Far-from-equilibirium gauge fields and early time dynamics of heavy-ion collisions

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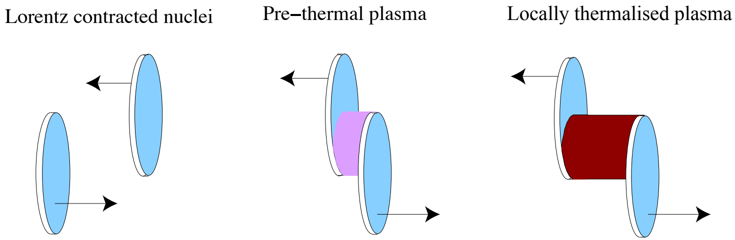
Blois 2016

Motivation



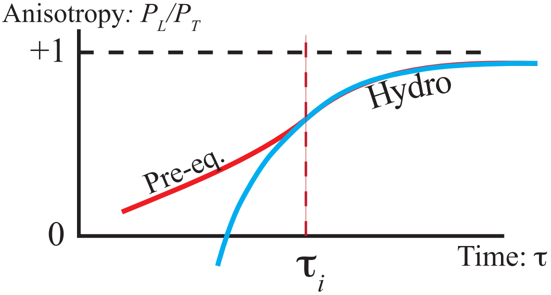
- Quark-Gluon plasma created in heavy-ion collisions flows hydrodynamically
- Hydro as gradient expansion around local thermal equilibrium:

Baier et al. JHEP 0804 (2008) 100

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

$$T^{\mu\nu} = T^{\mu\nu}_{\text{Therm. eq.}} - \eta 2 \nabla^{<\mu} u^{\nu>} + \ldots$$

Far-from-equilibrium evolution



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

Far-from-equilibrium evolution

Limited tool box

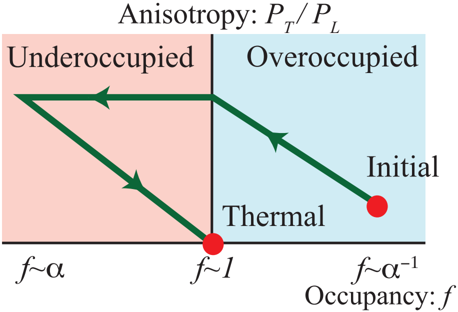
- Lattice techniques suffer from sign problem
- Strong coupling methods (holography) for some special cases

  $\mathcal{N} = 4, N_c \to \infty, \lambda \to \infty$

For generic theories weak coupling methods

- Physics often non-perturbative strong fields, instabilities, secular divergences ...
- Effective theory methods
  - Effective kinetic theory
  - Classical field theory
  - Vlasov theory
  - ...

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

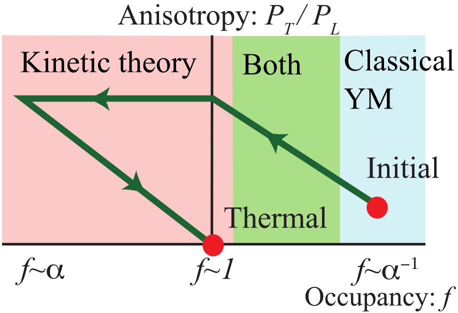
$$f(Q_s) \sim 1/\alpha_s, \qquad Q_s \sim 2\text{GeV}$$

- Expansion makes system underoccupied before thermalizing

Baier et al Phys.Lett. B502 (2001) 51-58

$$f(Q_s) \ll 1$$

Bottom-up thermalization at weak coupling

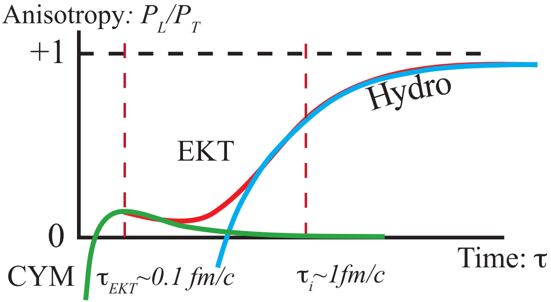


- Degrees of freedom:
  - $f \gg 1$: Classical Yang-Mills theory (CYM)
  - $f \ll 1/\alpha_s$: (Semi-)classical particles, Eff. Kinetic Theory (EKT)

- 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 ; AK, Moore PRD89 (2014) 7, 074036

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

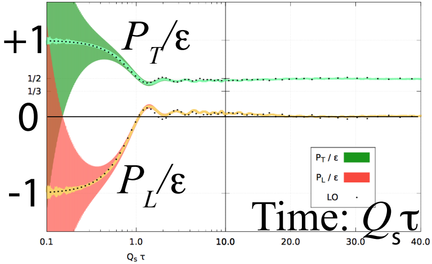
Stages of far-from-equilibrium evolution

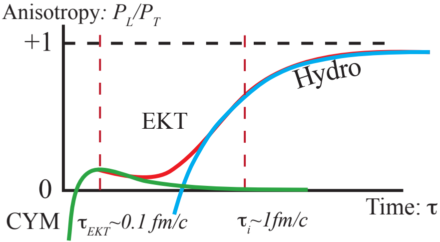


Strategy: Switch from CYM to EKT at τ_{EKT}, $\quad 1 \ll f \ll 1/\alpha_s$

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

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

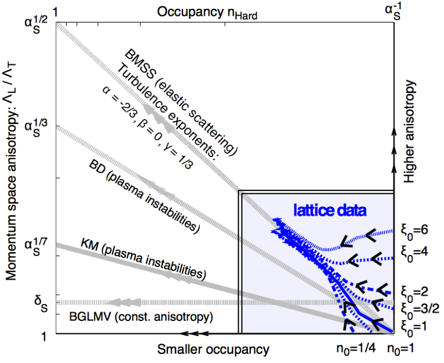




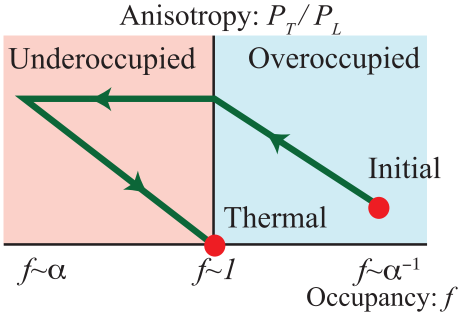
Epelbaum & Gelis, PRL. 111 (2013) 23230

- Melting of the coherent boost invariant CGC fields
  - After $\tau \sim 1/Q_s$, fields decohere, $P_L > 0$

First stage of the evolution



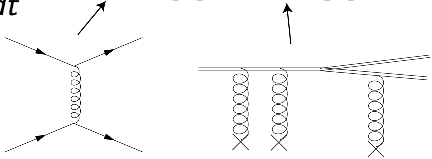
Berges et al. Phys.Rev. D89 (2014) 7, 074011



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

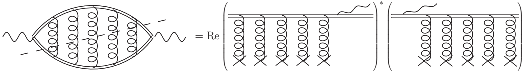
Effective kinetic theory Arnold et al. JHEP 0301 (2003) 030

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



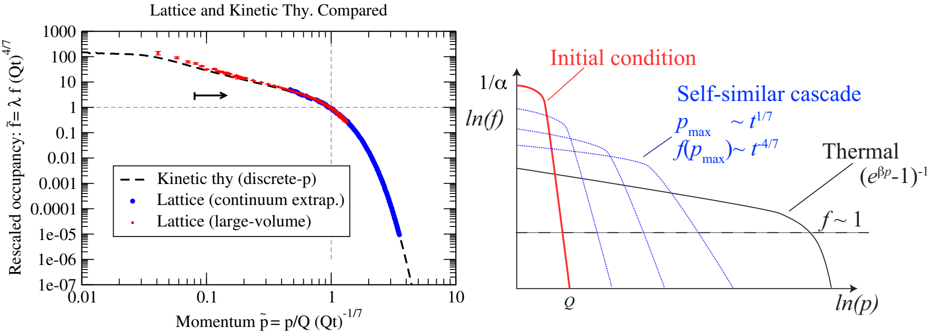
- Soft and collinear divergences lead to nontrivial matrix elements

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; AK, Wiedemann PLB740 (2015) 172-178; Iancu, Wu JHEP 1510 (2015) 155
- Progress in NLO $\mathcal{O}(\sqrt{\alpha_s})$ Ghiglieri et al. JHEP 1603 (2016) 095

Comparison between CYM and EKT: Isotropic



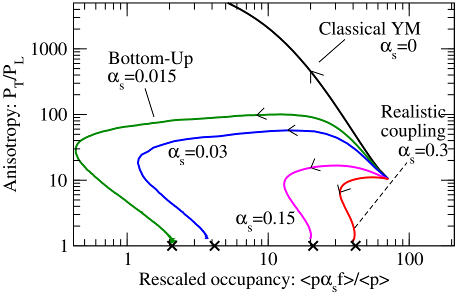
- Quantitative agreement between CYM and EKT for

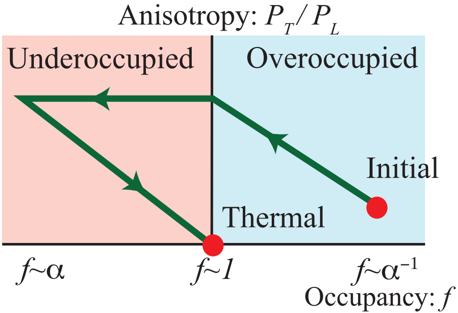
$$1 \ll f \ll 1/\alpha_s$$

Abraao et al. PRD89 (2014) 7, 074036

Route to equilibrium in EKT

AK, Zhu PRL 115 (2015) 18, 182301

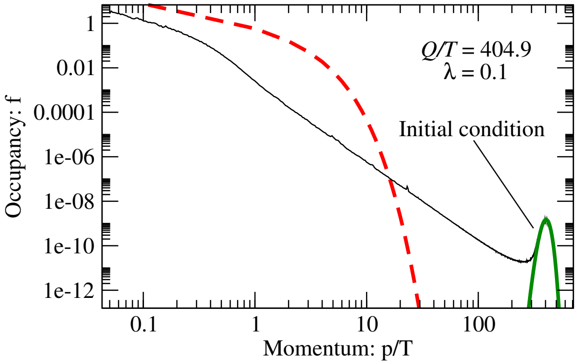


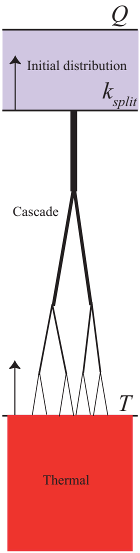


- In the classical limit ($\alpha_s \to 0, \alpha_s f$ fixed), no thermalization
- At small values of couplings, clear Bottom-Up behaviour
- Features become less defined as α_s grows

Radiative break-up

AK, Lu, PRL 113 (2014) 18, 182301

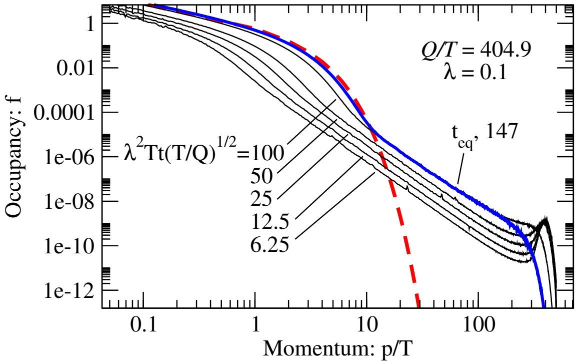


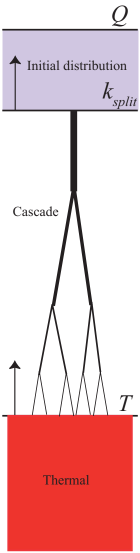


- Soft radiation quick: creation of a thermal bath ("Bottom")
- Hard particles quenched by interactions with the bath
- Heating the soft bath rises longitudinal pressure

Radiative break-up

AK, Lu, PRL 113 (2014) 18, 182301





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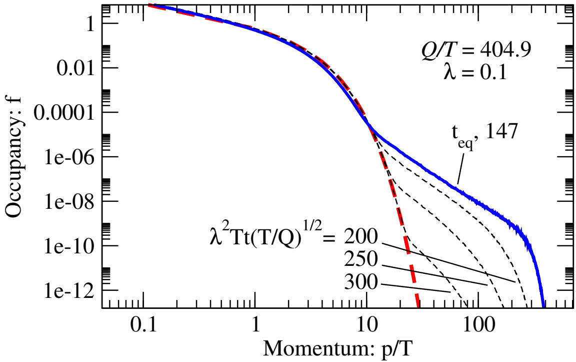

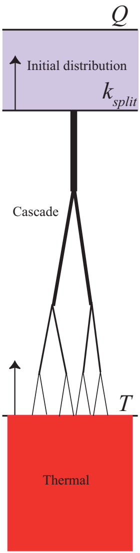

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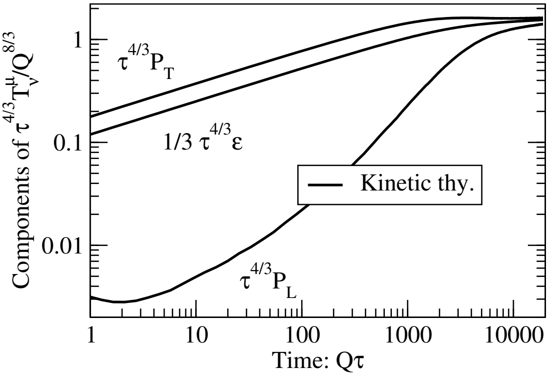
Smooth approach to hydrodynamics AK, Zhu PRL 115 (2015) 18, 182301

$$\alpha_s = 0.03$$



- Kinetic theory converges to hydro smoothly and automatically

Smooth approach to hydrodynamics AK, Zhu PRL 115 (2015) 18, 182301

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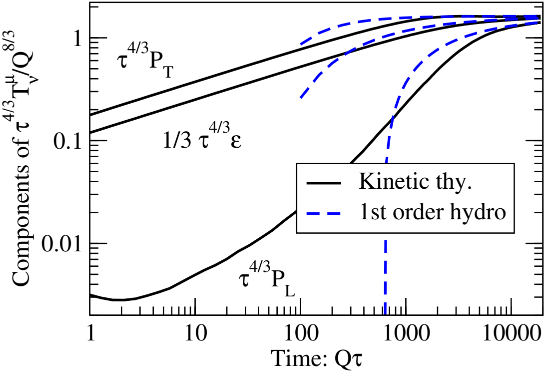
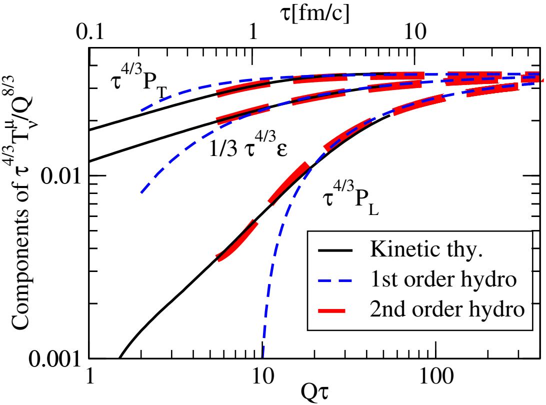


- Kinetic theory converges to hydro smoothly and automatically
- Hydro prediction fixed by perturbative η/s

Arnold et al. JHEP 0305 (2003) 051

Smooth approach to hydrodynamics AK, Zhu PRL 115 (2015) 18, 182301

$$\alpha_s = 0.3$$



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

Thermalization $\neq$ hydrodynamization

Other recent directions

Phenomenology: Transverse dynamics, preflow Keegan et al. 1605.04287

Other theories at weak coupling:

- Several studies in scalar theory
  - Classical Berges et al. 1508.03073
  - Kinetic theory Epelbaum et al. JHEP 1509 (2015) 117
- Exact solutions to kinetic theory in relaxation time approximation Denicol et al. PRL 113 (2014) 20, 202301

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

Approaching from the hydro side:

- What limits the convergence of hydrodynamics Heller, Spalinksi PRL 115, 072501 (2015)
- Modifying hydro to work further from equilibrium, aHydro Phys.Rev. C92 (2015) no.4, 044912

Summary

- Development of generic leading order perturbative far-from-equilibrium methodology in QCD

- Combination of classical Yang-Mills simulations and effective kinetic theory allows to follow the time evolution from highly occupied initial condition to thermal equilibrium.

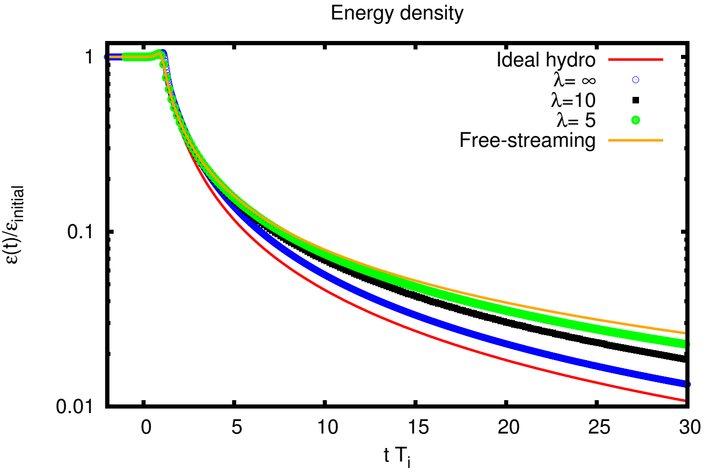
- Applications beyond heavy-ion collisions

  reheating, parametric resonance, relics, phase transitions

Backup sildes

Weakly or strongly coupled thermalization?

Apples to apples comparison of weak and strong coupling



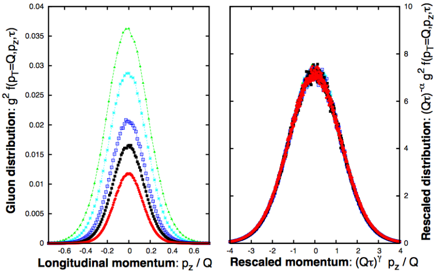
Under construction, AK, Romatschke, van der Schee

Comparison between CYM and EKT: Expanding

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

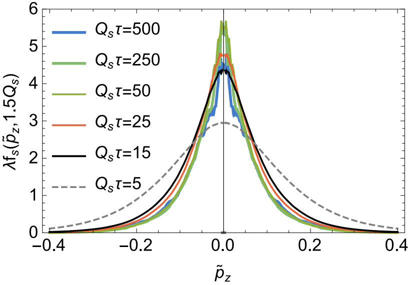
$$f(p_z, p_\perp, \tau) = (Q_s\tau)^{-2/3} f_S((Q_s\tau)^{1/3} p_z, p_\perp),$$

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



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

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



AK, Zhu 1506.06647