Holographic thermalization

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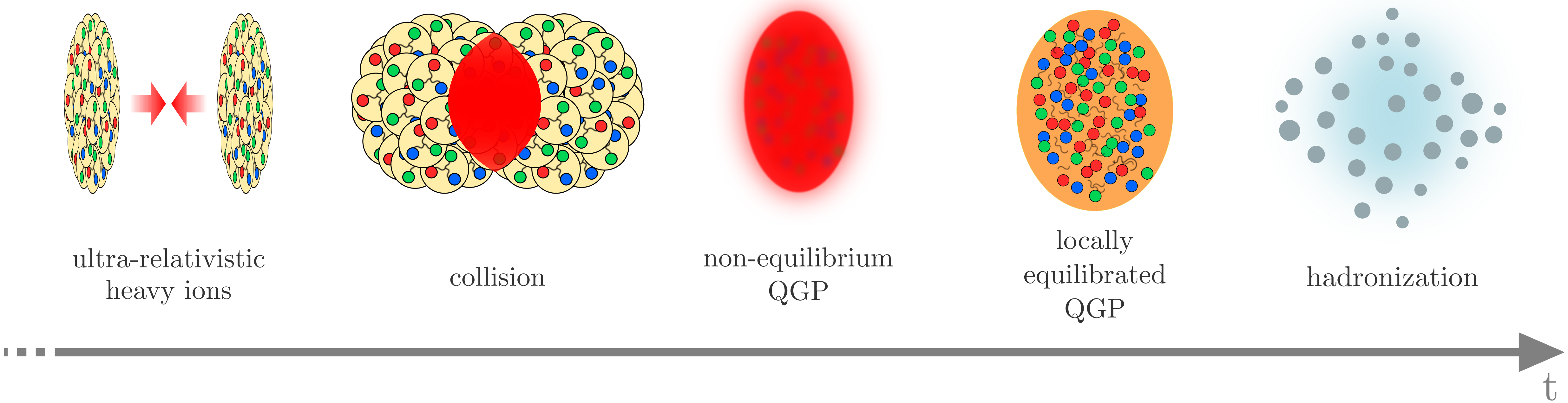
Based on: PRL 106 (2011) 191601, PRD 84 (2011) 026010, PRL 111 (2013) 231602, JHEP 10 (2013) 082.
In collaboration with: V. Balasubramanian, J. de Boer, N. Copland, B. Craps, L. Franti, F. Galli, E. Keski-Vakkuri, B. Müller, A. Schäfer, M. Shigemori, W. Staessens.

Heavy-ion collisions

- RHIC & LHC: evidence for a deconfined phase of QCD at $T_c \approx 170\,\mathrm{MeV}$

  $\longrightarrow$ quark-gluon plasma (QGP)



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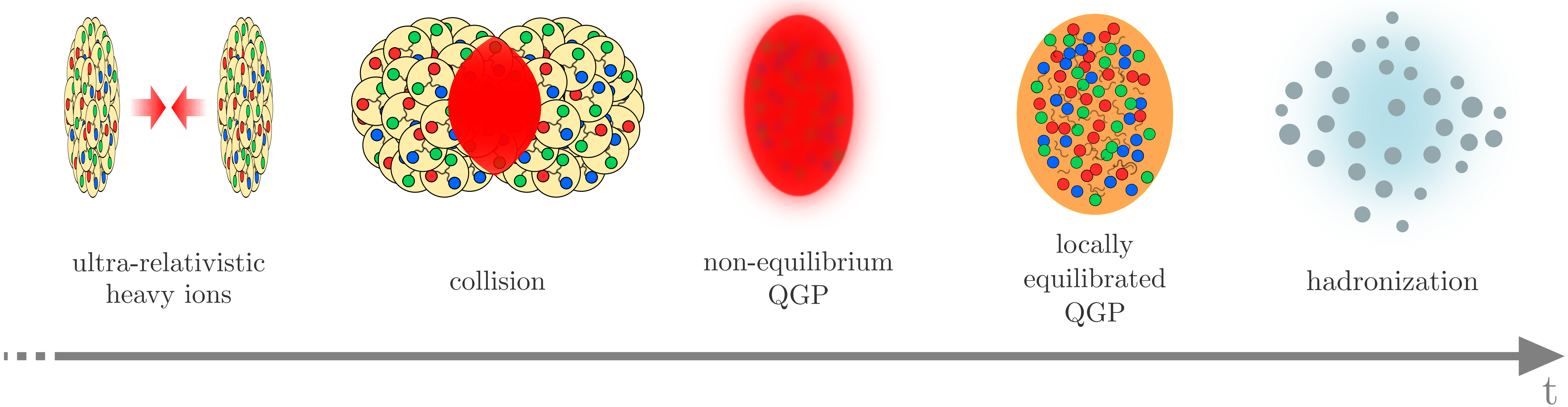
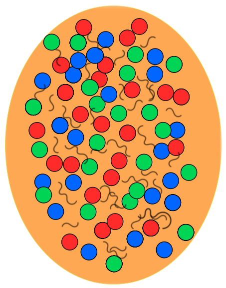


- Rapid thermalization: $t_{\mathrm{th}} = 0.5 - 1\ \mathrm{fm/c}$ (cf. $(t_{\mathrm{th}})_{\mathrm{pQCD}} \gtrsim 2.5\ \mathrm{fm/c}$)

- Strongly coupled plasma described by almost ideal hydrodynamics

QGP thermalization



- Locally equilibrated phase: effective description in terms of almost ideal hydrodynamics

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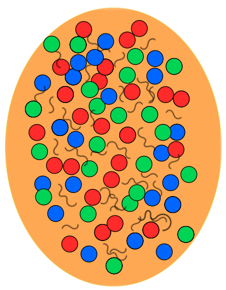

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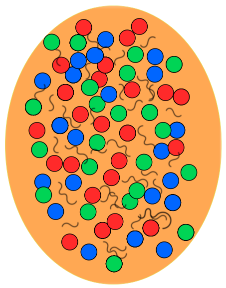

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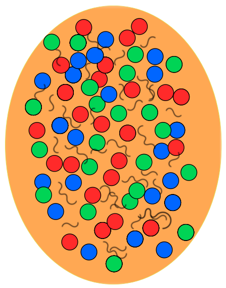

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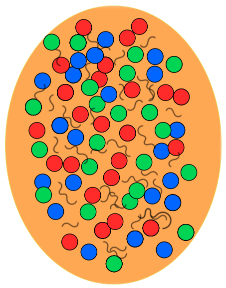

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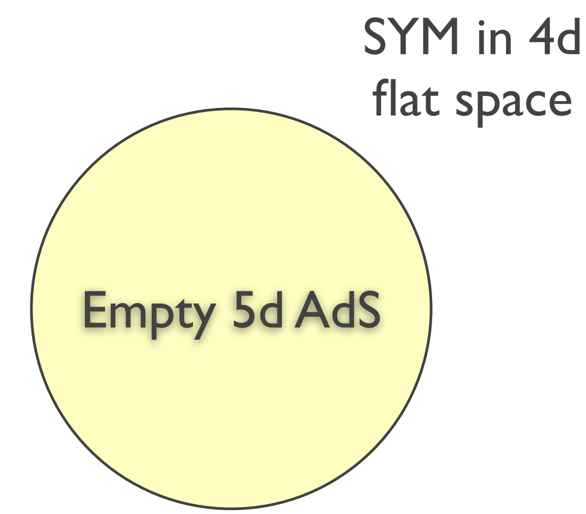
- Apply holographic methods to real-time dynamics

Holographic approach

- Zero temperature:

Strongly coupled supersymmetric YM theory (SYM) in 4d flat space	⟷	Gravity theory in 5d Anti de Sitter (AdS) spacetime



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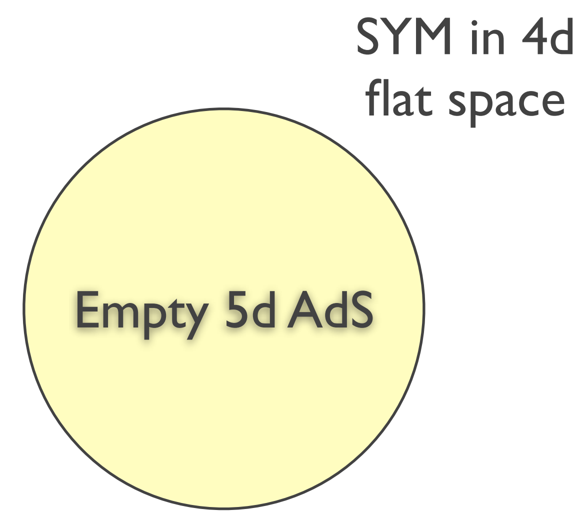

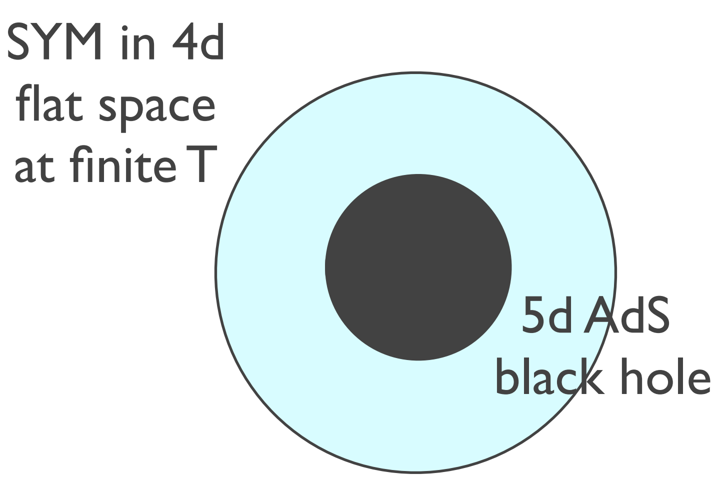

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Static SYM plasma at T	⟷	Black hole in AdS with $T_H = T$

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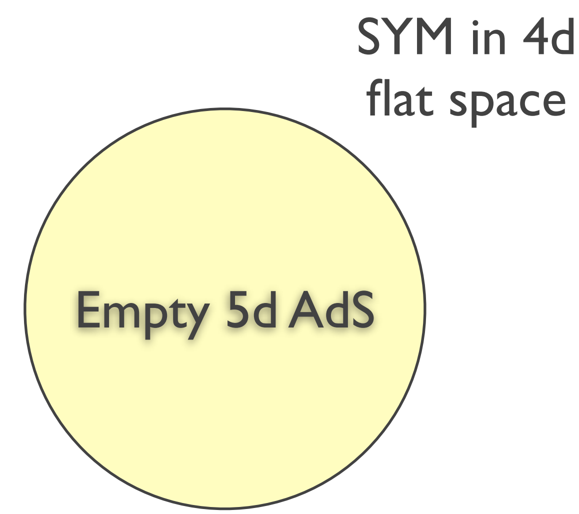

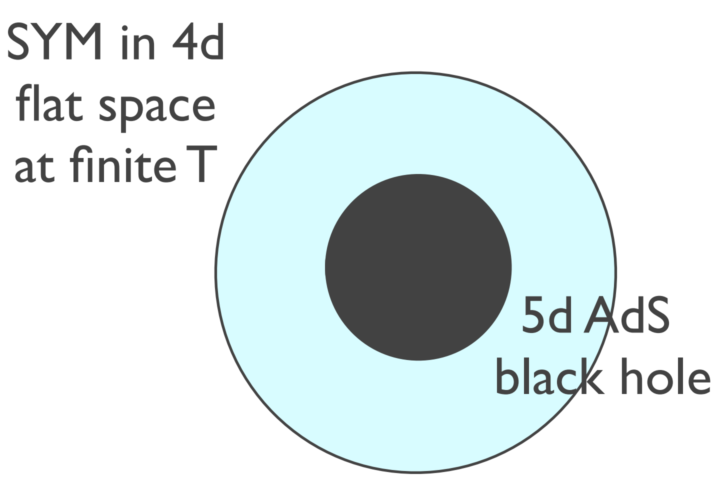

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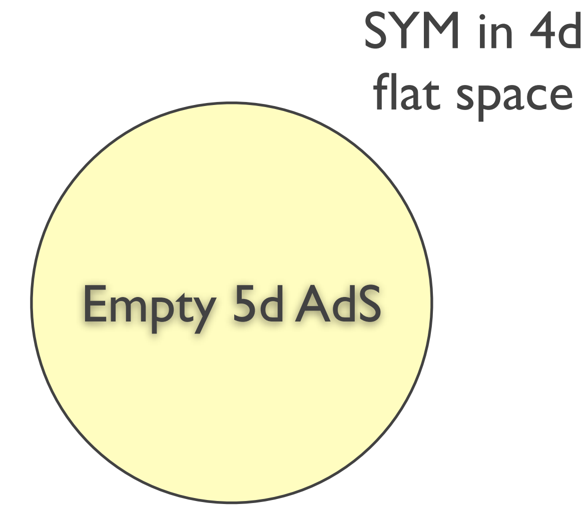

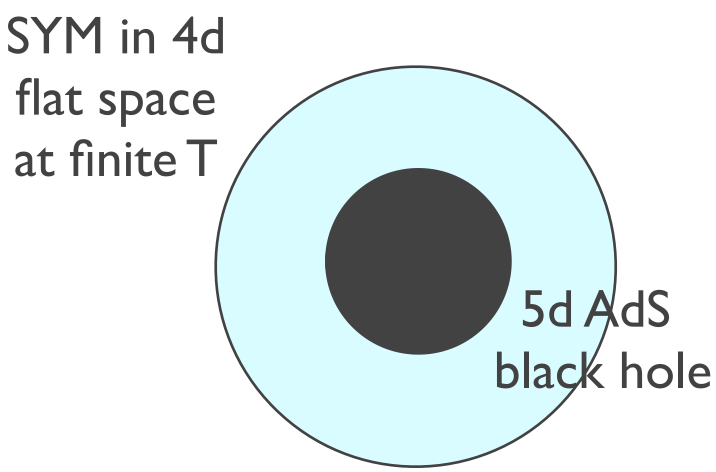

- **Finite temperature:**

Static SYM plasma at T	⟷	Black hole in AdS with $T_H = T$

Holographic approach: model the hydrodynamical phase of QGP with a SYM plasma at finite T.

- Practical advantage: gravitational setups are easier to deal with and in general explicit computations simpler to perform.

Holography & QGP

- How reliable?

	$\mathcal{N}=4$ SYM	QCD
$T=0$	supersymmetric, conformal, not confining	non-susy, non-conformal, confined
$T_c < T < 2T_c$	non-susy, tunable coupling, deconfined	non-susy, strongly coupled, deconfined
$T \gg T_c$	remains strongly coupled	runs to weak coupling

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Plasma at finite T ⟷ Black hole in AdS with $T_H = T$

- Learn about the far-from-equilibrium dynamics of strongly coupled field theories.
- Find results that are robust enough to make contact with experimental QGP.

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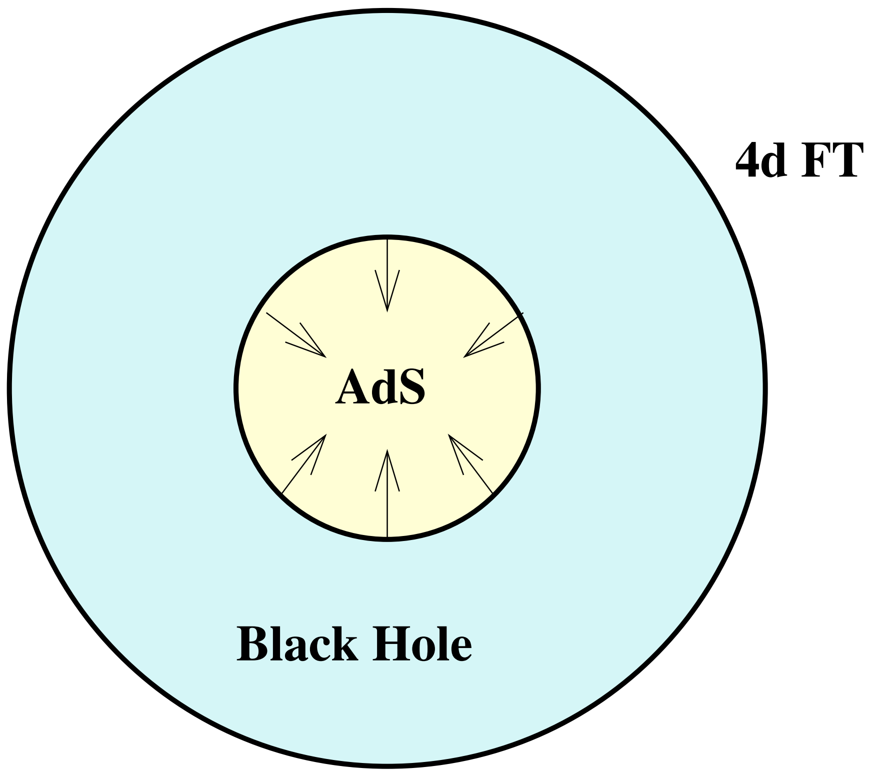

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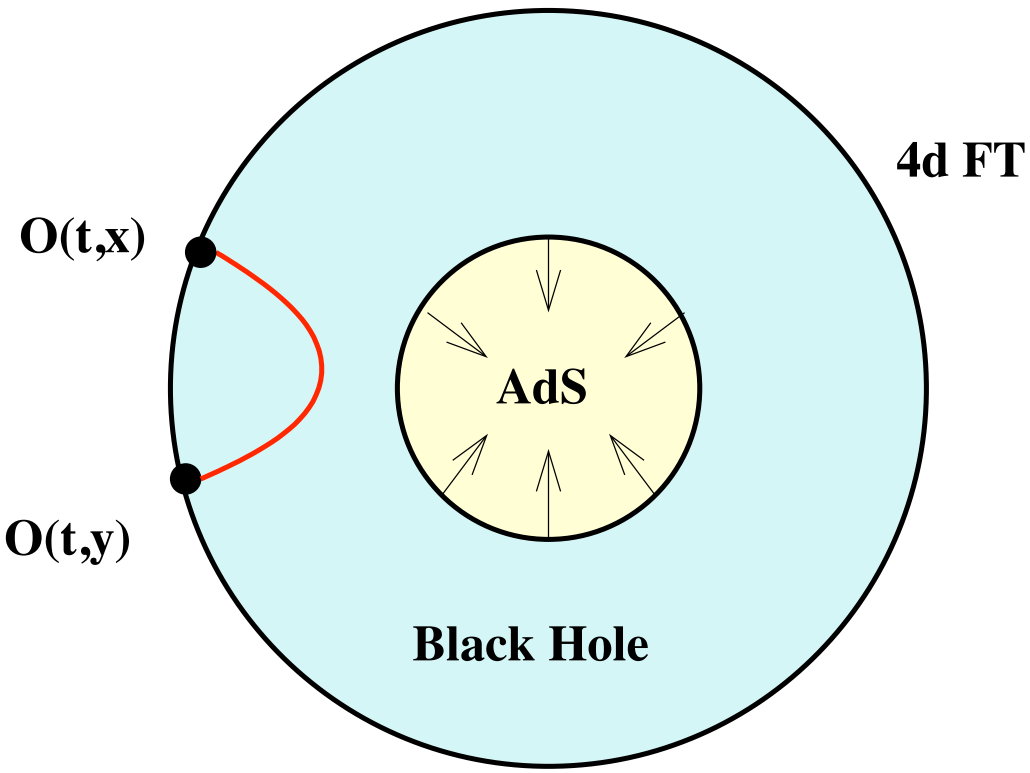

Probes of thermality:

- non-local probes: equal-time two point functions $\langle \mathcal{O}(t,\vec{x})\mathcal{O}(t,\vec{y})\rangle_{\rm shell}$
- For operators $\mathcal{O}$ of large conformal Δ dimension: geodesic approximation

$$\langle \mathcal{O}(t,\vec{x})\mathcal{O}(t,\vec{y})\rangle_{\rm shell} \approx e^{-\Delta \mathcal{L}(\vec{x},\vec{y})}$$

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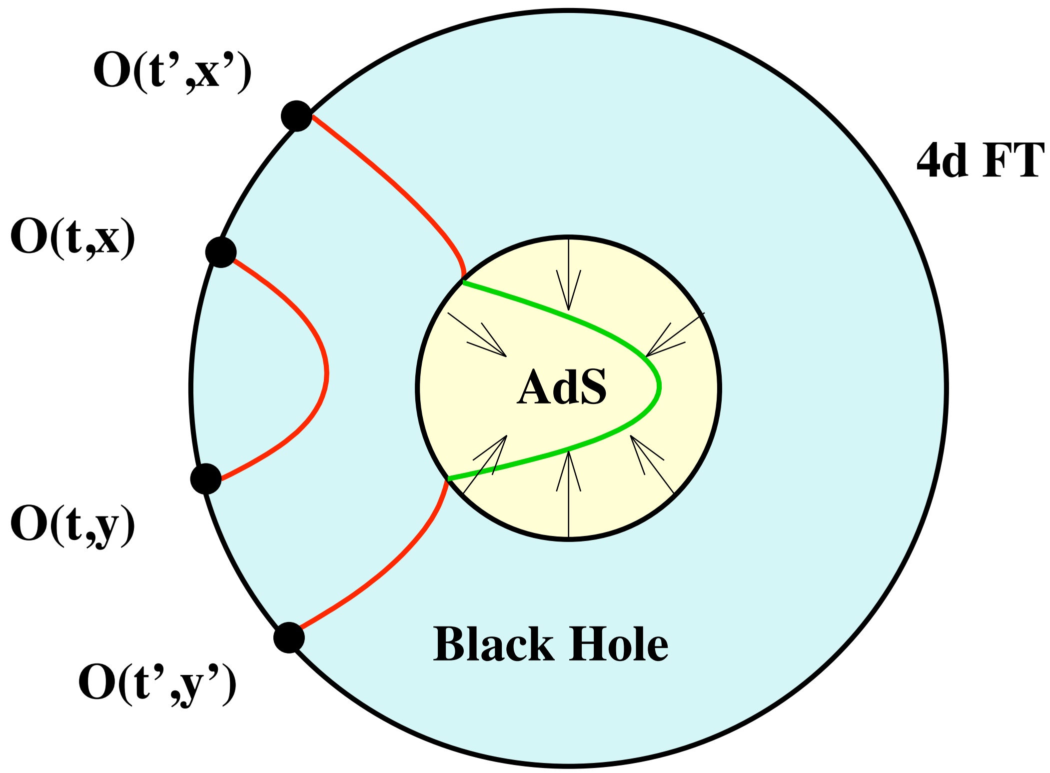

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- Top-down thermalization, short distance correlators thermalize first (cf standard view: bottom-up)

- Homogeneous setups: fast thermalization, fast applicability of viscous hydrodynamics

Inhomogeneous thermalization

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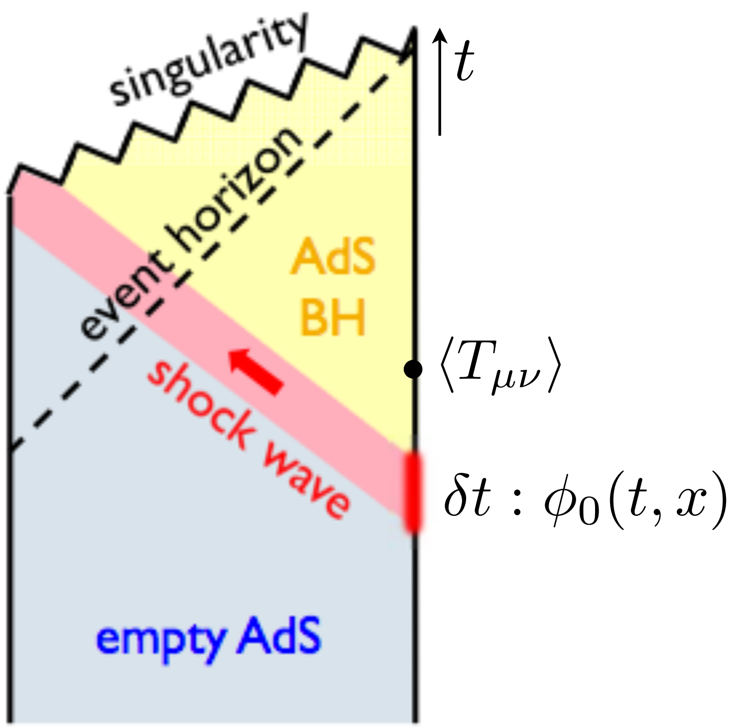

Setup: model the thermalization process of the plasma through an inhomogeneous infalling shell in AdS that leads to black hole formation.

AdS/CFT dictionary: follow the boundary $\langle T_{\mu\nu} \rangle$ to study how energy density fluctuations evolve.

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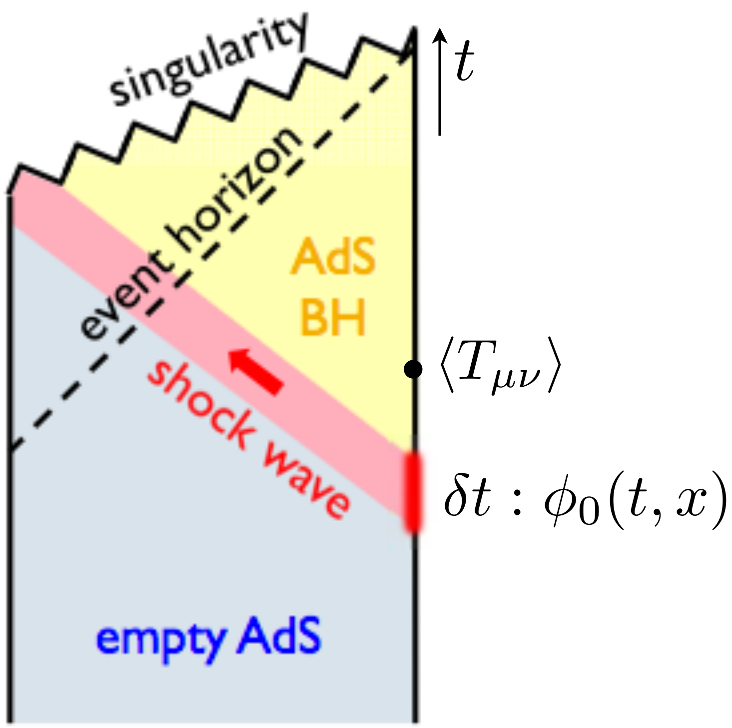

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AdS/CFT dictionary: follow the boundary $\langle T_{\mu\nu} \rangle$ to study how energy density fluctuations evolve.

- The analytic computations we perform are reliable only for very short times and long wavelength fluctuations compared to the local inverse temperature.

Pressure anisotropies

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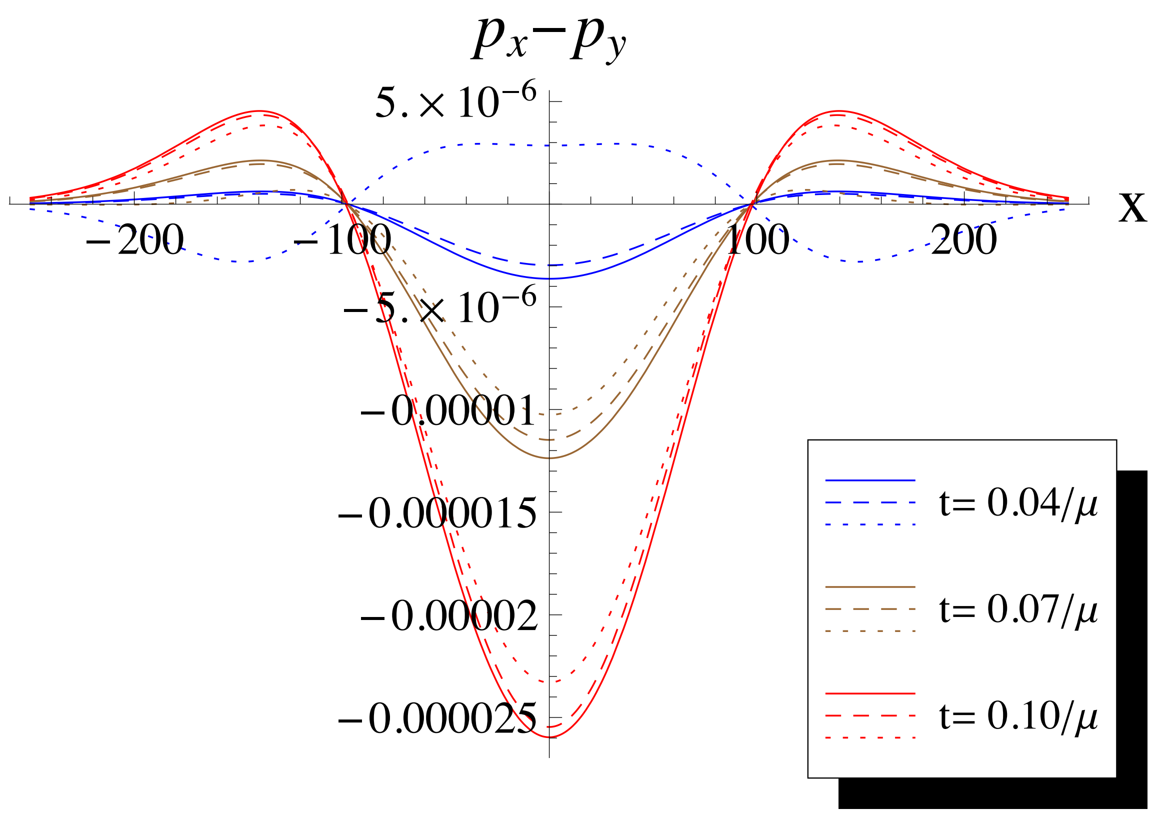
- After the energy injection, the inhomogeneities in energy density and pressures start to smooth out, although pressure anisotropies still grow.



AdS/CFT

free streaming

2nd order viscous hydro

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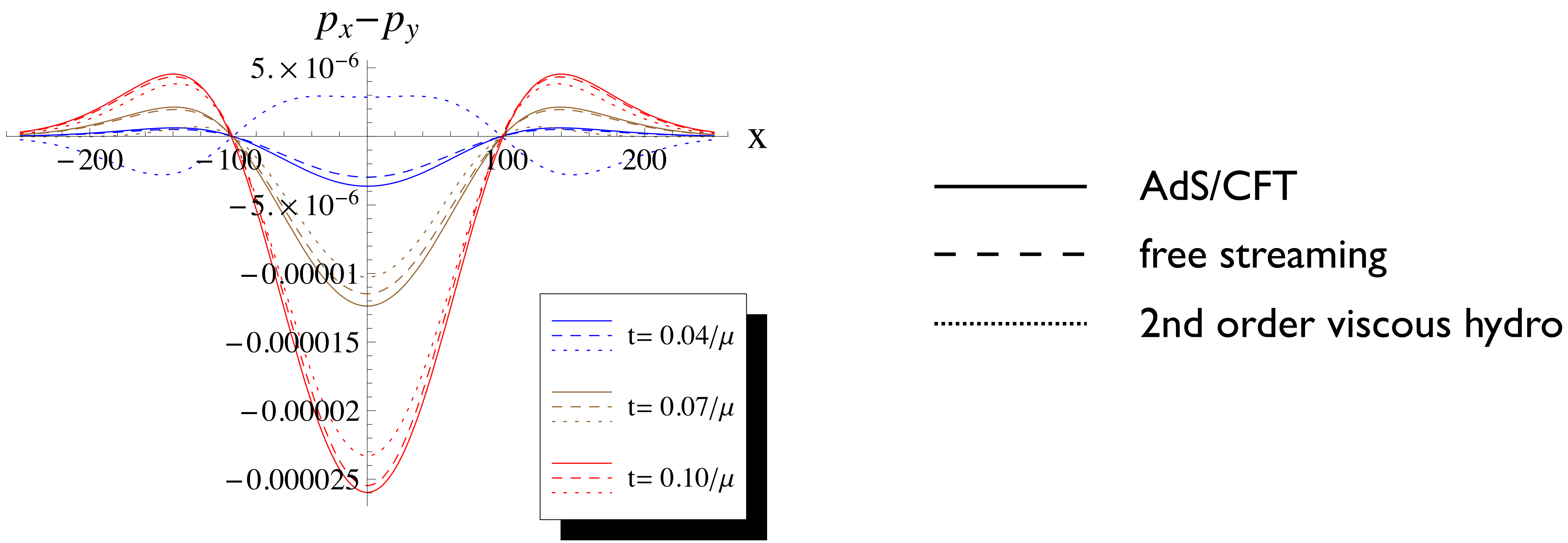

Results :

- Qualitative and quantitative agreement with free streaming.
- Near the end of the early time interval we explore, the stress tensor agrees with that of 2nd order viscous hydrodynamics.

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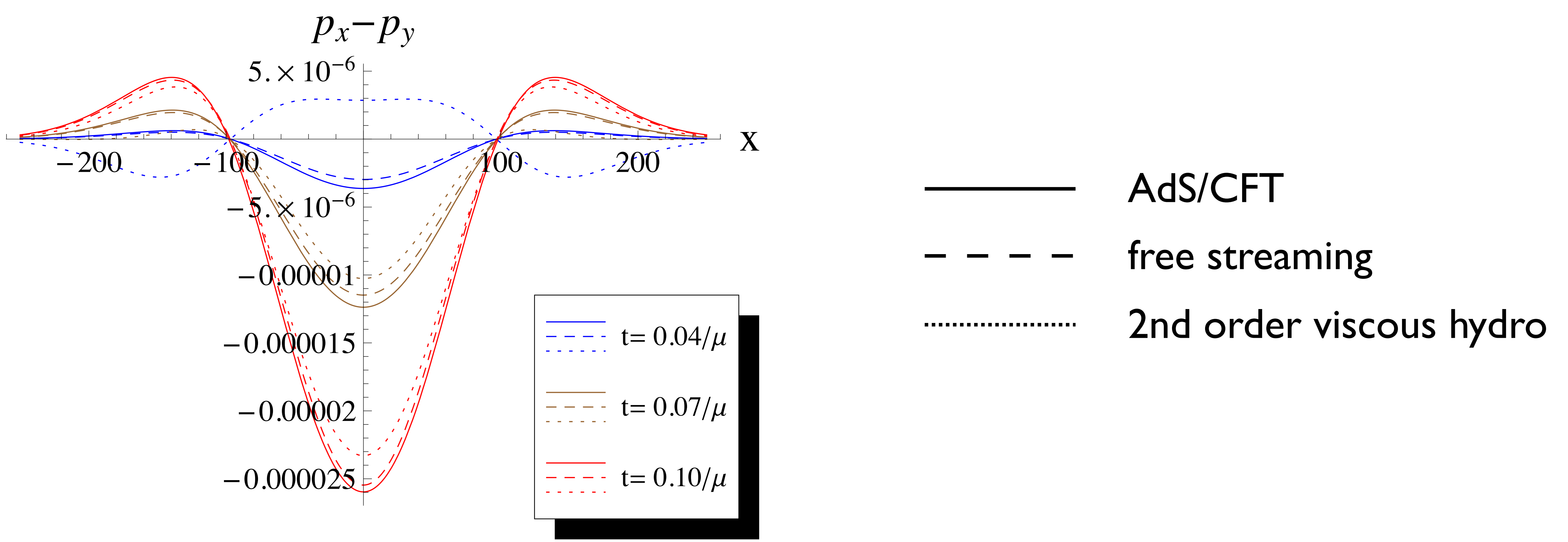

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- Does this agreement persist to later times? If so, it would provide a justification for the standard approach used in simulations (free streaming + viscous hydro).

Summary

- Holographic methods are a powerful tool to obtain insight in the far-from-equilibrium dynamics of strongly coupled field theories.
- Homogeneous models: top-down thermalization, fast isotropization of the energy-momentum tensor and thermalization.
- Recent experimental results reveal the importance of event-by-event fluctuations.
- Early-time evolution with inhomogeneities: free streaming $\longrightarrow$ second order viscous hydrodynamics.
- Does the agreement with hydrodynamics extend to later times?
- Explore the robustness of these results in more realistic models of heavy-ion collisions.