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Simulating the Glasma in 3+1D

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Particles and Interactions

1 Introduction

Color glass condensate (CGC)

- Effective theory of QCD for high energy nuclei
- Initial state and early stages of heavy-ion collisions
- Nuclei as highly Lorentz contracted disks (“pancakes") of color sources J^μ (valence quarks) coupled to color fields A^μ (gluons)
- Collision of two CGCs ⇒ **Glasma**:
  - Intermediate state between color glass and quark-gluon plasma (transition $\tau \approx 1\,\mathrm{fm}/c$)
  - Pre-equilibrium stage (before hydrodynamic stage)
- Classical Yang-Mills at leading order

Standard approach

- Ultrarelativistic limit
- Infinite collision energy: $\sqrt{s_{\mathrm{NN}}} \to \infty$
- Infinitesimally thin nuclei
- Boost invariant and effectively 2+1 dimensional Glasma
- Source-free Yang-Mills (YM) eqs. in comoving frame

$$D_\mu F^{\mu\nu}(\tau, x_T) = 0,$$

where $\tau = \sqrt{t^2 - z^2}$ is proper time

2 Setup for 3+1D

- Collisions at finite collision energy $\sqrt{s_{\mathrm{NN}}}$ with finite thickness of nuclei along beam axis $\propto R/\gamma$
- YM eqs. in 3+1D with color sources

$$D_\mu F^{\mu\nu}(t, x_T, z) = J^\nu(t, x_T, z)$$

⇒ Simulation in **laboratory frame** [1]

Colored particle-in-cell (CPIC)

- Large number of charged particles coupled to gauge field
- Movement of particles generates color current J^μ ⇒ YM eqs.
- Numerical treatment of nuclei
  - Sources J^μ: ensemble of colored, point-like particles
  - Fields A^μ: real-time lattice gauge theory
- Charge conserving, discrete equations of motion for both fields and sources
- Large lattices and computational resources required (VSC-3)

3 Broken boost invariance in the Glasma

- Collisions of Au nuclei at energies $\sqrt{s_{\mathrm{NN}}} \simeq 200\,\mathrm{GeV}$ (RHIC) [2]
- Initial condition: 3D generalization of the McLerran-Venugopalan (MV) model
  - New parameter for thickness along beam axis
  - Simple transverse structure
- Observables: energy density ε, pressure densities p_L, p_T, energy flux along beam axis S_L

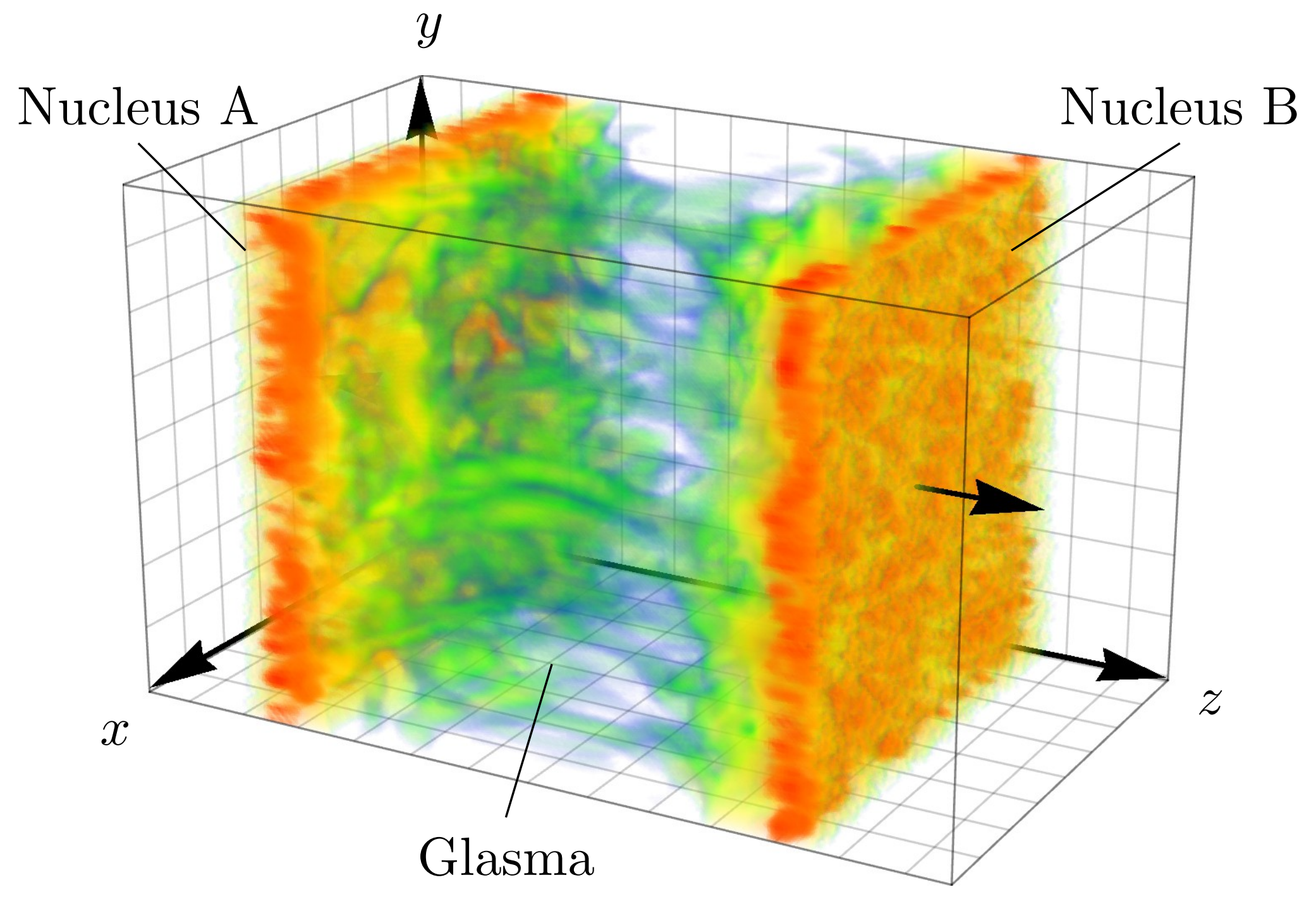

Figure 1: Plot of energy density of color fields in a 3+1D collision from [2]. We only simulate a small part of the nuclei in the transverse directions.

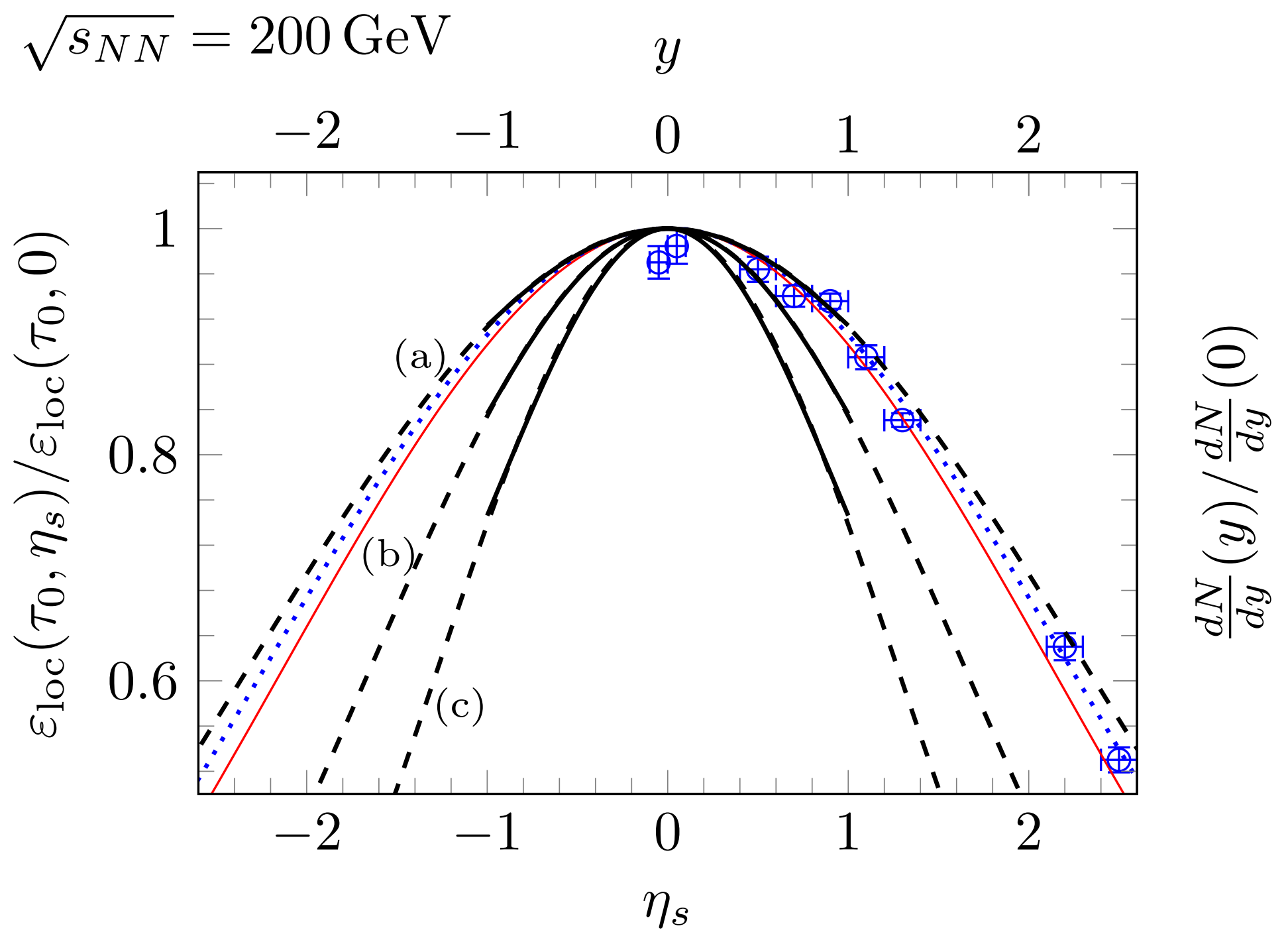

Figure 2: Rapidity profile of local rest frame energy density for $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ at $\tau = 1\,\mathrm{fm}/c$ from [2]. Solid black lines: simulation data; (a), (b), (c) correspond to different values of the infrared regulator. Dashed lines: Gaussian fits. Blue dots and curve: measured pion multiplicities at RHIC. Red solid line: Landau model.

Explicitly broken boost invariance

- Observables depend on rapidity η_s
- Reasonable agreement with data [2]
- Rapidity dependence due to classical time evolution: leading order result
- Different from rapidity dependence of JIMWLK (next-to-leading order renormalization group equations)
- Large pressure anisotropy
- Free-streaming expansion of Glasma

4 Semi-implicit solver for real-time lattice gauge theory

Numerical Cherenkov instability

- High momentum modes propagate slower than the speed of light due to **numerical dispersion**
- Unphysical Cherenkov radiation of color charges
- Instability less severe with higher lattice resolution

Semi-implicit numerical scheme

- New scheme derived from gauge-invariant action: similar to Wilson action with time-averaged terms [3]
- Linear dispersion along beam axis
- **Eliminates numerical instability**
- Conserves Gauss constraint

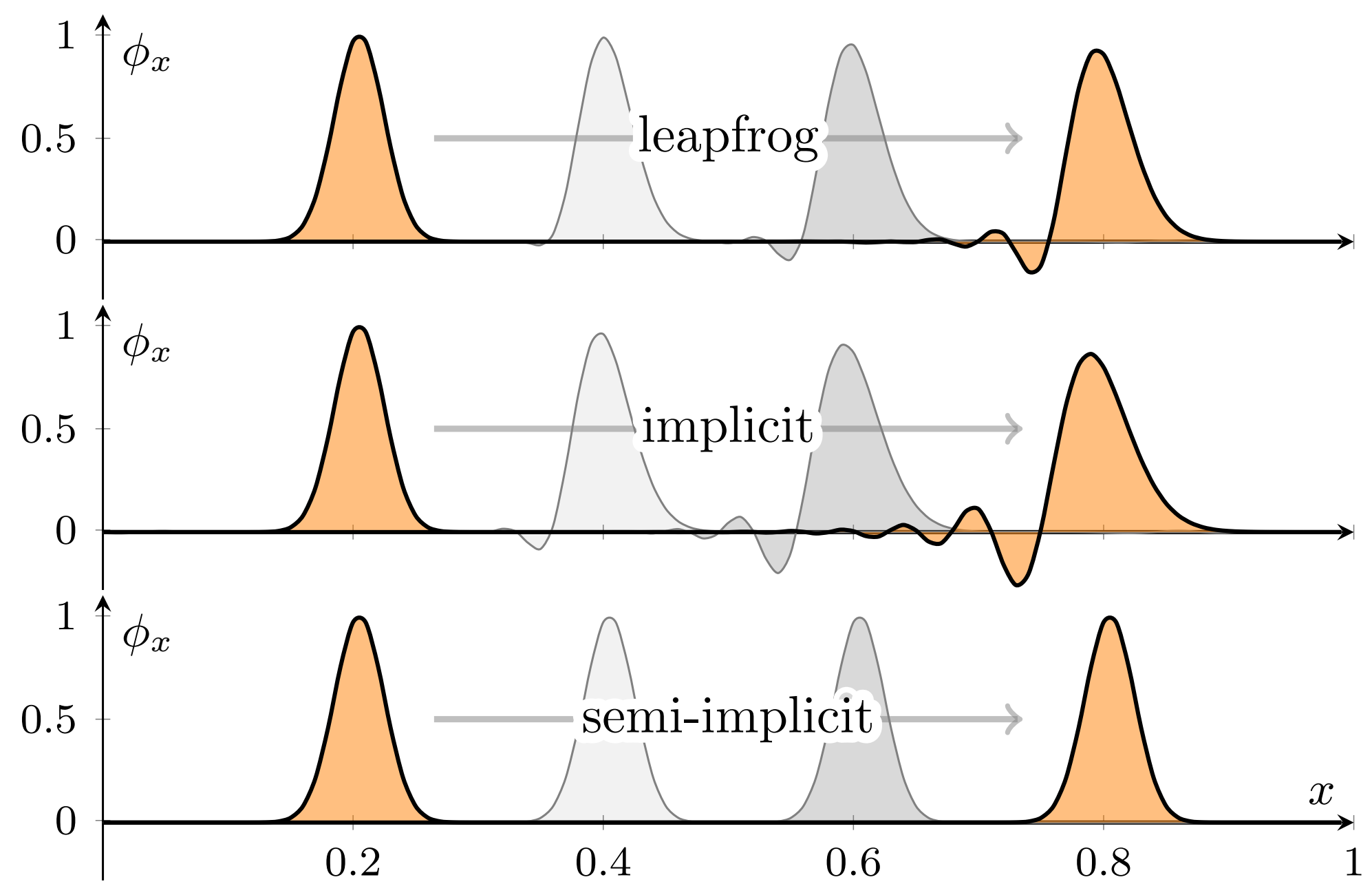

Figure 3: Example of numerical dispersion from [3]: wave pulses disperse over time due to non-linear dispersion relation. New semi-implicit scheme is free of dispersion along propagation direction and preserves pulse shape. Analogous phenomenon present in lattice gauge theory, where this drives a numerical instability. The semi-implicit scheme eliminates this problem entirely.

5 Summary & References

- **3+1D setup** for studying collisions at finite collision energy within CGC framework
- **Explicit breaking of boost invariance** from classical time evolution (leading order)
- **New semi-implicit scheme** to study complicated initial conditions at higher energies

[1] D. Gelfand, A. Ipp and D. Müller, PRD **94**, no. 1, 014020 (2016) [arXiv:1605.07184]
[2] A. Ipp and D. Müller, PLB **771**, 74 (2017) [arXiv:1703.00017]
[3] A. Ipp and D. Müller, EPJC **78**, no. 11, 884 (2018) [arXiv:1804.01995]

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