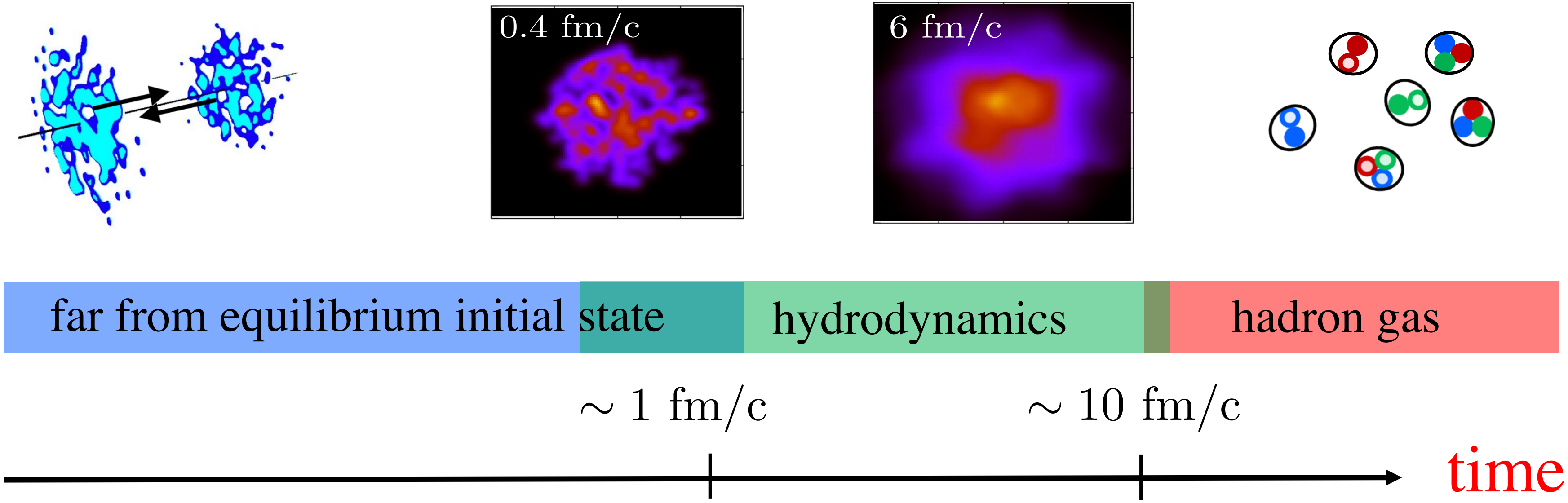
Slow modes in rapidly-expanding quark–gluon plasma

Jasmine Brewer

Based on [1910.00021] and ongoing work
with Weiyao Ke, Li Yan, and Yi Yin

Equilibration of strongly-interacting matter in heavy-ion collisions



Hydrodynamization near equilibrium

Near-equilibrium

Microscopic theories

Kinetic theory

AdS/CFT

…

QGP

Hydrodynamics

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

Perturbation in microscopic theory

many degrees of freedom are important

dynamics governed by conservation laws

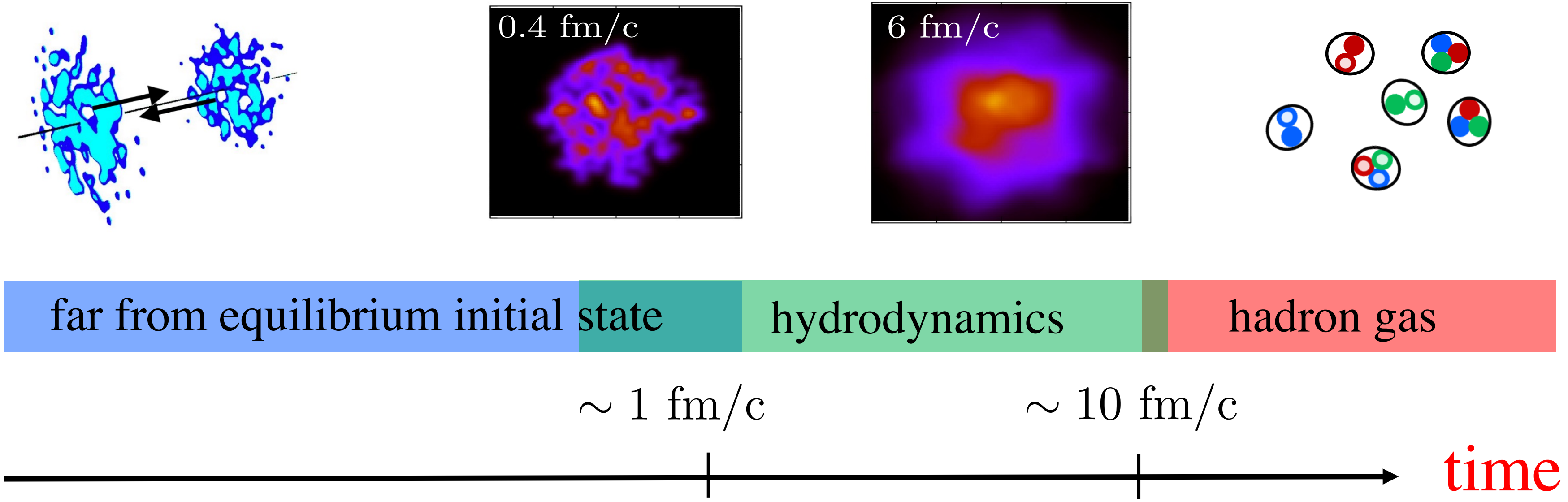
τ_{Hydro}

τ

Decay of fast "non-hydrodynamic" modes

Slow "hydrodynamic modes"

Equilibration of strongly-interacting matter in heavy-ion collisions



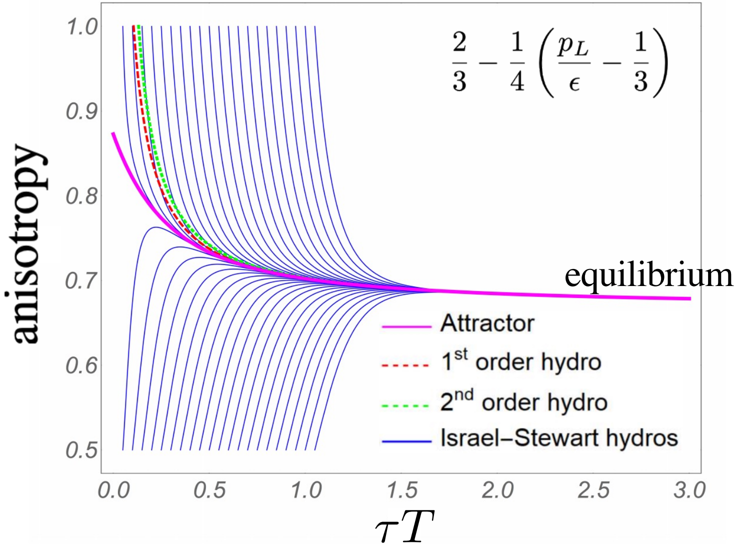
Evolution of initial state to hydrodynamics in kinetic theory

A. Mazeliauskas, next talk
X. Du 15:20

This talk: description of far-from-equilibrium systems and onset of hydrodynamics

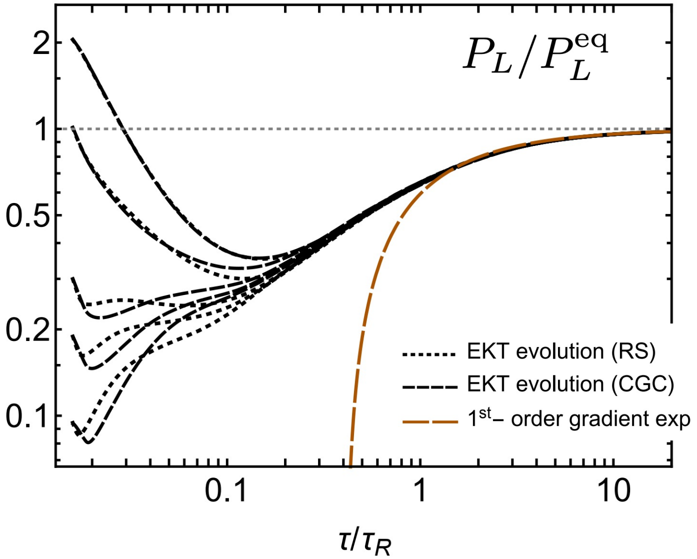
Onset of hydrodynamics far-from-equilibrium?

Far-from-equilibrium universality in hydrodynamics



Heller, Spalinski [1503.07514]

QCD effective kinetic theory

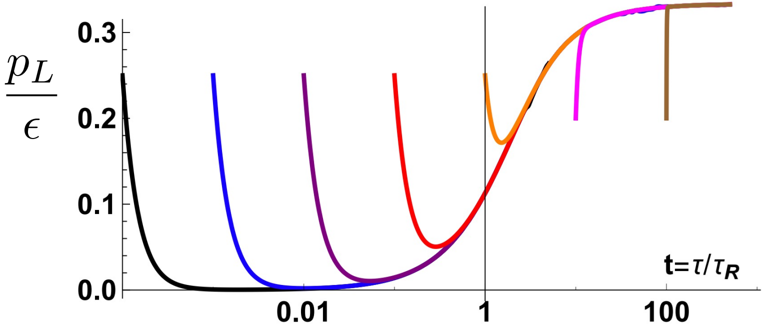


Almaalol, Kurkela, Strickland [2004.05195]

Extensive work: Heller, Spalinski, Svensson, Romatschke, Strickland, Noronha, Denicol, Kurkela, Wiedemann, Wu, Martinez, ….

Free-streaming and hydrodynamic attractors

relaxation time approximation



(qualitatively similar results for Israel-Stewart)

τ_R: relaxation timescale

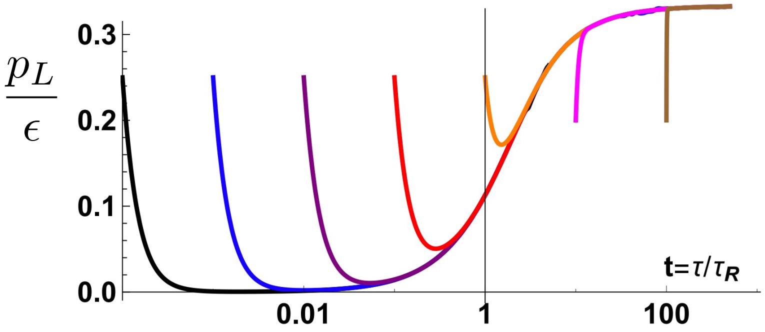
Kurkela, van der Schee, Wiedemann, Wu [1907.08101]

Rapid expansion without collisions

Collisions

Free-streaming and hydrodynamic attractors

relaxation time approximation



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τ_R: relaxation timescale

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

Rapid expansion without collisions

Collisions

Collectivity can be generated by small number of final-state interactions   R. Tornkvist, 15:00

Borghini, Feld, Kerstig [1804.05729], Kurkela, Wiedemann, Wu [1905.05139], Kurkela, Mazeliauskas, Tornkvist [2104.08179]

Motivates understanding the transition from free-streaming to hydrodynamics

Hydrodynamization in kinetic theory

$$\partial_\tau f - \frac{p_z}{\tau}\partial_{p_z} f = -C[f]$$

longitudinal expansion

collisions

Hydrodynamization in kinetic theory

$$\int_p p \left(\underbrace{\partial_\tau f}_{\partial_\tau F} - \underbrace{\frac{p_z}{\tau}\partial_{p_z} f}_{-\frac{1}{\tau}(\dots)F} = \underbrace{-C[f]}_{(\dots)F} \right)$$

(sometimes)

Here: RTA

Nonlinear kernels:
JB, Scheihing-Hitschfeld, Yin (in progress)

F: angular distribution with dimension of the stress tensor

Truncate using moment expansion

Bjorken expansion

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

Evolution of F $\longleftrightarrow$ $\tau\partial_\tau \psi = -\mathcal{H}(\tau)\psi$

Truncate using moment expansion

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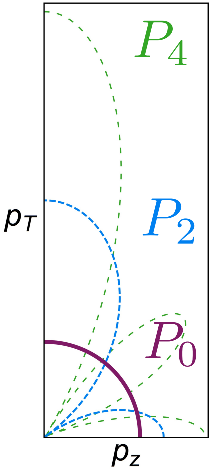


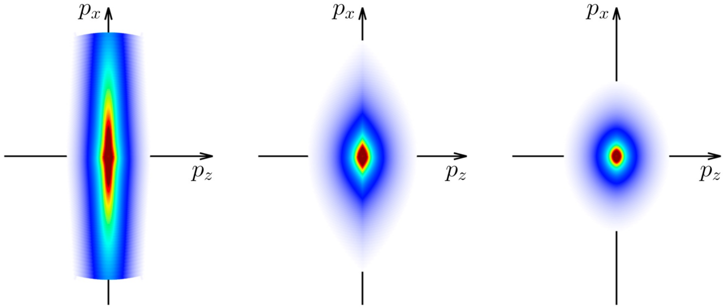
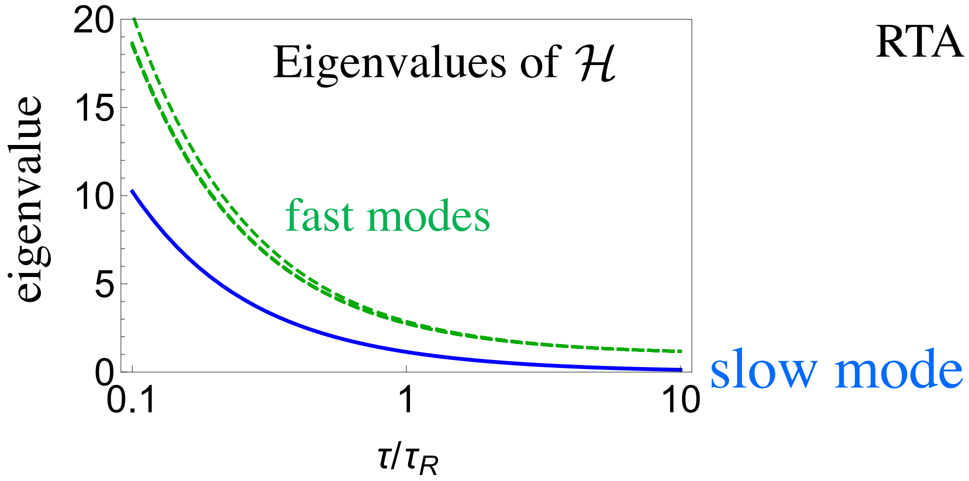


Fig adapted from KoMPoST [1805.00961]

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

hydrodynamization

Ground state: far-from-equilibrium slow mode

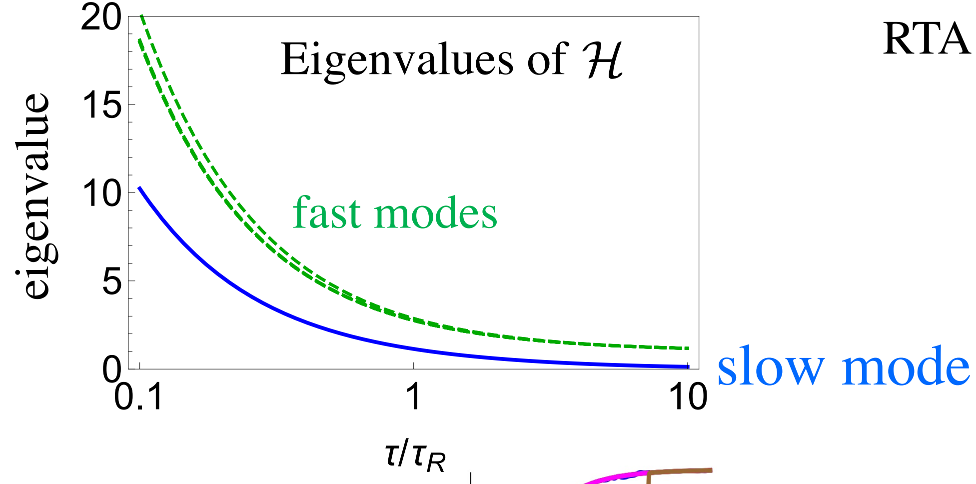


RTA: $\mathcal{H} = \mathcal{H}_F + \frac{\tau}{\tau_R}\mathcal{H}_H$

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

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

Ground state: far-from-equilibrium slow mode



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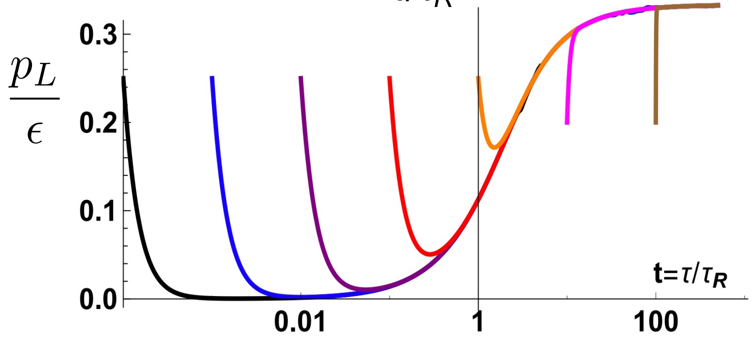
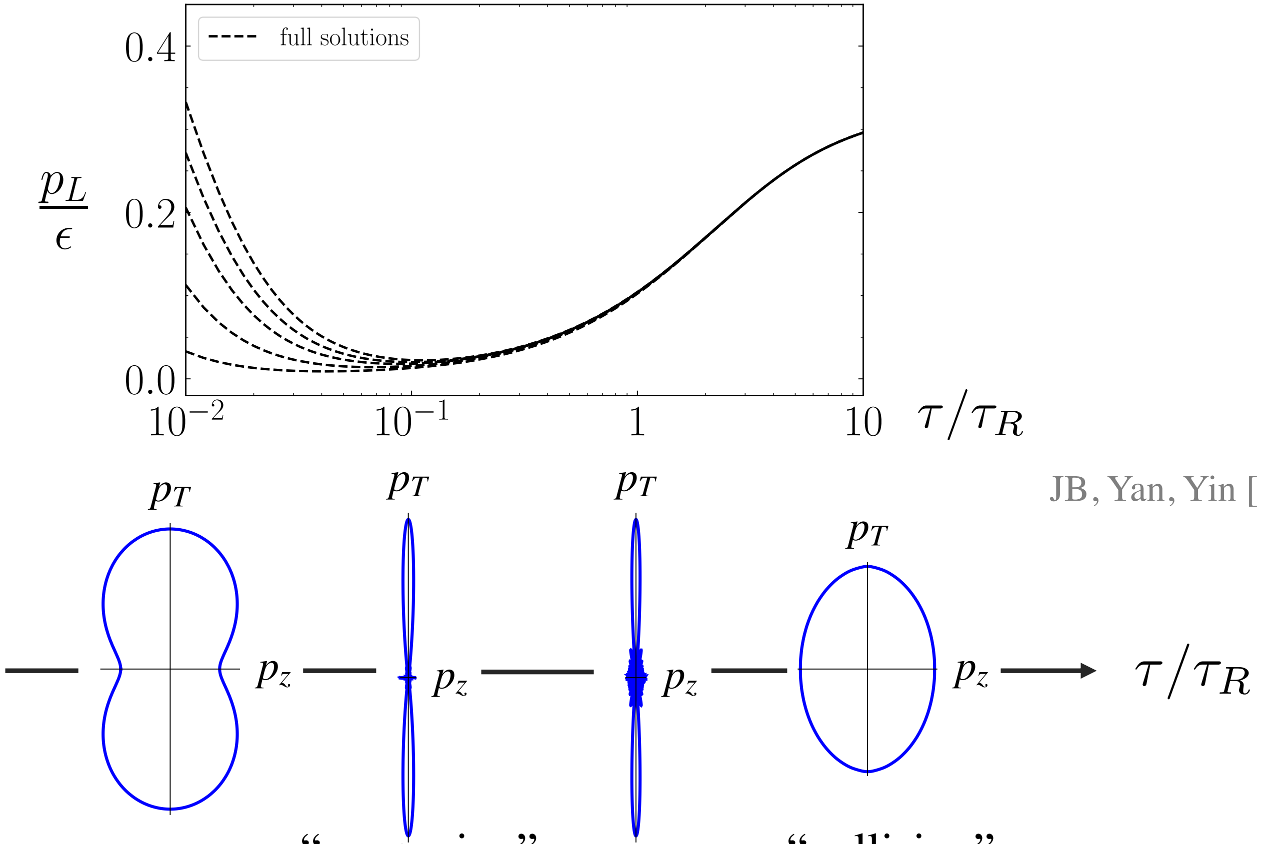


Initial conditions decay to ground state on time scale set by energy gap

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

Ground state: far-from-equilibrium slow mode

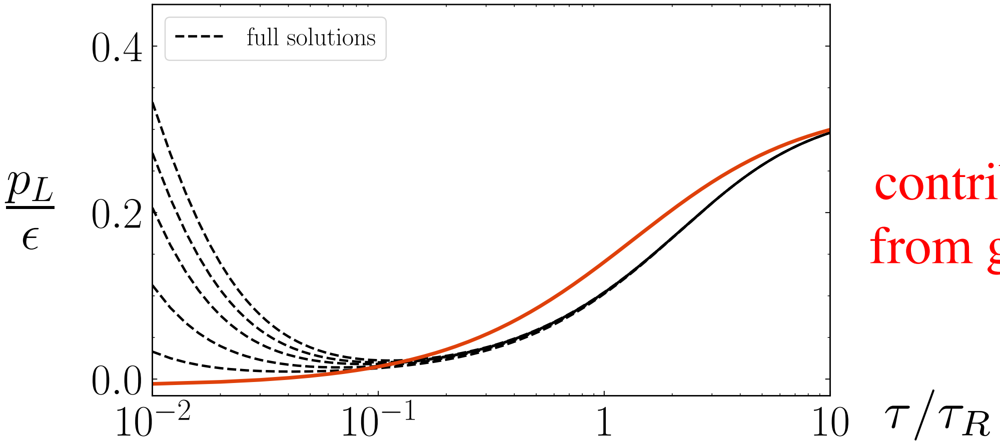


JB, Yan, Yin [1910.00021]

“expansion” slow mode

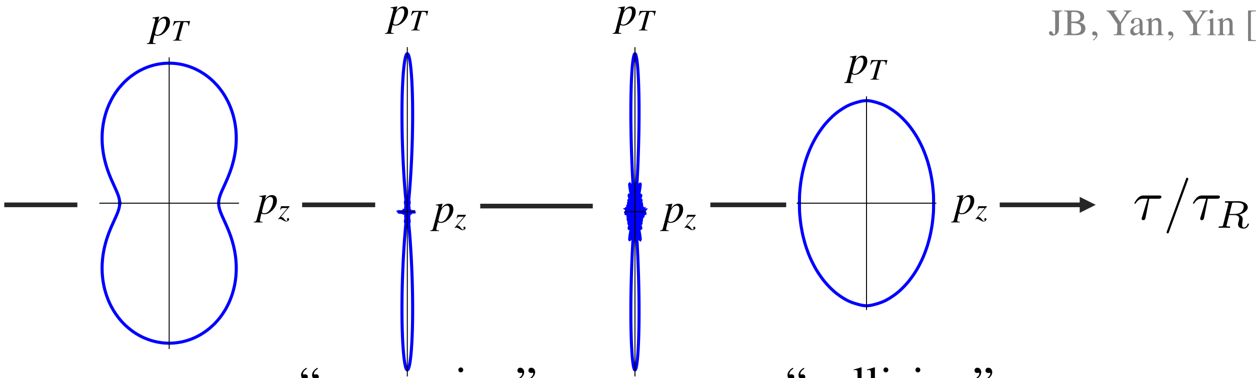
“collision” slow mode

Ground state: far-from-equilibrium slow mode



contribution only from ground state

JB, Yan, Yin [1910.00021]



"expansion" slow mode

"collision" slow mode

A system prepared in its (instantaneous) ground state remains in its (instantaneous) ground state if transitions are suppressed

$$\text{Transition rate} \sim \frac{\partial_\tau \log \lambda}{\Delta E_n} \langle 0(\tau)|H|n(\tau)\rangle \qquad \lambda = \tau/\tau_R$$

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“Slow quench” adiabaticity

- Hamiltonian evolution slow compared to energy gap
- Small close to hydro limit

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"Slow quench" adiabaticity

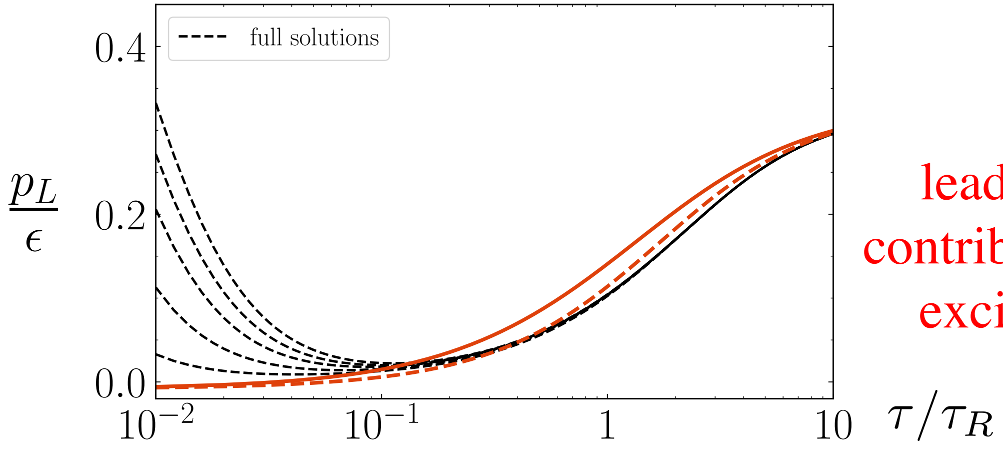
- Hamiltonian evolution slow compared to energy gap
- Small close to hydro limit

"Fast quench" adiabaticity

- Matrix element suppressed
- Small at early times because H suppressed by τ

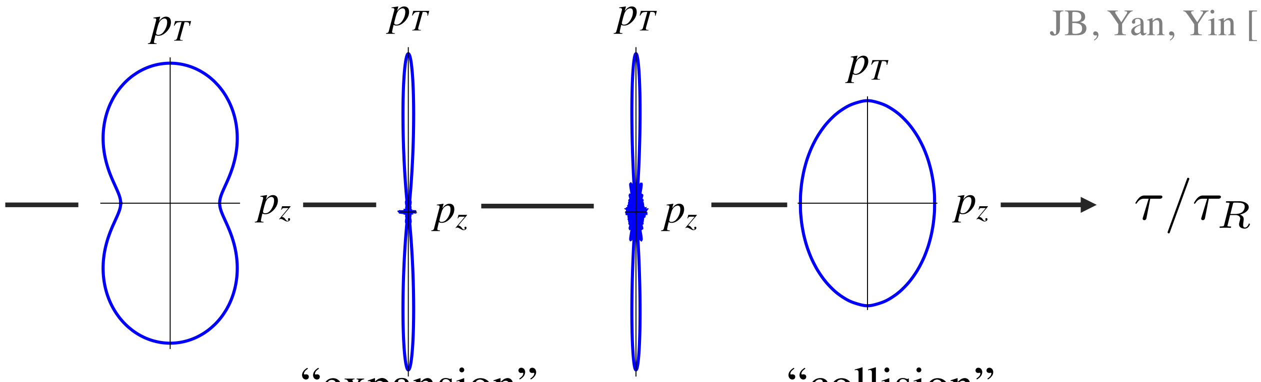
De Grandi, Polkovnikov [0910.2236]

Ground state: far-from-equilibrium slow mode



leading order contributions from excited states

JB, Yan, Yin [1910.00021]

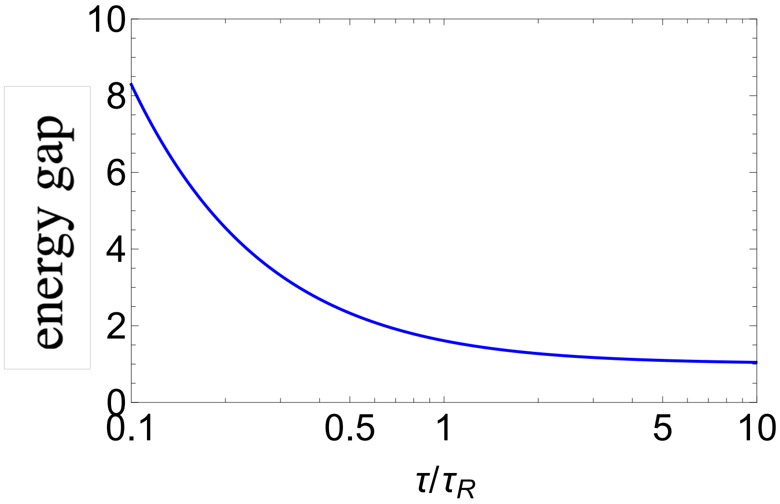


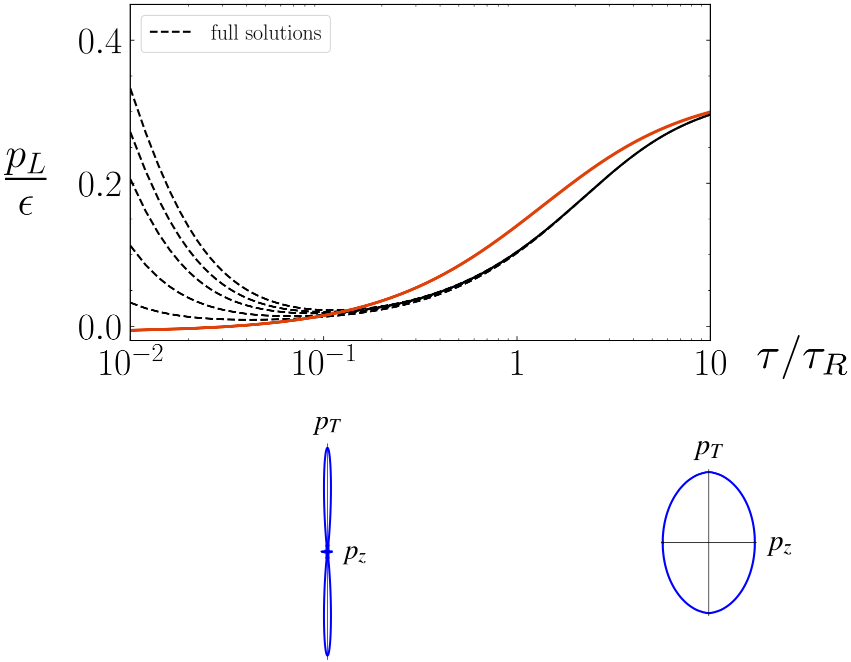
“expansion” slow mode

“collision” slow mode

Bjorken expansion

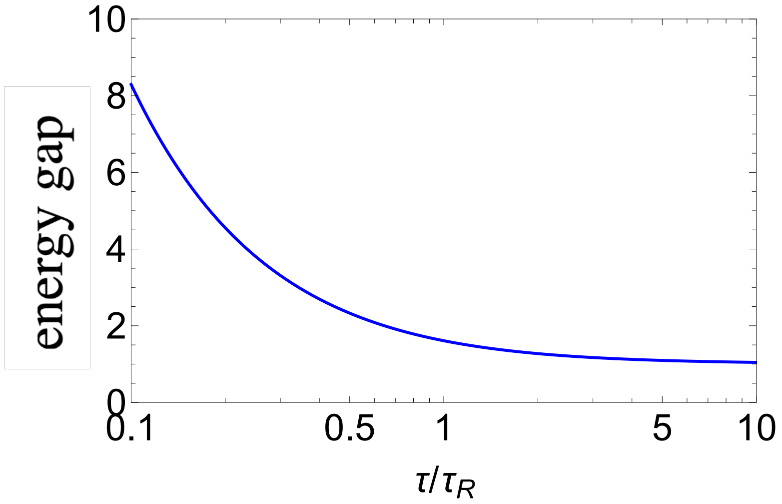
$$P_{2n}(\cos\theta = \frac{p_z}{p})$$





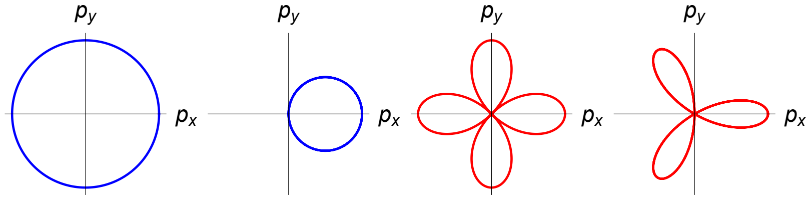
Bjorken expansion

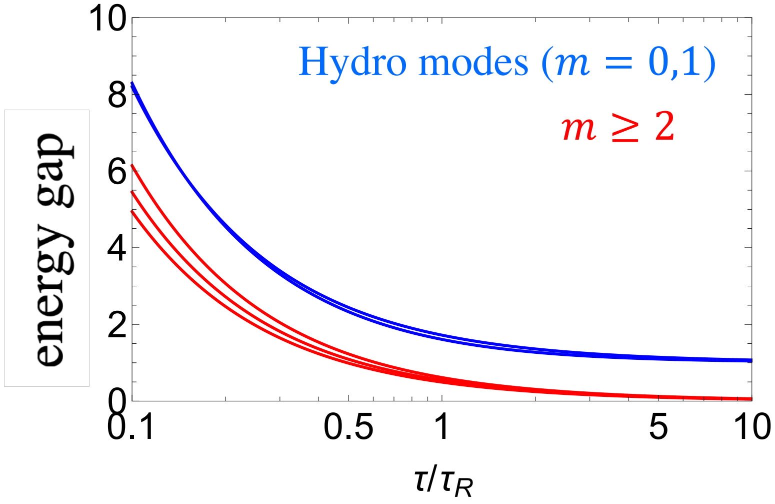
$$P_{2n}(\cos\theta = \frac{p_z}{p})$$



Transverse momentum anisotropy

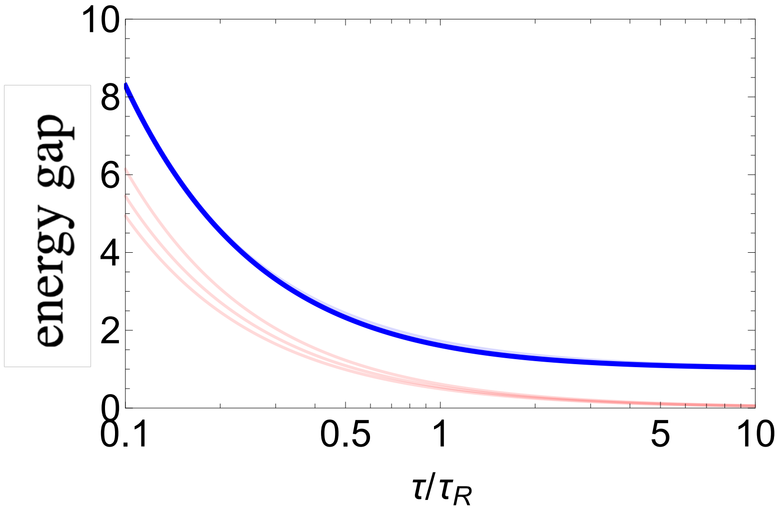
$$Y_l^m(\cos\theta, \phi) = (-1)^m \cos(m\phi) P_l^m(\cos\theta)$$

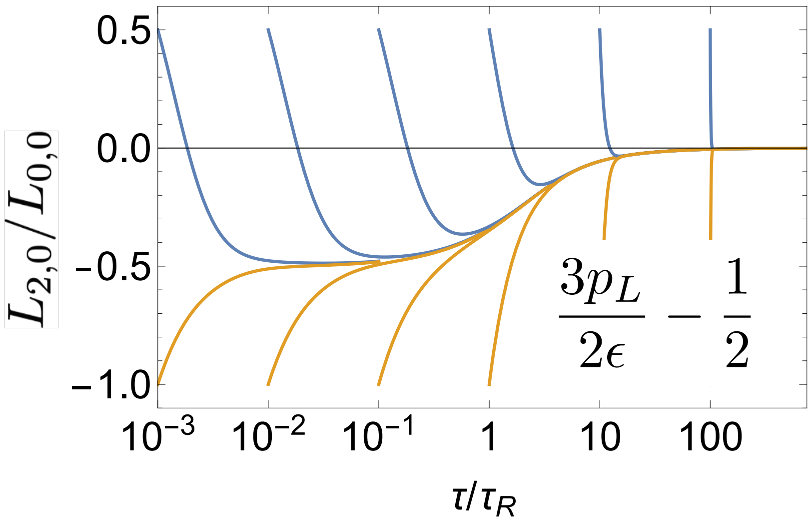




JB, Weiyao Ke, Li Yan, Yi Yin (in progress)

Beyond Bjorken expansion





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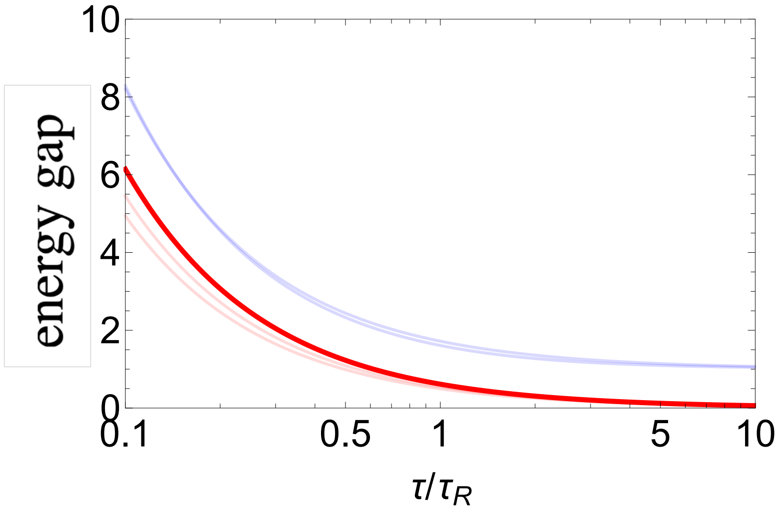
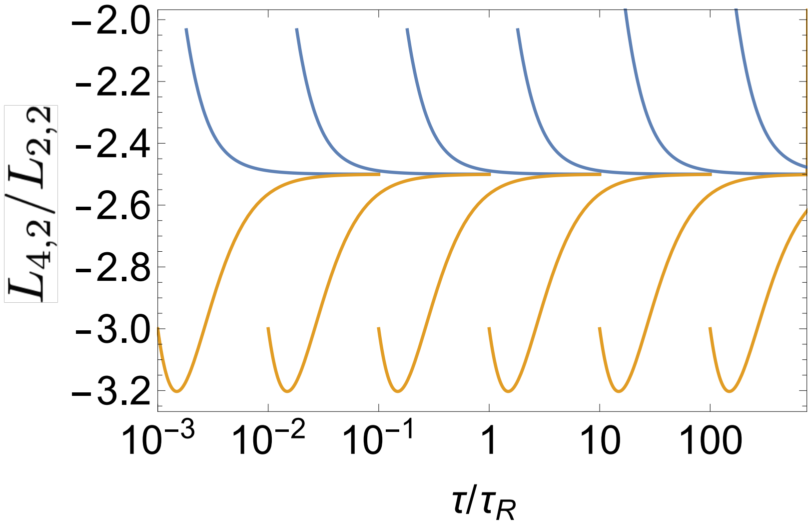
Beyond Bjorken expansion



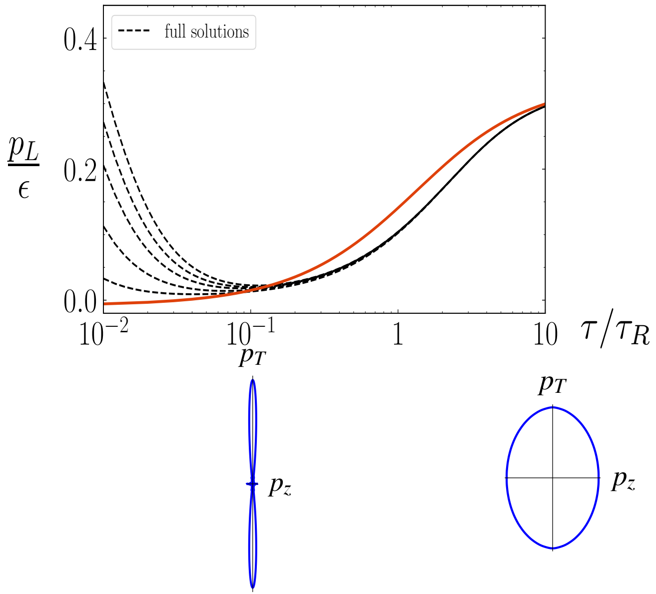


Suggests attractor for non-hydrodynamic modes

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

Summary

Transition from free-streaming to hydrodynamics described by ground state far-from-equilibrium



New insights for far-from-equilibrium behavior of moments beyond hydrodynamics