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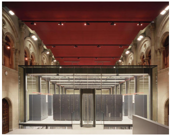

MARIE CURIE ACTIONS

Holographic collisions in non-conformal theories

Maximilian Attems

arXiv:1603.01254 **arXiv:1604.06439** **arXiv:1703.02948**

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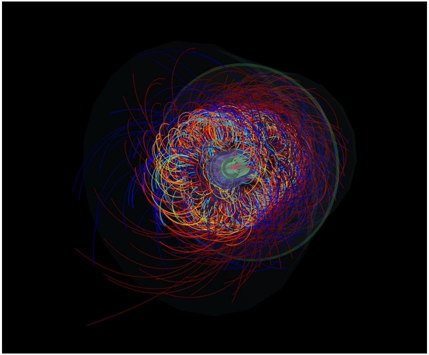
CPOD 2017

Motivations

Quark-Gluon Plasma:



LHC reconstructed event from the first heavy ion collisions [ALICE 2010]

Black Holes:

Collision of two Black Holes, merging into one [Simulating eXtreme Spacetimes 2016]

gauge/gravity correspondence:

bridge between physical phenomena in gauge theories and gravity.

Outline

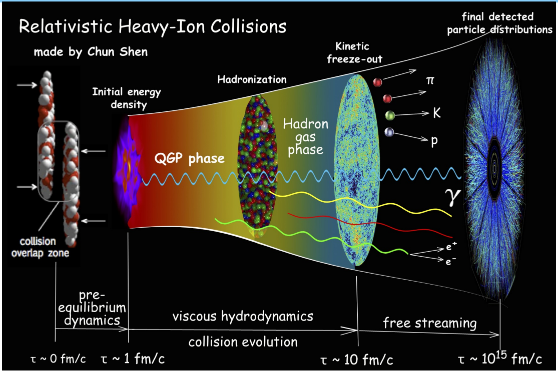
Non-conformal theories

- Introduction Heavy-Ion collision
- Introduction gauge gravity duality
- Non-conformal General Relativity setup
- Non-conformal Thermodynamics

Dynamics of the scalar potential

- Quasi-Normal-Modes
- Hydrodynamization and EoSization
- Condensate relaxation times
- Equilibration times

Introduction Heavy-Ion collision - the ‘little bang’



Stages of HI collision:

1) Out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

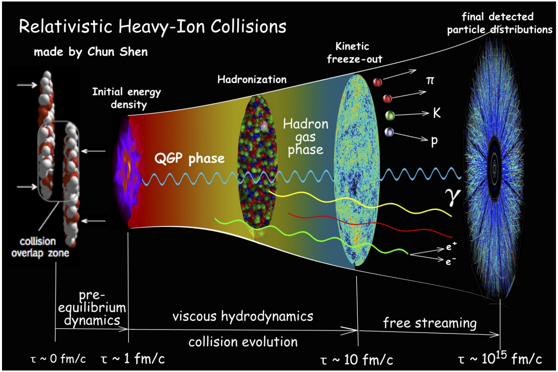
How to solve initial multibody Quatum-ChromoDynamics problem?

equilibrium aspects → lattice QCD

classical aspects → kinetic theory

weak coupling → perturbative QFT

strongly coupled dynamics → ?



Stages of HI collision:

1) Out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

How can we describe the first stage at strong coupling?

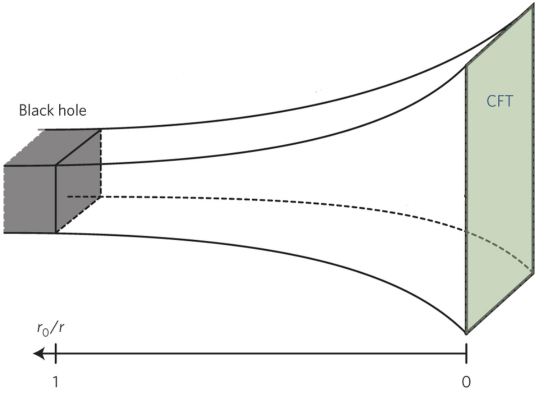
How long is the first stage? LHC Data indicates $\leq 10^{-23}$ **s**

What determines when hydro becomes applicable?

What are the initial conditions for the Quark-Gluon-Plasma?

Introduction gauge gravity duality

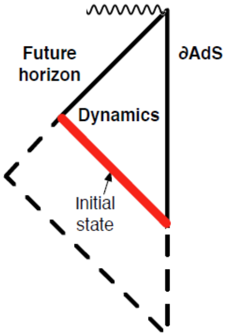
Quantum gravity in $d+1$ dimension AdS $\leftrightarrow$ QFT in d dimension

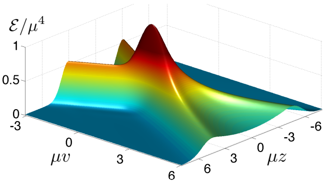


IIB string theory on $\mathrm{AdS}_5 \times \mathrm{S}_5 \leftrightarrow \mathcal{N} = 4$ Super-Yang-Mills
[Maldacena 1998, Witten 1998]

shear visocity over entropy density ratio $\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$
[Policastro, Son, Starinets 2001]

stage I: holographic shock waves properties





Strong coupling toolkit for out of equilibrium dynamics [Albacete, Kovchegov, Taliotis 08; Grumiller, Romatschke 08; Beuf, Heller, Janik, Peschanski 09]:

Fast hydrodynamization with first shock wave collisions in the characteristic formulation $t_{\rm hyd} < 10^{-23}$ although very anisotropic $\frac{P_T}{P_L}\Big|_{t_{\rm hyd}} \gg 1$ at hydrodynamization [Chesler, Yaffe 2011]

Thin shocks hydrodynamize fast too, Initial energy per unit transverse area μ relates to shock product after collision: $t_{\rm hyd} T_{\rm hyd} < \frac{1}{2}$, $T_{\rm hyd} = 0.3\mu$ [Casalderrey-Solana, Heller, Mateos, van der Schee 2013]

Non-conformal General Relativity setup

Einstein-Hilbert action coupled to a scalar with non-trivial potential in five-dimensional bottom-up model:

$$S = \frac{2}{\kappa_5^2} \int d^5x \sqrt{-g} \left[\frac{1}{4}\mathcal{R} - \frac{1}{2} (\nabla\phi)^2 - V(\phi) \right]$$

Holographic renormalization [Bianchi, Freedman, Skenderis 2002]

$$V(\phi) = -\frac{1}{12\phi_M^4}\phi^8 + \left(\frac{1}{2\phi_M^4} \pm \frac{1}{3\phi_M^2} \right) \phi^6 - \frac{1}{3}\phi^4 - \frac{3}{2}\phi^2 - 3$$

Deforming $\mathcal{N} = 4$ Super Yang-Mills with an operator $\mathcal{V}$ dual to the scalar field. The source Λ breaks scale invariance explicitly and triggers a non-trivial Renormalization Group (RG) flow.

Einstein-Hilbert action coupled to a scalar with non-trivial potential in five-dimensional bottom-up model:

$$S = \frac{2}{\kappa_5^2} \int d^5x \sqrt{-g} \left[\frac{1}{4}\mathcal{R} - \frac{1}{2} (\nabla\phi)^2 - V(\phi) \right]$$

Holographic renormalization [Bianchi, Freedman, Skenderis 2002]

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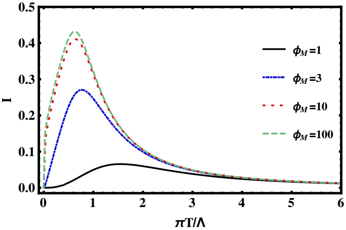
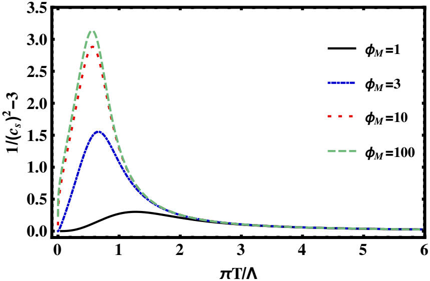
Interaction measure $I = \frac{\epsilon - 3p}{\epsilon + p}$ as a measure of non-conformality, NON-conformal at intermediate temperatures, conformal at IR and UV

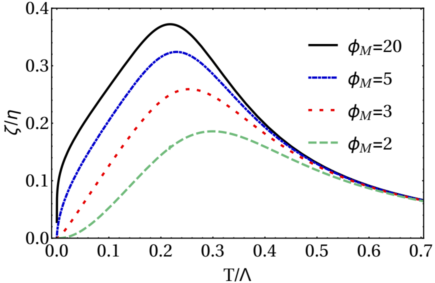


Non-conformal Thermodynamics

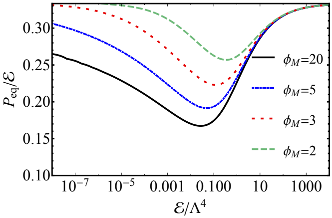
Deviation of speed of sound c_s^2:



Bulk viscosity over entropy:



Maxima of speed of sound and bulk to shear viscosity different!

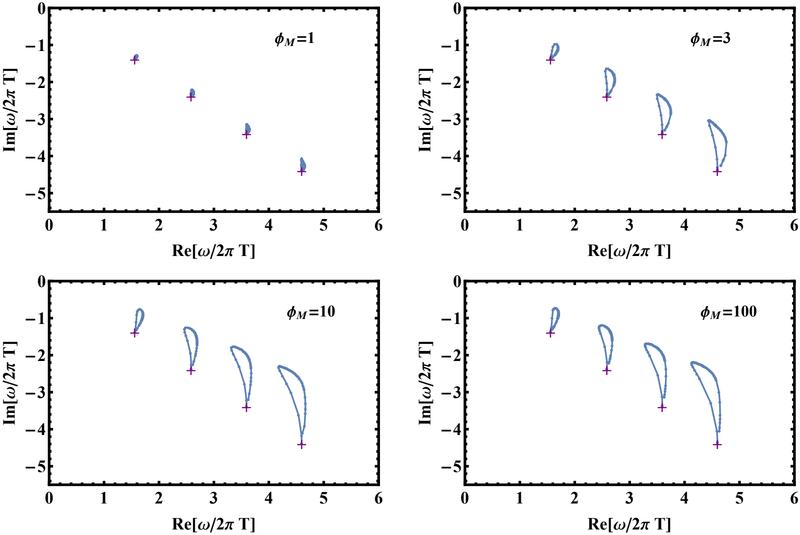


$$\left\langle T^{\mu}_{\mu} \right\rangle = -\Lambda \left\langle \mathcal{V} \right\rangle \ .$$

Out of equilibrium the average pressure is not determined by the energy density alone, as the scalar expectation value $\mathcal{V}$ fluctuates independently.

Quasi-Normal-Modes

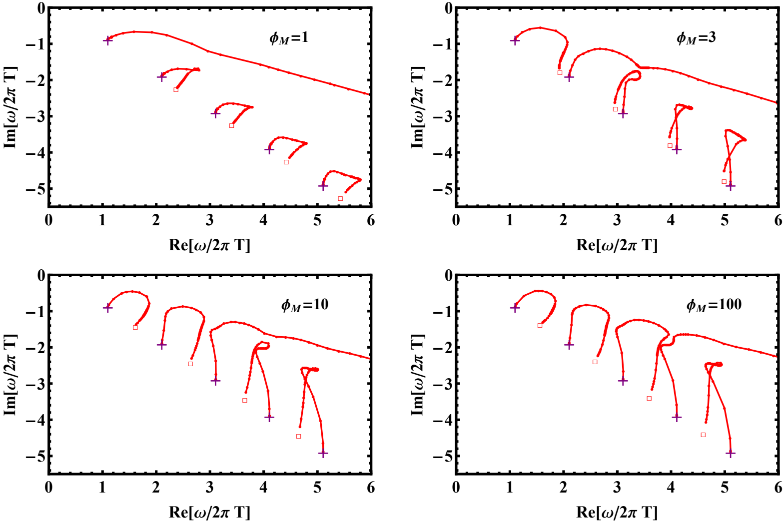
anisotropic perturbation Z_{aniso}



Fluctuations of the stress energy tensor with same IR + UV limit

Quasi-Normal-Modes

non-conformal scalar mode $Z_{\mathrm{b}ulk}$



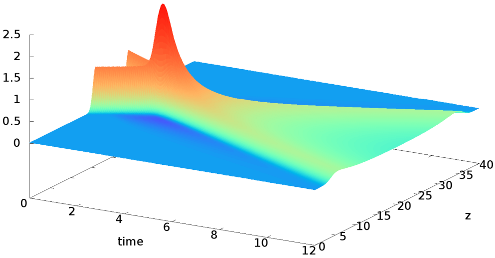
n-th scalar mode decoupling with anti-crossing and different IR/UV limits

Non-conformal holographic shock waves

Heavy-Ion collision: QGP formation $\Longleftrightarrow$ shock wave collision: black hole formation

$$\Big(\mathcal{E}, P_{x^i}, \mathcal{V}\Big) \Longleftrightarrow \frac{\kappa_5^2}{2L^3}\Big(-T^t_t, T^{x^i}_{x^i}, \mathcal{O}\Big)$$

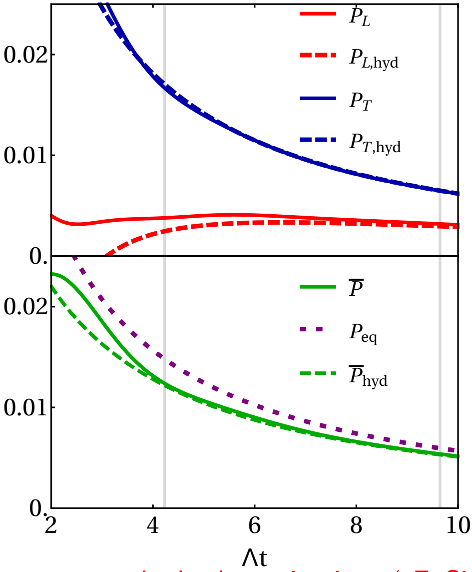
Holography allows to explore far from equilibrium dynamics:



Energy density evolution of a typical scalar shock wave collision

- at strong coupling
- non-perturbatively
- non-conformal
- almost ideal fluids
- fast hydrodynamization
- initial condition for hydrodynamics

Non-conformal shock collision



Hydrodynamics expansion:

$$\begin{aligned}\partial_\mu T^{\mu\nu} &= 0\\ T^{\mu\nu} &= (\epsilon + p)u^\mu u^\nu + pg^{\mu\nu}\\ &\quad + \eta\Pi^{\mu\nu} + \zeta\Pi(g^{\mu\nu} + u^\mu u^\nu)\end{aligned}$$

Hydrodynamization:

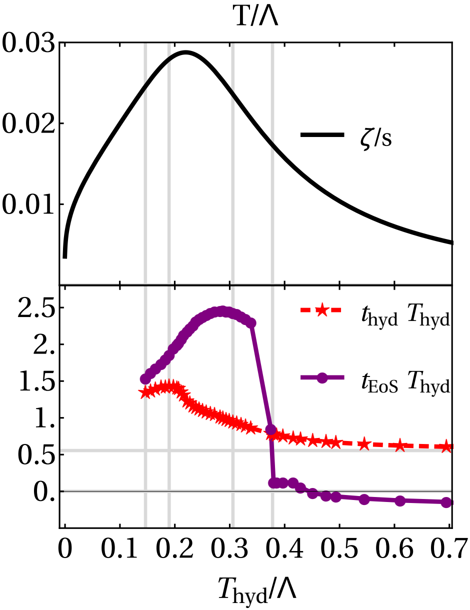
$$\left|P_{L,T} - P_{L,T}^{\mathrm{hyd}}\right| / \bar{P} < 0.1$$

EoSization:

$$\left|\bar{P} - P_{\mathrm{eq}}\right| / \bar{P} < 0.1$$

hydrodynamization $\neq$ EoSization $\neq$ isotropization

Equilibration times I

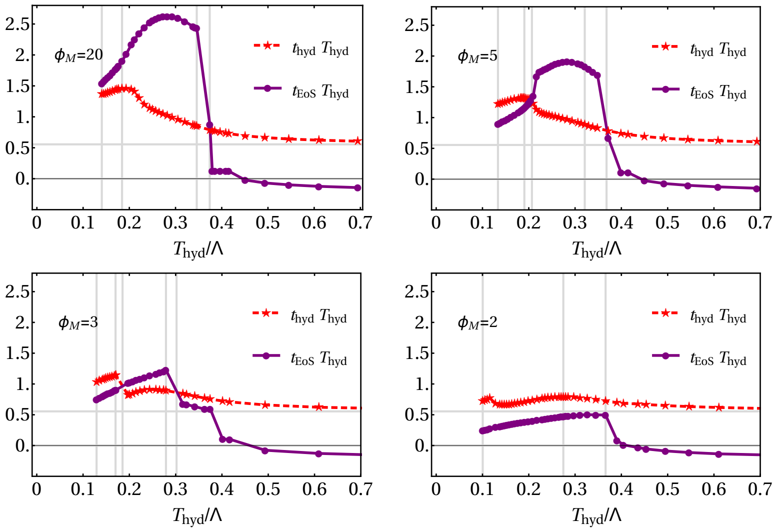


Non-conformal T scan:

- $t_{\rm hyd}$ slow down, still very fast
- required ζ $1/10$ of QCD at T_c for non-conformal effects
- ordering of $t_{\rm EoS}$ and $t_{\rm hyd}$ depends on bulk viscosity

Hydrodynamization and EoSization

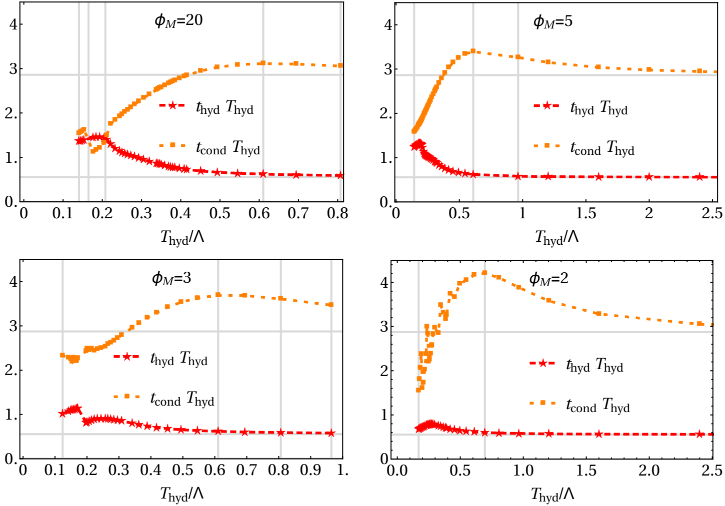
Comparing varying non-conformality ϕ_M:



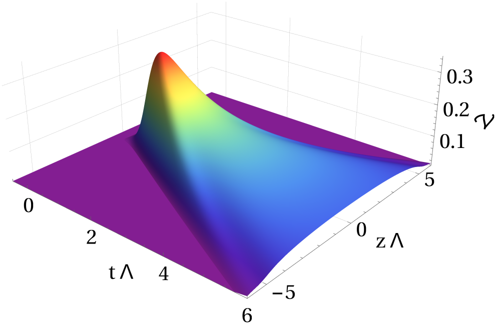
conservative estimate $\zeta/\eta > 0.22$ needed for $t_{EoS} > t_{hyd}$

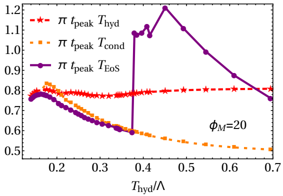
Condensate relaxation times I

Comparing varying non-conformality ϕ_M:



$|\mathcal{V}-\mathcal{V}_{\text{eq}}|/\mathcal{V} < 0.1$ condensate relaxation time



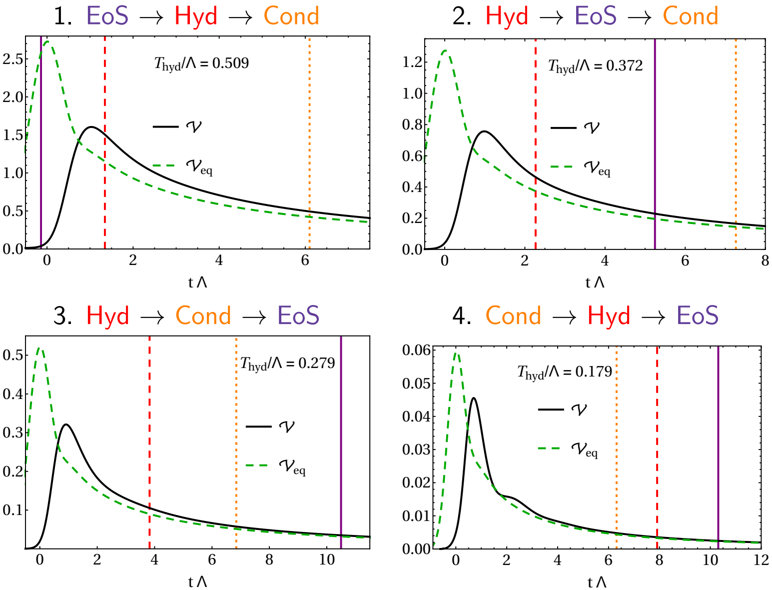


$$t_{peak} \approx \frac{c}{\pi T_{\text{hyd}}}$$

Paths to equilibrium in non-conformal collisions:

1. EoSization → Hydrodynamization → Condensate relaxation,
2. Hydrodynamization → EoSization → Condensate relaxation,
3. Hydrodynamization → Condensate relaxation → EoSization,
4. Condensate relaxation → Hydrodynamization → EoSization.

Equilibration times

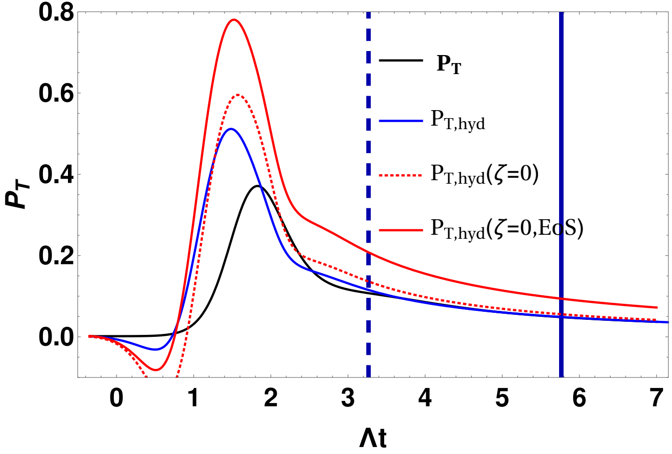


Paths to equilibrium in non-conformal collisions

Conclusions

- First simulation of a holographic non-conformal model for heavy ion collisions:
  - New relaxation channel from bulk viscosity: *EoSization*
    Conservative estimate $\zeta/eta \approx 0.22$ for non-conformal effects
  - Paths to equilibrium in non-conformal collisions:
    Four orderings of Condensate relaxation, EoSization, Hydrodynamization times
  - Fast hydrodynamization at early time
    despite non-trivial equation of state
    despite sizable ζ/s bulk viscosity over entropy
- New example of the applicability of hydrodynamics to systems with large gradients: Gregory-Laflamme instability settling to static inhomogeneous black brane (previous talk)
- More studies are on the way

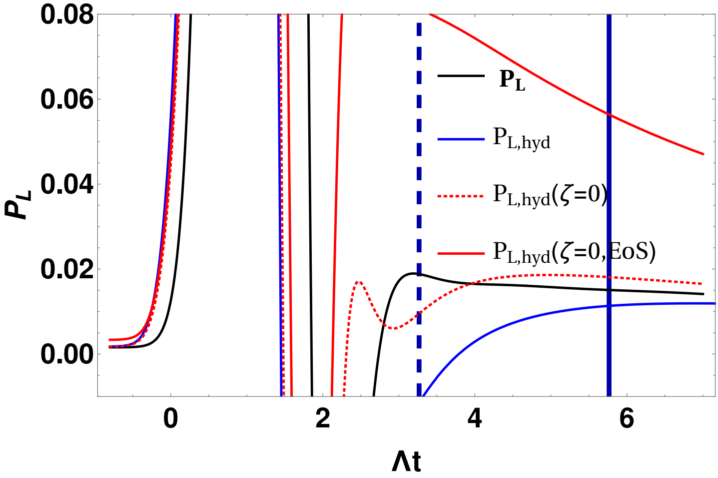
Landau match of the transverse pressure,
Landau frame assumes no momentum flow $T'_{0i} = 0$



Equation of state essential for hydrodynamics prediction,
bulk viscosity slows down evolution lowers pressures

Backup: Longitudinal pressure

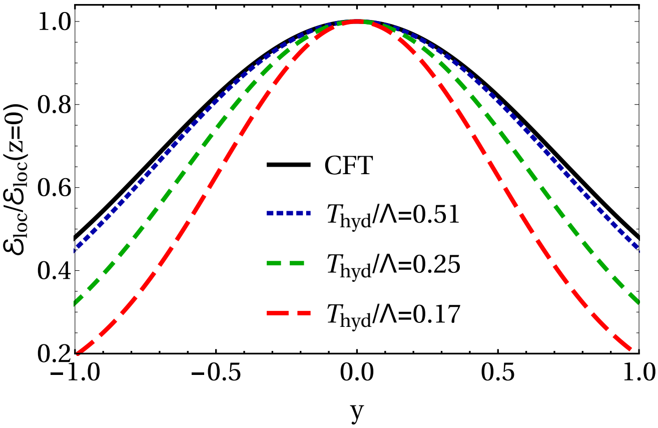
Landau match of the longitudinal pressure



Solid vertical line indicates hydrodynamization time t_{hyd} once both pressures agree with hydrodynamics

Backup: Rapidity profile

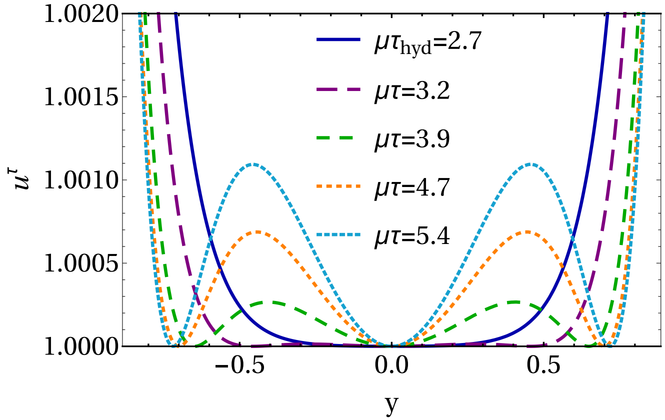
At Hydrodynamization time almost Gaussian distribution:



Higher energy densities results in broader rapidity profile

Backup: Proper velocity

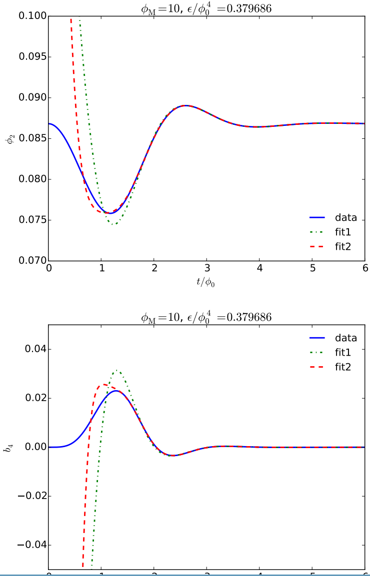
Boost invariant flow at mid rapidity:



the component of the velocity field along the proper time direction

$$u^\tau = \cosh(y)\, u^t - \sinh(y)\, u^z$$

ϕ_2 and b_4 as functions of time for a z-independent configuration



Differences between the coarse and medium (blue solid line) and the medium and fine (red dashed line) resolution run