

# Initial stage of the HIC: thermalization and isotropization

Yan Zhu

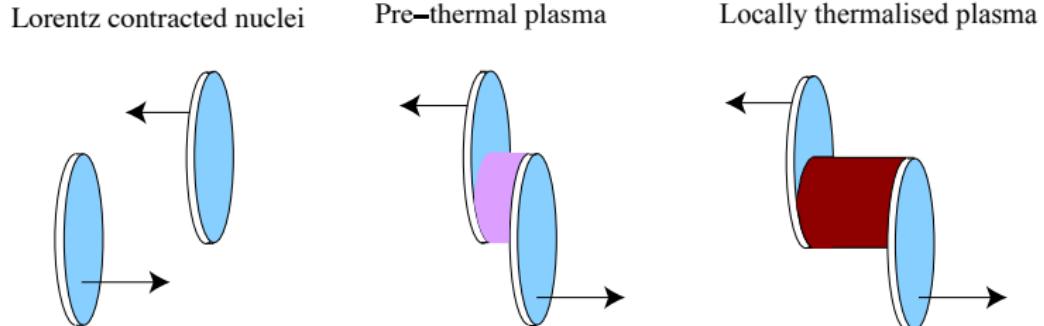


JYVÄSKYLÄN YLIOPISTO  
UNIVERSITY OF JYVÄSKYLÄ



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# Motivation



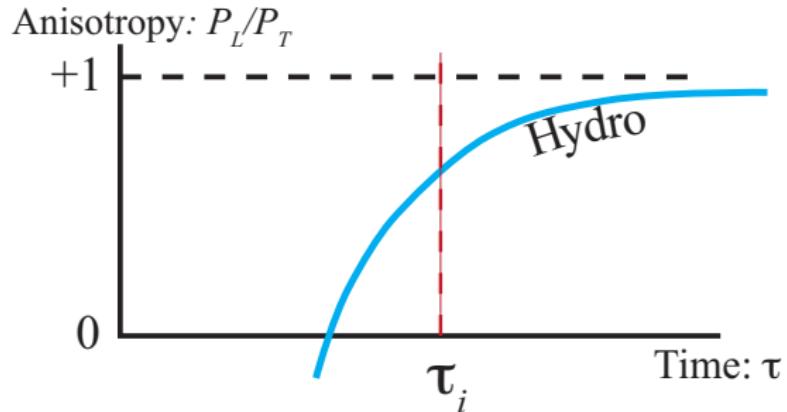
- Locally thermalized plasma described by relativistic hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0$$

- Gradient expansion around local thermal equilibrium

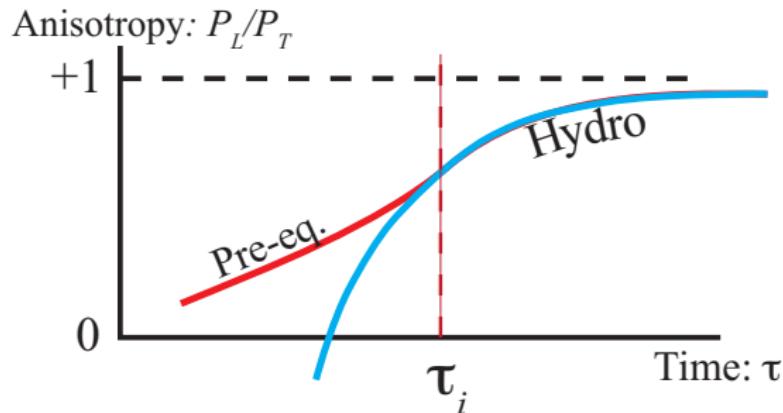
$$T^{\mu\nu} = T_0^{\mu\nu} - \eta(\epsilon)\sigma^{\mu\nu} - \zeta(\epsilon)\{g^{\mu\nu} + u^\mu u^\nu\}(\nabla \cdot u) + \dots$$

## Motivation



- Strong anisotropy  $P_L/P_T \ll 1$ , sign of large corrections
- At early times *pre-equilibrium* evolution
- Hydro simulations start at *initialization time*  $\tau_i$

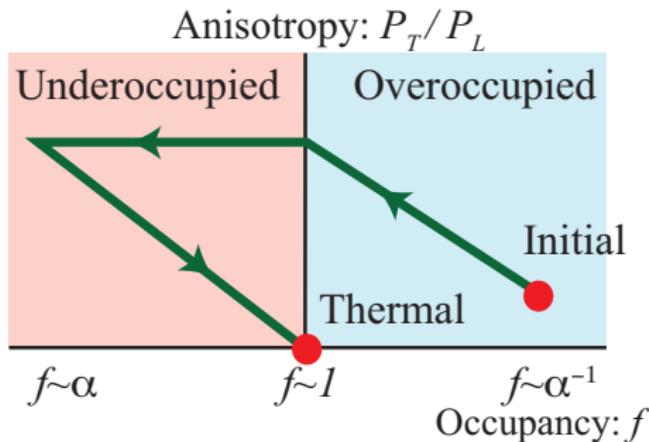
# Motivation



- If prethermal evolution converges smoothly to hydro, independence of unphysical  $\tau_i$
- Explicit example: Strong coupling  $\mathcal{N} = 4$  SYM  
Chesler, Yaffe PRL 106 (2011) 021601; van der Schee et al. PRL 111 (2013) 22, 222302,  
[arXiv:1507.08195](https://arxiv.org/abs/1507.08195)

This has proven to be challenging in QCD, even at weak coupling

# Bottom-up thermalization at weak coupling



- Color Glass Condensate: Initial condition overoccupied

McLerran, Venugopalan PRD49 (1994) 2233-2241 , PRD49 (1994) 3352-3355 ; Gelis et. al Int.J.Mod.Phys. E16 (2007) 2595-2637 , Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489

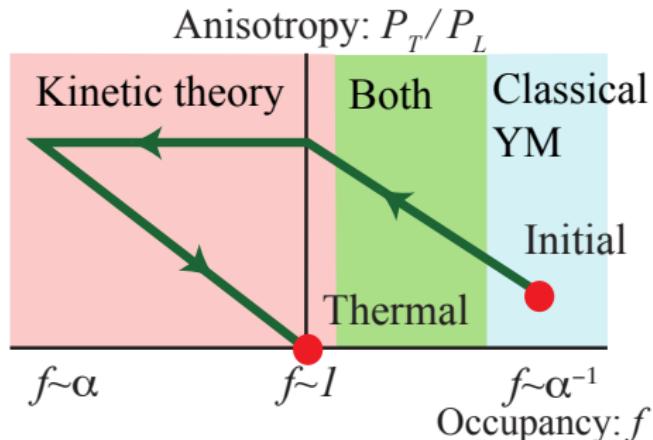
$$f(Q_s) \sim 1/\alpha_s, \quad Q_s \sim 2\text{GeV}$$

- Expansion makes system underoccupied before thermalizing

Baier et al Phys.Lett. B502 (2001) 51-58; Kurkela, Moore JHEP 1111 (2011) 120

$$f(Q_s) \ll 1$$

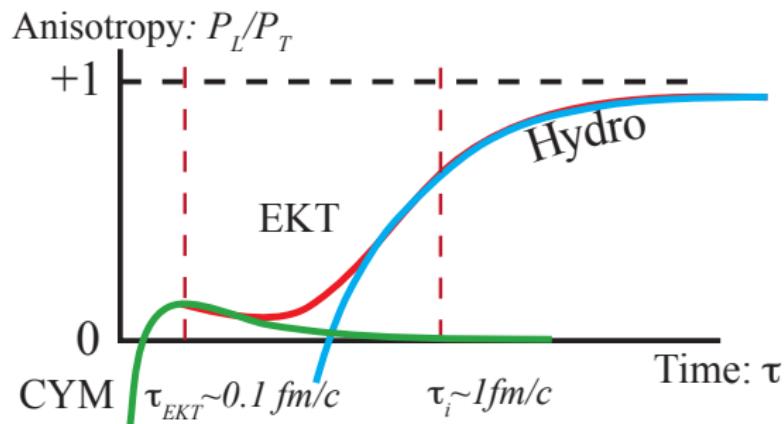
# Bottom-up thermalization at weak coupling



- Degrees of freedom:
  - $f \gg 1$ : Classical Yang-Mills theory (CYM)
  - $f \ll 1/\alpha_s$ : (Semi-)classical particles, Eff. Kinetic Theory (EKT)
- Transmutation of fields to particles: Field-particle duality  
Son, Mueller PLB582 (2004) 279-287; Jeon PRC72 (2005) 014907; Mathieu et al EPJ C74 (2014) 2873 ; Kurkela, Moore PRD89 (2014) 7, 074036

$$1 \ll f \ll 1/\alpha_s$$

## Strategy at weak coupling



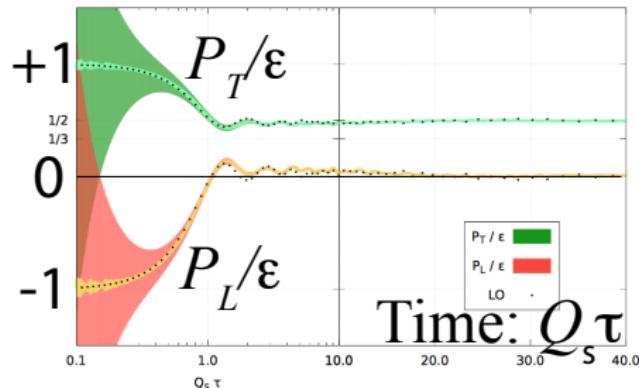
Strategy: Switch from CYM to EKT at  $\tau_{EKT}$ ,

$$1 \ll f \ll 1/\alpha_s$$

From EKT to hydro at  $\tau_i$ ,

$$P_L/P_T \sim 1$$

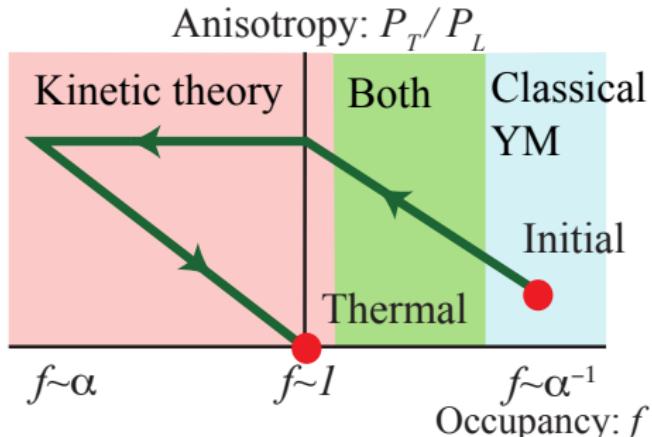
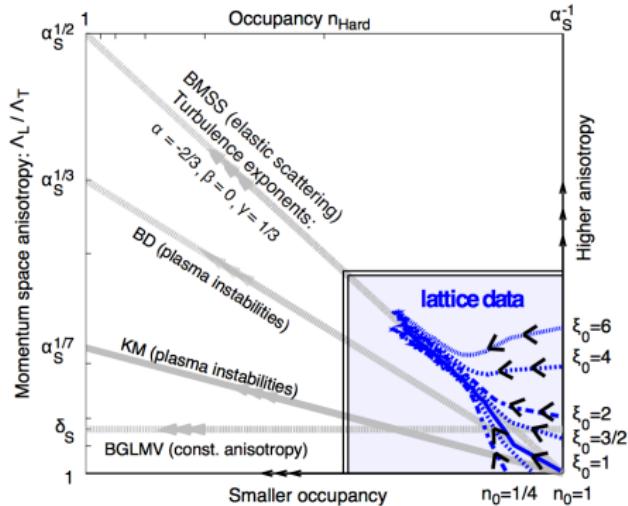
## Early times $0 < Q_s \tau \lesssim 1$ : classical evolution



Epelbaum & Gelis, PRL. 111 (2013) 23230

- Melting of the coherent boost invariant CGC fields
  - The initial condition from CGC: MV-model, JIMWLK
  - After  $\tau \sim 1/Q_s$ , fields decohere,  $P_L > 0$

# Later times $Q_s \tau > 1$ : classical evolution



Berges et al. Phys.Rev. D89 (2014) 7, 074011

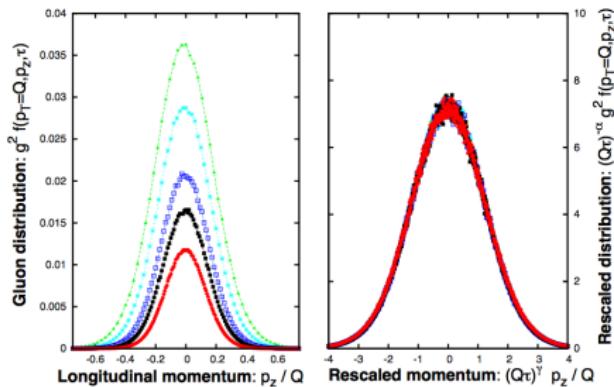
- Numerical demonstration of classical/overoccupied part of the diagram
- Classical theory never thermalises or isotropizes
- Before  $f \sim 1$ , must switch to kinetic theory

# Self-similar scaling in the classical approximation

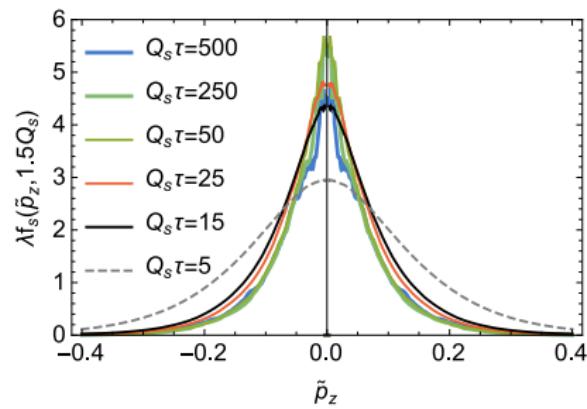
In non-pert classical regime  $1 \ll f \ll 1/\alpha_s$

$$f(p_z, p_\perp, \tau) = (Q_s \tau)^{-2/3} f_S((Q_s \tau)^{1/3} p_z, p_\perp),$$

CYM  $\alpha_s f \ll 1$  limit but  $f \gg 1$



EKT  $f \gg 1$  limit but  $f \ll 1/\alpha_s$



Berges et al. Phys.Rev. D89 (2014) 7, 074011

Kurkela, YZ arXiv:1506.06647

- The quantitative connection allows for smooth matching between classical Yang-Mills and kinetic theory

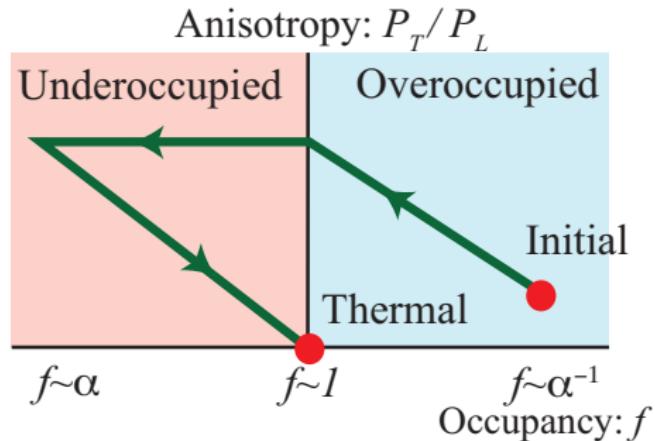
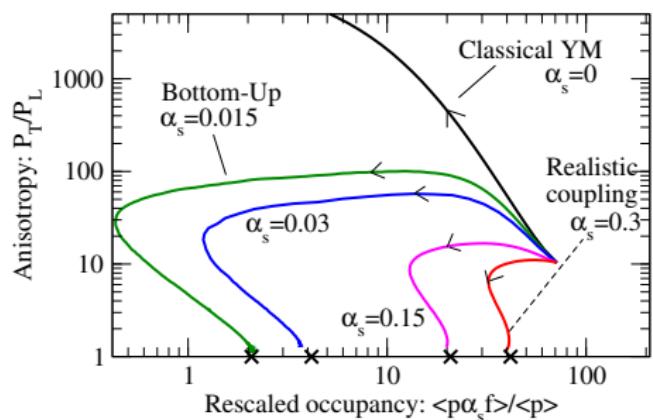
# Effective kinetic theory of Arnold, Moore, Yaffe

JHEP 0301 (2003) 030

$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$

- Soft and collinear divergences lead to nontrivial matrix elements  
soft: screening, Hard-loop; collinear: LPM, ladder resum
- Momentum of quasiparticle  $p > 2N_c g^2 \int_{\mathbf{p}} f(p)/p$
- No free parameters; LO accurate in the  $\alpha_s \rightarrow 0, \alpha_s f \rightarrow 0$  limit.
- Used for LO transport coefficients in QCD, jet energy loss  
[Arnold et al. JHEP 0305 \(2003\) 051](#); [Moore, York PRD79 \(2009\) 054011](#); [Ghiglieri, Teaney 1502.03730](#); [Kurkela, Wiedemann PLB740 \(2015\) 172-178](#); [Iancu, Wu 1506.07871](#)
- Now also available in NLO  $\mathcal{O}(\sqrt{\alpha_s})$   
[Ghiglieri 1509.07773](#)

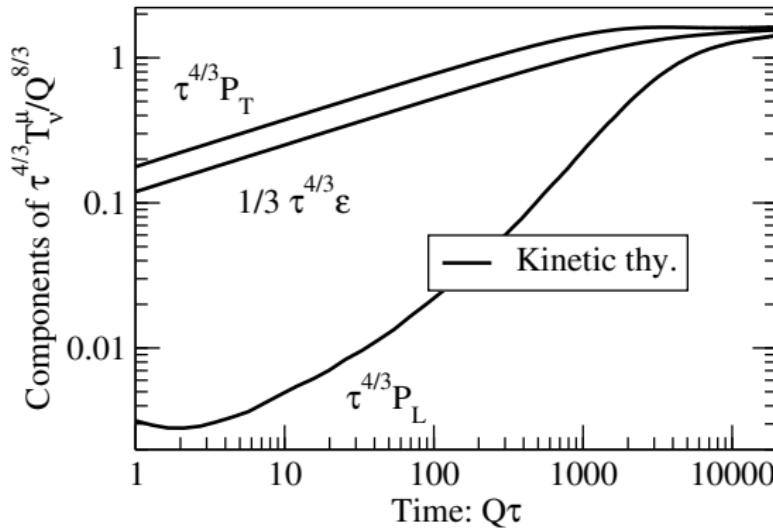
# Route to equilibrium in EKT



- Initial condition ( $f \sim 1/\alpha_s$ ) from classical field theory calculation  
[Lappi PLB703 \(2011\) 325-330](#)
- In the classical limit ( $\alpha_s \rightarrow 0, \alpha_s f$  fixed), no thermalization
- At small values of couplings, clear Bottom-Up behaviour
- Features become less defined as  $\alpha_s$  grows

# Smooth approach to hydrodynamics

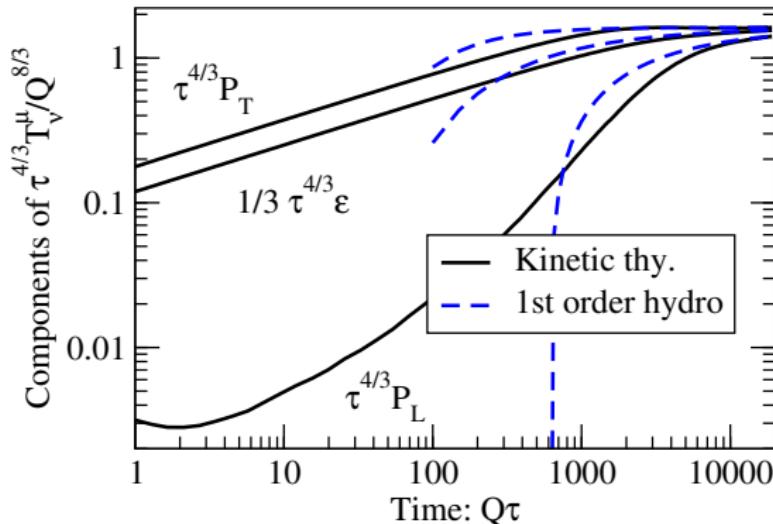
$$\alpha_s = 0.03$$



- Kinetic theory converges to hydro smoothly and automatically

# Smooth approach to hydrodynamics

$$\alpha_s = 0.03$$

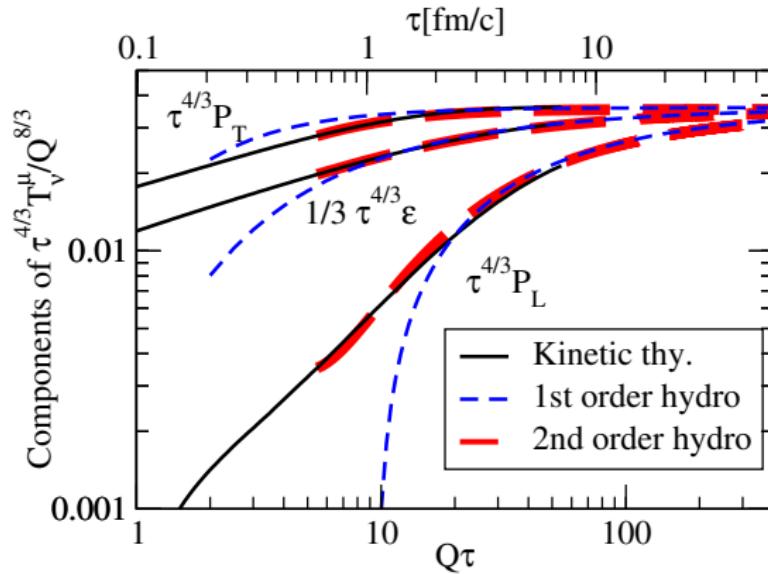


- Kinetic theory converges to hydro smoothly and automatically
- Hydro prediction fixed by perturbative  $\eta/s$

Arnold et al. JHEP 0305 (2003) 051

## Smooth approach to hydrodynamics

$$\alpha_s = 0.3$$



- For realistic couplings, hydrodynamics reached around  $\lesssim 1\text{fm}/c$ .
- Hydro seems to give a good description even when  $P_L/P_T \sim 1/5$

## Summary

- Combination of classical Yang-Mills simulations and effective kinetic theory allows to follow the time evolution from highly occupied initial condition to thermal equilibrium.
- Weak coupling thermalization extrapolated to realistic couplings shows agreement with hydro around

$$\tau_i \sim 1\text{fm}/c$$

- Unified description of soft and hard physics: hydro, jets, etc.