Holographic Heavy Ion Collisions in Non-Conformal Theories

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July 12 2016, GR21, New York, USA

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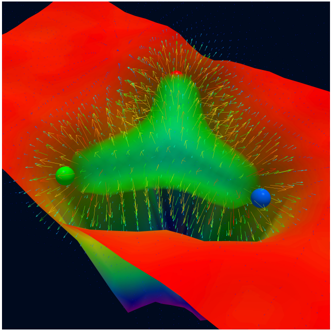
QCD

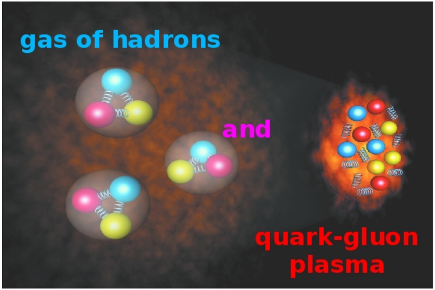
A non-Abelian gauge field theory with Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$



- The theory of strong interactions
- Very difficult to study
- Peculiar properties:
  - Confinement
  - Asymptotic freedom

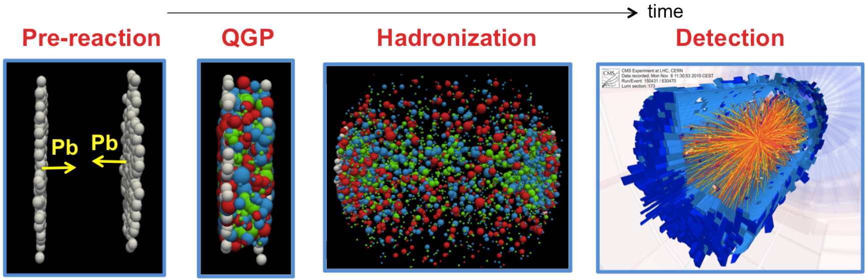
A new phase: Quark-Gluon Plasma



- $T \ll T_c$: Hadron Gas. Colour is confined;
- $T \sim T_c \sim 10^{12}K$: Rapid crossover;
- $T \gg T_c$: Quark-Gluon Plasma. Gas of quarks and gluons; colour is liberated;

In today's large accelerators, QGP can be created in a heavy-ion collision

Ultra-relativistic heavy-ion collisions

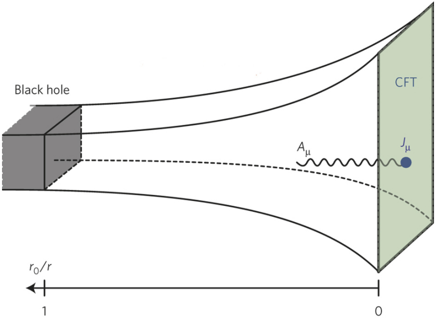


two nuclei approach, collide, form a QGP, the QGP expands and hadronizes, finally hadrons rescatter and freeze out

AdS/CFT

$\mathcal{N} = 4$ super-Yang-Mills is dual to IIB string theory on $AdS_5 \times S_5$

[Maldacena, Gubser, Klebanov, Polyakov, Witten 1998]



- We can learn about strongly coupled phenomena through gravity computations

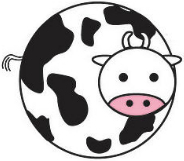
AdS/CFT

QCD

- non-conformal
- confinement
- not supersymmetric

$\mathcal{N} = 4$ SYM

- conformally invariant
- no confinement
- supersymmetric



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Einstein-Scalar

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\pi T_{\mu\nu} \,,$$
$$\Box\phi = \frac{\partial V}{\partial \phi} \,,$$

where

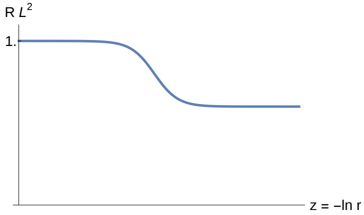
$$8\pi T_{\mu\nu} = 2\partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi + 2V(\phi)\right) \,,$$
$$V(\phi) = -3 - \frac{3}{2}\phi^2 - \frac{1}{3}\phi^4 + \left(\frac{1}{2\phi_{\rm M}^4} + \frac{1}{3\phi_{\rm M}^2}\right)\phi^6 - \frac{1}{12\phi_{\rm M}^4}\phi^8 \,,$$

$\phi_{\rm M}$ is a free parameter

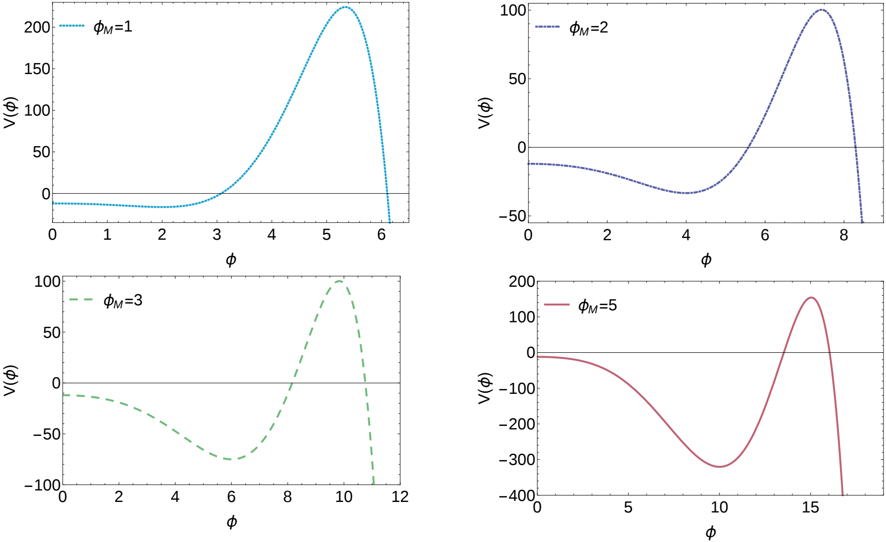
Scalar field

Deforming $\mathcal{N} = 4$ Super Yang-Mills with a dimension 3 operator $\mathcal{O}$ dual to the scalar field ϕ

We choose V to interpolate between two AdS spaces:



Potential shapes



with varying ϕ_M parameter

Characteristic formulation

$D = 5$ metric in Eddington-Finkelstein coordinates

$$ds^2 = -Adt^2 + \Sigma^2 \left(e^B dx_\perp^2 + e^{-2B} dz^2 \right) + 2dt(dr + Fdz) \,,$$

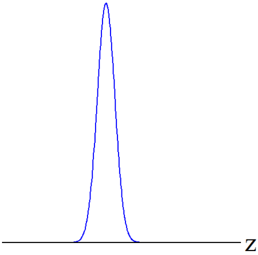
Schematic evolution equations:

$$\begin{aligned} \partial_r S &= H_S(S, B) \\ \partial_t \partial_r B &= H_B(B, S, \partial_t B) \end{aligned}$$

Advantages of characteristic evolution

- Initial data is free (no elliptic constraints on the data);
- No second time derivatives (therefore smaller number of basic variables);
- Equations have convenient hierarchical structure in which variables are integrated in turn in terms of characteristic data from prior members of the hierarchy.

Initial data



$$ds^2 = \frac{du^2}{u^2} + e^{2A(u)}(-dz_+ dz_- + d\mathbf{x}_\perp^2) + f(u)h(z_\pm)dz_\pm^2$$

$$e^{2A} = \frac{\Lambda^2}{\phi^2}\left(1 - \frac{\phi^2}{\phi_M^2}\right)^{\frac{\phi_M^2}{6}+1} e^{-\frac{\phi^2}{6}}$$

$$\phi = \frac{\Lambda\, u}{\sqrt{1 + \frac{\phi_0^2}{\phi_M^2} u^2}}$$

Using the Gaussian profile (h height, ω width):

$$h(z_\pm) = \frac{\mu^3}{w\sqrt{2\pi}}\, e^{-z_\pm^2/2\omega^2}$$

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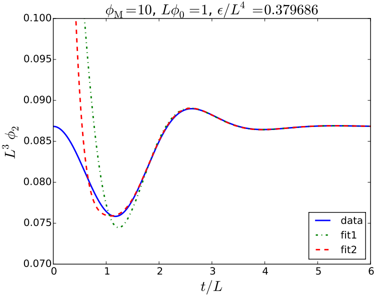
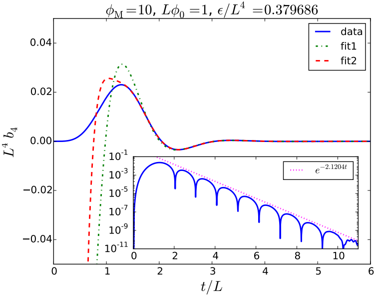
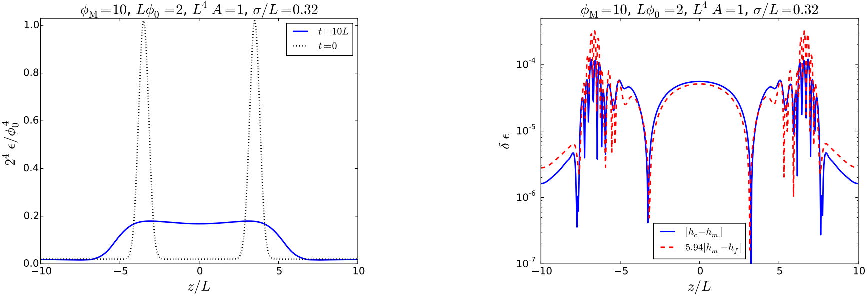
Quasi-Normal Modes





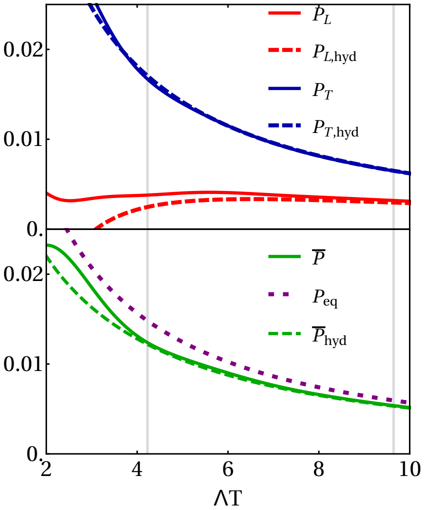
- Excellent agreement with perturbative computations

Convergence analysis



- Results show fourth order convergence

Hydrodynamics: pressure evolution



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

Hydrodynamization:

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

Equilibration:

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

Outline

Final Remarks

- Collisions in AdS spaces provide convenient framework to study heavy-ion collisions.
- First simulation of a holographic non-conformal model for heavy-ion collisions.
- Hydrodynamics becomes successful even before the equation of state is satisfied (equilibration).
- TODO:
  - explore parameter space;
  - asymmetrical collisions;
  - different potentials;