Emergence of collectivity near a critical point

Maximilian Attems

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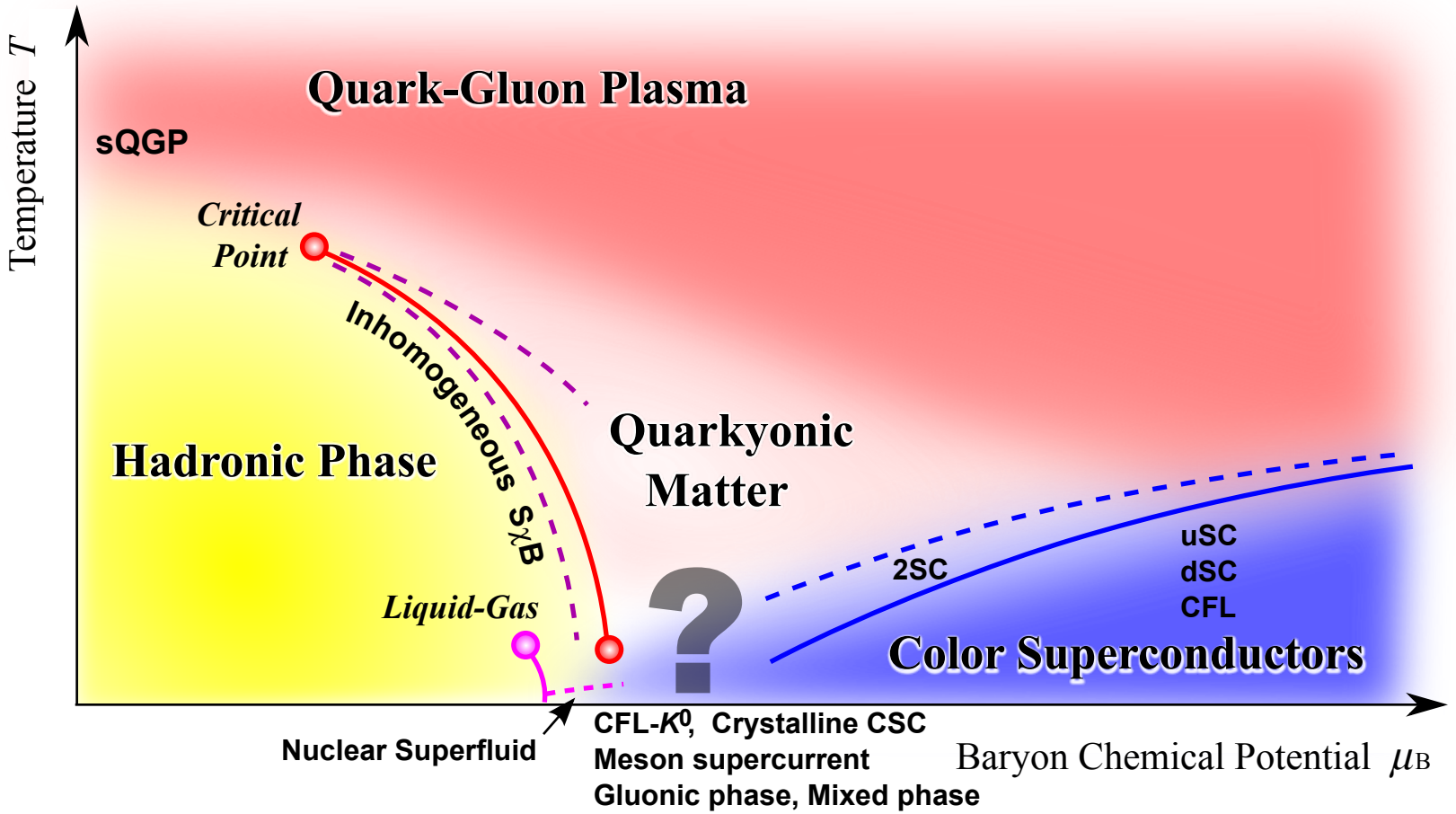
2nd joint workshop IGFAE/LIP

Motivation I - QCD phase diagram

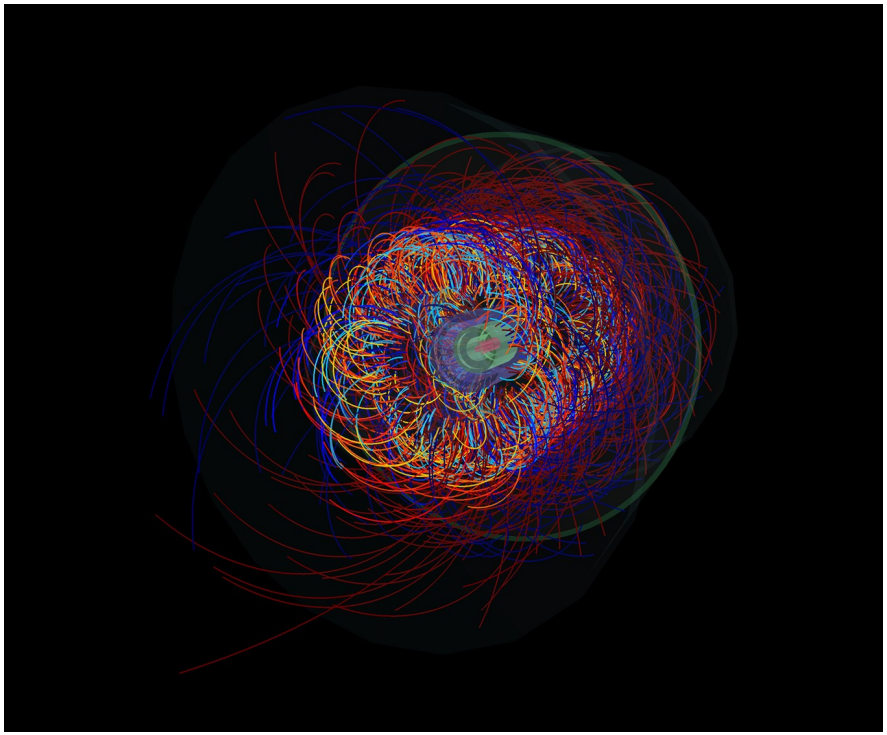
RHIC and FAIR colliders search for the critical point,
the endpoint of the phase transition between QGP and Hadrons:



Crucial to probe dynamical properties of a critical point
[Fukushima, Hatsudo 2010]

Motivation II - model building

Quark-Gluon Plasma:



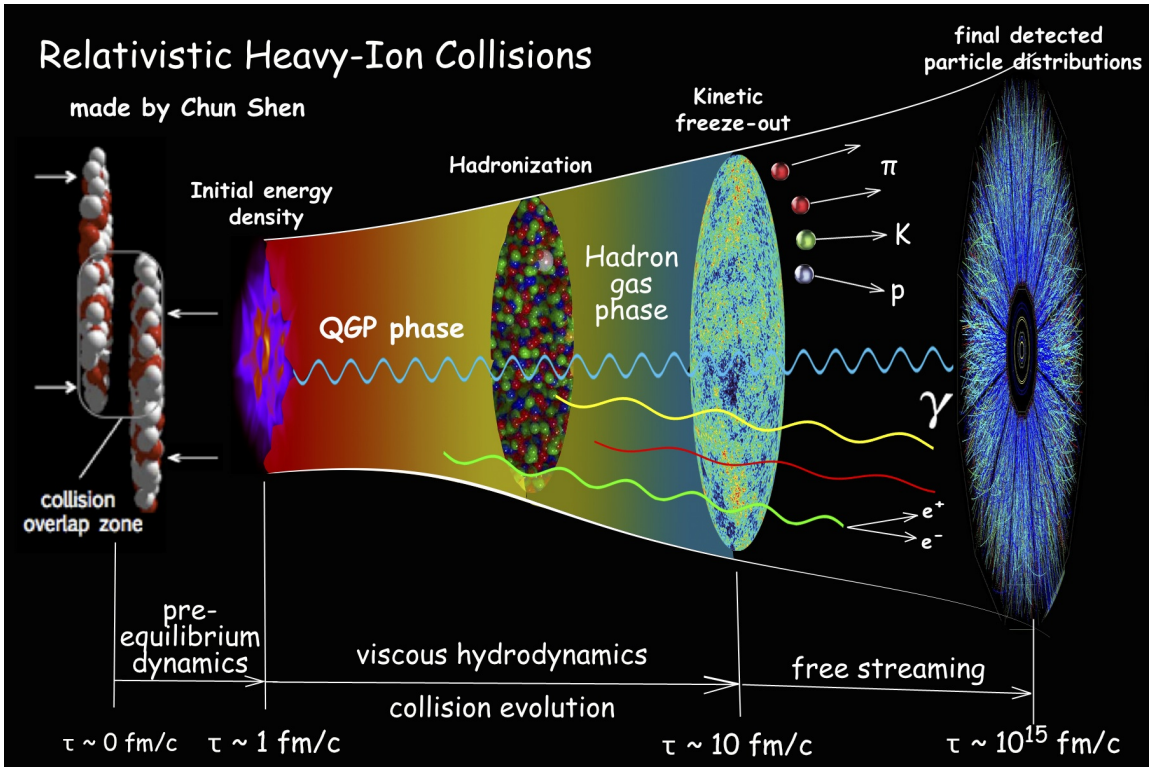
LHC reconstructed event from the first heavy ion collisions [ALICE 2010]

Black Holes:

First Black Hole image (M87)
[Event Horizon Telescope Collaboration 2019]

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

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?

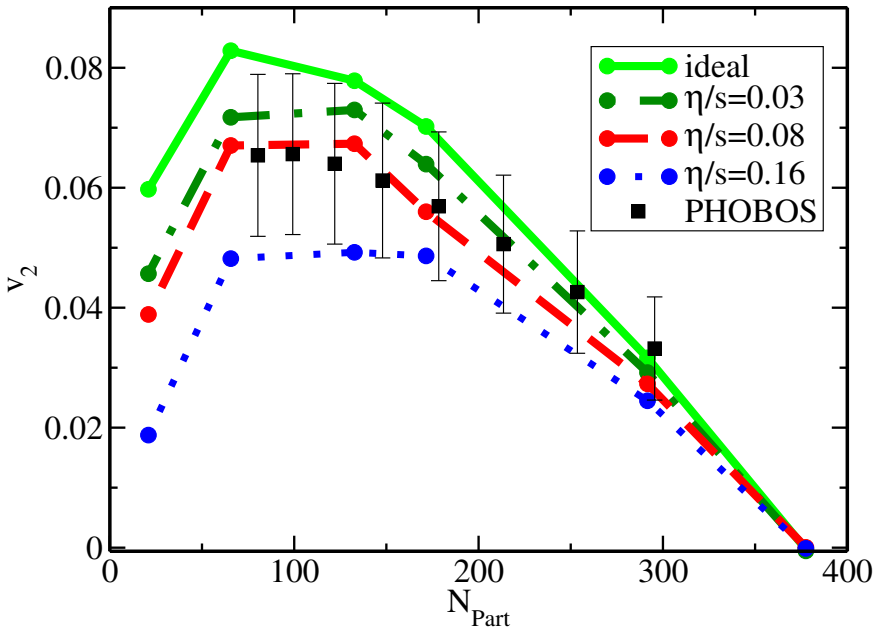
How long is the first stage? LHC Data indicates $\leq 10^{-23}$ **s**

What determines when hydro becomes applicable?

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

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]

Quark-Gluon Plasma

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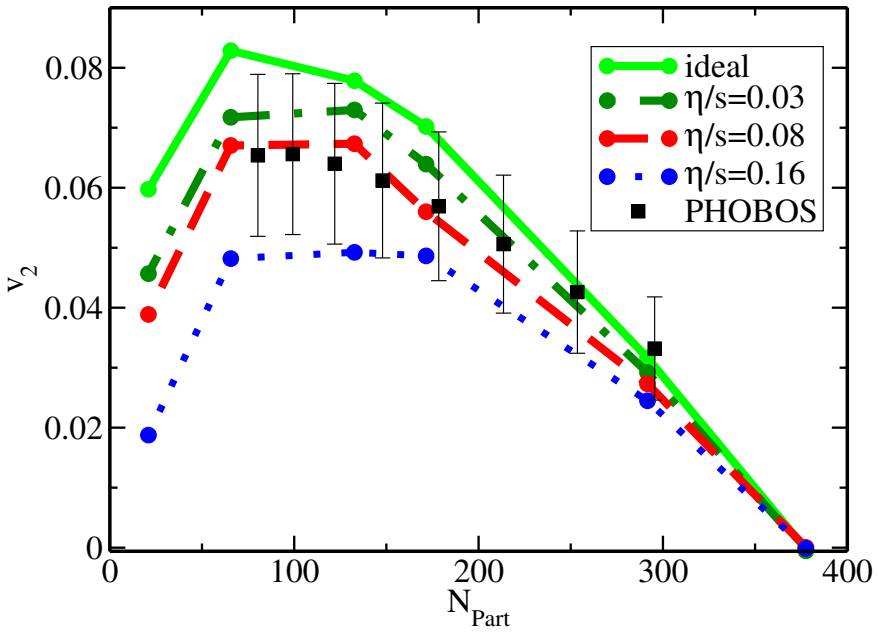

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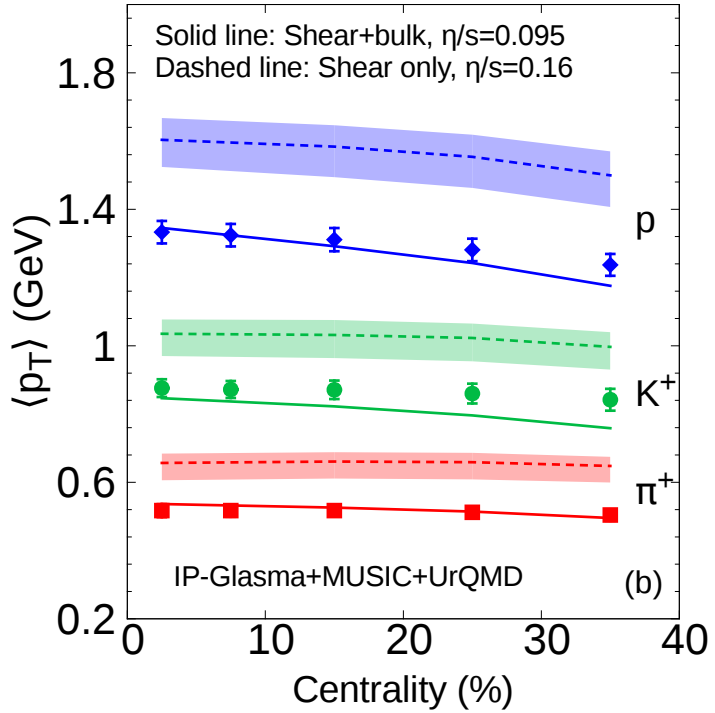
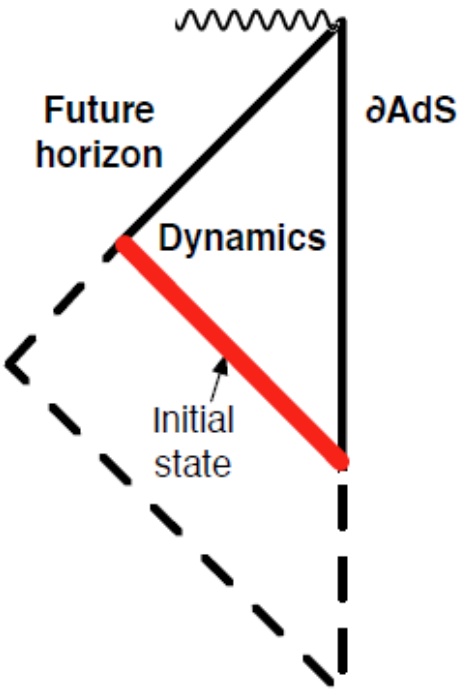
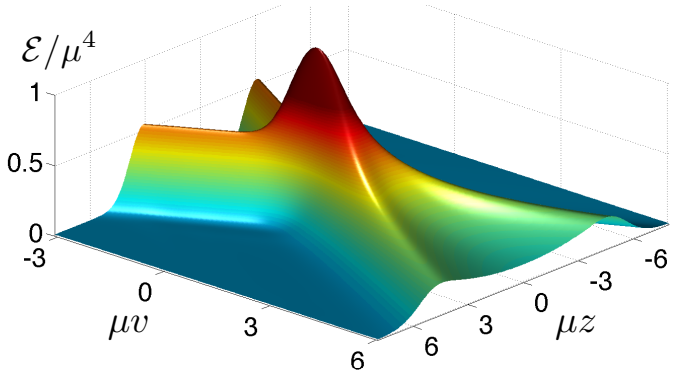


Hydro simulation agreement improves with bulk viscosity ζ

[Denicol *et al.* 2015]

Out-of-equilibrium challenges





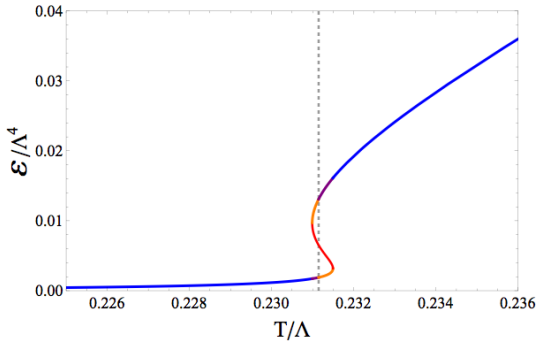
Strong coupling toolkit for out of equilibrium dynamics:

Fast hydrodynamization with first shockwave 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]

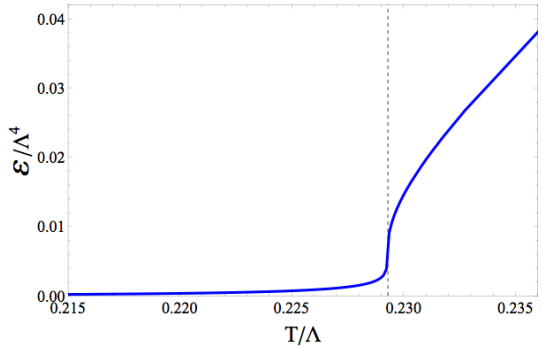
EoSization: seen in first non-conformal temperature scan new non-conformal relaxation time scale (= when ideal equation of state applies) [MA et al. 2016/2017]

Collisions near a critical point

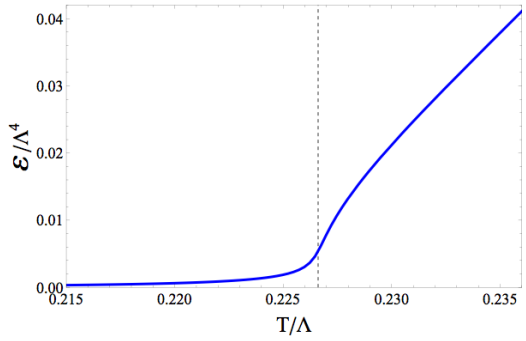
1st order:



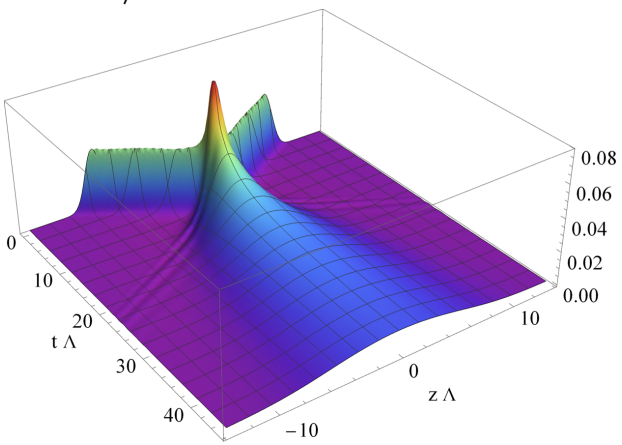
2nd order:



crossover:



$10^2\ \mathcal{E}/\Lambda^4$



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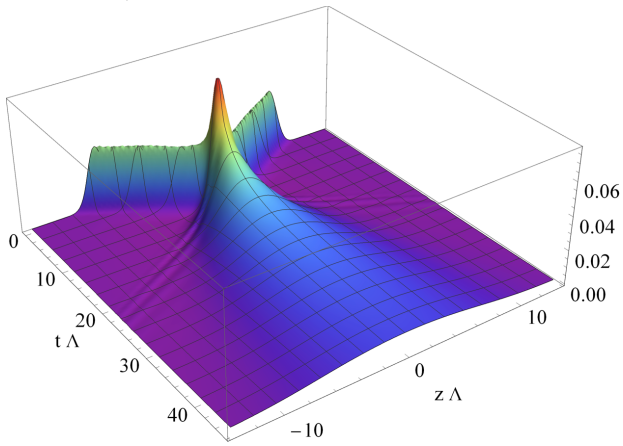

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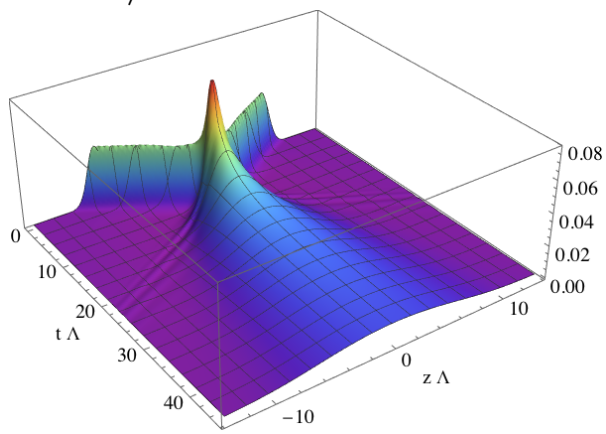
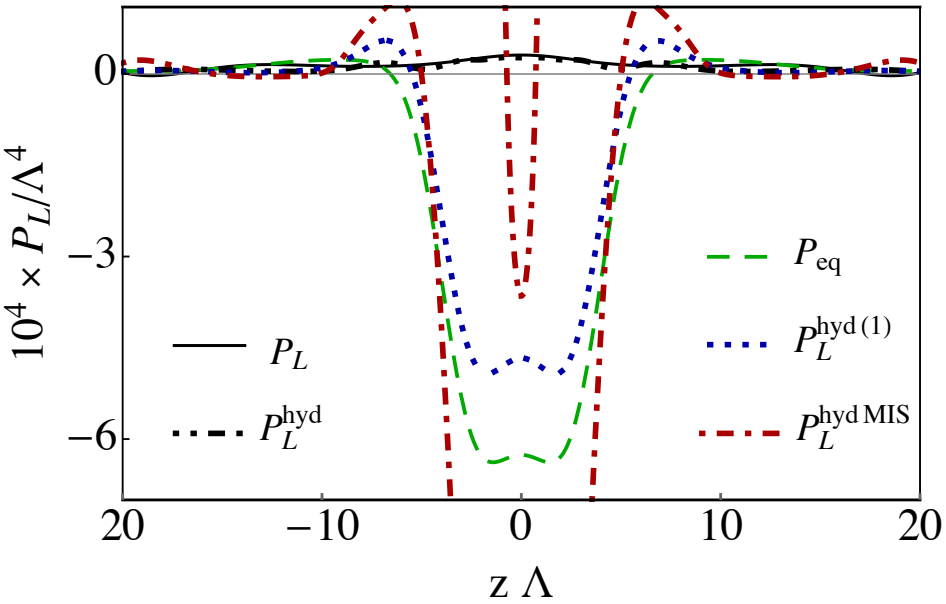
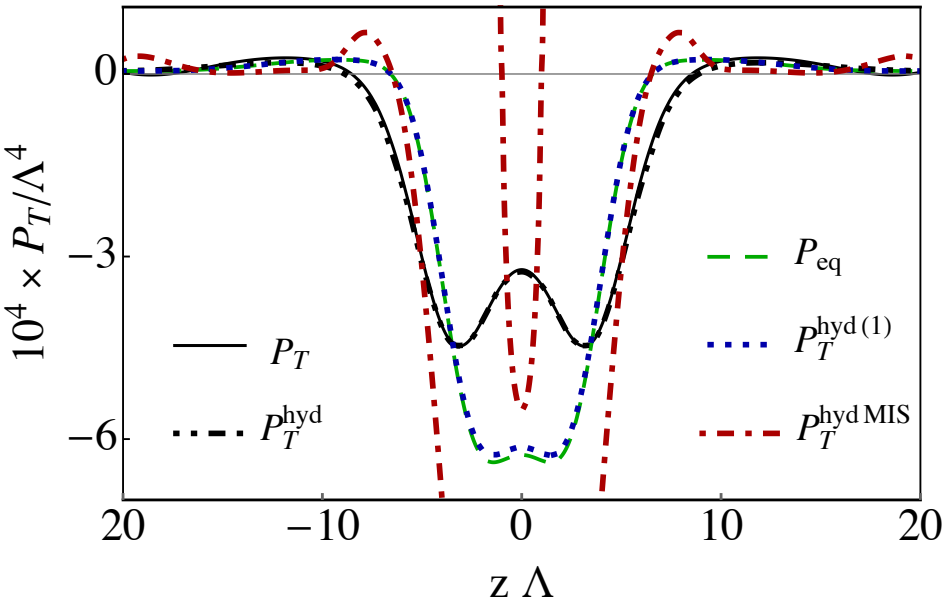


Discovers long-lived, quasi-static blob of energy at mid-rapidity, with slow down of the dynamics, no remnants [MA et al. 2018]

Pressures near a critical point

Müller-Israel-Stewart-type hydrodynamics fails to describe the pressure evolution at mid rapidity in the formed blob ($t\Lambda = 50$):

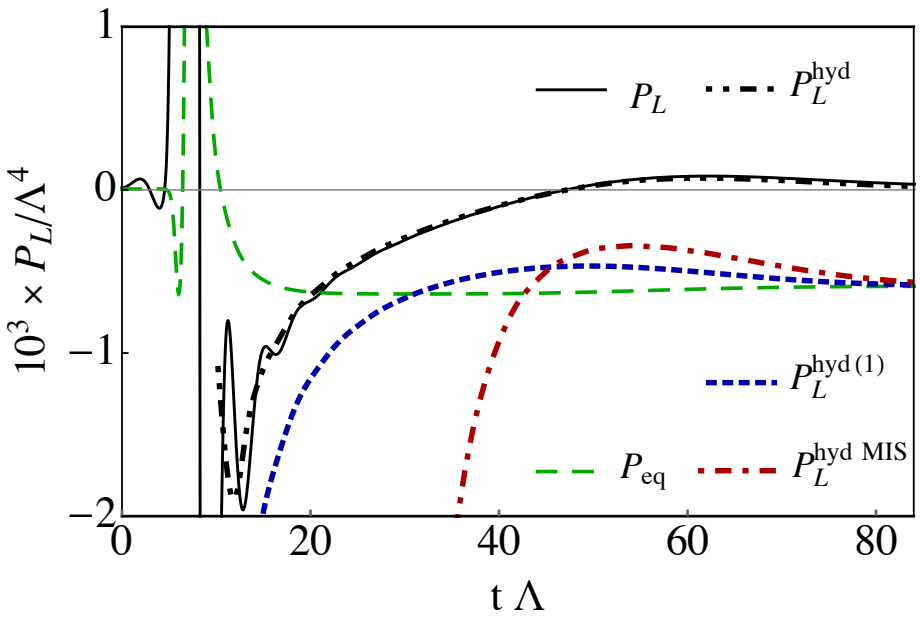


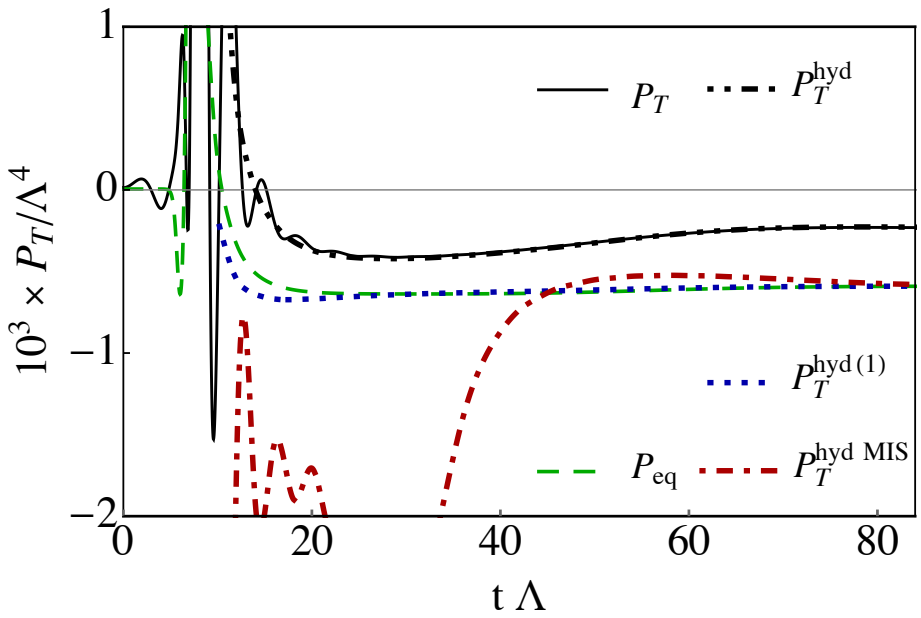


Well described by the constitutive relations of second-order hydrodynamics that include all spatial second-order gradients.

Pressure evolution near a critical point

Differences to QCD: no dynamical baryon charge density, no conserved order parameter, fluctuations $1/N_c^2$ suppressed
Similarities to QCD: vanishing speed of sound, large bulk viscosity





Need of a new causal hydrodynamics formulation near CP with suppressed first order gradients, but large second-order purely spatial gradients.

Conclusions

- New example of the applicability of hydrodynamics to systems with large gradients in energy densities - even in non-trivial phase structure
- First simulation of holographic heavy-ion collisions near a critical point
- Fluid slows down near CP to a long-lived, quasi-static blob
- MIS hydrodynamics fails near a critical-point
  - missing 2nd order spacial derivatives
- More studies on the way: spinodal instability, baryonic matter