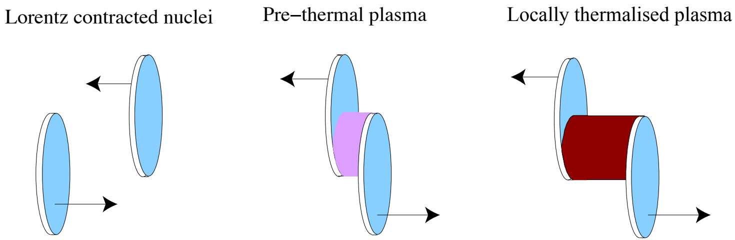
# Initial state of the HIC: thermalization and isotropization

Yan Zhu

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Particle Physics Day, 30 Oct. 2015, Helsinki

# Where are we at?



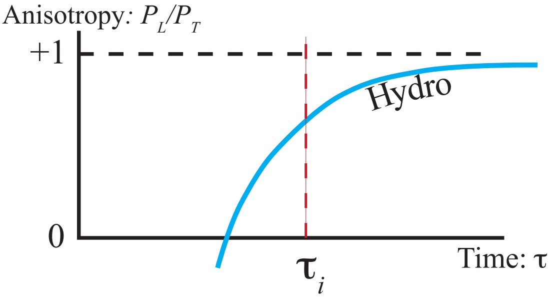

- Soft physics of HIC described by relativistic hydrodynamics

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

- Gradient expansion around local thermal equilibrium

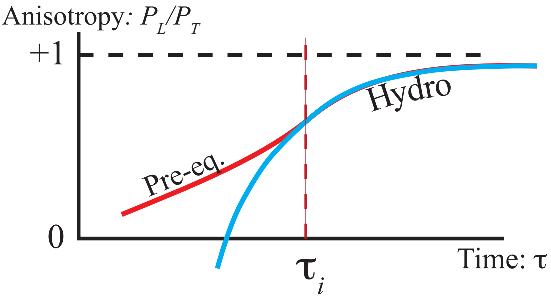
$$T^{\mu\nu} = T^{\mu\nu}_{\text{Thermal equilibrium}} - \eta(\epsilon)\sigma^{\mu\nu} - \zeta(\epsilon)\{g^{\mu\nu} + u^\mu u^\nu\}(\nabla \cdot u) + \ldots$$

# Where are we at?




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

# Where are we at?

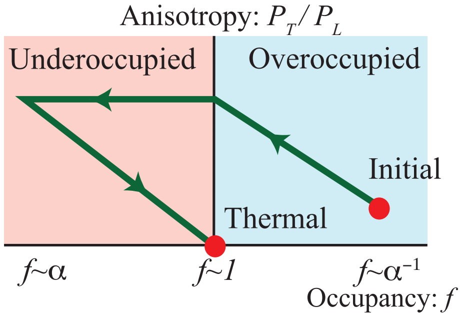



- If prethermal evolution converges smoothly to hydro, independence of unphysical $\tau_i$

- 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

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

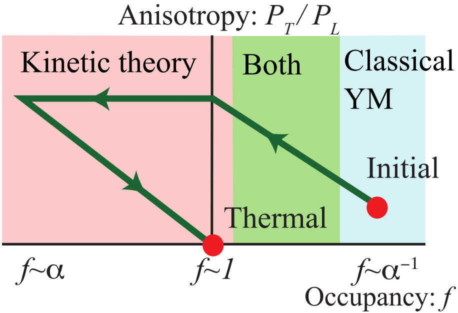
$$f(Q_s) \sim 1/\alpha_s, \qquad Q_s \sim 2\text{GeV}$$

- 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

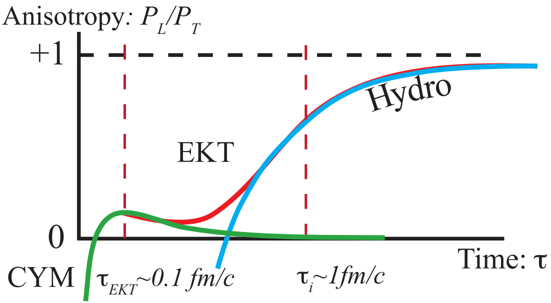



- Degrees of freedom:
  - $f \gg 1$: Classical Yang-Mills theory (CYM)
  - $f \ll 1/\alpha_s$: (Semi-)classical particles, Eff. Kinetic Theory (EKT)

- 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



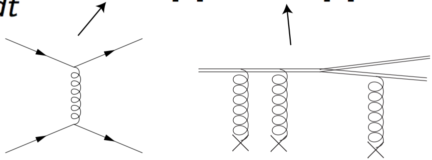

Strategy: Switch from CYM to EKT at $\tau_{EKT}$, $1 \ll f \ll 1/\alpha_s$

From EKT to hydro at $\tau_i$, $P_L/P_T \sim 1$

# Effective kinetic theory of Arnold, Moore, Yaffe

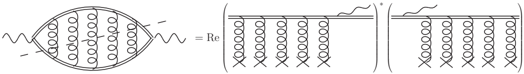
JHEP 0301 (2003) 030

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



- Soft and collinear divergences lead to nontrivial matrix elements

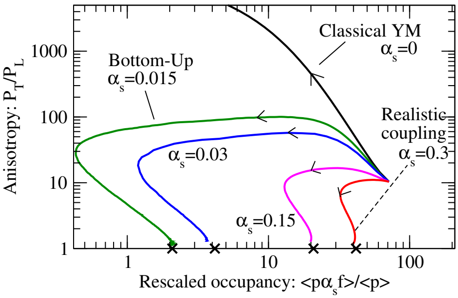
soft: screening, Hard-loop; collinear: LPM, ladder resum

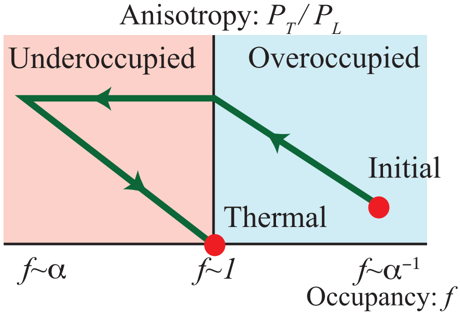



- No free parameters; LO accurate in the $\alpha_s \to 0$, $\alpha_s f \to 0$ limit.
- Used for LO transport coefficients in QCD, jet energy loss
  Arnold et al. JHEP 0305 (2003) 051; Moore, York PRD79 (2009) 054011; Ghiglieri, Teaney 1502.03730; Kurkela, Wiedemann PLB740 (2015) 172-178; Iancu, Wu 1506.07871
- Now also available in NLO $\mathcal{O}(\sqrt{\alpha_s})$ Ghiglieri 1509.07773

# Route to equilibrium in EKT

Kurkela, YZ, PRL in press



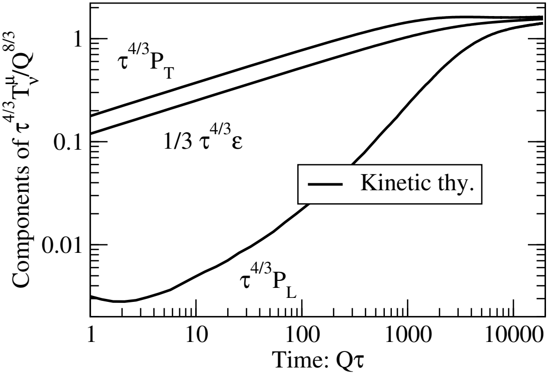




- Initial condition ($f \sim 1/\alpha_s$) from classical field theory calculation
  Lappi PLB703 (2011) 325-330
- In the classical limit ($\alpha_s \to 0, \alpha_s f$ fixed), no thermalization
- At small values of couplings, clear Bottom-Up behaviour
- Features become less defined as $\alpha_s$ grows

# Smooth approach to hydrodynamics

Kurkela, YZ, PRL in press

$$\alpha_s = 0.03$$

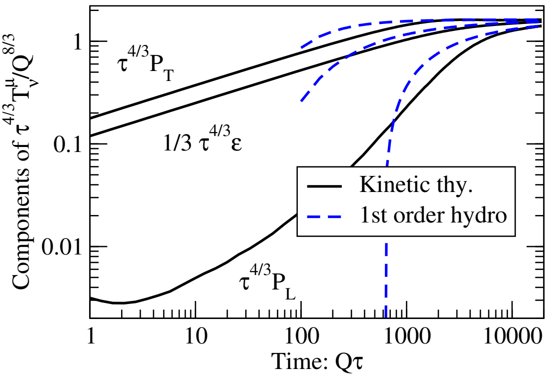



- Kinetic theory converges to hydro smoothly and automatically

# Smooth approach to hydrodynamics

Kurkela, YZ, PRL in press

$$\alpha_s = 0.03$$



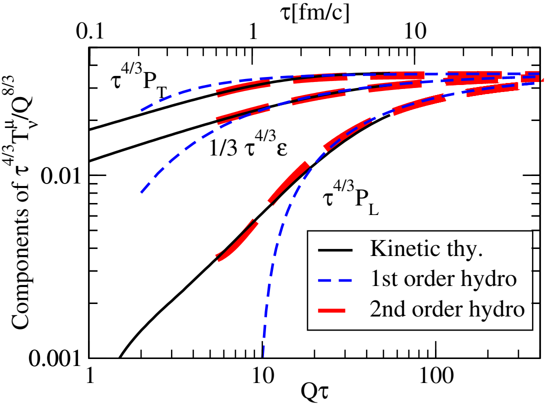

- Kinetic theory converges to hydro smoothly and automatically
- Hydro prediction fixed by perturbative $\eta/s$

Arnold et al. JHEP 0305 (2003) 051

# Smooth approach to hydrodynamics

Kurkela, YZ, PRL in press

$$\alpha_s = 0.3$$




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

# Where are we going?

- 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

$$\tau_{\mathrm{i}} \sim 1\mathrm{fm/c}$$

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