EVENT-BY-EVENT PRE-EQUILIBRIUM DYNAMICS WITH CONSERVED CHARGES

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In collaboration with:
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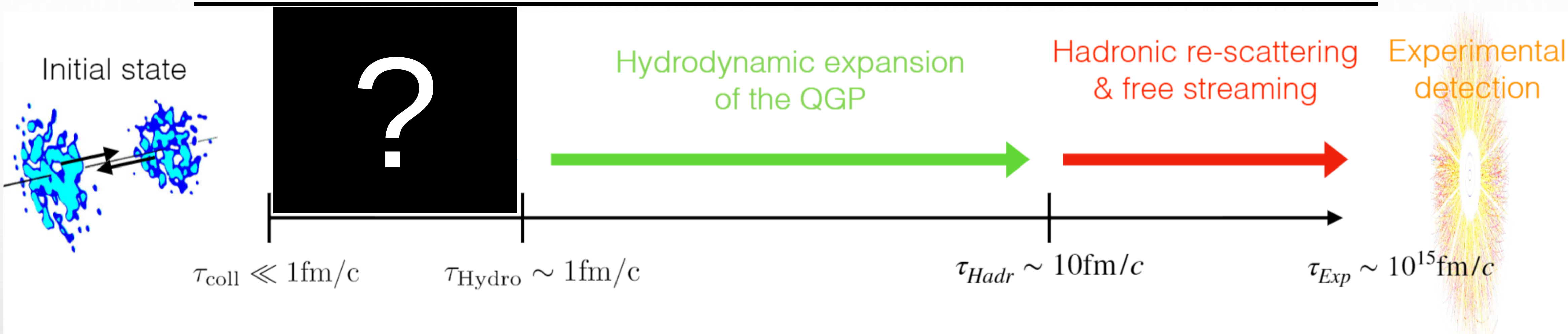
UNIVERSITÄT BIELEFELD

CRC–TR 211
Strong-interaction matter under extreme conditions

THE IMPORTANCE OF EARLY TIME DYNAMICS



Far-from-equilibrium
initial state

Near thermal description
at only slightly later times

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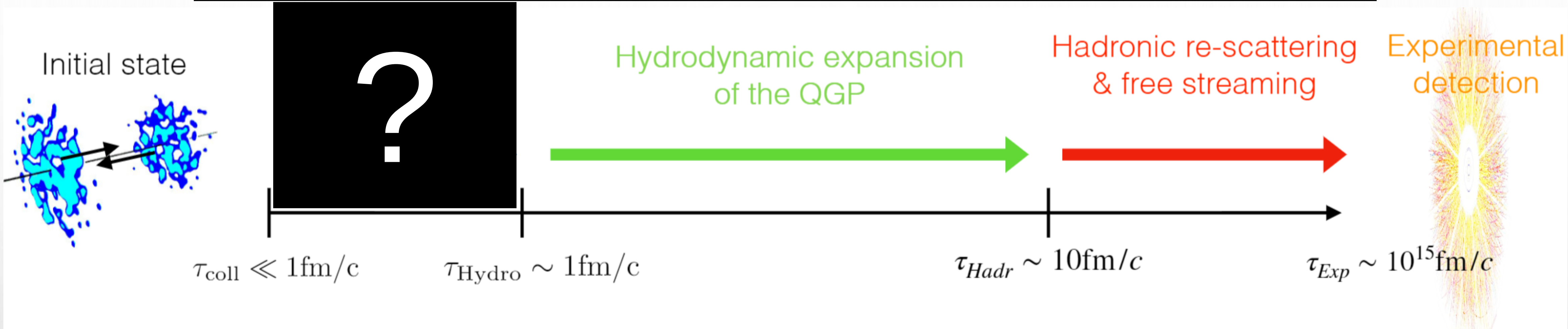


Far-from-equilibrium
initial state

Near thermal description
at only slightly later times

- How to evolve from the non-equilibrium initial state to a hydrodynamic description?

DISTINCT NON-EQUILIBRIUM INITIAL STATE FEATURES

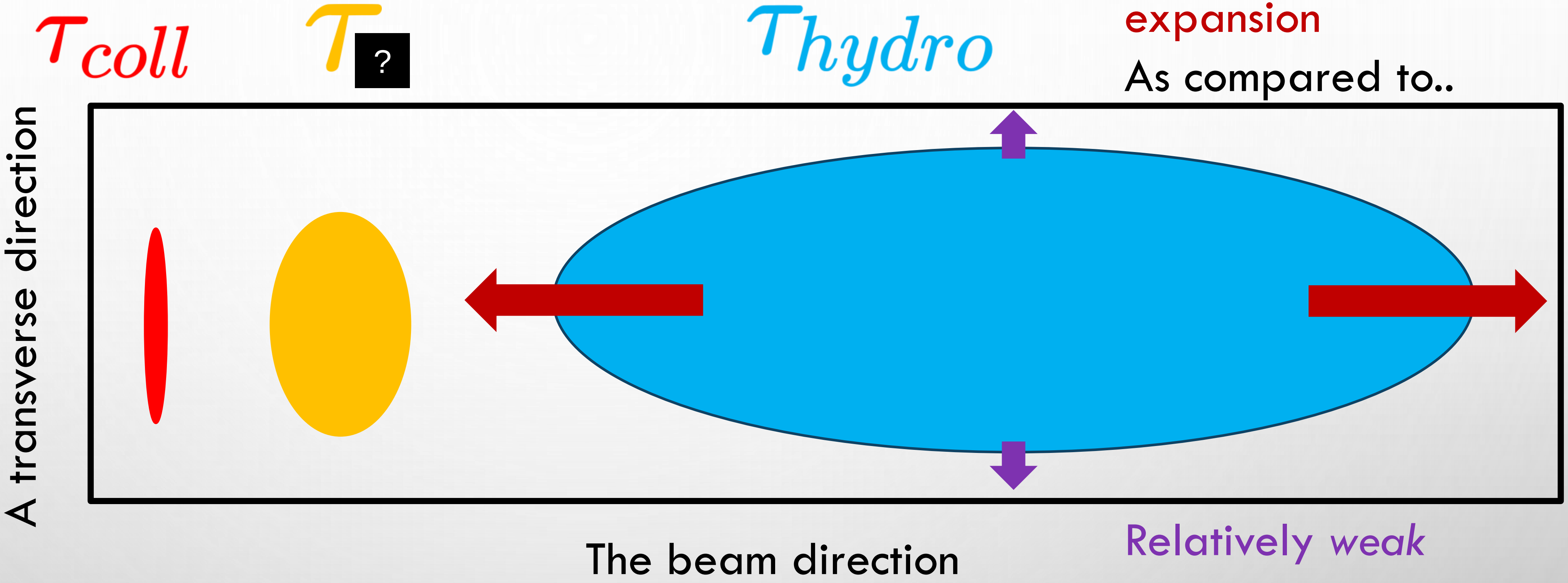
Large pressure anisotropy in the bulk of the system

Vs.

Spatial fluctuations

Strong longitudinal expansion

As compared to..



Relatively *weak* transverse expansion

- Difference in expansion rate leads to large pressure anisotropy
- These are *essential* features of early-time thermalization in high energy nuclear collisions: **hydrodynamic attractors** and **universal dynamics**

Heller, Spalinski PRL 115 (2015) no.7, 072501; G. S. Denicol, U. W. Heinz, M. Martinez, J. Noronha, and M. Strickland, Phys. Rev. D 90, 125026 (2014); C. Chattopadhyay, S. Jaiswal, L. Du, U. Heinz, and S. Pal, Phys. Lett. B 824, 136820 (2022); D. Almaalol, A. Kurkela, and M. Strickland, Phys. Rev. Lett. 125, 122302 (2020); G. Giacalone, A. Mazeliauskas, and S. Schlichting, Phys. Rev. Lett. 123, 262301 (2019); P. Romatschke, Phys. Rev. Lett. 120, 012301 (2018)

DISTINCT NON-EQUILIBRIUM INITIAL STATE FEATURES

Large pressure anisotropy in the bulk

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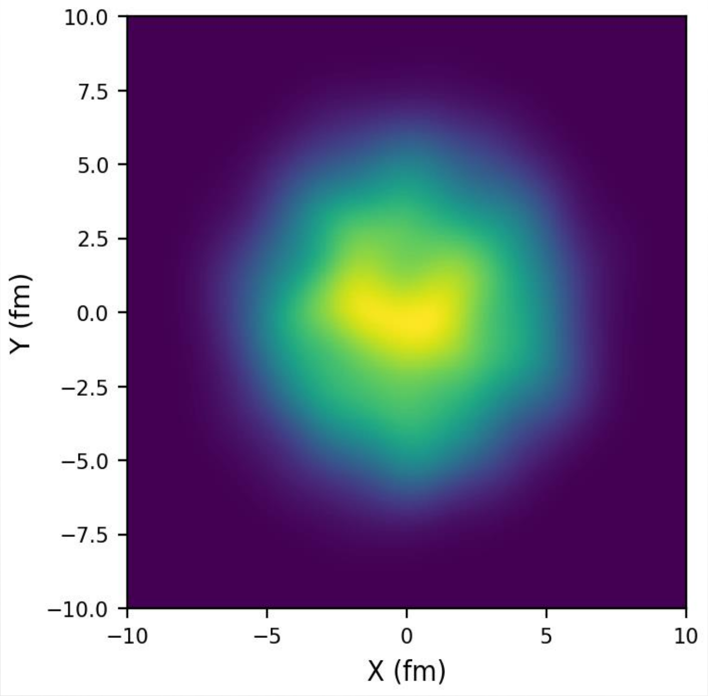
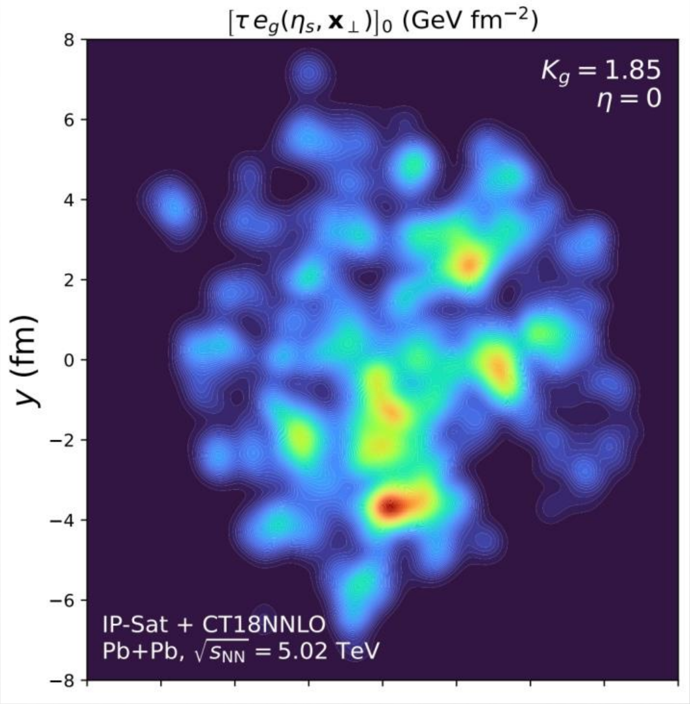
Spatial fluctuations

Averaged Event



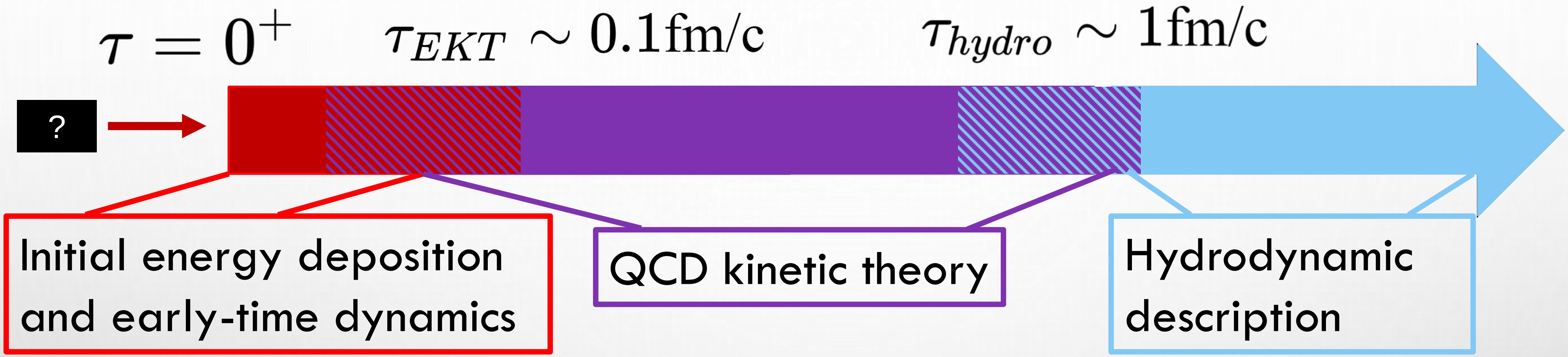
Fluctuating Event



O. Garcia-Montero, H. Elfner, S. Schlichting arXiv 2308.11713

- Fluctuating initial states are the essential feature of event-by-event models
- Large spatial fluctuations and gradients require far-from-local equilibrium, event-by-event evolution
- Capturing this physics correctly is essential for interpreting fine structure features

INITIAL STATE TO HYDRO: PHYSICAL CONNECTIONS



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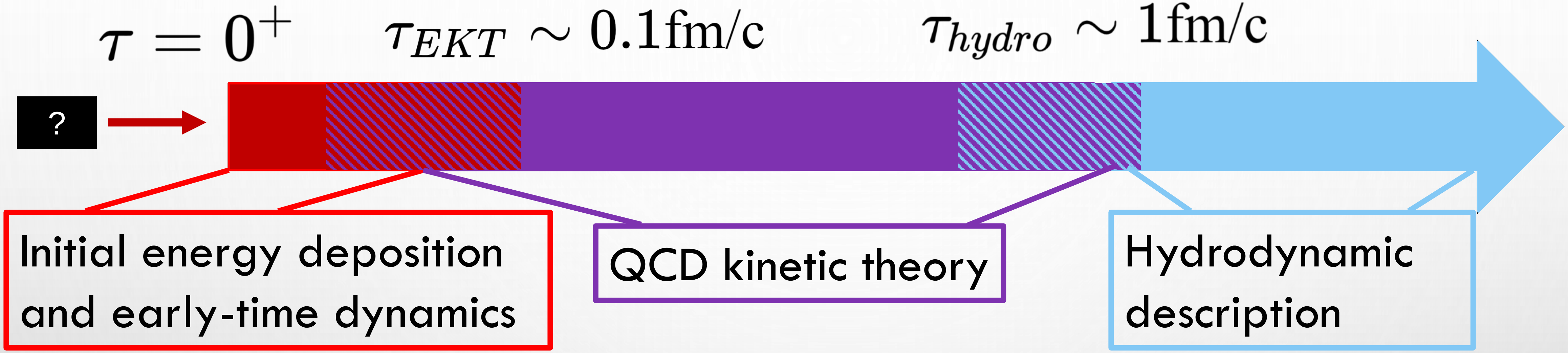


Overlap in validity offers less sensitivity for switching times

Arnold, Moore, Yaffe, *JHEP* 01 (2003) 030, R. Baier, et al, Phys.Lett.B 502 (2001),

In this work, **we employ QCD effective kinetic theory** which brings the system towards its hydrodynamic description

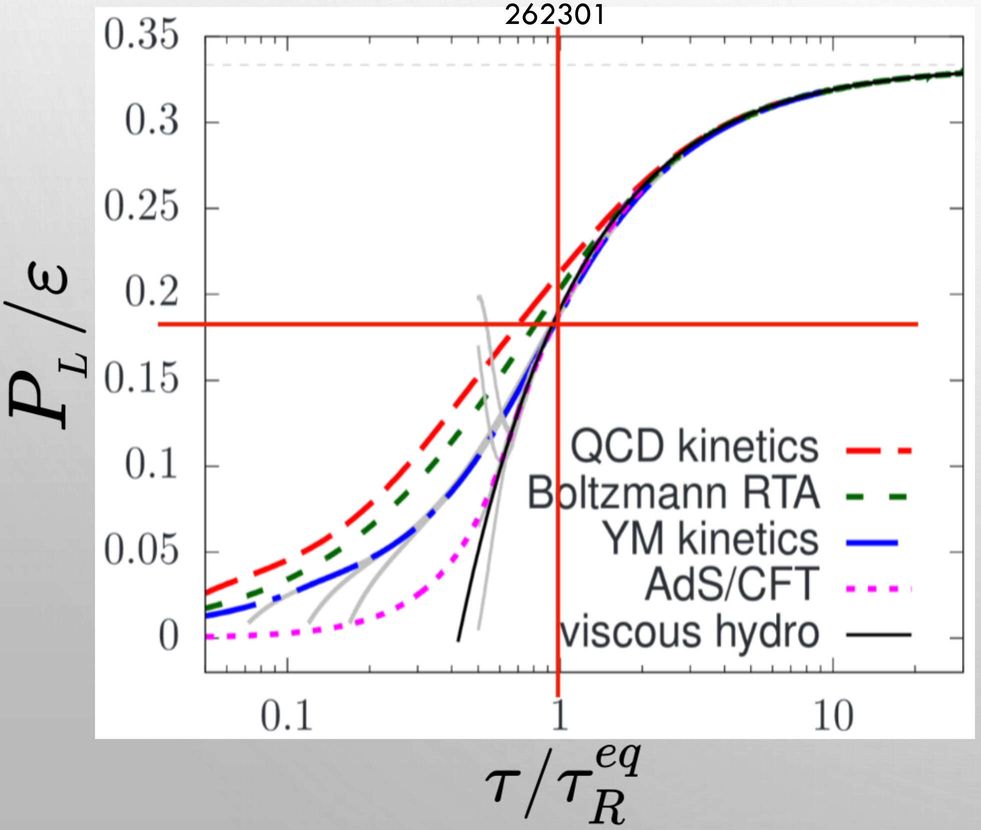
$$p^\mu \partial_\mu f(x,p) = C_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

HYDRODYNAMIZATION IN HIGH ENERGY PLASMA

Hydrodynamization for the bulk of the system

Symmetries of the bulk (or *background*) :

- Isotropic in transverse plane (no fluctuations)
- No transverse expansion
- Boost invariance G. Giacalone, A. Mazeliauskas, S. Schlichting Phys.Rev.Lett. 123 (2019) 26, 262301



On time scales of a relaxation time, τ_R^{eq}, the system is well described by hydrodynamics

$$\tau_R^{eq}(\tau) = \frac{4\pi\,\eta/s}{T_{eff}(\tau)}$$

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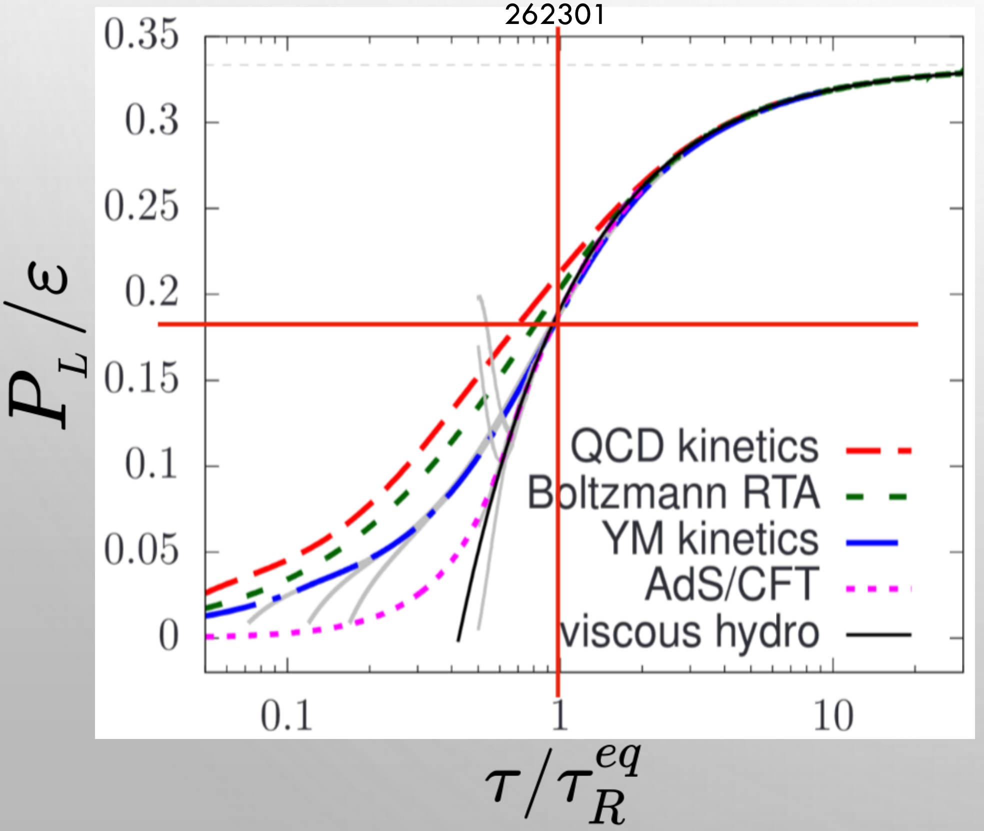

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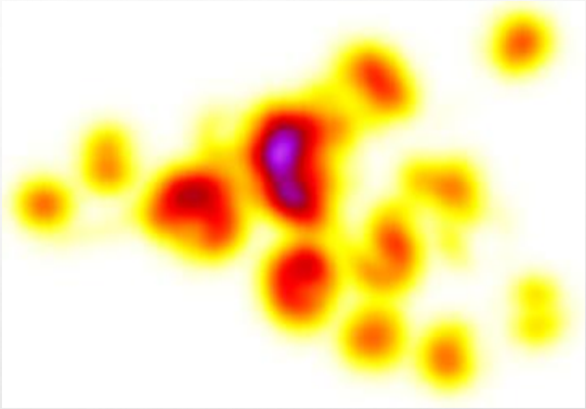
Hydrodynamization for inhomogeneous systems

V. Ambrus, S. Schlichting, C. Werthmann, Phys.Rev.Lett. 130 (2023) 15



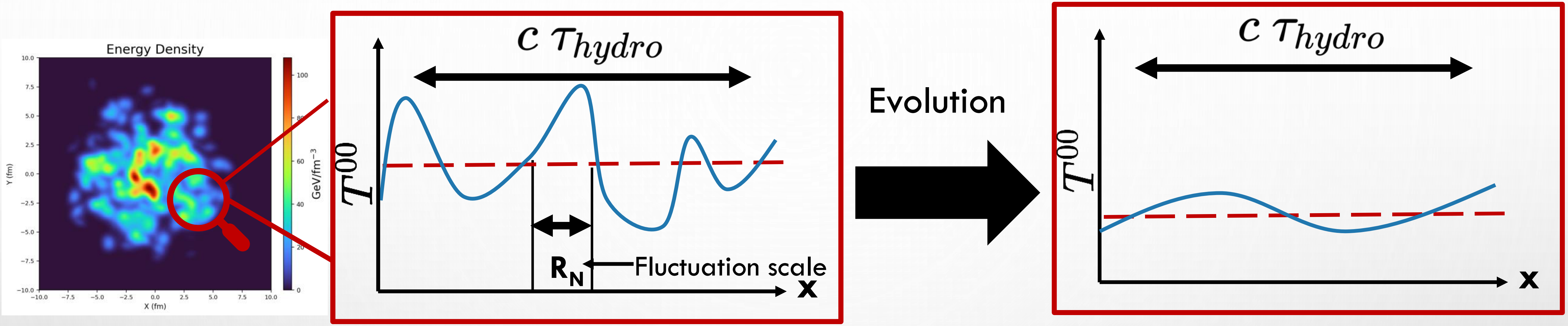
Two approaches:

1) Full kinetic theory and quantification in (2+1) scenario, see talk from **Clemens Werthmann** Tues. Sept 5, *Collective Dynamics*

2) Treat inhomogeneities as fluctuations on a locally symmetric background: **KøMPøST framework**

DEALING WITH FLUCTUATIONS: THE KØMPØST FRAMEWORK

A. Kurkela, et al., *Phys.Rev.Lett.* 122 (2019) 12, 122302, *Phys.Rev.C* 99 (2019) 3, 034910



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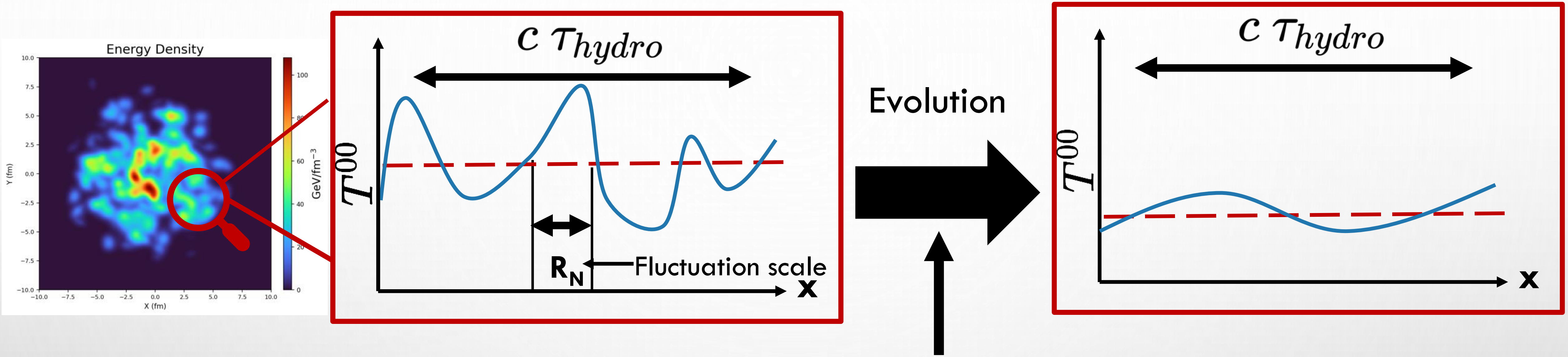
A. Kurkela, et al., *Phys.Rev.Lett.* 122 (2019) 12, 122302, *Phys.Rev.C* 99 (2019) 3, 034910



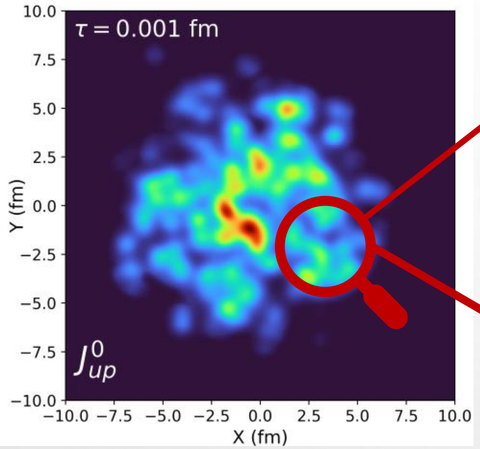
$$T^{\mu\nu}(\tau, x) = T^{\mu\nu}_{BG} + \int_\circ G^{\mu\nu}_{\alpha\beta}(\tau_0, \tau, x_0, x)\, \delta T^{\alpha\beta}(\tau_0, x_0)$$

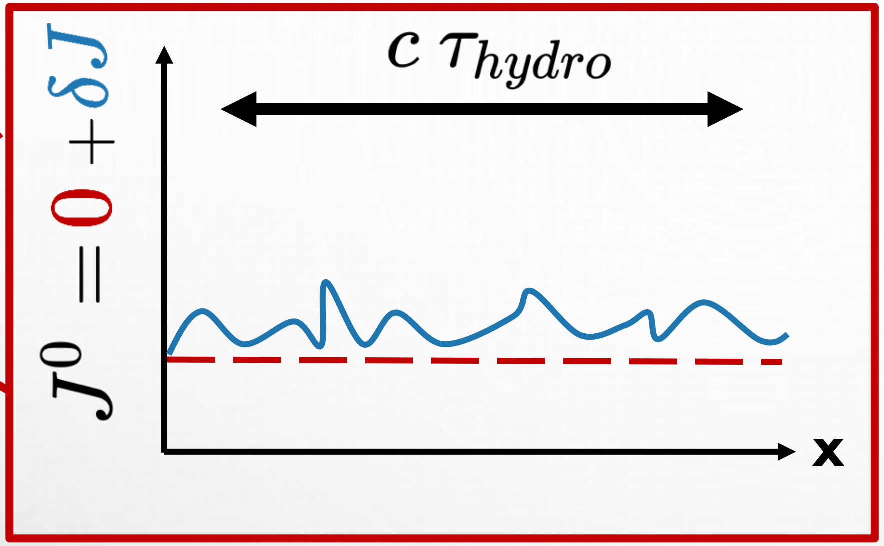
Non-Equilibrium Linear Response

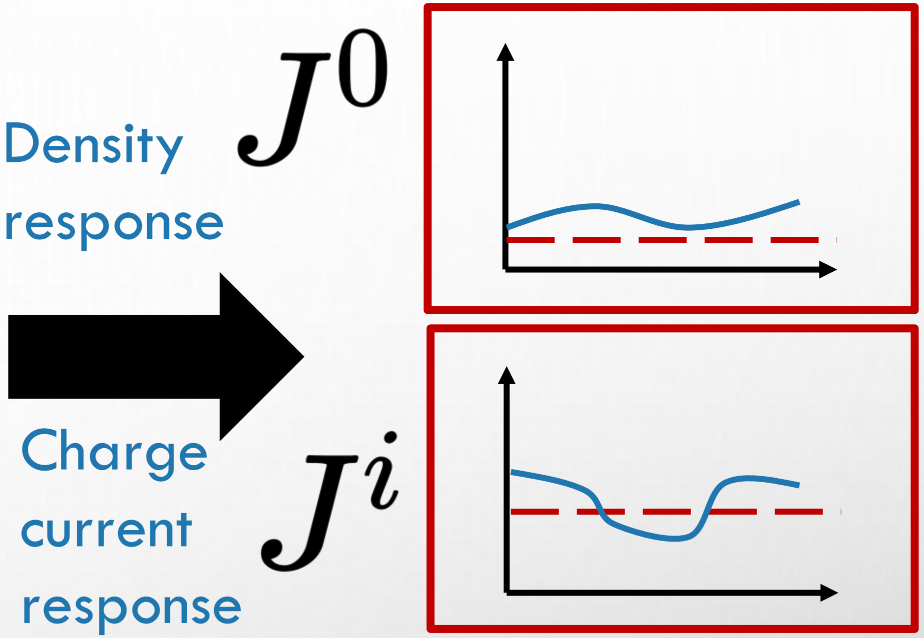
- Attractor solution evolves background. Response functions, $G^{\mu\nu}_{\alpha\beta}$, evolve fluctuations
- ***Generic framework for any microscopics*:**
  - System has attractor background that can be calculated
  - Response functions can be calculated
- In this work we use QCD kinetic theory with conserved charges

DEALING WITH FLUCTUATIONS: CONSERVED CHARGES

X. Du, S. Schlichting, Phys.Rev.Lett. 127 (2021) 12, 122301, Phys.Rev.D 104 (2021) 5, 054011, TD, X. Du, S. Schlichting, in prep







First step: zero charge background, all initially deposited charge treated as perturbation

$$J^\mu(\tau, x) = 0 + \int_\circ F^\mu_\alpha(\tau_0, \tau, x_0, x)\delta J^\alpha(\tau_0, x_0)$$

IMPLEMENTATION IN PRACTICE

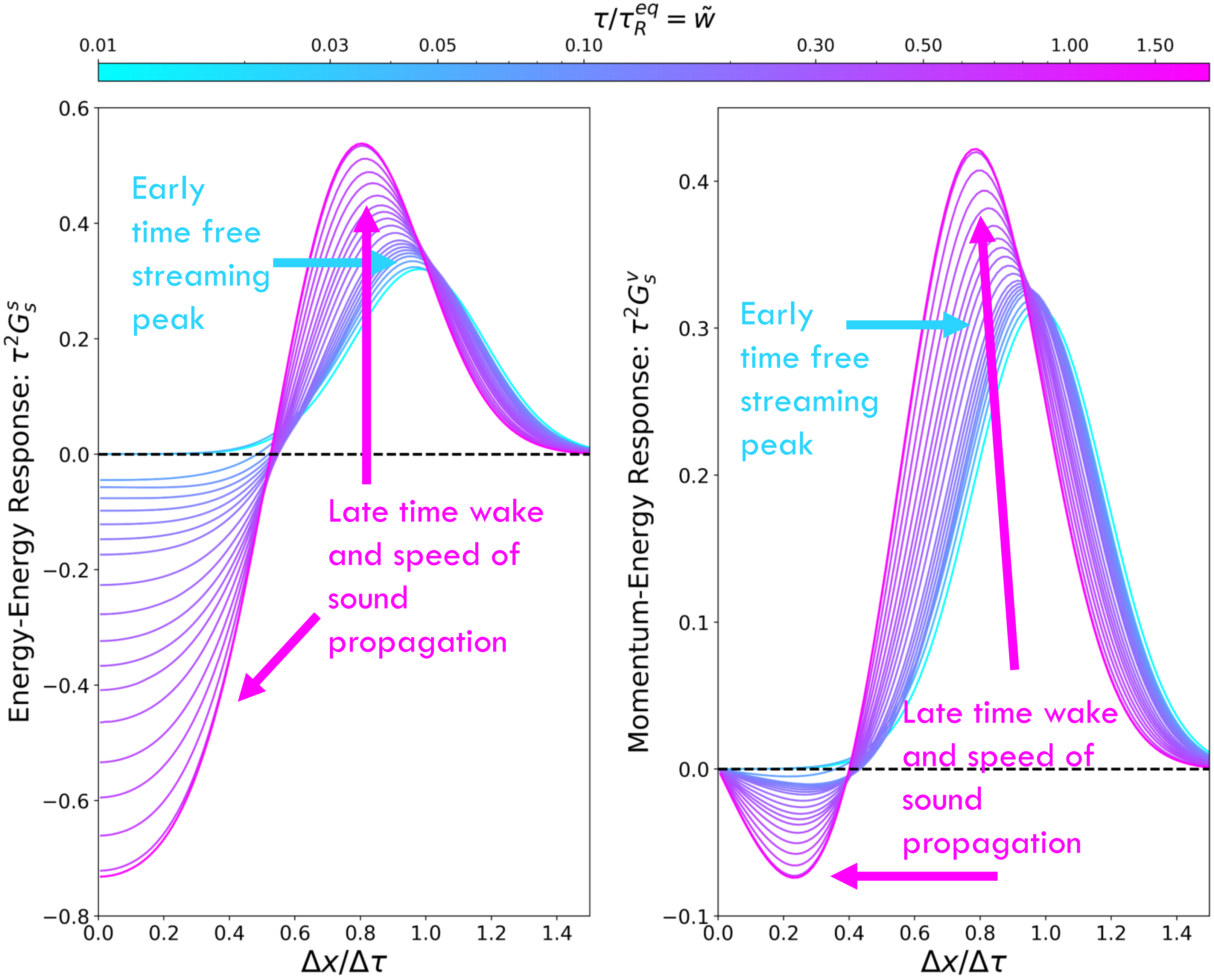
1. Decompose response functions into irreducible tensor components

2. Calculate the full dynamics in kinetic theory simulations for all tensor component perturbations off non-equilibrium background

3. Tabulate results of simulations in momentum space and Fourier transform into position space so that response functions can be used efficiently for a large number of events

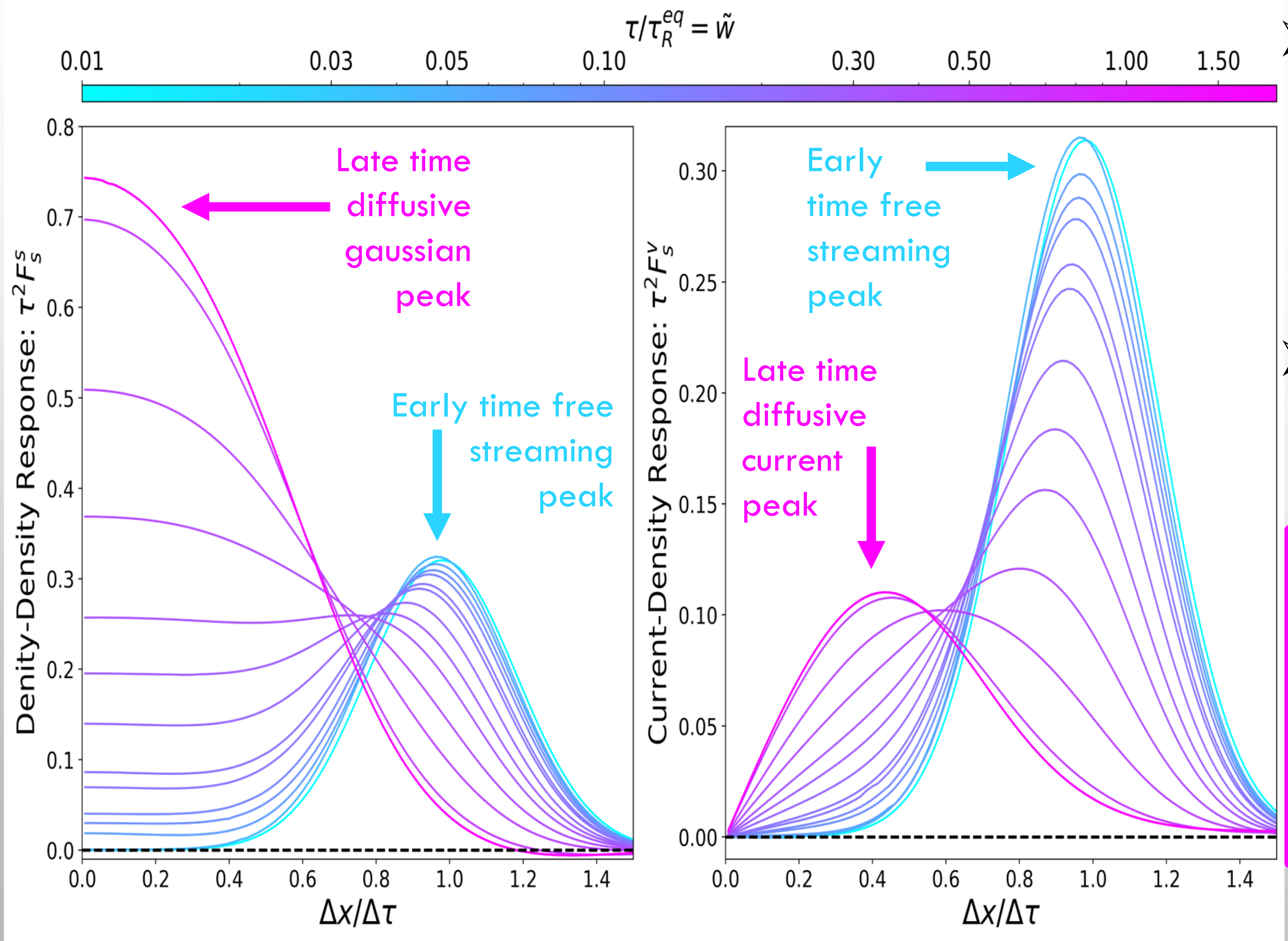
What do these response functions look like?

ENERGY RESPONSE FUNCTIONS

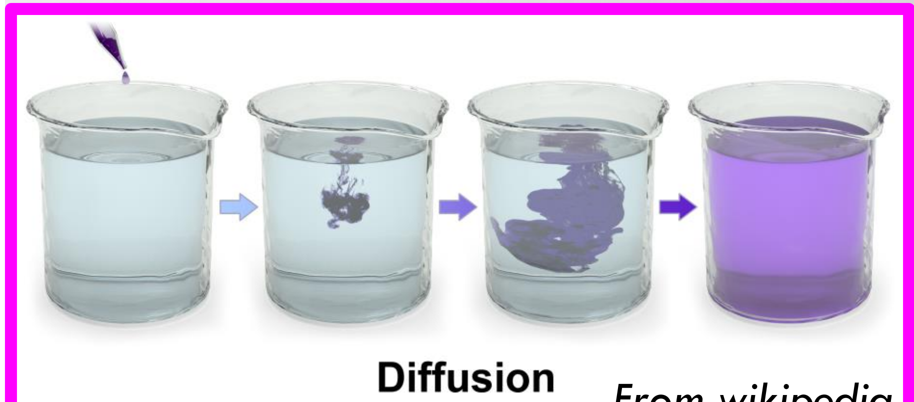


- Response functions give information on *redistribution* of quantities at a given τ/τ_R^{eq}
  - Scalar-Scalar: energy density redistribution
  - Vector-Scalar: change of transverse flow
- From free streaming to wakes and wave fronts with speed of sound propagation

CHARGE RESPONSE FUNCTIONS: DEGENERATE LIGHT QUARKS

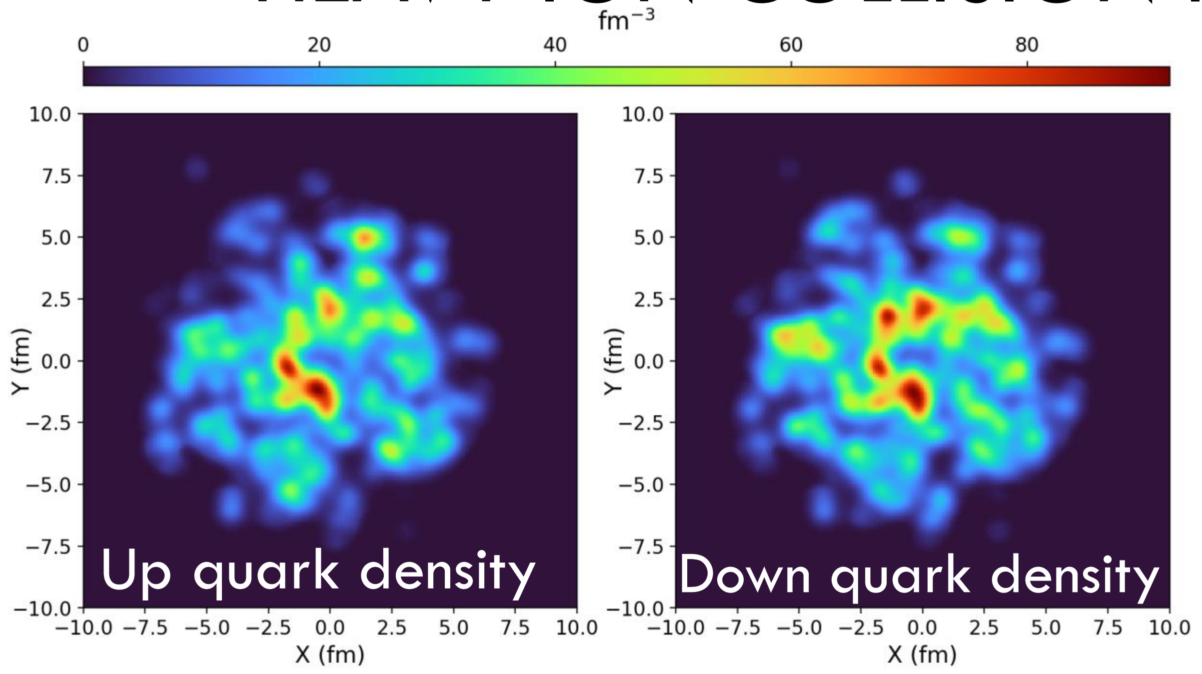


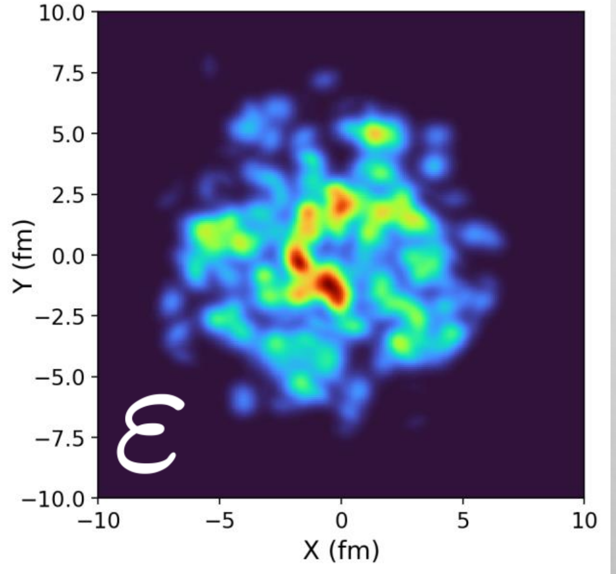
- *Redistribution* of quantities at a given τ/τ_R^{eq}
  - Scalar-Scalar: charge density redistribution
  - Vector-Scalar: change of charge current, $n^\nu \sim \nabla^\nu\left(\frac{\mu}{T}\right)$
- From free streaming to diffusive behavior



From wikipedia

HEAVY ION COLLISION INITIAL STATE WITH CHAGES



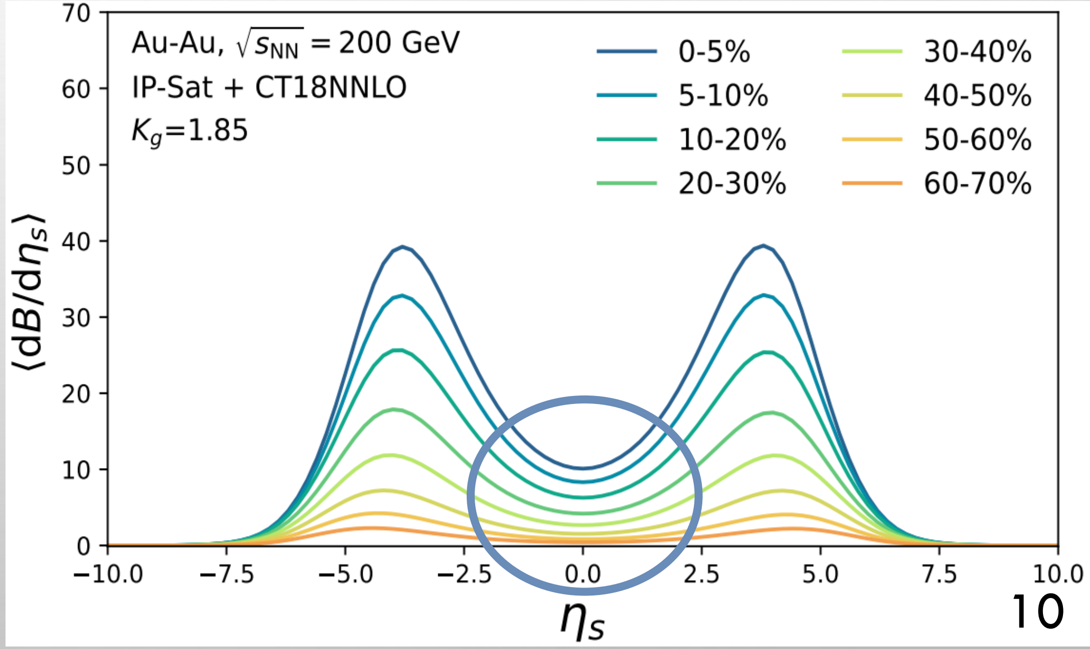


In reality, the baryon density deposited at high energies is not vanishing!

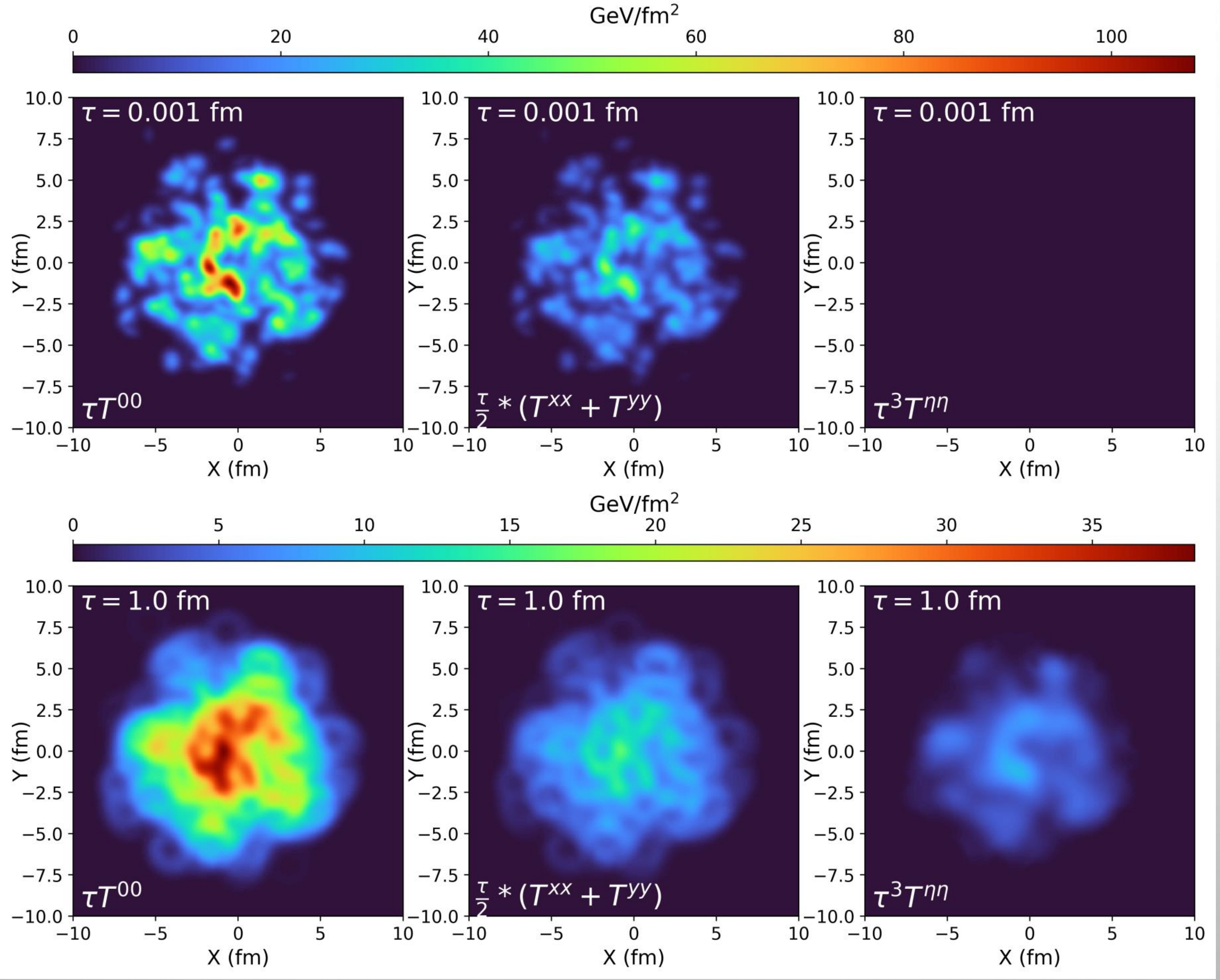
Oscar Garcia-Montero
Poster, Initial State 308

The McDIPPER framework can be used to initialize energy and charge densities in high energy nucleus collisions

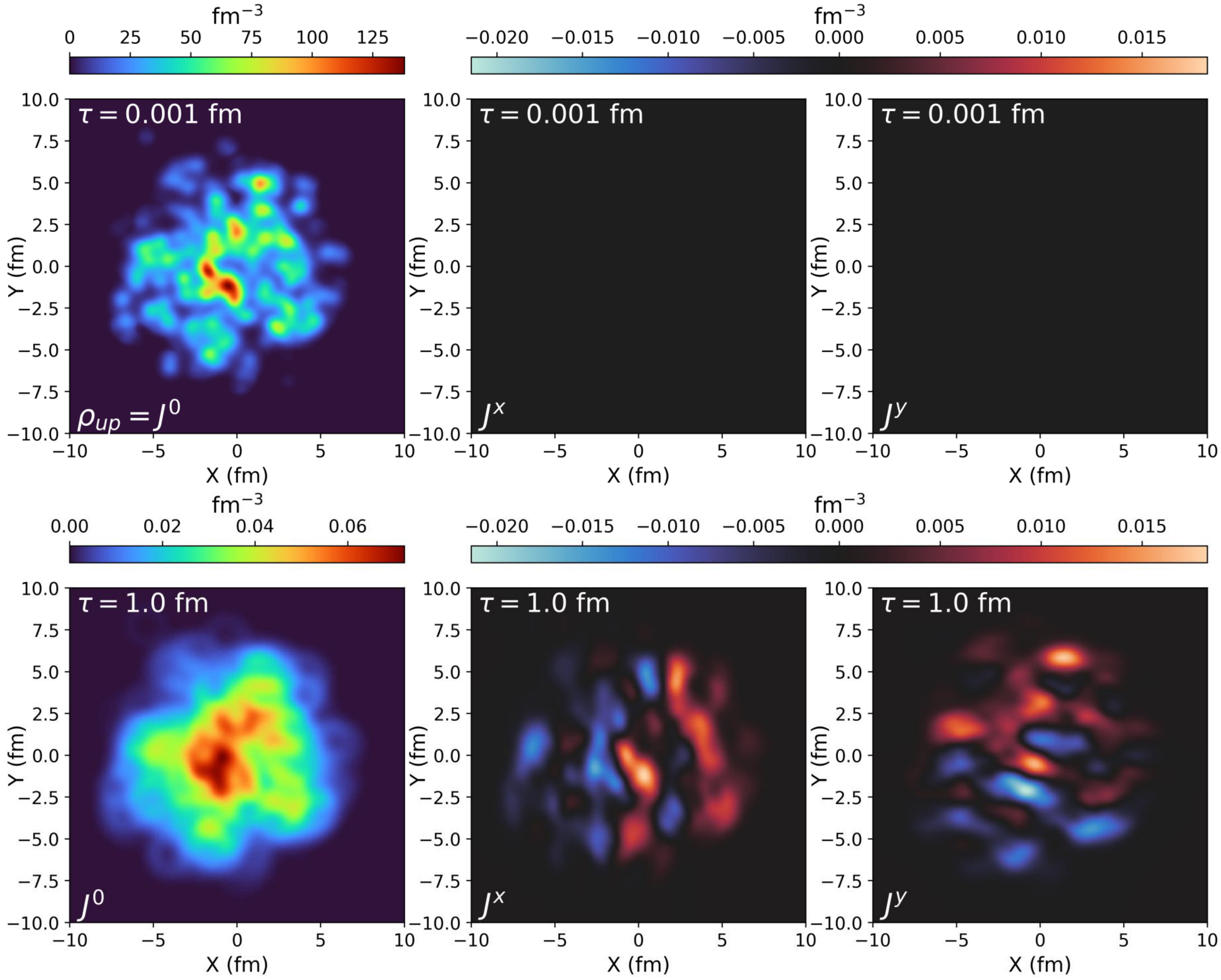
Oscar Garcia-Montero, Hannah Elfner, Sören Schlichting, arXiv2308.11713



KØMPØST EVOLUTION: ENERGY



KØMPØST EVOLUTION: CHARGE



SUMMARY AND OUTLOOK

- IT IS IMPERATIVE TO UNDERSTAND NON-EQUILIBRIUM QCD DYNAMICS IN AS MANY FIRST PRINCIPLE CHANNELS AS POSSIBLE
  - NON-EQ PHOTON PRODUCTION: PHILIP PLASCHKE, EM PROBES, 2:40 PM

- IN THE KØMPØST FRAMEWORK IT IS NOW POSSIBLE TO INCLUDE EVENT-BY-EVENT DYNAMICS OF CONSERVED CHARGES
- NEXT STEPS:
  - HYDRODYNAMIC SIMULATION
  - QCD KINETIC THEORY WITH FINITE CHARGE BACKGROUND
  - (3+1) KØMPØST