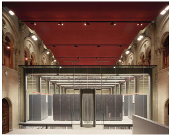


Fast non-conformal hydrodynamization of the quark-gluon plasma

Maximilian Attems

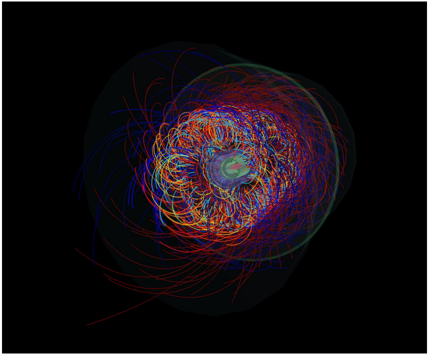
arXiv:1603.01254 **arXiv:1604.06439** **arXiv:1703.09681**

Collaborators:
Jorge Casalderrey-Solana (Oxford),
David Mateos (UB), Miguel Zilhao (CENTRA)

1st joint workshop IGFAE/LIP

Motivations

Quark-Gluon Plasma:

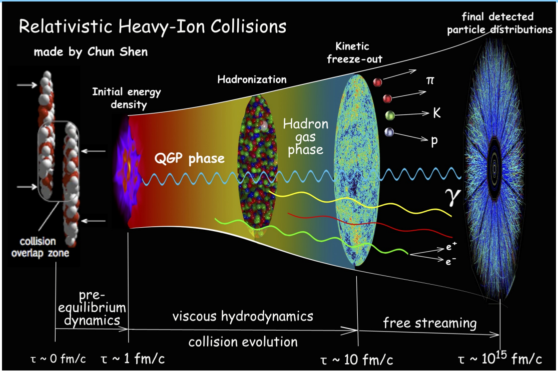


LHC reconstructed event from the first heavy ion collisions [ALICE 2010]

Black Holes:

Black Holes coalesence
[Simulating eXtreme Spacetimes 2016]

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



Stages of HI collision:

1) Out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

How to solve initial multibody Quatum-ChromoDynamics problem?

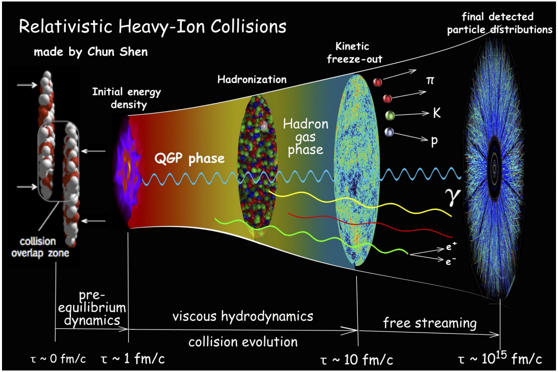
equilibrium aspects $\to$ lattice QCD

classical aspects $\to$ kinetic theory

weak coupling $\to$ perturbative QFT

strongly coupled dynamics $\to$?

Introduction Heavy-Ion collision - the 'little bang'



Stages of HI collision:

1) Out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

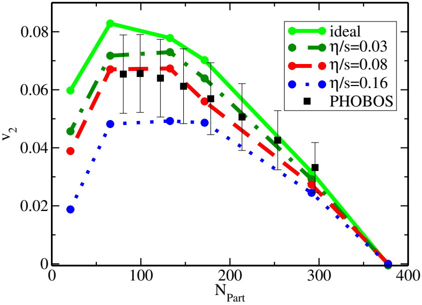
How can we describe the first stage at strong coupling?

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

What determines when hydro becomes applicable?

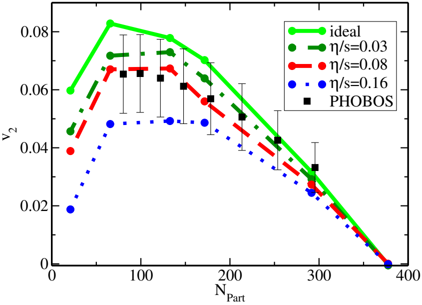
What are the initial conditions for the Quark-Gluon-Plasma?

$> 10\mathrm{y}$ success of viscous hydrodynamics



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

$> 10\text{y}$ success of viscous hydrodynamics



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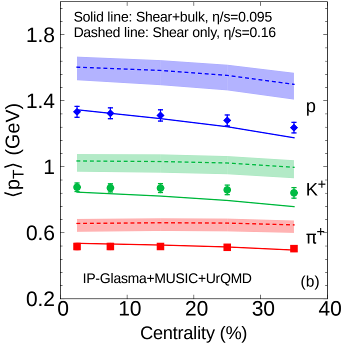


Hydro simulation agreement improves with bulk viscosity ζ [Denicol *et al.* 2015]

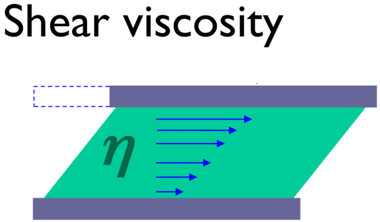
Hydrodynamics assumes mean free path goes to zero and conservation of energy and momentum

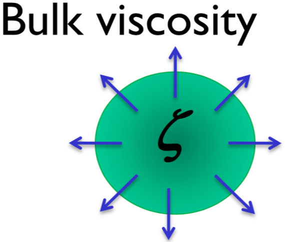
$$\partial_\mu T^{\mu\nu} = 0$$

expansion around isotropic equilibrium distribution:

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

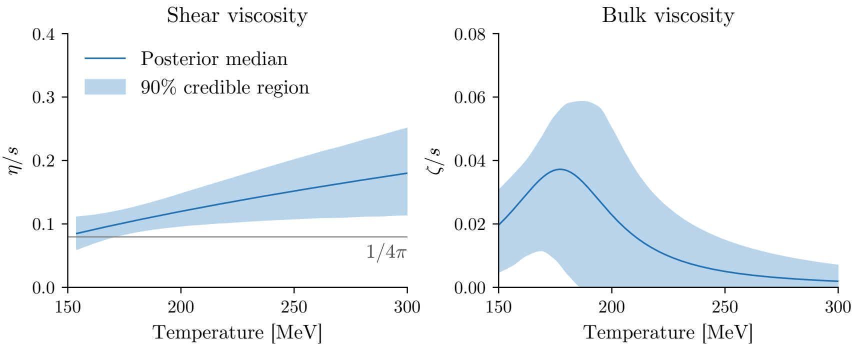
Together with the equation of state of the fluid, which is defined as a functional relation between conserved quantities $\mathcal{E}$, P, they form a closed system of equations.





Bayesian modelling

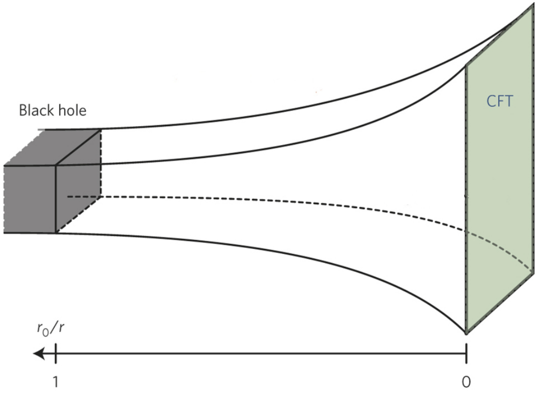
Extracted via yields, flow cumulants and transverse momentum:



[Steffen Bass, Jonah E. Bernhard 2018]

$min(\eta/s) = 0.081, \; max(\zeta/s) = 0.052, \; t_{\text{fs}} = 1.16 fm/c$

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



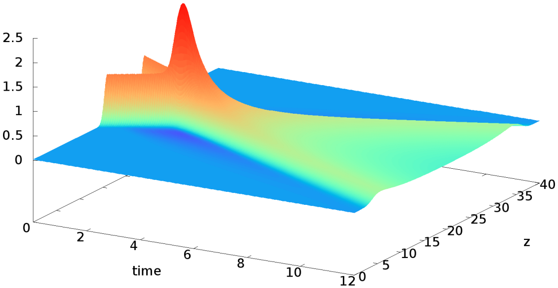
IIB string theory on $\mathrm{AdS}_5 \times \mathrm{S}_5 \leftrightarrow \mathcal{N} = 4$ Super-Yang-Mills
[Maldacena 1998, Witten 1998]

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

Plasma formation

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

Holography allows to explore far from equilibrium dynamics:



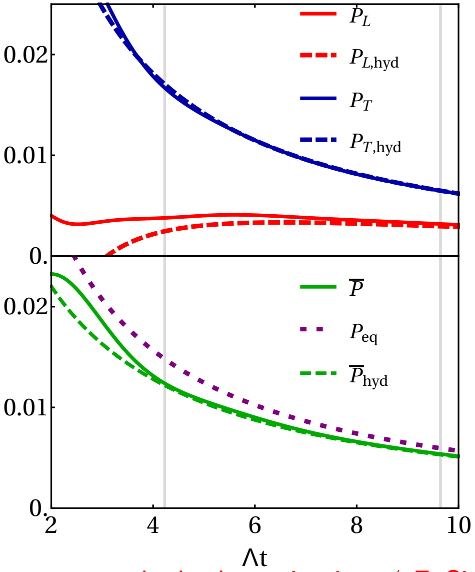
Energy density evolution of a typical scalar shock wave collision

at strong coupling

non-perturbatively

with fast hydrodynamization time

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:

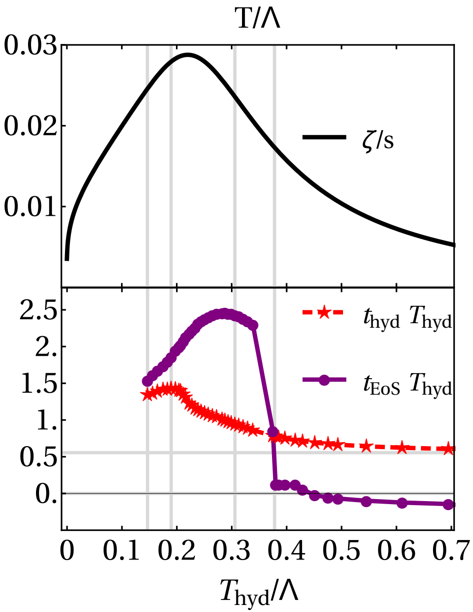
$$\left| P_{L,T} - P_{L,T}^{\mathrm{hyd}} \right| / \bar{P} < 0.1$$

EoSization:

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

hydrodynamization ≠ EoSization ≠ isotropization

Hydrodynamization with bulk viscosity

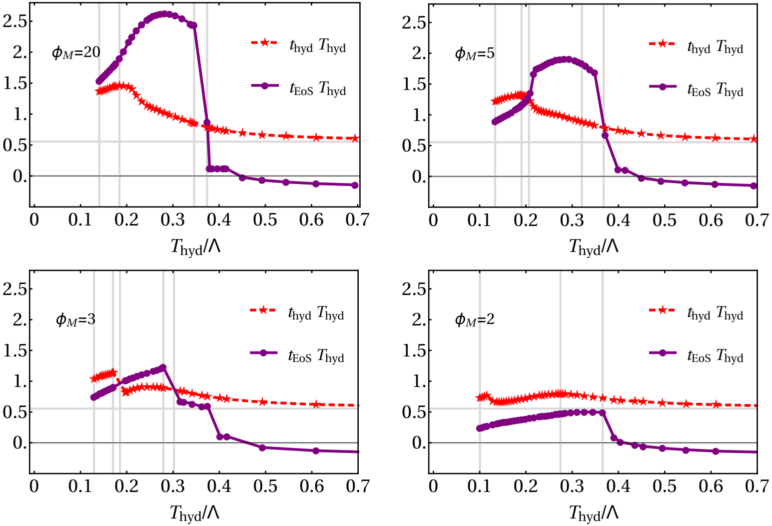


Non-conformal T scan:

- $t_{\rm hyd}$ slow down, still very fast
- new relaxation channel: EoSization (= time when ideal equ. of state applies)
- $\zeta/s > 0.025$ for $t_{\rm EoS}$ and $t_{\rm hyd}$

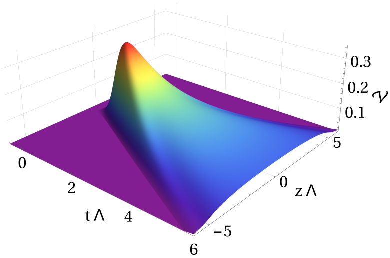
[MA, Casalderrey-Solana, Mateos, Santos, Sopuerta, Triana, Zilhao 2017]

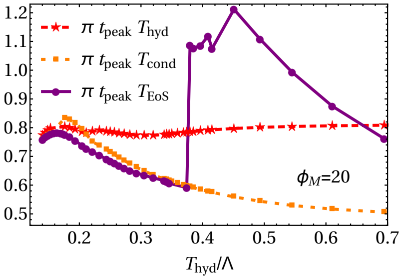
Comparing varying non-conformality ϕ_M:



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

Universal response:





$\pi t_{\rm peak} T_{\rm hyd} \approx 0.8$

time for the effects of the dynamics near the horizon that forms deep in the bulk when the shocks collide to reach the boundary.

Conclusions

- First simulation of a holographic non-conformal model for heavy ion collisions:
  - Fast hydrodynamization at early time
    despite non-trivial equation of state
    despite sizeable ζ/s bulk viscosity over entropy
  - New relaxation channel from bulk viscosity: *EoSization*
  - Conservative estimate $\zeta/s \approx 0.025$ for non-conformal effects
  - Universal response of the scalar condensate