Coarse Graining and Hydrodynamic Profile of PHSD time evolution

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Great Success of Relativistic Hydro Approaches in Relativistic Heavy Ion Collisions …

- Flow Observables (V2, V3..Vn) vs. Global Parameters(pT, Centrality..) in AA Collisions
- Ridge, and possbile initial geometric nature

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- Big Expectations for Extracting QGP properties and Initial Condition !…

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- But in pA also ? YES - WHY NOT - NO! - Maybe..

Let us start with **trivialities** (maybe till the end..)

What is Hydrodynamics?

What is a True Hydrodynamics?

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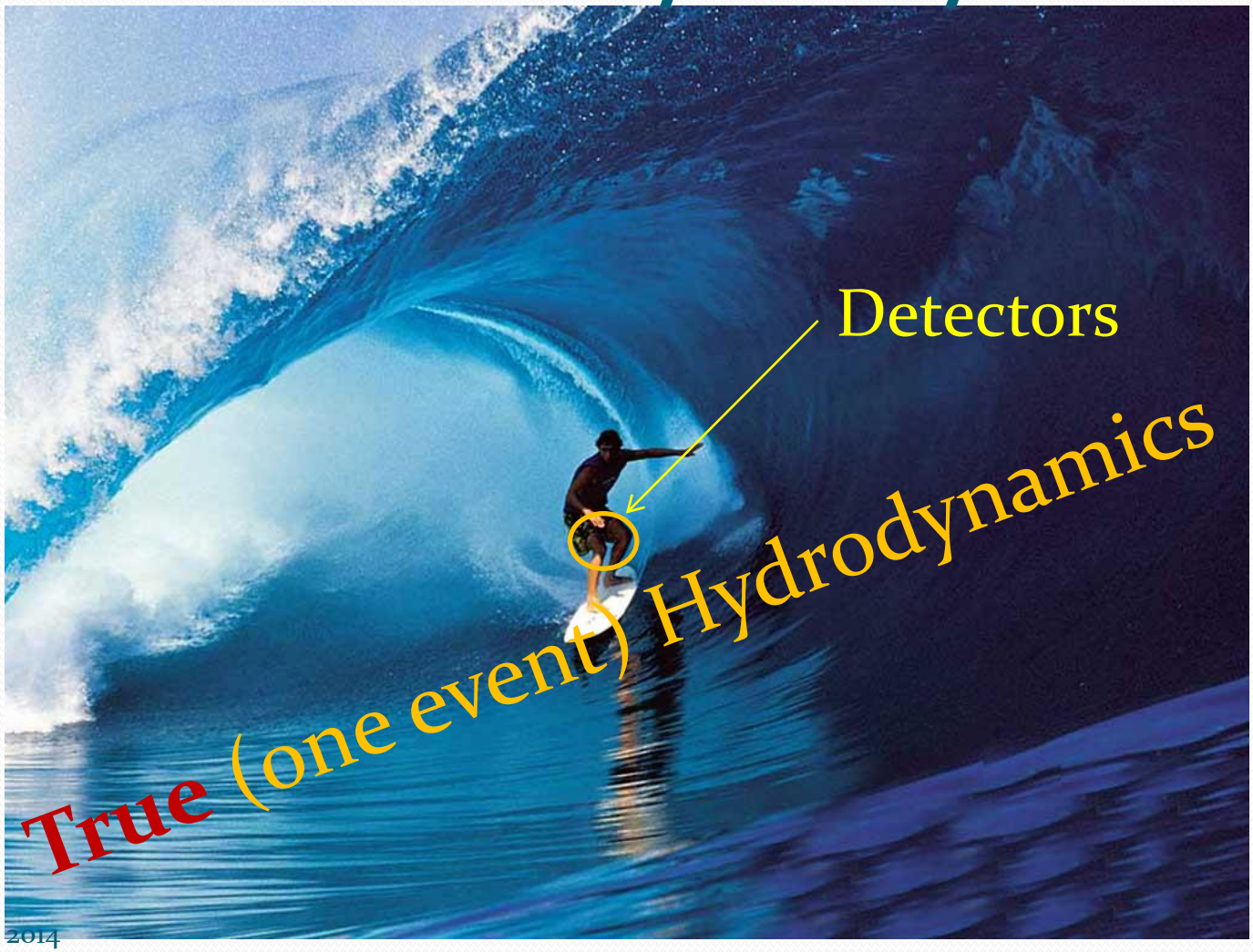


But we only know later the effects..

Or,…

What is a "TRUE" Hydrodynamics?

A closed system of equations for local macroscopic variables, based of conservation Laws for the Energy and Momentum Tensor, and conserved currents,

$$\partial_\mu T^{\mu\nu}(\vec{x},t) = 0, \qquad \text{(ideal)}$$

$$\partial_\mu j^{\mu}(\vec{x},t) = 0,$$

with additional equations to describe the **well-defined thermodynamical properties** of the matter in question (EoS, Relaxation equations with transport coefficients, if necessarly) in **LOCAL THERMAL EQUILIBRIUM**

What is a “TRUE” Hydrodynamics?

- A **precise analysis** of hydro-profile (dynamics) would furnish the information of properties of the matter and initial condition….. but
- Question is: How precise we are looking the profile ?
- Are we really observong a true hydro in Relativistic Heavy Ion collisions?

What is a "TRUE" Hydrodynamics?

- A **precise analysis** of hydro-profile (dynamics) would furnish the information of properties of the matter and initial condition.....
- Question is: How precise we are looking the profile ?
- If we don't have (or don't care) a good resolution of macroscopic dynamics, the properties of the matter we deduce may not be precise also.

What is a "TRUE" Hydrodynamics?

- A **precise analysis** of hydro-profile (dynamics) would furnish the information of properties of the matter and initial condition.....

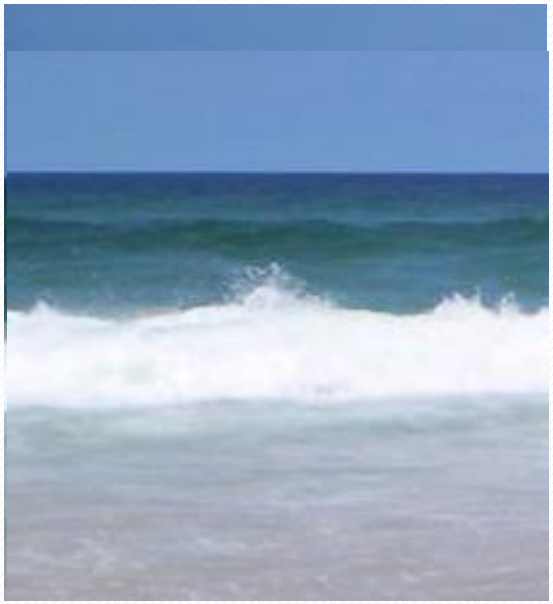
- Relativistic Heavy Ion Case

1. Violent process (short time scale) in a Small system, large fluctuation
2. What is the resolution? Effective EoS ? (Conservation law, continuum effective variables)

P. Mota et al, The European Physical Journal A 48 (11), 1-12, 2012

Waves on the beach

Waves on the beach



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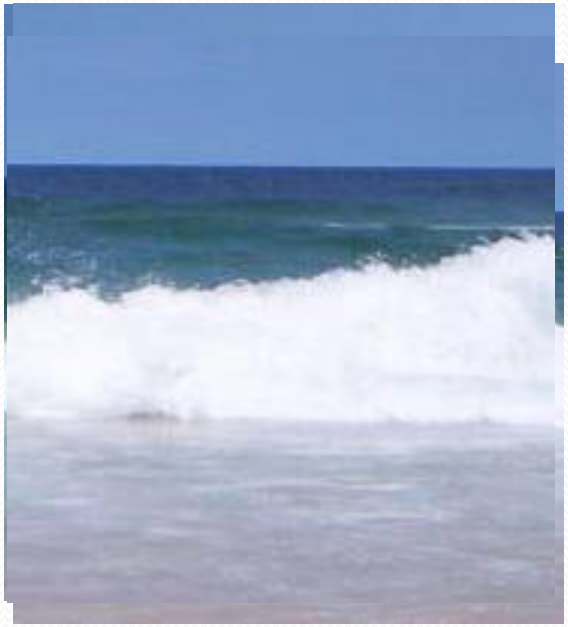

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They are different, nice to look, but
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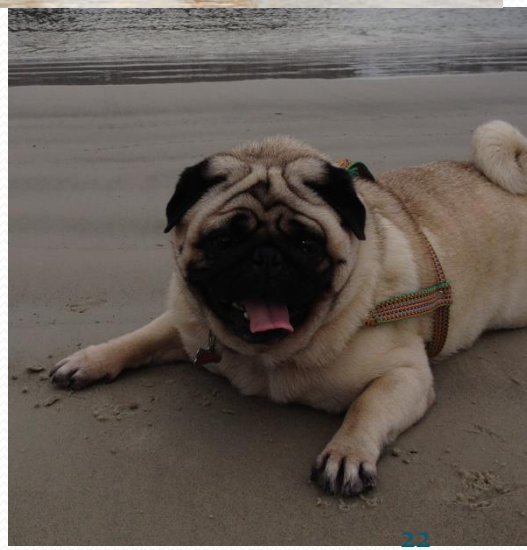


But some do care!

What are “hydro” Observables?

Dependence on parameters associated with the (loosely guessed) initial geometry of final state observables (spectra, particle correlations).

Usually not determined for ONE single event..

Three directions of Hydro Approach

Quantitative Approach	Qualitative Approach	Theoretical Foundation
Assume "Real Hydro" is valid, and try to determine "precise" values of Transport Coefficients comparable to LQCD results.	Hydro is dominated by just conservation laws plus compression effects and look for new physical information for initial states.	To understand from where the observed hydro behaviors come and clarify the limitation of hydro approach

Hydro in Relativistic Heavy Ion Collision
How Quantitatively precise ?

Uncertainties associated

- EoS, Transport Coefficients (?)
- Freezeout Mechanism (Tough)
- Initial Condition (Challenging)
- Event-by-Event vs. Ensemble Average? (To be clarified)

Counter-examples of Real Hydro ("Pseudo Hydro")

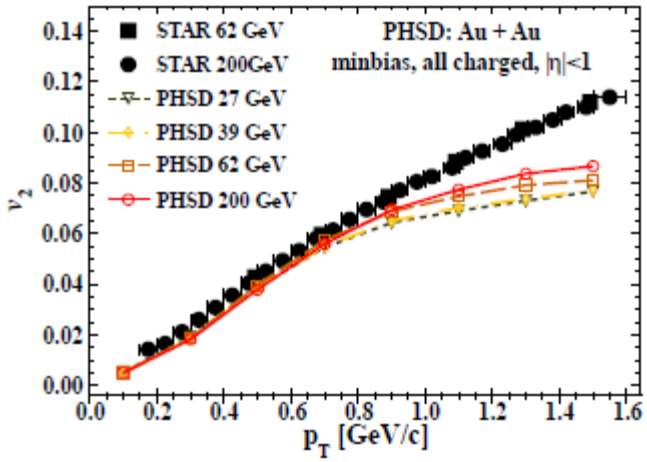
- Schrödinger Equation – Quantum Hydro
- Isotropic massless gas – Non Equilibrium
- Initial state correlation in free streaming case
- Event average -> Effective EoS

:

Hydrodynamical Representation of microscopic dynamics

- Starting from a microscopic dynamical model which contains many-body interactions (compression effects), define the energy momentum tensor and current and compare with the hydrodynamics
- and reproduce the Collective flows…
- PHSD as one available microscopic model for this purpose

The Parton Hadron String Dynamics



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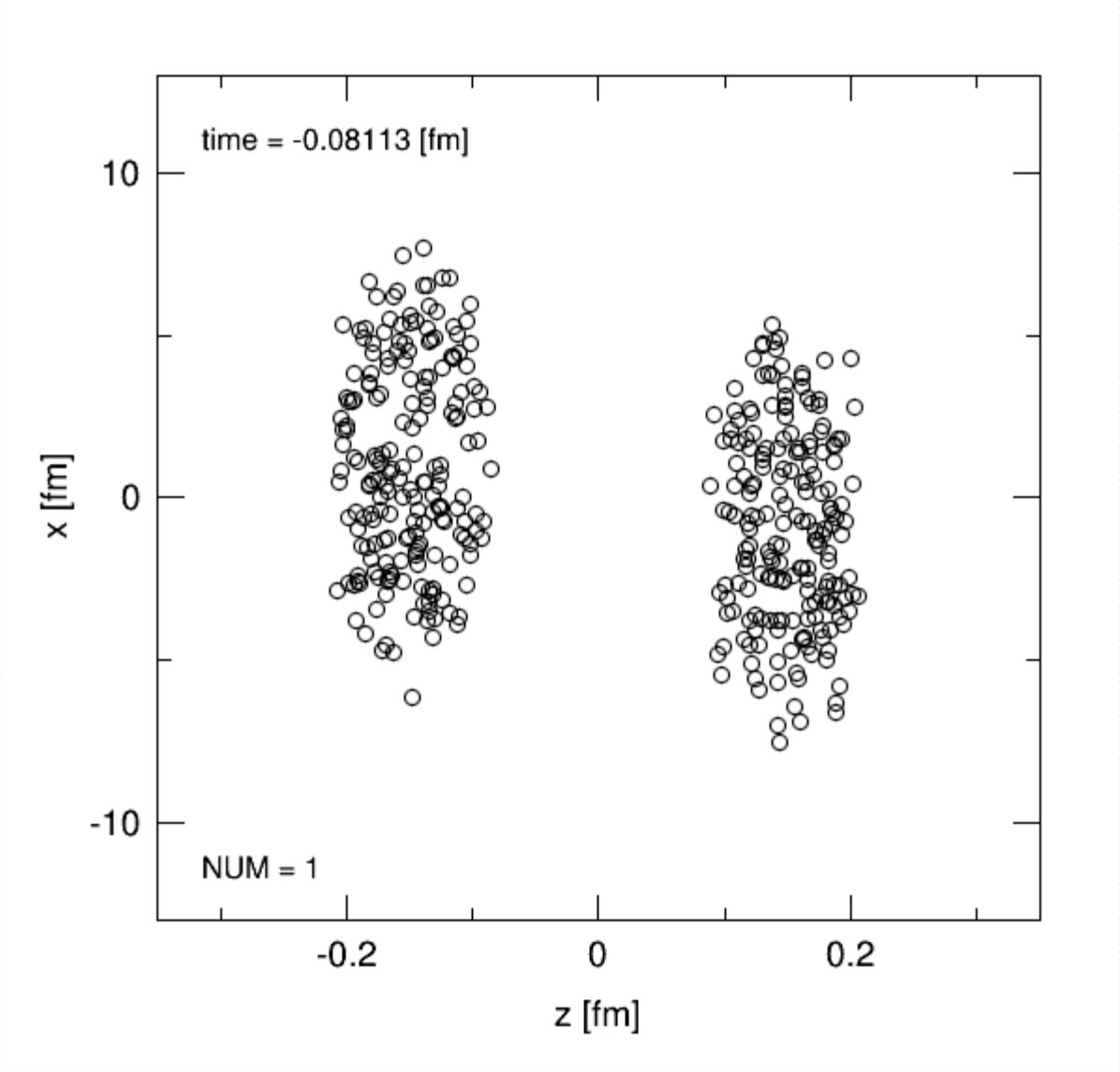

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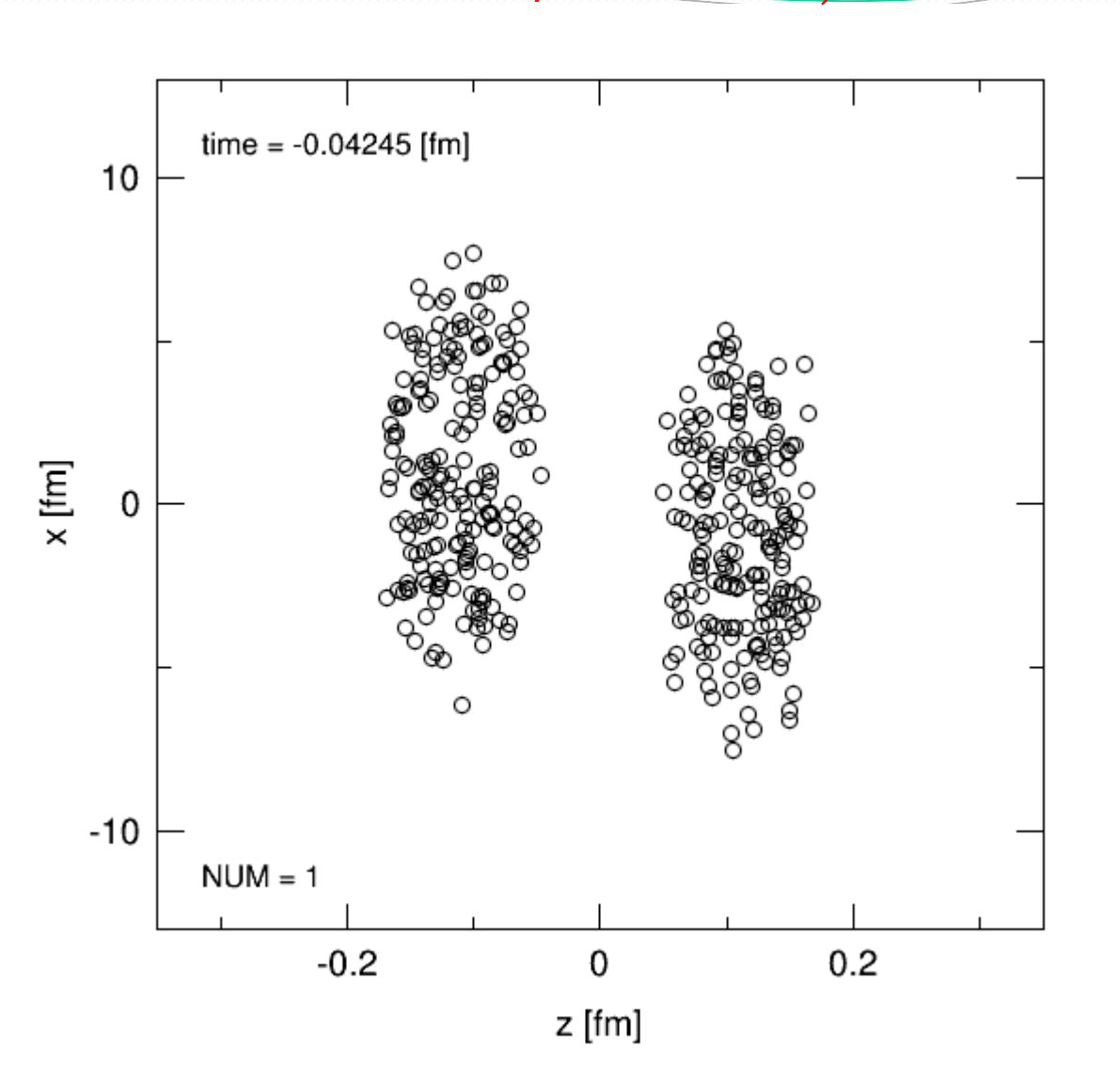

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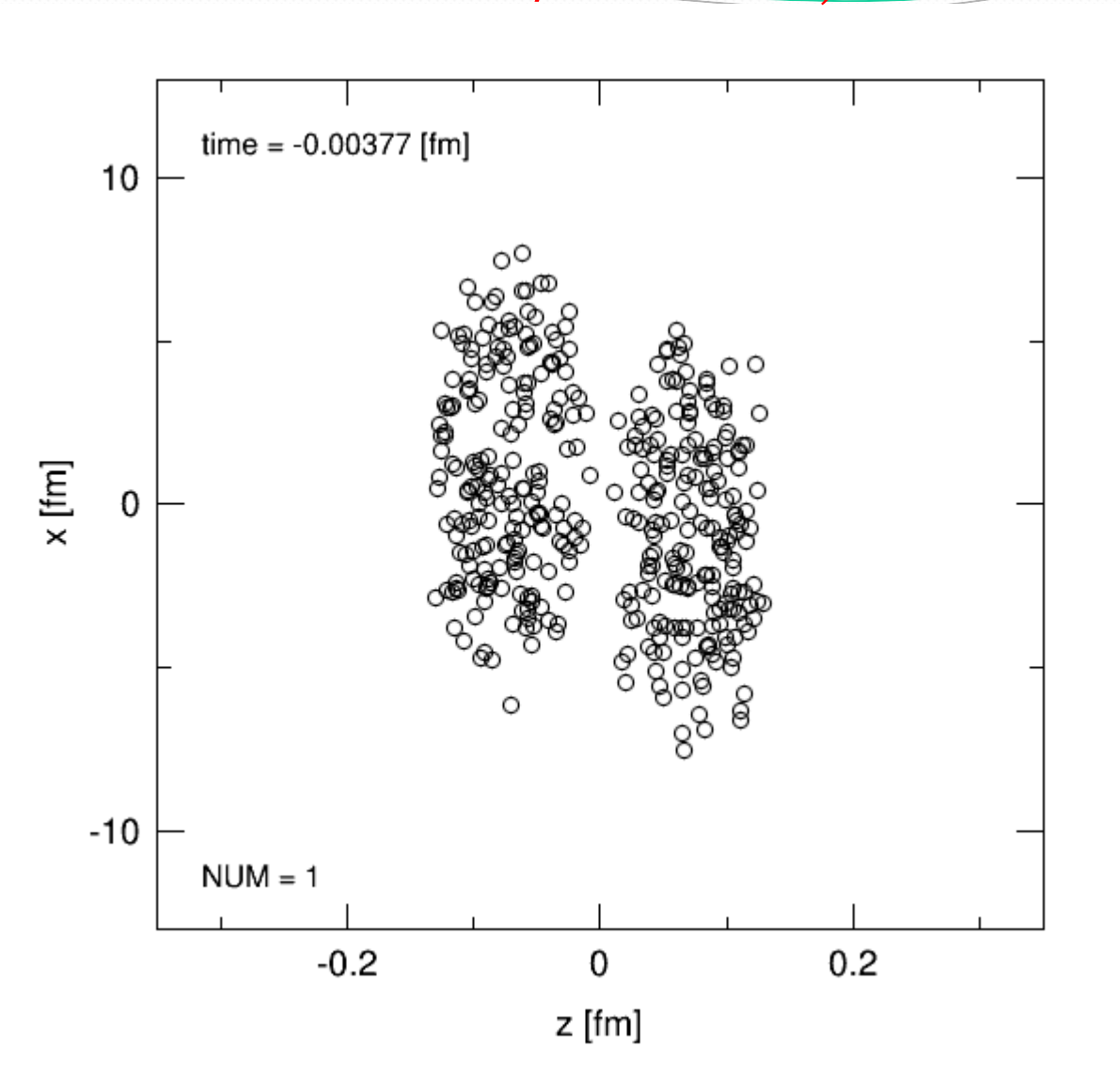

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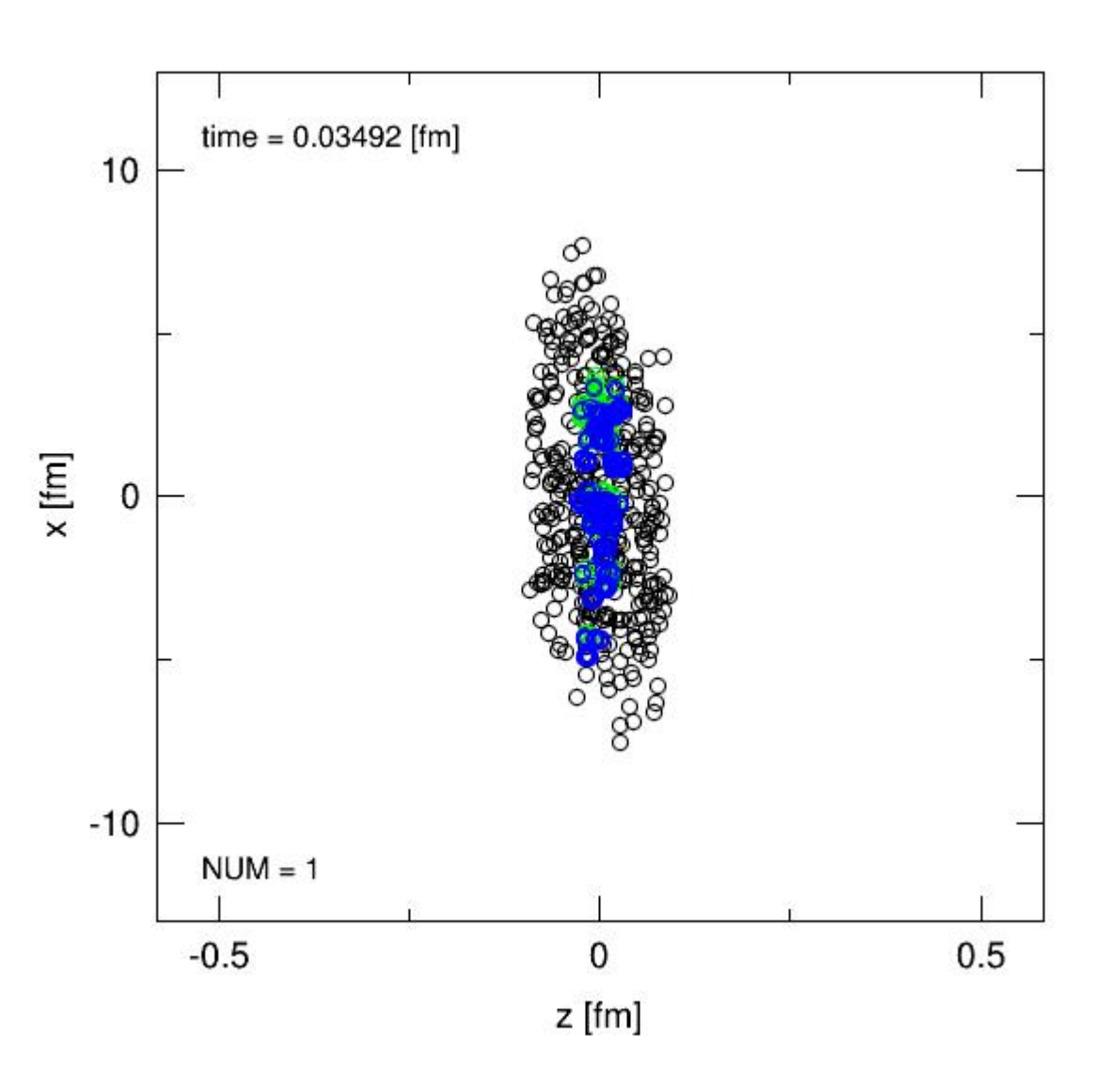

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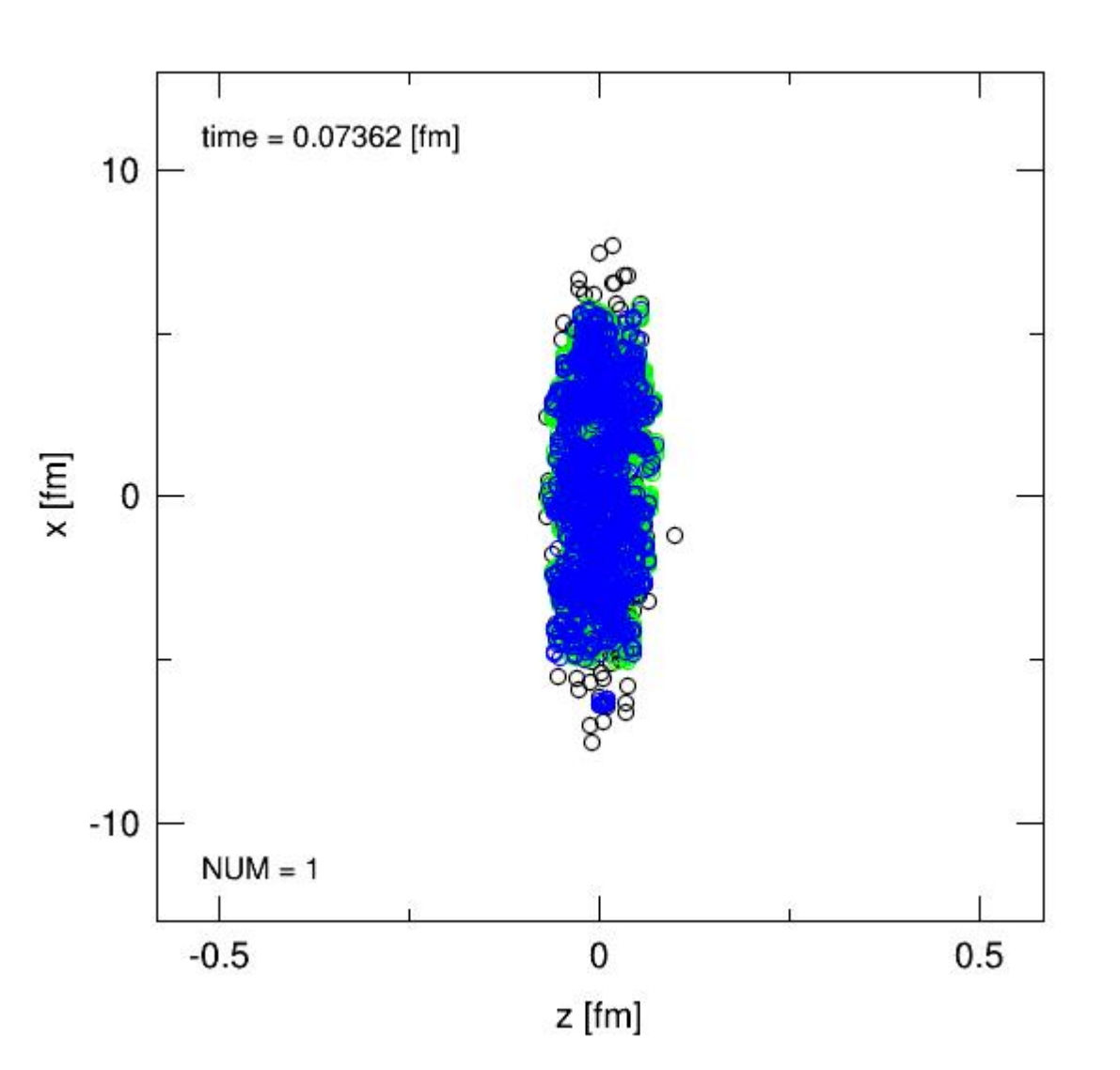

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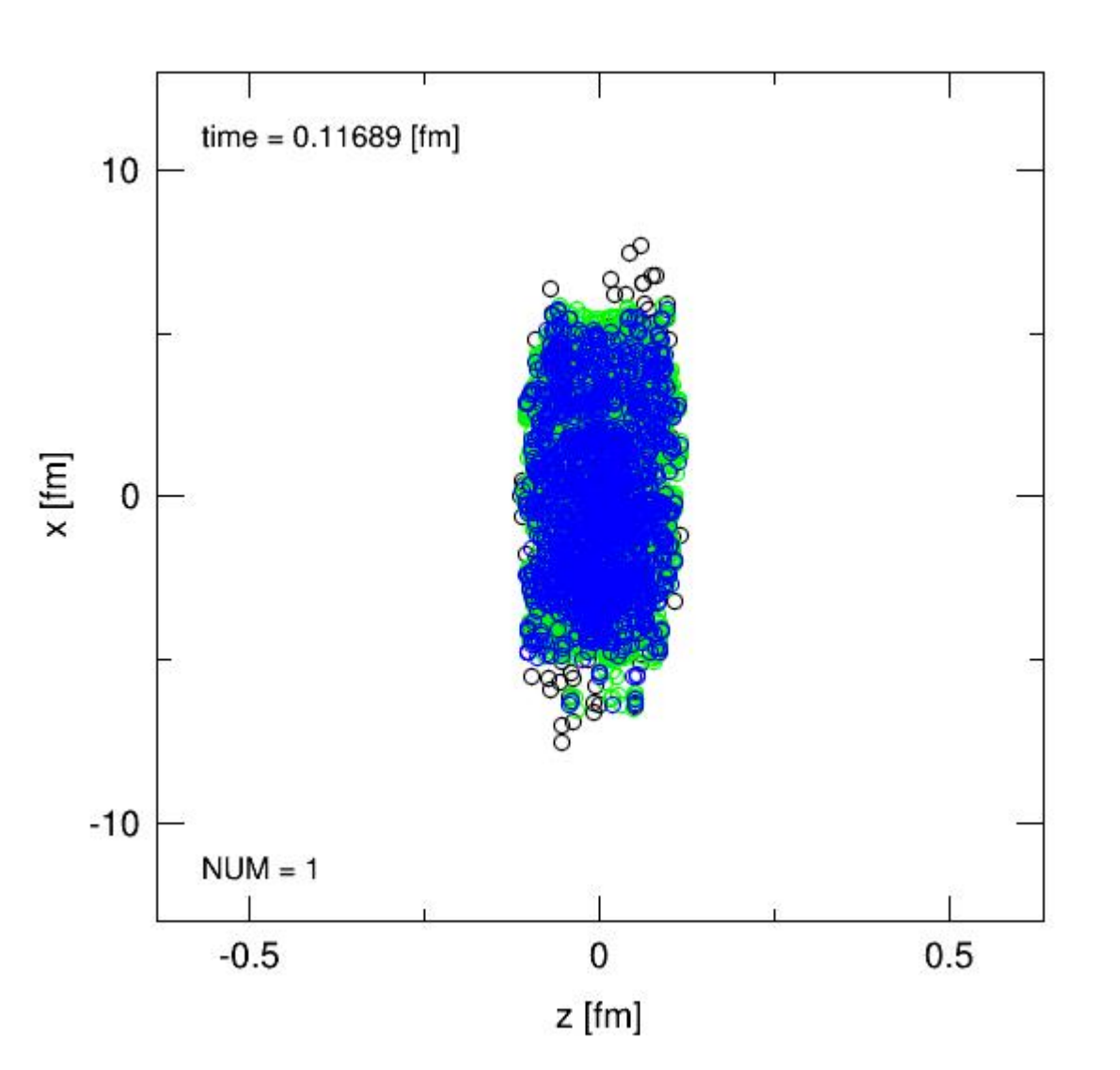

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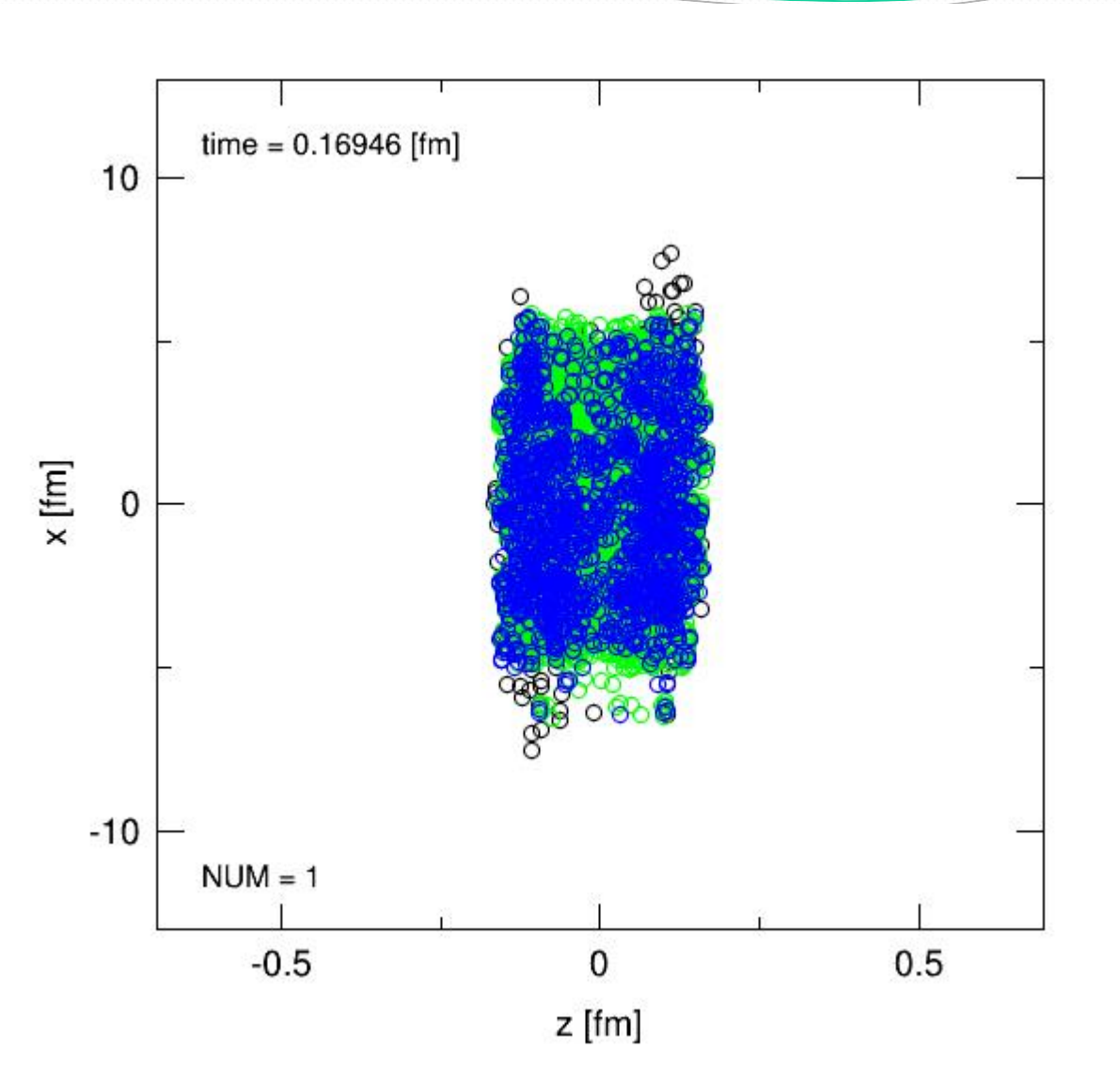

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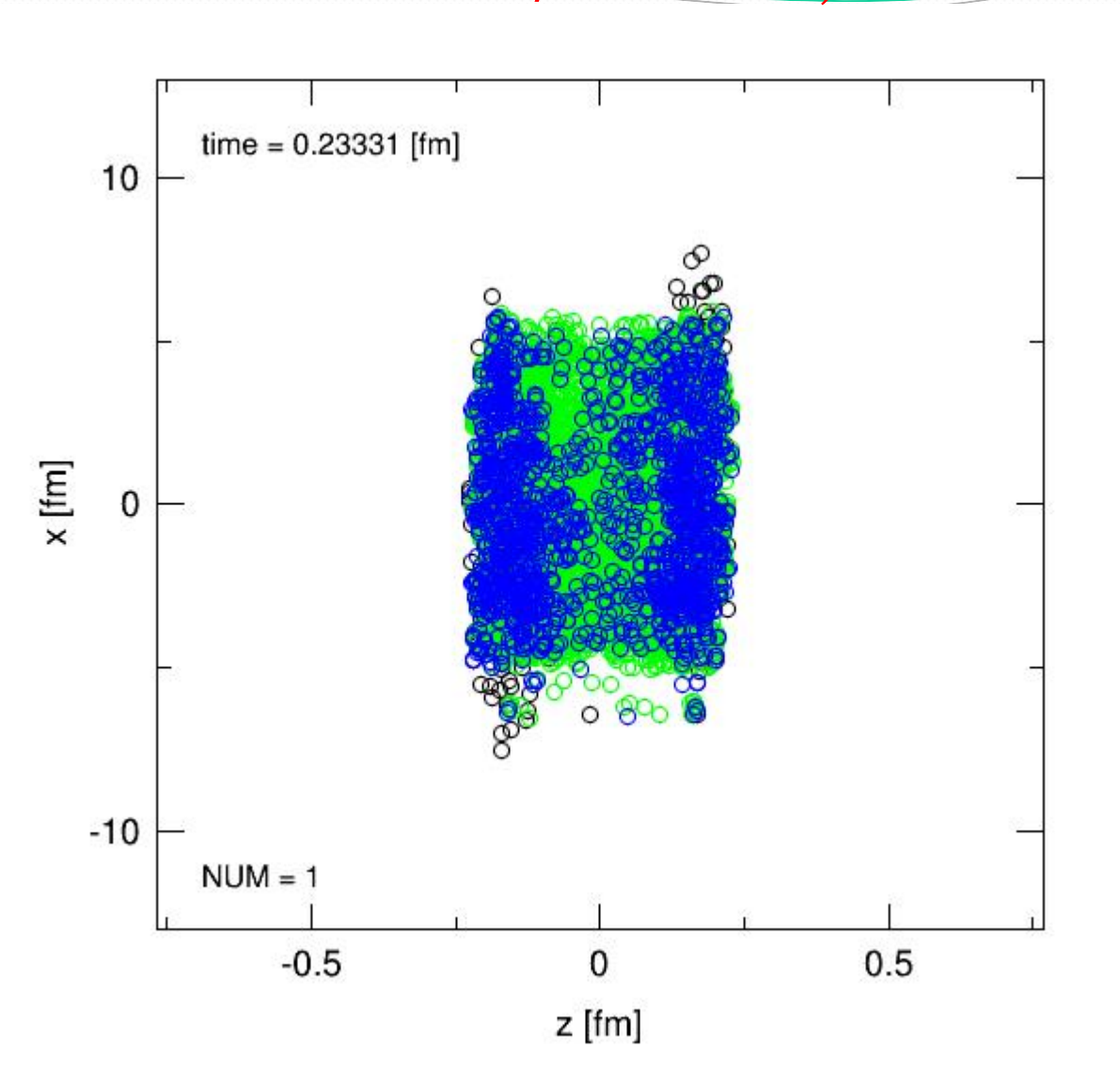

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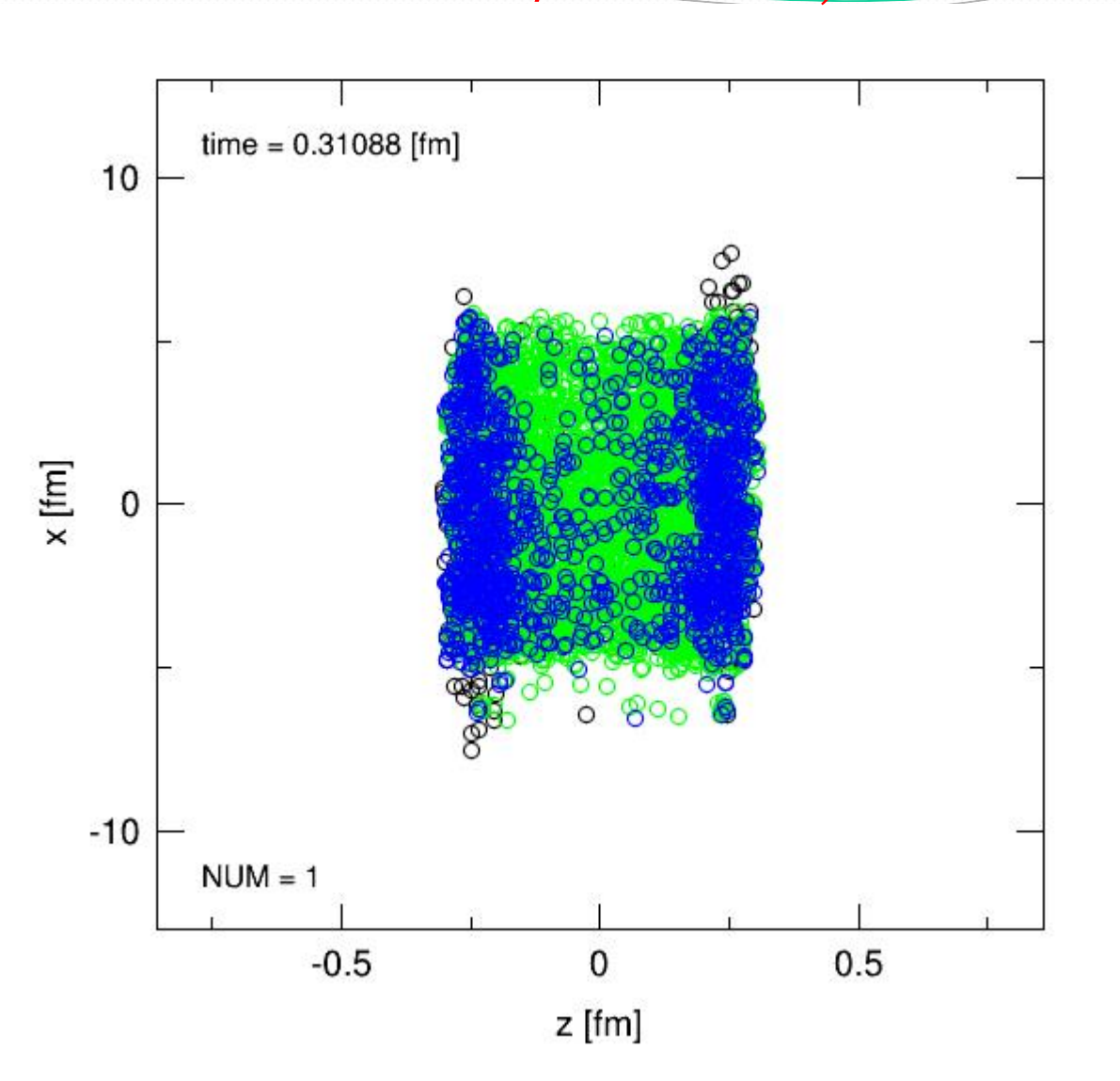

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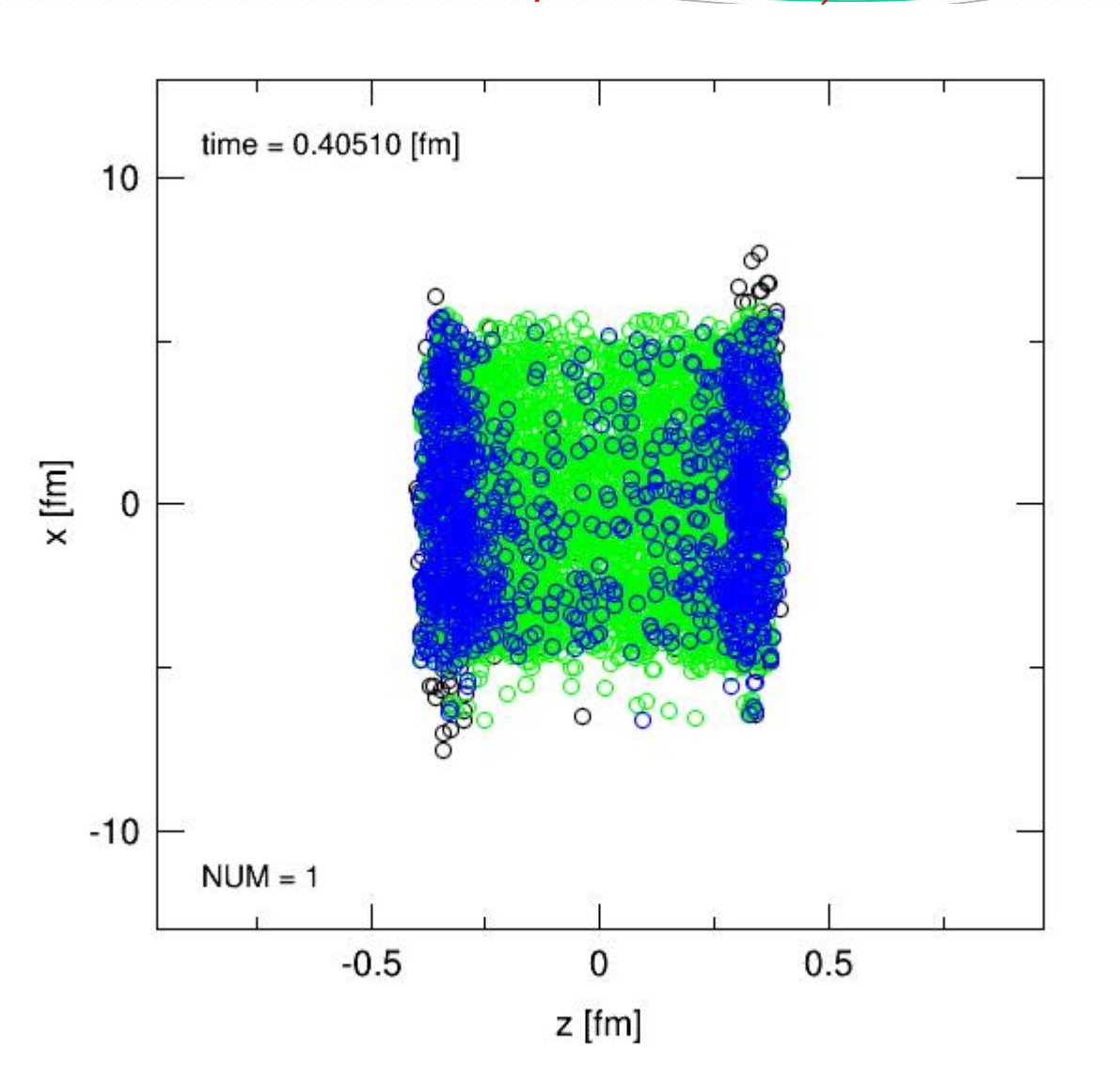

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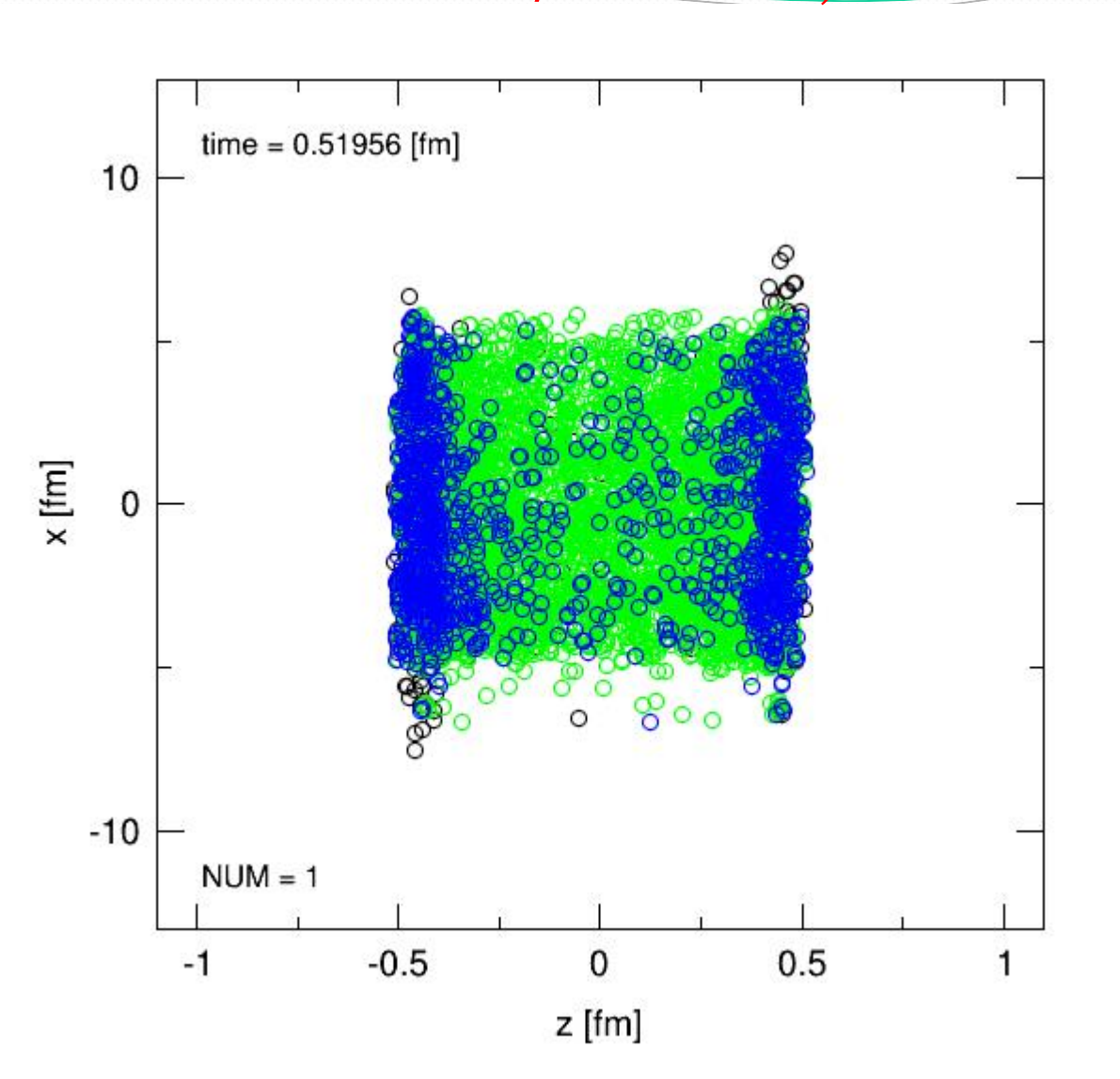

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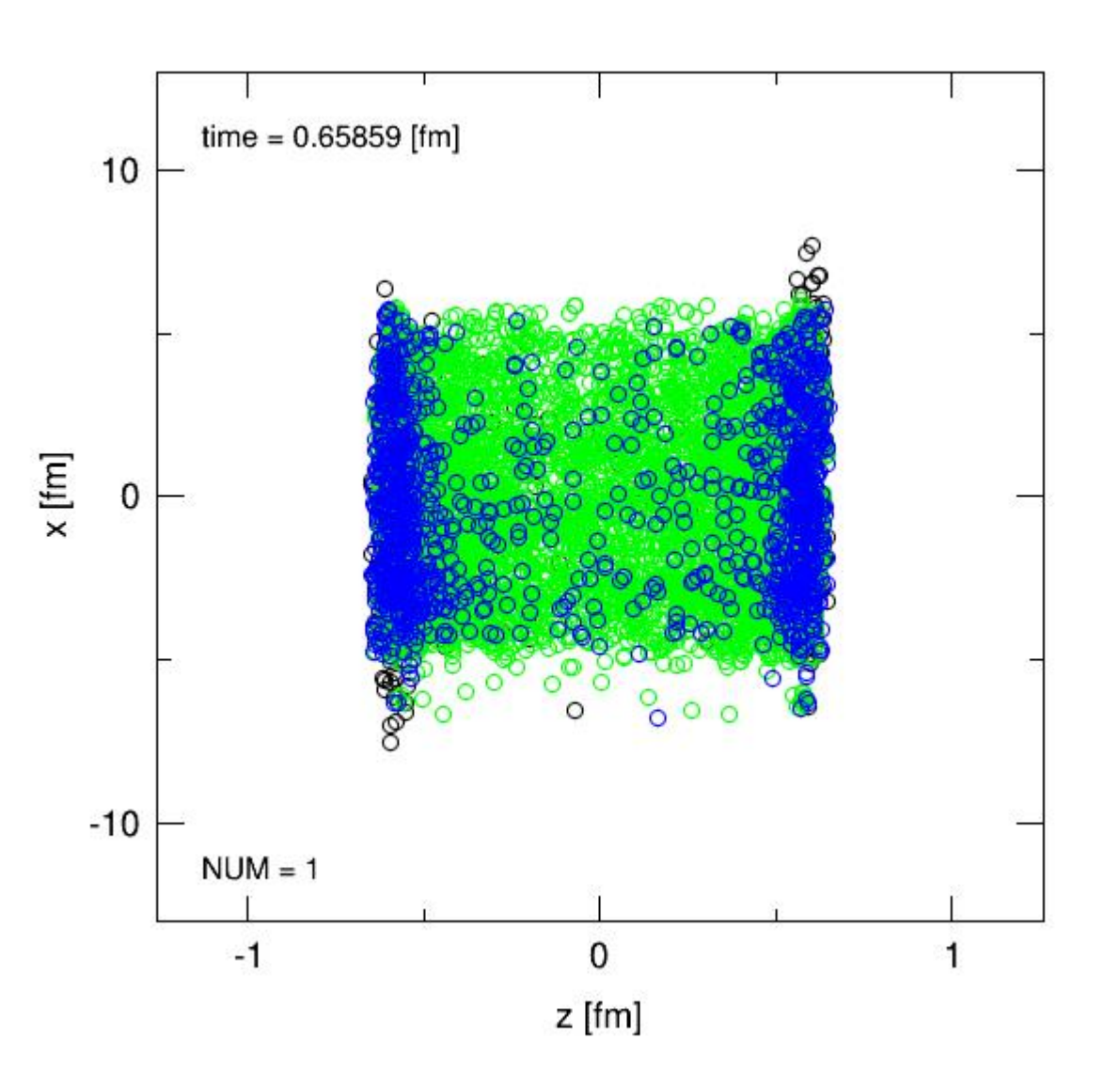

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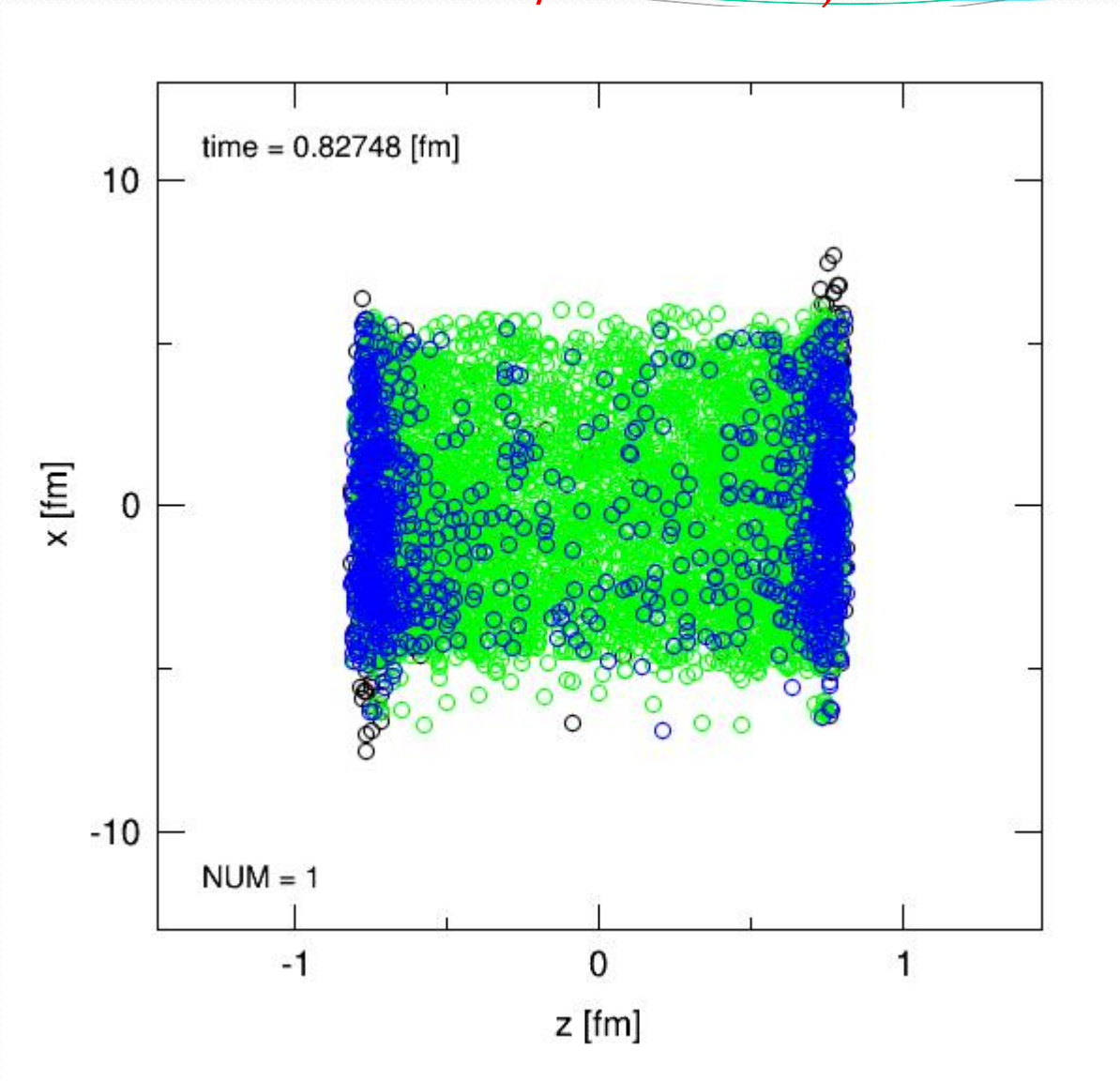

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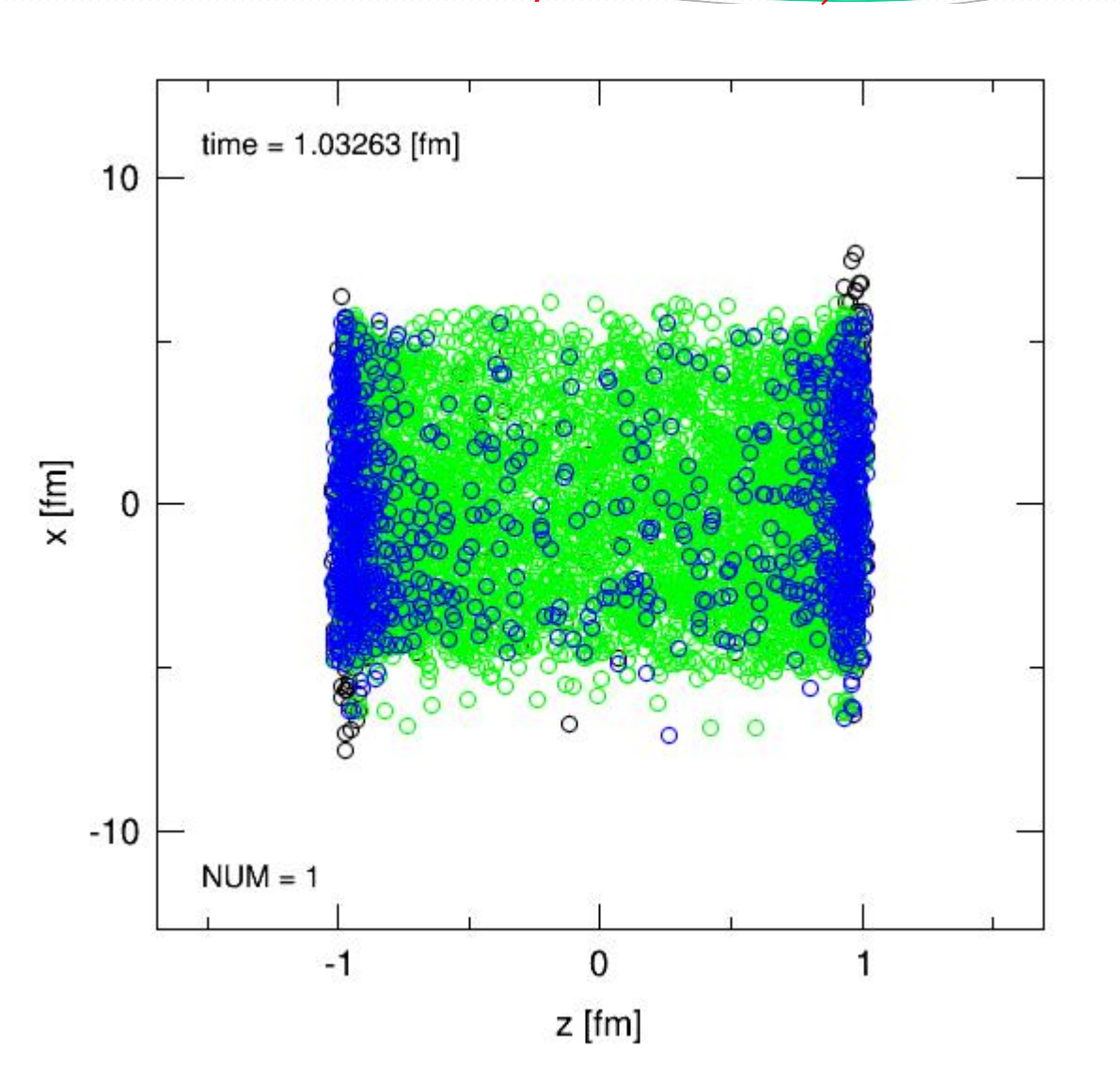

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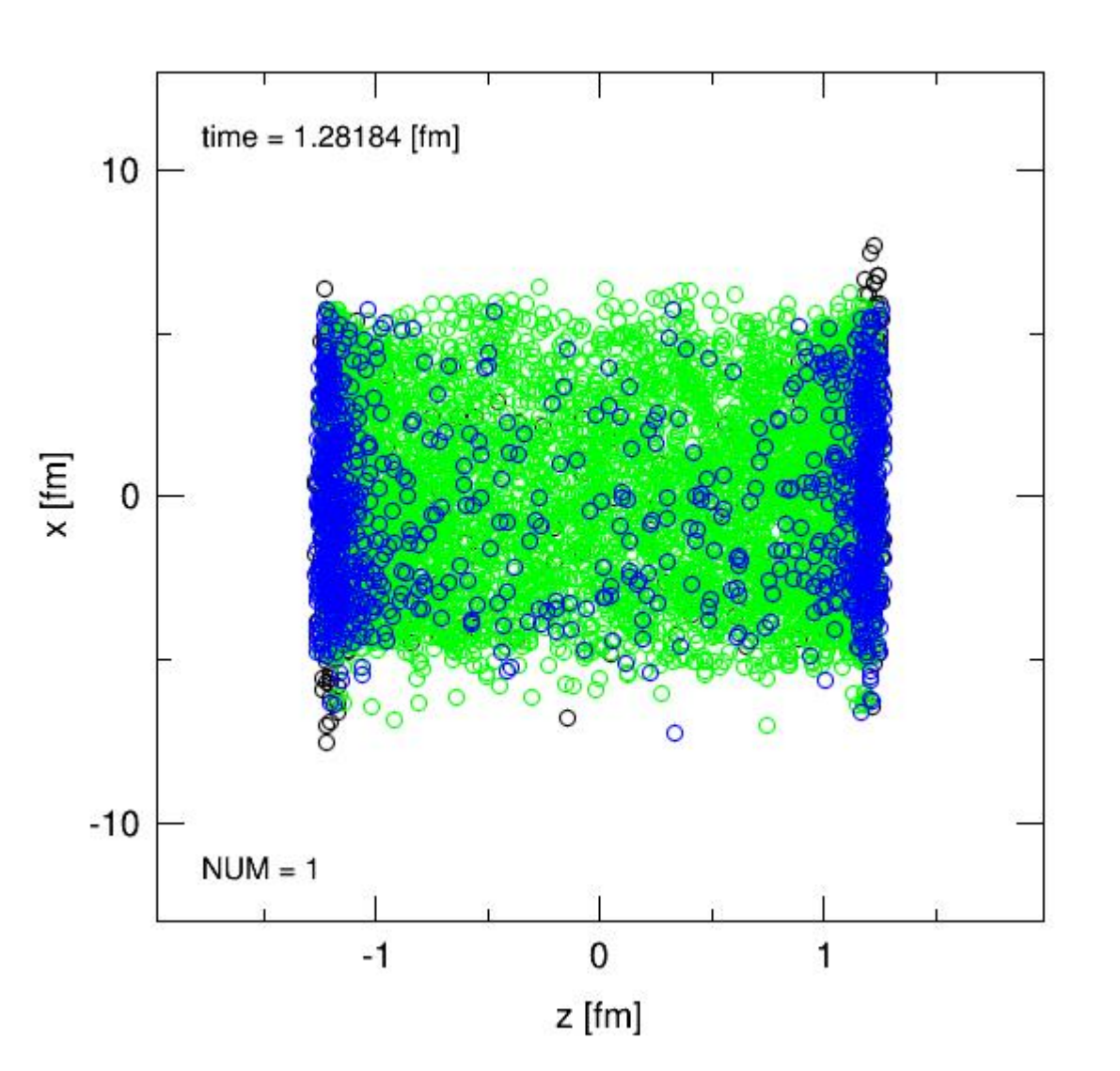

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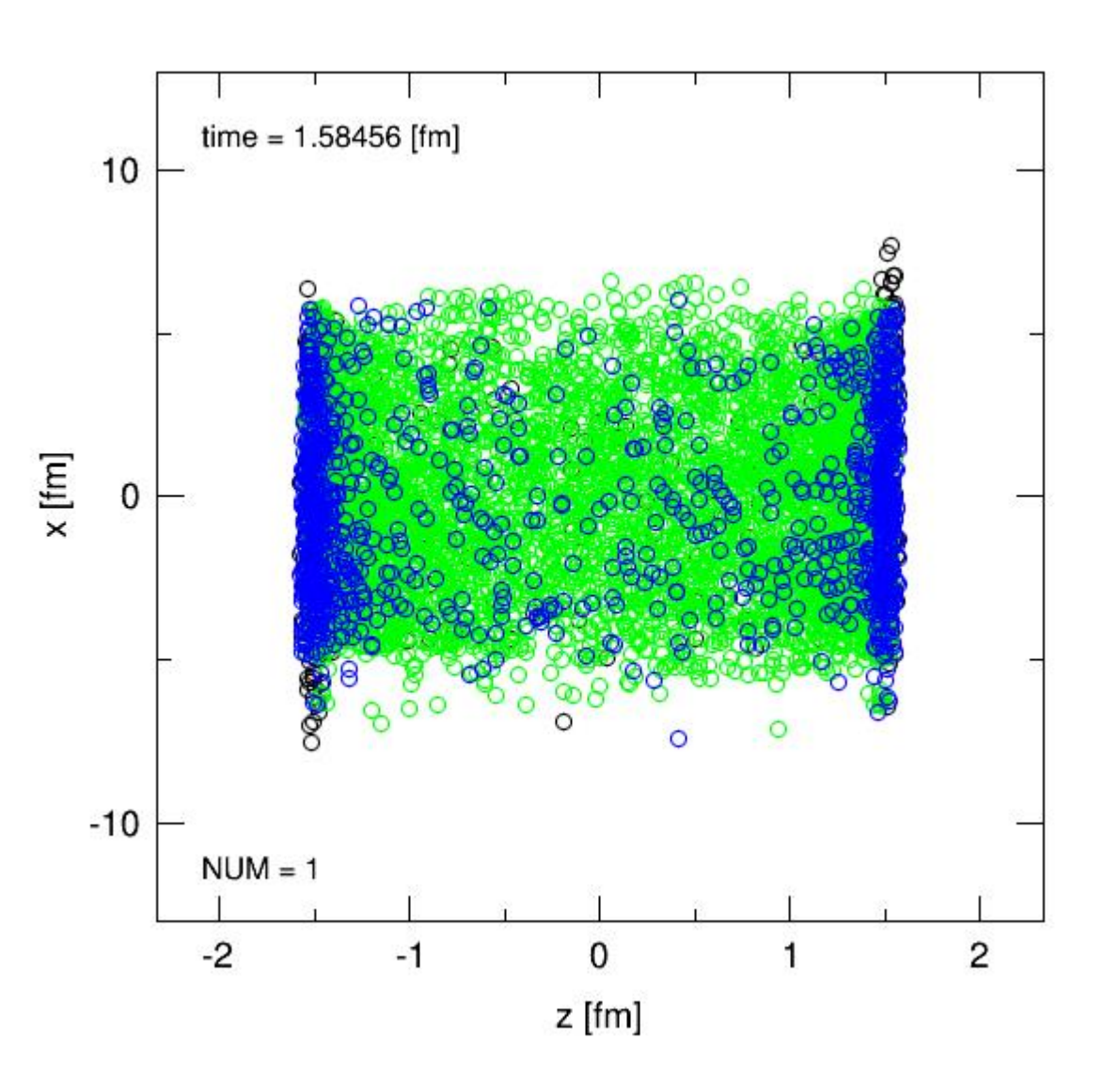

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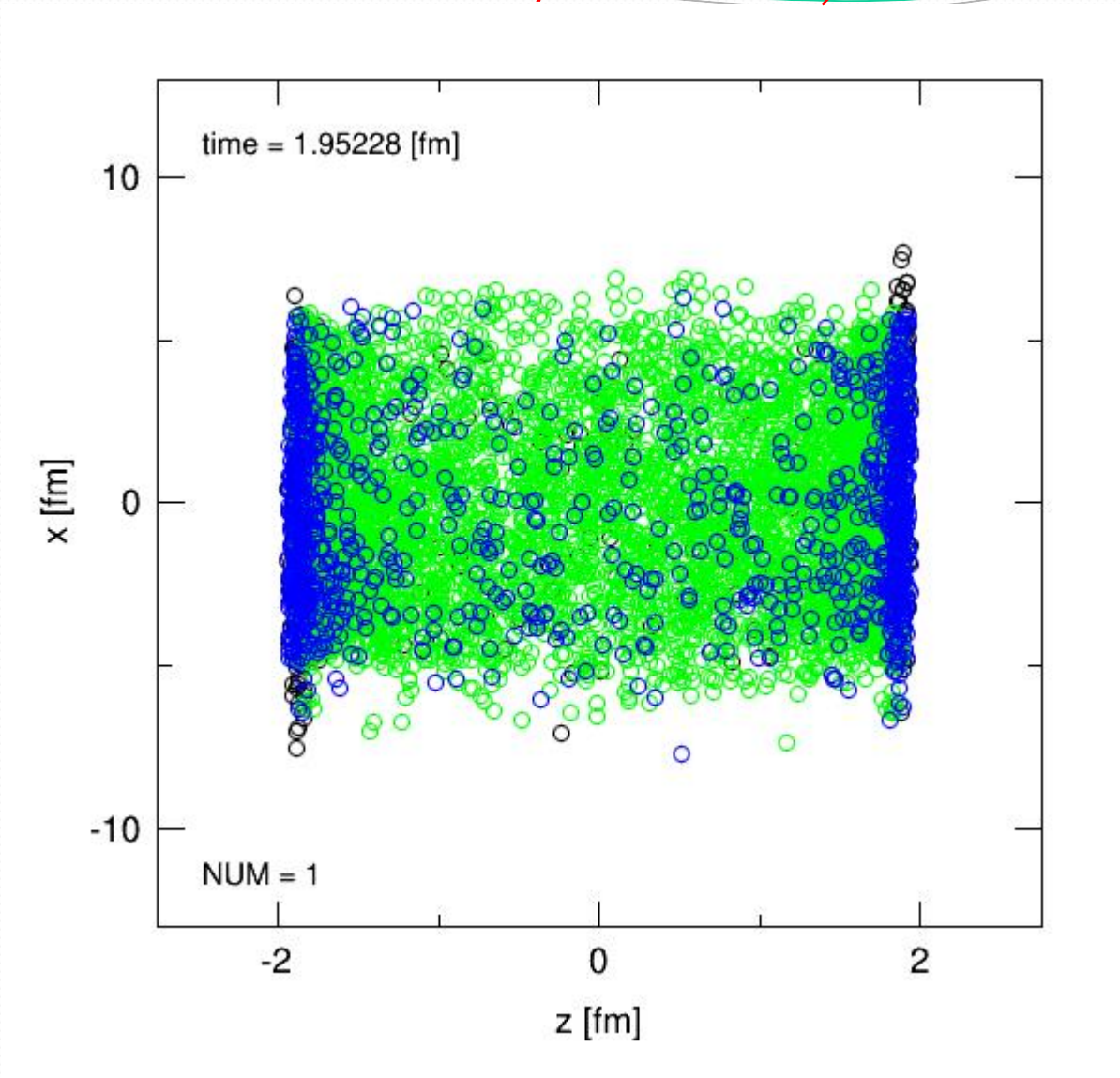

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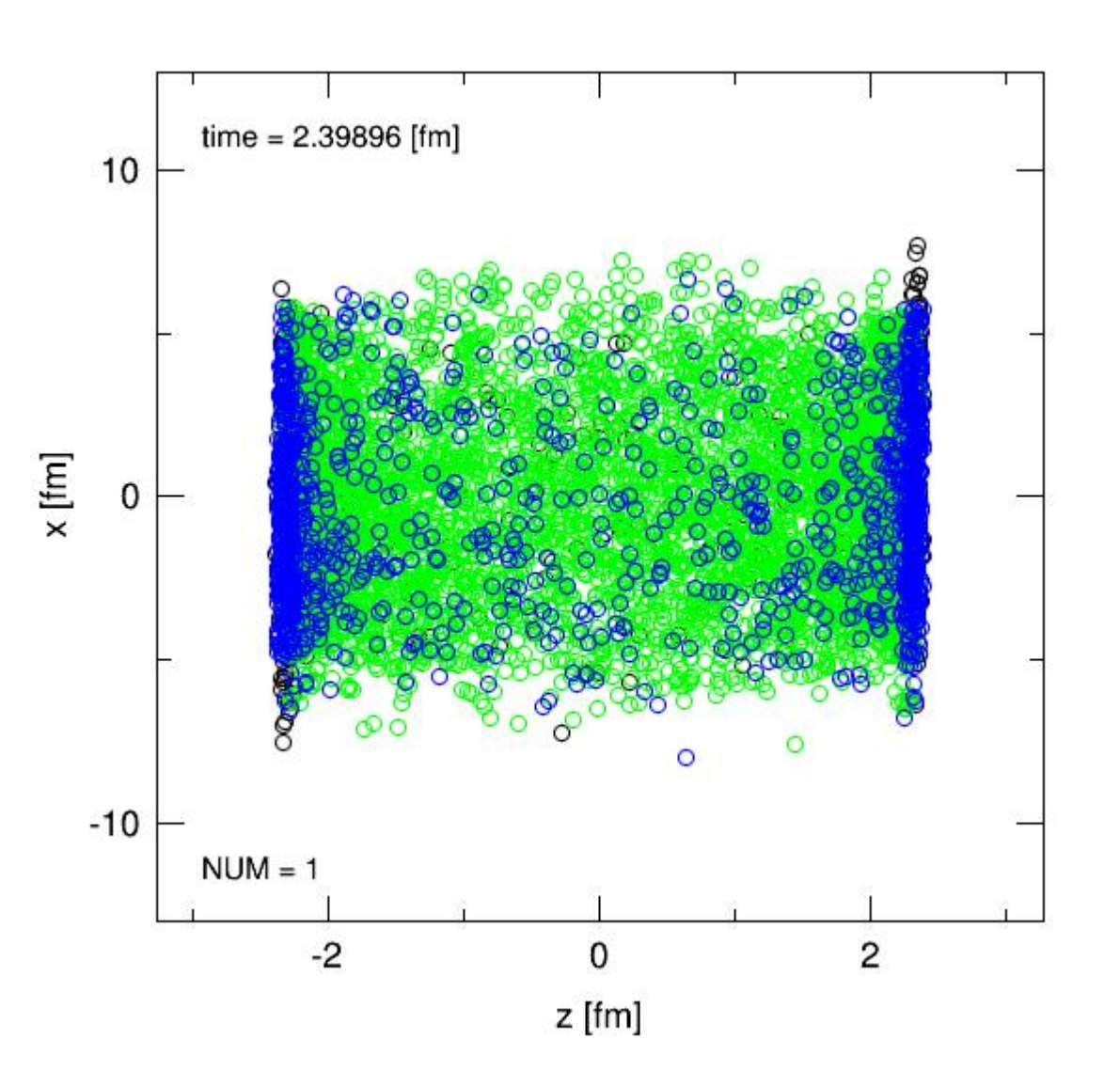

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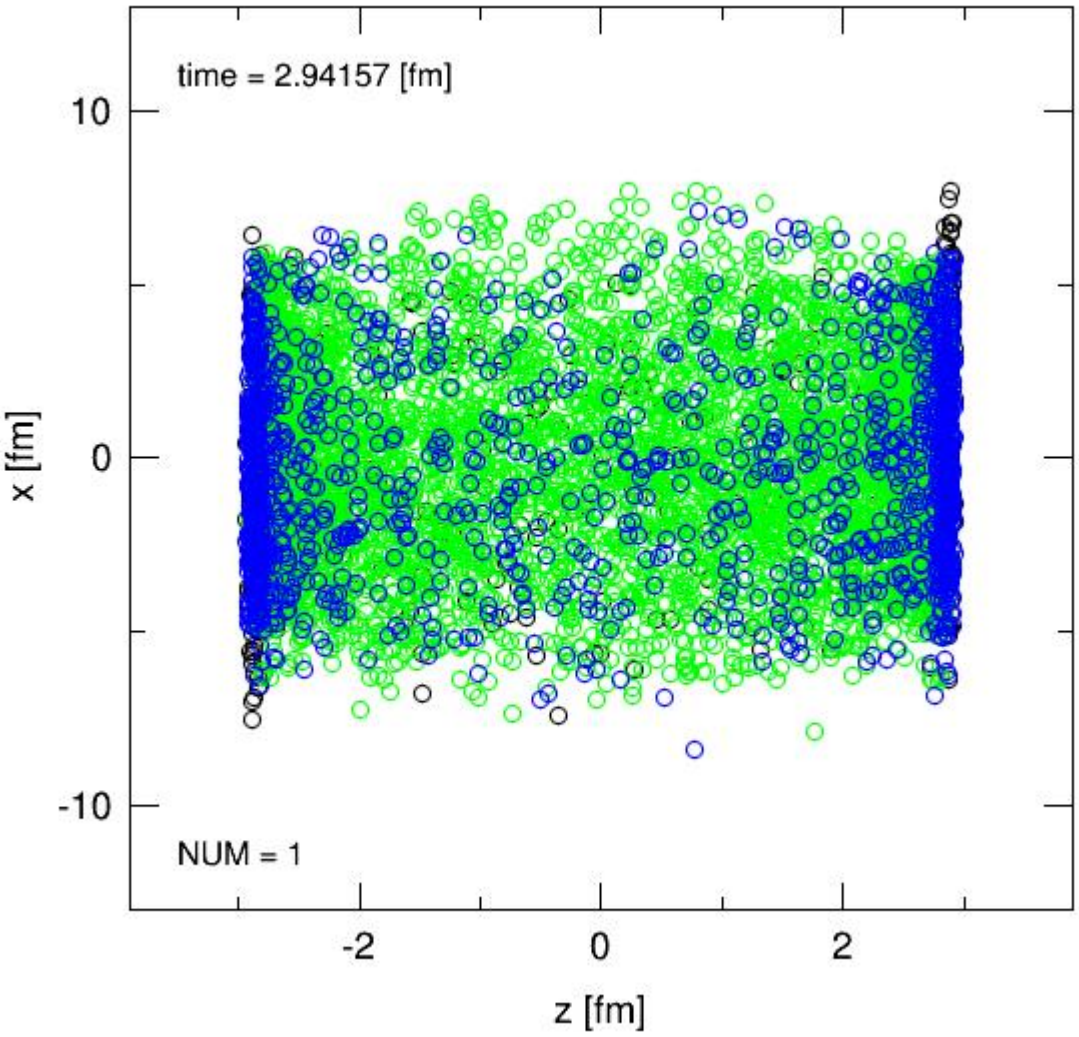

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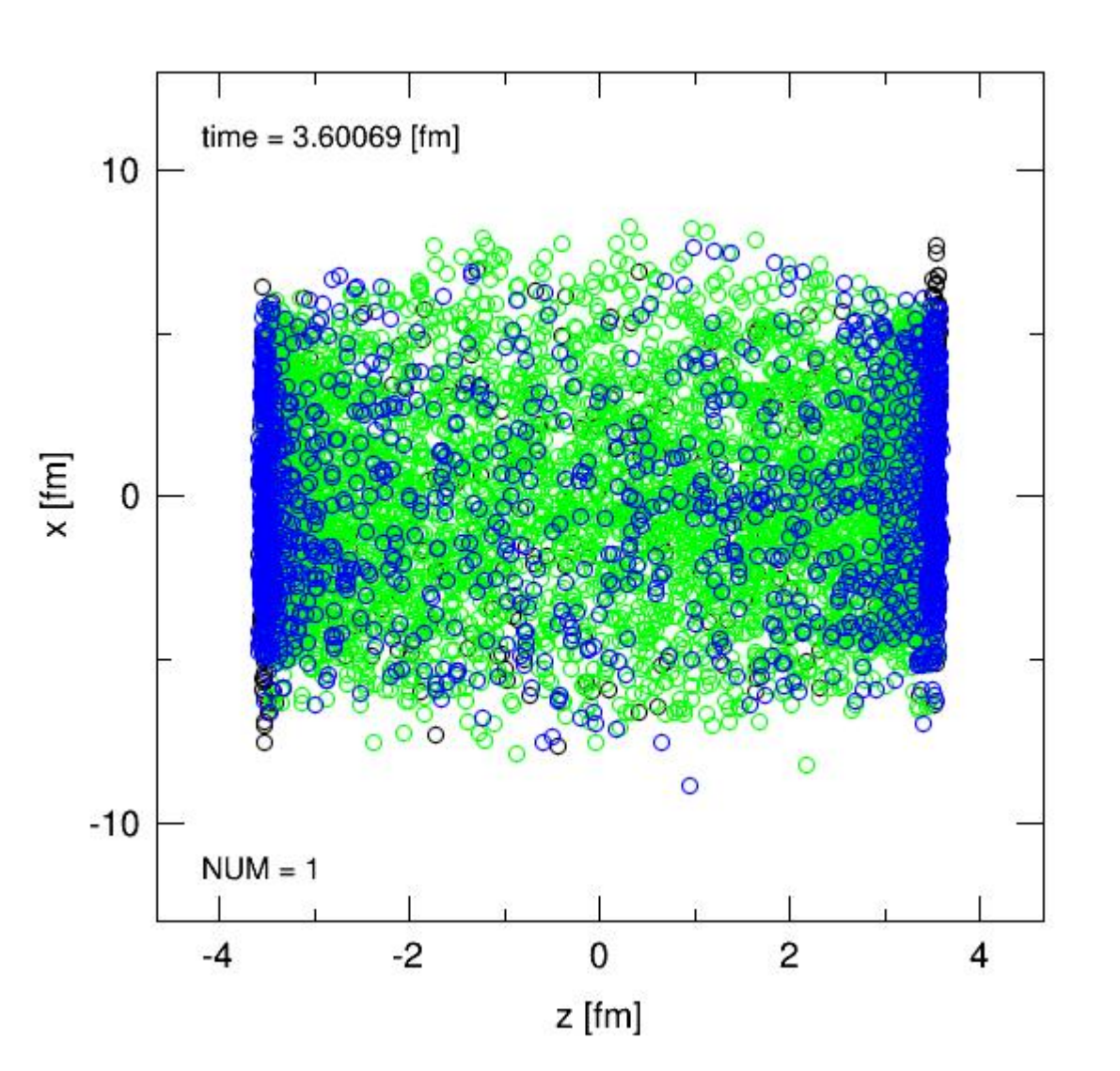

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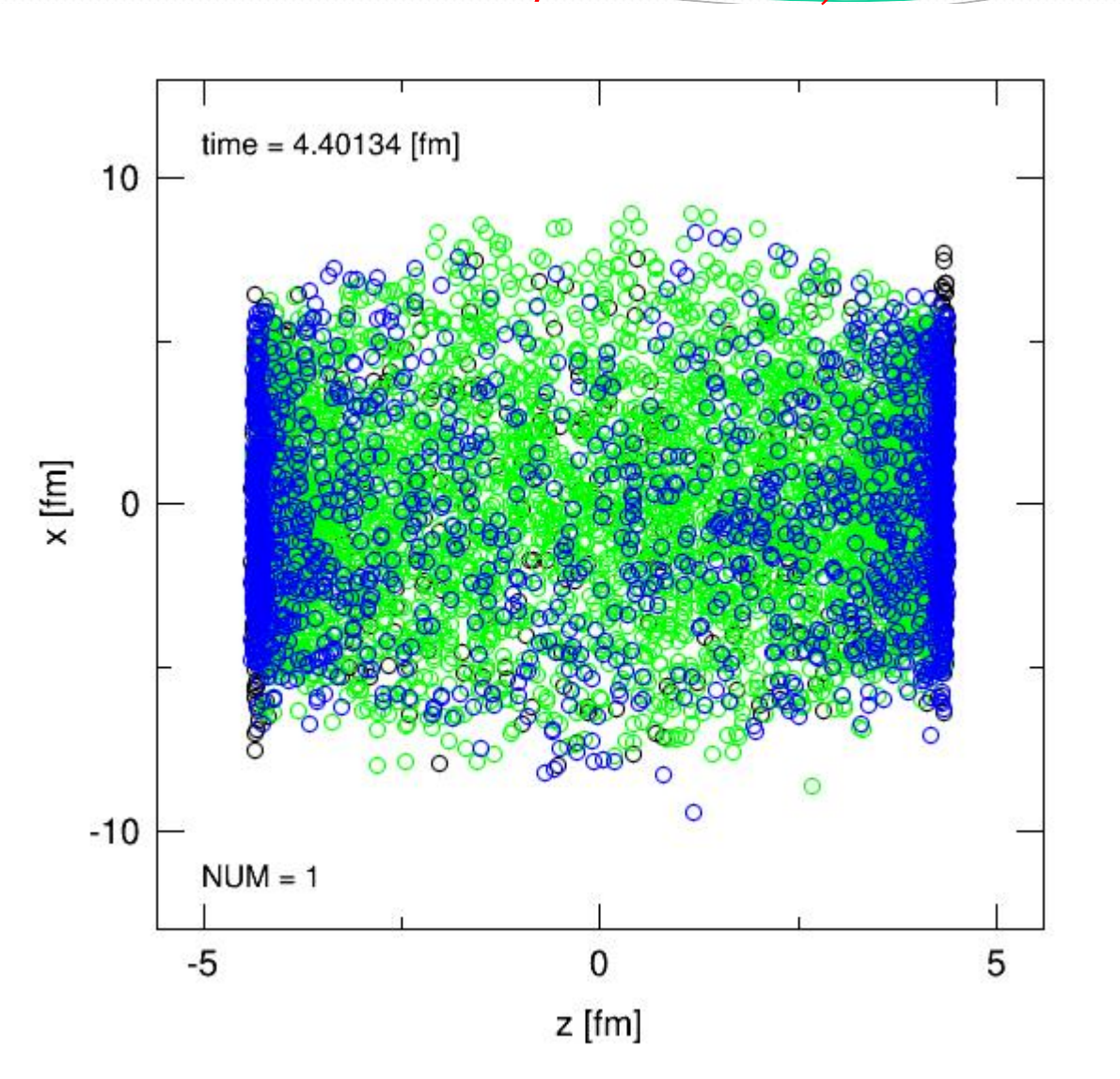

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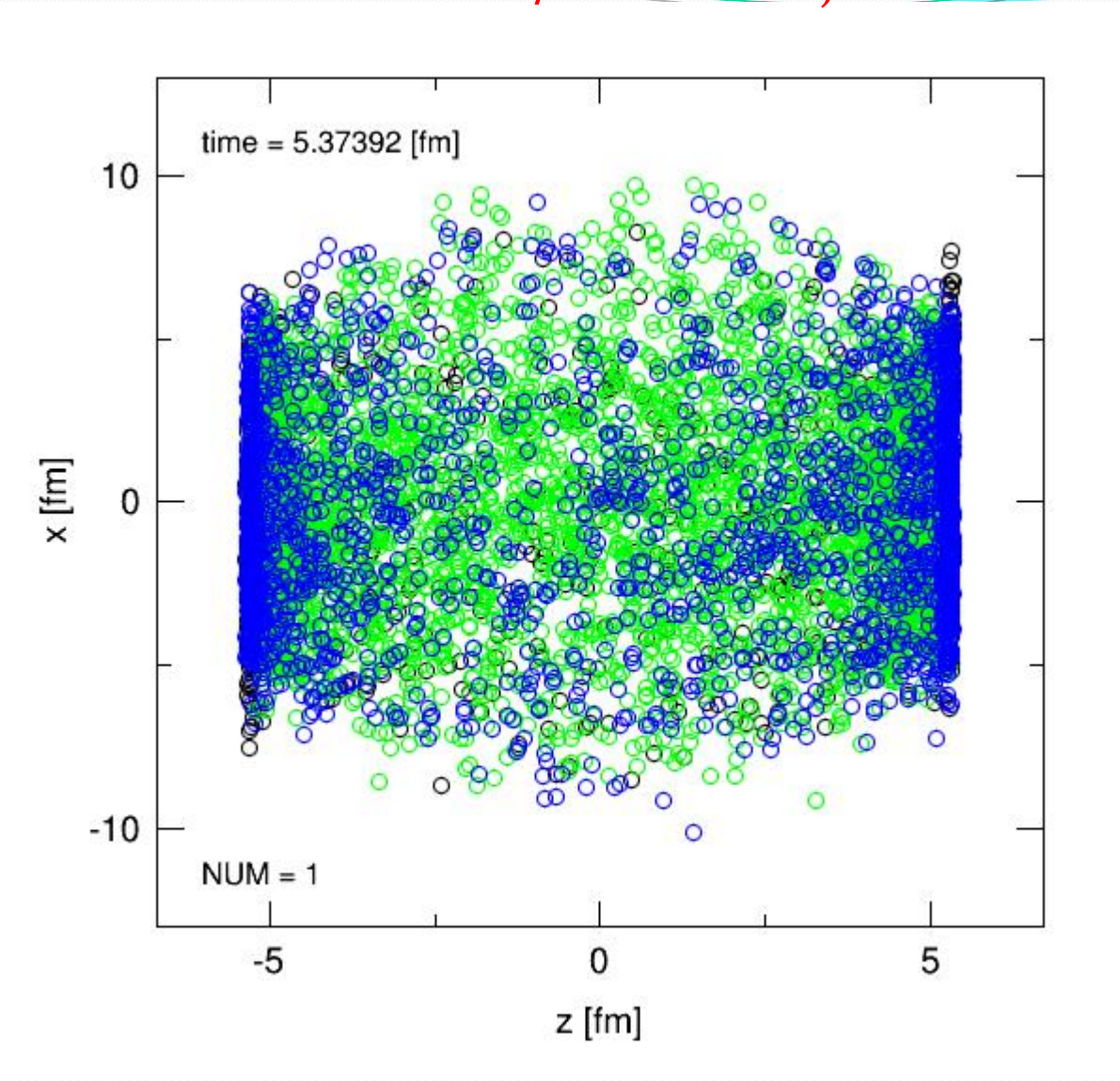

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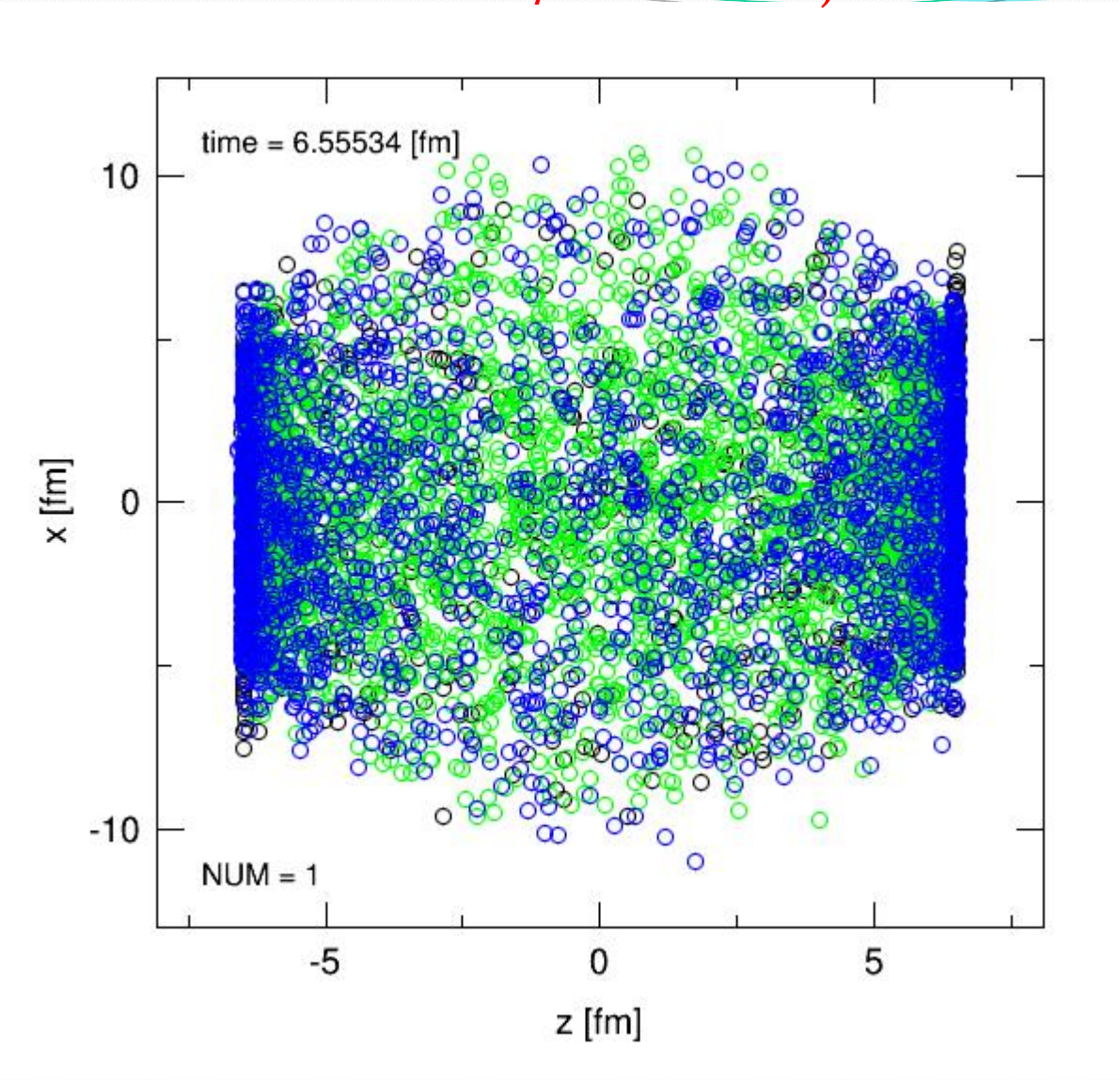

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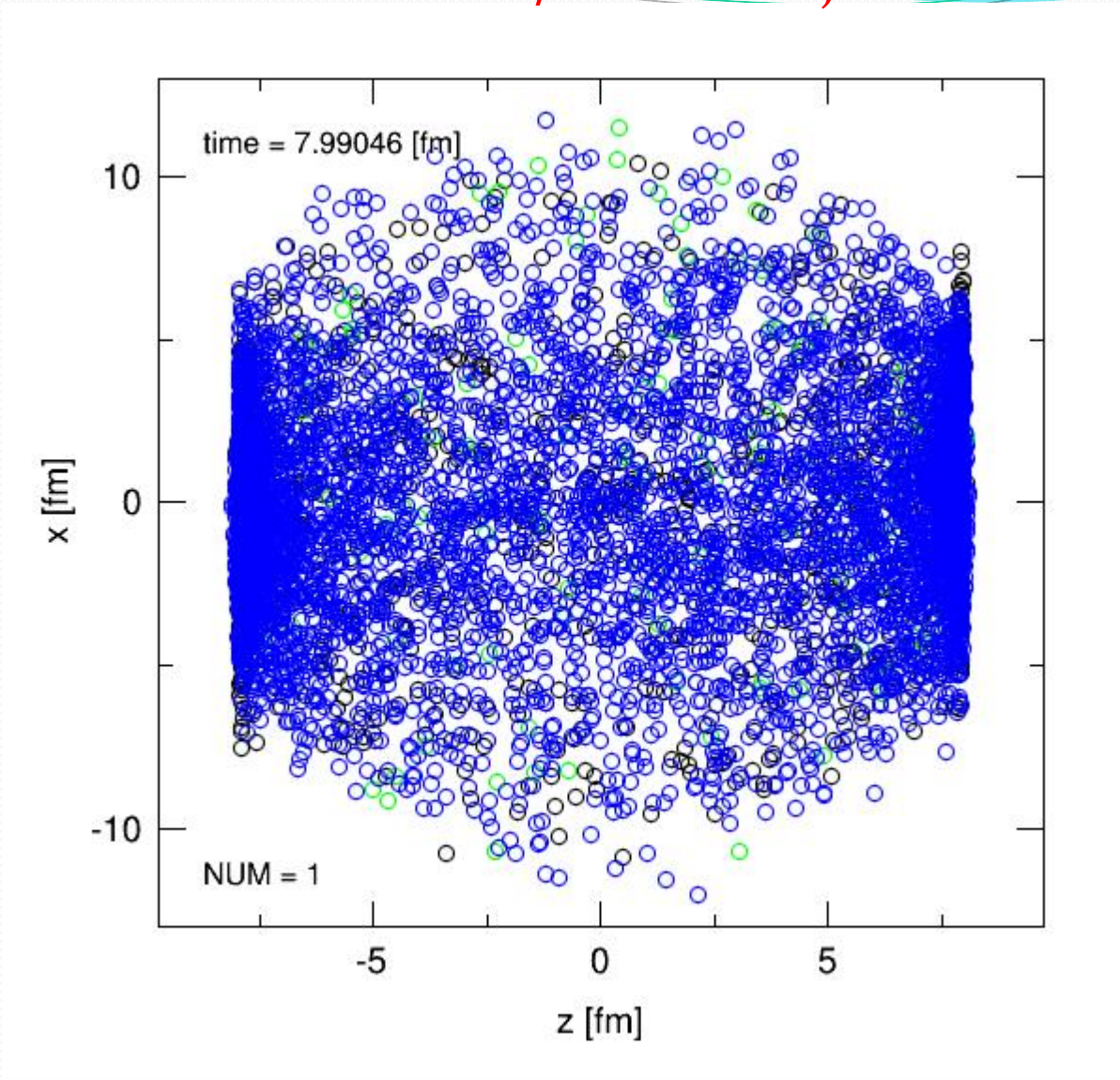
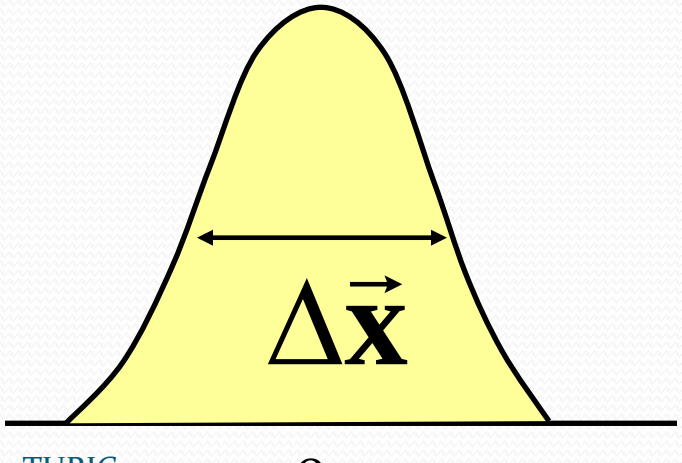


Define the Energy-Momentum Tensor by smoothing function

$$T^{\mu\nu}(\vec{x},t) = \sum_i \frac{p^{\mu}{}_i(t)\, p^{\nu}{}_i(t)}{p^{0}{}_i(t)} W(\vec{x} - \vec{x}_i(t); \Delta\vec{x})$$

$$W(\vec{\mathbf{x}}; \Delta\vec{\mathbf{x}}) \leftrightarrow \text{smoothing kernel}$$



$$\int W(\vec{\mathbf{x}}; \Delta\vec{\mathbf{x}}) d^3\vec{\mathbf{x}} = 1$$

Diagonalization of $T^{\mu\nu}(\vec{x},t)$

$$T^{\mu}{}_{\nu}(\vec{x},t) \rightarrow (T_L)^{\mu}{}_{\nu} = \begin{pmatrix} \varepsilon(\vec{x},t) & 0 \\ 0 & \vec{p}(\vec{x},t) \end{pmatrix}$$

by a Lorentz Boost $\Lambda(\beta)$ + Spatial Rotation

$$(T_L)^{\mu}{}_{\nu} = \begin{pmatrix} \varepsilon(\vec{x},t) & 0 \\ 0 & \vec{p}(\vec{x},t) \end{pmatrix}$$

Local Rest Frame (Landau)

Diagonalization of $T^{\mu\nu}(\vec{x},t)$

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$T^{\mu}{}_{\nu}(\vec{x},t)$ depends on the coarse-graining size, so do

$\vec{\beta},\ \varepsilon,\ \vec{p}$ (the flow profile)

Diagonalization of $T^{\mu\nu}(\vec{x},t)$

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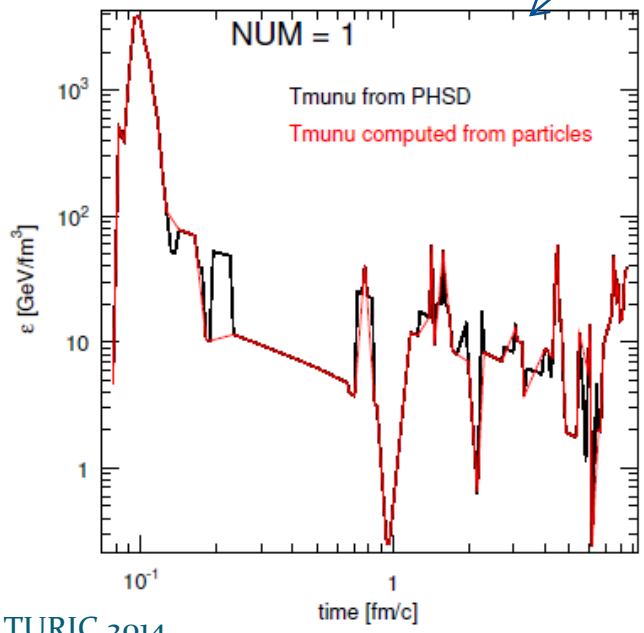

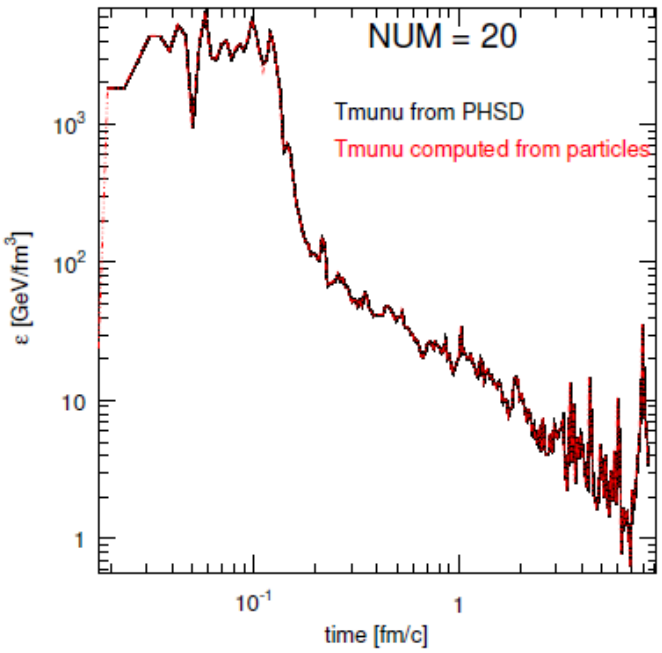

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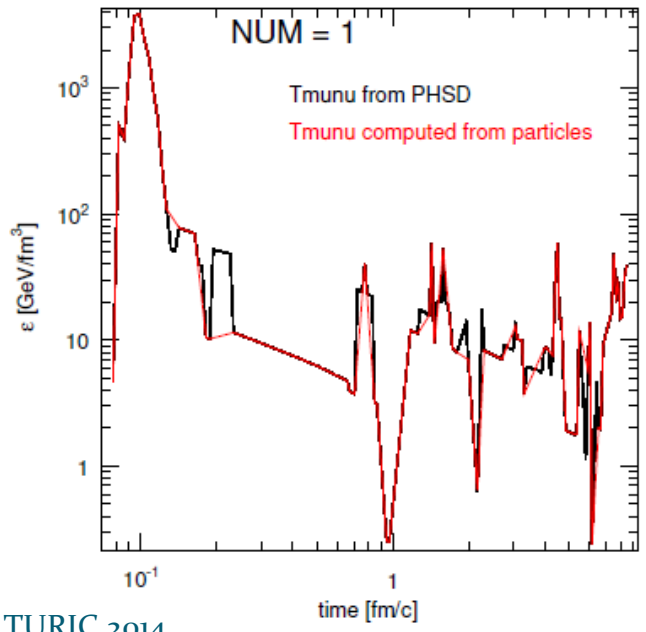
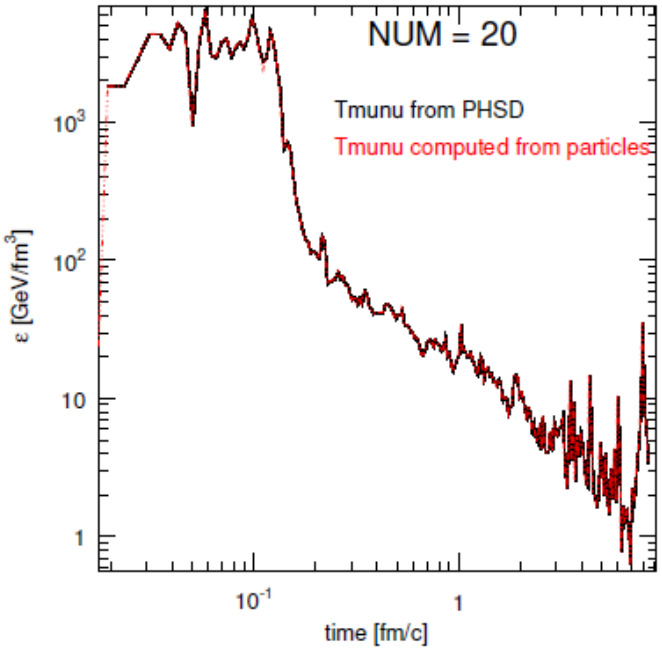
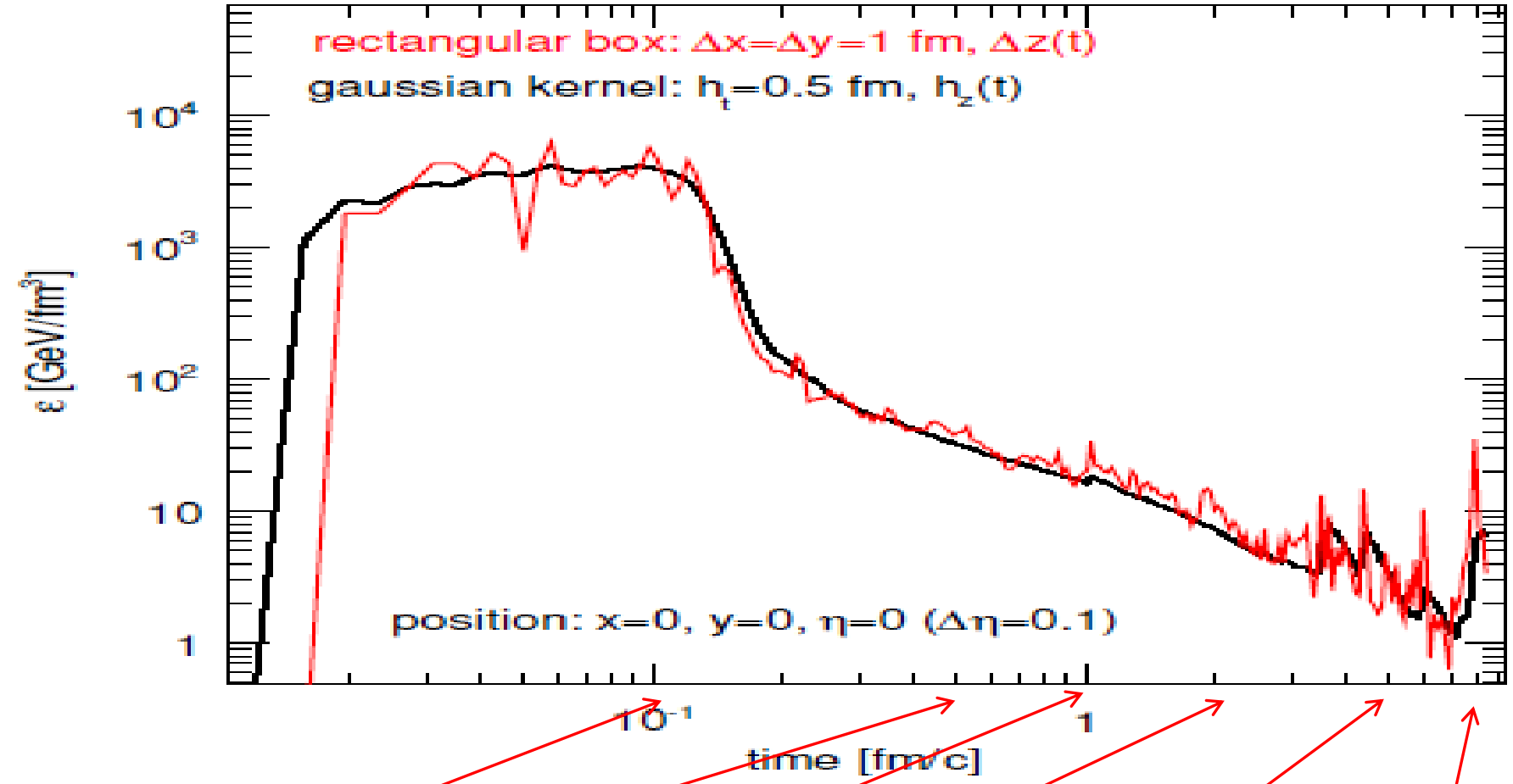
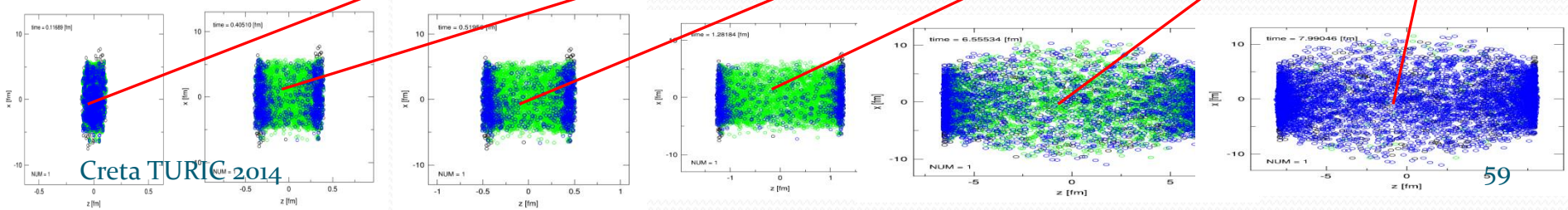
Mean Field effects

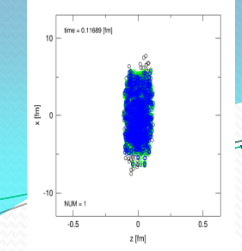


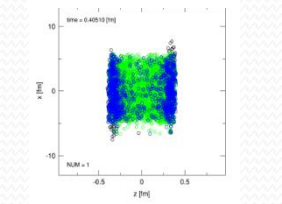


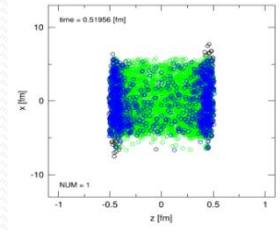

rectangular box: Δx=Δy=1 fm, Δz(t)
gaussian kernel: h_t=0.5 fm, h_z(t)
position: x=0, y=0, η=0 (Δη=0.1)
ε [GeV/fm³]
10⁴
10³
10²
10
1
10⁻¹
1
time [fm/c]

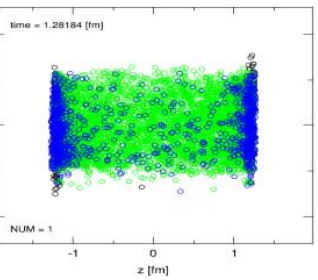


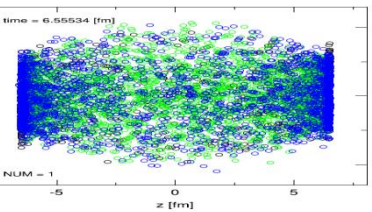
$\vec{\beta}(z,t)$

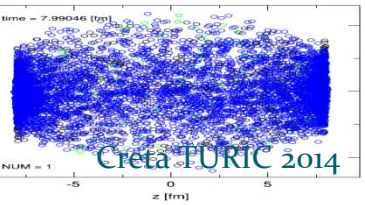


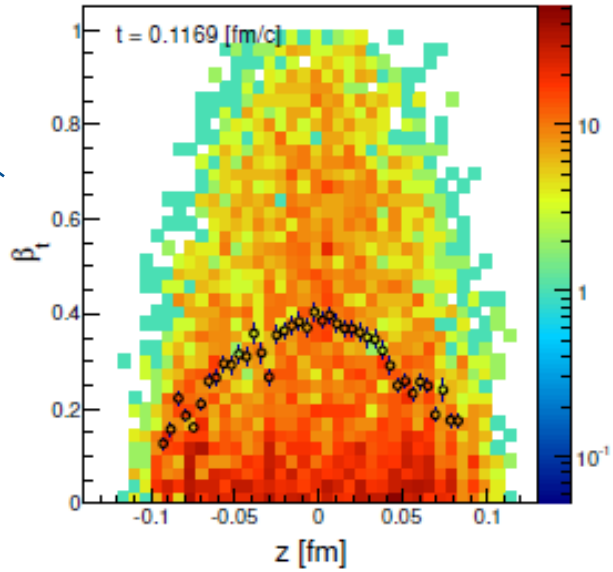


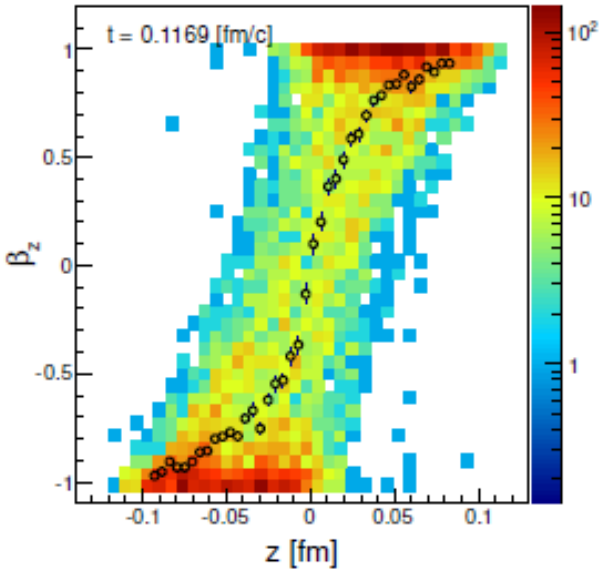


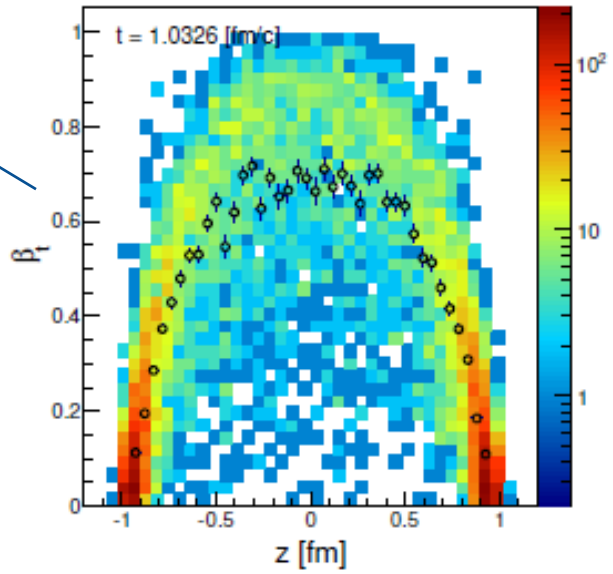


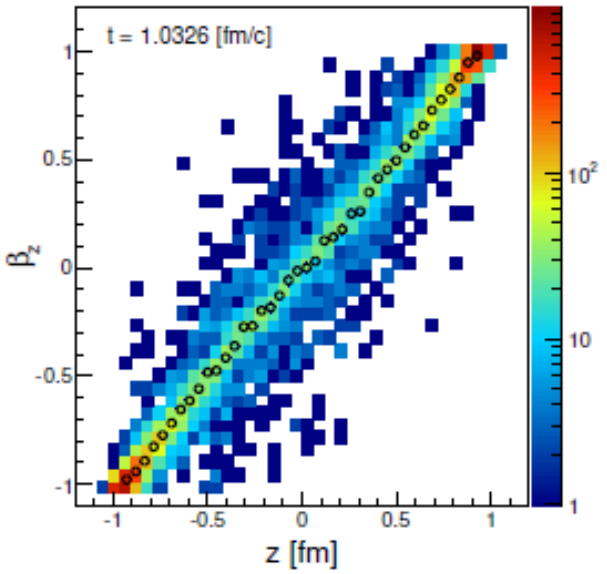




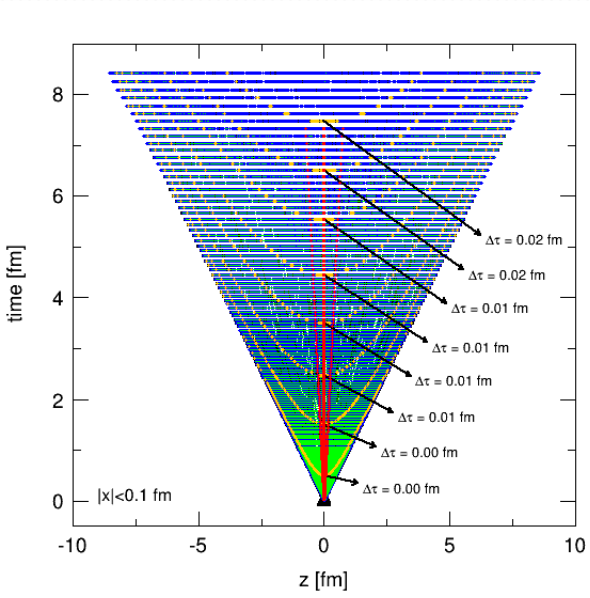

t = 0.1169 [fm/c]
β_t
z [fm]


t = 0.1169 [fm/c]
β_z
z [fm]

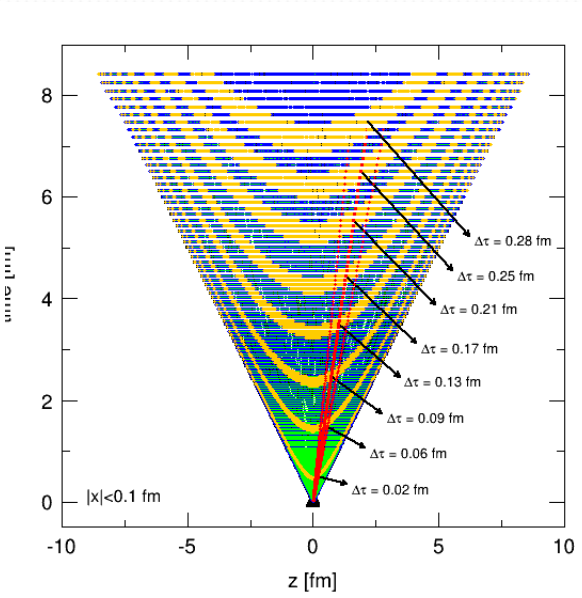

t = 1.0326 [fm/c]
β_t
z [fm]


t = 1.0326 [fm/c]
β_z
z [fm]

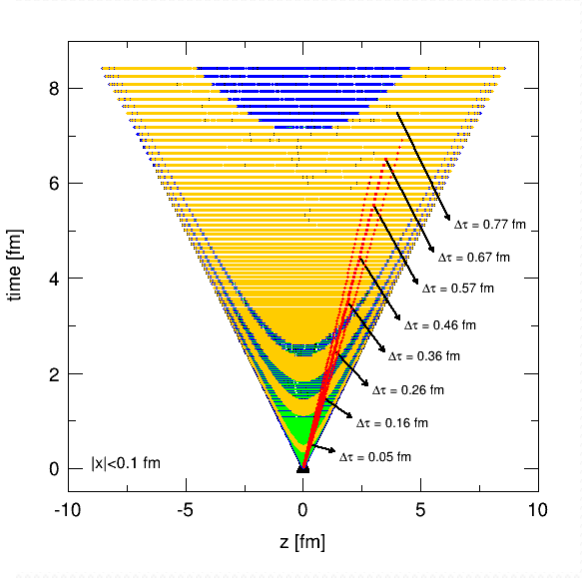
Time Evolution of Eigenvalues in the three different fluid elements with η const.



$\eta = 0$
$\Delta\eta = 0.1$

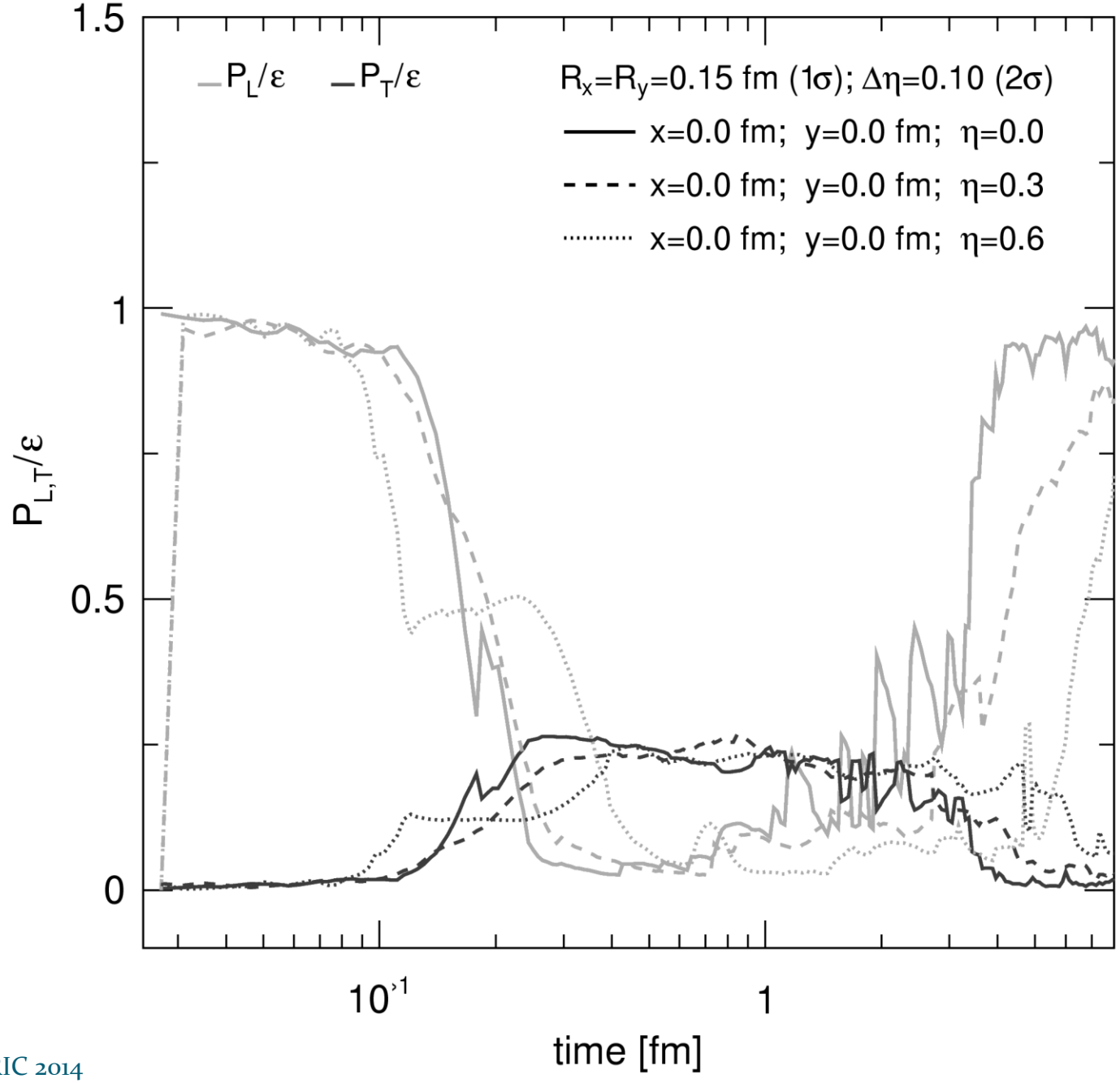


$\eta = 0.3$
$\Delta\eta = 0.1$



$\eta = 0.6$
$\Delta\eta = 0.1$

Good Resoluton case (small hydro cell)



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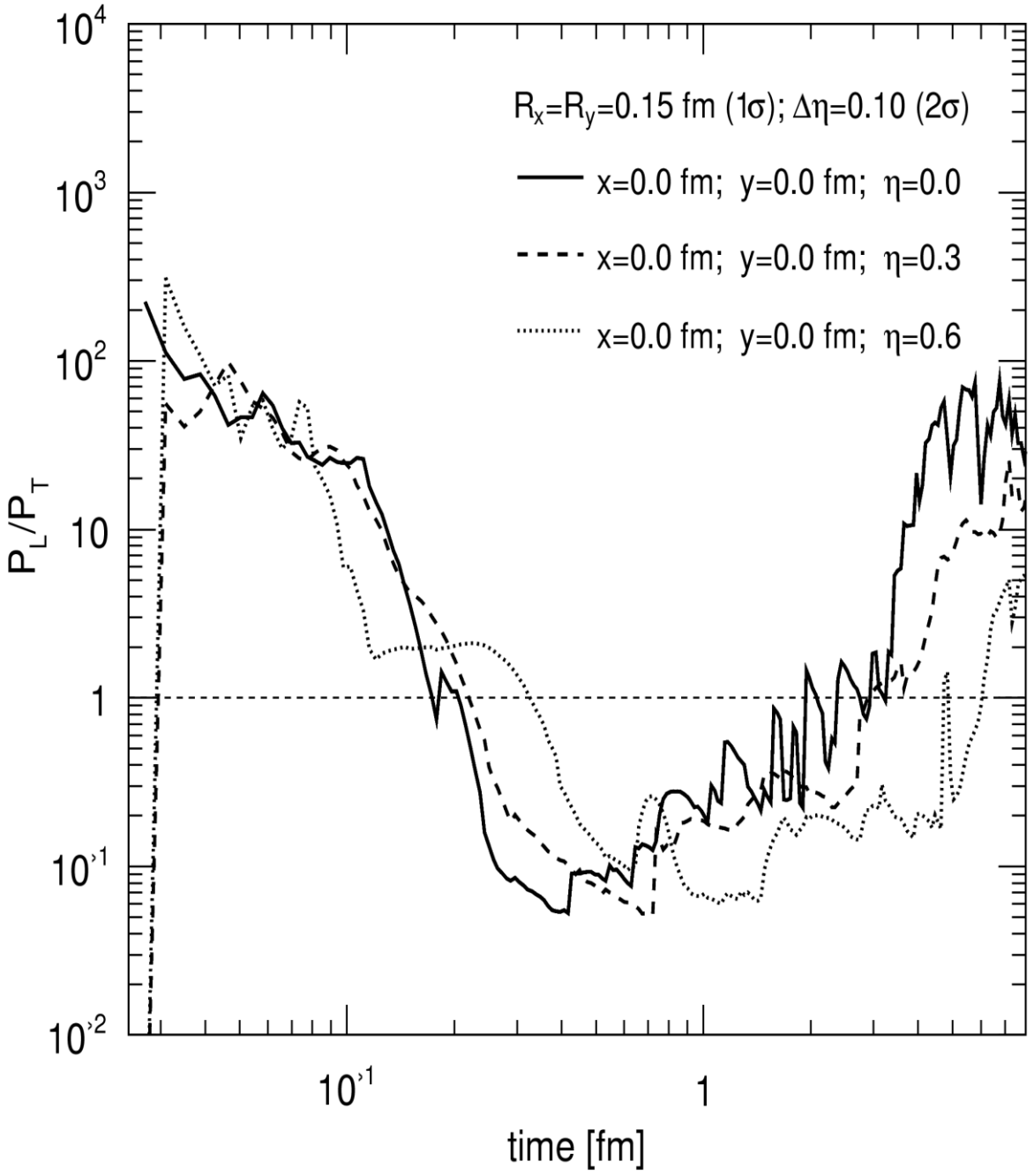
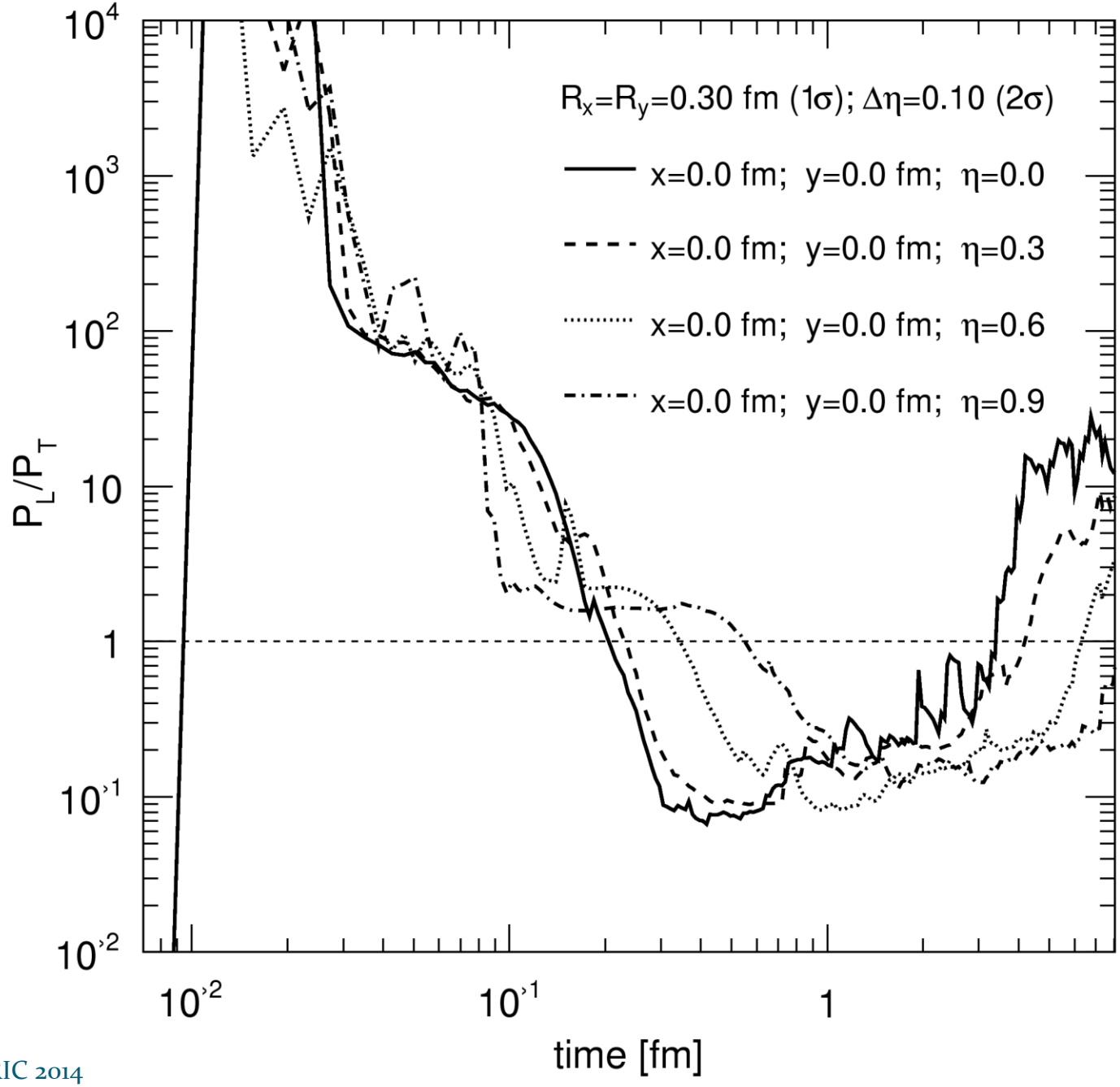
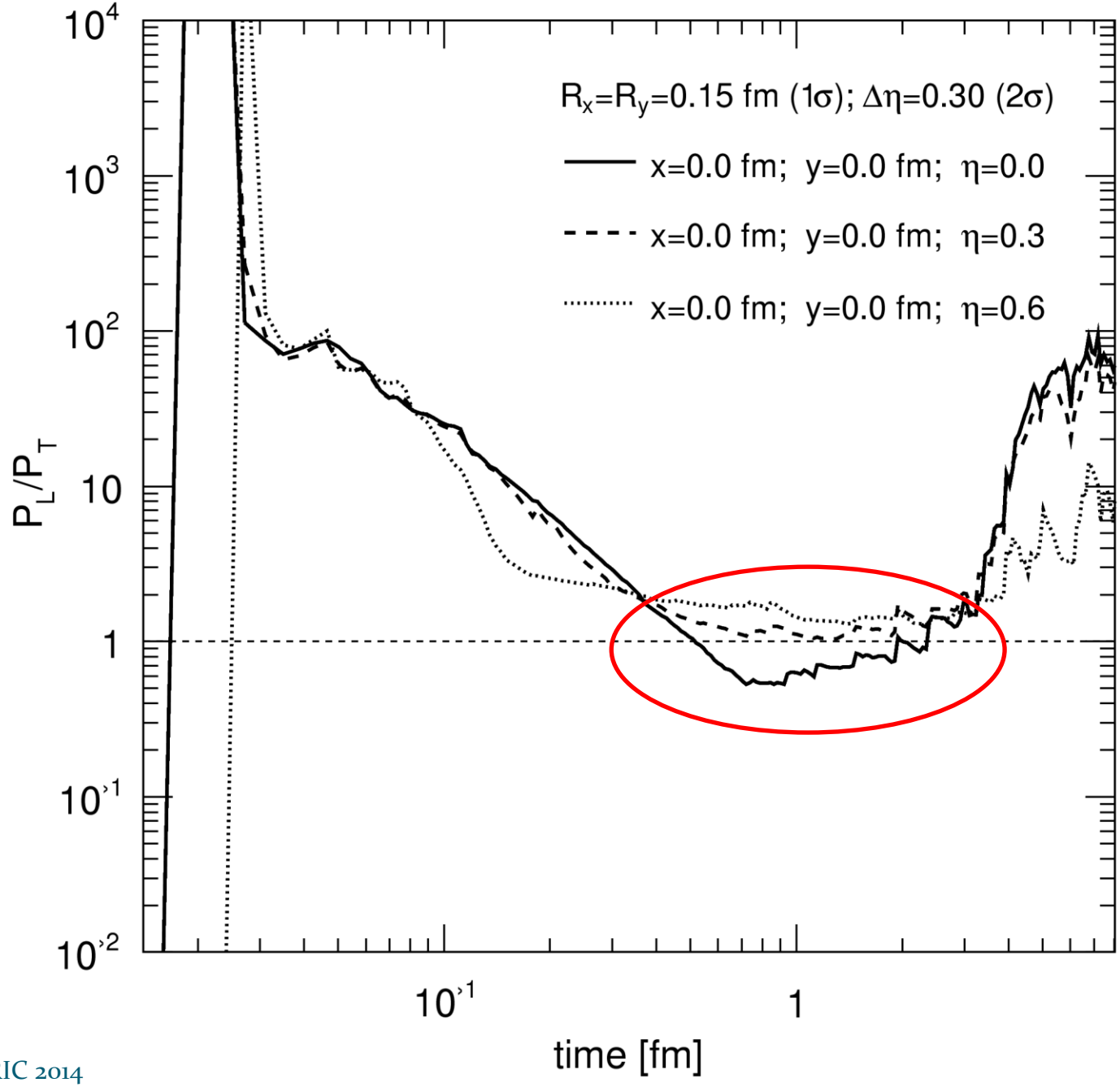


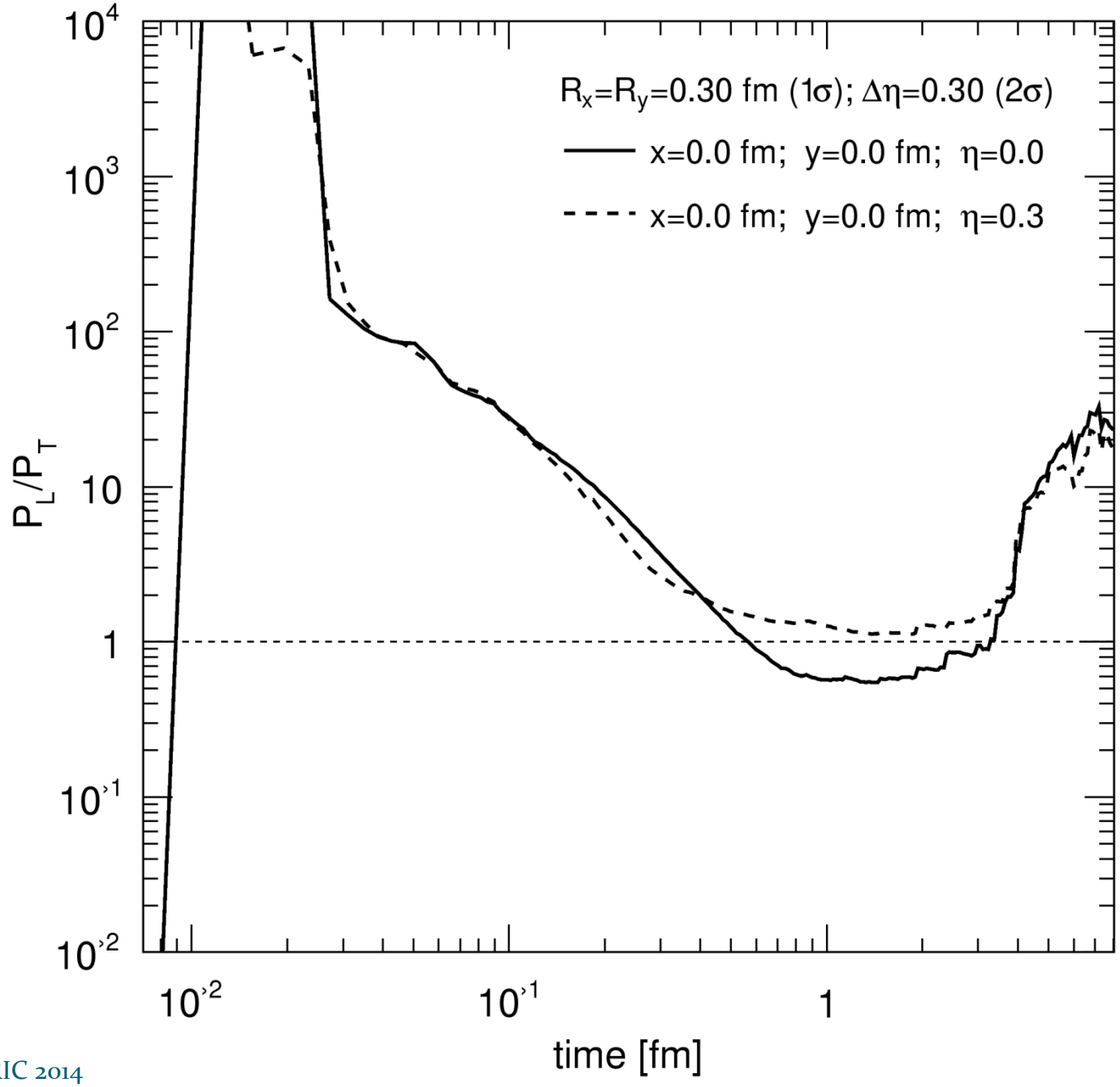
Larger Transverse Cell Size



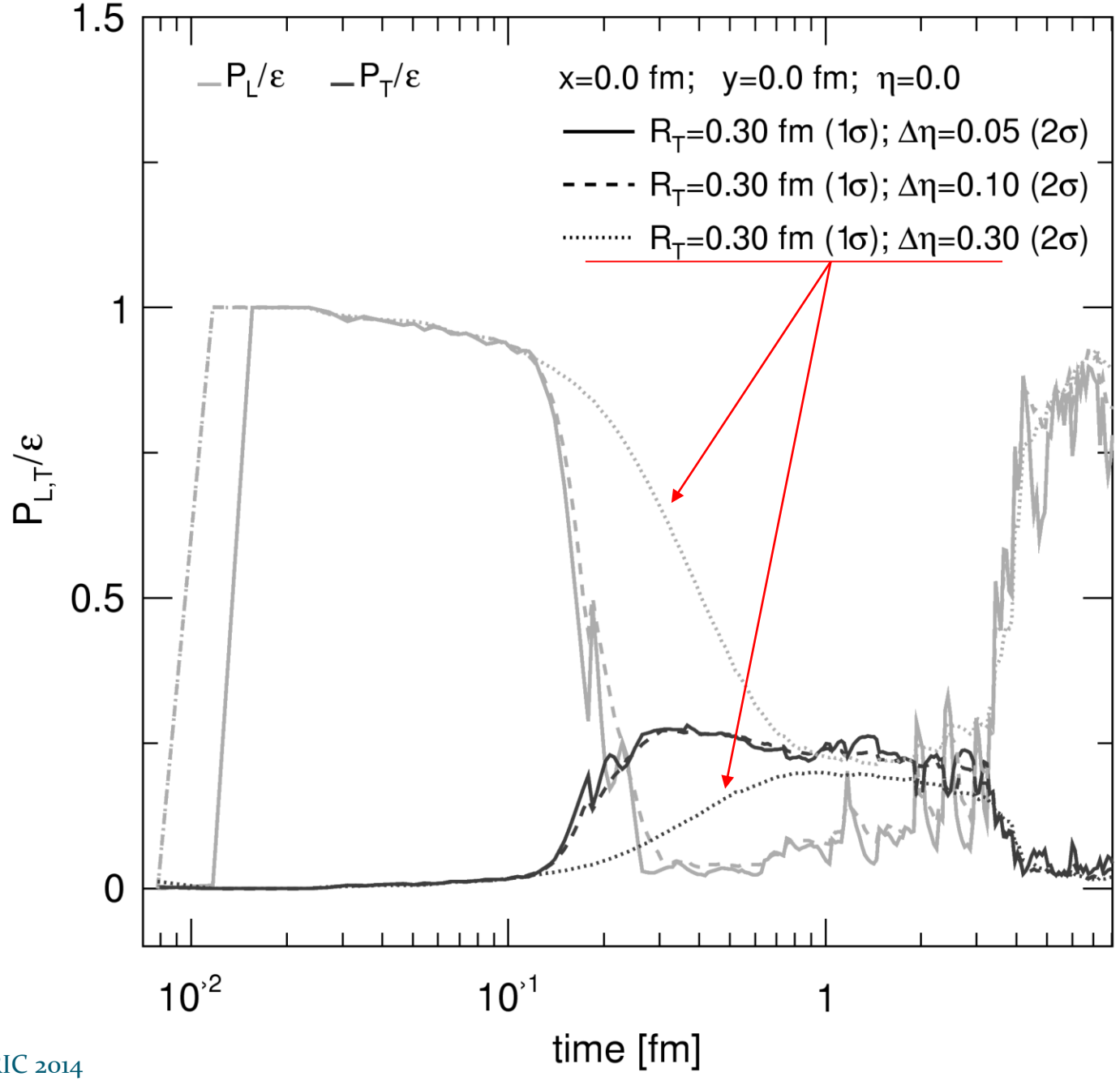
Larger Longitudinal Cell Size



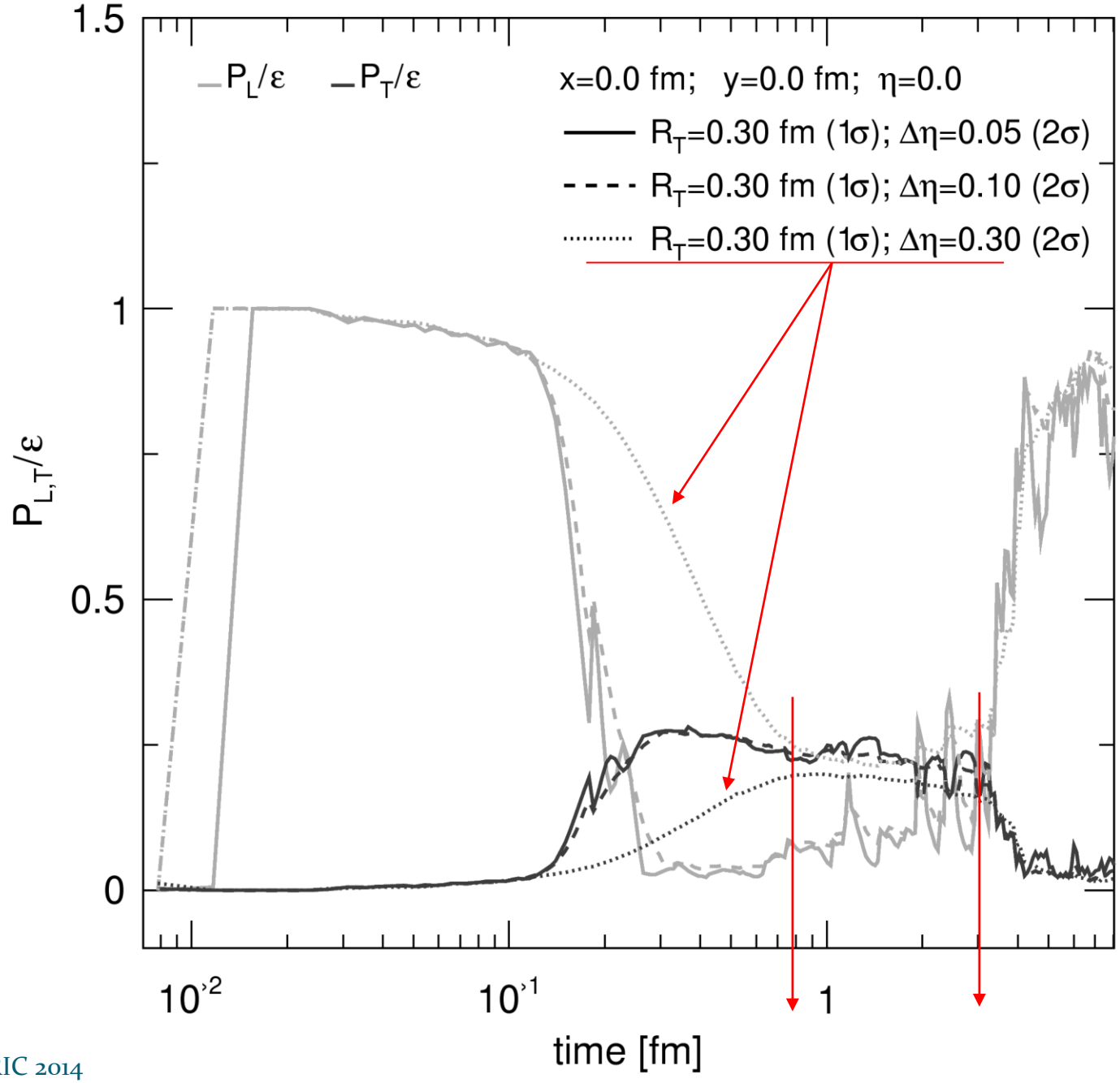
Larger Longitudinal/Transversal Cell Size



Larger Longitudinal/Transversal Cell Size

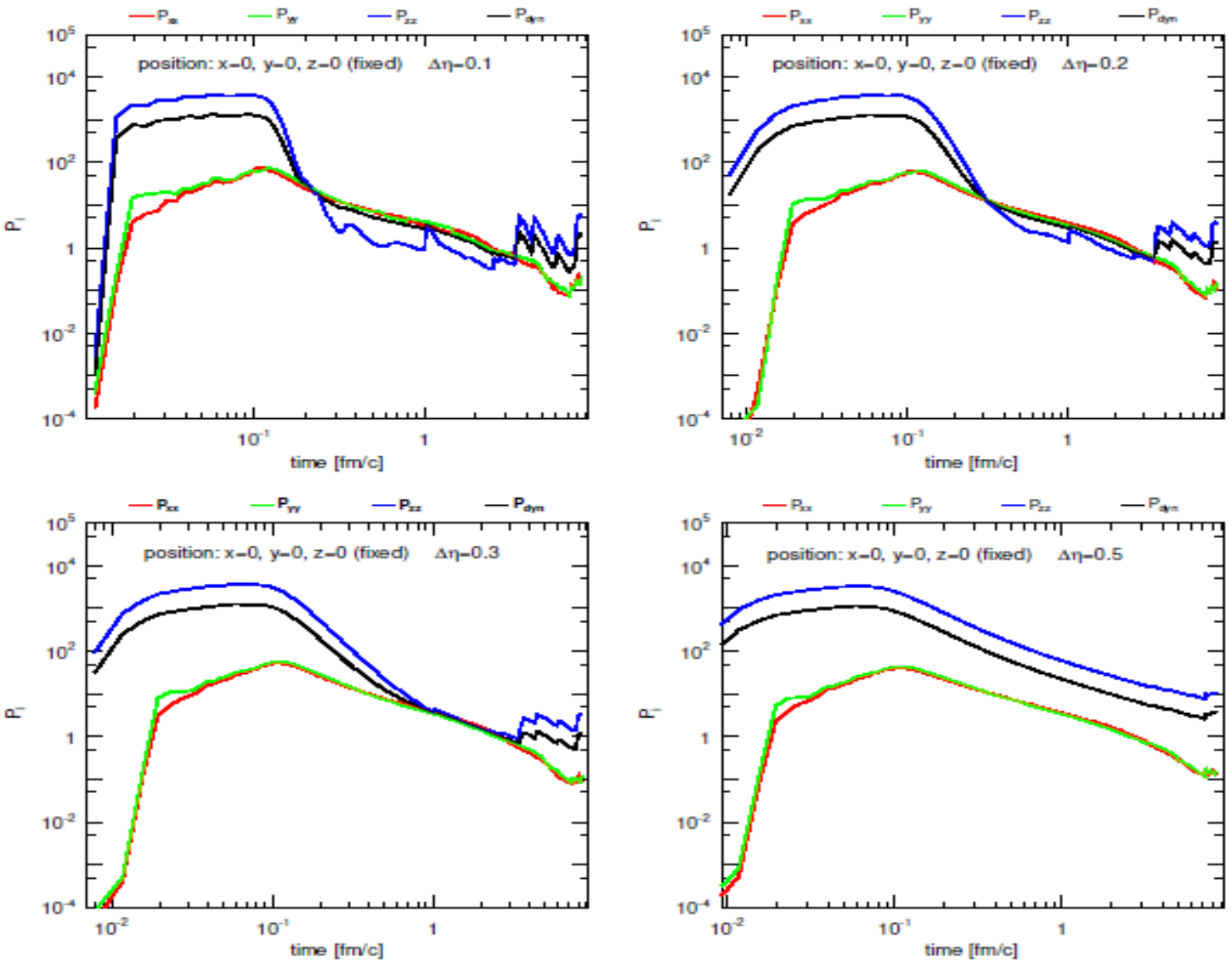


Larger Longitudinal/Transversal Cell Size



Spatial Eigenvalues (pressures)

Pressures



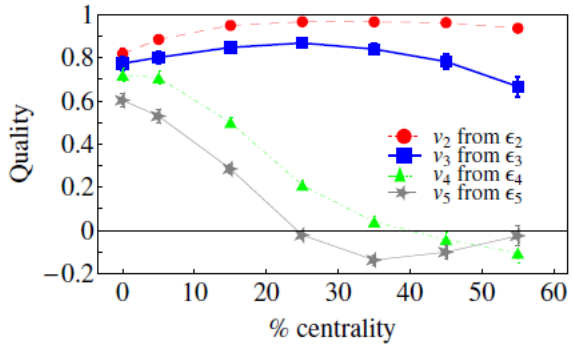
Time

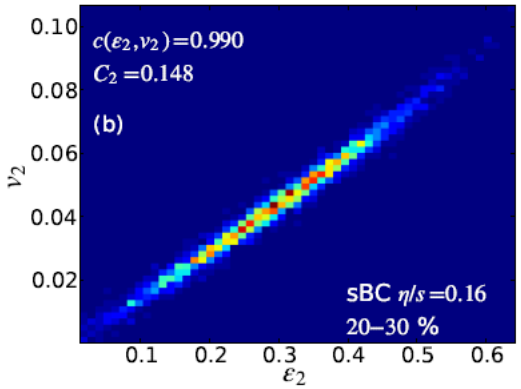
Results so far

- PSHD -> Hydro behavior appears only for a very short time interval near the center.
- Coare graining dependence – We need a rather large cell.
- Most of other places do not approach “equilibrium”
- Ensemble Average -> recover hydro for the whole system?

Gardim, Grassi, Luzum and Ollitrault,
Nucl. Phys. A904-905 **2013**, 503c (2013)

HN, Denicol, Holopainen and Huovinen,
Phys. Rev. C **87**, 054901 (2013)

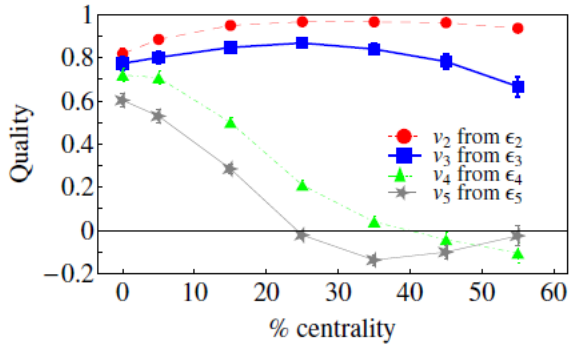




- Strong correlation between $v_{2/3}$ and $\varepsilon_{2/3}$, i.e. $v_n \sim C\varepsilon_n$
- At least within sufficiently narrow centrality bin: $v_n/\varepsilon_n \sim \text{constant}$ $(n = 2, 3)$
- Relative fluctuations of $\varepsilon_n \longrightarrow$ relative fluctuations of v_n
- Probability distributions $P(\delta v_n) = P(\delta\varepsilon_n)$, $\delta v_n = (v_n - \langle v_n \rangle)/\langle v_n \rangle$

H. Niemi – Quark Matter 2014

Gardim, Grassi, Luzum and Ollitrault,
Nucl. Phys. A904-905 **2013**, 503c (2013)



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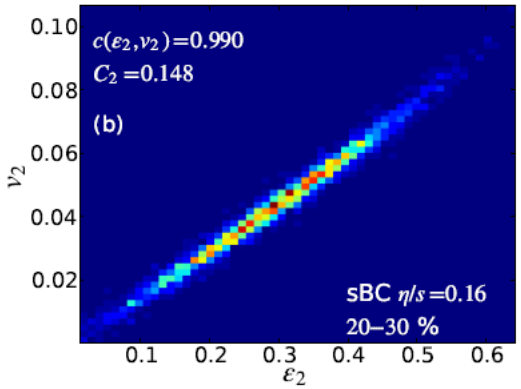
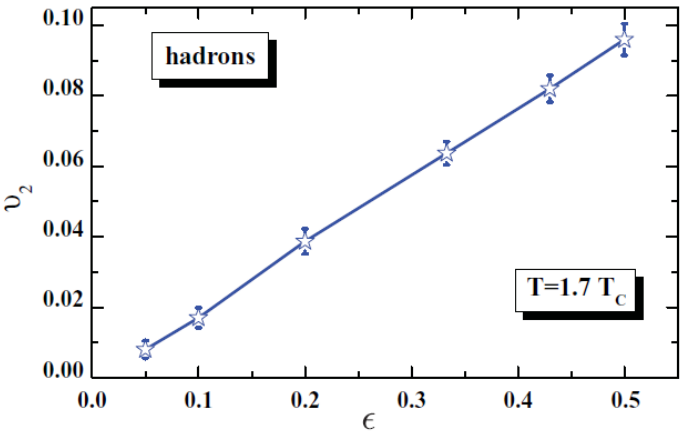
H. Niemi – Quark Matter 2014

HN, Denicol, Holopainen and Huovinen,
Phys. Rev. C **87**, 054901 (2013)





W. Cassing, E.Bratkovskaya

PHYSICAL REVIEW C **78**, 034919 (2008)

Temporary Speculation

- PHSD reproduces hydro signal well even the local thermal equilibrium is not attained everywhere.
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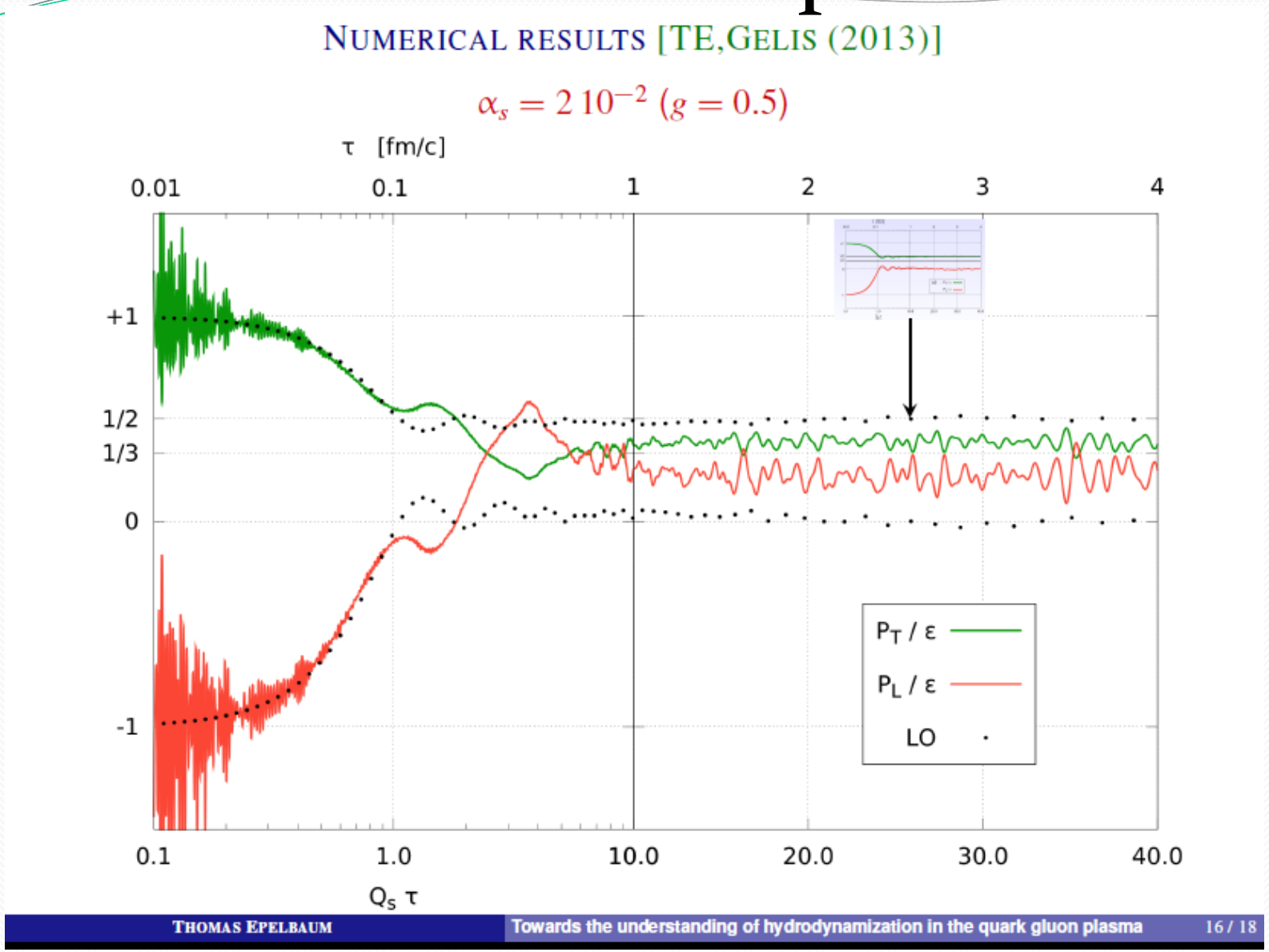
- Signal for the violation of hydro -> non-linear response observables!

- Transversal vs Longitudinal pressure starts very high!

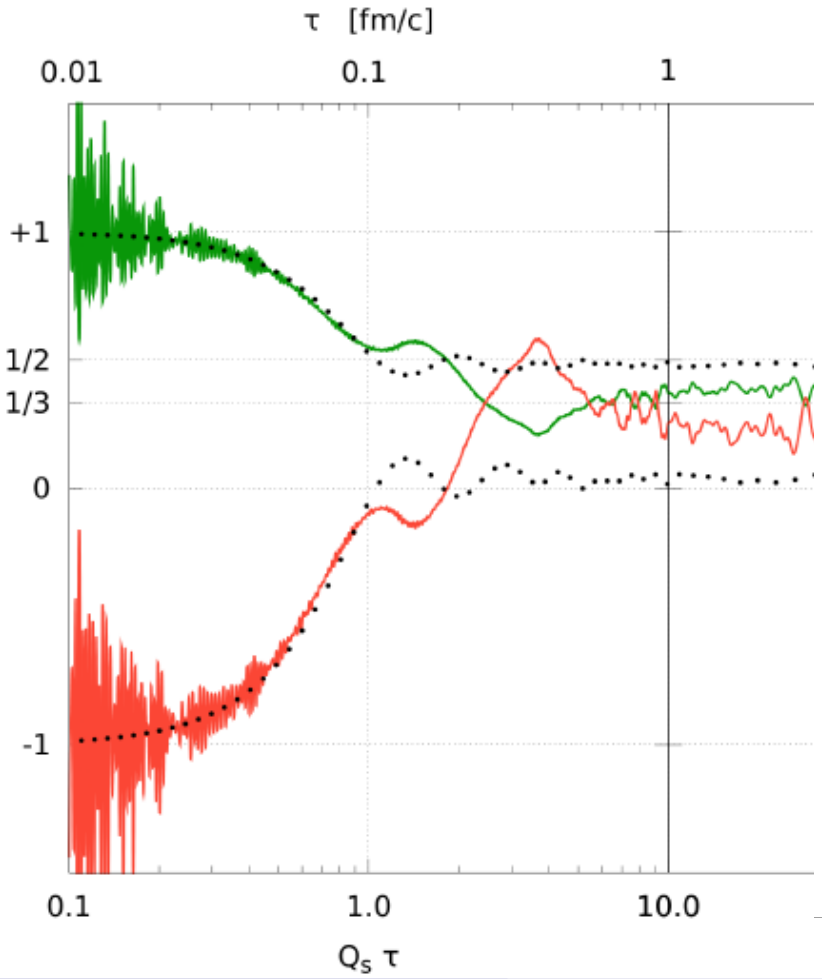
Partile vs Field pressure

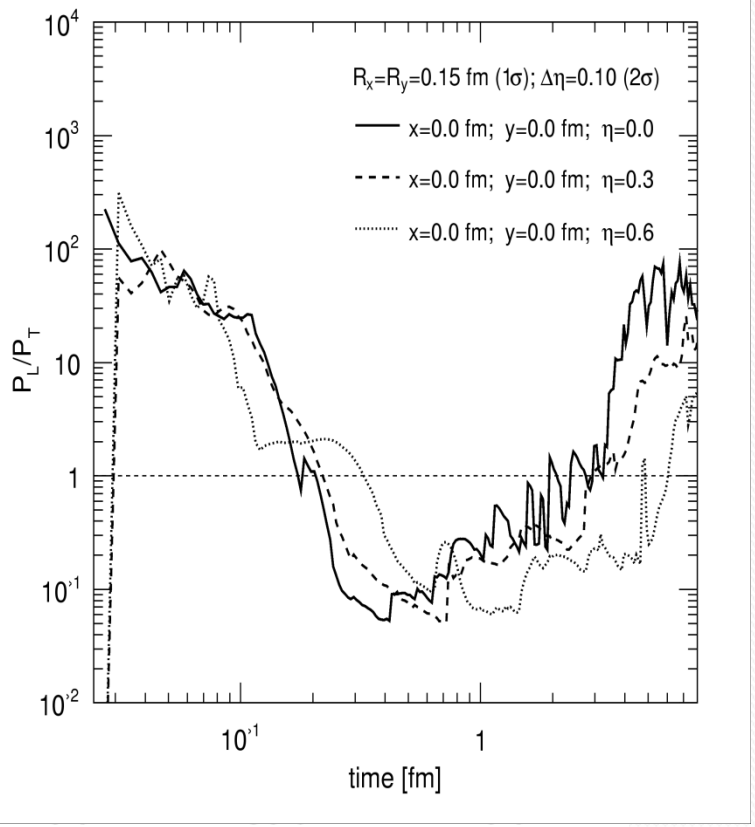


Partile vs Field pressure

NUMERICAL RESULTS [TE, GELIS (2013)]

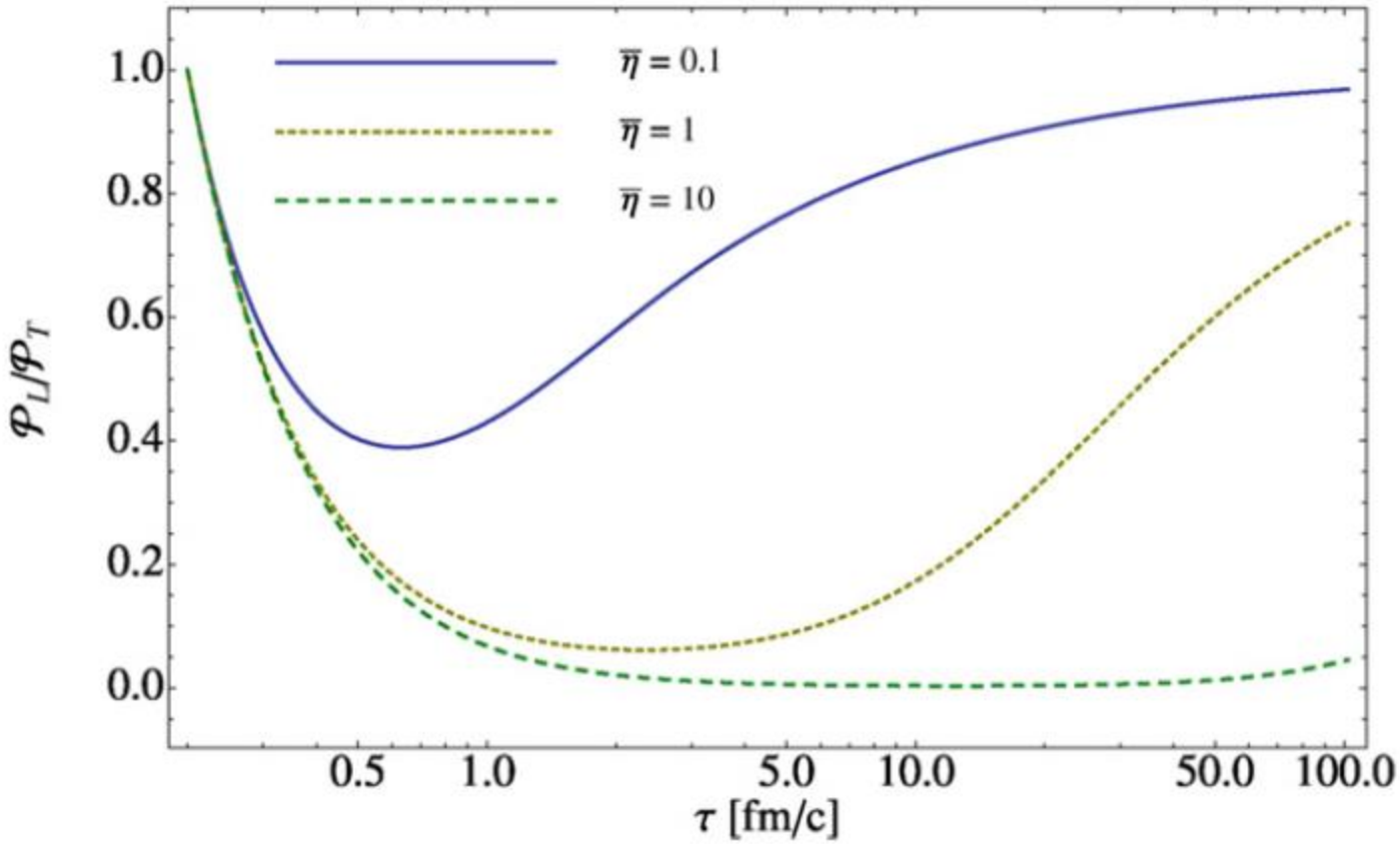
$\alpha_s = 2\,10^{-2}$ $(g = 0.5)$





aHydro

M. Martinez, M. Strickland / Nuclear Physics A 848 (2010) 183–197



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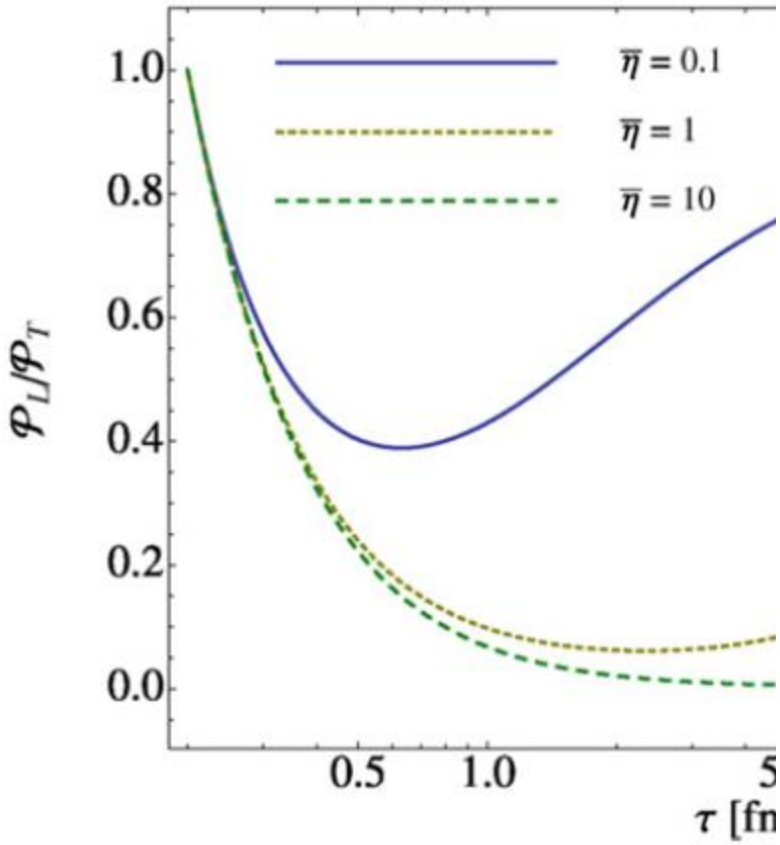

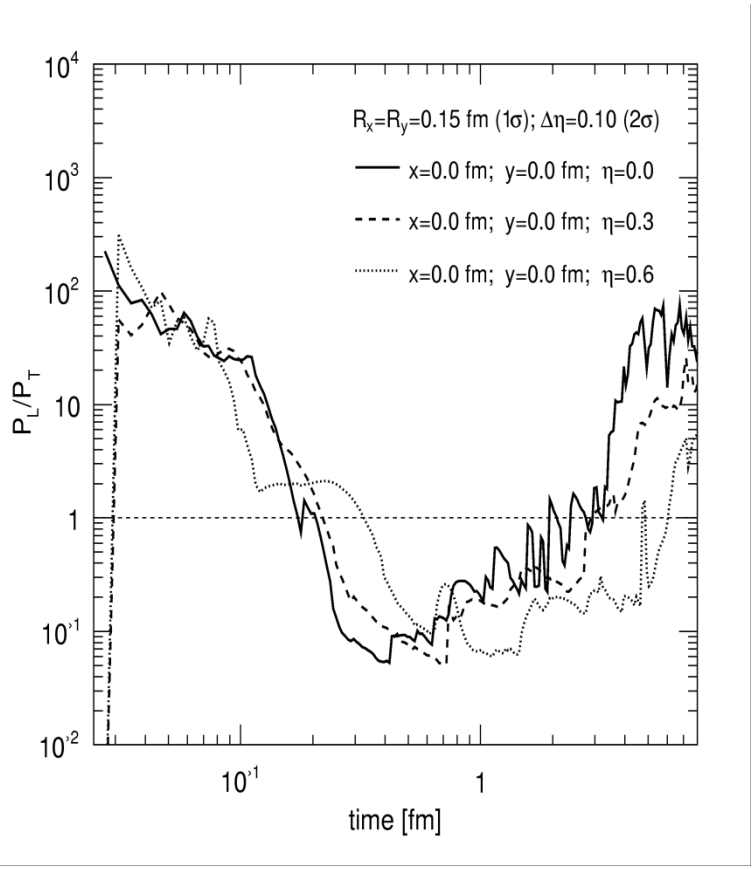

TO-DO list

- Coarse Graining in the time resolution
- Event average and Scatter plot (ε_n vs. v_n)
- Look for non-linear signals
- High multiplicity *pA* Case

Is this fluid good?