EARLY TIME DYNAMICS OF CONSERVED CHARGES IN HEAVY-ION COLLISIONS

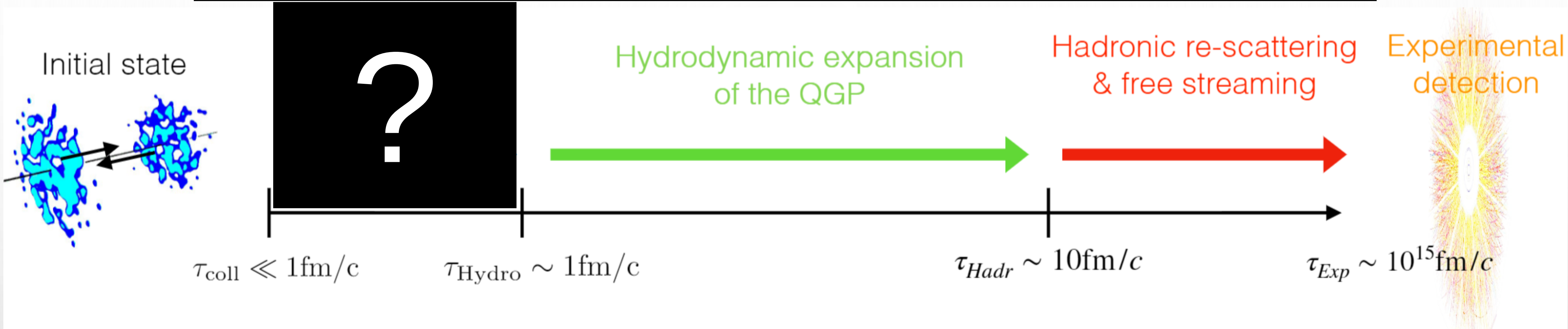
TRAVIS DORE

In collaboration with:
Xiaojian Du and Soeren Schlichting

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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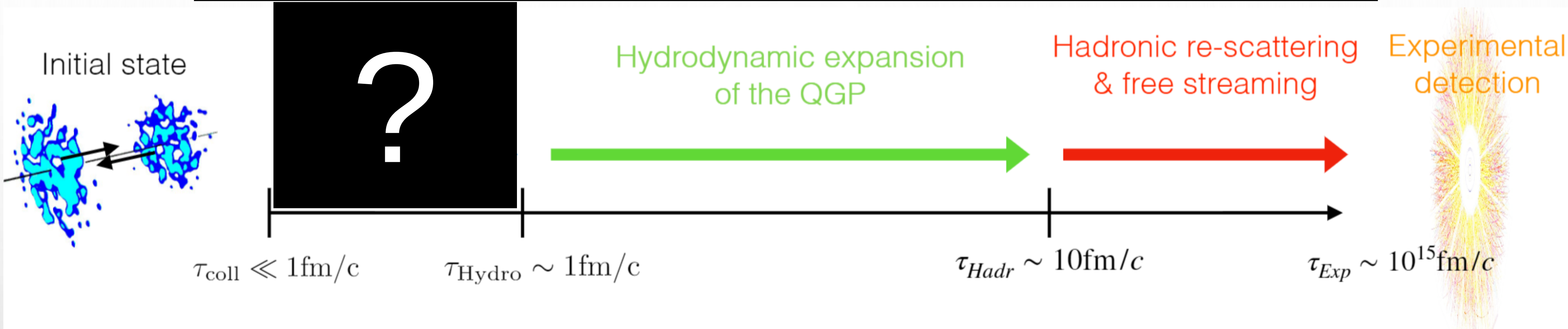

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➢ How to evolve from the non-equilibrium initial state to a hydrodynamic description?

DISTINCT NON-EQUILIBRIUM INITIAL STATE FEATURES

Large pressure anisotropy in the bulk

Vs.

Spatial fluctuations

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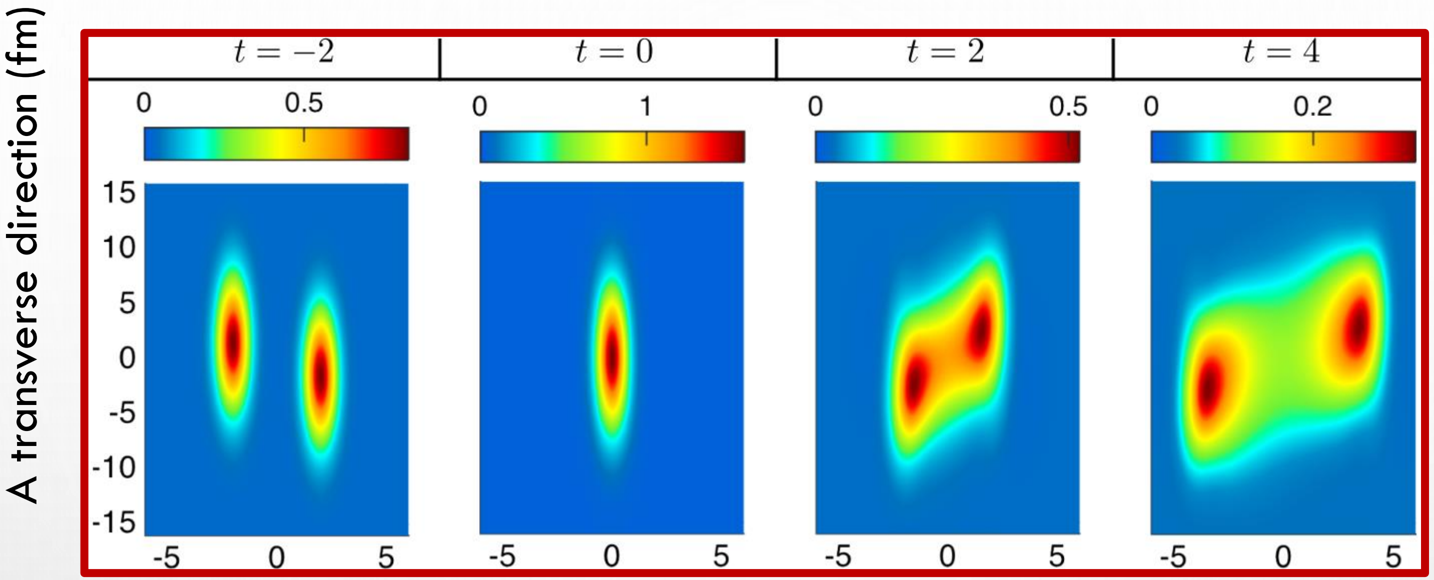

P. Chesler, L. Yaffe, *JHEP* 10 (2015) 070

The beam direction (fm)

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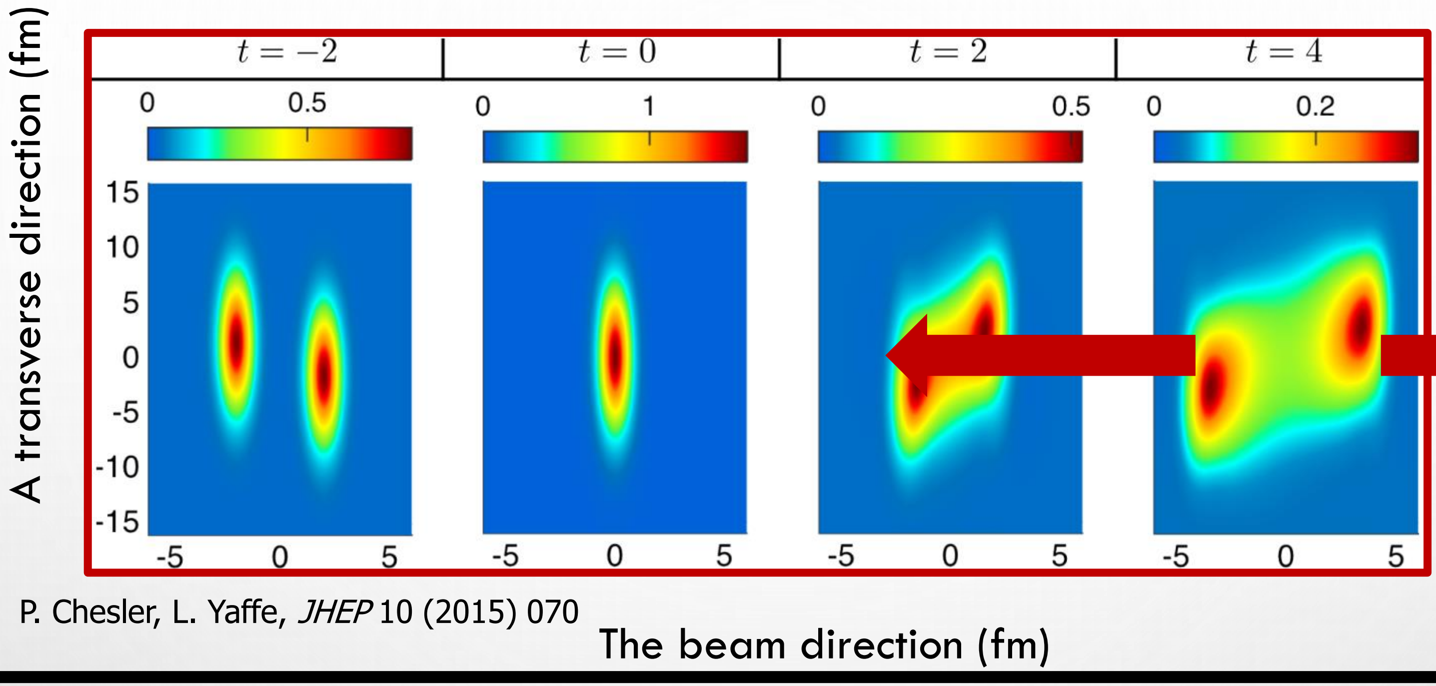

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As compared to..

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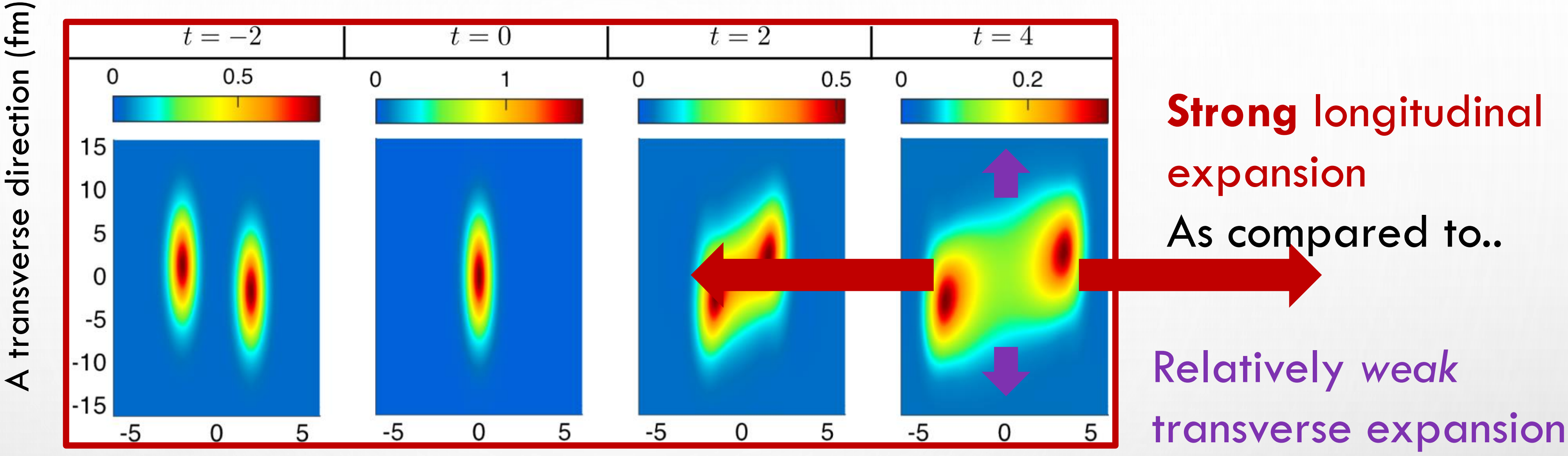

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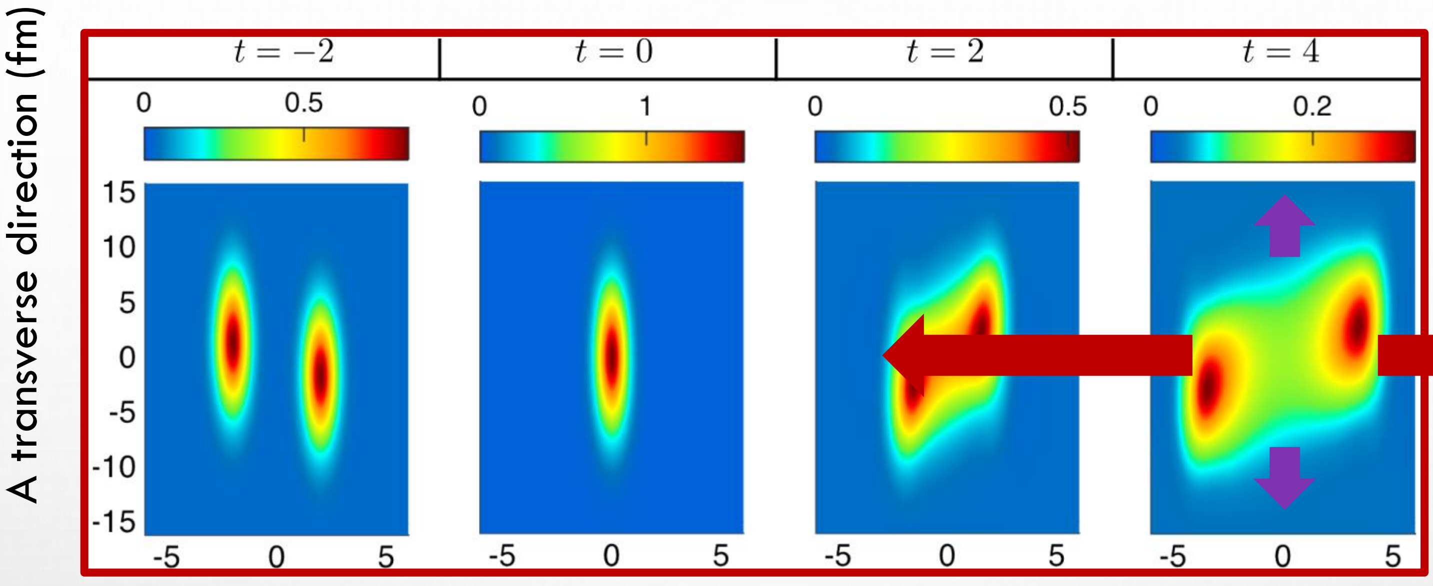

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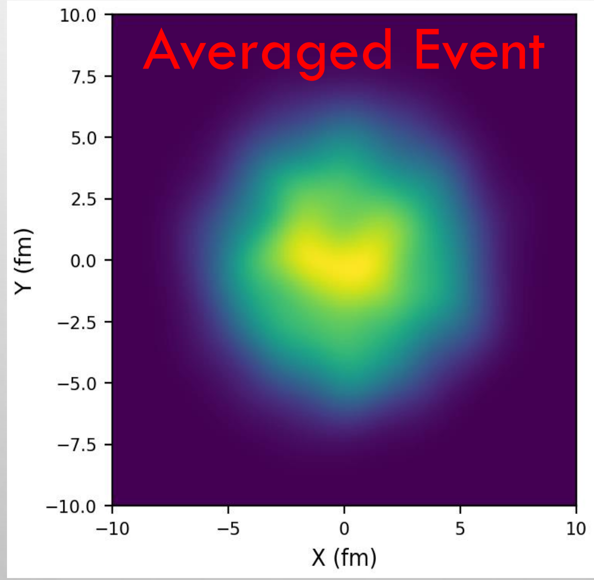

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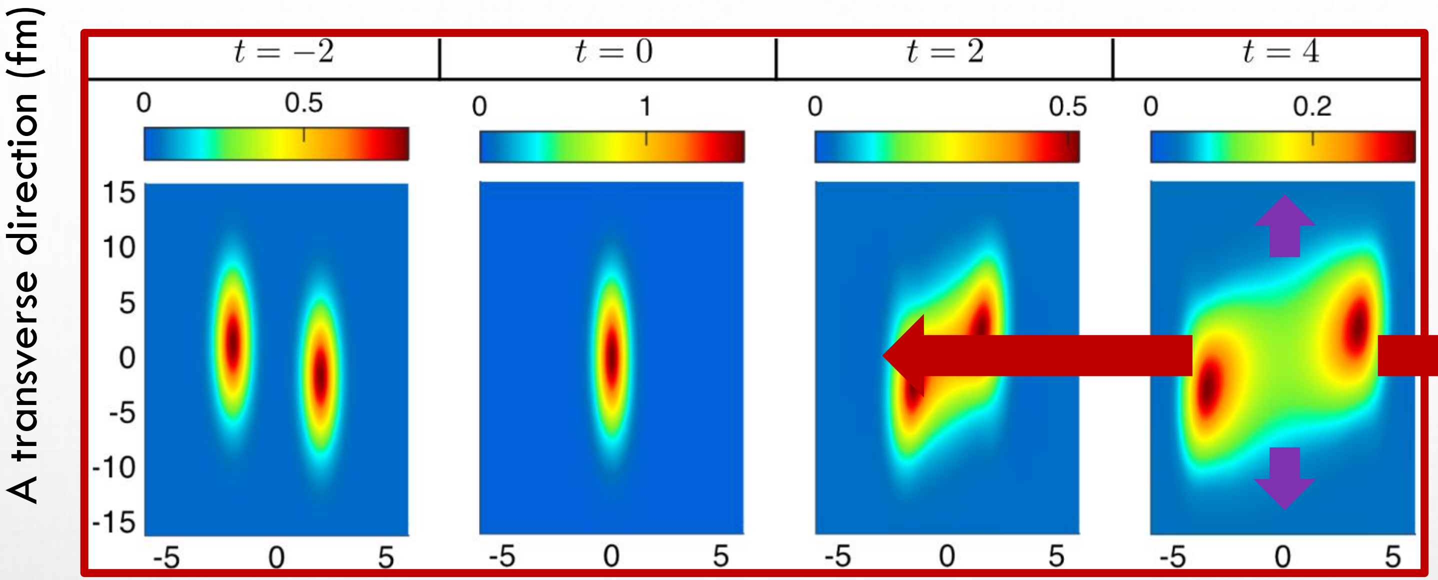

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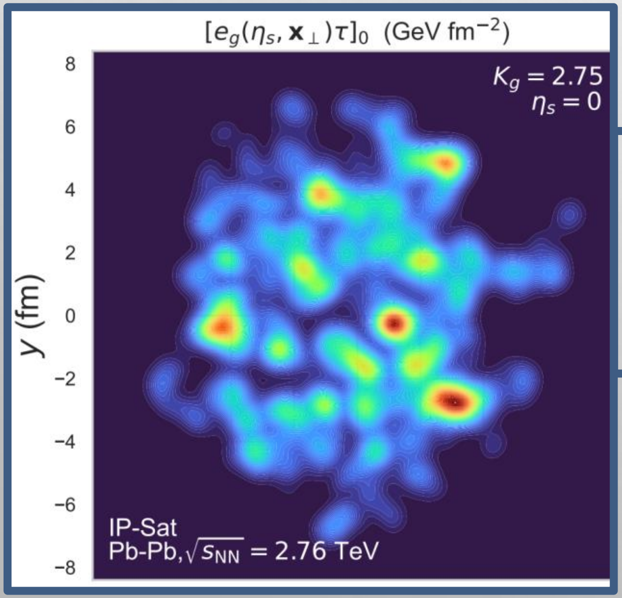
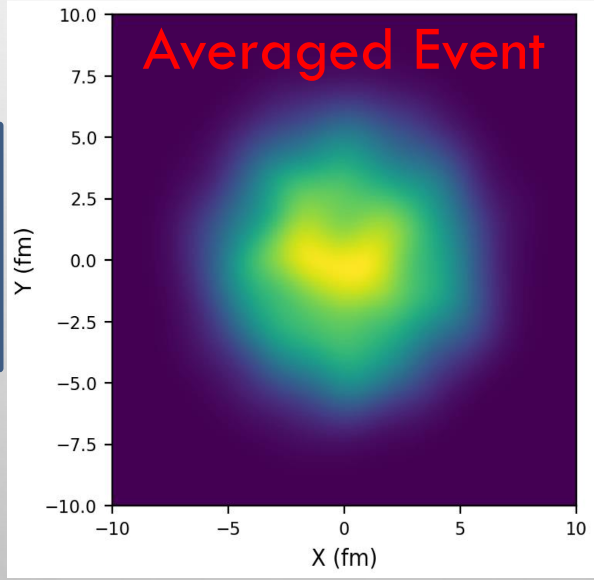


Fluctuations at nucleonic scale



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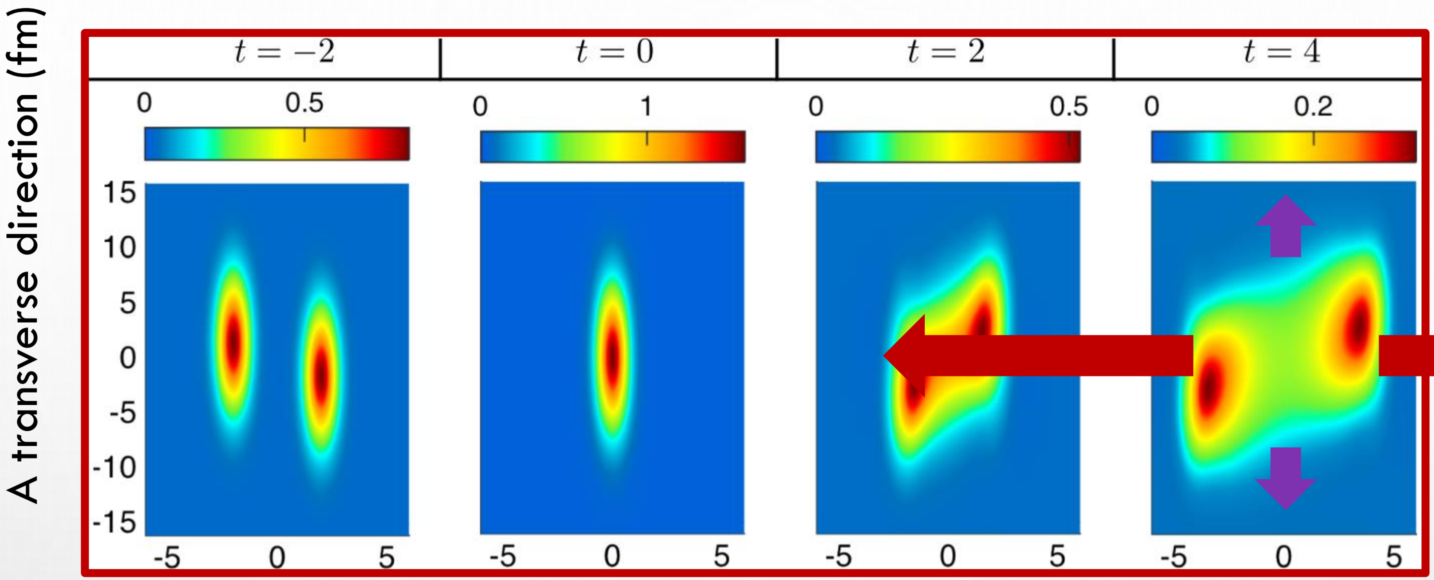

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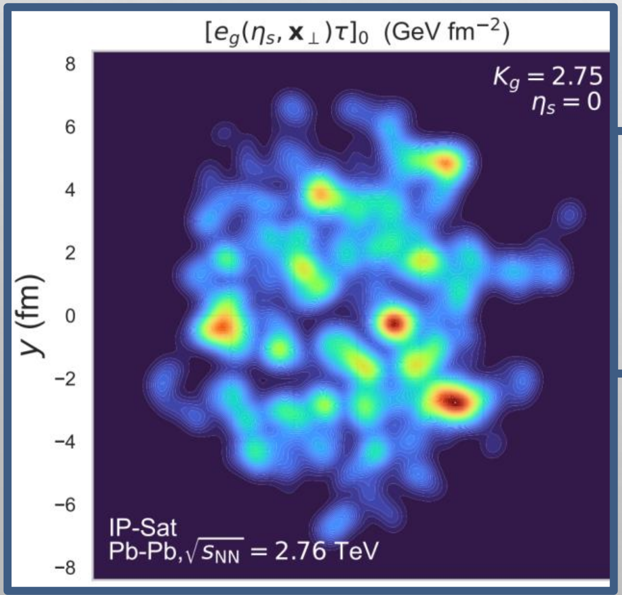

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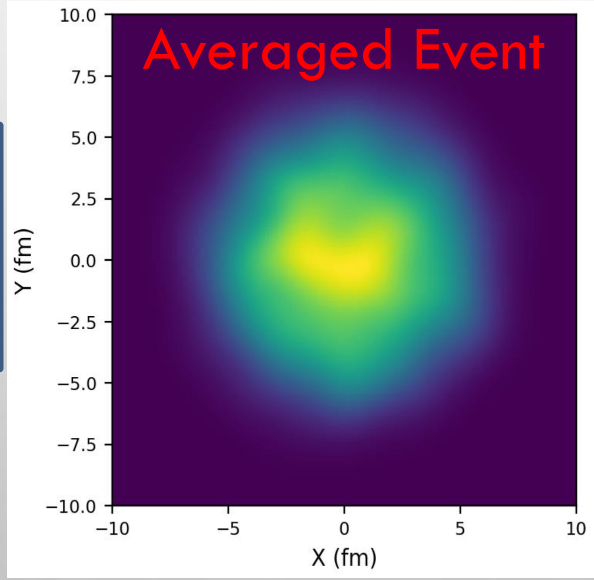
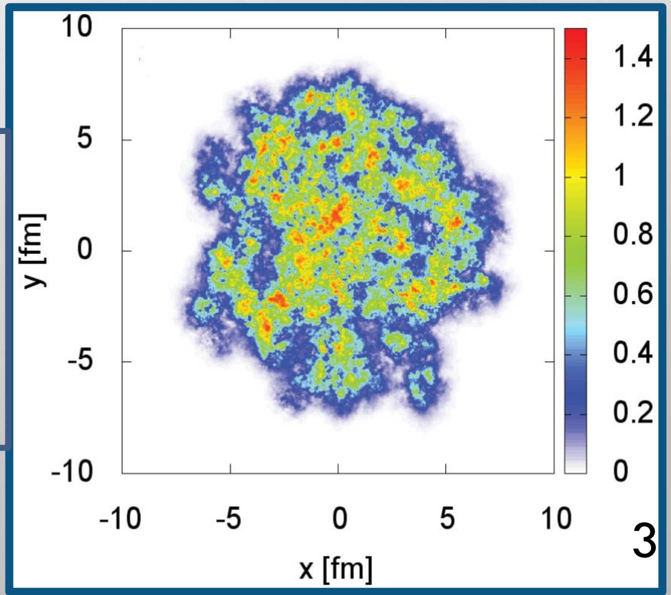
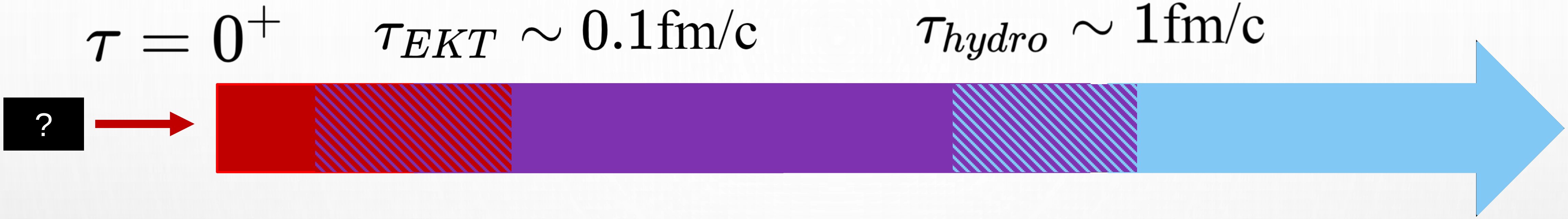


Fluctuations at sub-nucleonic scale

S. Schliching, B. Schenke Phys.Rev.C 94 (2016) 4, 044907



INITIAL STATE TO HYDRO: PHYSICAL CONNECTIONS



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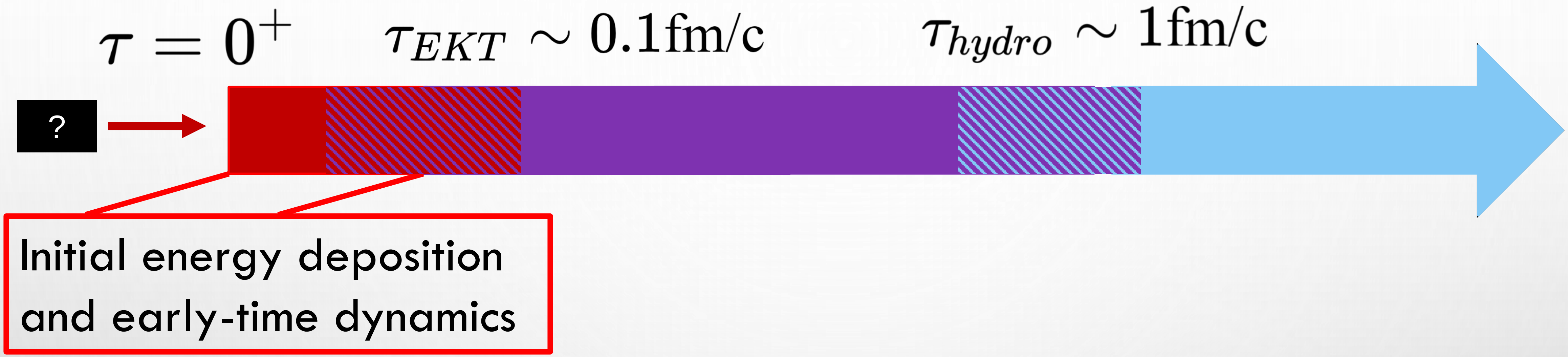

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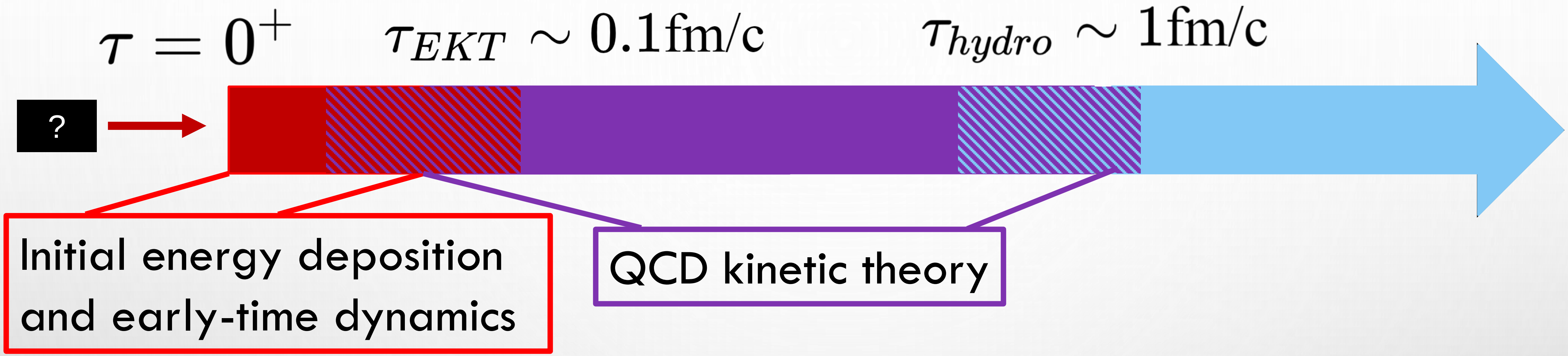

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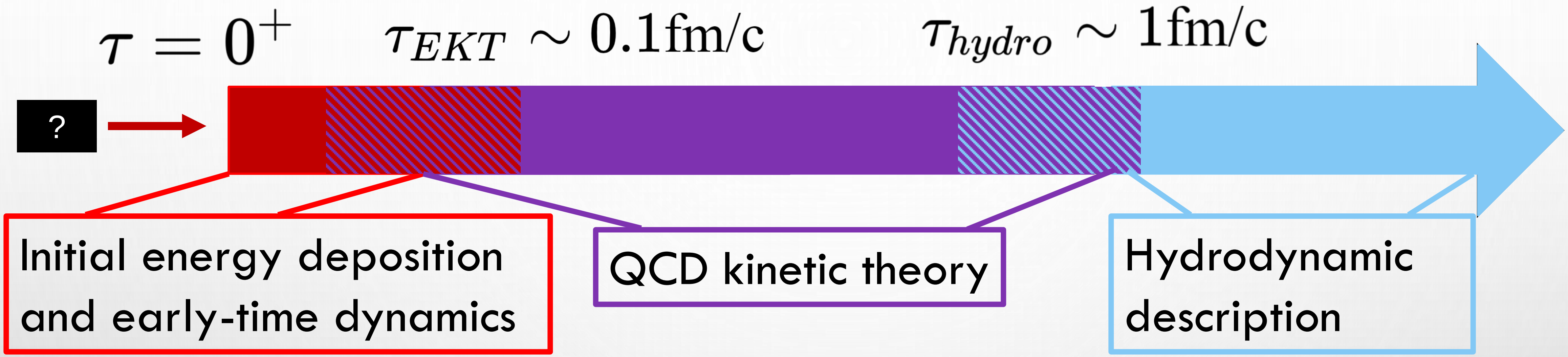

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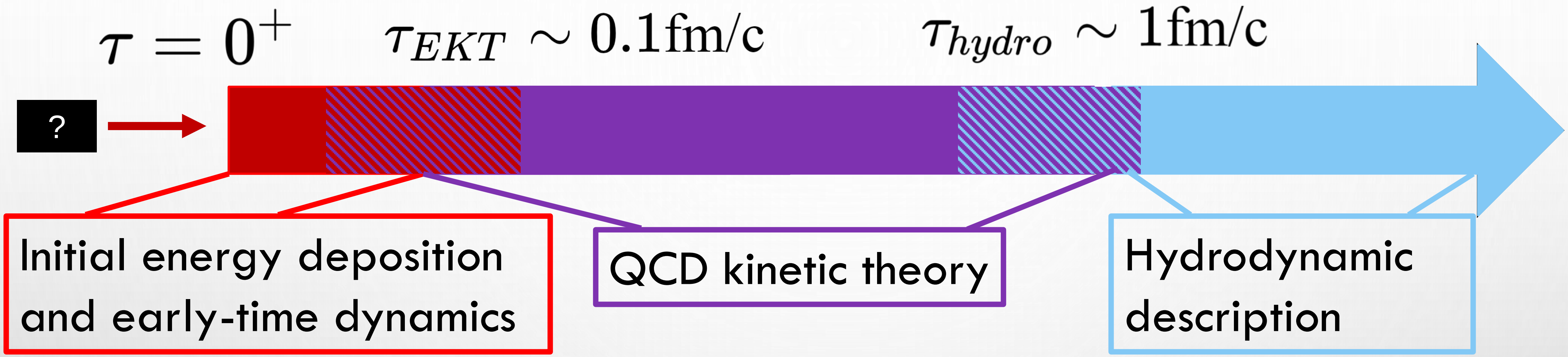

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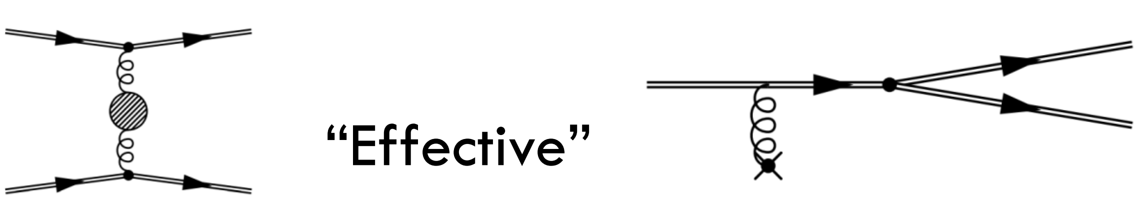

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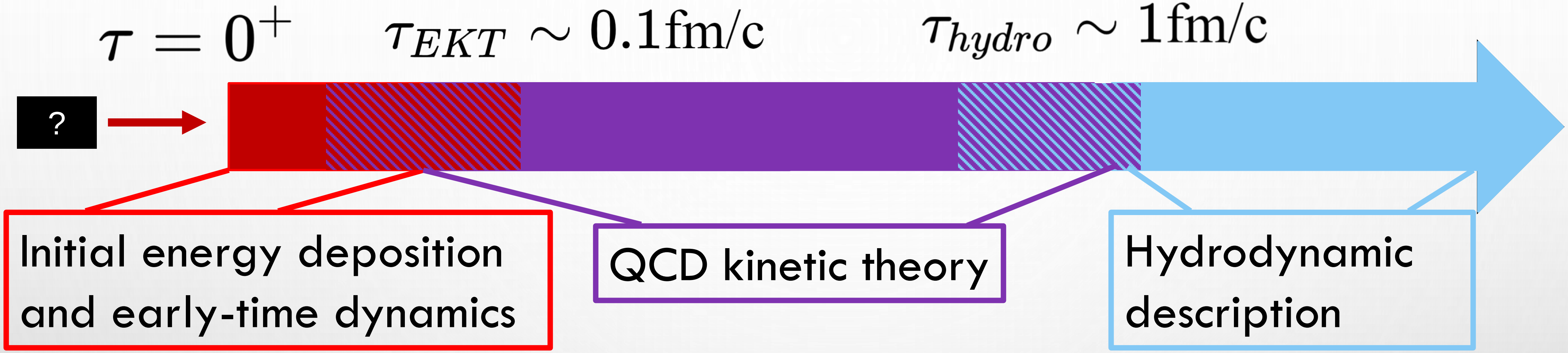

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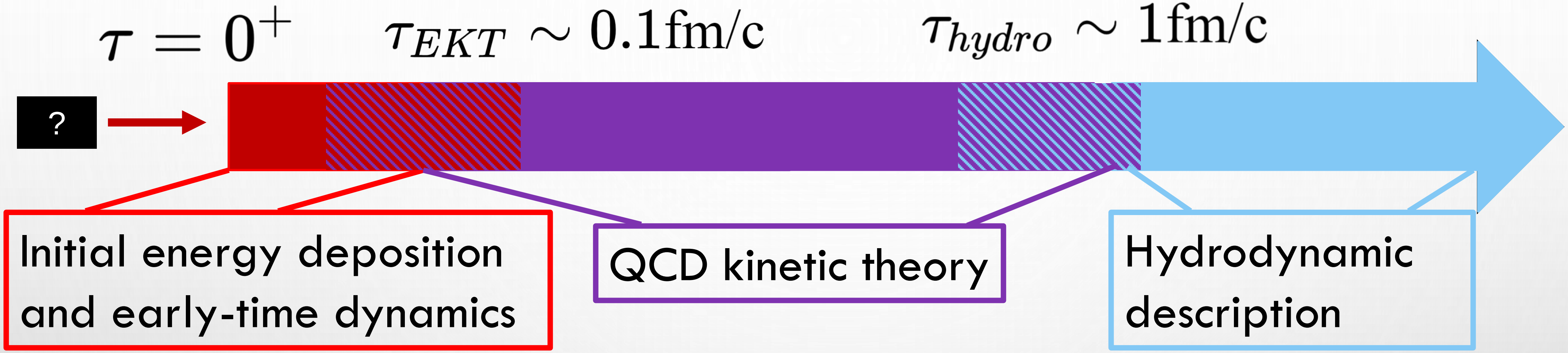

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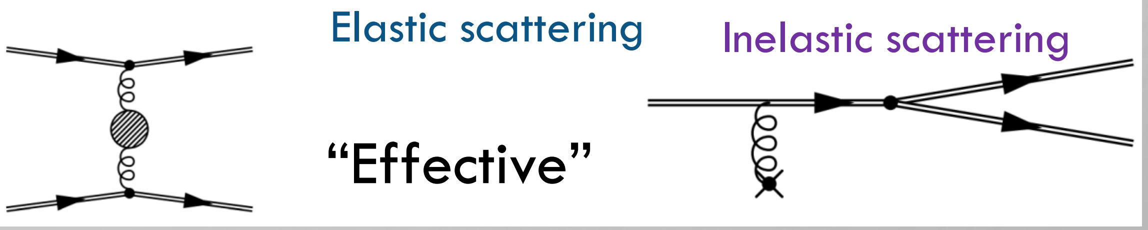

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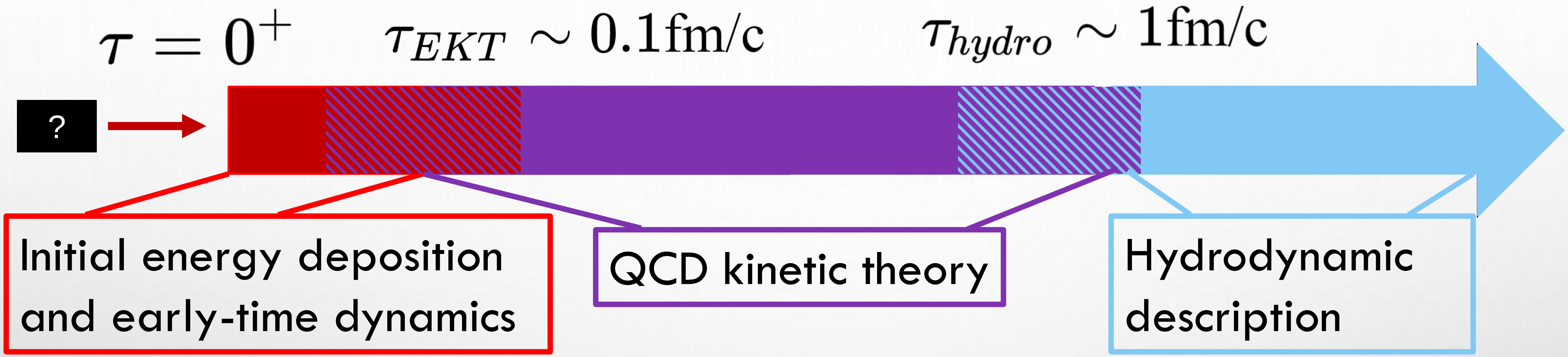

Overlap in validity offers less sensitivity for switching times

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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
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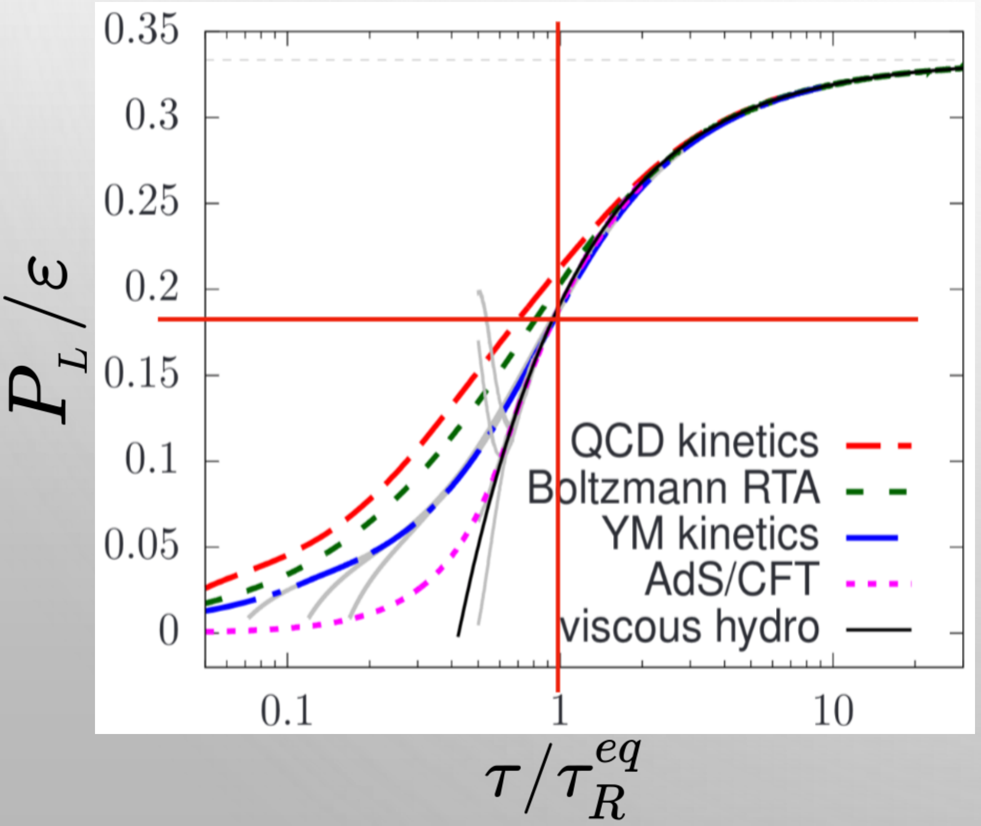

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$$\tau_R^{eq}(\tau) = \frac{4\pi\, \eta/s}{T_{eff}(\tau)}$$

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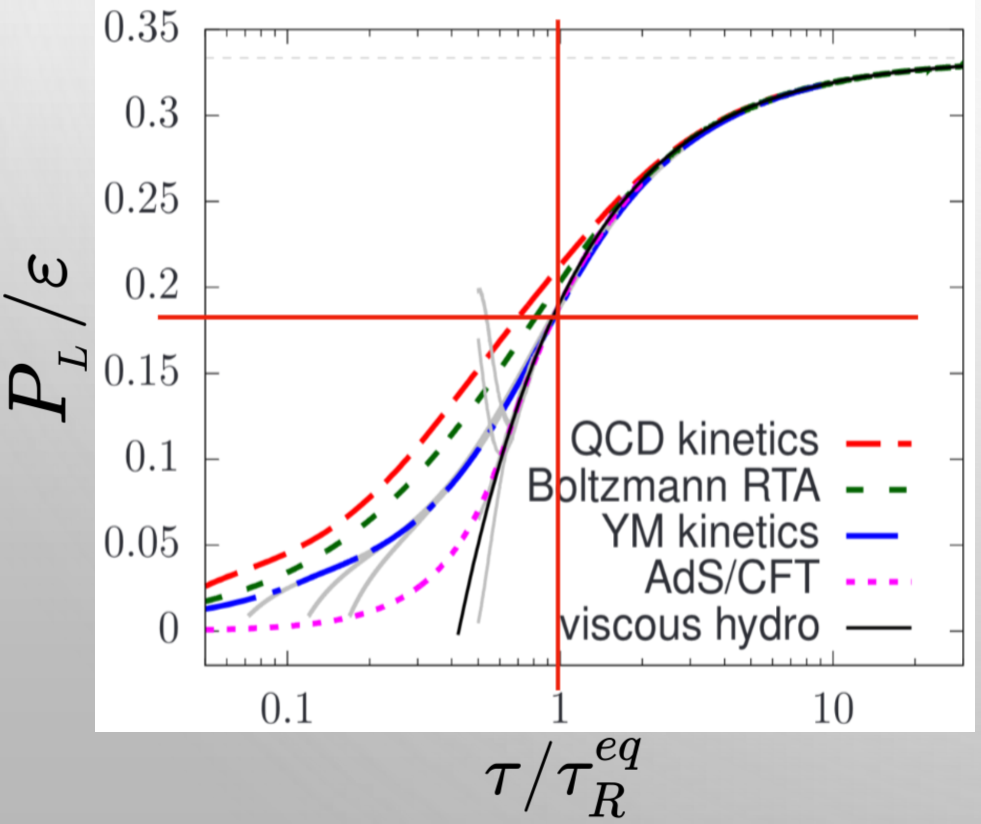

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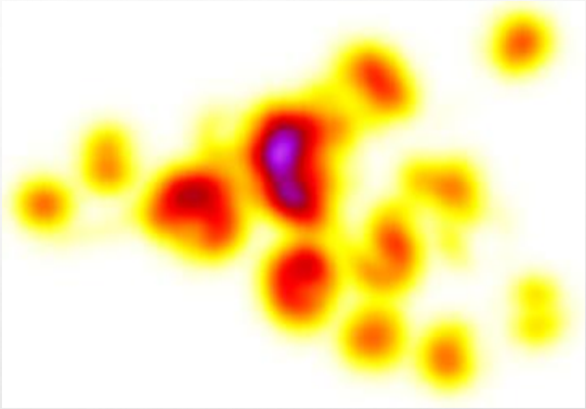
Hydrodynamization for inhomogeneous systems



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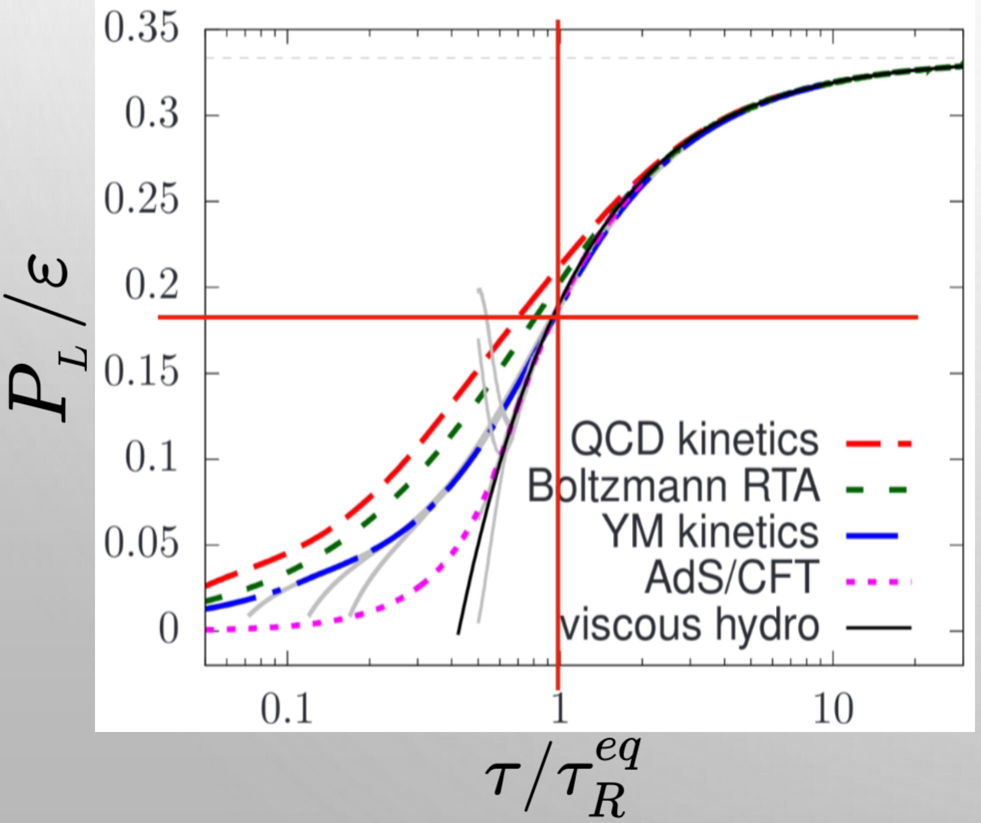

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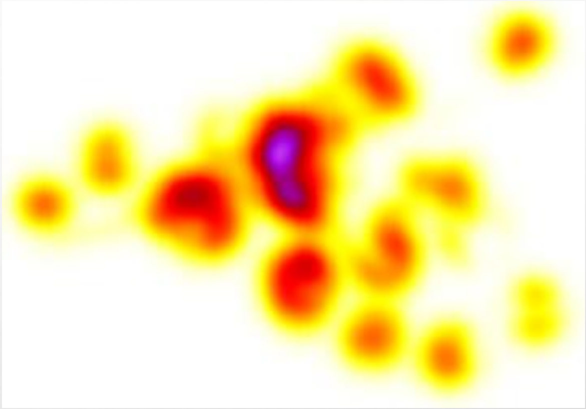

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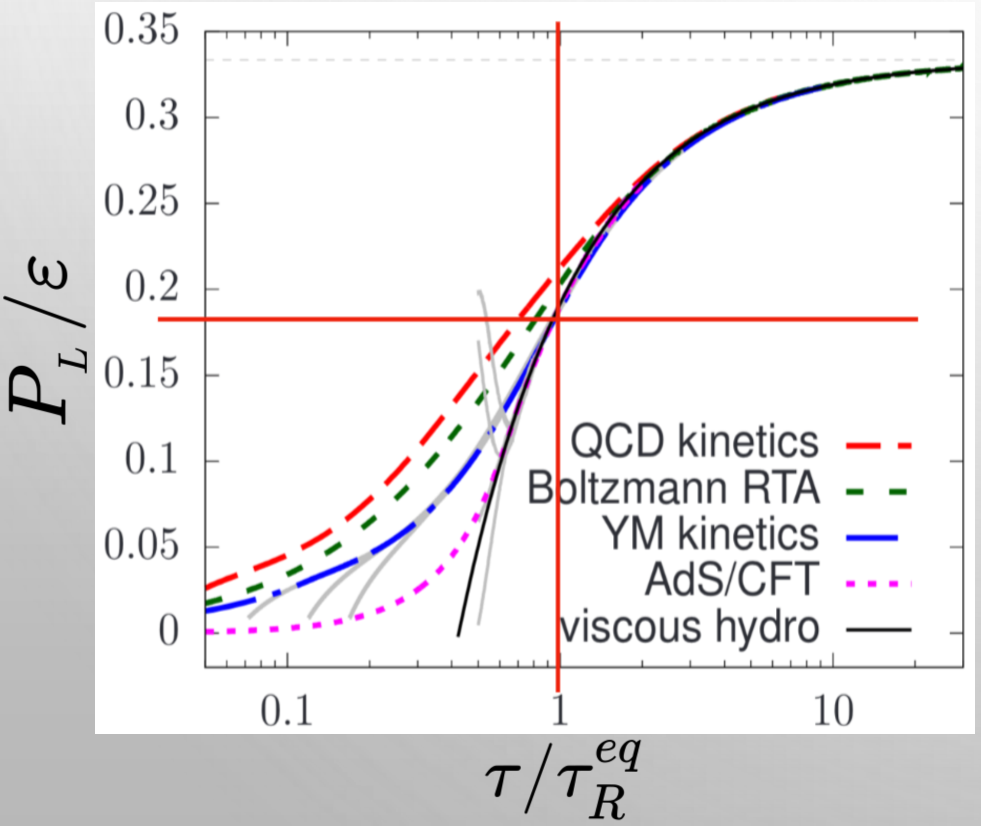

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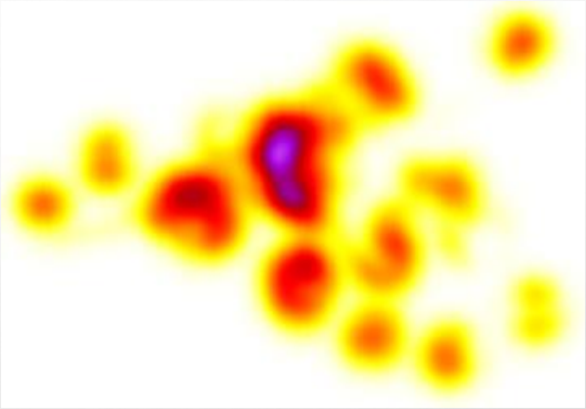
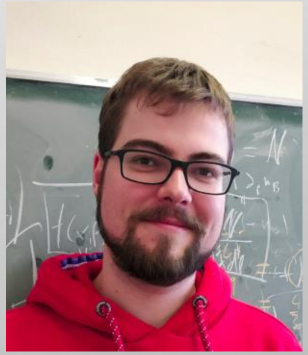


Two approaches:

1) Full kinetic theory and quantification in (2+1) scenario, see talk from **Clemens Werthmann** right before coffee break



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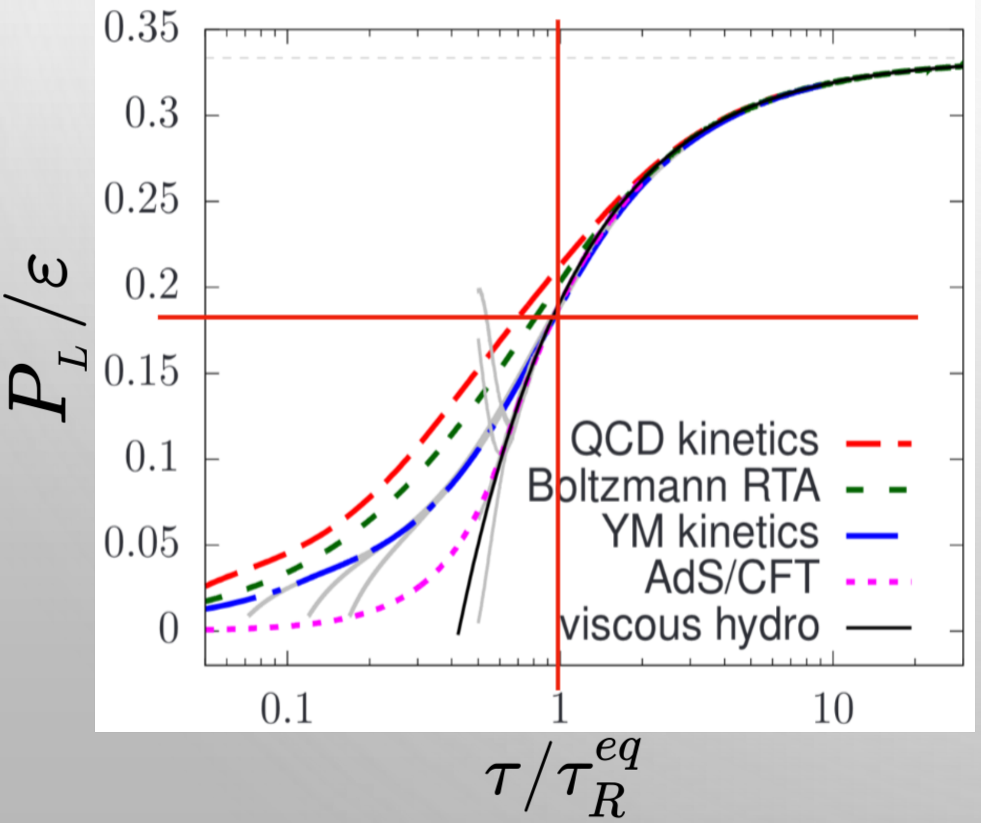

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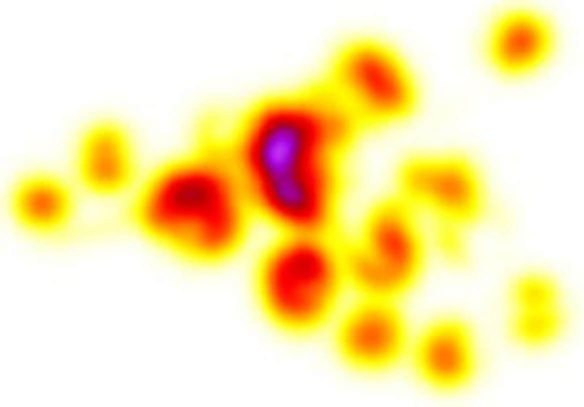

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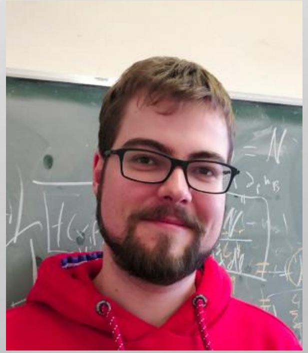
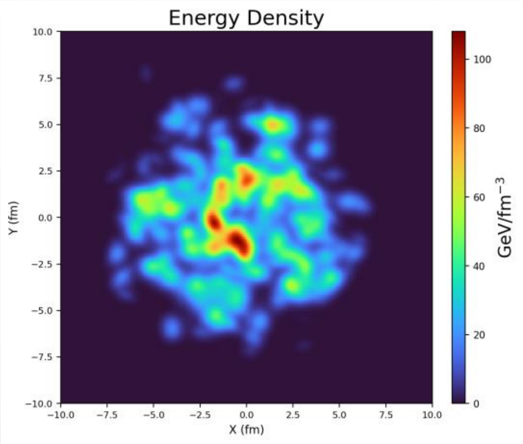


2) Treat inhomogeneities as fluctuations on a locally symmetric background: **KøMPøST framework**

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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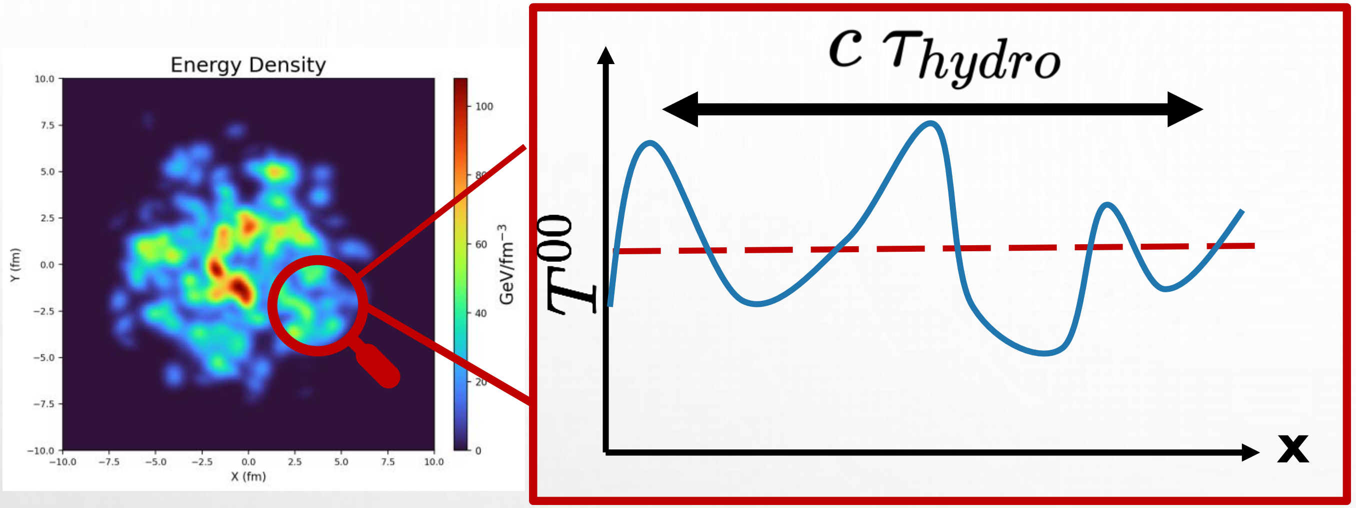

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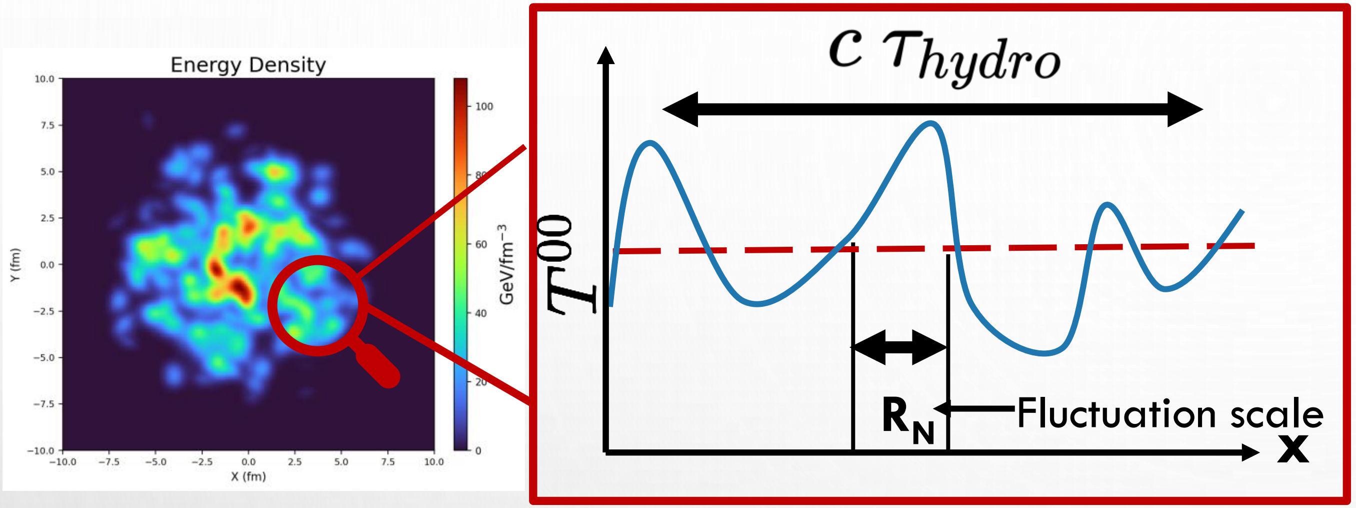

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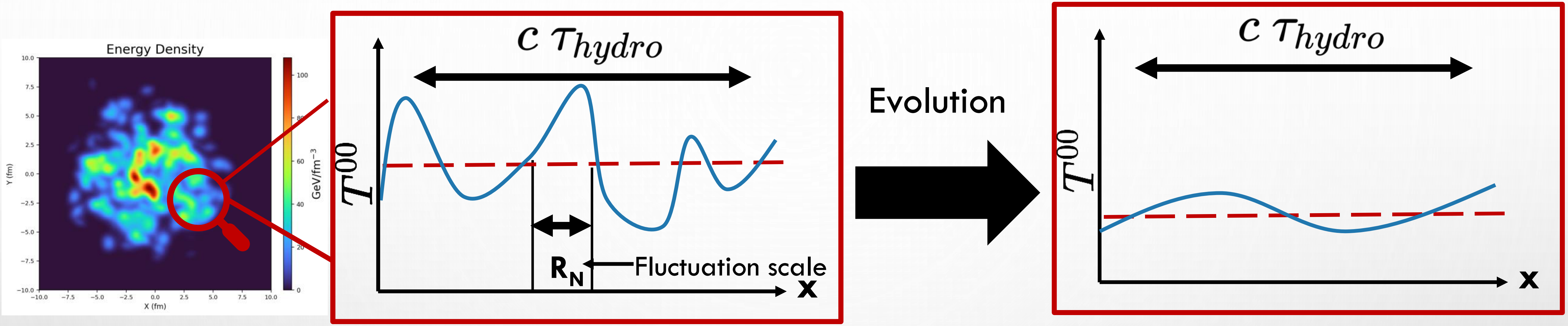

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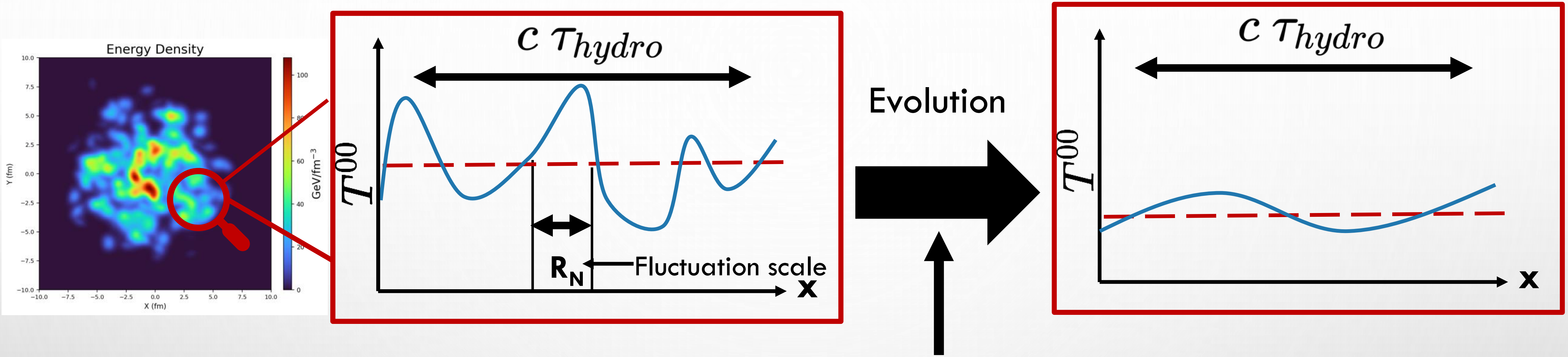

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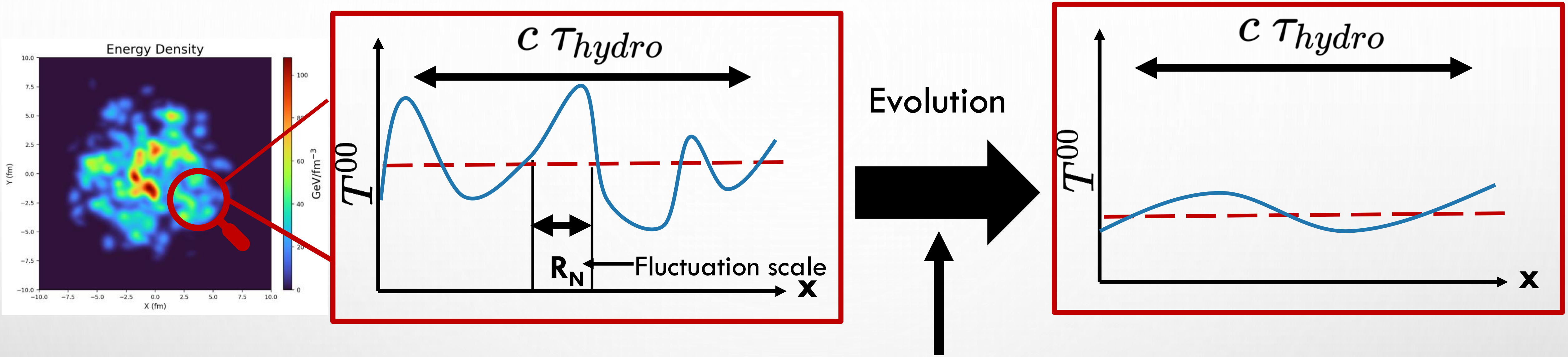

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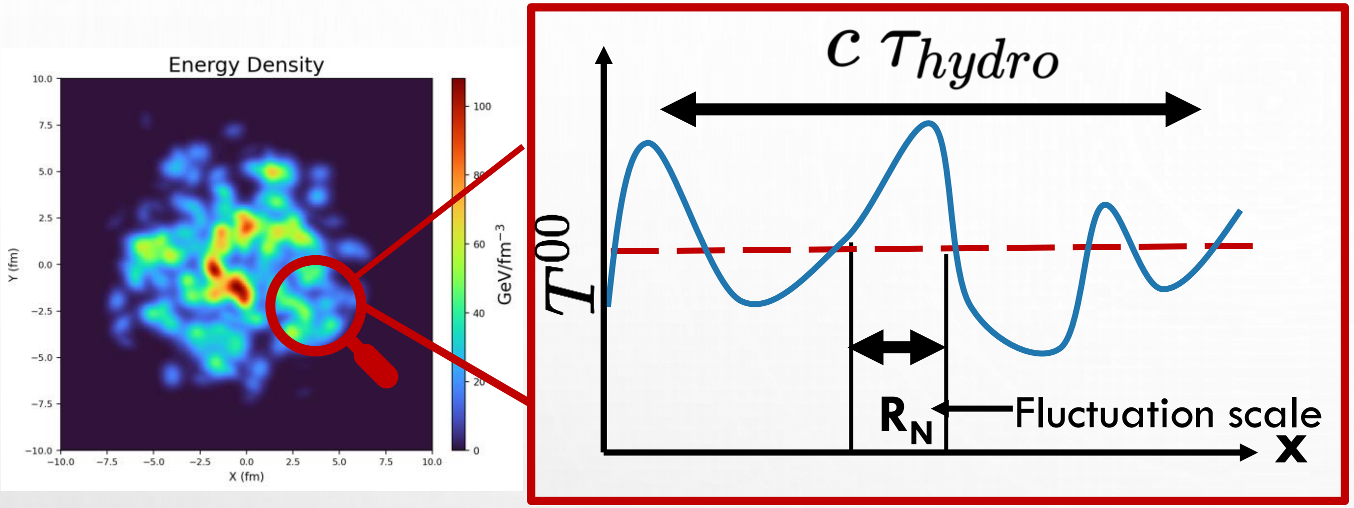

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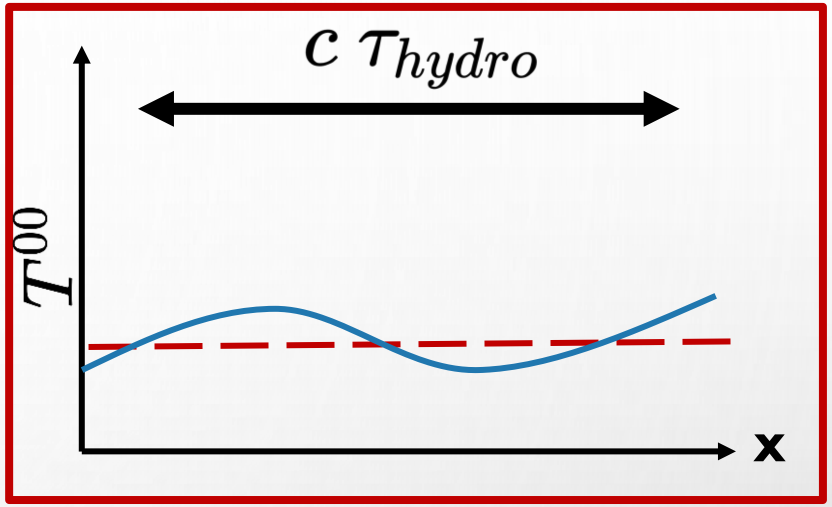

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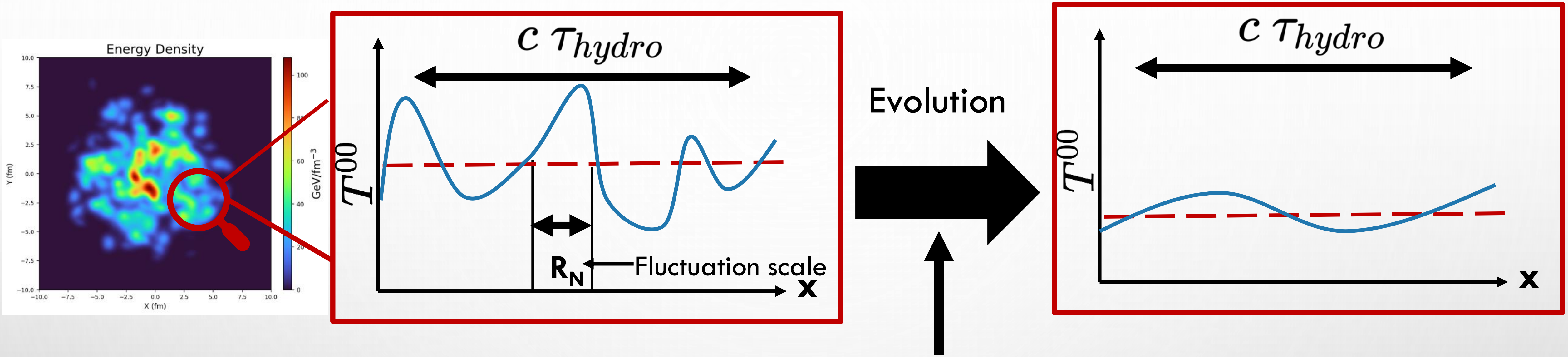

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- ***Generic framework for any microscopics*:**
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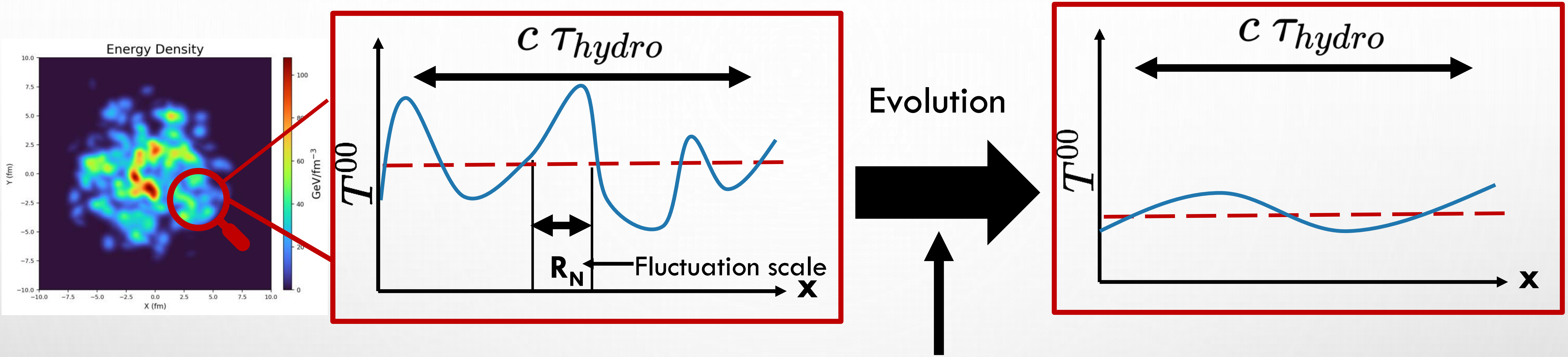

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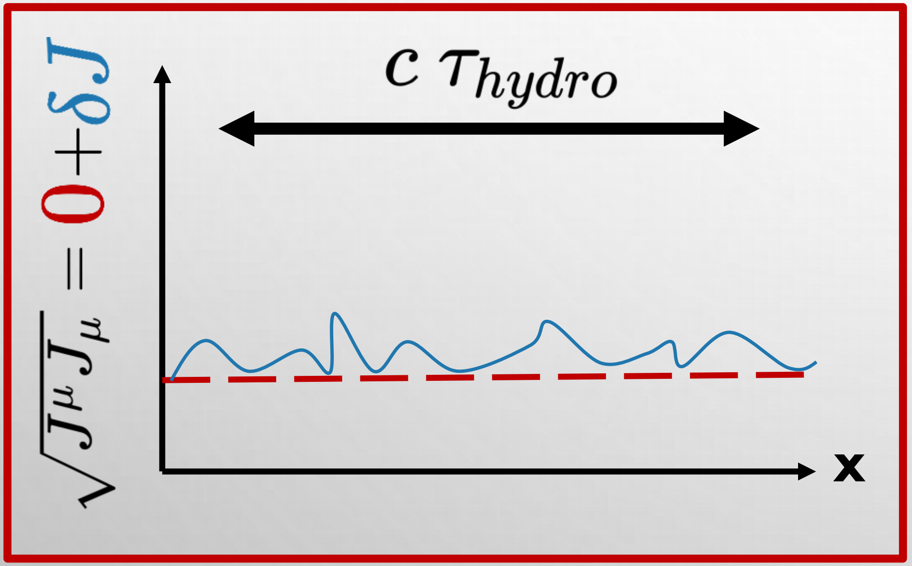
- In this work we use QCD kinetic theory with conserved charges

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

ADDING CONSERVED CHARGES

First step: zero charge background

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



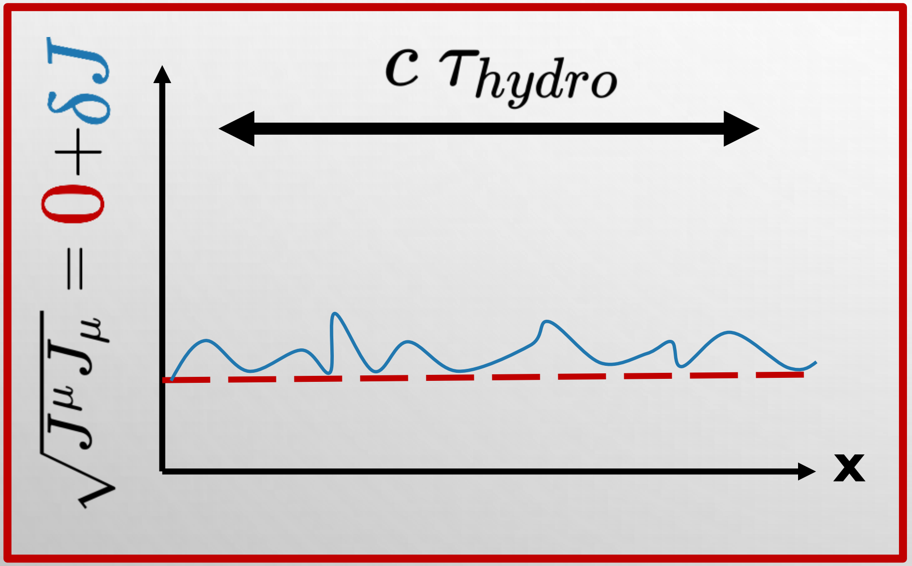
By expanding off a vanishing density background, light quarks can be treated with the same response functions without density dependence

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

ADDING CONSERVED CHARGES

First step: zero charge background

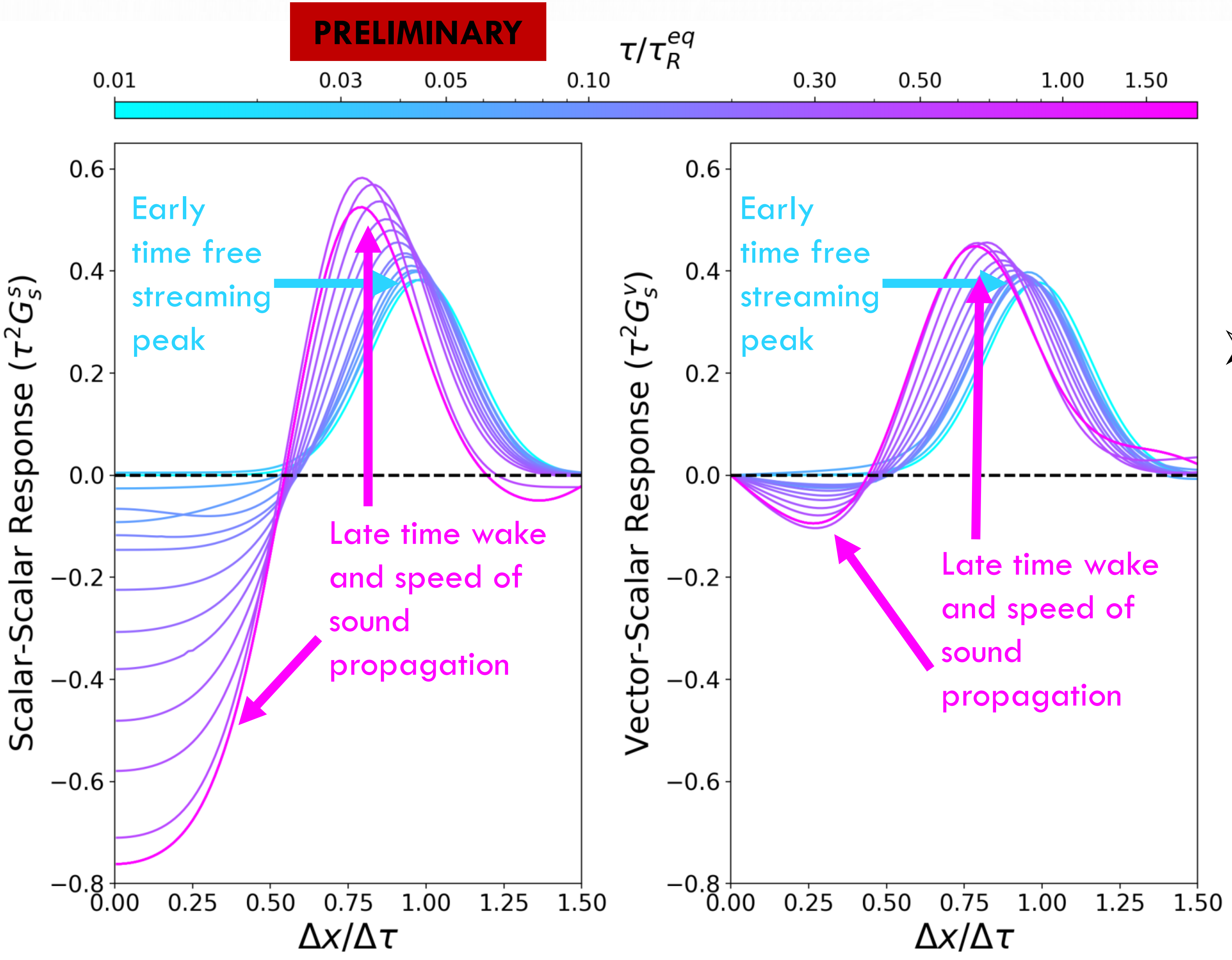
$$J^\mu(\tau, x) = \ 0 \ + \int_\circ F^\mu_\alpha(\tau_0, \tau, x_0, x)\delta J^\alpha(\tau_0, x_0)$$



By expanding off a vanishing density background, light quarks can be treated with the same response functions without density dependence

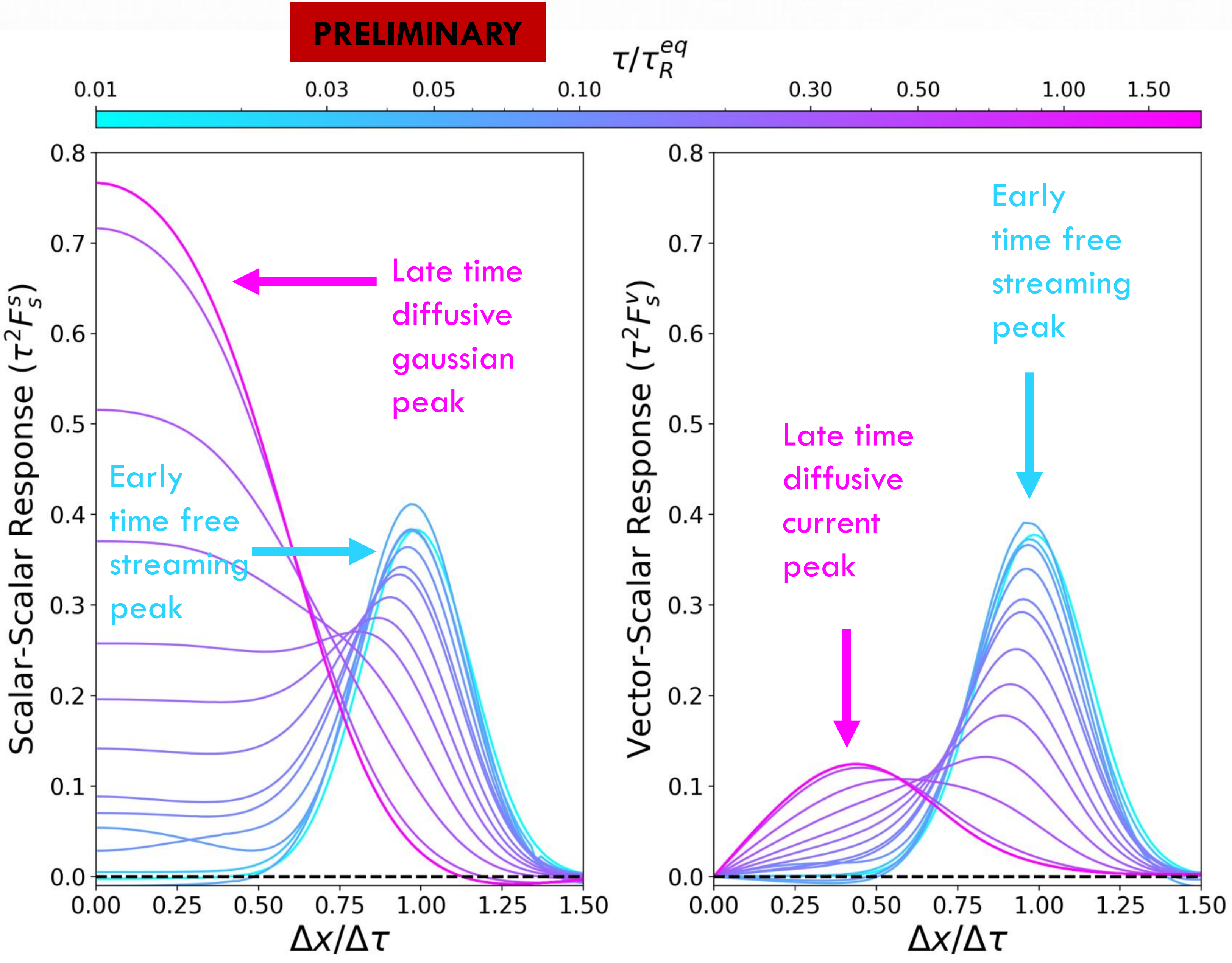
What do these response functions look like?

ENERGY RESPONSE FUNCTIONS

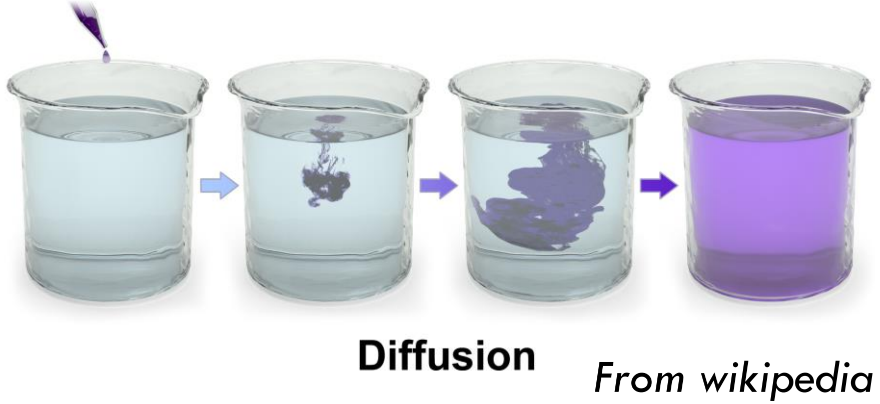


- Response functions give information on *redistribution* of quantities at a given τ/τ_R^{eq}
  - Scalar-Scalar: energy density redistribution
  - Vector-Scalar: change of transverse flow
- From free streaming to wakes and wave fronts with speed of sound propagation

CHARGE RESPONSE FUNCTIONS: DEGENERATE LIGHT QUARKS

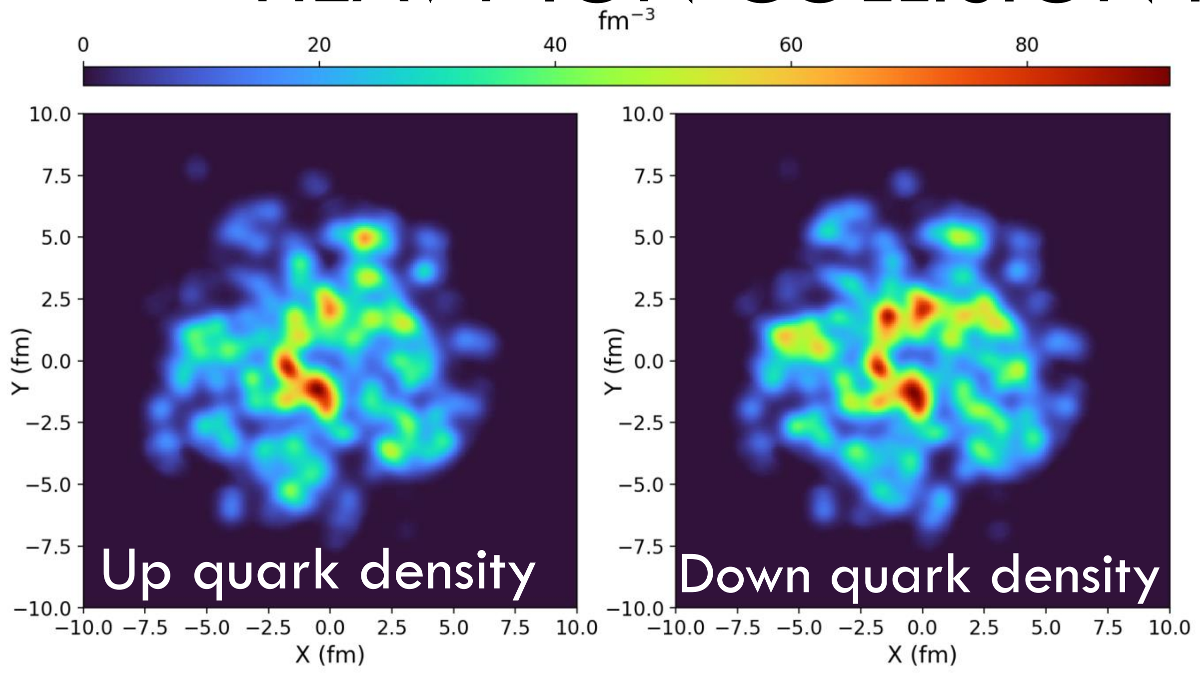


- *Redistribution* of quantities at a given τ/τ_R^{eq}
  - Scalar-Scalar: charge density redistribution
  - Vector-Scalar: change of charge current, $n^\nu \sim \nabla^\nu\left(\frac{\mu}{T}\right)$
- From free streaming to diffusive behavior

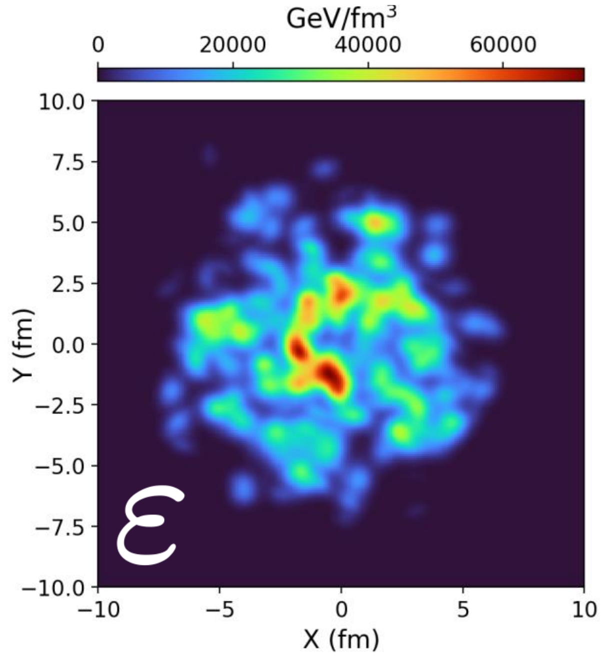


From wikipedia

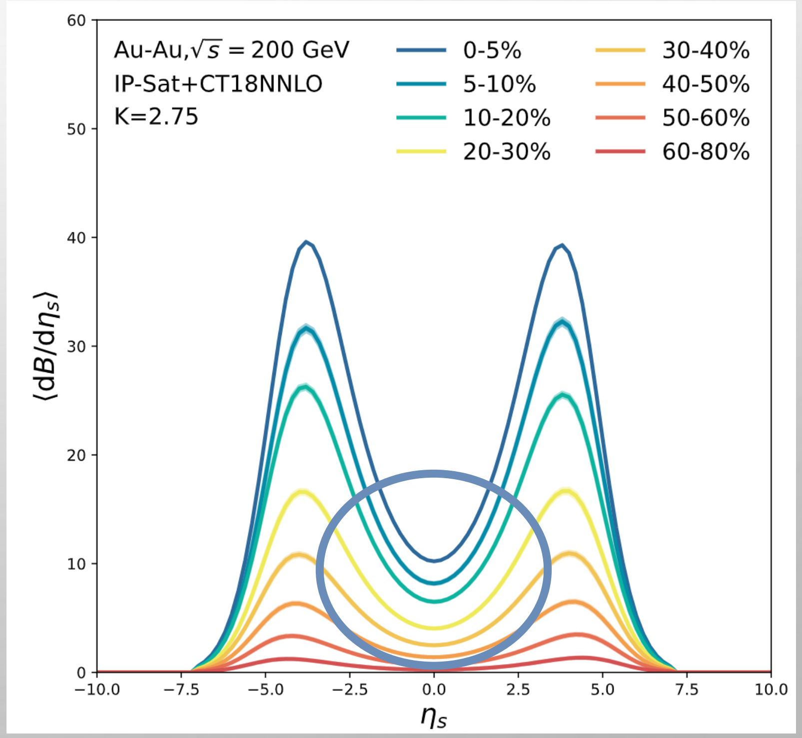
HEAVY ION COLLISION INITIAL STATE WITH CHAGES



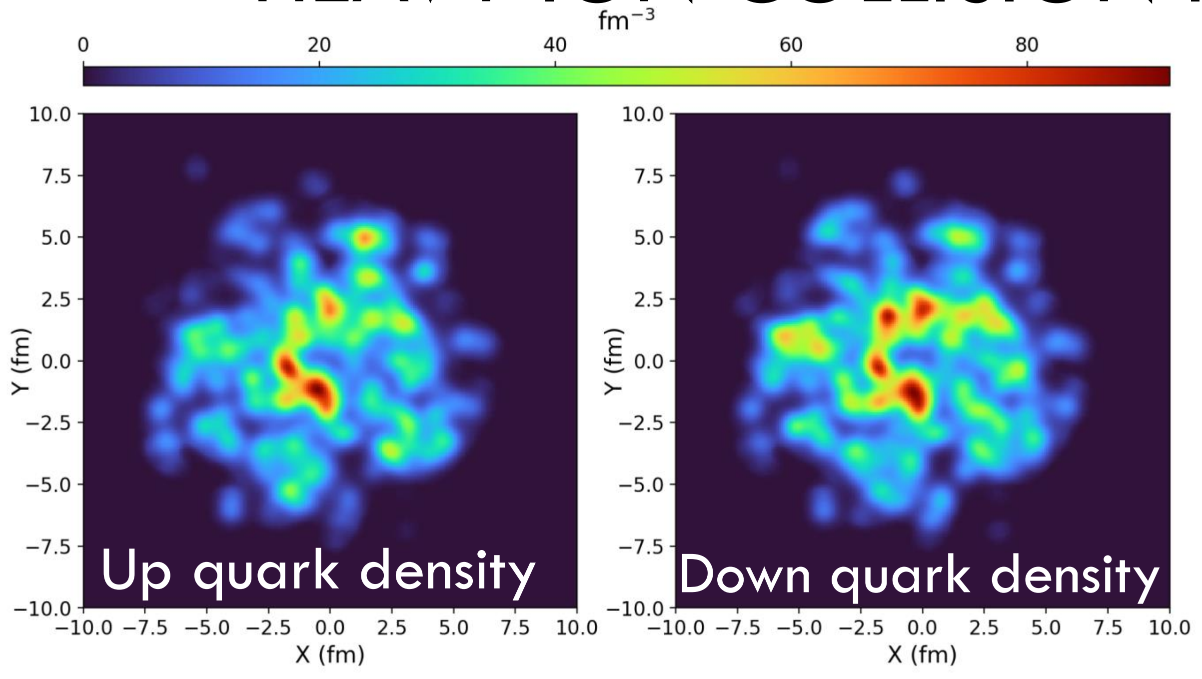
In reality, the baryon density deposited at high energies is not vanishing!



The rapidity distribution of baryon density and energy density can be calculated in an IP-Sat model and is non-zero at mid rapidity!

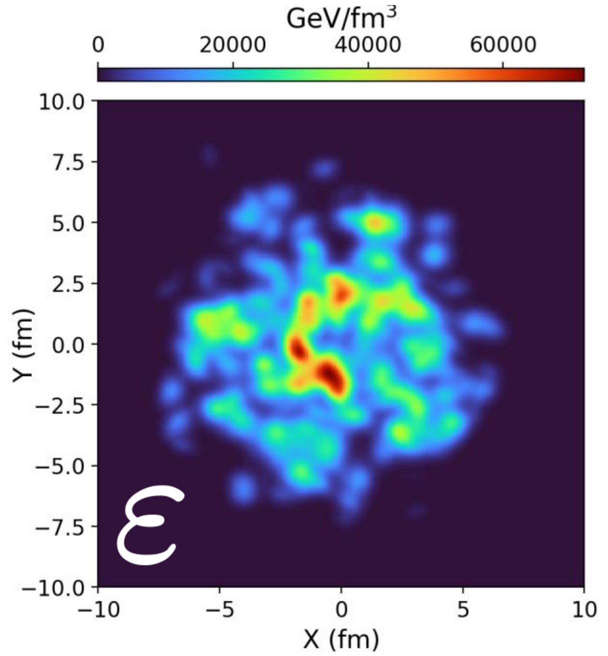


HEAVY ION COLLISION INITIAL STATE WITH CHAGES



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

Oscar Garcia-Montero
Wednesday, 14:00 *Early-time dynamics*



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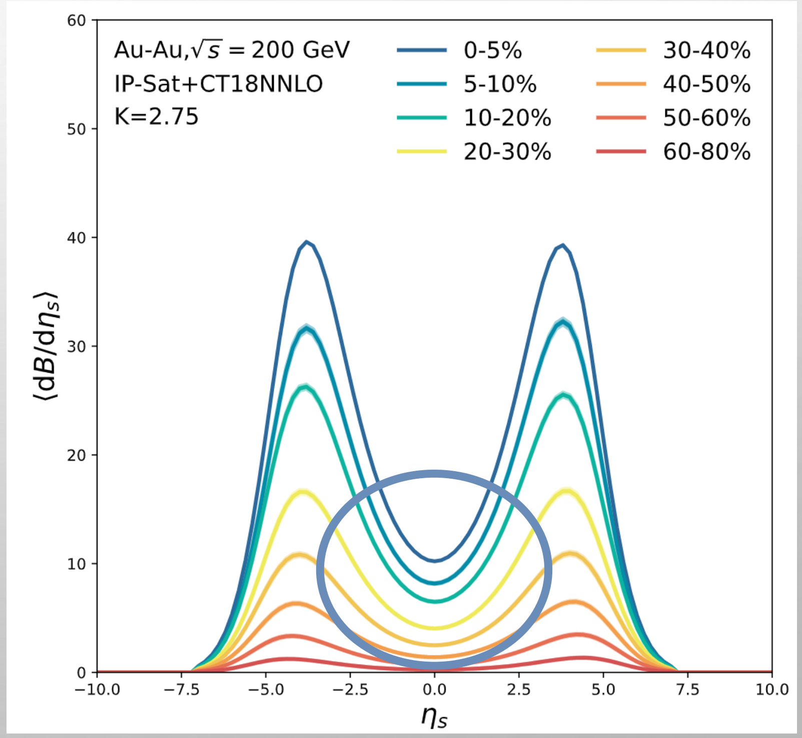
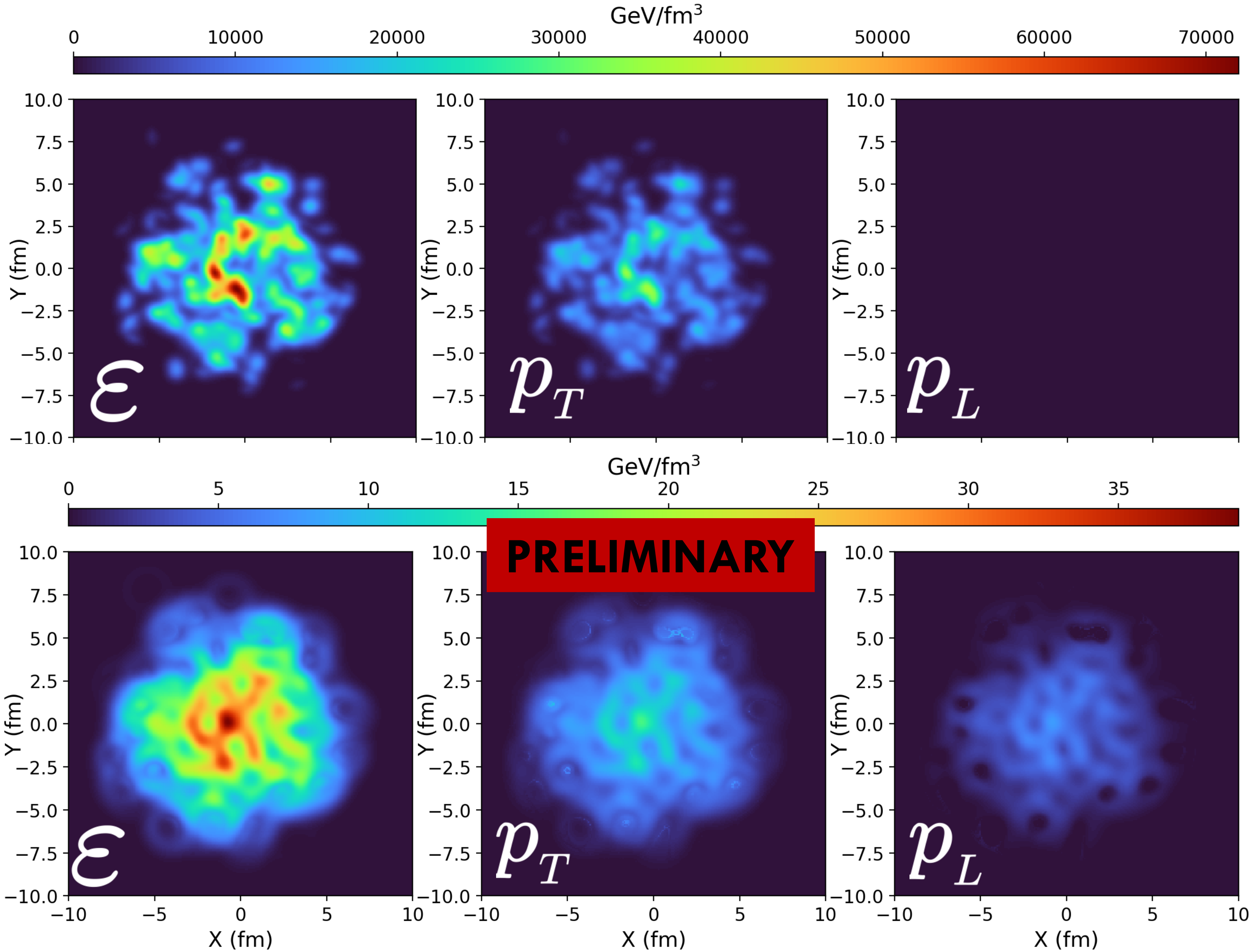


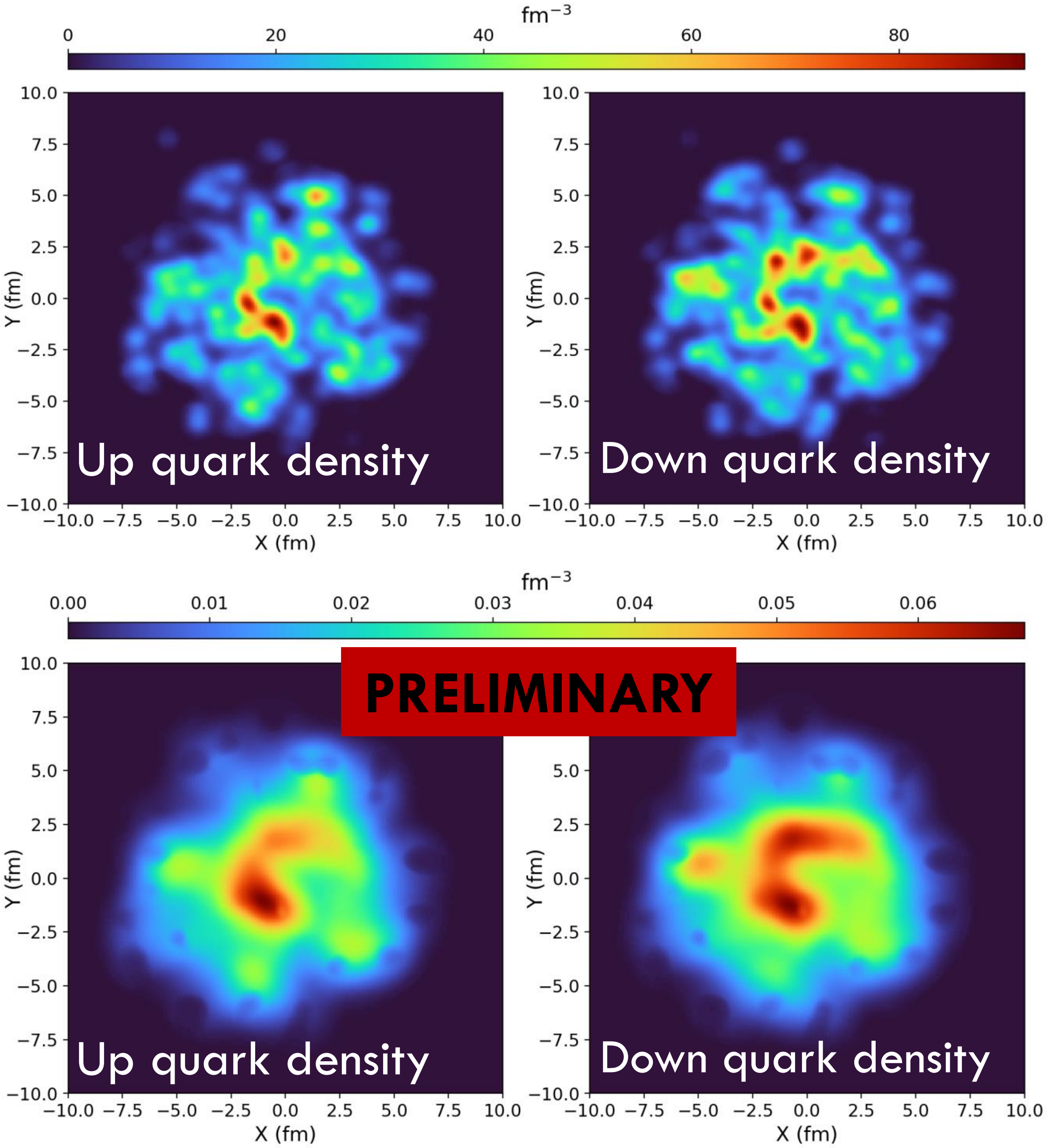
KØMPØST EVOLUTION: ENERGY



$\tau_0 = 0.0015$

$\tau_{hydro} = 1.2005$

KØMPØST EVOLUTION: CHARGE



$$\sqrt{J^{\mu} J_{\mu}}$$

$$\tau_0 = 0.0015$$

$$\tau_{hydro} = 1.2005$$

SUMMARY AND OUTLOOK

- IT IS INTEGRAL TO UNDERSTAND THE THERMALIZATION PROCESSES OF QCD AND TO SIMULATE IT ACCURATELY IN OUR MODELS
- THE EVOLUTION OF CONSERVED CHARGES IN HIGH ENERGY HIC'S IS A MISSING PIECE OF OUR UNDERSTANDING
- THE KøMPøST FRAMEWORK CAN HANDLE THIS TASK
- NEXT STEPS:
  - HYDRODYNAMIC SIMULATION
  - QCD KINETIC THEORY WITH FINITE CHARGE BACKGROUND
  - (3+1) KøMPøST