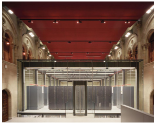


Holographic Heavy Ion Collisions in Non-Conformal Theories

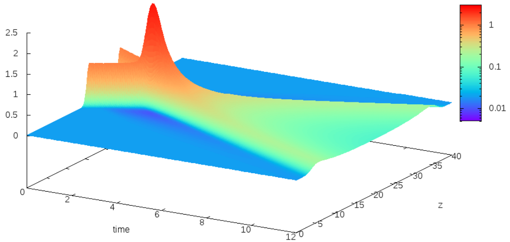
Maximilian Attems

arXiv:1603.01254 **arXiv:1604.06439**

Collaborators: Jorge Casalderrey-Solana, David Mateos, Ioannis Papadimitriou, Daniel Santos, Carlos Sopuerta, Miquel Triana i Iglesias, Miguel Zilhao

NumHol2016

Motivations I

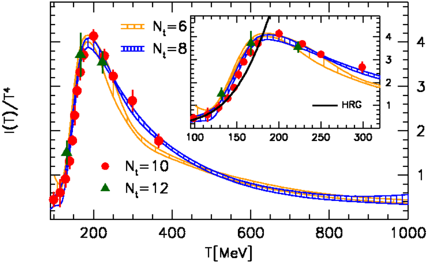


Non-conformal holographic shockwaves

Far from equilibrium dynamics:

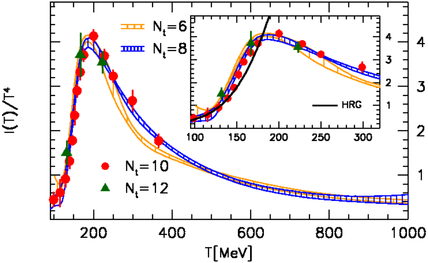
- at strong coupling
- fast hydrodynamization time
- IC hydrodynamics

Motivations II

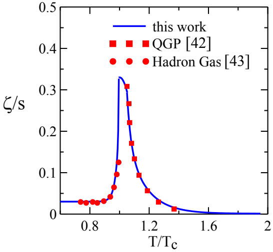


[S. Borsanyi *et alii* arXiv:1007.2580 [hep-lat]]

Motivations II

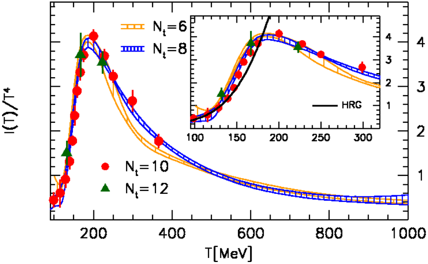


[S. Borsanyi *et alii* arXiv:1007.2580 [hep-lat]]

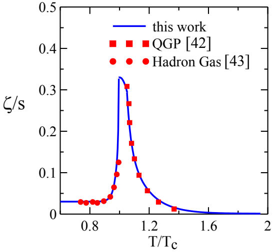


[Denicol *et alii* arXiv:0903.3595 [hep-ph]]

Motivations II

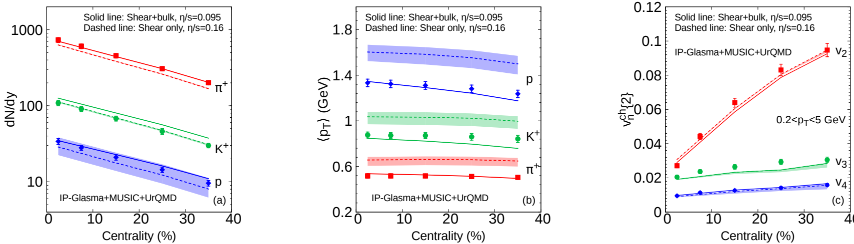


[S. Borsanyi *et alii* arXiv:1007.2580 [hep-lat]]



[Denicol *et alii* arXiv:0903.3595 [hep-ph]]

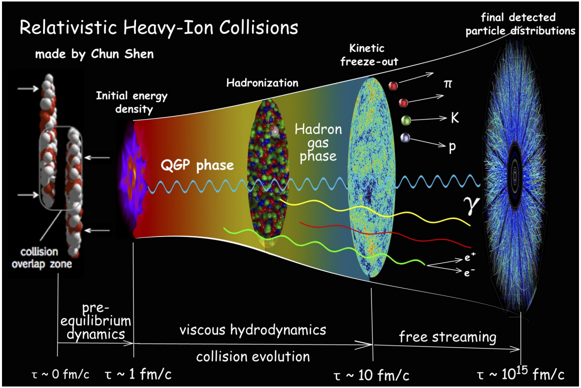
Hydro simulation agreement improves with bulk viscosity:



[Denicol *et alii* arXiv:1502.01675 [nucl-th]]

Outline

1. Non-conformal shockwave collisions
   - Heavy-Ion collision
   - General Relativity setup
   - Scalar potential
   - Interaction measure
   - Bulk viscosity
   - Buchel bound
   - Quasi-Normal-Modes
   - Shockwaves Initial Conditions
   - Hydrodynamization / equilibration time
   - Non-conformal temperature scan



Stages:

1) Early out of equilibrium

2) Quark-Gluon Plasma

3) Particularization

Can we describe all the stages at strong coupling?

Yes! (up to the last one)

Shockwave collisions in N=4 SYM

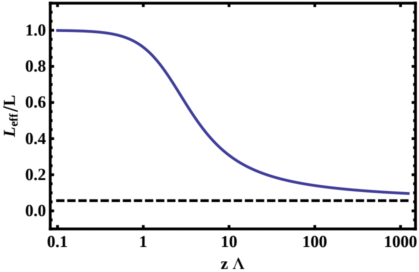
[Chesler, Yaffe 11; Albacete, Kovchegov, Taliotis 08; Grumiller, Romatschke 08]

Einstein-Hilbert action with scalar potential in five-dimensional bottom-up model:

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

Potential $V(\phi)$ interpolating between two AdS with L radius of the UV AdS solution:

$$ds^2 = \frac{L_{\text{eff}}(z)^2}{z^2} \left(-dt^2 + d\mathbf{x}^2 + dz^2 \right) .$$



Scalar potential

$V(\phi)$ depends on single parameter $\phi_{\mathbf{M}}$, setting non-conformality for this bottom-up model:

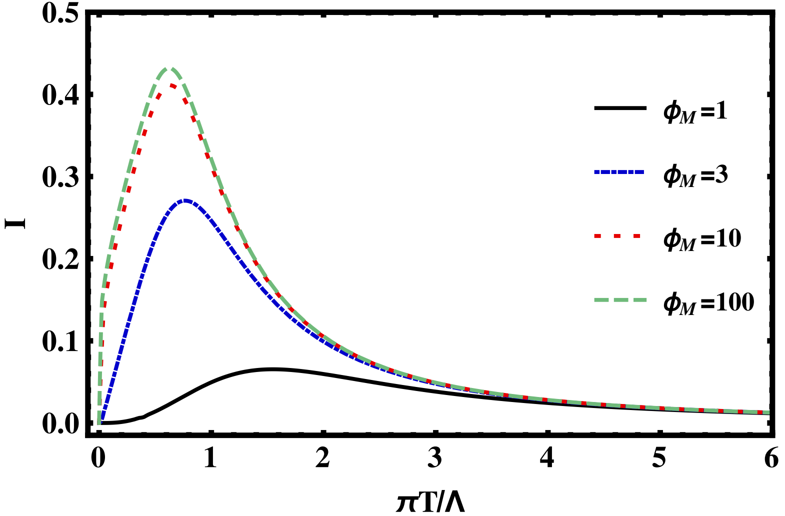
$$L^2 V(\phi) = -\frac{1}{12\phi_M^4}\phi^8 + \left(\frac{1}{2\phi_M^4} + \frac{1}{3\phi_M^2}\right)\phi^6 - \frac{1}{3}\phi^3 - \frac{3}{2}\phi^2 - 3\,.$$

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

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

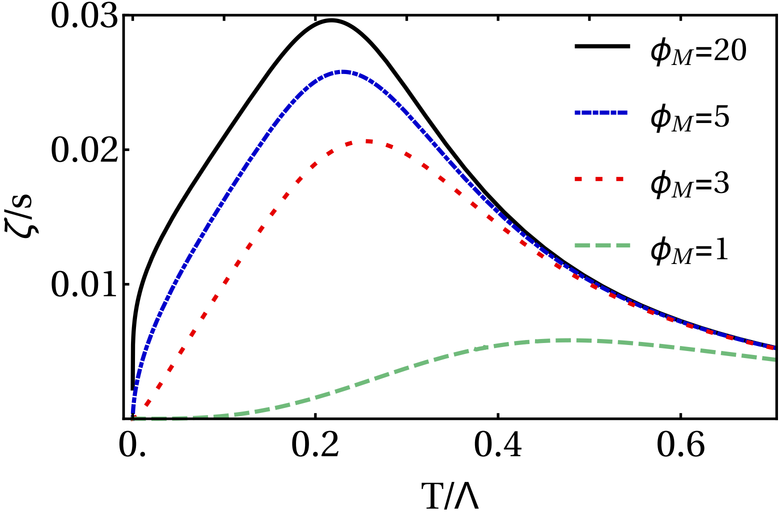
The source Λ triggers RG flow responsible for the breaking of conformal invariance.

Non-conformality measure as function of the temperature:



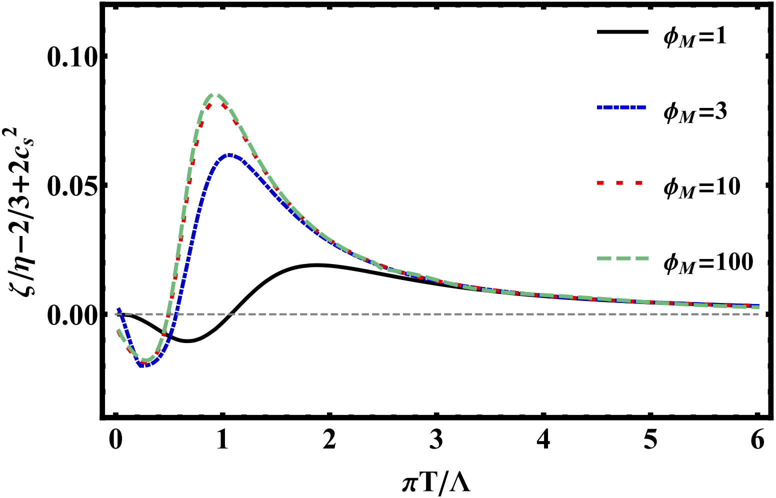
conformal at low and high T, **non-conformal** in between

Ratio of bulk viscosity over entropy as a function of temperature:



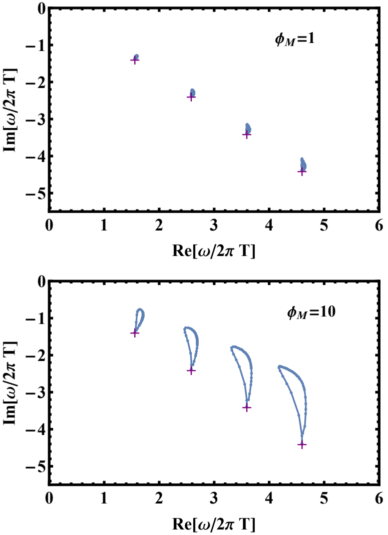
non-conformal behaviour reflects in transport coefficients

Violation of Buchel's bound at low temperatures:



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

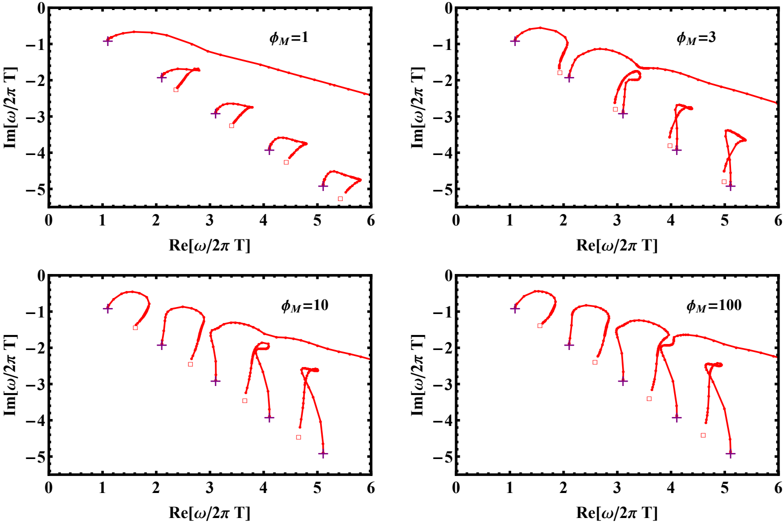
anisotropic perturbation $Z_{\text{aniso}} = e^{-2A}(h_{zz} - h_{aa})$



Fluctuations of the stress energy tensor

Quasi-Normal-Modes

non-conformal mode $Z_{\mathrm{bulk}} = \phi - \frac{e^{-2A(\phi)}}{2A'(\phi)} h_{aa}$



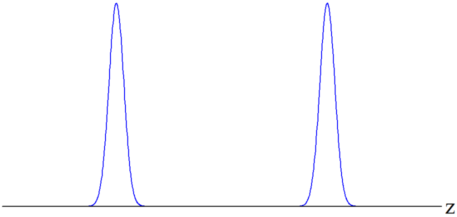
n-th scalar mode decoupling with anti-crossing

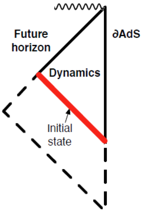
Shockwaves Initial Conditions

5D metric Ansatz in Eddington-Finkelstein:

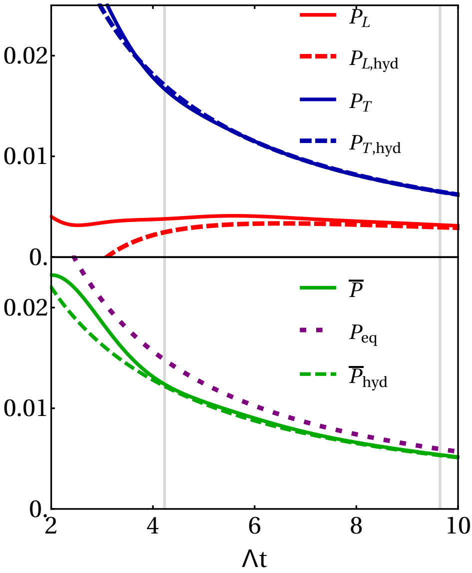
$$ds^2 = -Adt^2 + \Sigma^2 \left(e^B d\boldsymbol{x}_\perp^2 + e^{-2B} dz^2 \right) + 2dt(dr + Fdz)$$

- Field theory interpretation:
  - Defined by energy density
  - Move in AdS5 space
  - Demand that shockwaves move at speed of light
  - Quantum state/AdS geometry completely fixed for pure gravity
- Homogeneous in transverse plane (‘infinite nucleus’)





Hydrodynamization / equilibration time



Hydrodynamics assumes mean free path goes to zero:

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

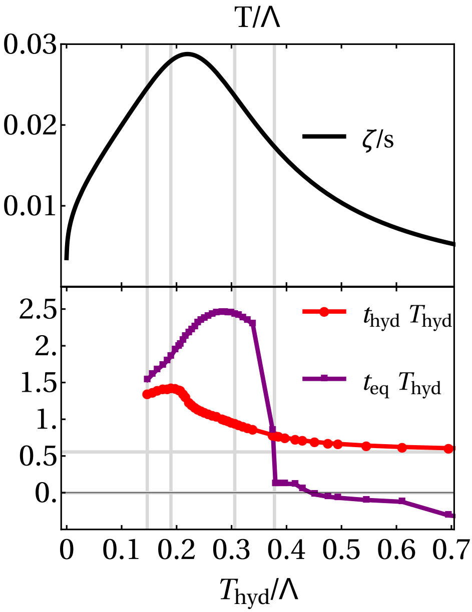
Hydrodynamization:

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

Equilibration:

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

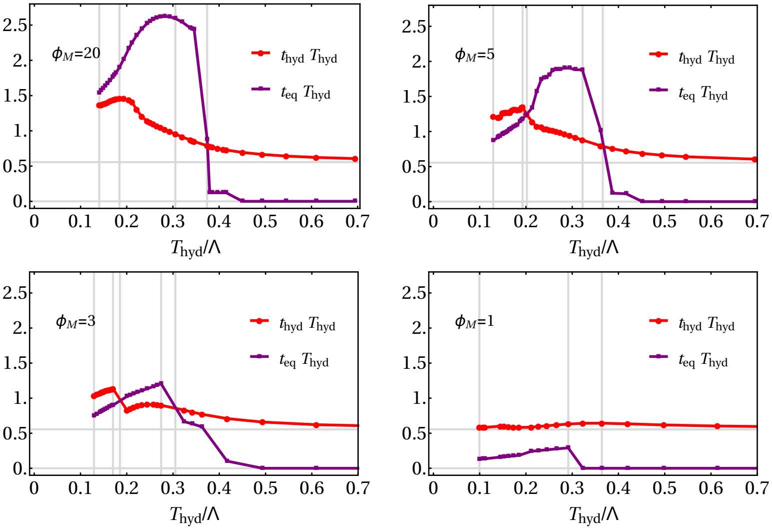
hydrodynamization ≠ equilibration ≠ isotropization



Non-conformal T scan:

- EOS does NOT hold out of equilibrium
- t_{hyd} slow down
- ordering of t_{eq} and t_{hyd} depends on bulk viscosity
- required ζ 1/10 of QCD at T_c

Non-conformal temperature scan



$\zeta/s \approx 0.02$ for $t_{eq} > t_{hyd}$

Conclusions

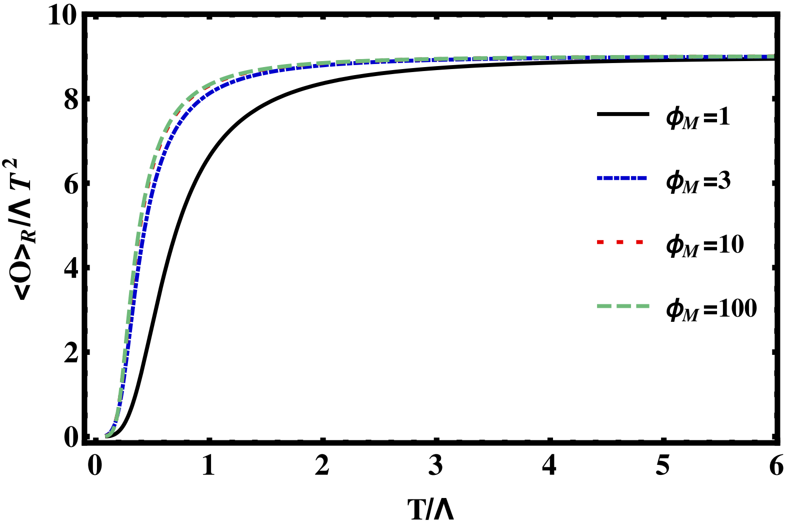
- First simulation of a holographic non-conformal model for heavy ion collisions

- New relaxation channel from bulk viscosity:
  hydrodynamization without equilibration

- Hydrodynamics works at early time (though max delayed ≈ 3)
  despite non-trivial equation of state
  despite sizeable ζ/s bulk viscosity over entropy

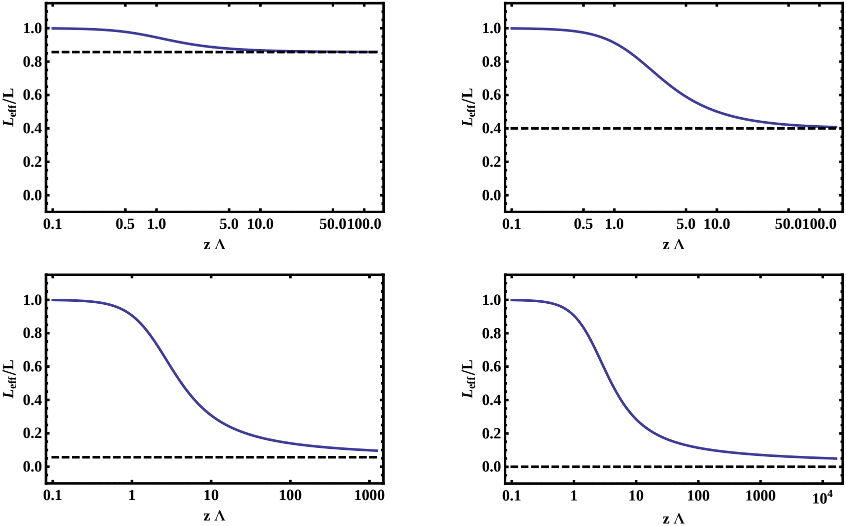
- More studies are on the way:
  - Systematic exploration of parameter space on *MareNostrum*
  - Asymmetrical collisions
  - Holographic energy scan
  - Different potentials

Backup: VEV



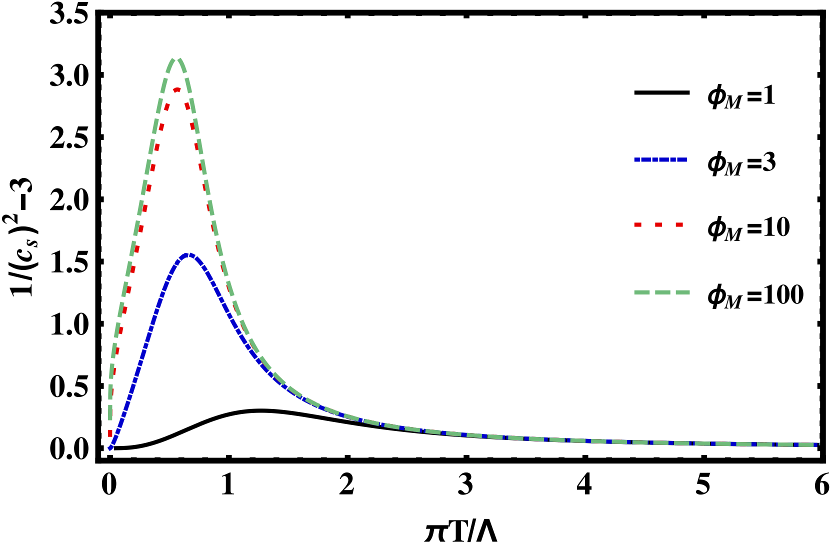
Temperature dependence of the VEV of the scalar operator $\langle\mathcal{O}\rangle_T$ for several values of ϕ_M. $\langle\mathcal{O}\rangle_R = \kappa_5^2 \langle\mathcal{O}\rangle_T / L^3$, $\epsilon - 3p = \Lambda \langle\mathcal{O}\rangle_T$.

Backup: Non-conformal effects



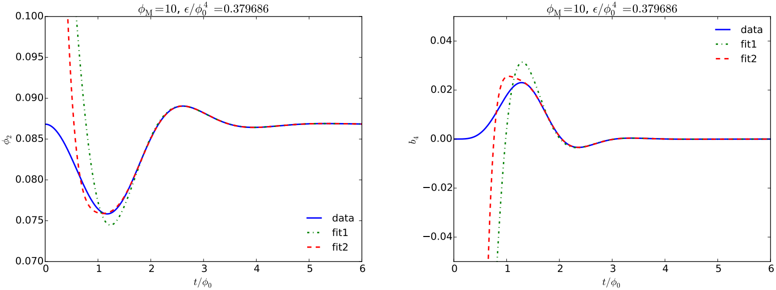
$$ds^2 = \frac{L_{\rm eff}(z)^2}{z^2}\left(-dt^2 + d\mathbf{x}^2 + dz^2\right) \,.$$

Backup: Speed of sound



Inverse speed of sound square as a function of T

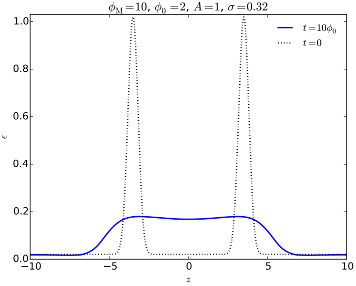
ϕ_2 and b_4 as functions of time for a z-independent configuration

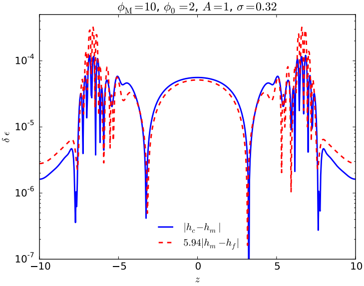


Blue full line corresponds to data from the code, green dash-dotted line correspond to a fit to the data using one QNM, red dashed line corresponds to a fit using two QNMs as explained in the text.

Backup: Convergence analysis

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





The results show fourth-order convergence.