CRC-TR 211
Strong-interaction matter under extreme conditions

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Visualizations of heavy-ion collisions based on a transport and a hybrid approach

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International School of Nuclear Physics, 46th Course

- **Hadronic transport approach**
  - Effective solution of relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C_i^{\text{coll}}$$

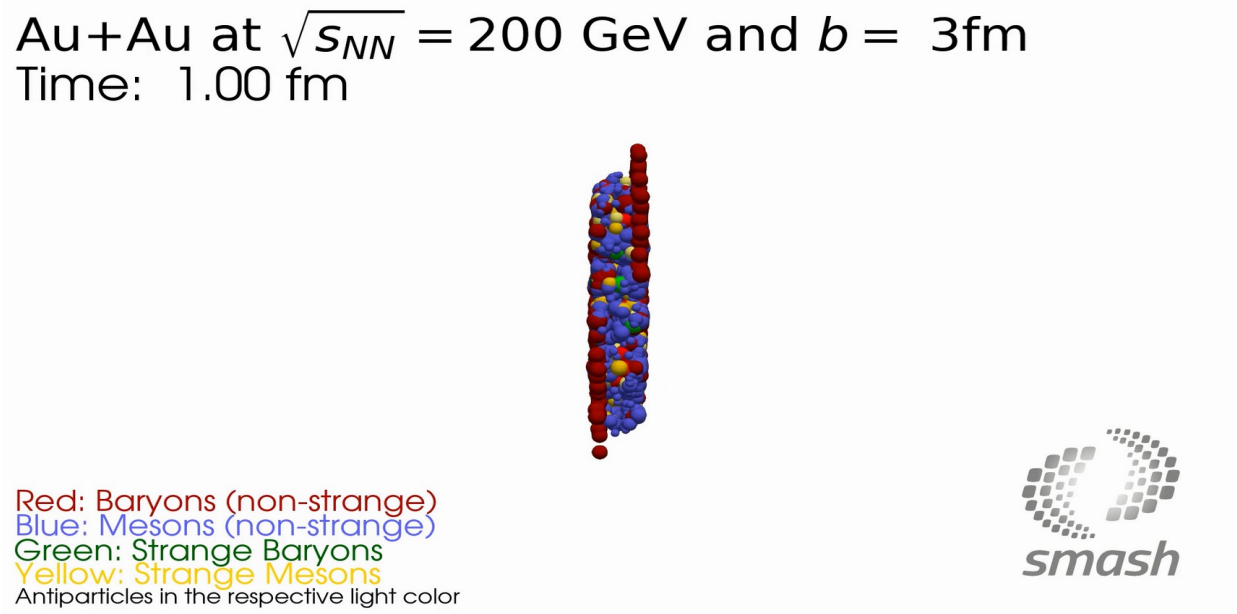
  - Geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \quad \text{with} \quad d^2_{\text{trans}} = (\vec{r}_a - \vec{r}_b)^2 - \frac{\left((\vec{r}_a - \vec{r}_b)\cdot(\vec{p}_a - \vec{p}_b)\right)^2}{(\vec{p}_a - \vec{p}_b)^2}$$

  - Includes all well-established hadrons up to a mass of ~2 GeV as degrees of freedom

DOI 10.5281/zenodo.3484711 J. Weil et al., Phys. Rev. C 94, 054905 (2016)

SMASH Animation



SMASH-vHLLE-Hybrid Approach

- **Initial Conditions → Hydro → Sampler → Afterburner**
- **Initial Conditions (SMASH)**
  - Hadronic initial state and non-equilibrium phase
- **Hydrodynamic Stage (vHLLE)**

  $\partial_\nu T^{\mu\nu} = 0$ with $T^{\mu\nu} = \epsilon u^\mu u^\nu - \Delta^{\mu\nu}(p + \Pi) + \pi^{\mu\nu}, \quad \partial_\nu N^\nu_{\mathrm{B,Q,S}} = 0$
- **Sampler (SMASH-Hadron-Sampler)**
  - Cooper-Frye particlization of the freeze-out hypersurface
- **Afterburner (SMASH)**
  - For dilute non-equilibrium stages of high beam energy heavy-ion reactions (hadronic rescattering)
- **Communication between codes for different stages → Hybrid-handler** DOI 10.5281/zenodo.15880336

A. Schäfer et al, Eur. Phys. J. A 58(2022)11, 230

SMASH-vHLLE-Hybrid Approach

- **Default settings of the IC and Hydro stages**
  - IC based on fixed hyperbolic time (iso-τ) set to the passing of nuclei
    → Info provided to Hydro
  - Hydro is run in hyperbolic coordinates
    → obviously not great for intuitive visualizations
  - For this and another project: vHLLE needs to run in Cartesian coordinates

SMASH-vHLLE-Hybrid Stages Animation

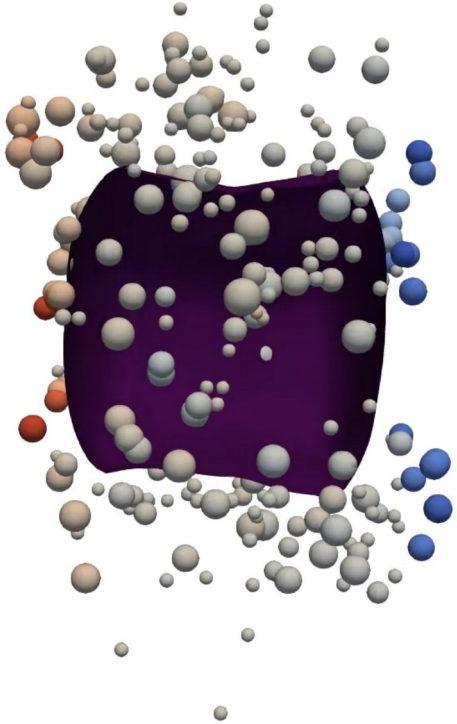
Why Visualizations?

- Visual insights into heavy-ion collision simulations
- Identification of potential issues (e.g., bugs in the code)
- For visual aid in talks and science communication & outreach

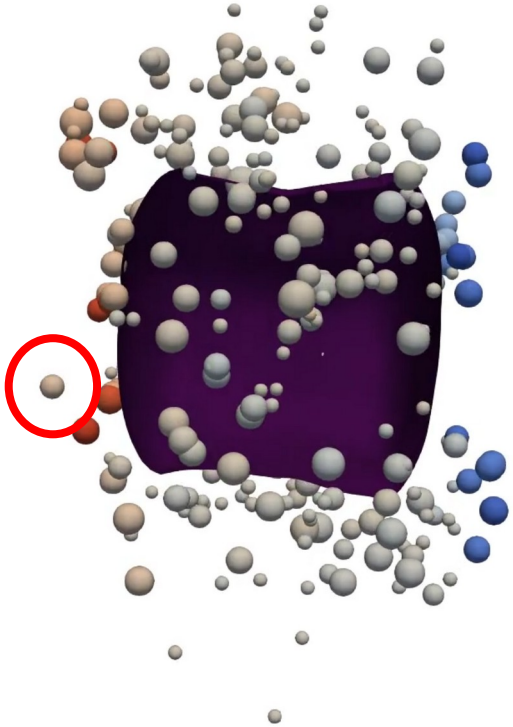
Identification of Potential Issues – Sampler Bug

Identification of Potential Issues – Sampler Bug

- t = 7.85 fm



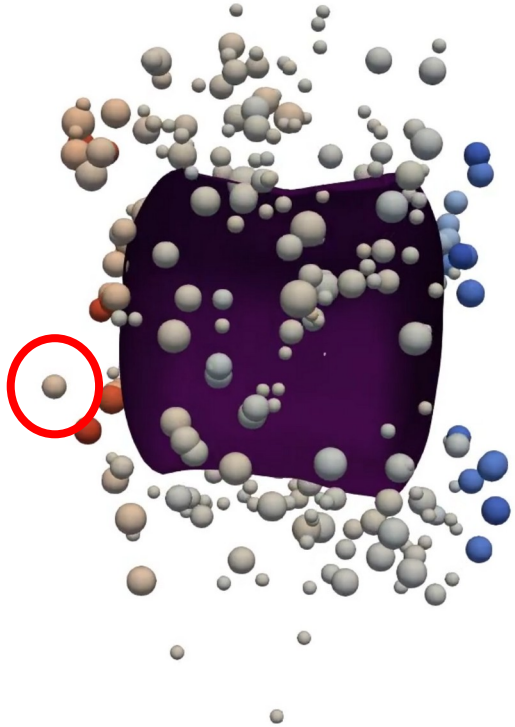
- t = 7.90 fm



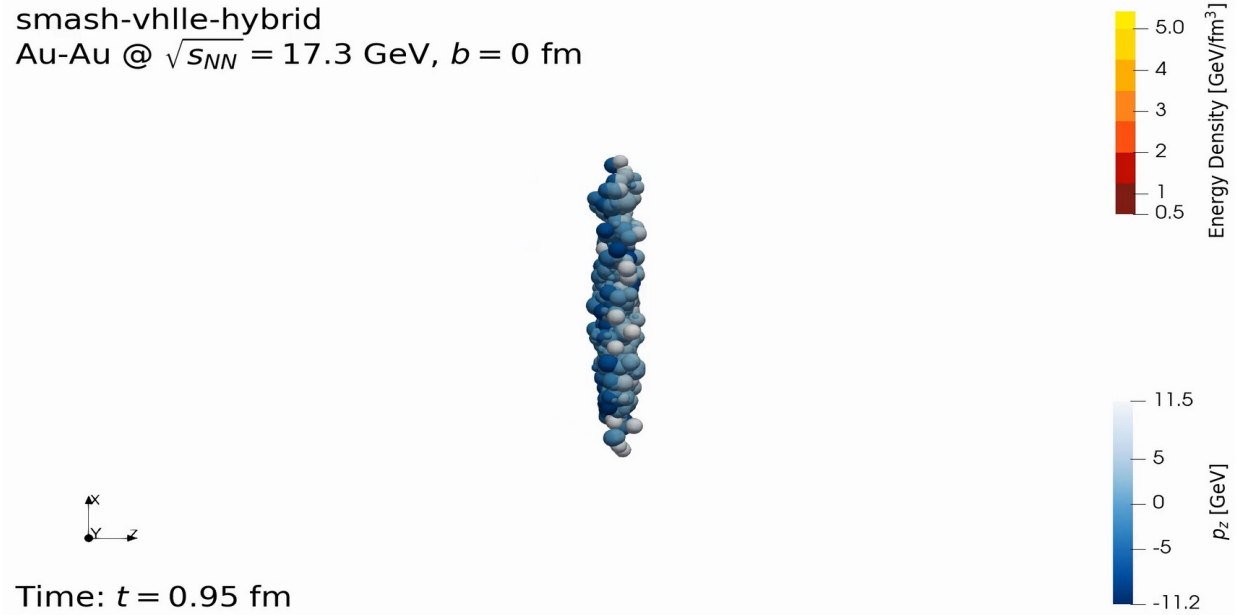
Identification of Potential Issues – Sampler Bug

- Implemented vHLLE (Hydro) feature: running in Cartesian coordinates
- Sampler was not adjusted to vHLLE providing space-time four-vectors in Cartesian coordinates

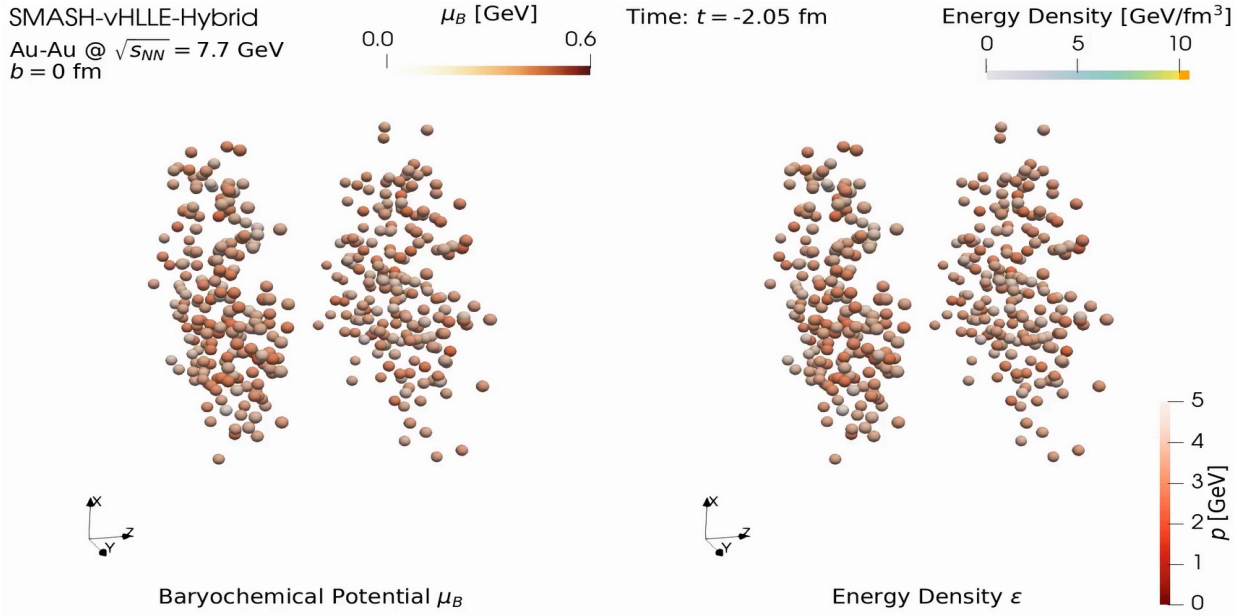
- t = 7.90 fm



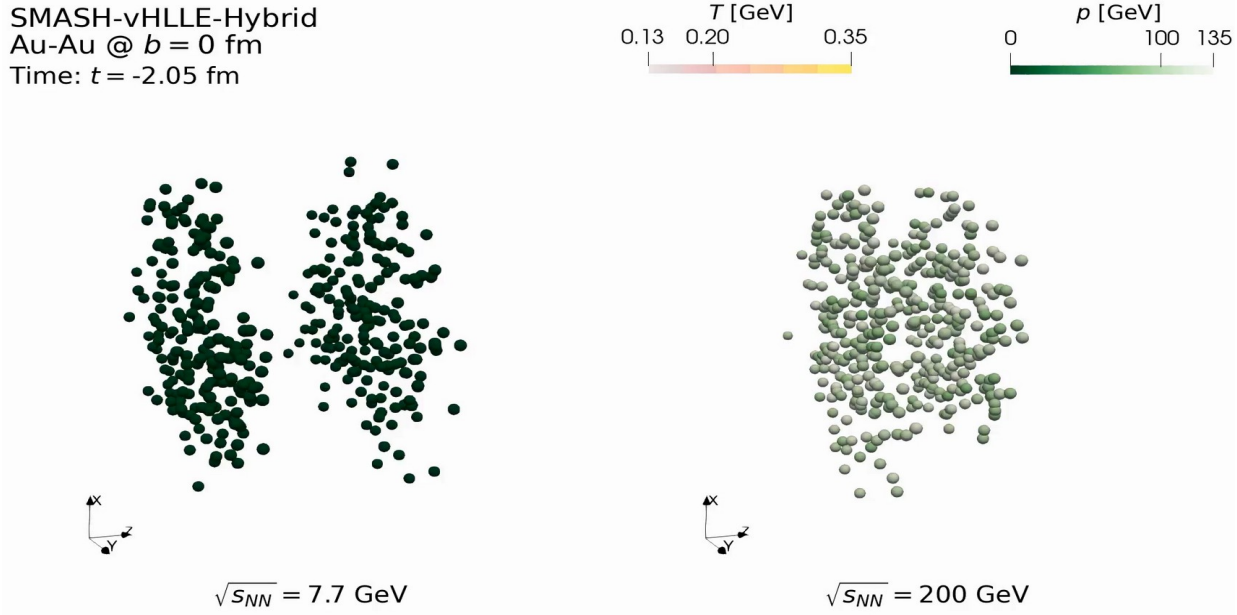
Identification of Potential Issues – Hydro Bug



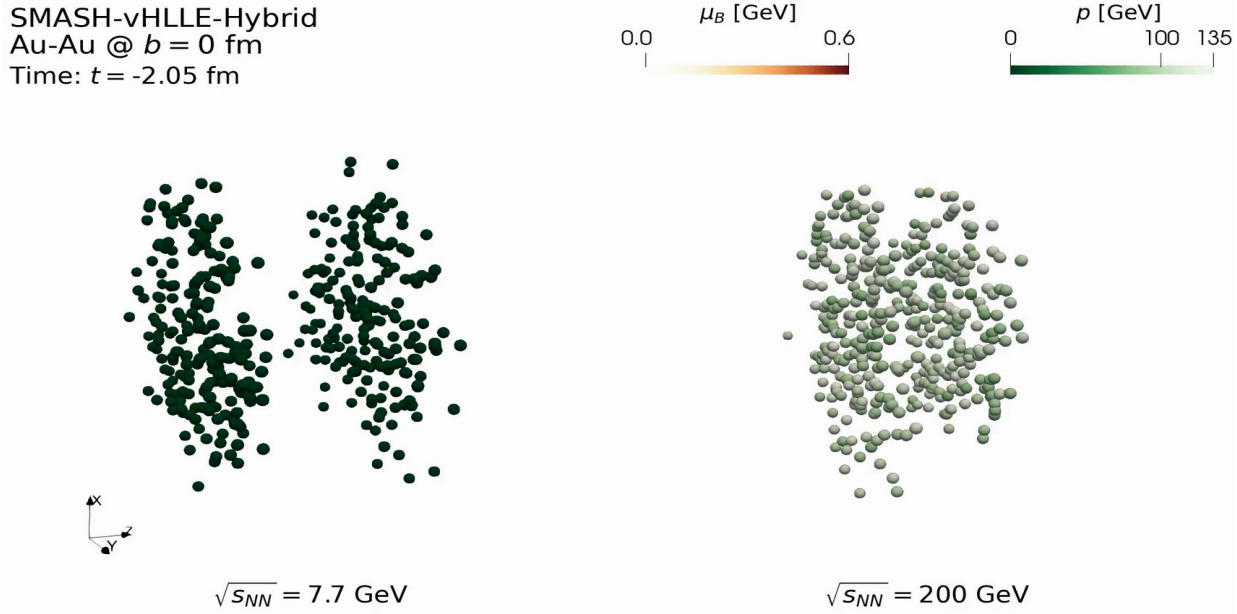
SMASH-vHLLE-Hybrid Animation #1



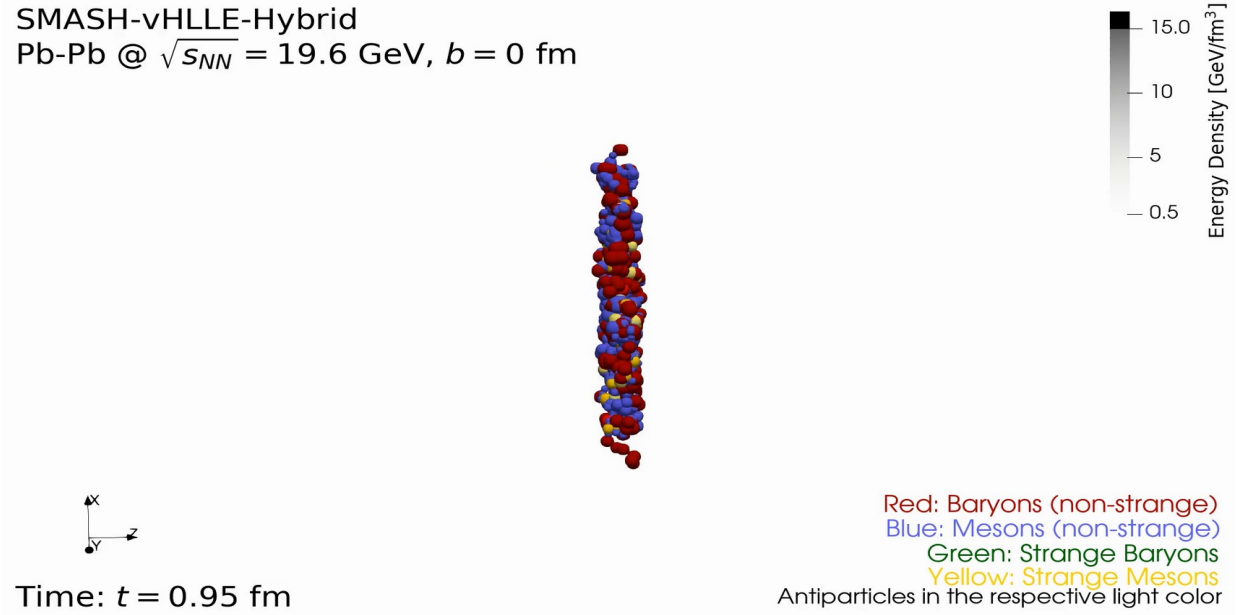
SMASH-vHLLE-Hybrid Animation #2



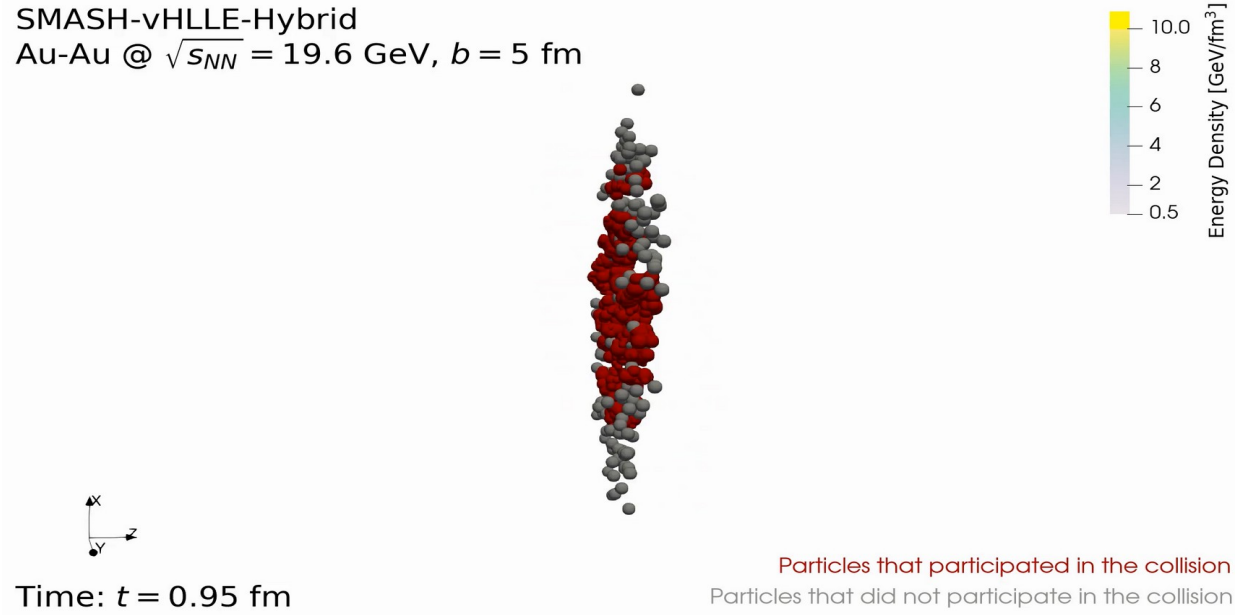
SMASH-vHLLE-Hybrid Animation #3



SMASH-vHLLE-Hybrid Animation #4



SMASH-vHLLE-Hybrid Animation #5

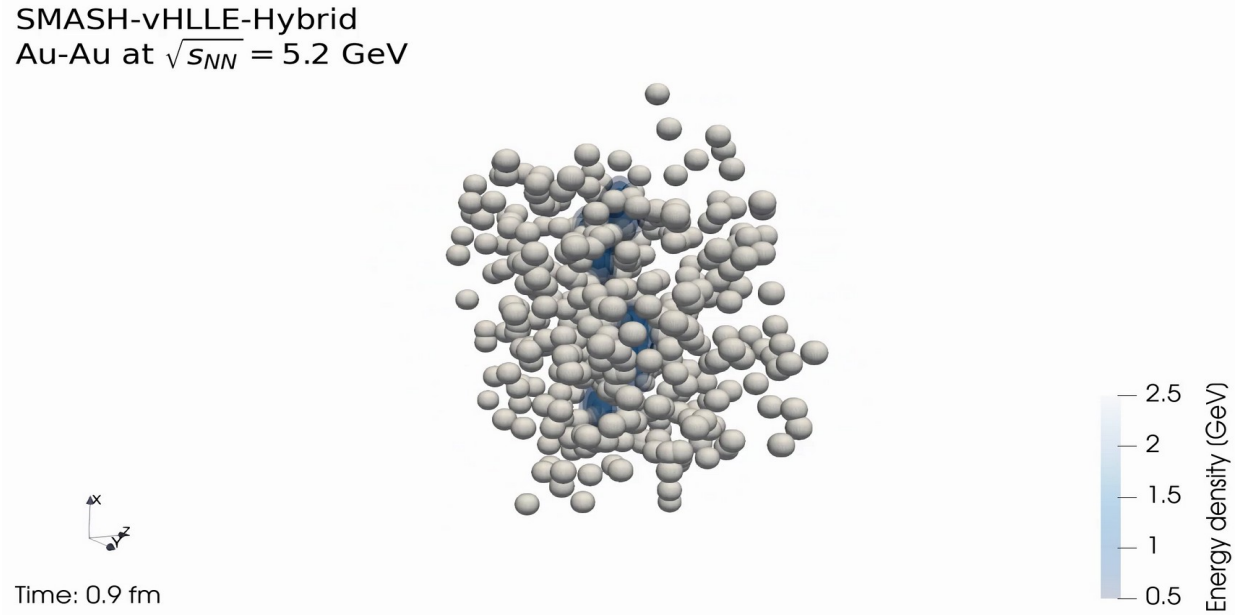


Dynamical Fluidization

- **Hybrid approach at lower beam energies**
  - Different parts of the nuclei will interact at different times
  - No guarantee that the entirety of the medium approaches equilibrium
- **Resolved by dynamic initial conditions**
  - Fluidization not at a fixed time instantaneously, but spread out over time depending on energy density threshold

R. Góes-Hirayama et al., arXiv:2507.19389 [hep-ph]

Dynamical Fluidization Animation



Final Remarks

- **More animations on smash-transport.github.io**
- **Recent mini-review on SMASH physics**

  H. Elfner and R. Góes-Hirayama, SMASH: Results from hadronic transport for heavy-ion collisions at high densities, arXiv:2508.21477 [nucl-th]
- **Further insights into dynamical fluidization**

  R. Góes-Hirayama et al., Pushing the hybrid approach to low beam energies with dynamic initial conditions from hadronic transport, arXiv:2507.19389 [hep-ph]

Backup

Output Format and Visualization Tool

- Usage of Visualization Toolkit (VTK) output format. Each VTK file contains a snapshot of the simulation for a certain time step
- Open source software ParaView used to animate the collisions based on VTK files
- Visit smash-transport.github.io for a tutorial on how to create animations

Dynamical Fluidization Animation Backup

- **Dynamical fluidization with core and corona particles separation**