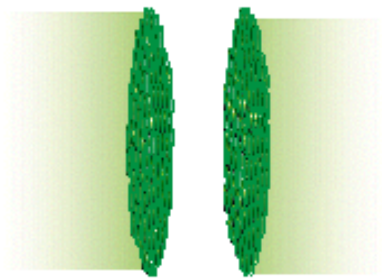
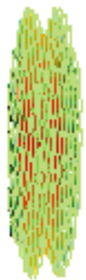
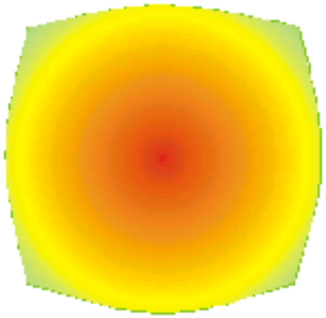
Matter as it Might Appear in High Energy Collisions



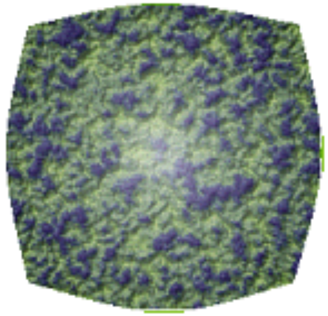
CGC



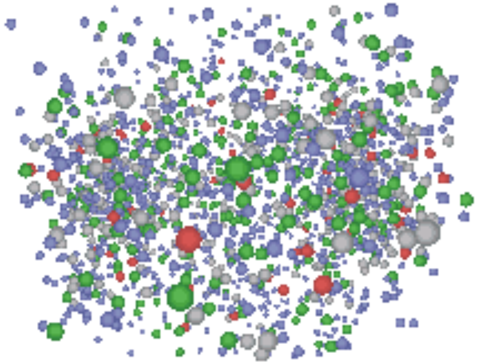
Initial Singularity



Glasma



sQGP



Hadron Gas

Color Glass Condensate:

High energy density highly coherent gluons that form the high energy hadron wavefunction

Glasma:

The matter that is formed in the collision of two sheets of Colored Glass, and eventually thermalizes into a Quark Gluon Plasma

sQGP:

Strongly interacting Quark Gluon Plasma

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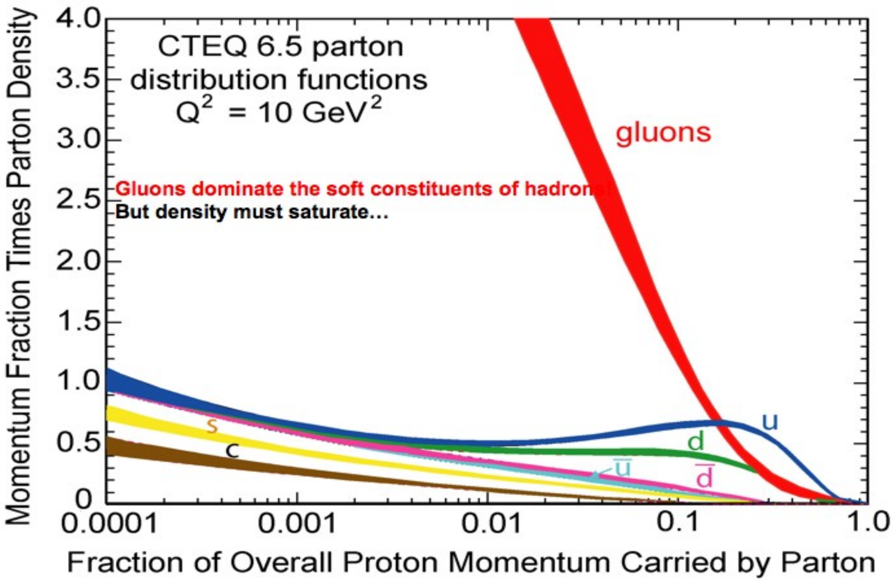
The gluon density is high in the high energy limit:

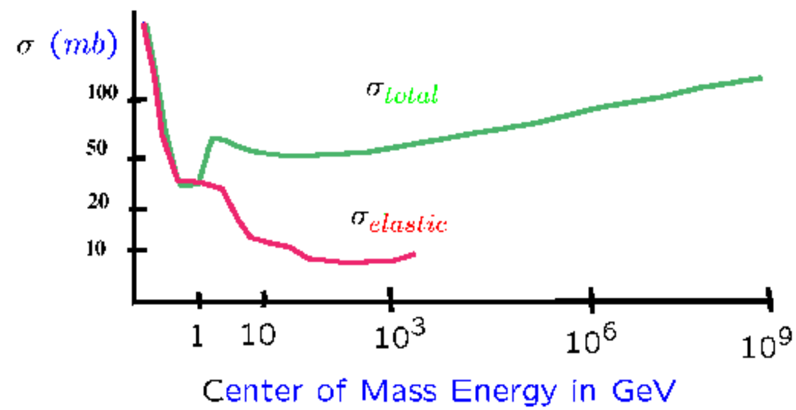
$$x = E_{gluon}/E_{hadron}$$

$$x_{min} \sim \Lambda_{QCD}/E_{hadron}$$

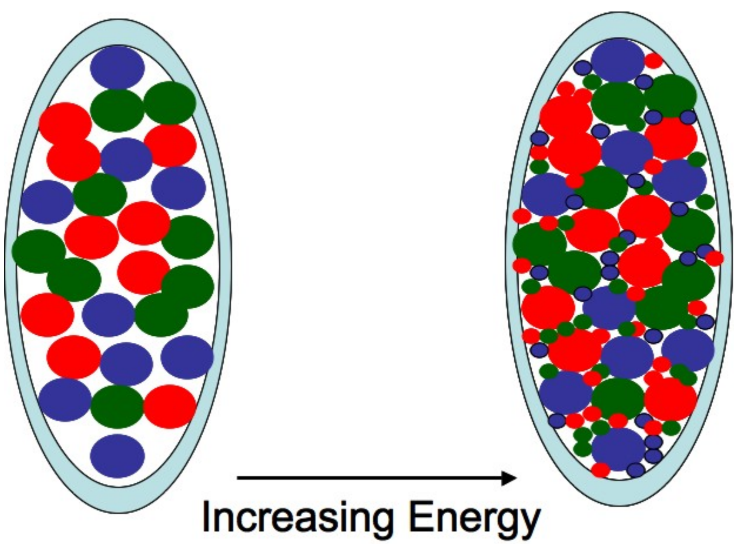


Gluons dominate the proton wavefunction

The total hadronic cross section:



Proton size grows slowly



Asymptotic Freedom: High density systems are weakly coupled because typical distances are short

$$\alpha_S << 1$$

Should be possible to understand from first principles

Color Glass Condensate

Color:
Gluons are colored

Condensate:
Gluon occupation number $1/\alpha_S$ **is as large as can be, like Higgs condensate or superconductor**
High density of gluons is self generated

Glass:
The sources of gluon field are static, evolving over much longer time scales than natural one
Resulting theory of classical field and real distribution of stochastic source is similar to pin glass

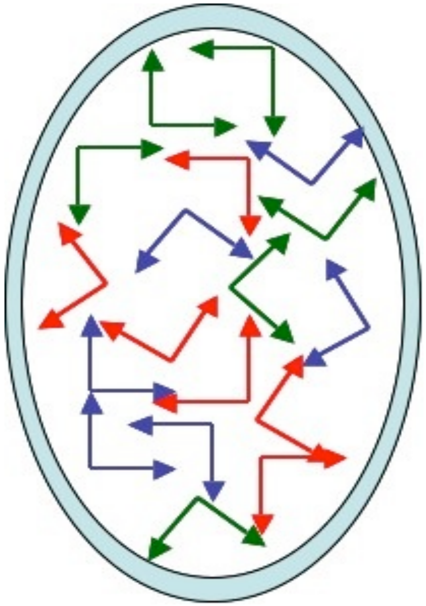
A sheet of Colored Glass:

$$z - t \; small; \quad z + t \; big$$

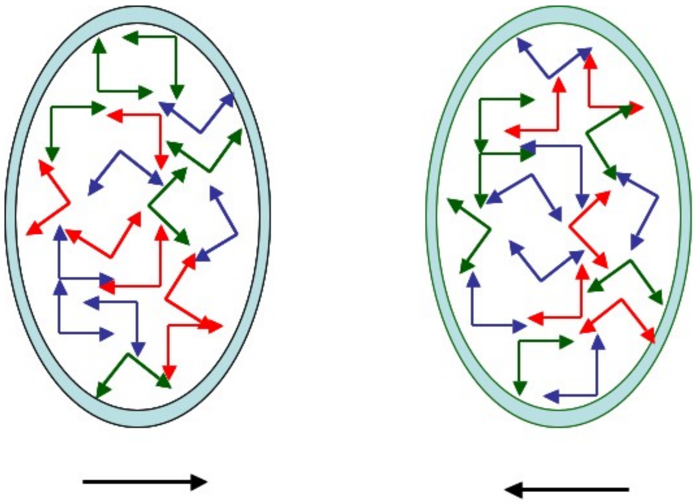
$$F^{i+} \; big; \quad F^{i-} \; small; \quad F^{ij} \sim O(1)$$

$$\vec{E} \perp \vec{B} \perp \hat{z}$$

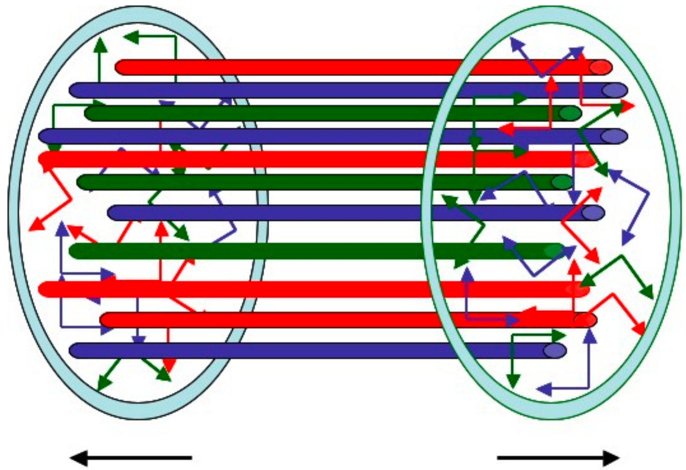
Stochastic Lorentz boosted
Coulomb fields



Hadron-Hadron Collisions and the Glasma



Two sheets of CGC collide



Sheets charge up with color electric and color magnetic charge

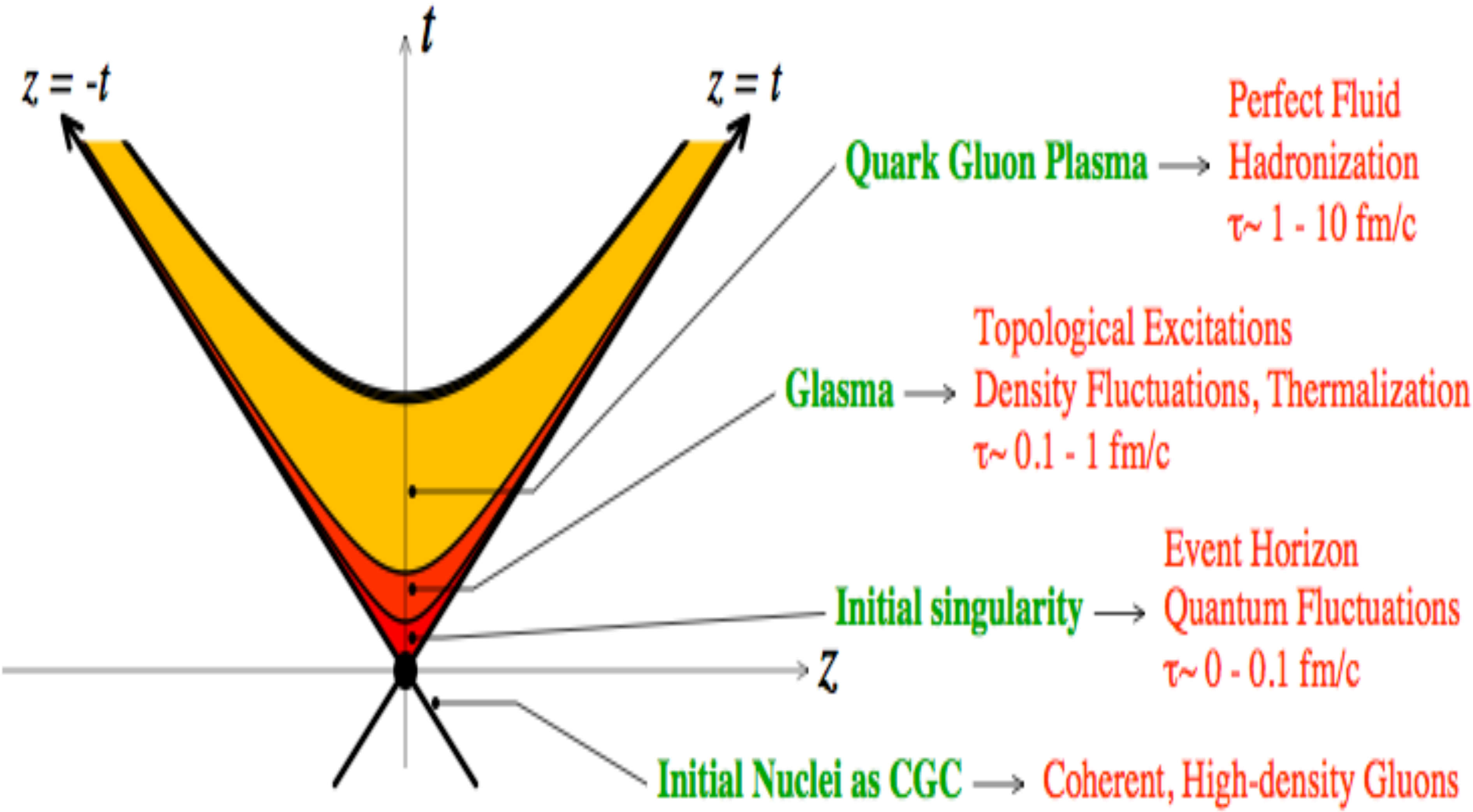
Long range color fields form in time

$$t \sim e^{-\kappa/\alpha_S}$$

Maximal local density of topological charge

$$\vec{E} \cdot \vec{B}$$

Glasma: Matter making the transition for Color Glass Condensate to Quark Gluon Plasma



Space Time Picture of Hadron Collisions very similar to that of Big Bang Cosmology

Time scales much smaller

Chaos and Turbulence:

CGC field is rapidity independent => occupies restricted range of phase space
Wiggling strings have much bigger classical phase space
A small perturbation that has longitudinal noise grows exponentially

$$A_{classical} \sim 1/g$$

$$A_{quantum} \sim 1$$

After a time

$$t \sim \frac{ln^p(1/g)}{Q_{sat}}$$

System becomes isotropic,

But it has not thermalized!
Entropy is being produced

Thermalization naively occurs when scattering times are small compared to expansion times. Scattering is characterized by a small interaction strength.

How can the system possibly thermalize, or even strongly interact with itself?

Initial distribution:

$$\frac{dN}{d^3x d^3p} \sim \frac{Q_{sat}}{\alpha_s E} \; F(E/Q_{sat})$$

A thermal distribution would be:

$$\frac{dN}{d^3x d^3p} \sim \frac{1}{e^{E/T} - 1} \sim T/E$$

Only the low momentum parts of the Bose-Einstein distribution remain

$$E \sim Q_{sat}$$

$$\text{“}T \sim Q_{sat}/\alpha_s\text{”}$$

As dynamics migrates to UV, how do we maintain isotropy driven by infrared modes with a scale of the saturation momentum?

Phase space is initially over-occupied

$$f_{thermal} = \frac{1}{e^{(E-\mu)/T} - 1}$$

Chemical potential is at maximum the particle mass

$$\rho_{max} \sim T^3 \qquad \epsilon_{max} \sim T^4$$

$$\rho_{max}/\epsilon_{max}^{3/4} \leq C$$

But for isotropic Glasma distribution

$$\rho/\epsilon^{3/4} \sim 1/\alpha_S^{1/4}$$

Where do the particle gluons go?

If inelastic collisions were unimportant, then as the system thermalized, the ratio of the energy density and number density are conserved

$$f_{thermal} = \rho_{cond}\delta^3(p) + \frac{1}{e^{(E-m)/T} - 1}$$

One would form a Bose-Einstein Condensate

Over-occupied phase space => Field coherence in
Interactions can be much stronger than

$$g^2$$

$$N_{coh} g^2$$

Blaizot, Gelis, Jin-Feng Liao, LM, Venugopalan

Might this be at the heart of the large amount of jet quenching, and strong flow patterns seen at RHIC?

Problem we tried to solve:

How does the system evolve from an early time over-occupied distribution to a thermalized distribution

We argue that the system stays strongly interacting with itself during this time due to coherence

No explicit IR effects: just power counting

First: Kinetic Evolution Dominated by Elastic Collisions in a Non-Expanding Glasma

$$\partial_t f(p, X) = C_p[f]$$

Blaizot, Gelis, Liao, LM, Venugopalan

$$f(p, X) = \frac{\Lambda_s(t)}{\alpha_s p} g(p/\Lambda(t))$$

$$\Lambda_s(t_i) \sim \Lambda(t_i) \sim Q_{sat}$$

Small angle approximation for transport equation:

$$\left.\frac{\partial f}{\partial t}\right|_{\mathrm{coll}} \sim \frac{\Lambda_s^2 \Lambda}{p^2} \partial_p \left\{ p^2 \left[\frac{df}{dp} + \frac{\alpha_s}{\Lambda_s} f(p)(1 + f(p)) \right] \right\}$$

$$\frac{\Lambda \Lambda_s}{\alpha_s} \equiv - \int_0^\infty dp\, p^2 \frac{df}{dp}$$

$$\frac{\Lambda \Lambda_s^2}{\alpha_s^2} \equiv \int_0^\infty dp\, p^2 f(1 + f)$$

Due to coherence, the collision equation is independent of coupling strength!

There is a fixed point of this equation corresponding to thermal equilibrium when

$$T \sim \Lambda \sim \Lambda_s / \alpha_s$$

Estimates of various quantities
(Momentum integrations are all dominated by the hard scale)

$$n_g \sim \frac{1}{\alpha_s}\Lambda^2\Lambda_s \qquad \epsilon_g \sim \frac{1}{\alpha_s}\Lambda_s\Lambda^3 \qquad \frac{\epsilon_g}{n_g} \sim \Lambda$$

$$n = n_c + n_g \qquad \epsilon_c \sim n_c m \sim n_c\sqrt{\Lambda\Lambda_s}$$

$$m^2 \sim \alpha_s \int dp\, p^2 \frac{df(p)}{d\omega_p} \sim \Lambda\Lambda_s$$

The collision time follows from the structure of the transport equation and is

$$t_{scat} = \frac{\Lambda}{\Lambda_s^2}$$

The scattering time is independent of the interaction strength

Thermalization in a non-expanding box

$$\epsilon = \Lambda_s \Lambda^3 \sim constant \qquad t_{scat} = \frac{\Lambda}{\Lambda_s^2} \sim t$$

So that

$$\Lambda_s \sim Q_s \left(\frac{t_0}{t}\right)^{\frac{3}{7}} \qquad \Lambda \sim Q_s \left(\frac{t}{t_0}\right)^{\frac{1}{7}}$$

$$n_g \sim n_0 \left(\frac{t_o}{t}\right)^{1/7} \qquad m \sim Q_s (t_0/t)^{1/7} \qquad \frac{\epsilon_c}{\epsilon_g} \sim \left(\frac{t_0}{t}\right)^{1/7}$$

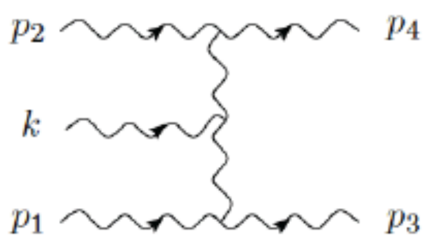
$$s \sim \Lambda^3 \sim Q_s^3 (t/t_0)^{3/7}$$

At thermalization $\Lambda_s = \alpha_s \Lambda$

$$t_{th} \sim \frac{1}{Q_s} \left(\frac{1}{\alpha_s}\right)^{\frac{7}{4}} \qquad s \sim Q_s^3 / \alpha_s^{3/4} \sim T^3$$

How do inelastic processes change this?

Rates of inelastic and elastic processes are parametrically the same



$$\frac{1}{t_{scat}} \sim \alpha_s^{n+m-2} \left(\frac{\Lambda_s}{\alpha_s}\right)^{n+m-2} \left(\frac{1}{m^2}\right)^{n+m-4} \Lambda^{n+m-5}$$

$$m^2 \sim \Lambda_s \Lambda$$

Baier, Mueller, Son...

$$t_{\text{scat}} = \frac{\Lambda}{\Lambda_{\text{s}}^2},$$

What about the condensate? Difficult to make definite statement.
In relaxation time limit, we would expect:

$$\frac{d}{dt}\rho_{cond} = -\frac{a}{t_{scat}}\rho_{cond} + \frac{b}{t_{scat}}n_{gluons}$$

Either $\rho_{cond} >> n_{gl}$ or $\rho_{cond} = \frac{b}{a}n_{gluons}$

Condensate would rapidly evaporate near thermalization time

Effect of Longitudinal Expansion

$$\partial_t f - \frac{p_z}{t}\partial_{p_z} f = \left.\frac{df}{dt}\right|_{p_z t} = C[f] \qquad \partial_t \epsilon + \frac{\epsilon + P_L}{t} = 0$$

Assume approximate isotropy restored by scattering.
Will check later that this is consistent.

$$P_L = \delta\epsilon \qquad 0 < \delta < 1/3$$

$$\epsilon_g(t) \sim \epsilon(t_0)\left(\frac{t_0}{t}\right)^{1+\delta} \qquad \Lambda_s \sim Q_s\left(\frac{t_0}{t}\right)^{(4+\delta)/7}, \qquad \Lambda \sim Q_s\left(\frac{t_0}{t}\right)^{(1+2\delta)/7}$$

$$\left(\frac{t_{th}}{t_0}\right) \sim \left(\frac{1}{\alpha_s}\right)^{\frac{7}{3-\delta}}$$

The asymmetry parameter:

Take moments of transport equation

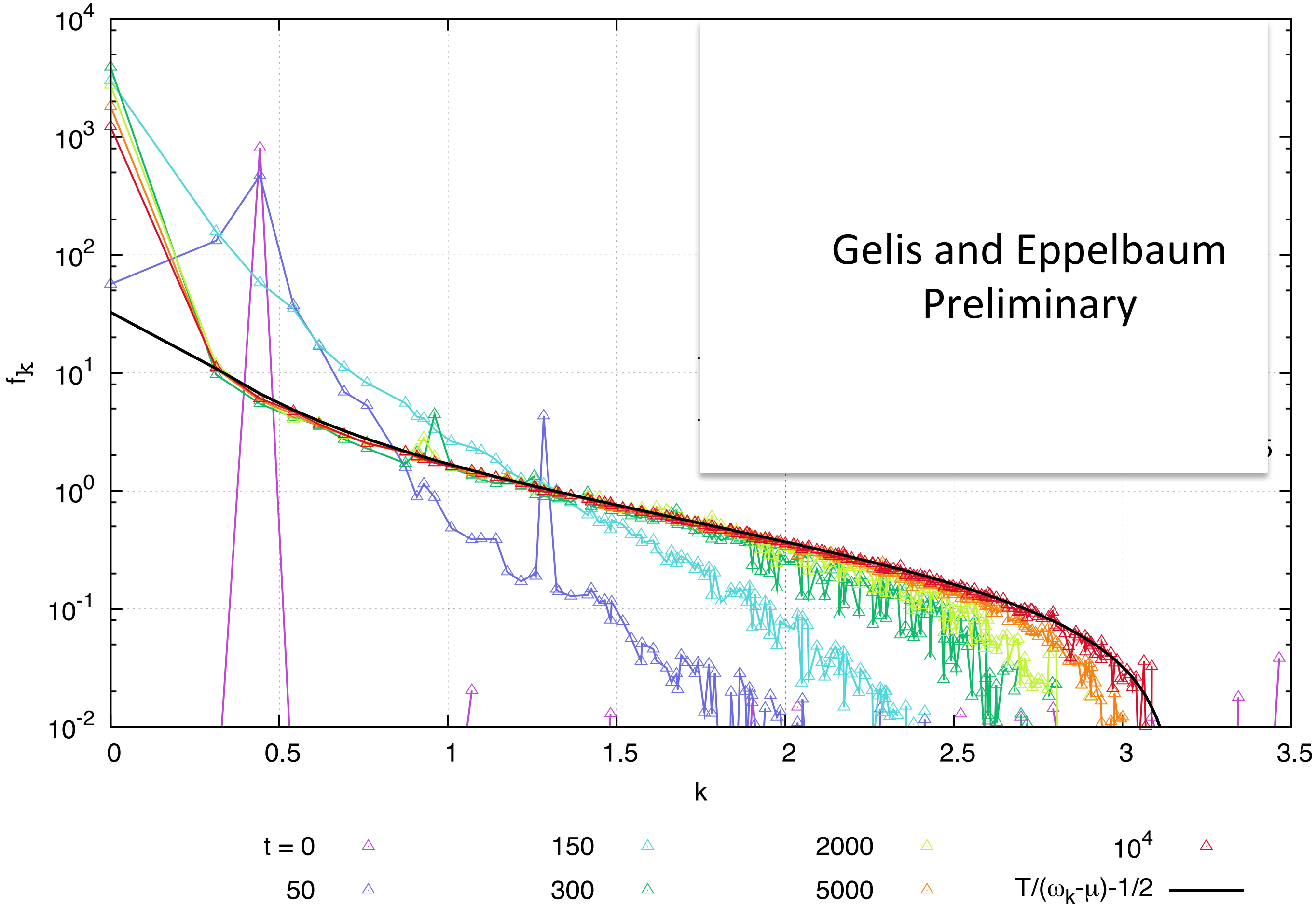
$$< p_x^2 > \qquad < p_T^2 >$$

Prove that the solutions for these moments reduce to constants times the ultraviolet scale at large times

$$< p_x^2 > / < p_T^2 > \sim constant$$

Need to know solutions to transport equation to determine the value of the anisotropy parameter

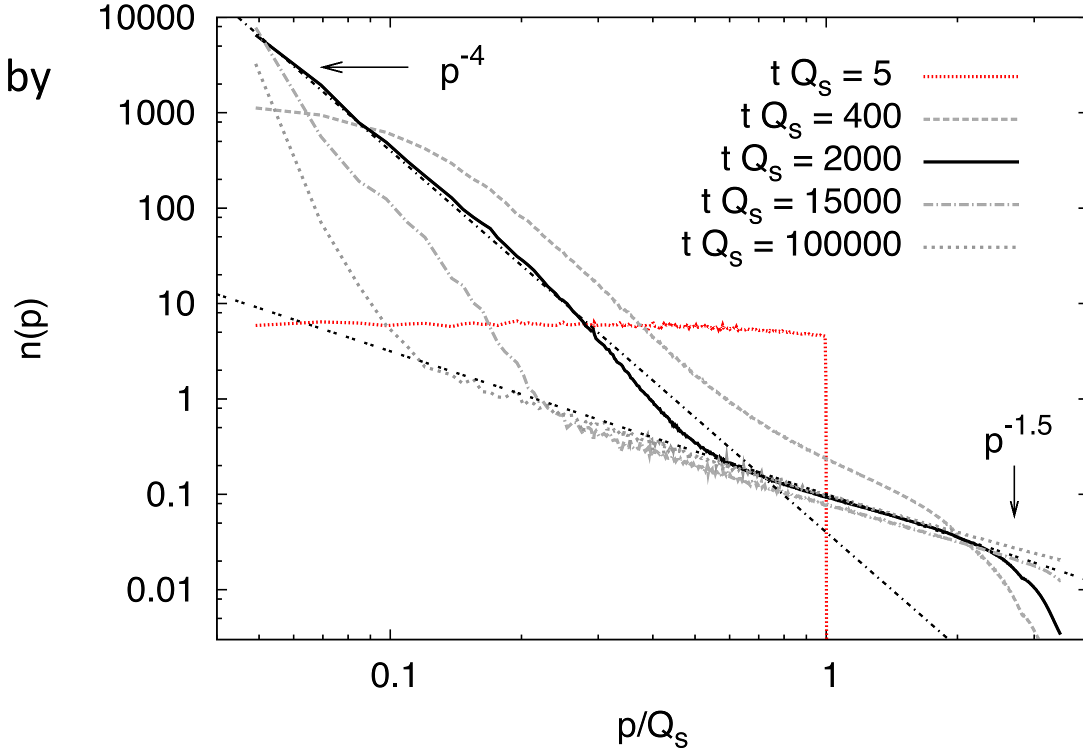
Simulations by Gelis and Eppelbaum seem to confirm this scenario in scalar field theory in non-expanding box



Rapid Reaction Task Force at Heidelberg sponsored by EMMI Dec 12-14

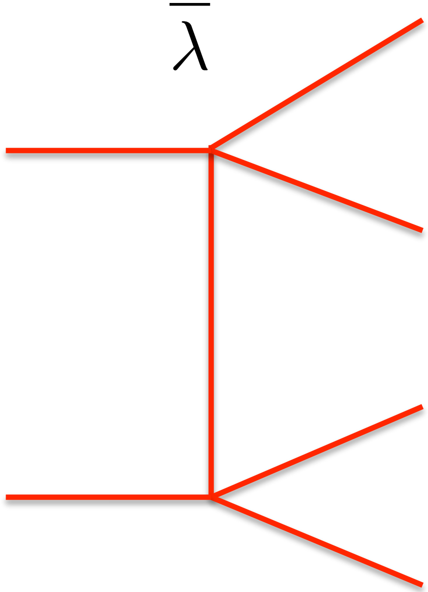
For Scalar Theory: Similar Results by Berges and Sexty:

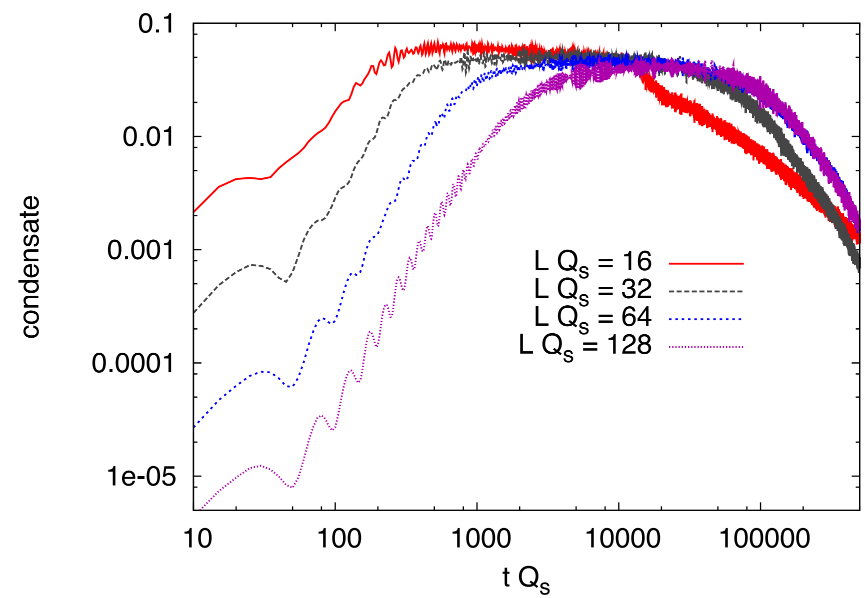
UV and IR Cascades at Intermediate Times



Particle number changing is a classical effect of order

$$\frac{1}{\lambda}$$





Temporal Condensate:

Does a transient condensate form in the Yang Mills Case?

Trade off between decay and absorption by soft modes?

It is a true instability so it simply runs away?

It does not exist?

Condensate or Not:

Does not affect the evolution of the hard modes,
since number conservation not needed to compute evolution of the hard modes

Need a solid numerical simulation!
Boundary conditions?
Gauge invariance?
Physical modes?
Is this related to IR instability considerations of Moore and Kurkela?
Relation to cascade computations of Greiner et. al.?
Viscosity (Muller et. al.)