QCD kinetic theory and its applications

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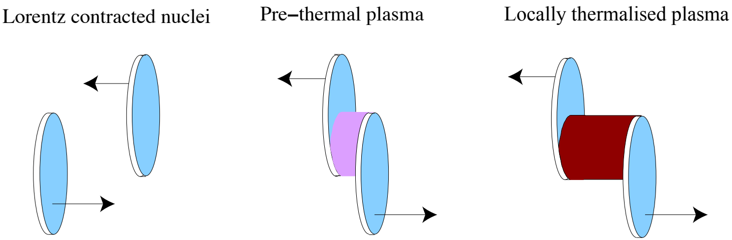
XIIth Confinenment 2016, Thessaloniki

Motivation



- Quark-Gluon plasma created in heavy-ion collisions flows as a fluid
- Unique opportunity:

  Emergence of collectivity from fundamental d.o.f's
- Theory challenge:

  Characterization of macroscopic properties from microphysics

Motivation

Some important questions are *static* equal time correlations of equilibrium system

- Equation of state $p(T)$, speed of sound c_s,. . . ..
- Susceptibilities $\chi_B(T)$, screening masses, . . .

Mature techniques of static quantities:

Euclidean methods, Non-perturbative lattice simulations

Motivation

Many phenomenologically interesting questions are *dynamical*:

Timelike correlation functions, correlation functions of non-equilibrium systems

- How the plasma flows: viscosities, $\eta/s, \zeta/s \ldots$
- How the plasma looks: production rates of photons/dileptons ...
- How the plasma feels: jet quenching and energy loss ...
- How the flow is reached: thermalization, hydrodynamization, isotropization ...

To address these question need a dynamical picture of the plasma:

- Strong coupling $\mathcal{N} = 4$, $N_c \to \infty$, $\lambda = g^2 N_c \to \infty$

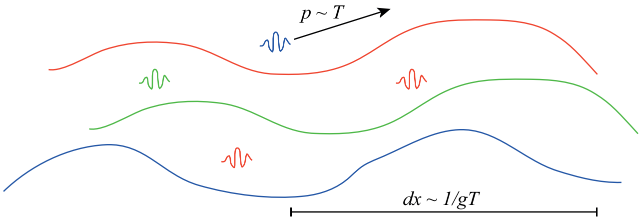
  Tuesday talks by Mukhopadhyay, Nitti, Gürsoy, Kiritsis
- Weak coupling, QCD kinetic theory

  this talk

Outline

- QCD kinetic theory
- Some recent applications to far-from-equilibrium problems
- Few words on NLO

Scales in thermal equilibrium at weak coupling



Degrees of freedom at weak coupling $g \ll 1$:

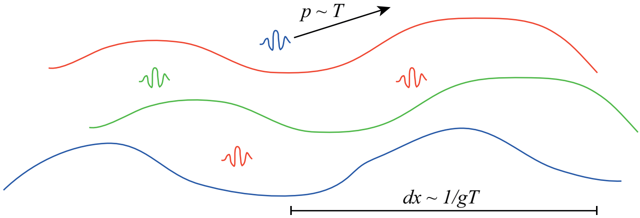
- Hard *particle* modes $p \sim T$: kinetic theory
- Soft (bosonic) *field* modes $p \sim m_D \sim gT$: classical field theory

$$n_B(p) = \frac{1}{e^{\omega/T} - 1} \sim \frac{T}{\omega} \sim \frac{1}{g}$$

- Distinction set by scale separation $m_D \ll \mu \ll \pi T$

in real life challenging

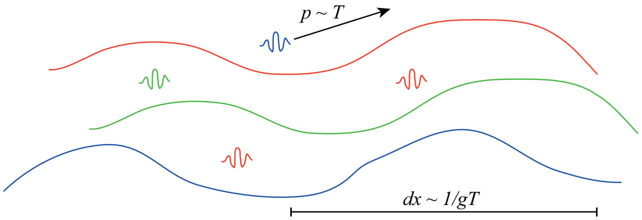
Scales in thermal equilibrium at weak coupling



- Out-of-equilibrium:

$$n_B(p) \to f(p), \quad m_D^2 \to g^2 \int d^3p \frac{f(p)}{p} \quad T \to \int d^3p p f(p) / \int d^3p f$$

Scales in thermal equilibrium at weak coupling



- Soft fields evolve according to classical nonabelian field equations

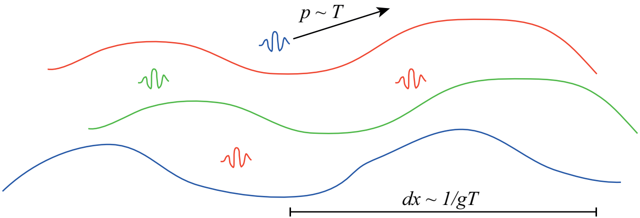
$$D_\mu F^{\mu\nu}(t, \mathbf{x}) = J^\mu(t, \mathbf{x})$$

- Hard modes see soft fields as classical fields, non-ab. Vlasov eq.

$$(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}}) f(p) = -\frac{1}{2} g \left\{ (\mathbf{E} + \mathbf{v} \times \mathbf{B})_i \frac{\partial f(\mathbf{p})}{\partial \mathbf{p}_i} \right\}$$

Blaizot, Iancu, Phys.Rept. 359 (2002) 355-528

Scales in thermal equilibrium at weak coupling



- *Hard loop theory*, linear in-medium response

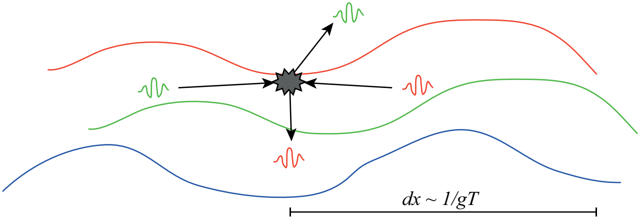
Non-trivial physics of plasma oscillations, screening, plasmons, Weibel instabilities, etc.

$$J^{\mu}_{ind.}(t) = \int dt' \Pi^{HL}_{\mu\nu}(t,t')\, \delta A^{\nu}(t'), \quad \Pi^{HL}_{\mu\nu} \sim g^2 T^2$$

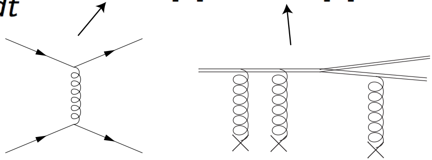
Blaizot, Iancu, Phys.Rept. 359 (2002) 355-528

Kinetic theory of hard modes

Arnold, Moore, Yaffe JHEP 0301 (2003) 030



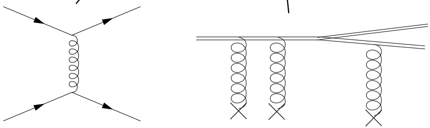
$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$



- Soft and collinear divergences lead to sensitivity to soft fields

Soft scattering

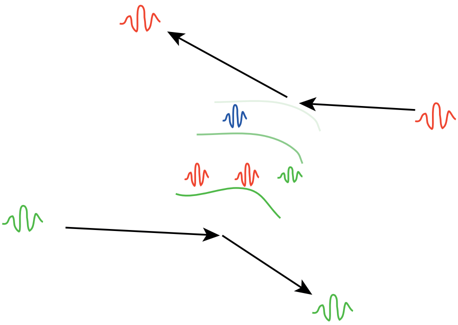
$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$



$$C_{2\leftrightarrow 2}[f] = \int_{k,p',k'} |M|^2 \left[f_p f_k (1 + f_{p'})(1 + f_{k'}) - f_{p'} f_{k'} (1 + f_p)(1 + f_k)) \right]$$

- Naively, Coulombic divergence $|M|^2 \sim 1/(q^2)^2$

Soft scattering



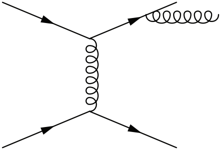
- Regulated by classical *in-medium responce*, screening

Kapusta et al. Phys.Rev. D44 (1991) 2774-2788

$$|M|^2 \propto \frac{1}{(q^2)^2} \longrightarrow \frac{1}{(q^2 + \Pi_{HL})^2}$$

Medium induced splitting/merging

- Screening makes soft scattering finite but fast
- Soft scattering can cause radiation/absorption



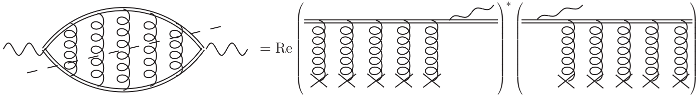
$$\Gamma_{split} \sim g^2 \left[1 + f\right] \Gamma_{\rm soft}$$

- Collinear radiation same order as elastic scattering

Aurenche et al Phys.Rev. D54 (1996) 5274-5279

- Formation time of splitting $t_{\rm form}$ comparable to soft scattering rate, interference, LPM suppression

Zakharov JETP Lett. 63 (1996) 952-957; Baier et. al NPB484 (1997) 265-282; Arnold et al. JHEP 0111 (2001) 057



Outline

- QCD kinetic theory
- Some recent applications to far-from-equilibrium problems in LO
- Few words on NLO

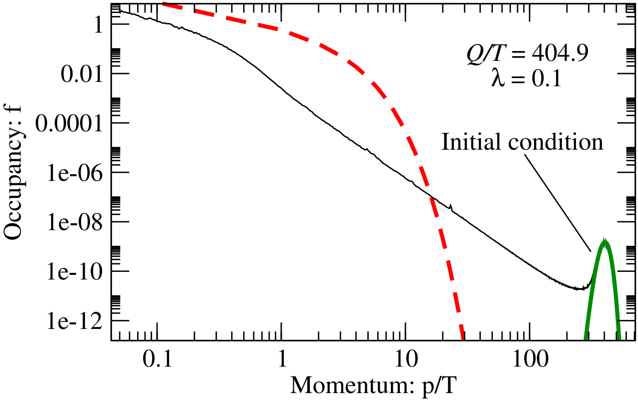
Applications in LO

- Reorganization and resummation of perturbation theory for pressure Braaten et al PRL. 83 (1999) 2139-2142; Blaizot et al PRD63 (2001) 065003; AK, Vuorinen PRL. 117 (2016) no.4, 042501; Talks by Su, Vuorinen

- Thermal photon/dilepton production rate
  Arnold et al JHEP 0112 (2001) 009; Aureche et al JHEP 0212 (2002) 006
- Transport coefficients
  Arnold et al. JHEP 0305 (2003) 051; Moore, York PRD. D79 (2009) 054011
- Jet energy loss
  Arnold PRD79 (2009) 065025; Schenke et al. PRC80 (2009) 054913
- Photon emission from medium under shear
  Shen et al. PRC91 (2015) no.2, 024908; Bhattacharya et al PRD93 (2016) no.6, 065005

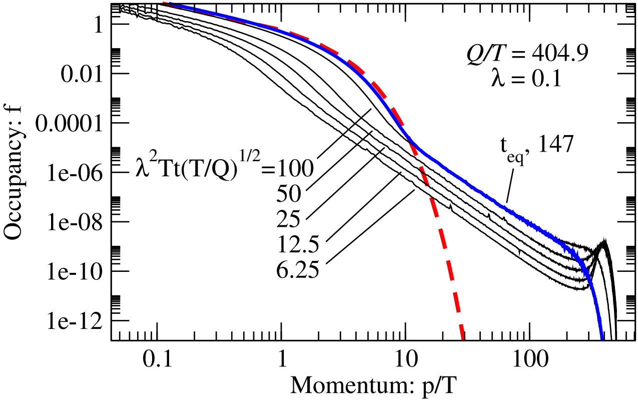
- Thermalization of far-from-equilibrium systems
- Hydrodynamization in Heavy-ion-collisions
- Jet thermalization

Thermalization of far-from-equilibrium systems



AK, Lu PRL. 113 (2014) no.18, 182301

Thermalization of far-from-equilibrium systems



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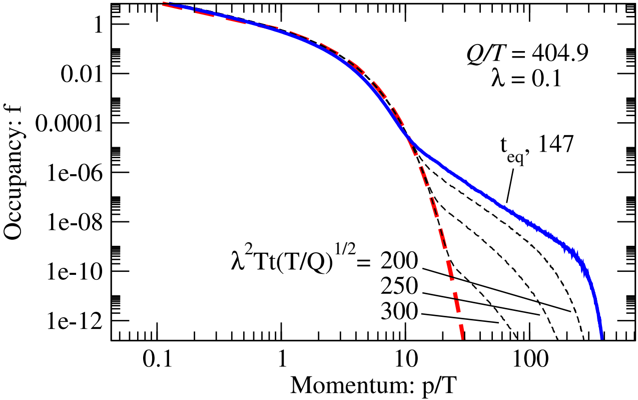
Thermalization of far-from-equilibrium systems



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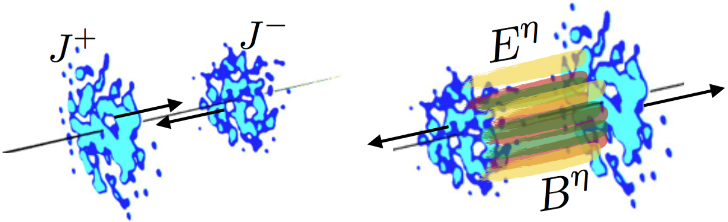
Hydrodynamization in heavy-ion collisions

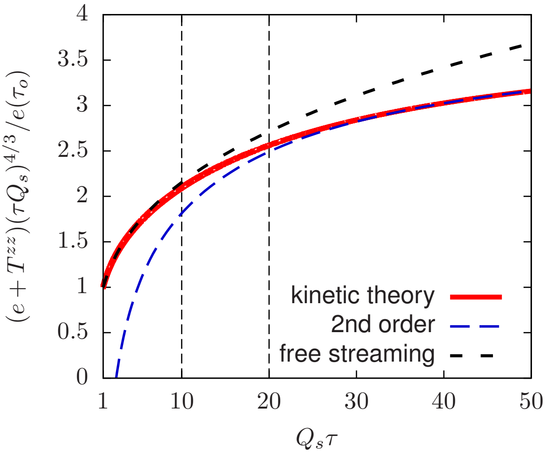
Yan Zhu's talk



- Initial condition in heavy-ion collisions far from equilibrium, color-glass condensate 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,
- After *prethermal* evolution, system flow described by hydrodynamics
- In small systems especially important

Hydrodynamization in heavy-ion collisions

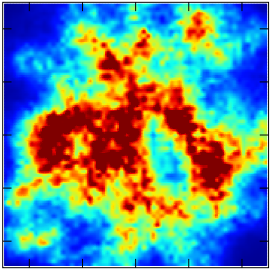
Yan Zhu's talk



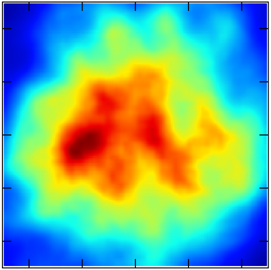
- Route to equilibrium can be followed in kinetic theory
- Late time agreement with hydrodynamics

AK, Zhu PRL. 115 (2015) no.18, 182301

Hydrodynamization in heavy-ion collisions



$\Rightarrow$

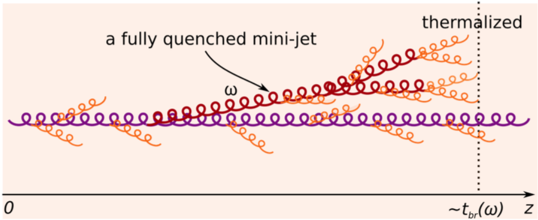


$\tau \sim 0\text{fm/c}$ $\qquad$ $\tau_{hydro.} \sim 1 - 2\text{fm/c}$

- Description of prethermal phase of heavy-ion collision
  - Smearing of initial geometry
  - Build up of hydrodynamical flow, preflow

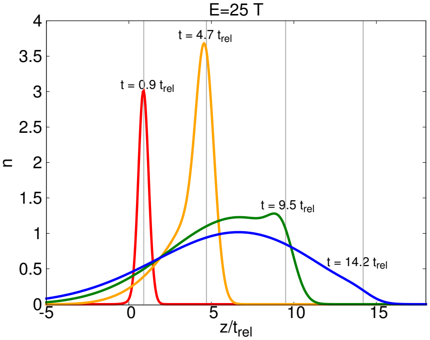
Keegan et al. 1605.04287

Thermalization of jets



- Hard jet loses energy
- Soft fragments left behind become part of medium, hydrodynamize

Thermalization of jets



Iancu, Wu JHEP 1510 (2015) 155

- Hard jet loses energy
- Soft fragments left behind become part of medium, hydrodynamize

also Blaizot, Mehtar-Tani, Torres PRL 114 (2015) no.22, 222002, AK, Wiedemann PLB740 (2015) 172-178; Talks by Apolinario, Escobedo

Outline

- QCD kinetic theory
- Some recent applications to far-from-equilibrium problems
- Few words on NLO

NLO corrections

- Expansion parameter hard processes $|\mathcal{M}|^2$ is α_s

- Expansion parameter for soft fields $\alpha_s f(gT) \sim g$

NLO $\mathcal{O}(g)$:

- All processes sensitive to the soft fields receive $\mathcal{O}(g)$ corrections
  - Corrections to soft screening alters soft scattering rate in $C_{2\leftrightarrow 2}$
  - Change in soft scattering rate alters spitting $C_{1\leftrightarrow 2}$
  - Change in in-medium dispersion relations affects splitting $C_{1\leftrightarrow 2}$

NNLO $\mathcal{O}(g^2)$:

  - Changes in the structure of theory (new processes, etc)

NLO corrections

Full NLO computations for

- Heavy quark diffusion rate Caron-Huot, Moore Phys.Rev.Lett. 100 (2008) 052301
- Photon production rate Ghiglieri et. al JHEP 1305 (2013) 010
- Dilepton prodction rate Ghiglieri, Moore JHEP 1412 (2014) 029
- Jet quenching Ghiglieri, Moore, Teaney JHEP 1603 (2016) 095

and partial NNLO contributions

- LPM corrections to sequential splitting Arnold, Iqbal JHEP 1504 (2015) 070
- Renormalization of the jet quenching parameter
  Liou et al, Nucl.Phys. A916 (2013) 102-125; Blaizot, Mehtar-Tani Nucl. Phys. A 929, 202 (2014);
  Iancu JHEP 1410, 95 (2014), Wu JHEP 1412, 081 (2014)

Summary

- Weak coupling provides with scale separations $gT \ll T$
- (semi)-classical field and particle behaviour

  quantum hidden in effective matrix elements
- Wide variety of physical questions accessible
- Extension to NLO