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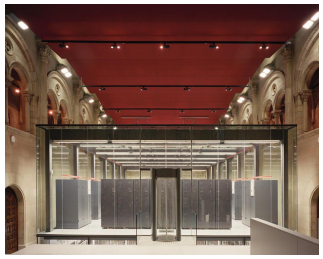

MARIE CURIE ACTIONS

Hydrodynamization of shockwave collisons in non-conformal theories

Maximilian Attems

arXiv:1603.01254 **arXiv:1604.06439** **arXiv:1701.xxxxx**

Collaborators: Jorge Casalderrey-Solana (Oxford), David Mateos (ICREA), Carlos Sopuerta (LISA), Miguel Zilhao (UB) et alii

33rd Winter Workshop on Nuclear Dynamics

Motivations I

Holography is a unique and powerful tool capable to explore an unexplored regime of quantum dynamics.

The AdS/CFT correspondence builds a bridge between problems from the Quantum world and methods from General Relativity.

In the fully non-linear regime the use of numerical methods is instrumental.

$\mathcal{N} = 4$ SYM properties:

- $\eta/s \geq 1/4\pi$
- supersymmetric
- conformal
- $\mathcal{N}_c \to \infty$

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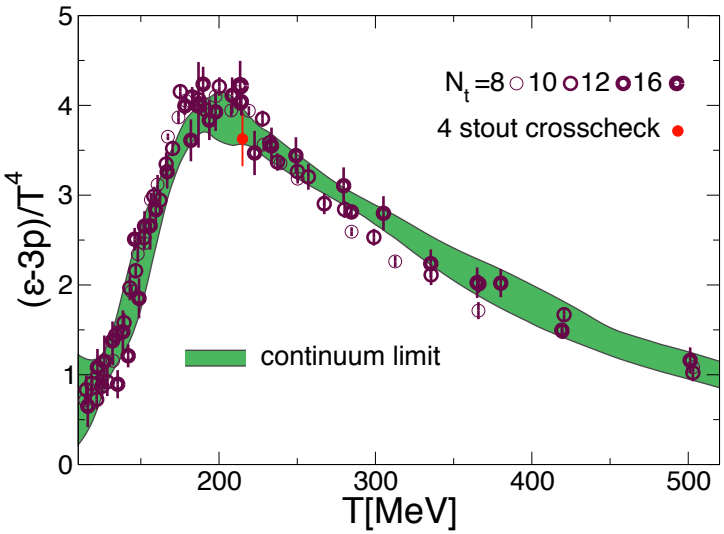
Far from equilibrium dynamics:

- at strong coupling
- non-perturtabitave
- fast hydrodynamization time
- IC hydrodynamics

Motivations II



[S. Borsanyi *et alii* arXiv:1309.5258 [hep-lat]]

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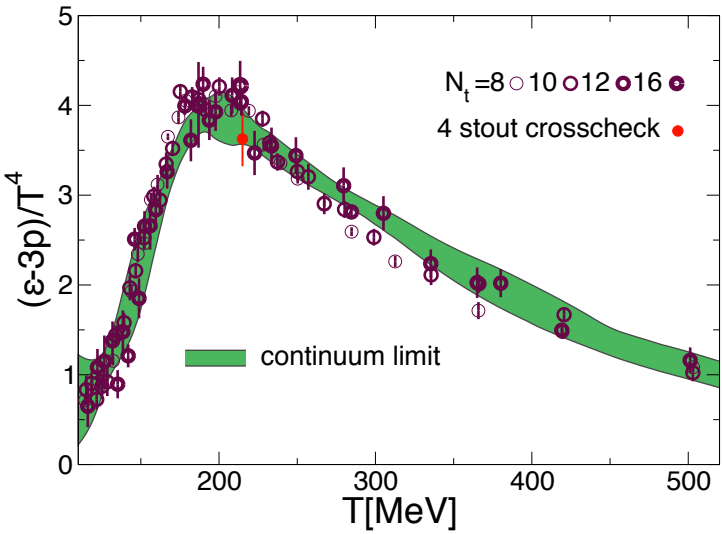

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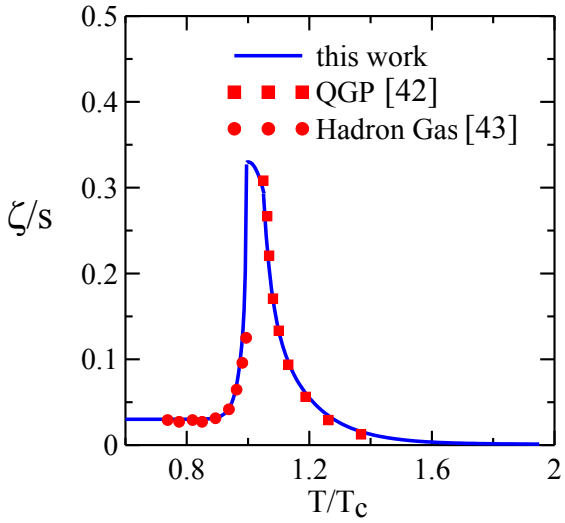

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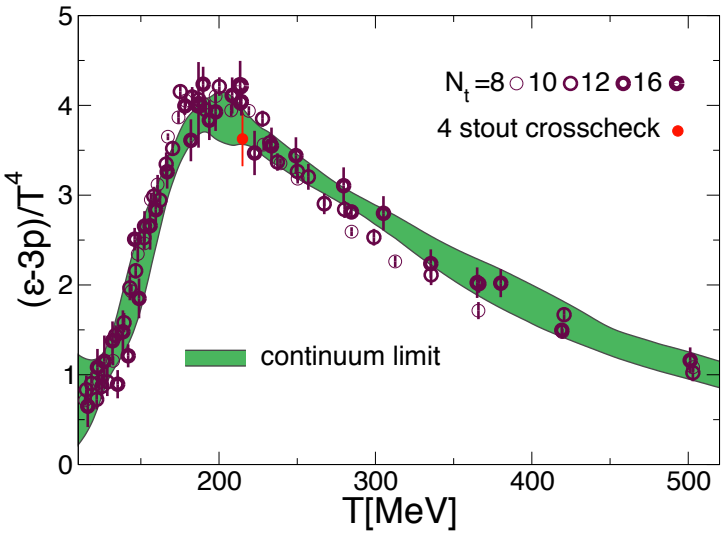

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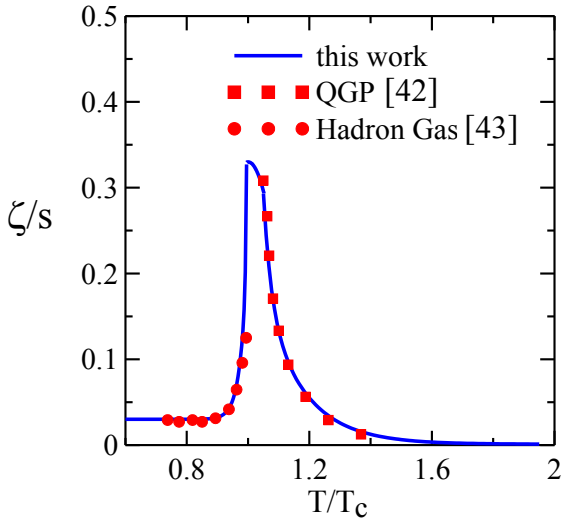

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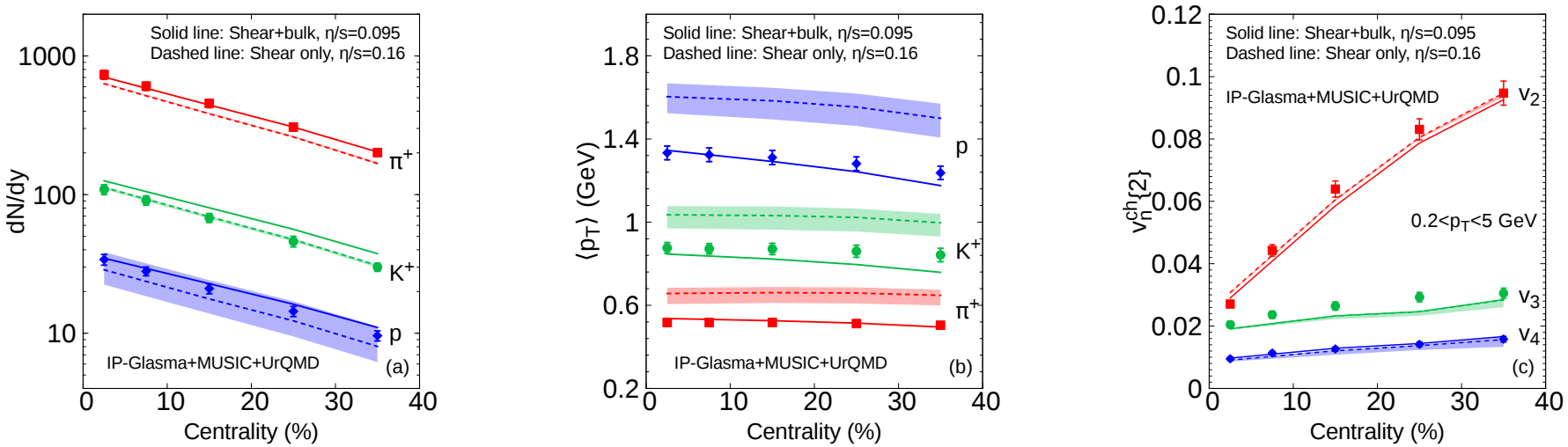
Hydro simulation agreement improves with bulk viscosity:



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

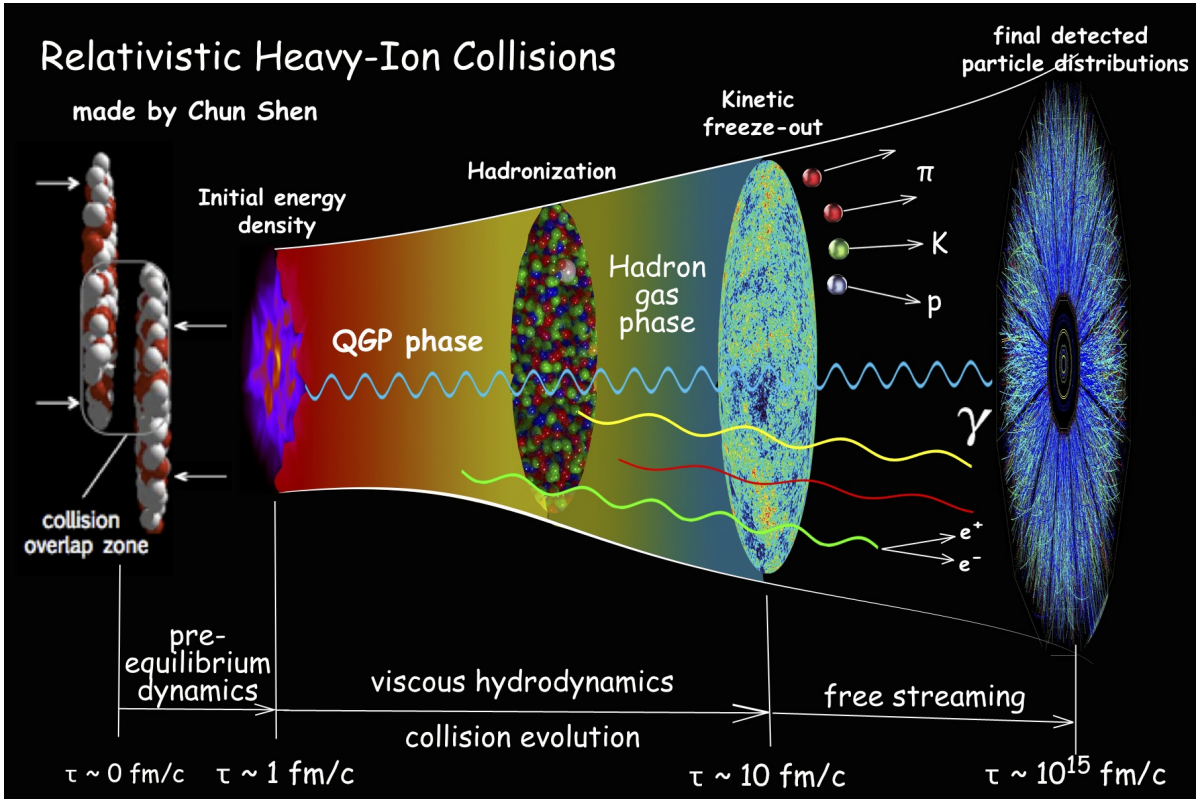
Outline

Non-conformal bottom-up thermodynamics

- Heavy-Ion collision
- General Relativity setup
- Scalar potential
- Equilibrium pressure
- Interaction measure
- Speed of sound
- Bulk viscosity
- Buchel bound
- Quasi-Normal-Modes

Dynamics of the scalar potential

Heavy-Ion collision - little bang



Stages:
1) Early out of equilibrium

2) Quark-Gluon Plasma

3) Hot Hadron Gas

Can we describe the first two stages at strong coupling? **Yes!**

AdS/CFT provides setups for strongly coupled phenomena that can be compared to heavy-ion collisions:
Shockwave collisions in N=4 SYM
[Chesler, Yaffe 11; Albacete, Kovchegov, Taliotis 08; Grumiller, Romatschke 08]

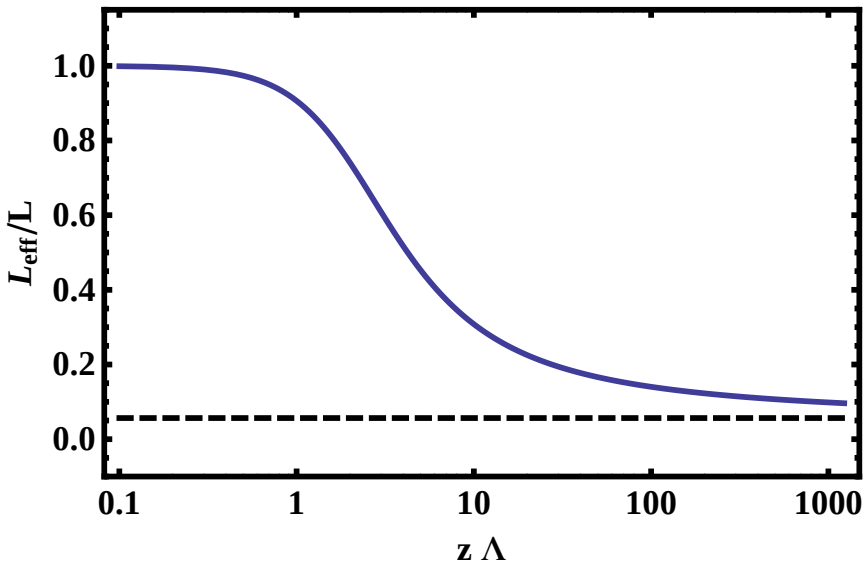
General Relativity setup

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

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

On the gravity side the flow is dual to a domain-wall geometry 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:

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

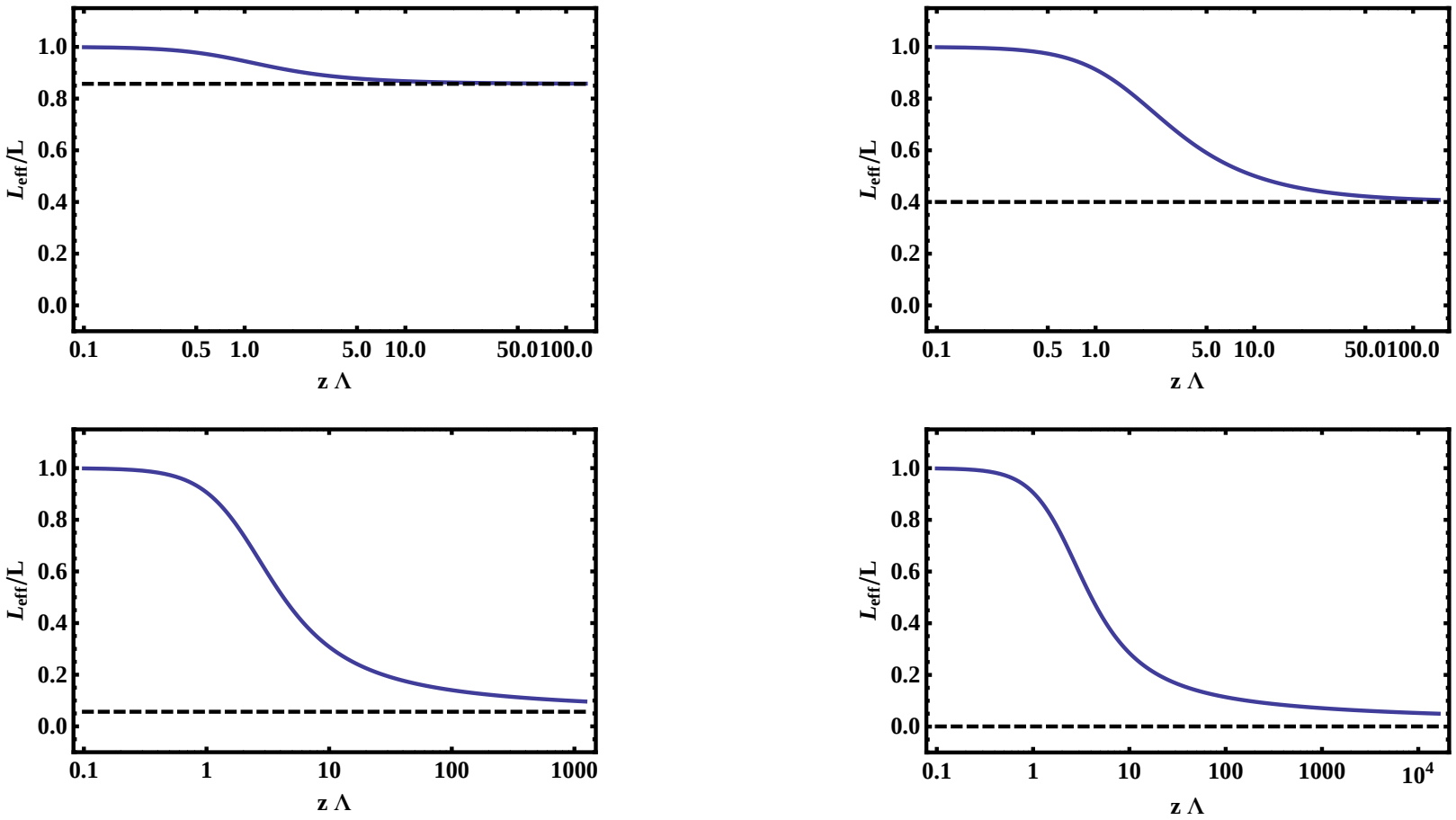
Deforming $\mathcal{N} = 4$ Super Yang-Mills with an dimension 3 operator $\mathcal{O}$ dual to the scalar field ϕ.

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

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

Non-conformal effects

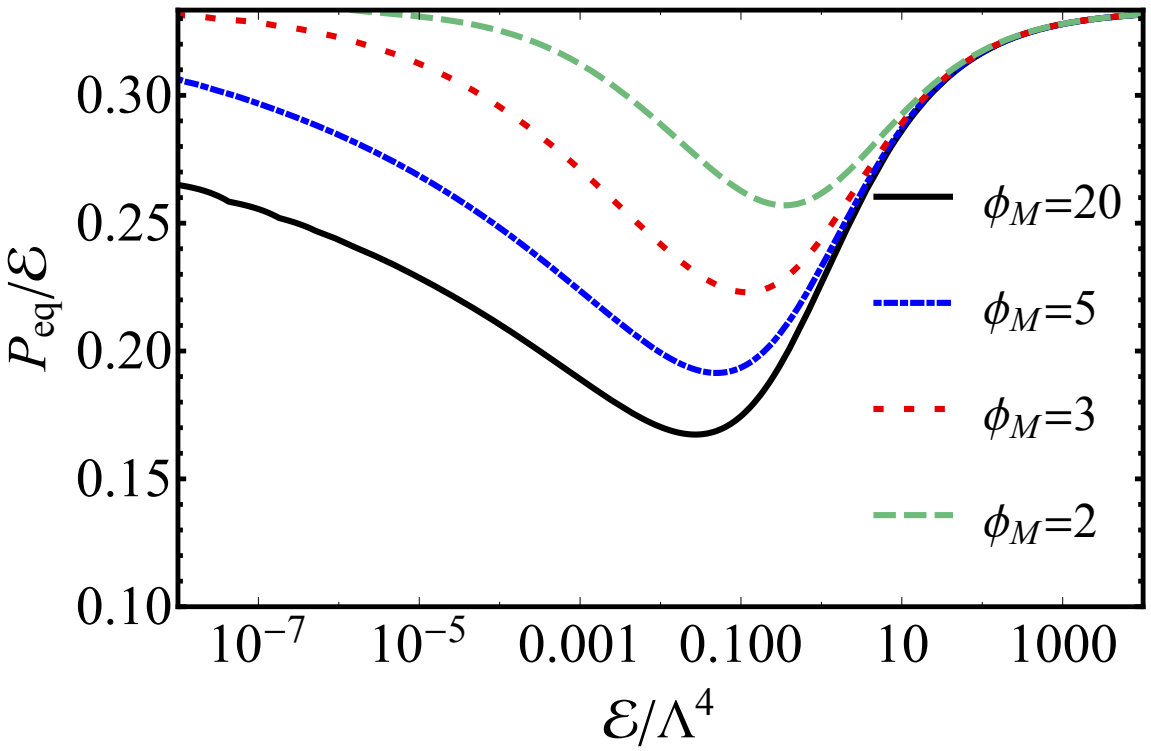
Change of variable in the holographic direction shows different approach to IR fixed point for $phi_M = \{1, 3, 10, 100\}$



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

Equilibrium pressure

Equilibrium pressure as a function of energy density:

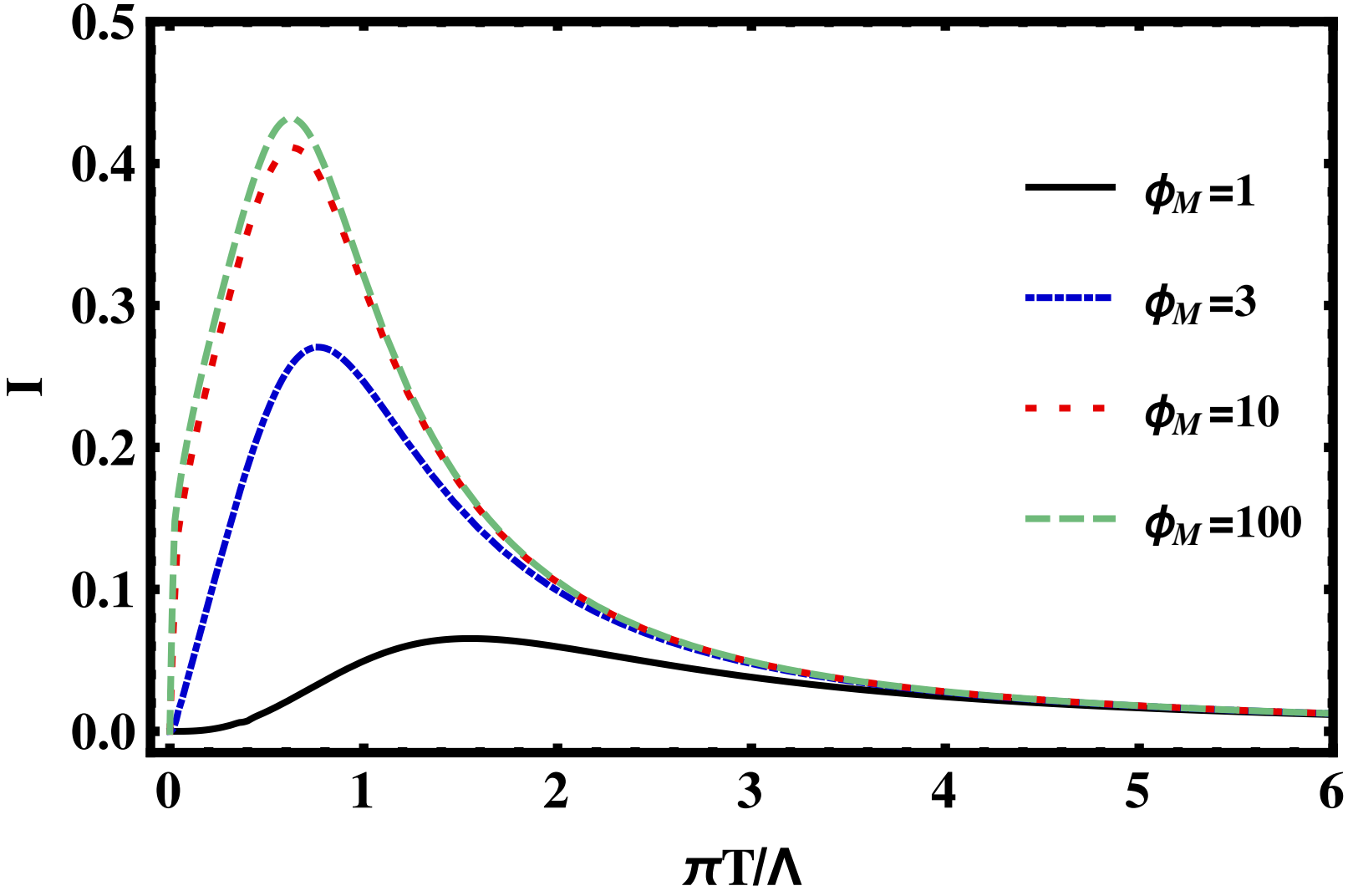


$$P_{\rm eq}(\mathcal{E}) = \frac{1}{3}\left[\mathcal{E} - \Lambda \mathcal{V}_{\rm eq}(\mathcal{E})\right] .$$

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

Interaction measure

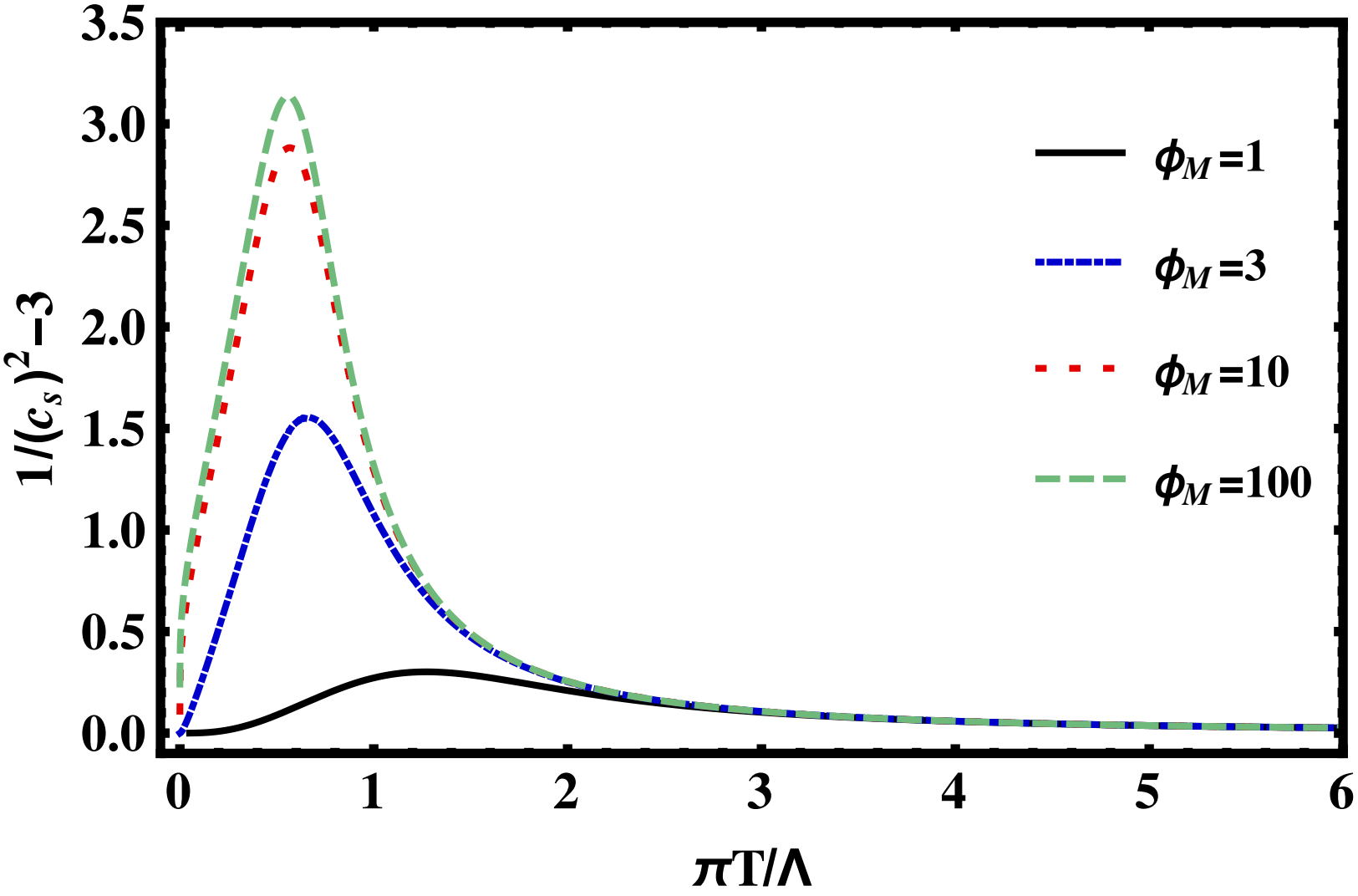
Non-conformality measure as function of the temperature:



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

Speed of sound

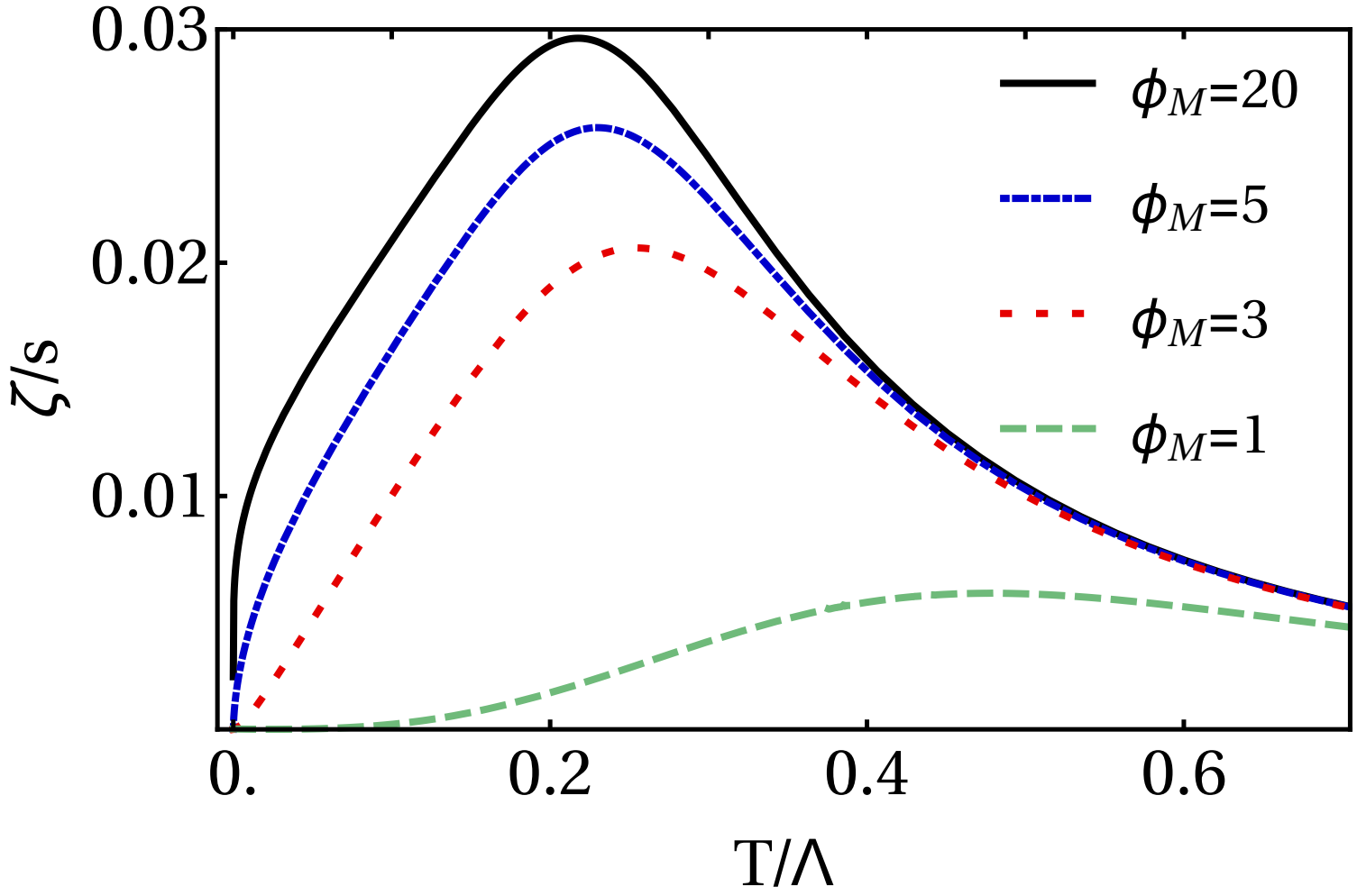
Deviation of c_s from its conformal value:



Temperature behaviour of the inverse speed of sound square

Bulk Viscosity

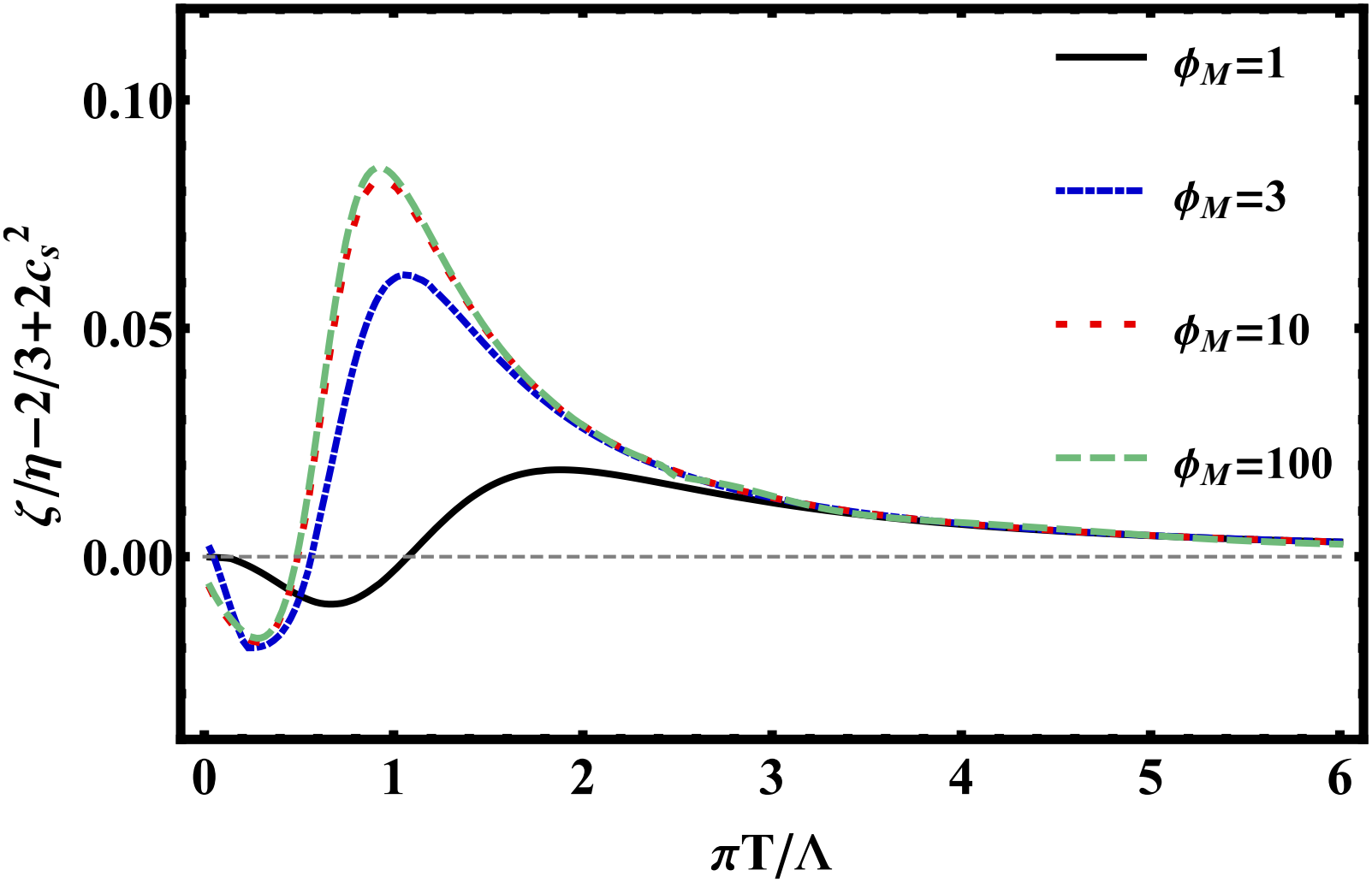
Ratio of bulk viscosity over entropy as a function of temperature:



non-conformal behaviour reflects in transport coefficients

Buchel bound

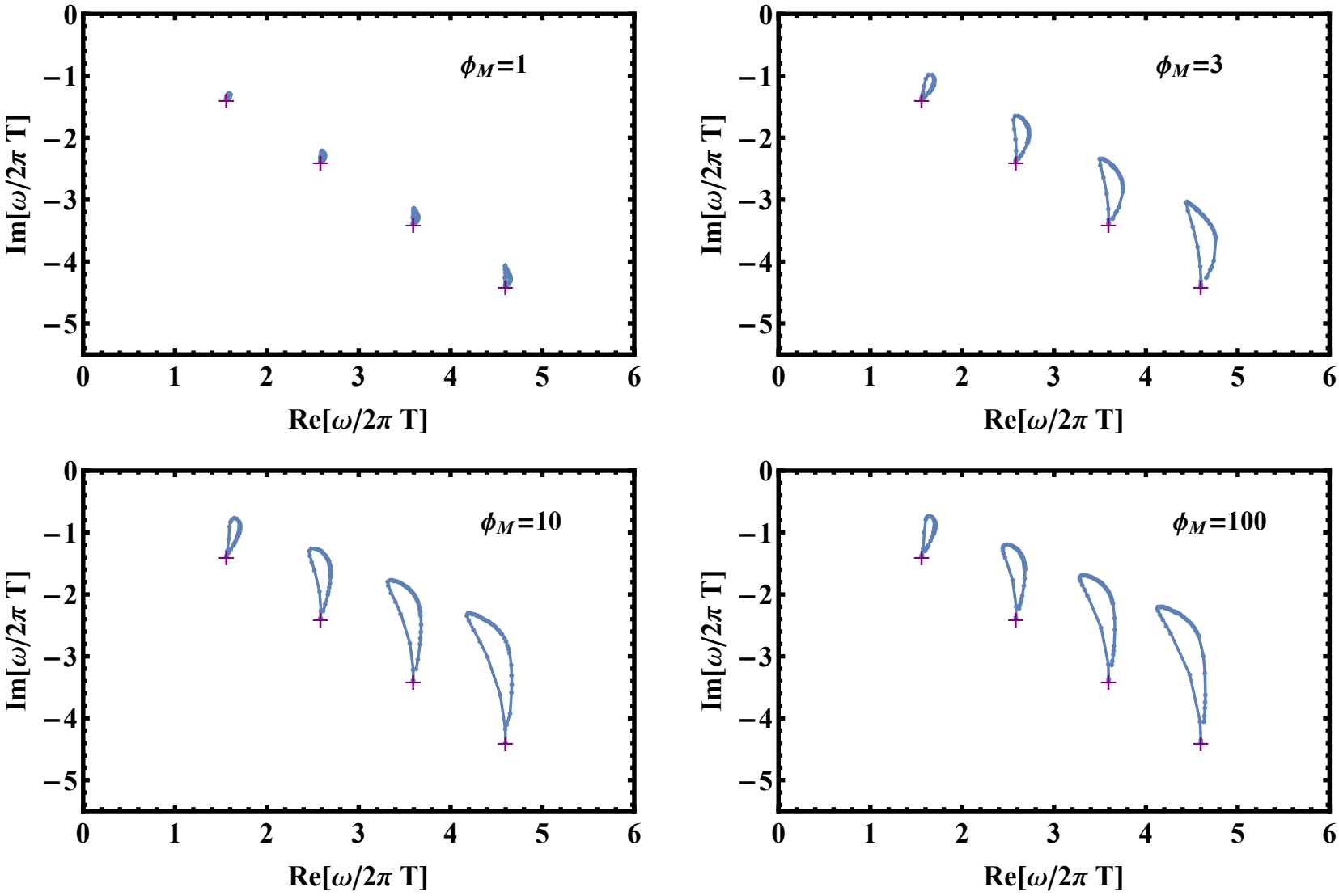
Violation of Buchel's bound at low temperatures:



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

Quasi-Normal-Modes

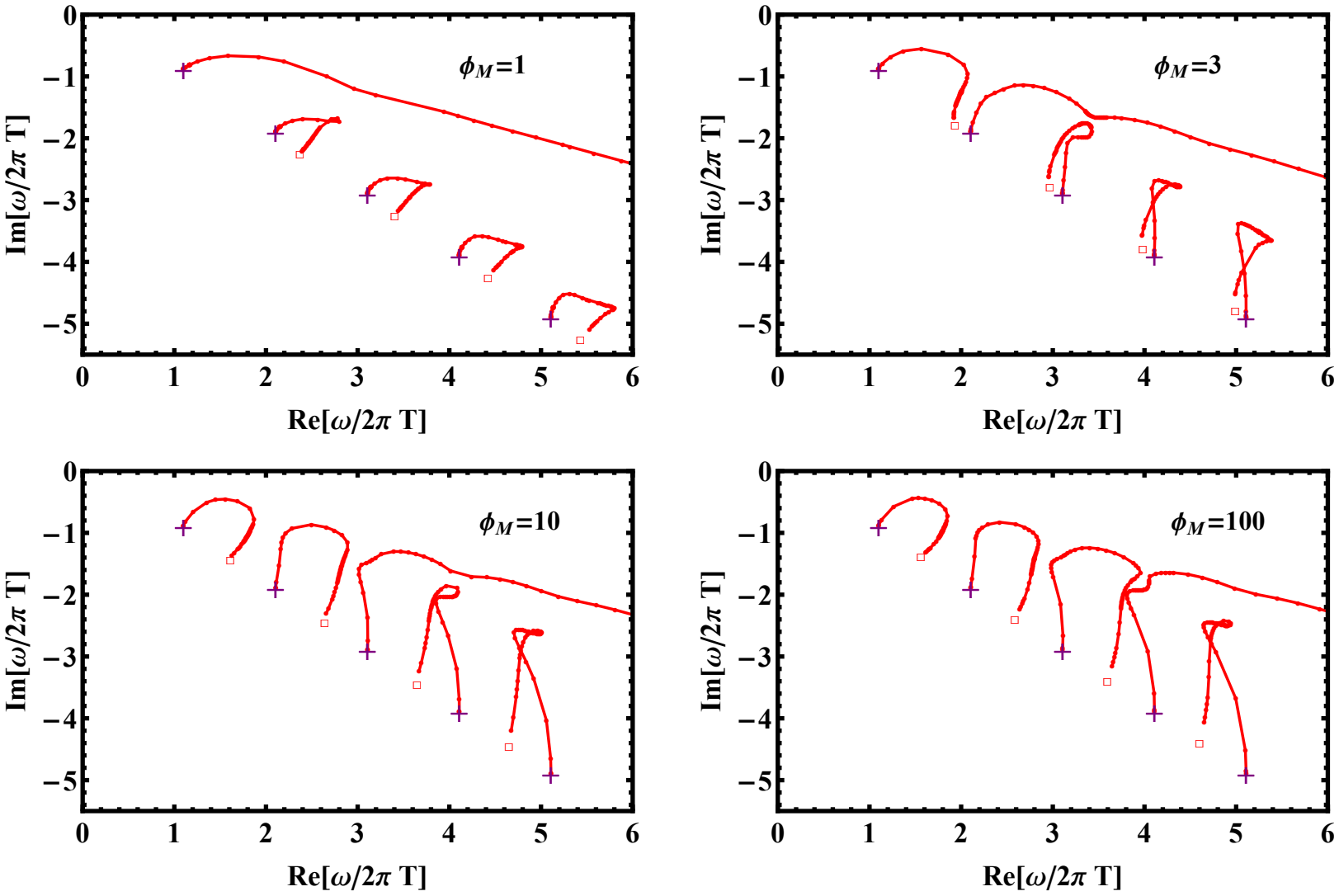
anisotropic perturbation $Z_{\mathrm{a}niso} = e^{-2A}(h_{zz} - h_{aa})$



Fluctuations of the stress energy tensor with same IR + UV limit

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 and different IR/UV limits

Outline

Non-conformal bottom-up thermodynamics

Dynamics of the scalar potential

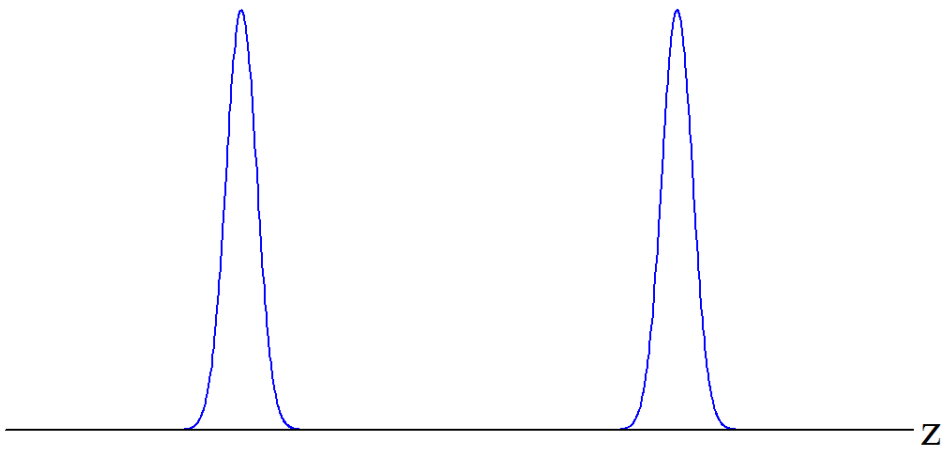
- Shockwaves Initial Conditions
- Hydrodynamization / EoSization time
- Non-conformal temperature scan
- Non-conformal theories
- Rapidity profile
- Scalar relaxation times

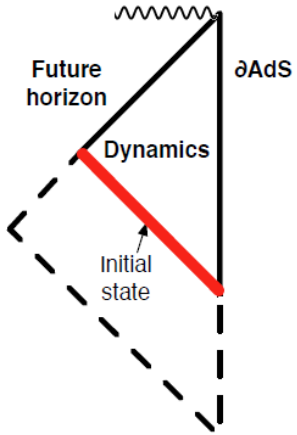
Shockwaves Initial Conditions

5D metric Ansatz in Eddington-Finkelstein:

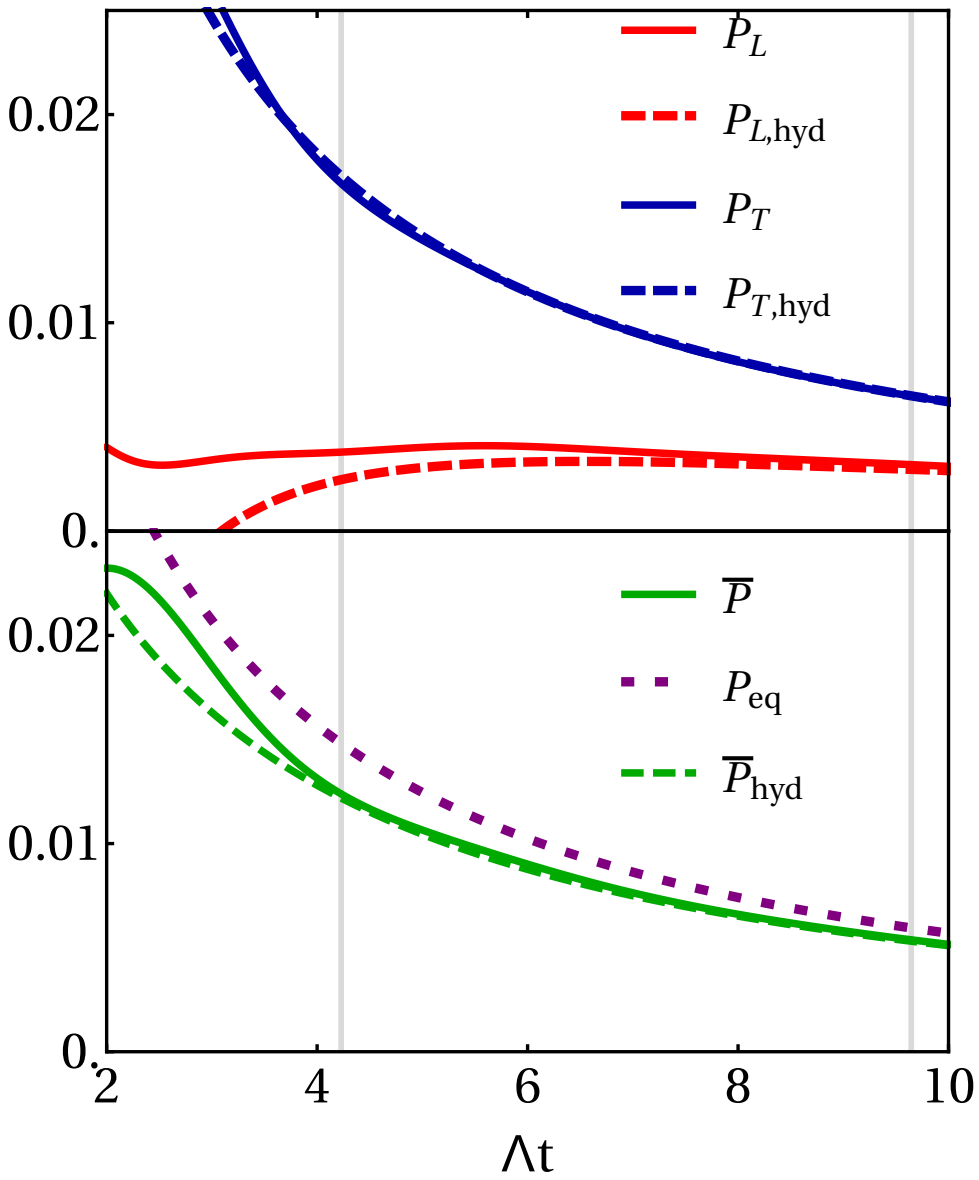
$$ds^2 = -Adt^2 + \Sigma^2 \left(e^B d\boldsymbol{x}_\perp^2 + e^{-2B} dz^2 \right) + 2dt(dr + Fdz)$$

- 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 / EoSization time



Hydrodynamics assumes mean free path goes to zero:

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

Hydrodynamization:

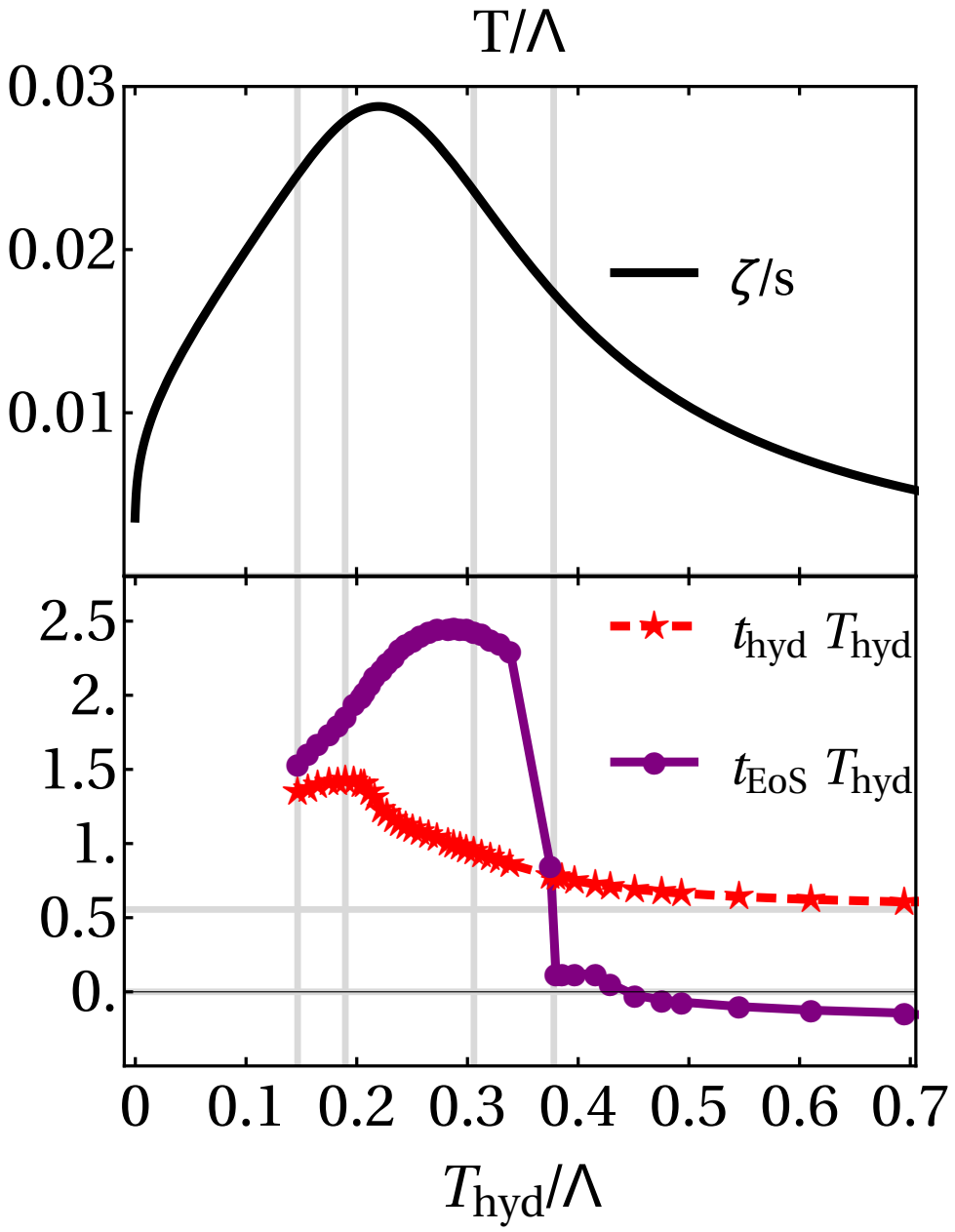
$$\left| P_{L,T} - P_{L,T}^{\mathrm{hyd}} \right| / \bar{P} < 0.1$$

EoSization:

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

hydrodynamization $\neq$ EoSization $\neq$ isotropization

Non-conformal temperature scan

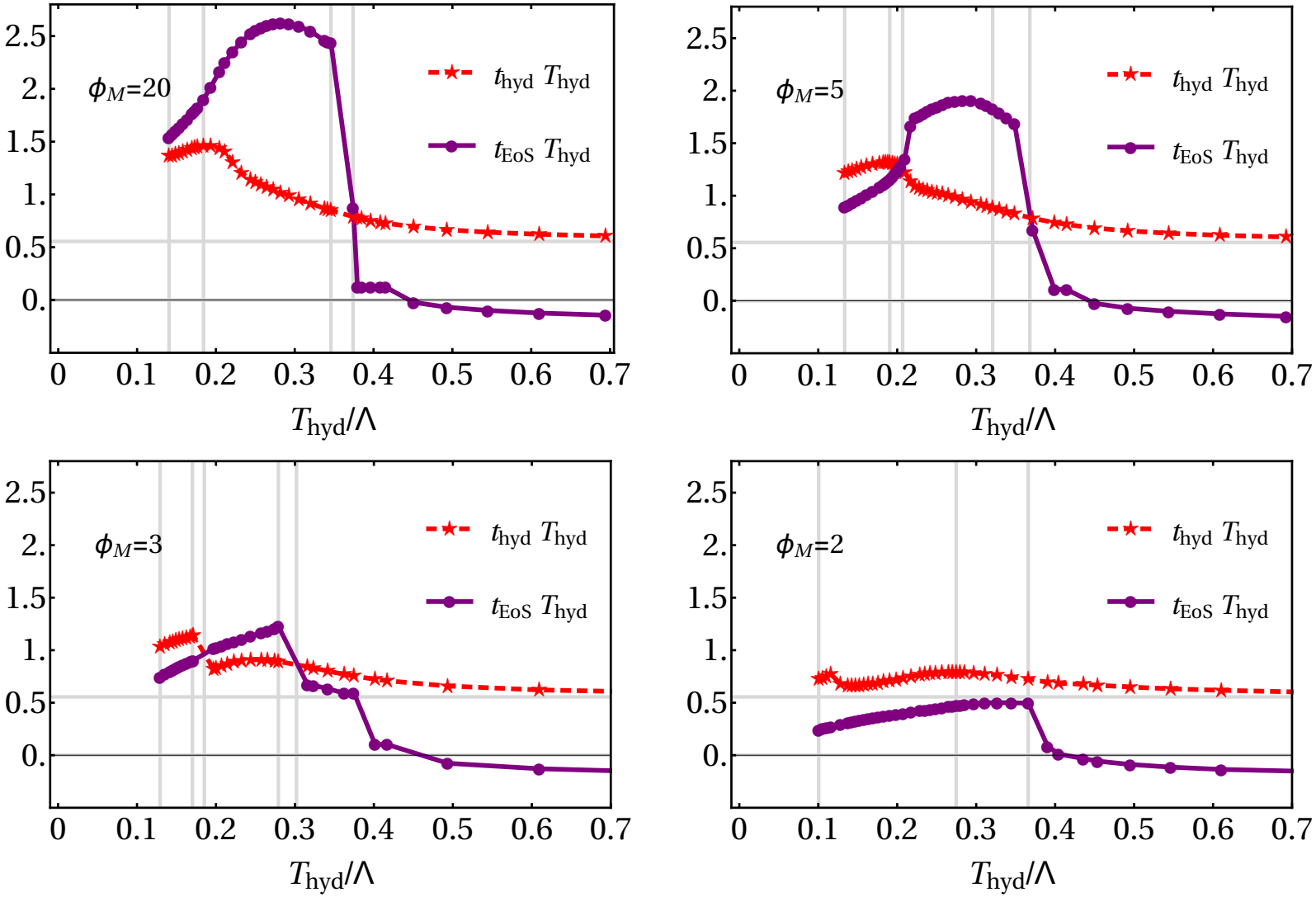


Non-conformal T scan:

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

Non-conformal theories

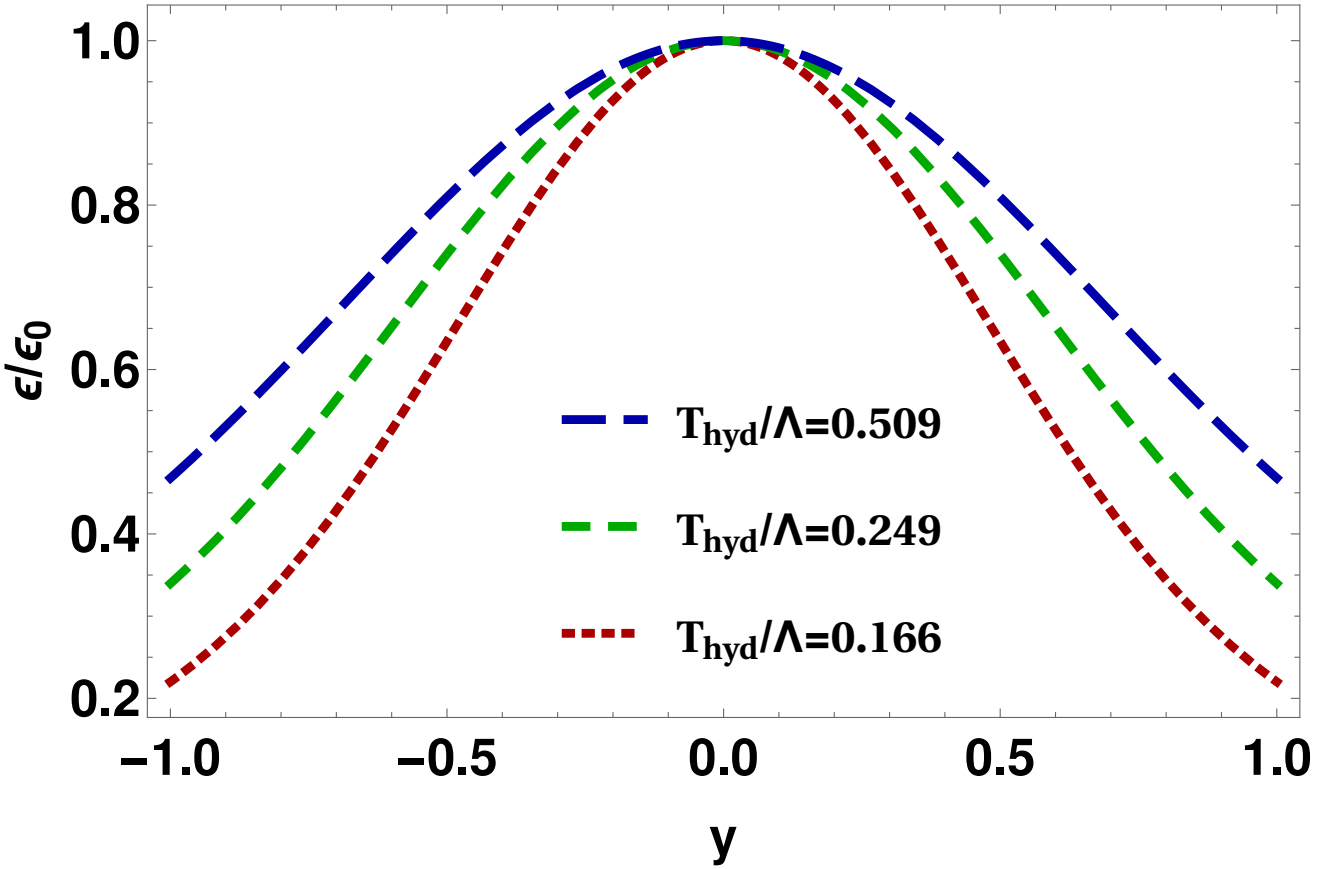
Comparing varying non-conformality ϕ_M:



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

Rapidity profile

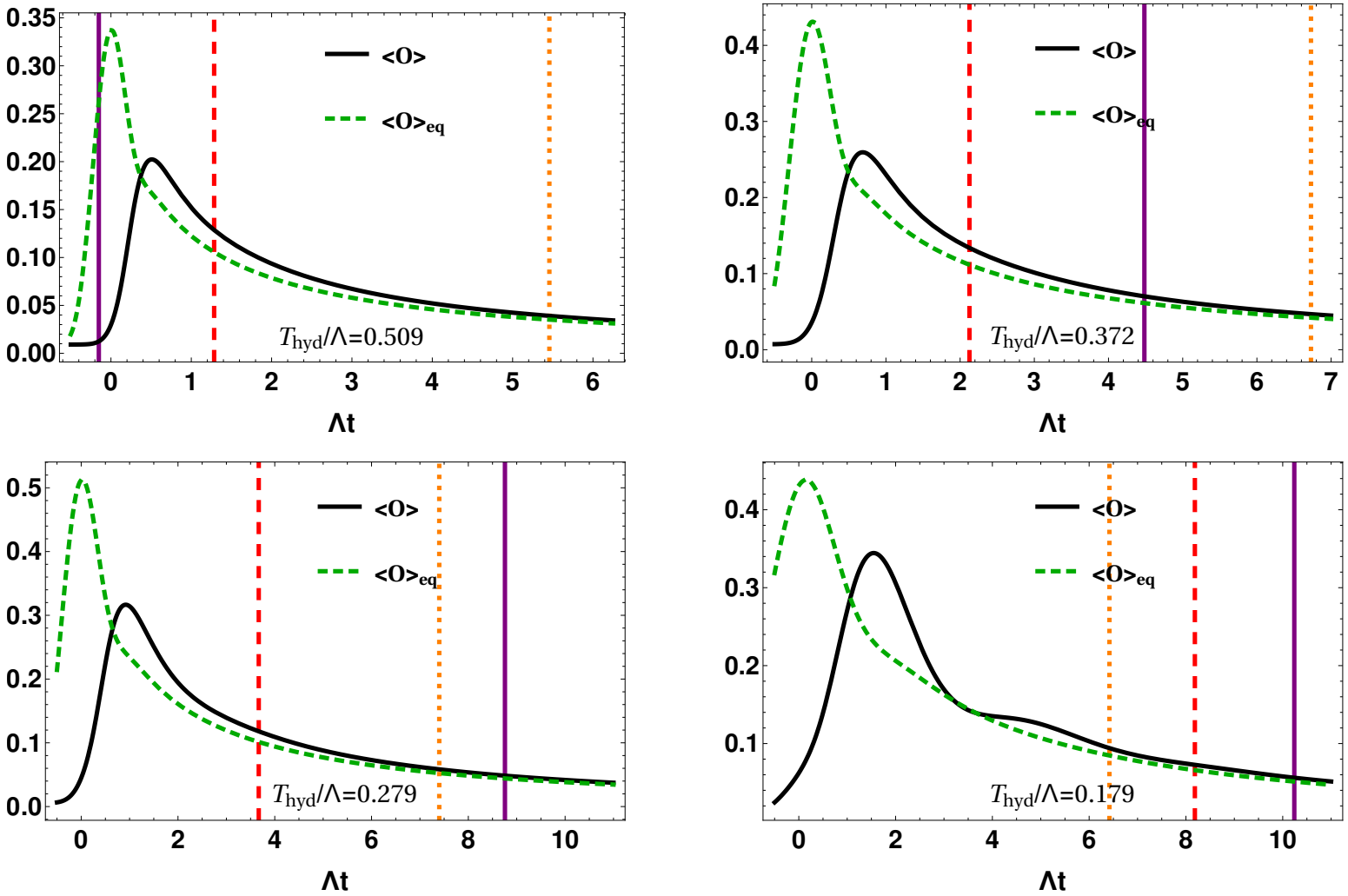
At Hydrodynamization time allmost gaussian distribution:



Higher energy densities results in broader rapidity profile

Scalar relaxation times

$|O - O_{eq}|/O$ relaxation time t_O of the VeV:



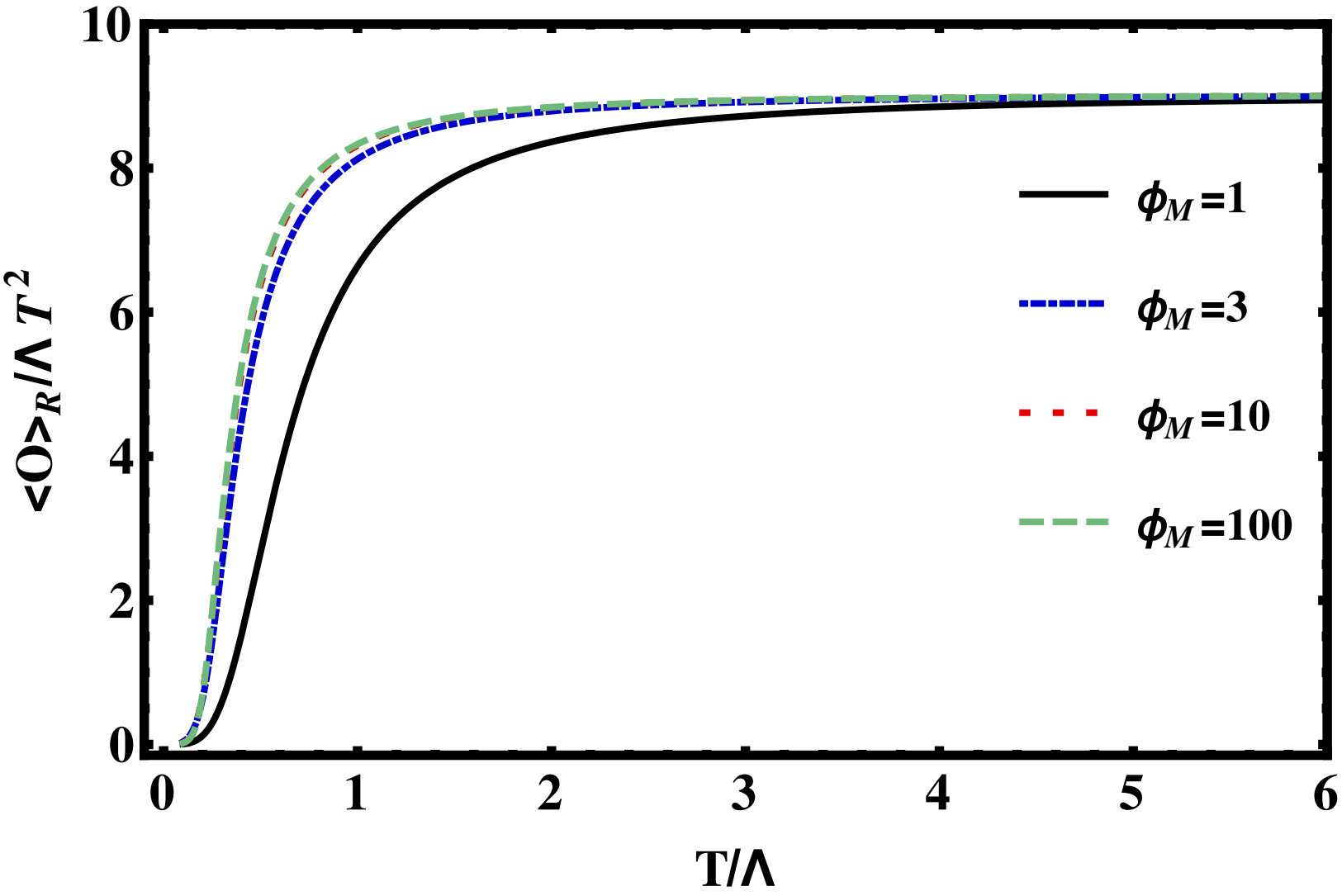
4 realized scenarios of t_{hyd}, t_{EoS}, t_O ordering

Conclusions

- First simulation of a holographic non-conformal model for heavy ion collisions
- New relaxation channel from bulk viscosity: *hydrodynamization without EoSization*
- Hydrodynamics works at early time (only max delayed ≈ 3)

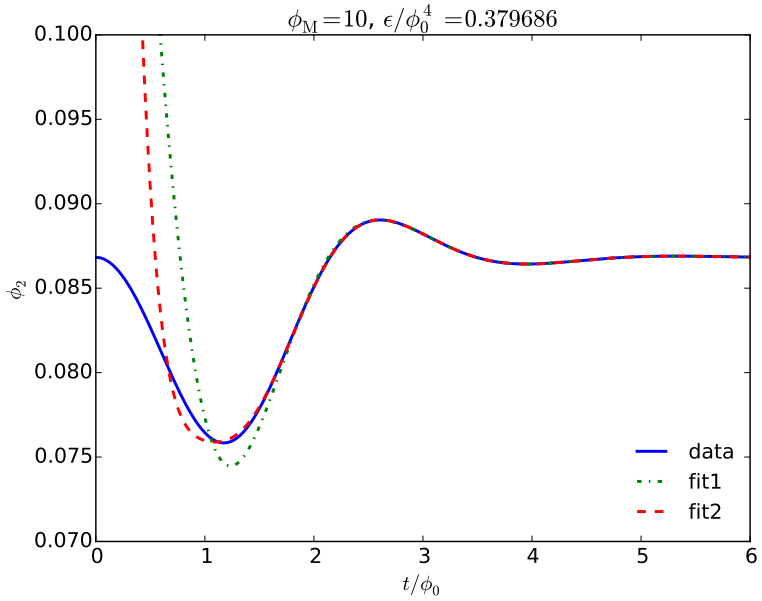
  despite non-trivial equation of state
  despite sizeable ζ/s bulk viscosity over entropy
- Conservative estimate $\zeta/s \approx 0.025$ for non-conformal effects
- More studies are on the way:
  - Asymmetrical collisions, exploding balls
  - phase transitions
  - Holographic energy scan
  - Different potentials: $\mathcal{N} = 2^*$, Gubser, ..

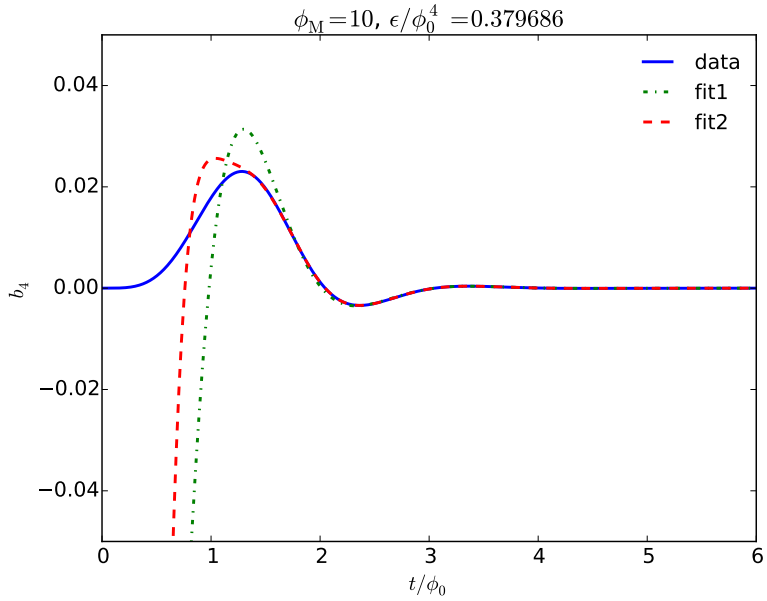
Backup: VEV



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

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

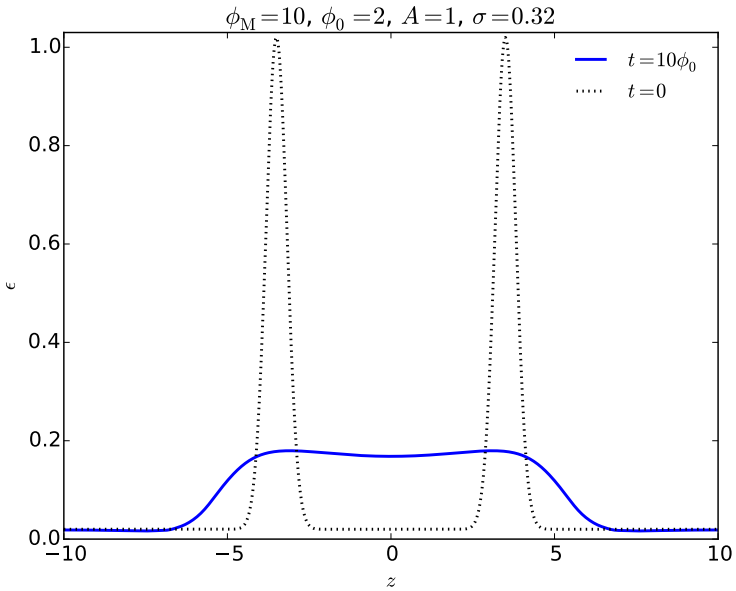


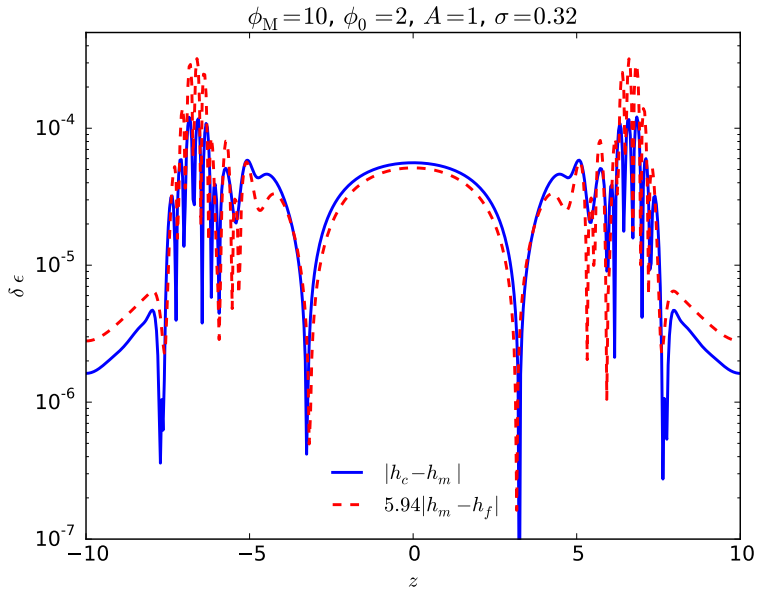


Blue full line corresponds to data from the code, green dash-dotted line correspond to a fit to the data using one QNM, red dashed line corresponds to a fit using two QNMs as explained in the text.

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.