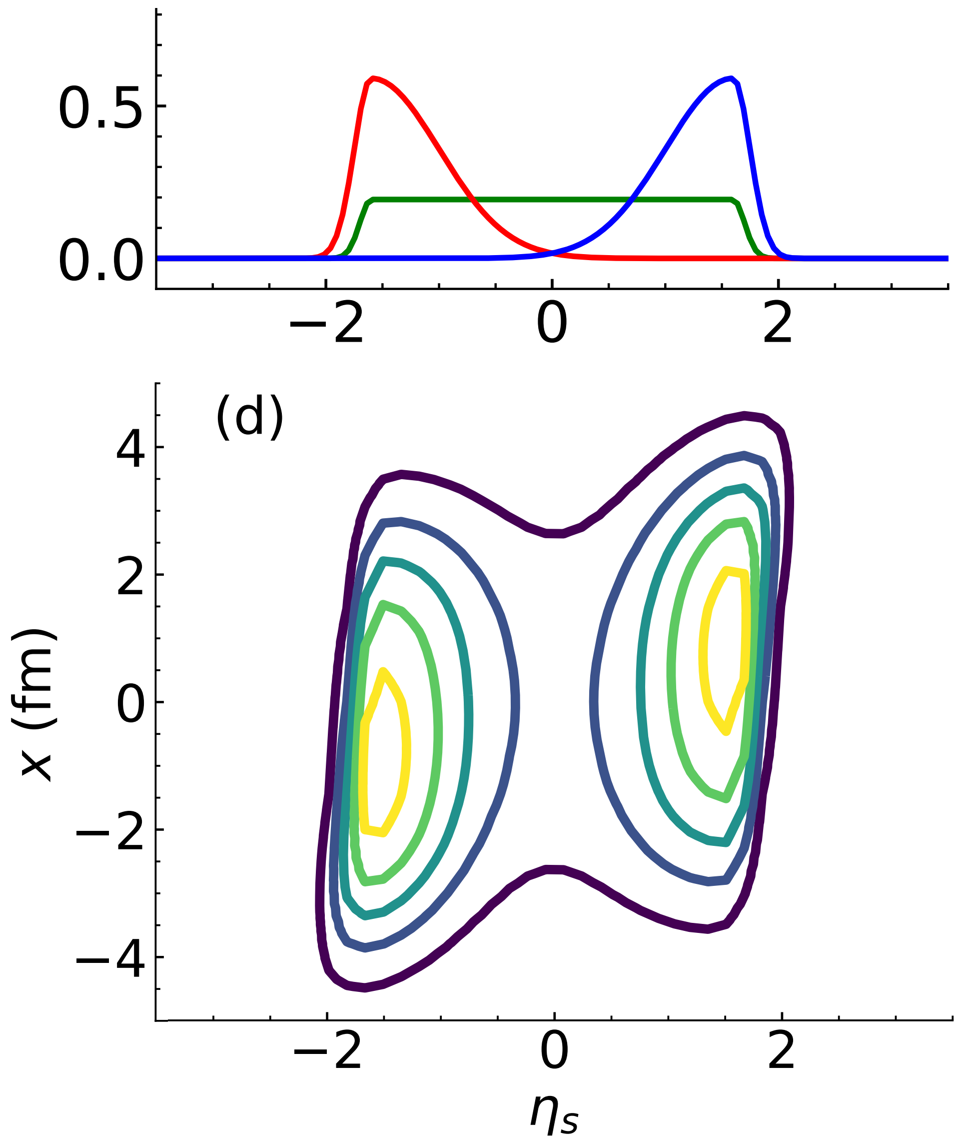
Longitudinal structure and charges stopping



String deceleration



Transport + smearing kernel



Parametric profiles + Glauber

- Charge stopping determines the rapidity distribution of energy and conserved charges
- Microscopic transport models describe the dynamical evolution of conserved charges
- Effective parameterizations allow flexible modeling of the longitudinal structure

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020); C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907; I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901; L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410; LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901; Garcia-Montero, Elfner, Schlichting, PRC 109 (2024) 4, 044916; Cimerman, Karpenko, Tomasik, Huovinen, PRC 107 (2023) 4, 4; … and many other advancements

Coupled charge evolution

- The EoS depends on several densities or chemical potentials:

$$p = p(T, \mu_B, \mu_Q, \mu_S) \quad \text{or} \quad p = p(e, n_B, n_Q, n_S)$$

- Diffusion of different charges is coupled

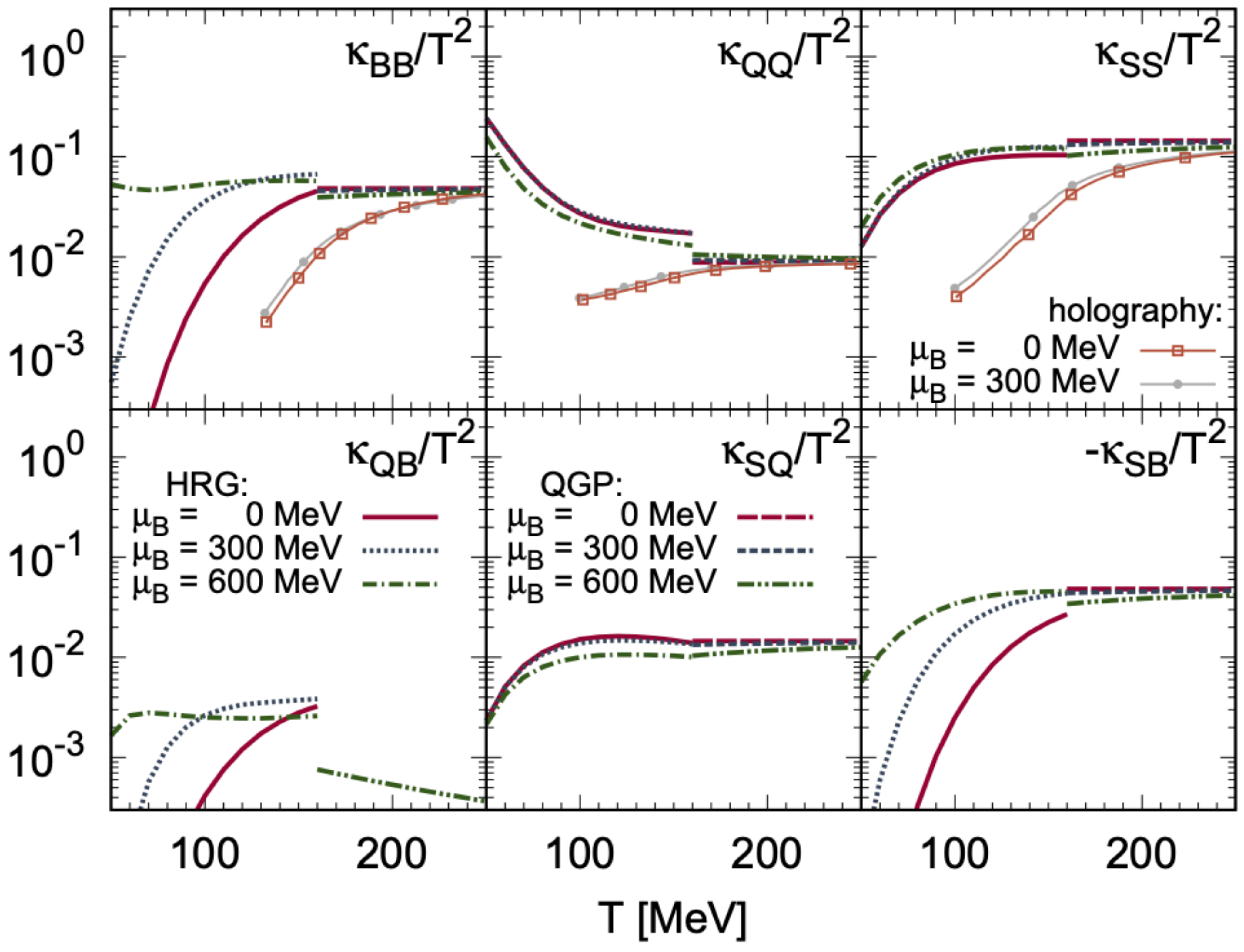
$$\sum_{q'} \tau_{qq'} \dot{V}_{q'}^{\langle\mu\rangle} + V_q^\mu = \sum_{q'} \kappa_{qq'} \nabla^\mu \left(\frac{\mu_{q'}}{T} \right) + \cdots, \quad q', q \in \{B, Q, S\}$$

- Uncertainty in transport coefficients

$$\eta/s,\ \zeta/s,\ \kappa_{qq'},\ \tau_{\text{relax}}(T, \mu_B, \mu_Q, \mu_S)$$

- Near a possible critical region, transport may change rapidly

Diffusion matrix



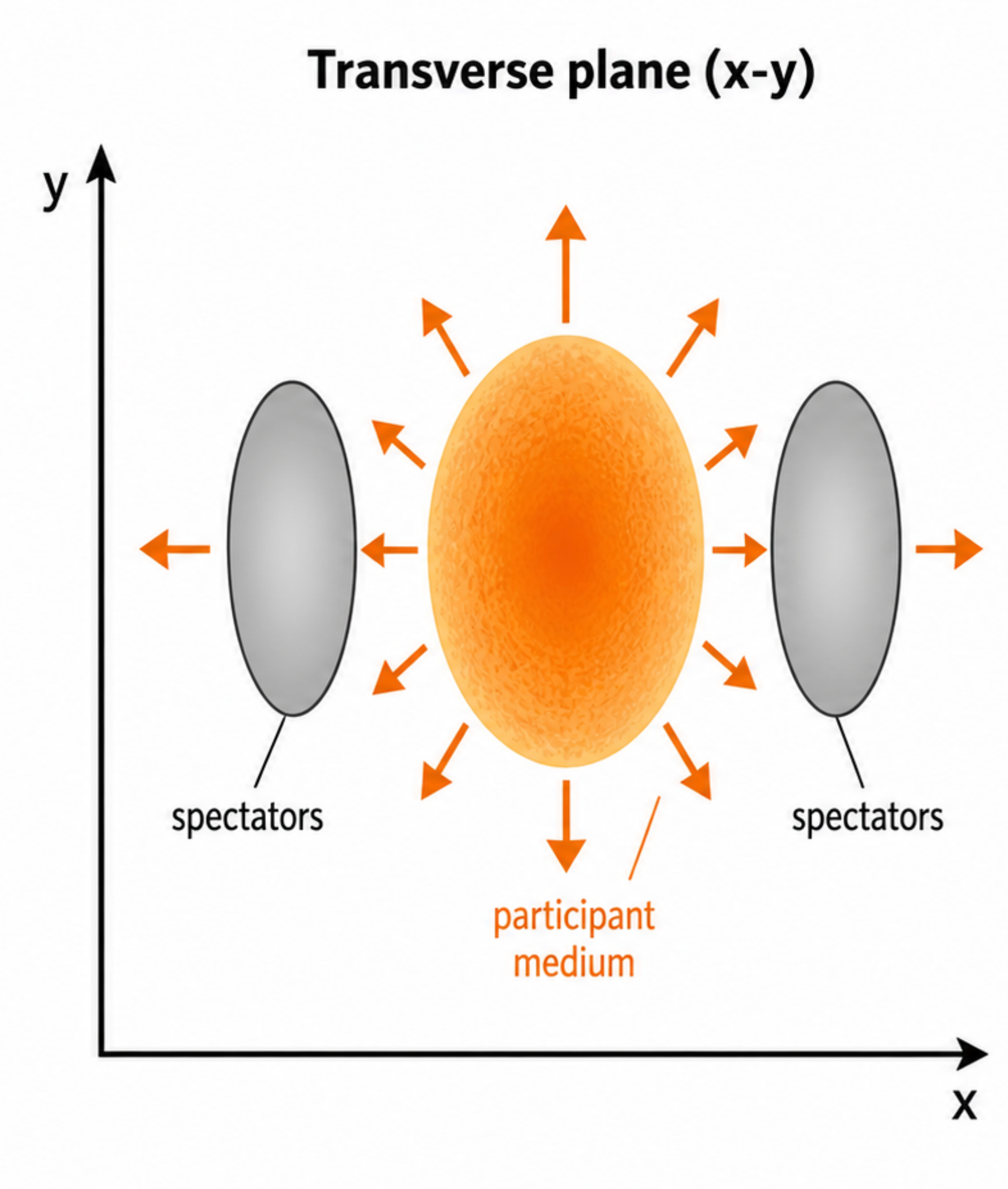
Greif, Fotakis, Denicol, Greiner, Phys.Rev.Lett. 120 (2018) 24, 242301

$$\kappa_{qq'} = \frac{1}{3}\sum_{i=1}^{N_{\text{Species}}} q_i \sum_{m=0}^{M} a^i_{q',m} \times \int \frac{\mathrm{d}^3 k_i}{(2\pi)^3 E_{i,\mathbf{k}}} E^m_{i,\mathbf{k}} \Delta_{\mu\nu} k^\mu_i k^\nu_i f^i_{0\mathbf{k}}.$$

- Conductivities are matrix-valued in charge space.
- Off-diagonal terms couple baryon, electric, and strangeness diffusion.
- Their (T, μ_B)-dependence is poorly constrained and can affect identified-particle and fluctuation observables.
- Diagonal-only diffusion can miss important physics, since off-diagonal couplings can be comparable to diagonal terms.

Spectator-coupled hybrid modeling

- At low fixed-target energies, spectator remnants can affect:
  - centrality and event geometry,
  - baryon stopping and fragmentation,
  - absorption/blocking and electromagnetic fields,
  - cumulant and flow interpretation.
- A realistic framework should couple:



dense fluid + dilute transport + spectator remnants

Particlization and hadronic afterburner at finite density

- Particlization must conserve energy-momentum and BQS- charges.

- Hadron distributions require finite-density corrections (in Cooper-Frye):

$$f_i = f_i^{(0)} + \delta f_i^{\text{shear}} + \delta f_i^{\text{bulk}} + \delta f_i^{\text{diffusion}}.$$

- Grand-canonical vs canonical treatment can matter for conserved-charge fluctuations.

- The hadronic stage can modify identified yields, strangeness, flow, cumulants.

Observable-to-simulation map

observables	simulation/physics sensitivity
dN/dy, net-proton dN/dy	baryon stopping and longitudinal initialization
p_T spectra, mean p_T	radial flow, EoS, hadronic rescattering
anisotropic flows v_n	pressure gradients, transport, collectivity
K, Λ, Ξ, Ω	strangeness chemistry and μ_S
net-proton cumulants	critical dynamics, baryon conservation
$p + A$	CNM, stopping, hadronization, non-hydro baselines

Simulation roadmap for EIC fixed-target

- Transport baseline for $p + A$ and low-energy $A + A$
- Dynamical initialization and stopping constraints
- Finite-density 3+1D spectator-coupled hybrid modeling
- Spectator-aware particlization and afterburner
- Fluctuation baselines and critical dynamics
- Model comparison / Bayesian inference

Summary

- Low-energy fixed-target collisions break the simplifying assumptions of high-energy hydro: $n_B \approx 0$, boost invariance, short initialization, and clean stage separation.
- Hydrodynamic simulations must become finite-density and multi-charge, with coupled evolution of $T^{\mu\nu}$ and N^{μ} of BQS, supported by finite-μ_{BQS} EoS and transport coefficients.
- The central challenge is hybrid and dynamical: 3+1D initialization, spectators, transport regions, particlization, and afterburner must be treated consistently.
- Consistent simulations are needed so that EIC fixed-target measurements constrain the EoS, transport, baryon stopping, and possible critical dynamics.

THANKS FOR YOUR ATTENTION!