From the Initial Conditions to Equilibrium

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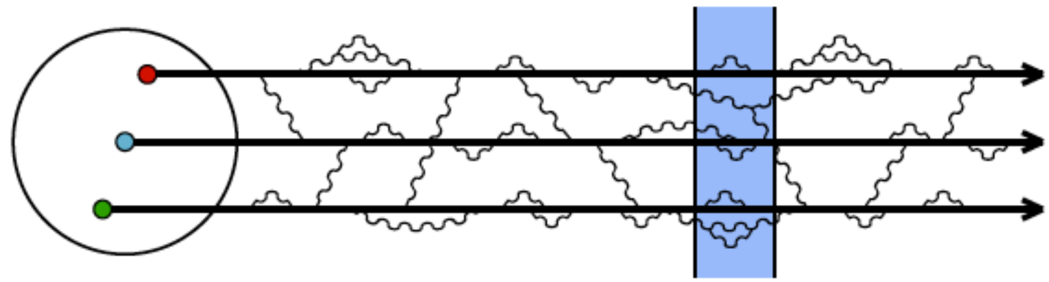
Outline

1. Part I: Multi-particle correlations
   Perfect fluidity without thermalization

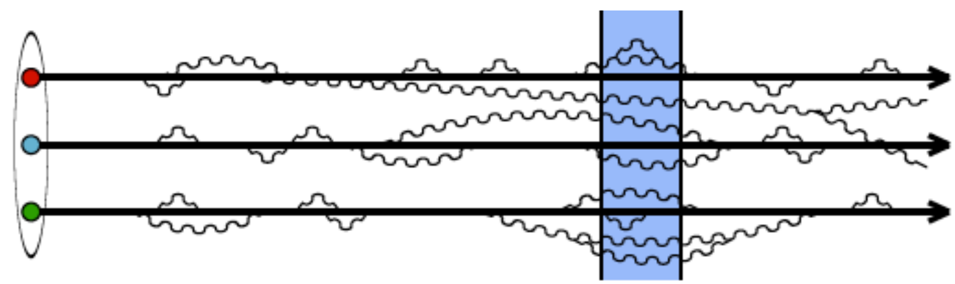
2. Part II: Probing the initial state with photons and dileptons

Classical Coherence

Low Energy:
(large x)



High Energy:
(small x)



1. Due to time dilation the probe sees free constituents
2. and more fluctuations are resolved leading to a growth in the gluon density at higher energies (smaller x)

The CGC Framework

1. Physical observables are computed as an average over fast partons (large x) which behave as static random charges

$$\langle \mathcal{O} \rangle_Y \equiv \int [D\rho] \; W_Y[\rho] \; \mathcal{O}[\rho]$$

2. and shouldn't depend on how we separate the fast and slow degreees of freedom (i.e. must satisfy JIMWLK equation)

$$\frac{\partial W_Y[\rho]}{\partial Y} = \mathcal{H}[\rho] W_Y[\rho]$$

The CGC Framework (cont.)

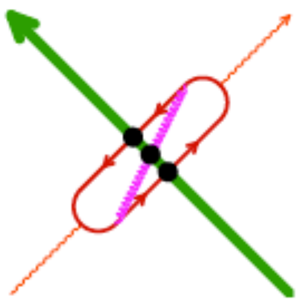
1. The operator of interest can be computed perturbatively

$$\mathcal{O} = \frac{1}{g^2}\left[c_0 + c_1 g^2 + c_2 g^4 + \cdots\right]$$

$$\mathcal{O}_{\mathrm{LO}} = \frac{c_0}{g^2} \qquad\qquad \mathcal{O}_{\mathrm{NLO}} = c_1$$

2. however these coefficients can contain large logarithms of $\ln\left(\frac{p^+}{\Lambda}\right)$ which become as large as classical term for $Y \gg 1/\alpha_s$

3. Note: these are similar to the large logarithms that appear in DIS which are re-summed in BFKL



Factorization in the Glasma

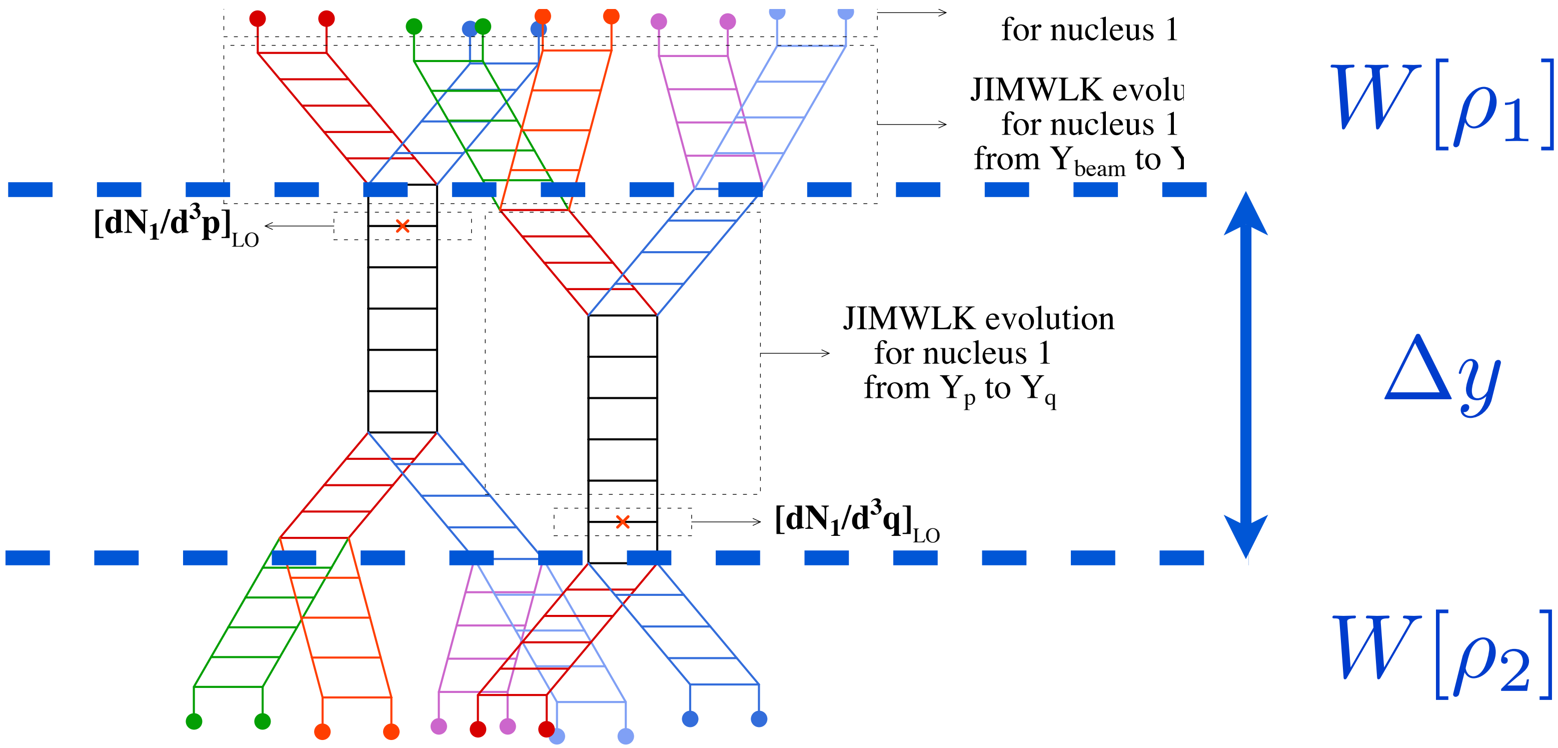
1. These logarithms can be re-summed and absorbed into the universal functionals W_Y with behavior governed by JIMWLK.

$$\langle \mathcal{O} \rangle_{\rm LLog} = \int \left[D\Omega_1(\bar{y}, \mathbf{x}_\perp) D\Omega_2(\bar{y}, \mathbf{x}_\perp) \right] W\left[\Omega_1(\bar{y}, \mathbf{x}_\perp) \right] W\left[\Omega_2(\bar{y}, \mathbf{x}_\perp) \right] \mathcal{O}_{\rm LO}$$

$$\Omega_{1,2}(\bar{y}, \mathbf{x}_\perp) \equiv \mathrm{P} \exp ig \int_0^{x_y^\mp} \mathrm{d}z^\mp \, \frac{1}{\nabla_\perp^2} \rho_{1,2}(z^\mp, \mathbf{x}_\perp)$$

F. Gelis, T. Lappi and R. Venugopalan,
PRD, aX:0810.4829 [hep-ph]

Example: Double Inclusive Spectra



$$C(\mathbf{p},\mathbf{q}) \quad \propto \quad \frac{g^4}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int \mathrm{d}^2\mathbf{k}_{1\perp}\ \Phi_{A_1}^2(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})$$

$$+ \quad \text{permutations}$$

K.D., Gelis, Lappi, Venugopalan
arXiv:0911.2720, NPA

Example: Double Inclusive Spectra

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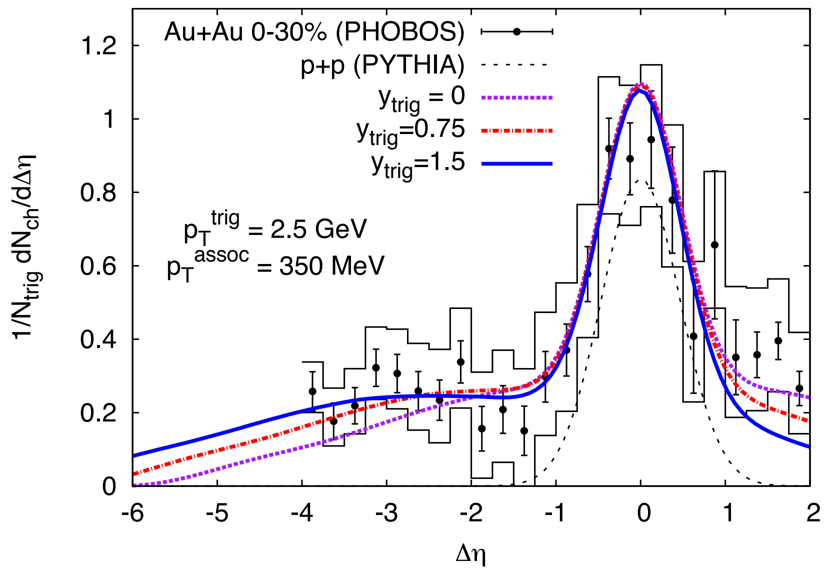
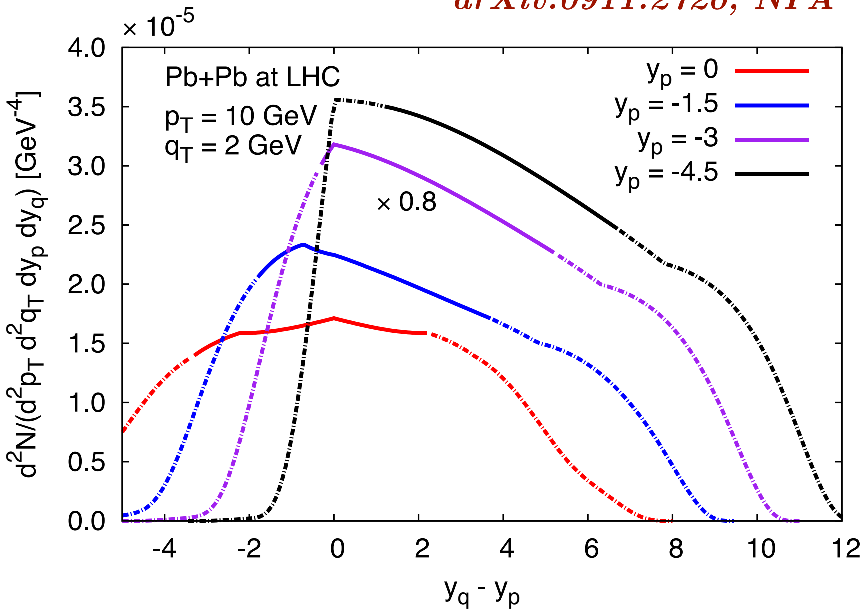


NOTE: peak is "standard" PYTHIA and not part of CGC calculation



More results and code made available by A. Dumitru:

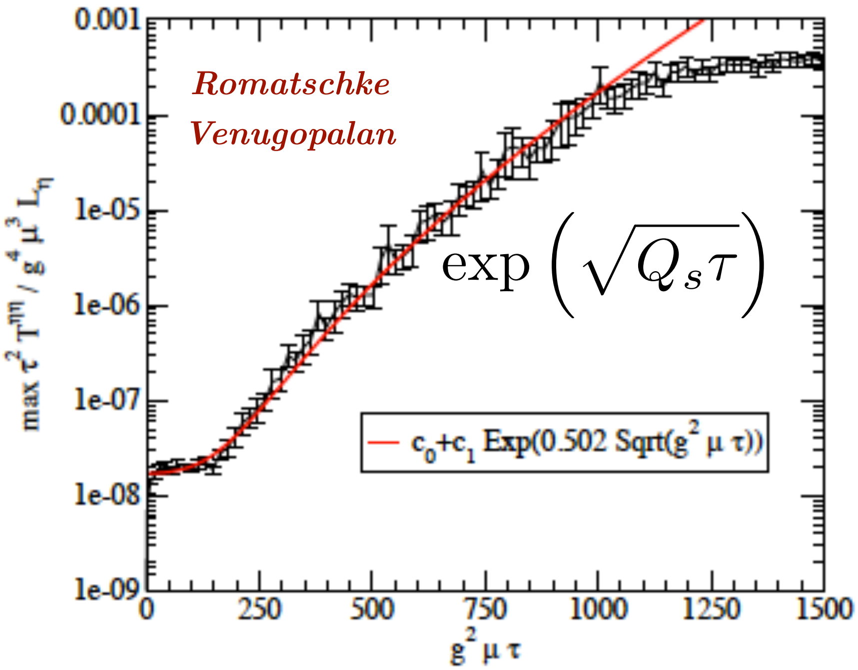
http://physics.baruch.cuny.edu/node/82

Two classes of fluctuations

1. Zero Modes having $p_\eta = 0$

2. Non-Zero Modes with $p_\eta \neq 0$

- These fluctuations grow exponentially after collision



Secular Divergences

1. Secular terms can also be re-summed

$$\begin{aligned}\langle \mathcal{O} \rangle_{\text{LLog+LInst.}} &= \int \left[D\Omega_1(\bar{y}, \mathbf{x}_\perp) D\Omega_2(\bar{y}, \mathbf{x}_\perp) \right] W \left[\Omega_1(\bar{y}, \mathbf{x}_\perp) \right] W \left[\Omega_2(\bar{y}, \mathbf{x}_\perp) \right] \\ &\times \int \left[D\omega(\bar{y}, \mathbf{x}_\perp) \right] Z \left[\omega(\bar{y}, \mathbf{x}_\perp) \right] \mathcal{O}_{\text{LO}} \left(\Omega_1 + \omega, \Omega_2 + \omega \right)\end{aligned}$$

2. The above expression re-sums terms of order

$$\mathcal{O}_{\text{LLog+LInst.}} = \frac{1}{g^2} \sum_n \sum_m d_{nm} g^{2n} e^{(m-n)\sqrt{\mu\tau}} \log^n \left(\frac{1}{x_{1,2}} \right)$$

3. The physics is contained in the spectrum of fluctuations

$$Z[\omega\left(\overline{y}, \mathbf{x}_\perp\right)]$$

In Progress with:
Srednyak, Gelis, Venugopalan

Perfect fluidity without thermalization

1. Let us now look at a scalar theory as a toy model

   In Progress with: Epelbaum, Gelis, Venugopalan

2. Similar mechanisms at work during preheating in the early universe

   See works of Kofman, Linde, Starobinsky; D.T. Son, Rubakov

Scalar theory as a toy model

1. Let's look at a classical scalar theory as an IVP

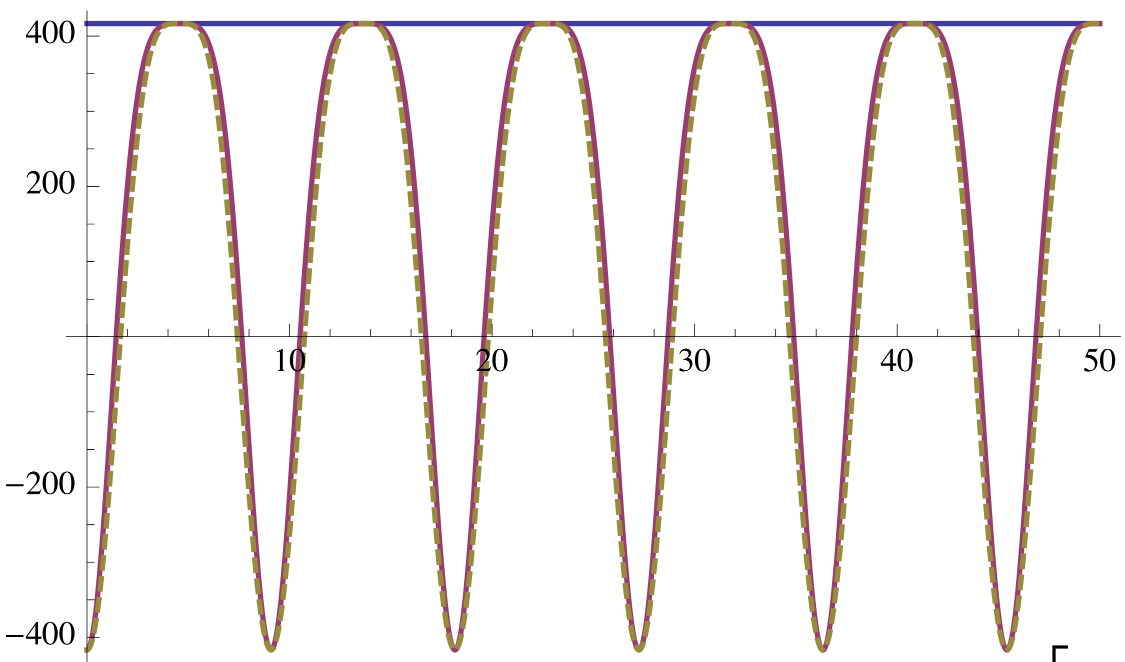
$$\ddot{\phi}^2 - 4\epsilon^2\phi^3 = 0 \qquad \begin{aligned} \phi(t=0) &= \phi_0 \\ \dot{\phi}(t=0) &= \dot{\phi}_0 \end{aligned} \qquad E_0 \equiv \frac{1}{2}\dot{\phi}_0^2 + \epsilon^2\phi_0^4$$

2. The solution is $\phi(t) \approx \dfrac{E_0^{1/4}}{\sqrt{\epsilon}} \cos\left[\dfrac{2\pi}{T}(t-\xi)\right]$

with period $T = \dfrac{2}{\sqrt{\epsilon}E_0^{1/4}} \mathrm{K}(1/2)$

Toy Model (cont.)

$$T^{00} = E_0 \equiv \frac{1}{2}\dot{\phi}_0^2 + \epsilon^2 \phi_0^4$$



$$p = T^{11} \approx E_0 \left[1 - 2\cos^4 \left(\frac{2\pi}{T}(t - \xi) \right) \right]$$

Quantum Decoherence

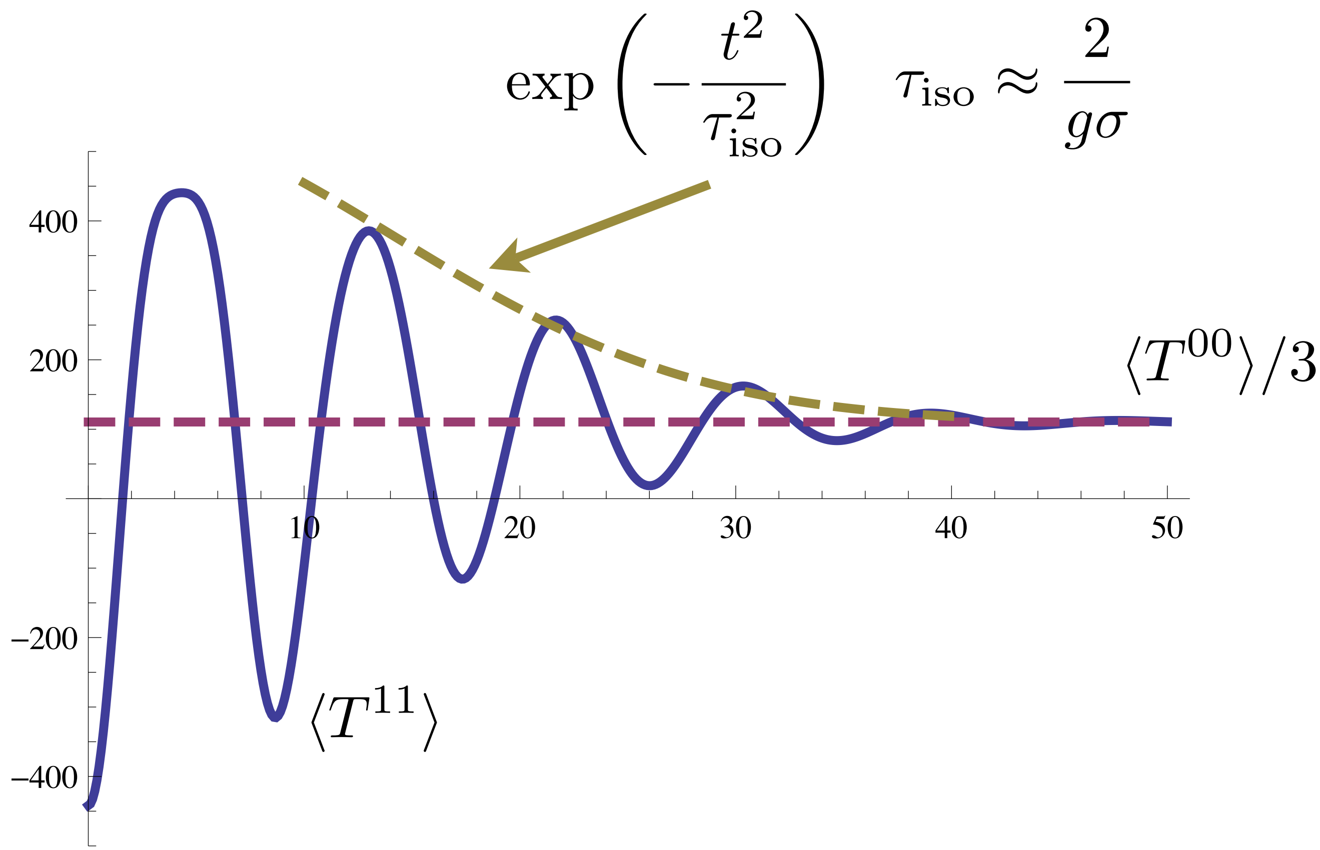
1. Now perform the ensemble average

$$\langle \mathcal{O} \rangle = \int_{-\infty}^{+\infty} da\ d\dot{a}\ \mathrm{F}(a, \dot{a}) \mathcal{O}(\phi_0 + a, \dot{\phi}_0 + \dot{a})$$

over a toy spectrum of fluctuations

$$\mathrm{F}(a, \dot{a}) = \delta(\dot{a}) \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{a^2}{2\sigma^2}\right)$$

Quantum Decoherence



Note: This won't happen in a ϕ^2 theory. The dependence of the period on the I.C. is a signature of non-linearity.

Part II

Probing the initial state with EM probes

arXiv: 0903.1764, NPA

arXiv: 0803.1262, NPA

Reminder on shear viscosity

1. In a fluid with finite shear viscosity and shear gradients the first correction to the stress energy tensor is

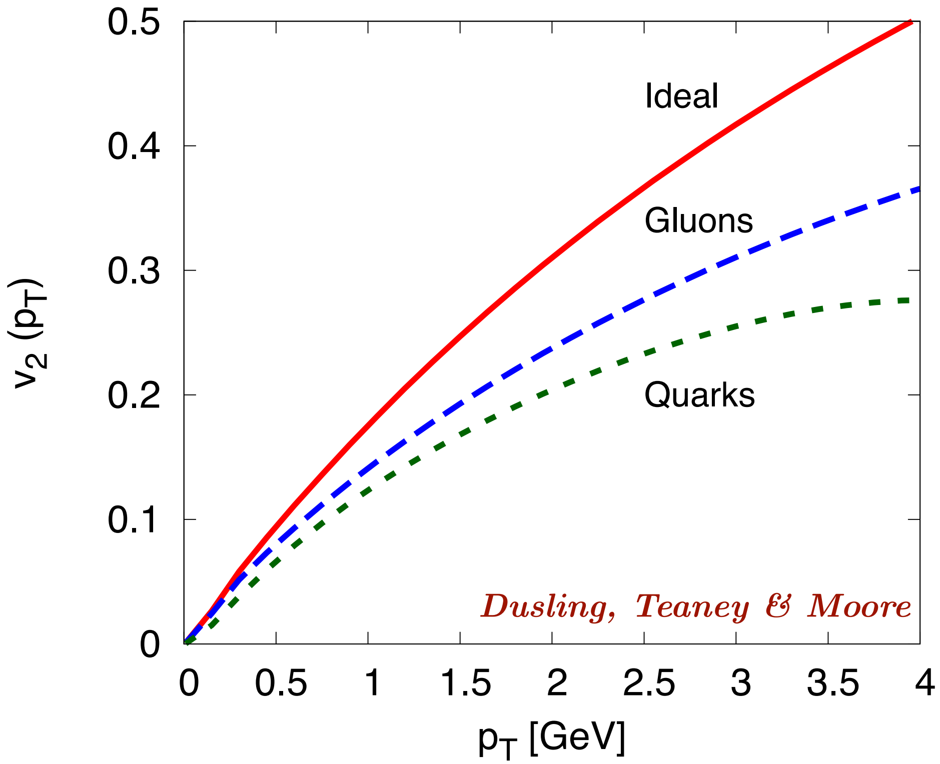
$$T^{ij} \equiv p\delta^{ij} - \eta\langle\partial^i u^j\rangle = \int_{\mathbf{p}} \frac{p^i p^j}{E_p}\, f_o + \delta f(p)$$

2. On the microscopic side this is contained in the viscous correction to the distribution function

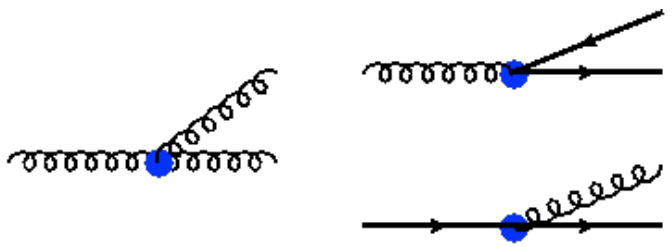
$$\delta f = -f_0 \frac{\tau_R(E_{\mathbf{p}})}{2E_{\mathbf{p}}T} p^\mu p^\nu \sigma_{\mu\nu}$$

Viscous corrections at work

1. Quark and gluons have different relaxation times and therefore different flows through δf

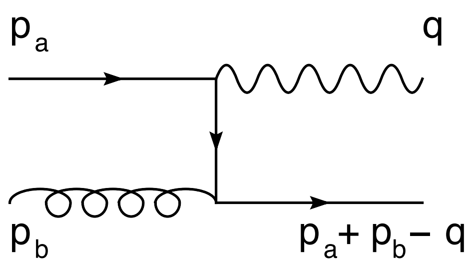


From the difference in the way quarks and gluons are equilibrated:

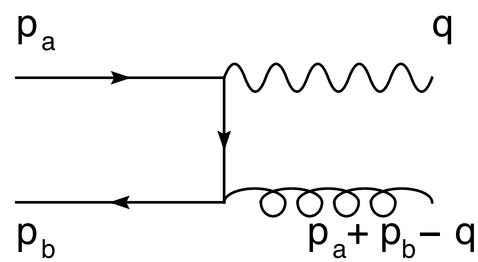


Leading log order photon production

Compton



Annihilation



1. At leading log order we have

$$p^{\mu}_{\text{quark}} \approx q^{\mu}_{\text{photon}}$$

Leading log order photon production

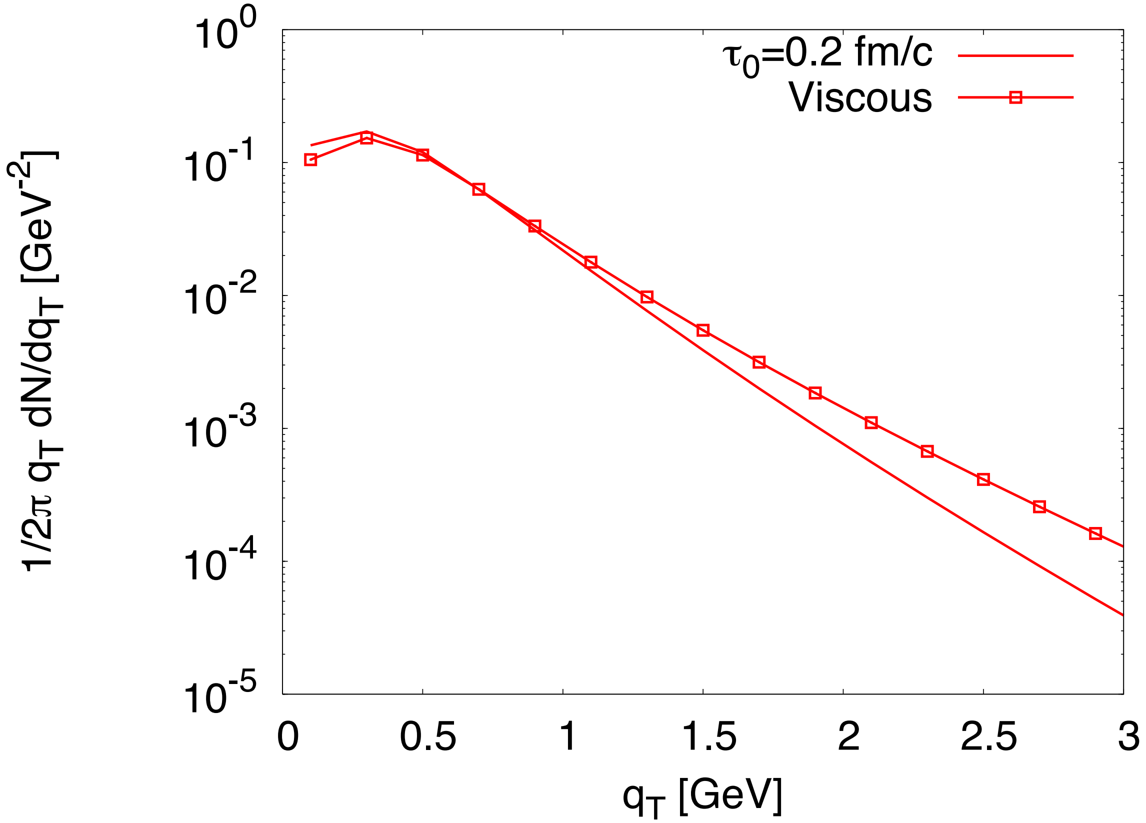
1. The photon rate from those two previous diagrams is

$$E_\gamma \frac{dN_\gamma}{d^3 q_\gamma} = \frac{5}{9} \frac{\alpha_e \alpha_s}{2\pi^2} f_q(q_\gamma) T^2 \ln\left(\frac{3.7 E_\gamma}{g^2 T}\right)$$

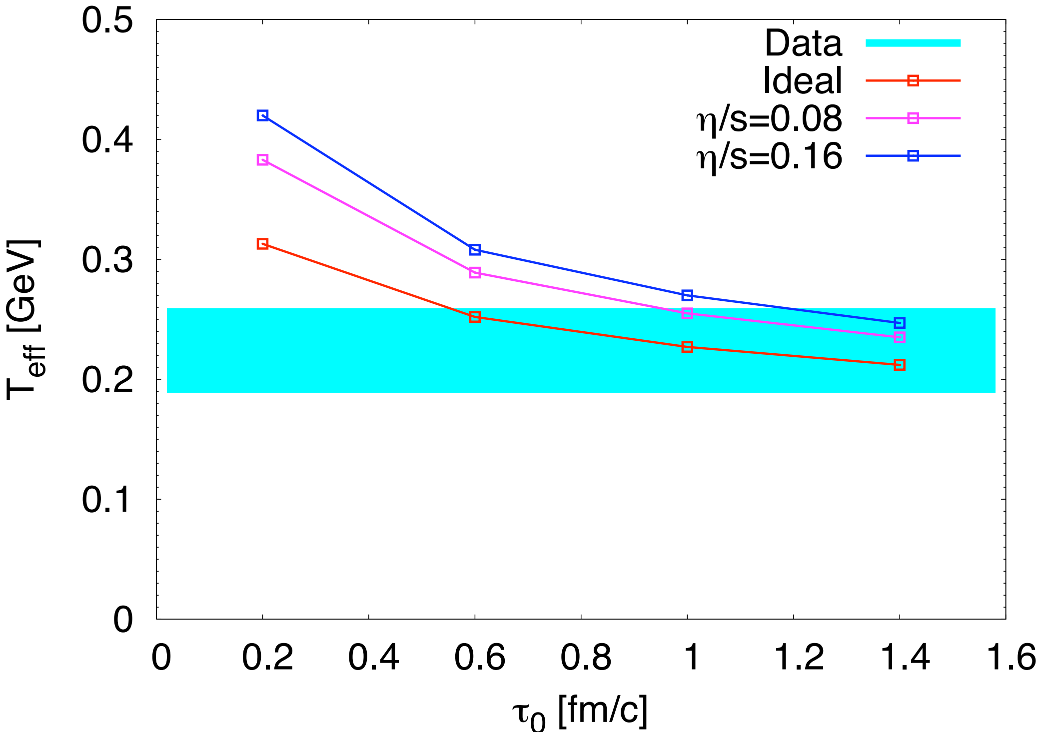
2. Note that $f_q(q_\gamma)$ is the thermal quark distribution function evaluated at the photon momentum q_γ .

$$f_q(q) = f_0(q) + 1.3 \frac{\eta}{2sT^3} f_0(q) q^i q^j \partial_{\langle i} u_{j\rangle}$$

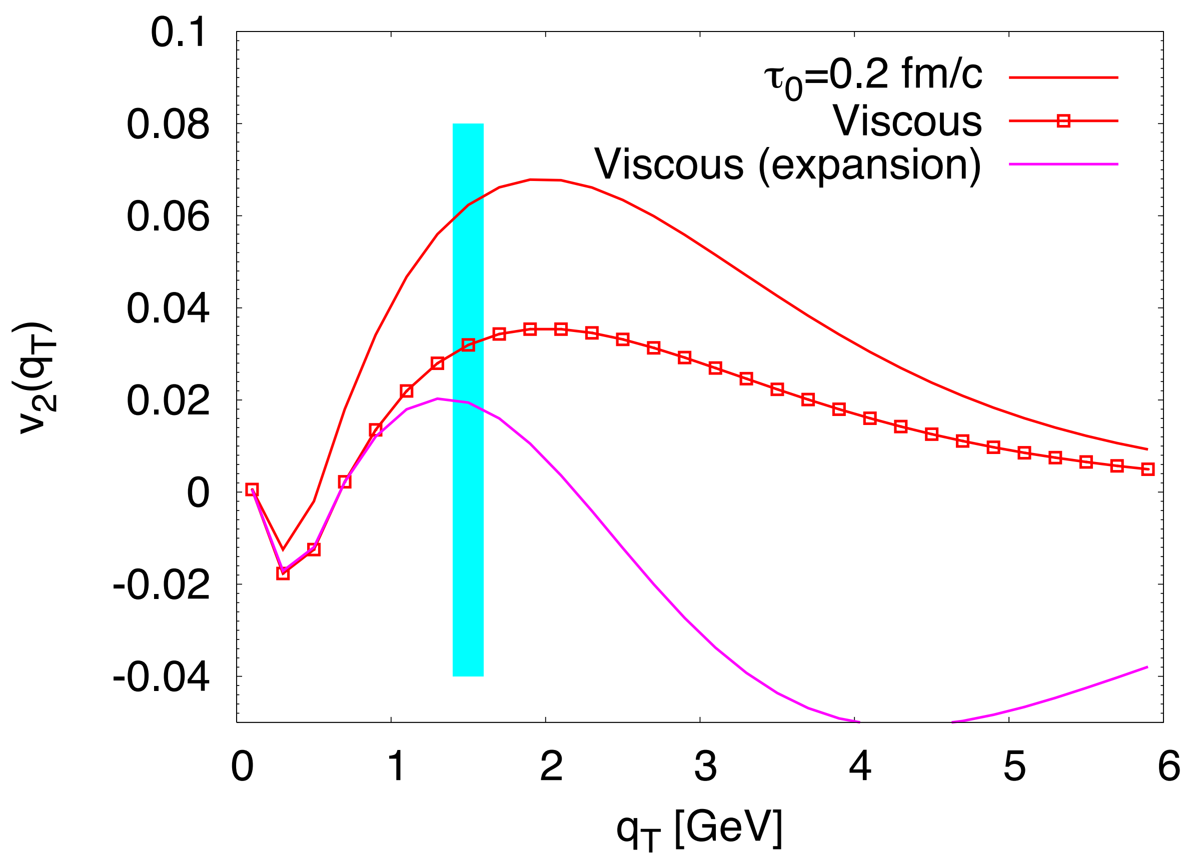
QGP Photon Spectra



QGP Photon "Temperature"



QGP Photon Elliptic Flow



Conclusions

1. Part I: Quantum decoherence is a critical part of understanding the space-time evolution of HICs.

   - Long range correlations
   - early flow / thermalization
   - topological fluctuations

2. Part II: Probing the initial state with EM probes

   - Photon and dilepton T_{eff} and elliptic flow are a sensitive probe to the shear viscosity, and early time dynamics of the medium.