Plasmon mass scale in classical nonequilibrium gauge theory in two and three dimensions

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Based on:
Phys. Rev. D95 (2017) no.1, 014025,
Phys.Rev. D97 (2018) no.3, 034017

Physics picture

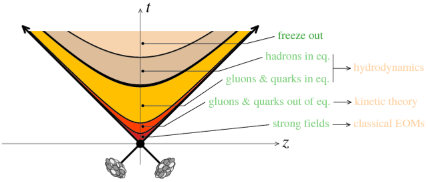


Figure : E. Iancu 1105.0751 [hep-ph]

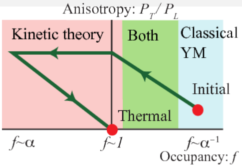


Figure : A. Kurkela, Nucl.Phys. A956 (2016) 136-143.

- Left: space-time evolution of an URHIC.
- Right: the validity ranges of classical and kinetic theory.
- We are interested in the quasiparticle interpretation of the classical theory.
- Simulate initial overoccupied gluon fields using classical Yang-Mills equations using real time lattice techniques.

Quasiparticles in nonequilibrium plasma

- Solid state physics: plasmons, collective longitudinal excitations in electron gas.
- Here: strongly interacting gluon plasma, both transverse and longitudinal excitations.
- Quasiparticles are gluons, measure their mass using different methods.

$$\epsilon = 2\left({N_c}^2 - 1\right) \int \frac{d^3k}{(2\pi)^3} \omega(k) f(k), \tag{1}$$

$$\mathscr{H} = \frac{1}{2} \int \frac{d^3k}{(2\pi)^3} \left(\left|E^i\right|^2 + |B_i|^2 \right). \tag{2}$$

Keeping only quadratic terms in gauge potential we get

$$f_{A+E}(k) = \frac{1}{4\left({N_c}^2 - 1\right)} \frac{1}{V} \left(\frac{|E_C(k)|^2}{\omega(k)} + \frac{k^2}{\omega(k)} |A_C(k)|^2 \right). \tag{3}$$

Measuring plasmon mass

Use 3 methods to determine their mass

- Effective dispersion relation (DR) at zero momentum

$$\frac{\left\langle \left|\dot{E}(k)\right|^2 \right\rangle}{\left\langle \left|E(k)\right|^2 \right\rangle} \approx \omega^2 \quad (4)$$

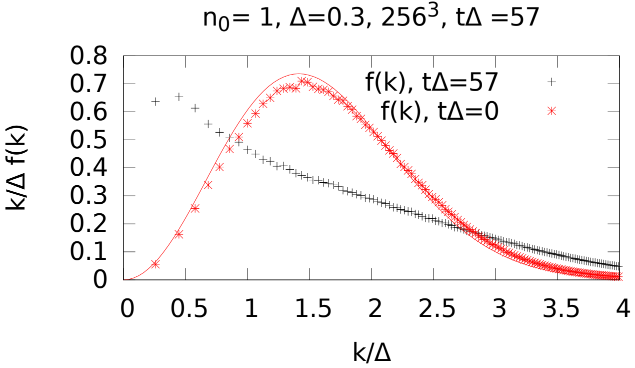
- Add uniform chromoelectric field, measure oscillations (UE , Kurkela & Moore Phys.Rev. D86 (2012) 056008).
- Perturbation theory, Hard Thermal Loops (HTL):

$$\omega_{\rm pl}^2 = \frac{4}{3} g^2 N_c \int \frac{{\rm d}^3 k}{(2\pi)^3} \frac{f(k)}{|k|} \quad (5)$$

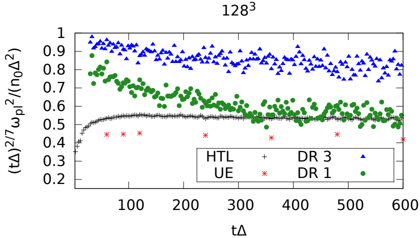
Quasiparticle spectrum, 3D

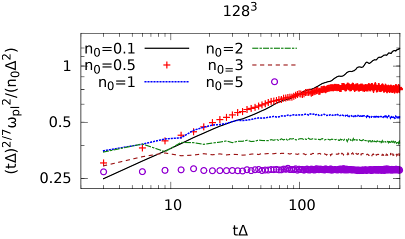
The initial quasiparticle spectrum satisfies

$$f(k, t = 0) = \frac{n_0}{g^2} \frac{k}{\Delta} \exp\left(\frac{-k^2}{2\Delta^2}\right). \tag{6}$$



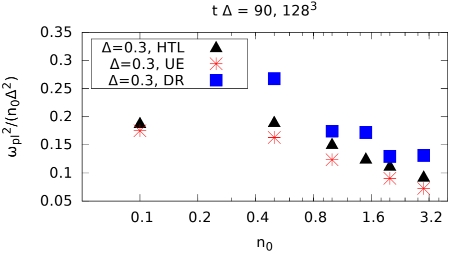
Time dependence, 3D





- Left: All methods agree on the proposed power law $\omega_{pl}^2 \sim t^{-2/7}$ (Kurkela & Moore Phys.Rev. D86 (2012) 056008) at late times.
- Left: DR method sensitive to fit cut off (3 and 1 different cutoffs in k/Δ).
- Right: More dense systems enter the scaling regime faster.

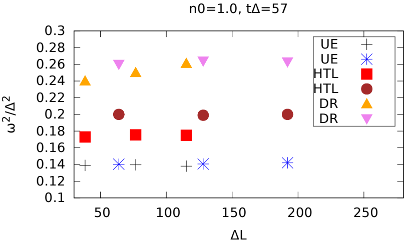
Dependence on occupation number, 3D

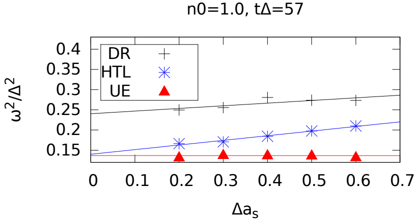


Decreasing trend in n_0 explained by self similar scaling (Berges et. al. Phys.Rev. D89 (2014) no.11, 114007), which classical Yang-Mills theory exhibits self-similar evolution at late times. More dense systems enter this scaling regime faster and have spent larger fraction of their history on the scaling solution.

Lattice cutoff dependence, 3D

- IR cutoff, two datasets for each method correspond to different UV cutoff.
- UV cutoff





- We see no IR cutoff dependence
- HTL method sensitive to UV cutoff. Agrees with UE in the continuum limit.

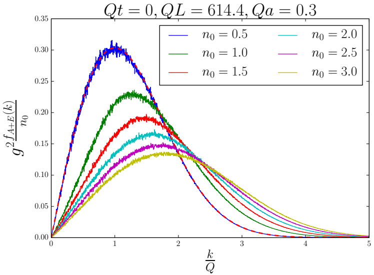
Two-dimensional systems

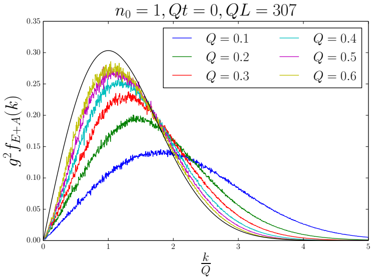
In the following consider 2D system in a fixed box. Mimic boost invariant expanding system.

- Use three dimensional lattice with $N_z = 1$.
- The differences between different definitions of the occupation numbers are larger in 2D. Use two different estimates, f_A and f_{EA}.
- Due to gauge fixing ambiguities, can not compare directly with the initial scales.
- Use also autocorrelation to measure frequency in UE method.

Occupation number and momentum scale in 2D

- Problem: After construction of links and gauge fixing the initial quasiparticle spectrum is deformed.

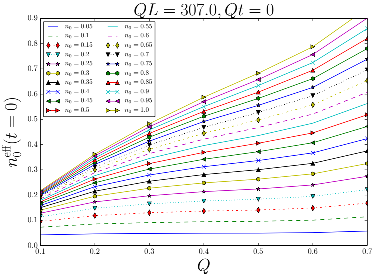


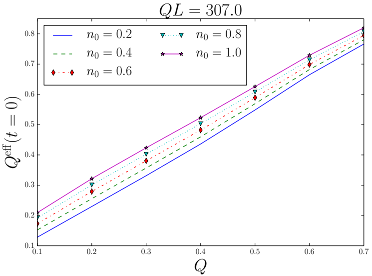


- Solution: Define Q and n_0 gauge invariantly so that they match to the initial condition for a dilute system.

Define

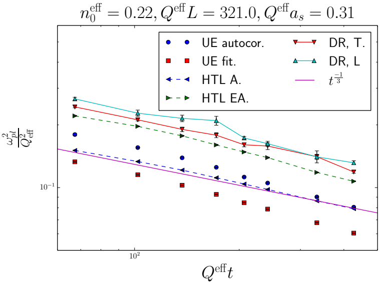
- $Q_{\mathrm{eff}}^2 = \dfrac{1}{2}\dfrac{\left\langle \mathrm{Tr}\left(\boldsymbol{D}\times\boldsymbol{B}\right)^2\right\rangle}{\left\langle \mathrm{Tr}\left(\boldsymbol{B}^2\right)\right\rangle}$
- $n_0^{\mathrm{eff}} \approx \dfrac{\pi g^2}{({N_c}^2-1)}\dfrac{\epsilon^{2d}}{Q_{\mathrm{eff}}^3}$



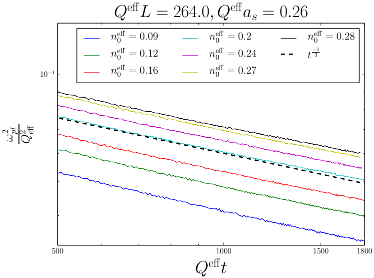


Time dependence, 2D

- Time dependence using all methods

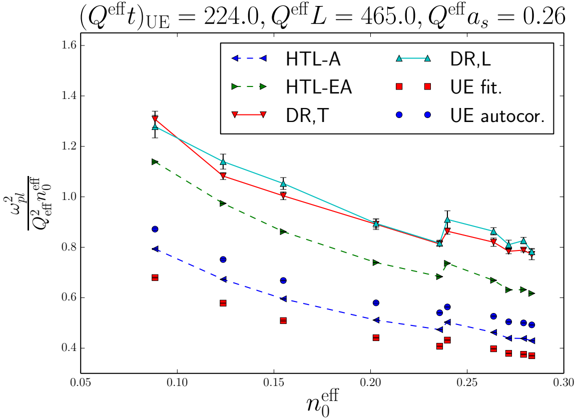


- Time dependence at later times with HTL-A method



- Time-evolution of ω_{pl}^2 consistent with $t^{-1/3}$ power law at late times.

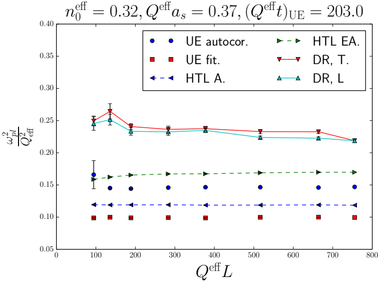
Dependence on occupation number, 2D

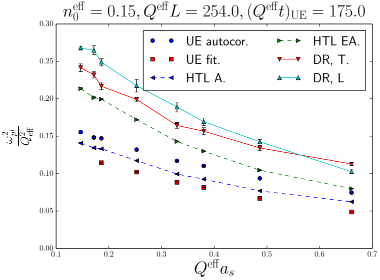


- Observe similar trend as in 3D. Faster decrease in $\frac{\omega_{pl}^2}{Q_{\rm eff}^2 n_0^{\rm eff}}$ for larger occupation number.

Cutoff dependence, 2D

- IR cutoff
- UV cutoff





- No IR cutoff dependence
- All results seem to increase when UV cutoff is taken to zero. The continuum limit does not seem to be divergent.

Conclusions

We have

- Measured quasiparticle mass in nonequilibrium gluon plasma
- Studied the time dependence of the mass. Results consistent with $\omega_{pl}^2 \sim t^{-2/7}$ (3D) $\omega_{pl}^2 \sim t^{-1/3}$ (2D).
- Studied the dependence of the mass on occupation number. $\frac{\omega_{pl}^2}{n_0 Q^2}$ falls faster for more dense systems.
- The UE and HTL seem to agree for 3D systems in the continuum limit. DR agrees with other methods within a factor of 2.

In the future we would like to

- Measure the quasiparticle properties in anisotropic and expanding geometries using linear response analysis (See talk by K. Boguslavski).