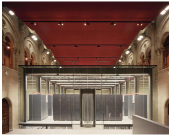


Holographic Heavy Ion Collisions

Maximilian Attems

Univ. of Barcelona → Univ. of Santiago de Compostela

arXiv:1603.01254 **arXiv:1604.06439** **arXiv:1703.02948** **arXiv:1703.09681**

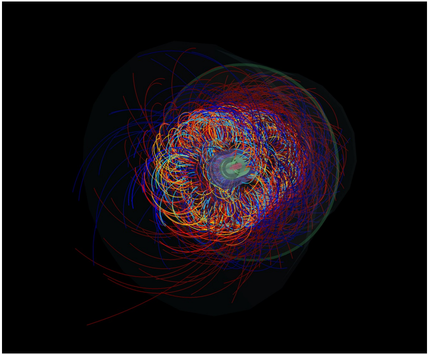
Collaborators:

Yago Bea (UB), Jorge Casalderrey-Solana (Oxford), David Mateos (UB/ICREA), Daniel Santos (UAB), Carlos Sopuerta (UAB/LISA), Miquel Triana (UB), Miguel Zilhao (UB)

11th RES Users' Meeting

Motivations

Quark-Gluon Plasma:



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

Black Holes:

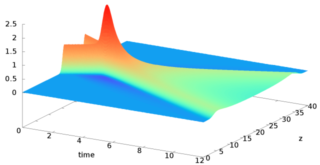
Collision of two Black Holes, merging into one [Simulating eXtreme Spacetimes 2016]

gauge/gravity correspondence:
bridge between physical phenomena in gauge theories and gravity.

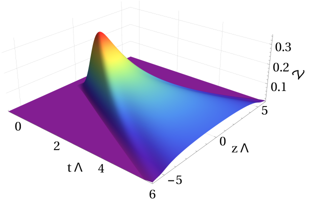
MareNostrum success story

$\approx$ 850 CPU khours computations on RES MareNostrum III/IV:

- scientific highlights:
  - **first non-conformal collisions**
  - **EoSization**
  - $\zeta/s \geq 0.025$ **estimate**
  - **spinodal instability across phase transition**
  - **New applicability of hydrodynamics**



- scientific output (from 03/2016):
  - 3 JHEP publications
  - MSCA fellowship, 2 PhD's
  - 4 plenaries + 20 talks at international conferences
  - 2 colloquium Utrecht/Harvard University + 7 seminars (CERN, CEA/Saclay, Brookhaven National Laboratory, ..)



Outline

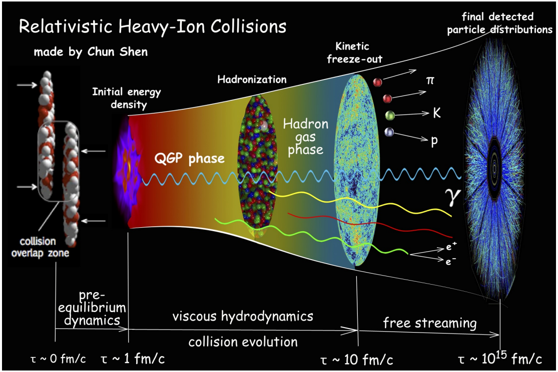
Non-conformal model

- Introduction Heavy-Ion collision
- stage II: Hydrodynamics and viscosities
- stage II: QGP properties
- Introduction Heavy-Ion collision - the 'little bang'
- Introduction gauge gravity duality
- stage I: Non-conformal General Relativity setup
- Non-conformal Thermodynamics

Shock wave dynamics

- Non-conformal shock collision
- Equilibration times I
- Equilibration times II
- Spinodal instability
- Spinodal instability: Hydrostatic + Hydrodynamic evolution

Introduction Heavy-Ion collision - the ‘little bang’



Stages of HI collision:

1) Out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

Cartoon of a ultra-relativistic heavy-ion collision: the two nuclei approach, collide, first are out-of-equilibrium, form a Quark-Gluon Plasma (QGP), the QGP expands and hadronizes, finally hadrons rescatter and freeze out

Hydrodynamics assumes mean free path goes to zero and conservation of energy and momentum

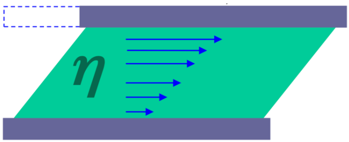
$$\partial_\mu T^{\mu\nu} = 0$$

expansion around isotropic equilibrium distribution:

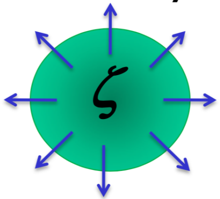
$$T_{\mu\nu}^{\mathrm{hyd}} = T_{\mu\nu}^{\mathrm{ideal}} - \eta\,\sigma_{\mu\nu} - \zeta\,\Pi\,\Delta_{\mu\nu} + \Pi_{\mu\nu}^{(2)}$$

Together with the equation of state of the fluid, which is defined as a functional relation between conserved quantities $\mathcal{E}$, P, they form a closed system of equations.

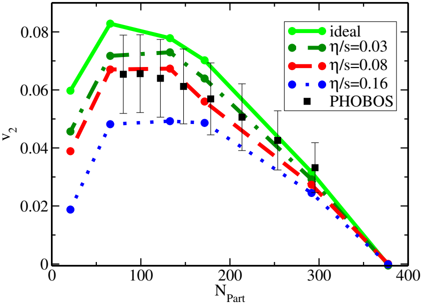
Shear viscosity



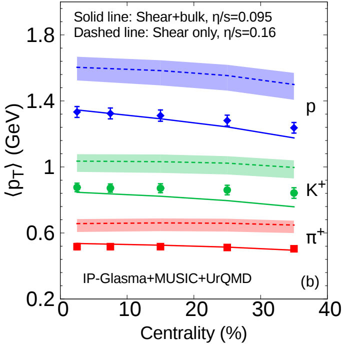
Bulk viscosity



Heavy-Ion collision flow observable match hydro simulation assuming early hydrodynamization [Heinz, Kolb 2001]

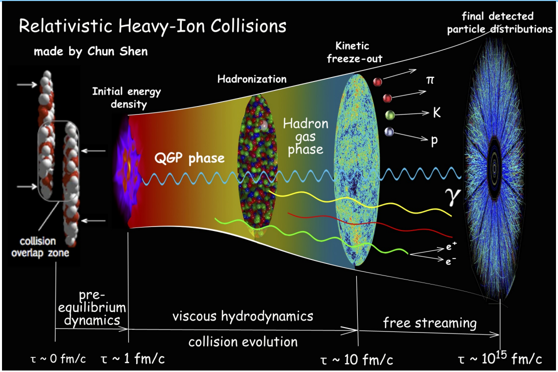


shear viscosity over entropy density ratio $\eta/s \approx 0.08$
$\rightarrow$ nearly perfect fluid
[Romatschke 2007]



Hydro simulation agreement improves with bulk viscosity ζ
[Denicol *et al.* 2015]

Introduction Heavy-Ion collision - the 'little bang'



Stages of HI collision:

1) Out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

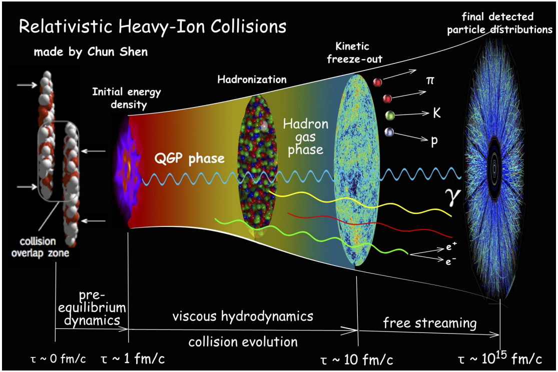
How to solve initial multibody Quatum-ChromoDynamics problem?

equilibrium aspects $\rightarrow$ lattice QCD

classical aspects $\rightarrow$ kinetic theory

weak coupling $\rightarrow$ perturbative QFT

strongly coupled dynamics $\rightarrow$?



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?

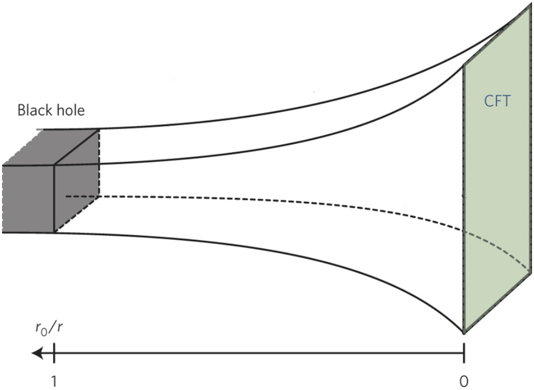
How long is the first stage? LHC Data indicates $\leq 10^{-23}$ **s**

What determines when hydro becomes applicable?

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

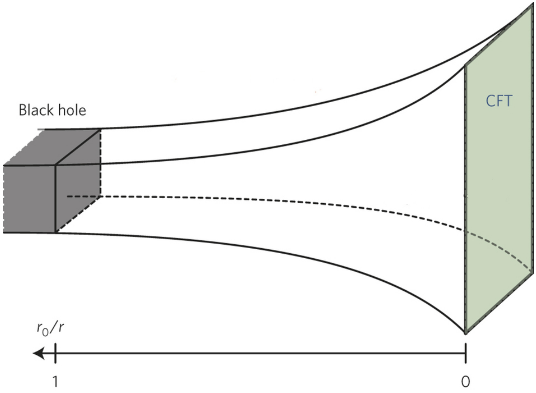
Introduction gauge gravity duality

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]

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

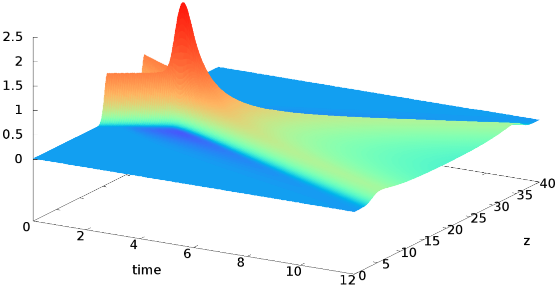


IIB string theory on $\mathrm{AdS}_5 \times \mathrm{S}_5 \leftrightarrow \mathcal{N} = 4$ Super-Yang-Mills
[Maldacena 1998, Witten 1998]

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

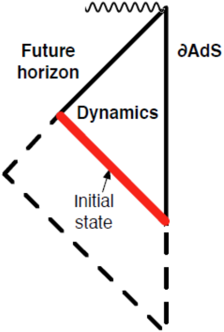
Heavy-Ion collision: QGP formation	$\Longleftrightarrow$	shock wave collision: black hole formation
$\left(\mathcal{E}, J_{\mathcal{E}}, P_{x^i}\right)$	$\Longleftrightarrow$	$\frac{\kappa_5^2}{2L^3}\left(-T_t^t, T_t^z, T_{x^i}^{x^i}\right)$

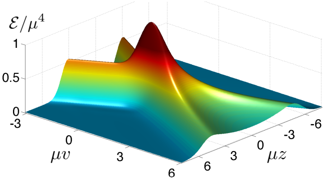
Holography allows to explore far from equilibrium dynamics:



Energy density evolution of a typical shock wave collision

stage I: holographic shock waves properties





Strong coupling toolkit for out of equilibrium dynamics:

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

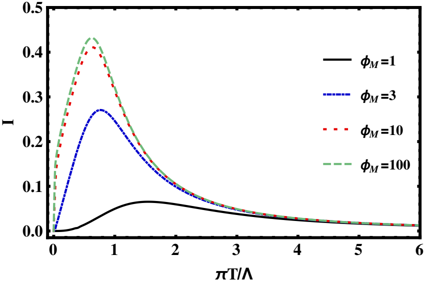
Thin shocks hydrodynamize fast too, Initial energy per unit transverse area μ relates to shock product after collision: $t_{\mathrm{hyd}} T_{\mathrm{hyd}} < \frac{1}{2}$, $T_{\mathrm{hyd}} = 0.3\mu$ [Casalderrey-Solana, Heller, Mateos, van der Schee 2013]

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

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

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

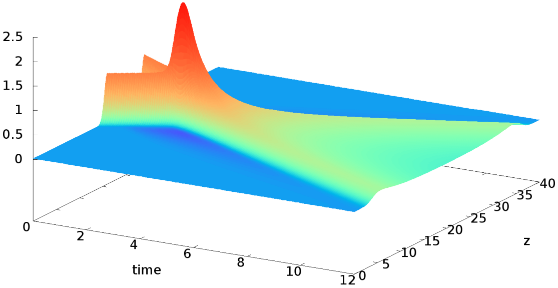
Interaction measure $I = \frac{\epsilon - 3p}{\epsilon + p}$ as a measure of non-conformality, NON-conformal at intermediate temperatures, conformal at *IR* and *UV*



Stage I: Non-conformal holographic shock waves

Heavy-Ion collision: QGP formation	$\Longleftrightarrow$	shock wave collision: black hole formation
$\left(\mathcal{E}, J_{\mathcal{E}}, P_{x^i}, \mathcal{V}\right)$	$\Longleftrightarrow$	$\frac{\kappa_5^2}{2L^3}\left(-T_t^t, T_t^z, T_{x^i}^{x^i}, \mathcal{O}\right)$

Holography allows to explore far from equilibrium dynamics:

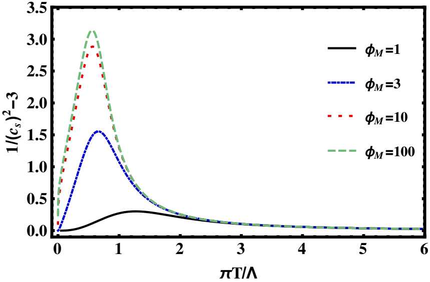


Energy density evolution of a typical scalar shock wave collision

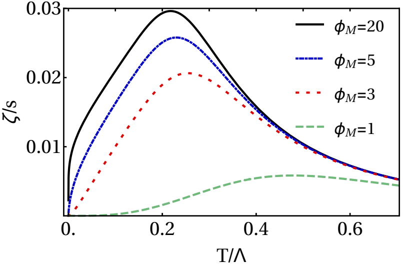
Deforming $\mathcal{N} = 4$ Super Yang-Mills with an operator $\mathcal{V}$ dual to the scalar field. The source Λ breaks scale invariance explicitly and triggers a non-trivial Renormalization Group (RG) flow.

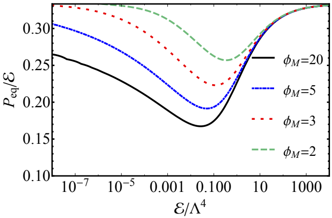
Non-conformal Thermodynamics

Deviation of speed of sound c_s^2:



Bulk viscosity over entropy:





$$P_{\rm eq}(\mathcal{E}) = \frac{1}{3}\left[\mathcal{E} - \Lambda \mathcal{V}_{\rm eq}(\mathcal{E})\right] .$$

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

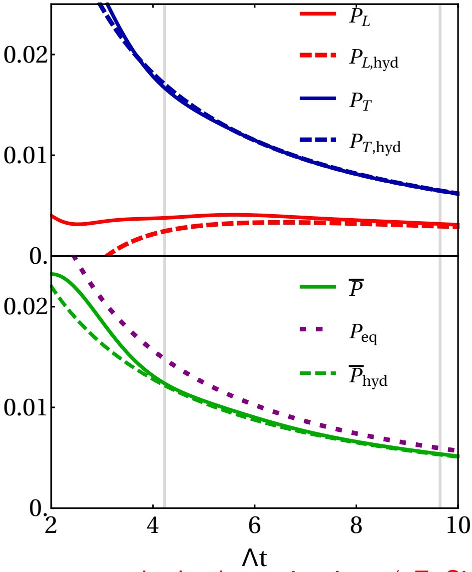
Outline

Non-conformal model

Shock wave dynamics

- Non-conformal shock collision
- Equilibration times I
- Equilibration times II
- Spinodal instability
- Spinodal instability: Hydrostatic + Hydrodynamic evolution

Non-conformal shock collision



Hydrodynamics expansion:

$$\partial_\mu T^{\mu\nu} = 0$$
$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu + p g^{\mu\nu} + \eta \Pi^{\mu\nu} + \zeta \Pi (g^{\mu\nu} + u^\mu u^\nu)$$

Hydrodynamization:

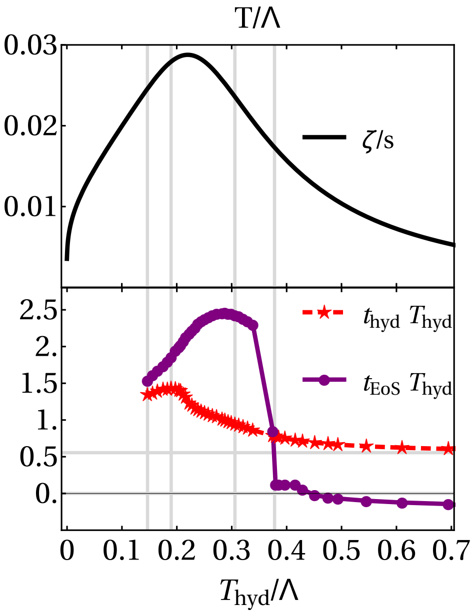
$$\left| P_{L,T} - P_{L,T}^{\mathrm{hyd}} \right| / \bar{P} < 0.1$$

EoSization:

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

hydrodynamization ≠ EoSization ≠ isotropization

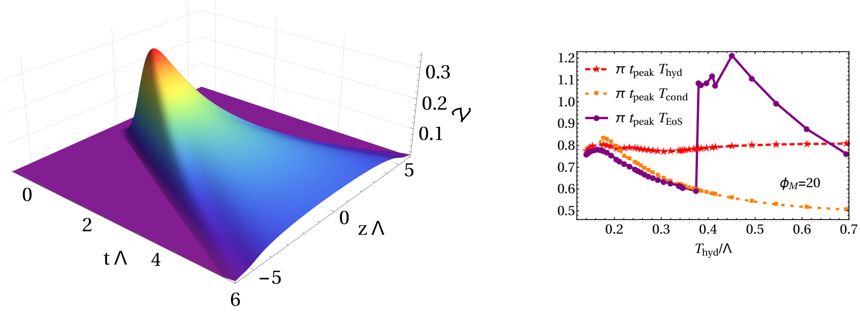
Equilibration times I



Non-conformal T scan:

- t_{hyd} slow down, still very fast
- small required $\zeta/s \geq 0.025$ for non-conformal effects
- ordering of t_{EoS} and t_{hyd} depends on bulk viscosity

Evolution of the scalar condensate:

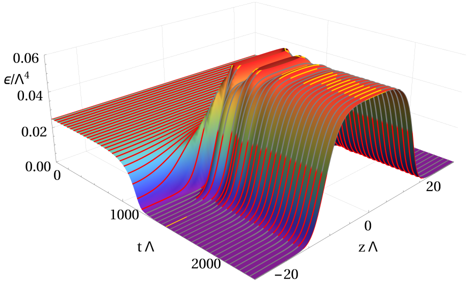


$$t_{peak} \approx \frac{c}{\pi\, T_{\mathrm{h}yd}}$$

Universal effects of the dynamics near the horizon that forms deep in the bulk even in non-conformal theories

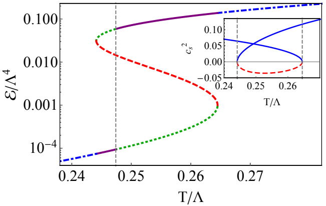
Spinodal instability

Energy density evolution of black branes afflicted by the Gregory-Laflamme instability:



excited unstable mode growth until non-linear saturation

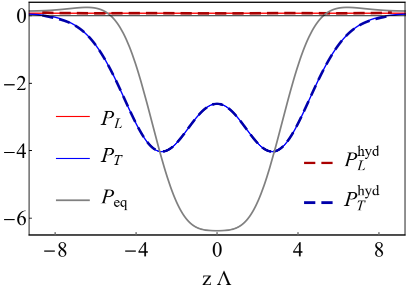
Energy density versus temperature for the gauge theory:



The dashed red curve is locally unstable, the dotted green curve metastable.

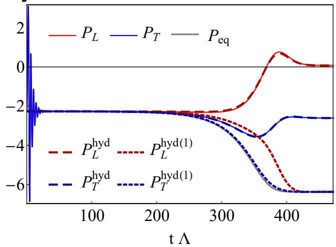
Hydrostatic + Hydrodynamic evolution

Hydro description $P^{\rm hyd}_{L/T} = P_{\rm eq}(\mathcal{E}) + c_{\rm L/T}(\mathcal{E})(\partial_z\mathcal{E})^2 + f_{\rm L/T}(\mathcal{E})(\partial_z^2\mathcal{E})$



Pressures agree with hydrodynamic prediction for a different state

Pressures predicted by hydro match:

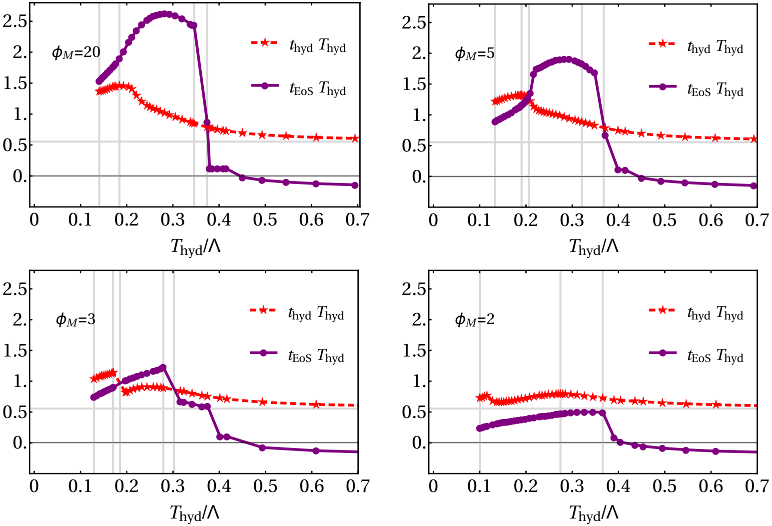


Early time behaviour with exponential decay of quasi-normal modes

Conclusions

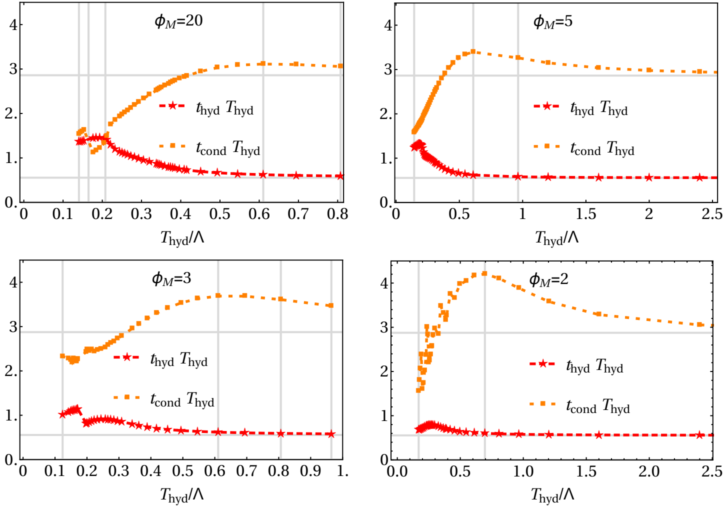
- First simulation of a holographic non-conformal model for heavy ion collisions:
  - New relaxation channel from bulk viscosity: *EoSization*
  - Fast hydrodynamization at early time with conservative estimate $\zeta/s \approx 0.025$ for non-conformal effects
  - Paths to equilibrium in non-conformal collisions: Four orderings of Condensate relaxation, EoSization, Hydrodynamization times
- New example of the applicability of hydrodynamics to systems with large gradients: Gregory-Laflamme dual to spinodal instability settling to static inhomogeneous black brane
- More studies are on the way:
  - Asymmetrical collisions, exploding balls
  - Different potentials: $\mathcal{N} = 2^*$, Gubser, ..

Comparing varying non-conformality ϕ_M:

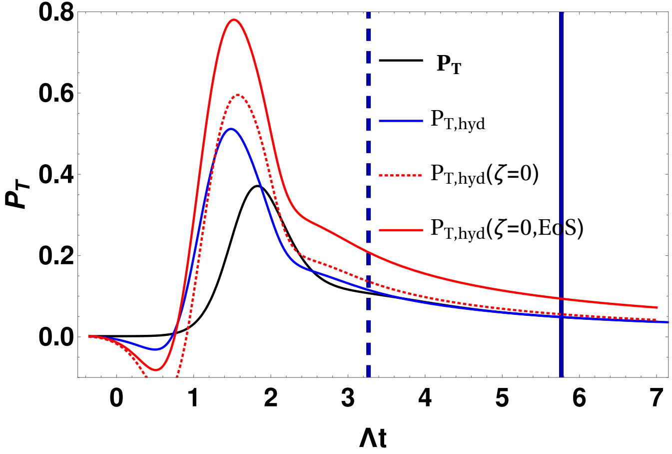


conservative estimate $\zeta/s > 0.025$ needed for $t_{EoS} > t_{hyd}$

Condensate relaxation times and hydrodynamization times for collisions with different ϕ_M:

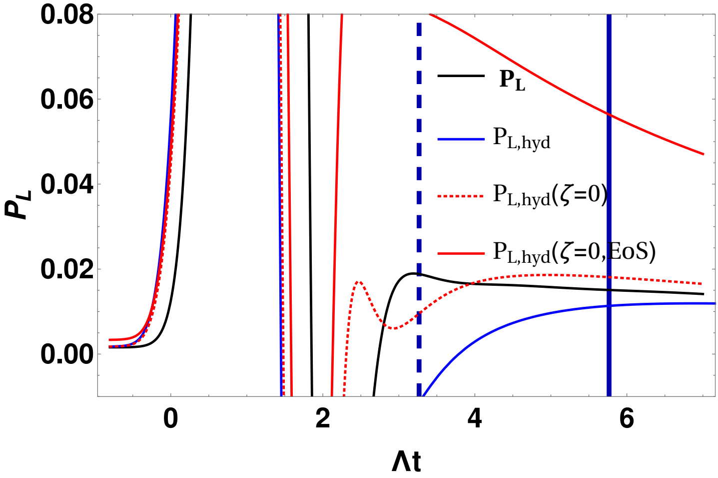


Landau match of the transverse pressure,
Landau frame assumes no momentum flow $T'_{0i} = 0$



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

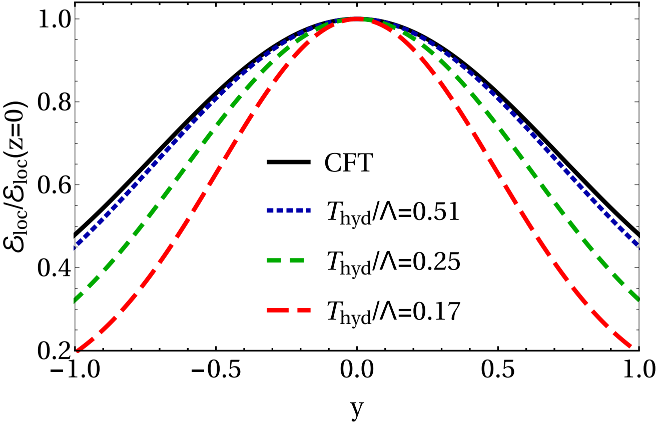
Landau match of the longitudinal pressure



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

Backup: Rapidity profile

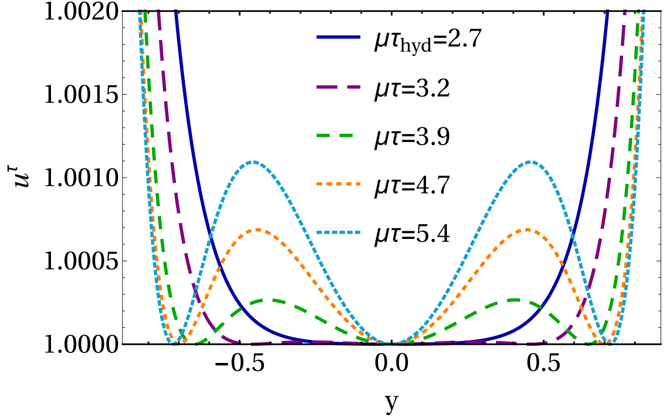
At Hydrodynamization time almost Gaussian distribution:



Higher energy densities results in broader rapidity profile

Backup: Proper velocity

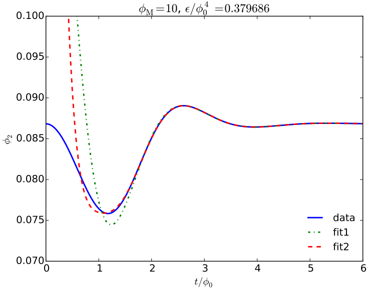
Boost invariant flow at mid rapidity:

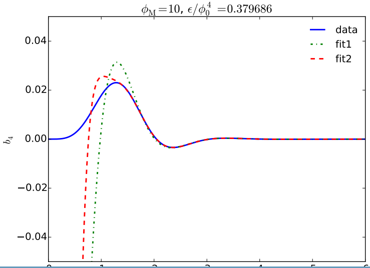


the component of the velocity field along the proper time direction

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

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





Backup: Convergence analysis

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