(Pre-) Hydrodynamization

Jasmine Brewer

Initial Stages 2021

Why do we care about pre-hydrodynamization?

Near-equilibrium

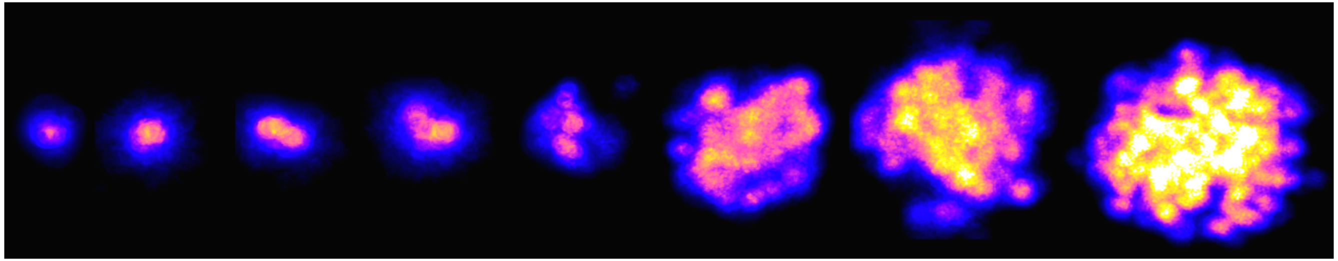
Microscopic theories

- Kinetic theory
- AdS/CFT
- …
- QGP

→ Hydrodynamics

$\epsilon(\tau),\ u^\mu(\tau)$

Paquet plenary



Chun Shen QM'19

← Further from equilibrium

Hydrodynamization may be incomplete in small systems

Hydrodynamization near equilibrium

Microscopic theories

Kinetic theory

AdS/CFT

…

QGP

Near-equilibrium

Hydrodynamics

$\epsilon(\tau),\ u^{\mu}(\tau)$

Perturbation in microscopic theory

many degrees of freedom are important

dynamics governed by conservation laws

τ_{Hydro}

τ

Decay of fast "non-hydrodynamic" modes

Slow "hydrodynamic modes"

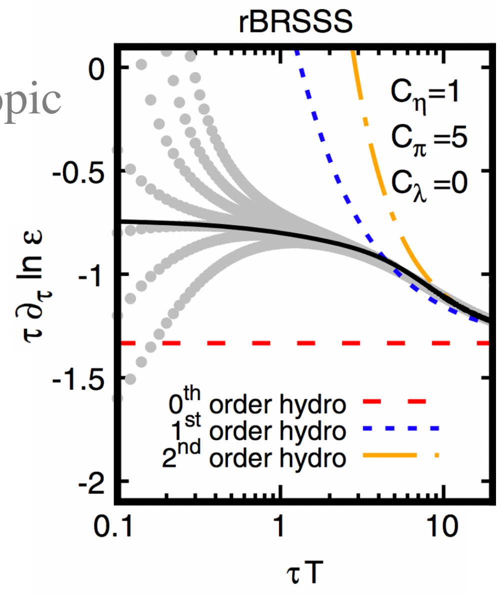
Hydrodynamics far-from-equilibrium?

Near equilibrium → hydrodynamics → reduction in degrees of freedom

Hydrodynamics far-from-equilibrium?

Near equilibrium → hydrodynamics → reduction in degrees of freedom

full microscopic evolution



equilibrium

Romatschke [1704.08699]

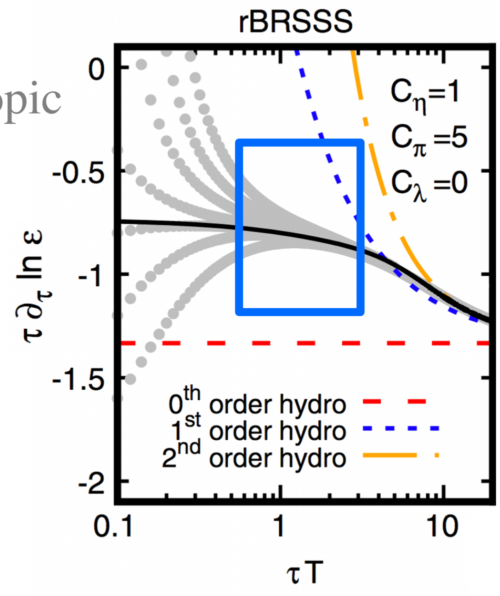
Bjorken flow in Israel-Stewart, DNMR, RTA, AdS/CFT [1503.07514, 1609.04803, 1704.08699, 1709.06644, 1712.03865, 1907.08101]

Gubser flow in aHydro, Israel-Stewart, DNMR [1711.01745]

Hydrodynamics far-from-equilibrium?

Near equilibrium → hydrodynamics → reduction in degrees of freedom

full microscopic evolution



Romatschke [1704.08699]

equilibrium

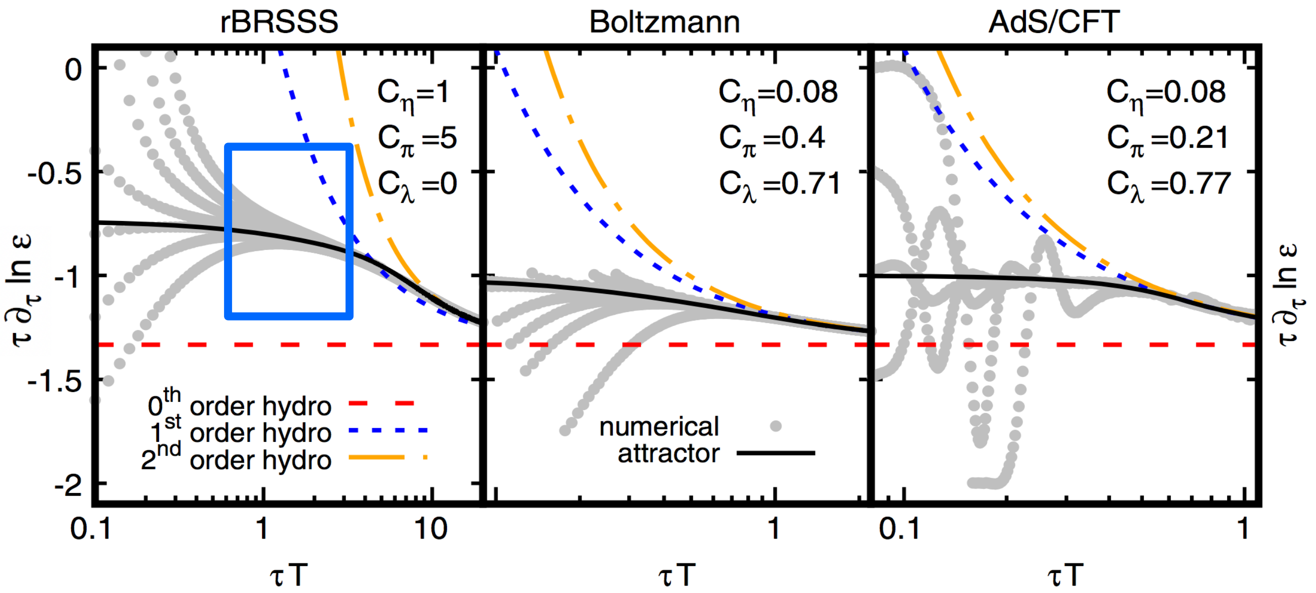
Universality far from equilibrium

Bjorken flow in Israel-Stewart, DNMR, RTA, AdS/CFT [1503.07514, 1609.04803, 1704.08699, 1709.06644, 1712.03865, 1907.08101]

Gubser flow in aHydro, Israel-Stewart, DNMR [1711.01745]

Hydrodynamics far-from-equilibrium?

Observed in several microscopic theories…



Romatschke [1704.08699]

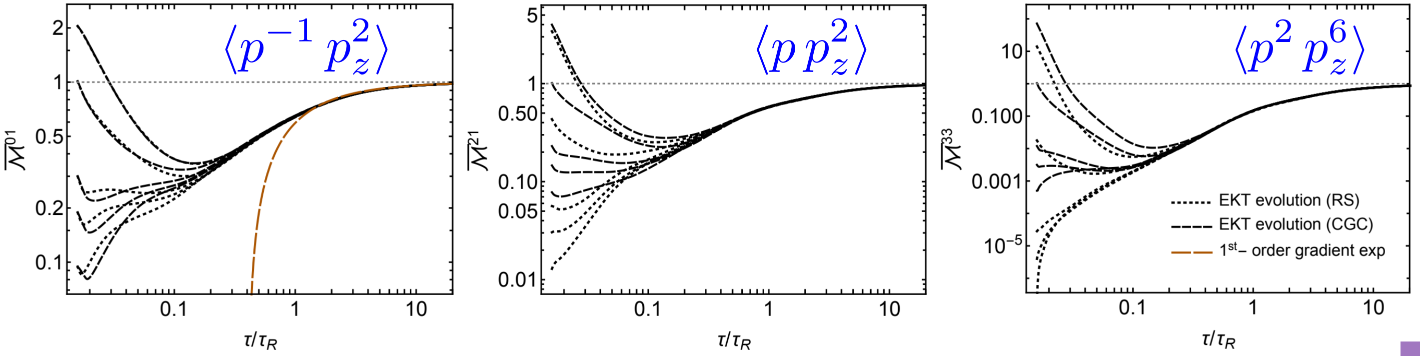
Relevance for phenomenology
Giacalone, Mazeliauskas, Schlichting [1908.02866]

Schlichting poster

Hydrodynamics far-from-equilibrium?

And for higher moments of the distribution function… [1809.01200, 2004.05195]

QCD kinetic theory



Almaalol, Kurkela, Strickland [2004.05195]

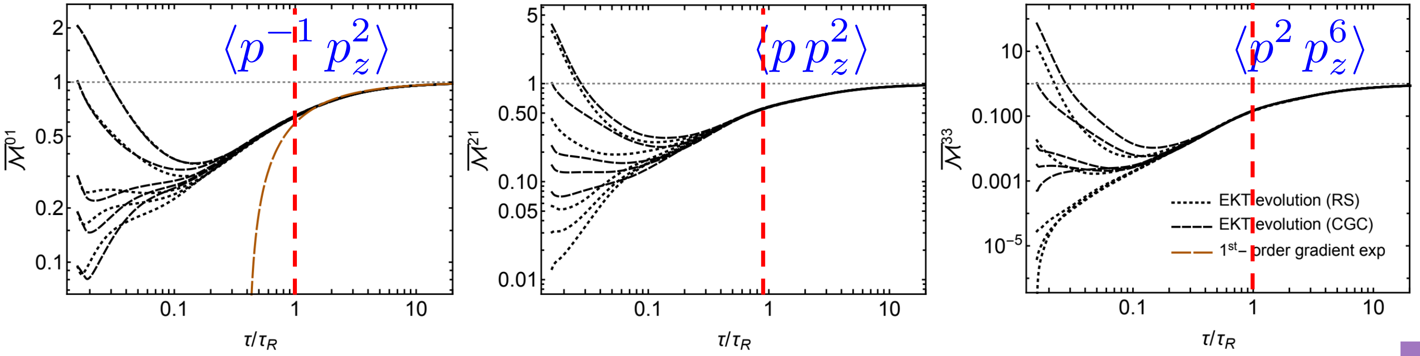
Almaalol plenary

Strickland Mon.

Hydrodynamics far-from-equilibrium?

And for higher moments of the distribution function… [1809.01200, 2004.05195]

QCD kinetic theory



Almaalol, Kurkela, Strickland [2004.05195]

Almaalol plenary

Strickland Mon.

Apparent reduction in degrees of freedom before relaxation time

What is the origin of reduced degrees of freedom before collisions?

What is the origin of reduced degrees of freedom before collisions?

Hydrodynamics is one way to cause a reduction in the effective degrees of freedom

Emerging picture: rapid expansion can also cause a reduction in degrees of freedom

Kurkela, van der Schee, Wiedemann, Wu [1907.08101]
JB, Yan, Yin [1910.00021]

Wiedemann Wed.

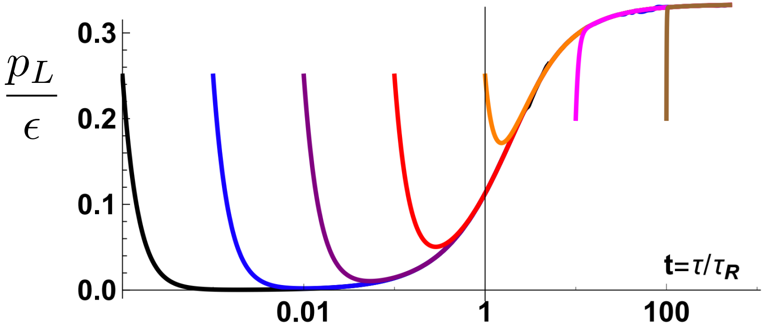
Motivates understanding the attractor in terms of far-from-equilibrium slow degrees of freedom

Scheihing-Hitschfeld Mon.

Berges, Mazeliauskas [1810.10554]
JB, Yan, Yin [1910.00021]
JB, Ke, Yan, Yi (in preparation)
JB, Scheihing-Hitschfeld, Yin (in preparation)

Hint: different physical origin of early- and late-time attractors

relaxation time approximation



(qualitatively similar results for Israel-Stewart)

τ_R: timescale for collisions

Kurkela, van der Schee, Wiedemann, Wu [1907.08101]

Reduction in degrees of freedom driven by…

Rapid expansion without collisions

Collisions

hydrodynamic modes

Suggests "slow mode" describing rapid expansion without collisions

Hydrodynamization in kinetic theory

Boost-invariant longitudinal expansion:

$$\partial_\tau f - \underbrace{\frac{p_z}{\tau}\partial_{p_z} f}_{\text{longitudinal expansion}} = \underbrace{-C[f]}_{\text{collisions}}$$

(homogenous in transverse plane)

Relaxation time approximation

Can connect to hydrodynamics by considering the distribution contributing to the stress tensor

$$F = \int_p p\, f$$

(e.g. [1905.05139])

Evolution of F can be described by effective "Hamiltonian"

$$\int_p p\left(\partial_\tau f - \frac{p_z}{\tau}\partial_{p_z} f = -C[f]\right)$$

(sometimes)

$$\partial_\tau F \quad -\frac{1}{\tau}(\ldots)F \qquad (\ldots)F$$

Evolution of F ⟷ $\partial_y \psi = -\mathcal{H}(y)\psi$

Eigenstates give effective degrees of freedom

Slow modes: ground states

$$y = \log\left(\frac{\tau}{\tau_I}\right)$$

JB, Yan, Yin [1910.00021]

Non-linear collision kernel

Scheihing-Hitschfeld Mon.

Truncate $\mathcal{H}$ using moment expansion

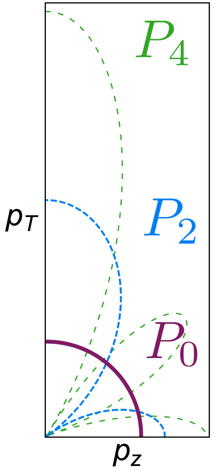
Bjorken expansion

$$F\left(\cos\theta;\tau\right) = \epsilon(\tau) + \sum_{n=1} \frac{4n+1}{2} \mathcal{L}_n(\tau) P_{2n}(\cos\theta) \longleftrightarrow \psi = (\epsilon, \mathcal{L}_1, \mathcal{L}_2, ...)$$

Truncate $\mathcal{H}$ using moment expansion

Bjorken expansion

$$F\left(\cos\theta;\tau\right)=\epsilon(\tau)+\sum_{n=1}\frac{4n+1}{2}\mathcal{L}_n(\tau)P_{2n}(\cos\theta)\quad\longleftrightarrow\quad\psi=(\epsilon,\mathcal{L}_1,\mathcal{L}_2,\ldots)$$



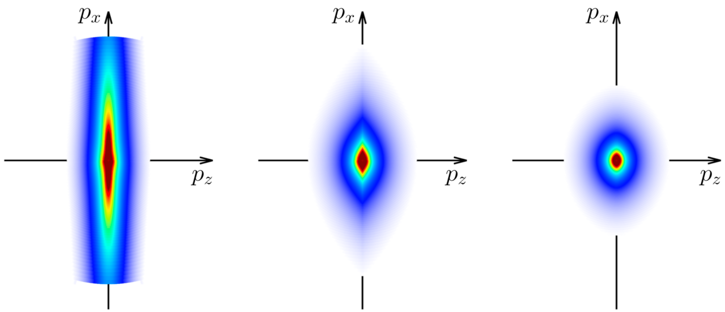


Fig adapted from KoMPoST [1805.00961]

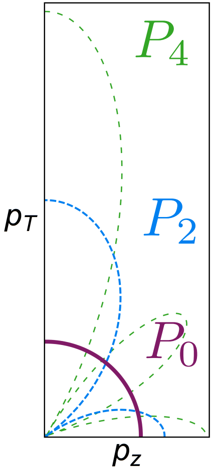
$$(\epsilon,\mathcal{L}_1,\mathcal{L}_2,\ldots)\longrightarrow(\epsilon,0,0,\ldots)$$

hydrodynamization

Truncate $\mathcal{H}$ using moment expansion

Bjorken expansion

$$F\left(\cos\theta;\tau\right) = \epsilon(\tau) + \sum_{n=1} \frac{4n+1}{2}\mathcal{L}_n(\tau)P_{2n}(\cos\theta) \quad \longleftrightarrow \quad \psi = (\epsilon, \mathcal{L}_1, \mathcal{L}_2, \ldots)$$



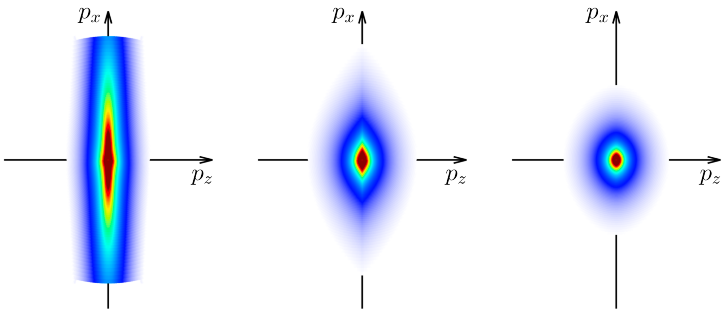


Fig adapted from KoMPoST [1805.00961]

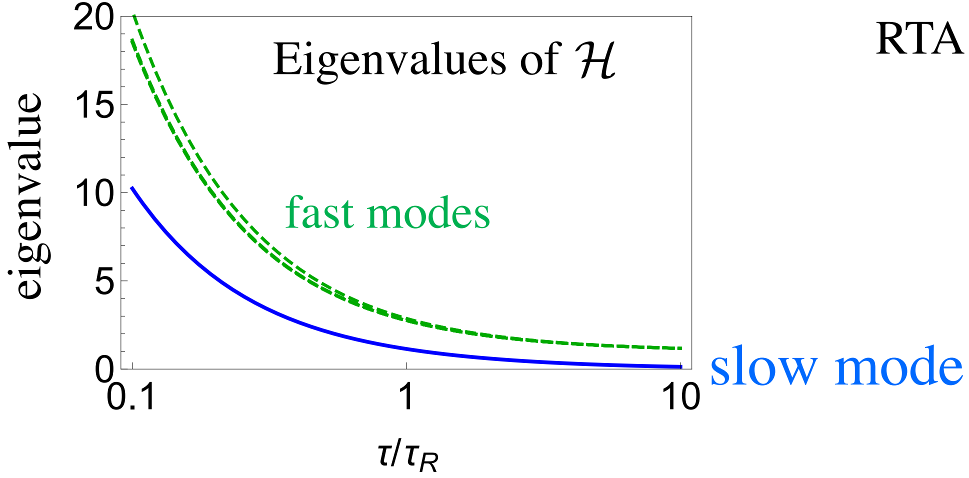
$$(\epsilon, \mathcal{L}_1, \mathcal{L}_2, \ldots) \longrightarrow (\epsilon, 0, 0, \ldots)$$

hydrodynamization

Transverse momentum anisotropy $\quad Y_l^m(\theta,\phi) \sim e^{im\phi}P_l^m(\cos\theta)$

JB, Weiyao Ke, Li Yan, Yi Yin (in progress)

Ground state: far-from-equilibrium slow mode

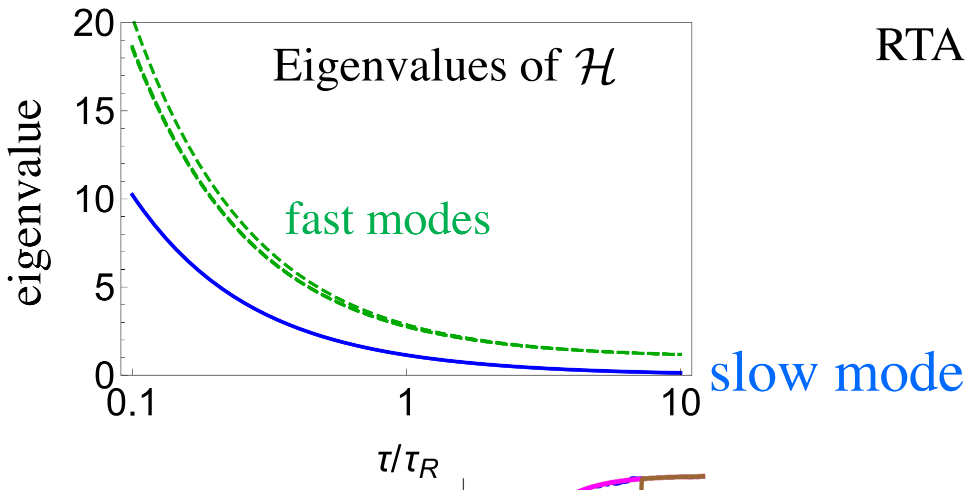


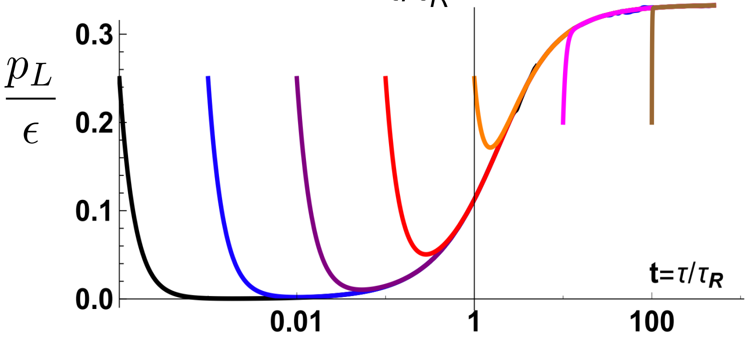
RTA: $\mathcal{H} = \mathcal{H}_F + \frac{\tau}{\tau_R}\mathcal{H}_H$

Early times: $\Delta E \sim \frac{1}{\tau}$

Late times: $\Delta E \sim \frac{1}{\tau_R}$

Ground state: far-from-equilibrium slow mode





RTA: $\mathcal{H} = \mathcal{H}_F + \frac{\tau}{\tau_R}\mathcal{H}_H$

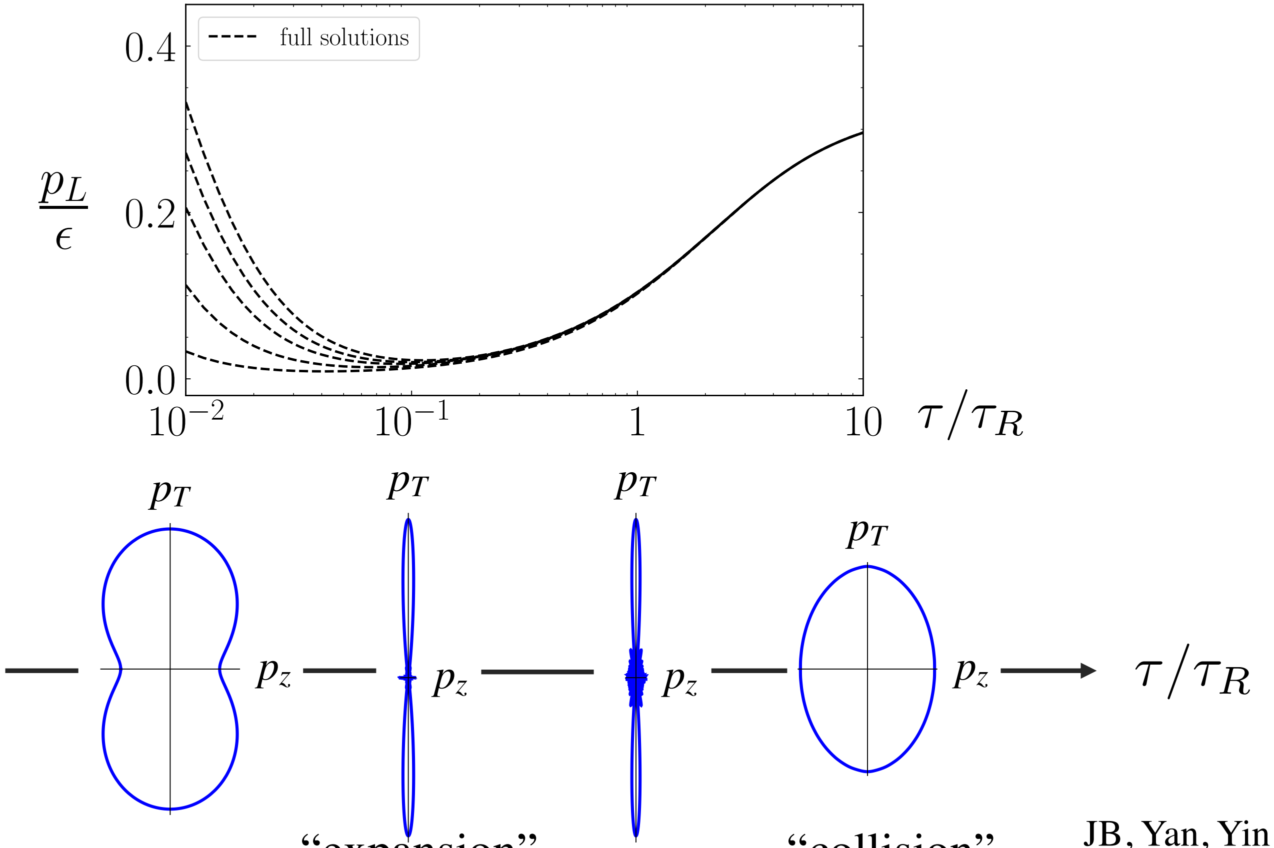
Early times: $\Delta E \sim \frac{1}{\tau}$

Late times: $\Delta E \sim \frac{1}{\tau_R}$

Initial conditions decay to ground state on time scale set by energy gap

Kurkela, van der Schee, Wiedemann, Wu [1907.08101]

But this slow mode is not a hydrodynamic mode

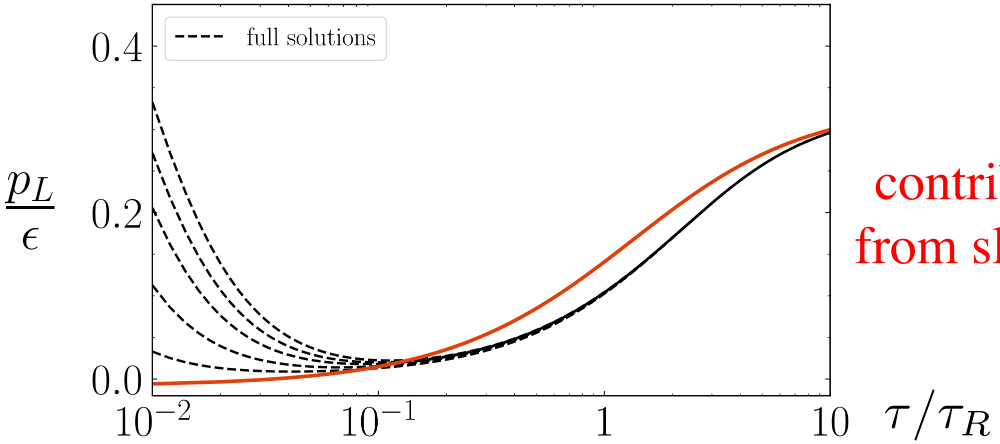


“expansion” slow mode

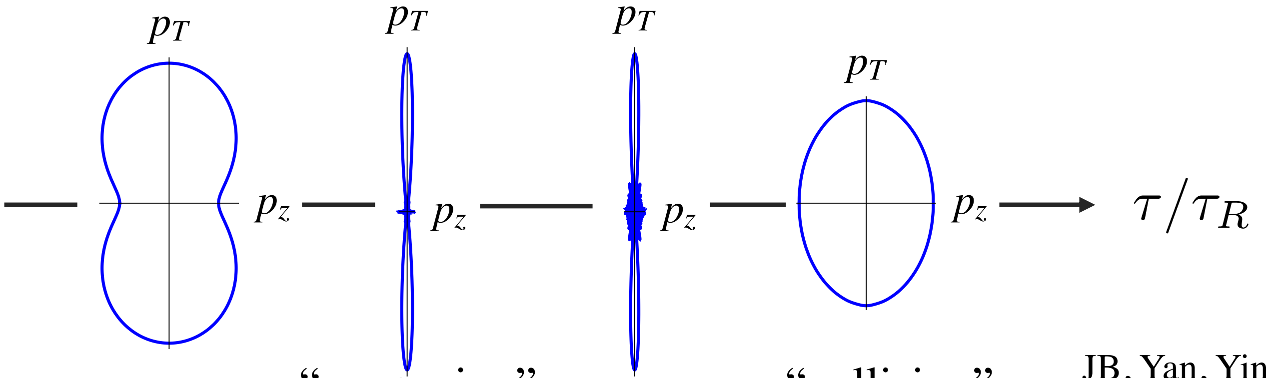
“collision” slow mode

JB, Yan, Yin [1910.00021]

But this slow mode is not a hydrodynamic mode



contribution only from slowest mode

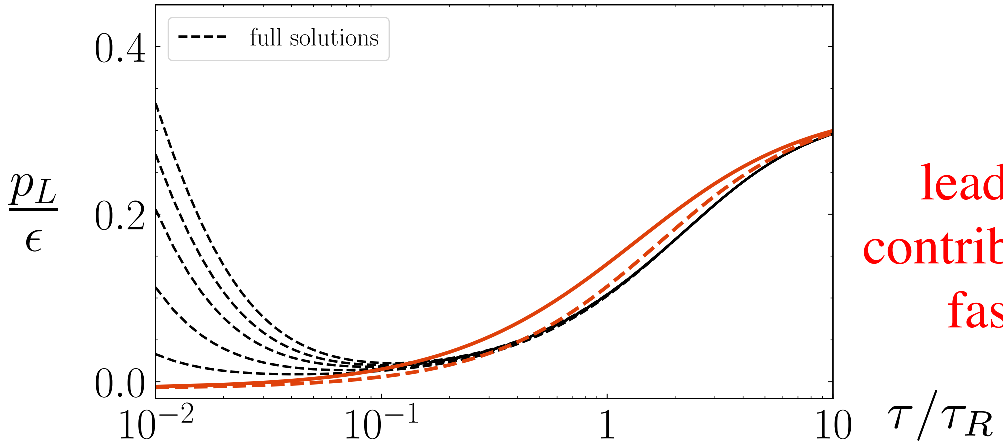


"expansion" slow mode

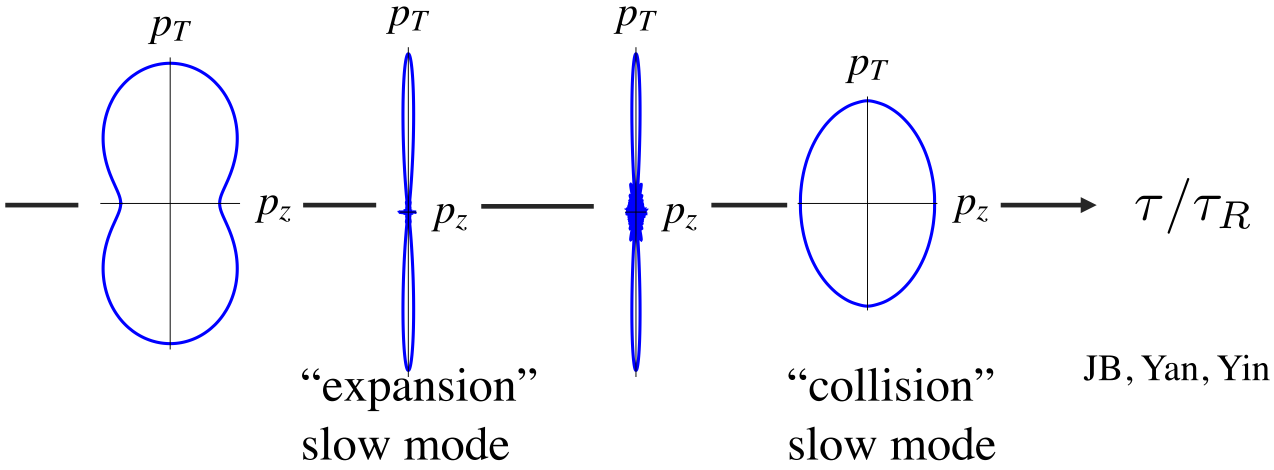
"collision" slow mode

JB, Yan, Yin [1910.00021]

But this slow mode is not a hydrodynamic mode



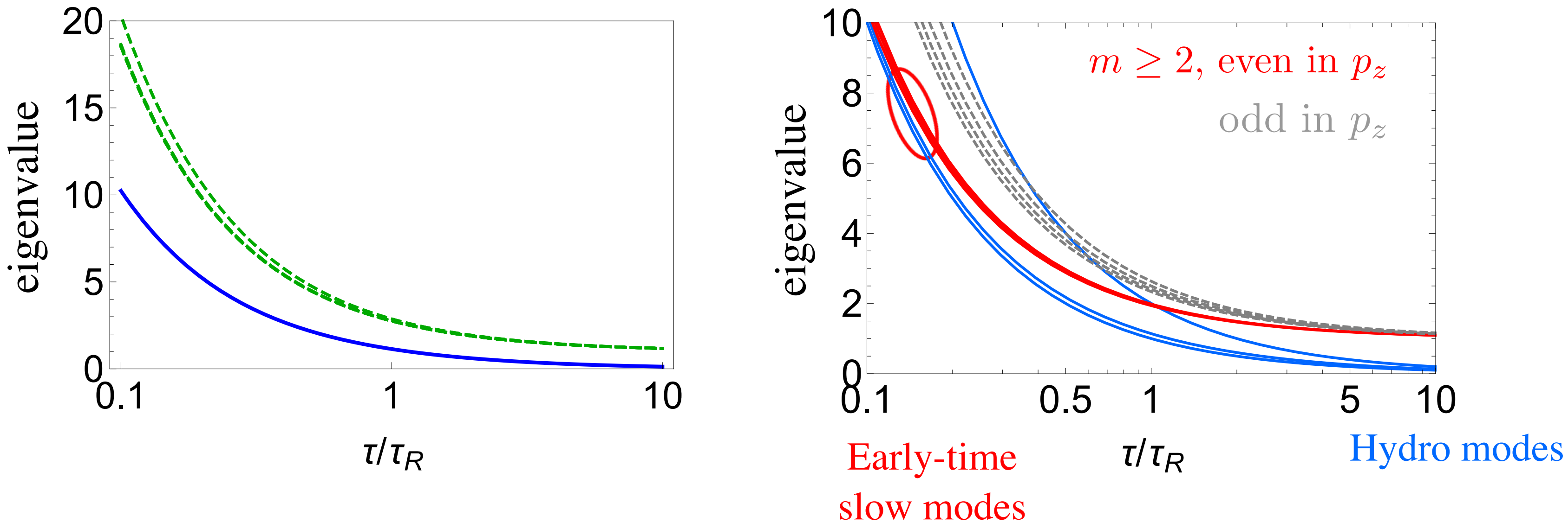
leading order contributions from fast modes



JB, Yan, Yin [1910.00021]

Beyond Bjorken expansion: transverse modes

$$Y_l^m(\theta,\phi) \sim e^{im\phi} P_l^m(\cos\theta)$$



Slow modes at early times are qualitatively different (including in number) than hydrodynamic modes

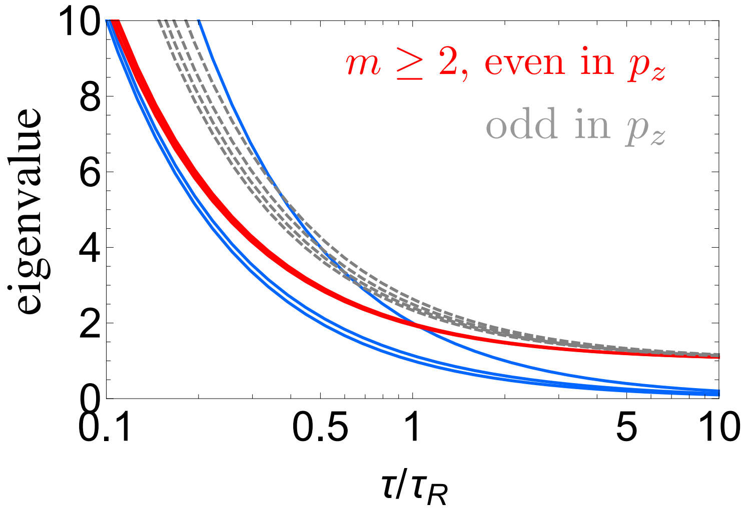
JB, Weiyao Ke, Li Yan, Yi Yin (in progress)

Why does it matter?

Qualitative differences between early- and late-time attractor due to different number of slow modes

$m \geq 2$ modes describe momentum anisotropy and are slow at early times. Attractor for momentum space anisotropy

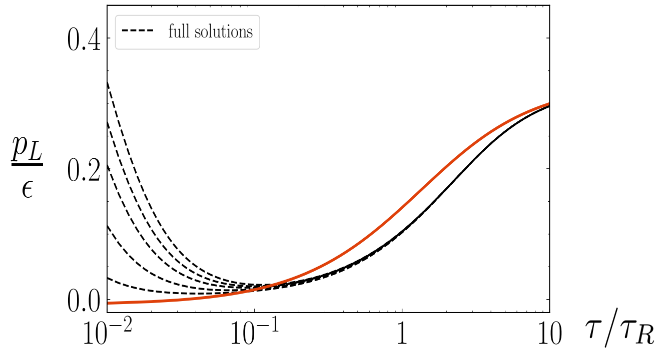
$$Y_l^m(\theta,\phi) \sim e^{im\phi} P_l^m(\cos\theta)$$



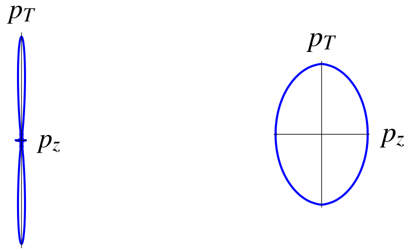
JB, Weiyao Ke, Li Yan, Yi Yin (in progress)

Summary and Outlook

Connection between attractor and far-from-equilibrium slow modes



Beyond Bjorken, different number of slow modes at early and late times



Implications for non-thermal scaling attractor

Scheihing-Hitschfeld Mon.

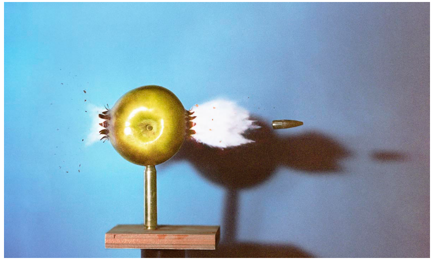
The bigger picture

Probing the far-from-equilibrium QGP

- Small systems

with Aleksas Mazeliauskas
and Wilke van der Schee

- Equilibration of hard processes



Special thanks to Aleksas, Bruno, Dekrayat, Gian Michele, Li, Urs, Weiyao, and Yi