Probes of the quark-gluon plasma and plasma instabilities

Siggi Hauksson
McGill University
In collaboration with Sangyong Jeon, Charles Gale

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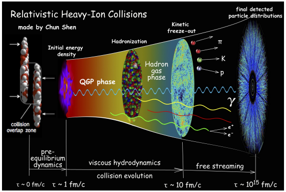
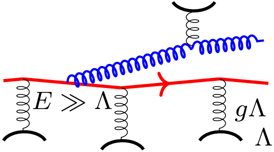
McGill

Introduction

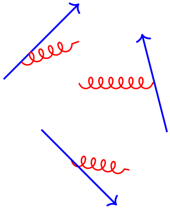
- Many probes in HIC: photons, heavy quarks, jets...
- Interaction with perturbative QGP known in thermal equilibrium.
- Use to learn about non-equilibrium QGP.
- Non-equilibrium calculations exist for some of these probes.
- For others there are fundamental theoretical challenges.
    - E.g. role of instabilities in momentum broadening.



[Chun Shen, 2014]



Perturbative QGP



- Hard quarks and gluons at energy Λ.

  [Arnold, Moore, Yaffe, 2003]

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \mathbf{F} \cdot \frac{\partial f}{\partial \mathbf{p}} = \mathcal{C}[f, A]$$

- Soft gluon fields at energy $g\Lambda$

$$\mathcal{D}_\mu F^{\mu\nu} = j^\nu[f]$$

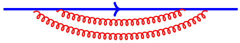
- Integrating out f gives HTL retarded correlator.

  [Blaizot, Iancu, 2001; Mrowczynski, Thoma, 2000]

$$D^{\mu\nu}_{\text{ret}}(x, y) = \theta(t_x - t_y) \, \langle \, [A^\mu(x), A^\nu(y)] \, \rangle$$

- Describes e.g. parton energy loss.

  [Romatschke, Strickland, 2004; Carrington, Deja, Mrowczynski, 2015]

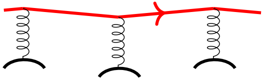


Perturbative QGP

- rr propagator equally important

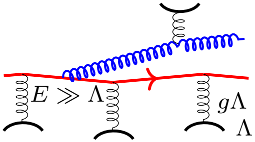
$$D_{rr}^{\mu\nu}(x,y) = \frac{1}{4}\,\langle\,\{A^\mu(x), A^\nu(y)\}\,\rangle$$

- In thermal equilibrium
  $D_{rr}(K) = \left[\frac{1}{2} + f_B(k^0)\right] \mathrm{Re}\, D_{\mathrm{ret}}$



- A new function out of equilibrium.
- E.g. describes
  - Jet transverse broadening
  - Jet splitting

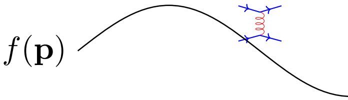
  [Hauksson, Jeon, Gale, 2017]



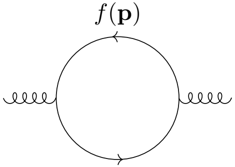
- Non-equilibrium calculations with adiabatic D_{rr} break down.

"Static" approximation

- "Static" approximation:
  - Medium changes slowly during process.
  - Only need to specify $f(\mathbf{p})$.



- Diagrammatically:
  - Initial time at $t_0 = -\infty$: Can Fourier transform.
  - Bare hard propagators only depend on $f(\mathbf{p})$.



- Can be used to calculate processes with D_{ret}.

[e.g. parton energy loss: Romatschke, Strickland, 2004

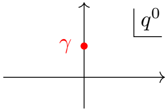
2-to-2 photon production: Schenke, Strickland, 2006]

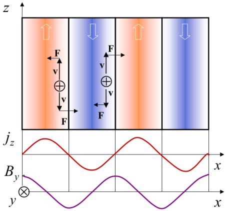
Breakdown of “static” approximation

- Unstable modes in soft gluon cloud, $D_{\text{ret}}(t_x, t_y) \sim e^{\gamma(t_x - t_y)}$
- Weibel instabilities dump energy from hard to soft modes.
  [Arnold, Lenaghan, Moore, 2003;

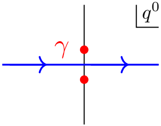
  Mrowczynski, Schenke, Strickland 2017]
- “Static” approximation gives:
  - $D_{rr}(Q) = D_{\text{ret}}\Pi_{aa}D_{\text{adv}}$
  - Transverse momentum broadening

$$\mathcal{C}(\mathbf{q}_\perp) \sim g^2 \int dq^0\, D^{\mu\nu}_{rr}(Q) v_\mu v_\nu$$
$$\sim \frac{1}{2\gamma} \to \infty$$



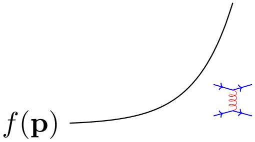


[Mrowczynski 2005]



Breakdown of “static” approximation

- “Static” approximation starting at $T_0 = -\infty$ doesn't work:
  - Unstable modes have infinite time to grow.



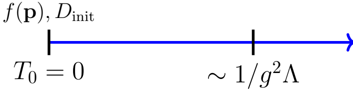
- Must start at an initial time $T_0 = 0$.
- No guarantee that can do Fourier transforms.
- Calculate D_{rr} in a simple setup to understand better.

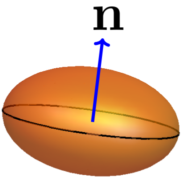
Calculation of D_{rr}.

- Specify initial condition at $T_0 = 0$.
- Consider early times where HTL valid.
- Assume $f(\mathbf{p})$ is close to isotropic distribution, anisotropy

$$\xi \sim \frac{|\langle p_z \rangle - \langle p_\perp \rangle|}{\langle p_z \rangle} \lesssim g$$

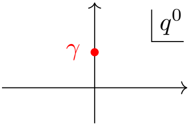
- Why such a small anisotropy?
  - Growth rate of instability modes $\gamma \sim \xi g \Lambda$.
  - Want $1/\gamma \ll 1/g^2\Lambda$, i.e. still in HTL regime during photon production.





- Assume two scales

$$D_{\text{ret}}(Q) = \underbrace{\color{blue}{\widehat{D}_{\text{ret}}(Q)}}_{\color{blue}{g\Lambda}} + \underbrace{\sum_i \frac{A_i}{q^0 - i\color{red}{\gamma_i}}}_{\color{red}{\xi g\Lambda}}$$



- Use novel methods to get

$$D_{rr}(t_x, t_y; \mathbf{q}) \approx D_{rr}^{\text{init}} + \int \frac{dq^0}{2\pi}\, e^{-iq^0(t_x - t_y)}\, \color{blue}{\widehat{D}_{\text{ret}}\, \Pi_{aa}\, \widehat{D}_{\text{adv}}(Q)}$$
$$+ \sum_{i,j} \frac{A_i \Pi_{aa}(0) A_j^*}{\color{red}{\gamma_i + \gamma_j}} \color{red}{\left[e^{\gamma_i t_x + \gamma_j t_y} - 1\right]}$$

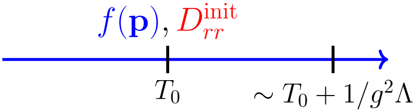
- Fluctuating modes at scale $g\Lambda$
- Instability modes at scale $\xi g\Lambda$.
  - Know about initial condition.
  - No divergence when $\gamma \to 0$.

Phenomenological prescription

$$D_{rr}(t_x, t_y; \mathbf{k}) \approx D_{rr}^{\text{init}} + \int \frac{dq^0}{2\pi}\, e^{-iq^0(t_x - t_y)}\, \widehat{D}_{\text{ret}}\, \Pi_{aa}\, \widehat{D}_{\text{adv}}(Q)$$

$$\cancel{+ \sum_{i,j} \frac{A_i \Pi_{aa}(0) A_j^*}{\gamma_i + \gamma_j} \left[e^{\gamma_i t_x + \gamma_j t_y} - 1 \right]}$$

- Start at a point in medium evolution.
- No spurious divergences.
- D_{rr}^{init} must come from simulations [Dumitru, Nara, Schenke, Strickland, 2007; Boguslavski, Kurkela, Lappi, Peuron, 2020]
  - They suggest that not heavily occupied in hydro stage. [Berges, Boguslavski, Schlichting, Venugopalan, 2014]
- Our analytic approach allows for more complicated probes.



Conclusions

- Need to calculate probes in non-equilibrium plasma.
- Our approach is flexible because only depends on $f(\mathbf{p})$.
- Spurious divergences come from ignoring time dependence.
- Derive time evolution of rr correlator.
- Will soon publish momentum broadening and photon production in our formalism.