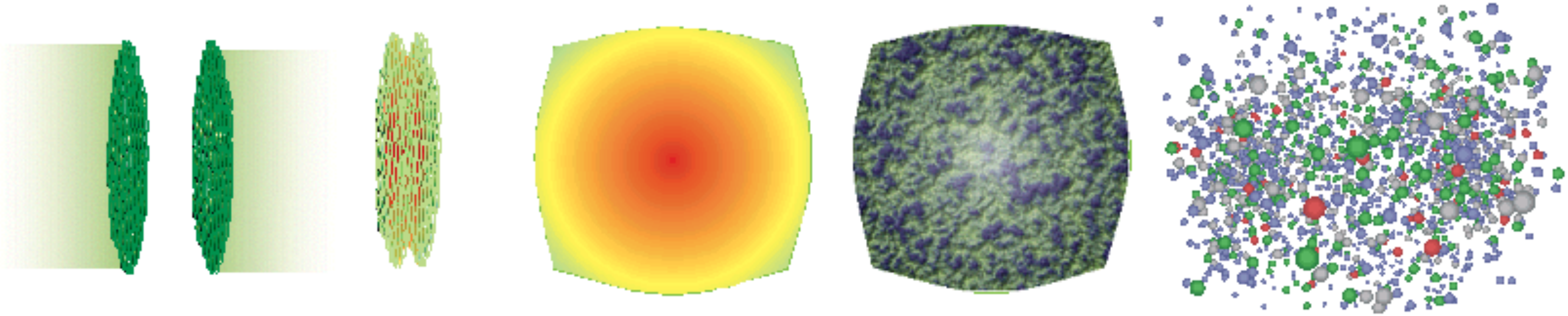
Photon Workshop at GSI

based on work with M. Chiu T. Hemmick, A. Leonidov, J. Liao, V. Khachatryan



CGC

Initial Singularity

Glasma

Thermalized sQGP

Hadron Gas

<-------------sQGP ------------->

The Space-Time Evolution of Heavy Ion Collisions

RIKEN BNL Research Center

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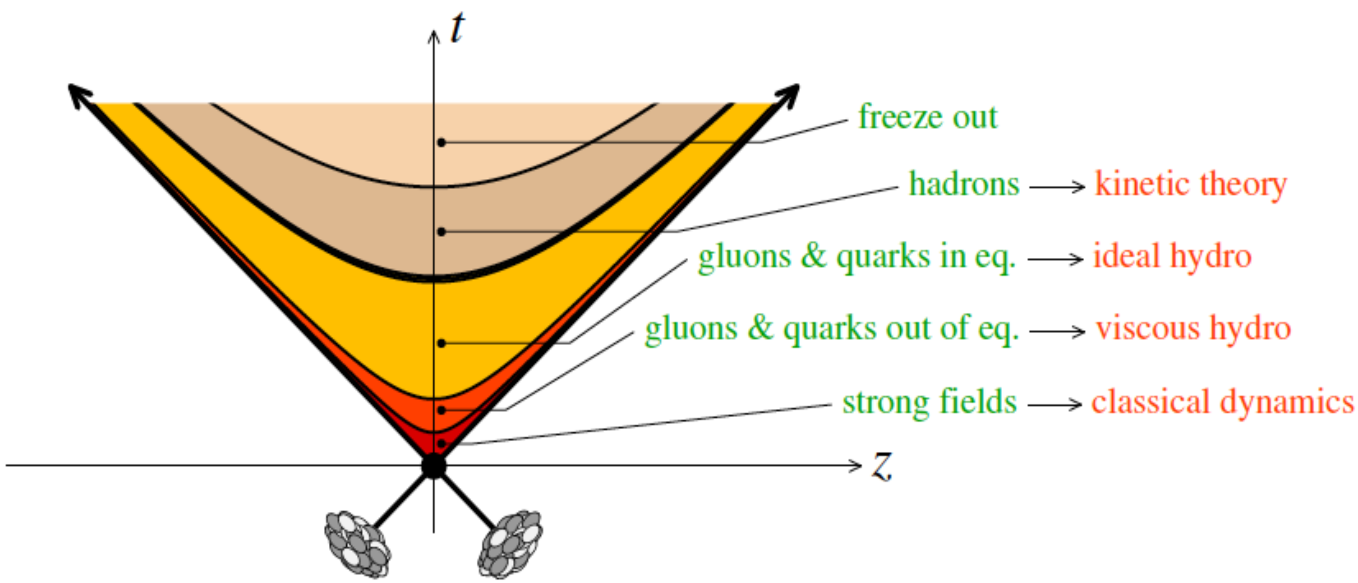
HUAZHONG UNIVERSITY

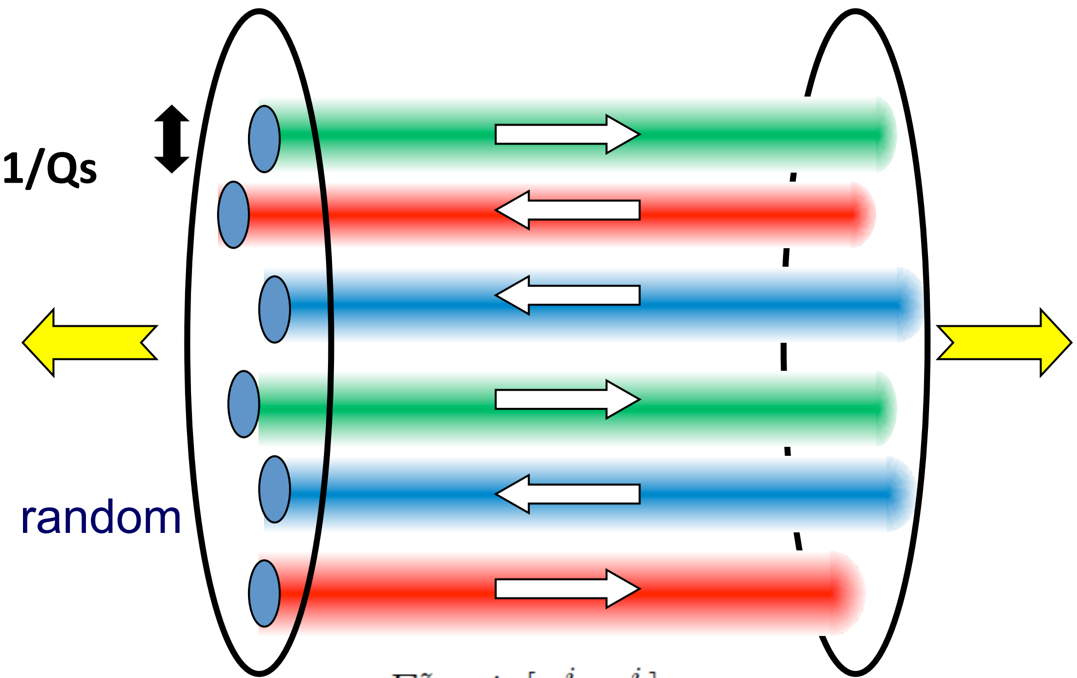


Color Glass Condensate:
The High Density Gluonic States of a high energy hadron that dominate high energy scattering.

Glasma:
Highly coherent gluon fields arising from the Glasma that turbulently evolve into the thermalized sQGP while making quarks

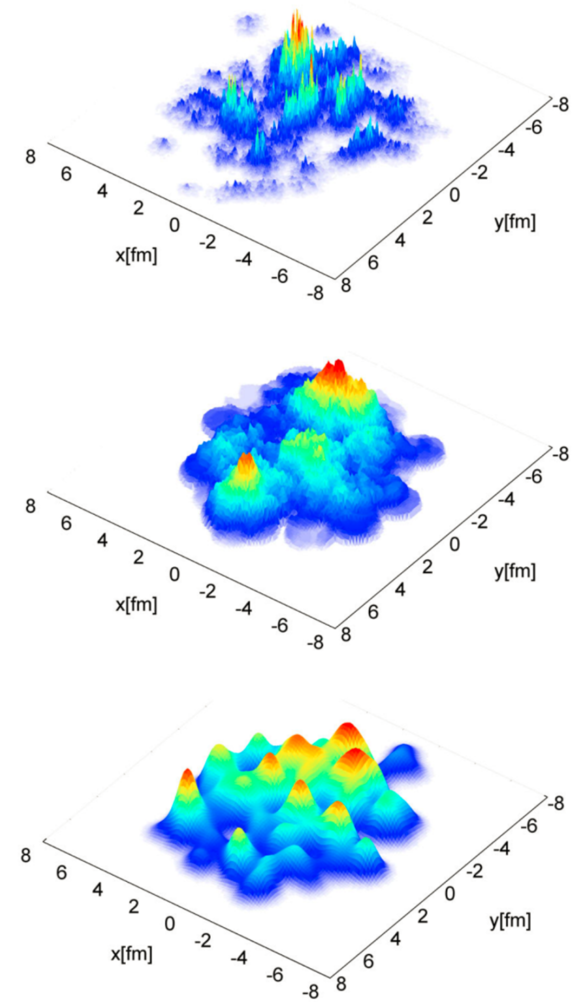
Thermalized sQGP:
Largely incoherent quark and gluons that are reasonably well thermalized

The Glasma



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

Typical configuration of a single event
just after the collision



Highly coherent colored fields:
Stringlike in longitudinal direction
Stochastic on scale of inverse saturation momentum in transverse direction
Multiplicity fluctuates as negative binomial distribution

Blaizot, Gelis, Liao, McLerran and Venugpalan

The Glasma:

Weak coupling but strongly interacting due to coherence of the fields

In transport or classical equations, the coupling disappears!

Two scales

$$\Lambda_{coh}(t_{in}) \sim \Lambda_{UV}(t_{in}) \sim Q_{sat}$$

But it takes time to separate the scales and make a thermal distribution

$$\Lambda_{coh}(t_{therm}) \sim \alpha_s \Lambda_{UV}(t_{therm}) \sim \alpha_s T_{init}$$

How long does it take to thermalize?

Are there Bose-Einstein Condensates formed?

For how long is the system in homogeneous with longitudinal pressure not equal to transverse?

Can we measure a difference between longitudinal and transverse pressure?

Order parameters: Electric and magnetic confinement

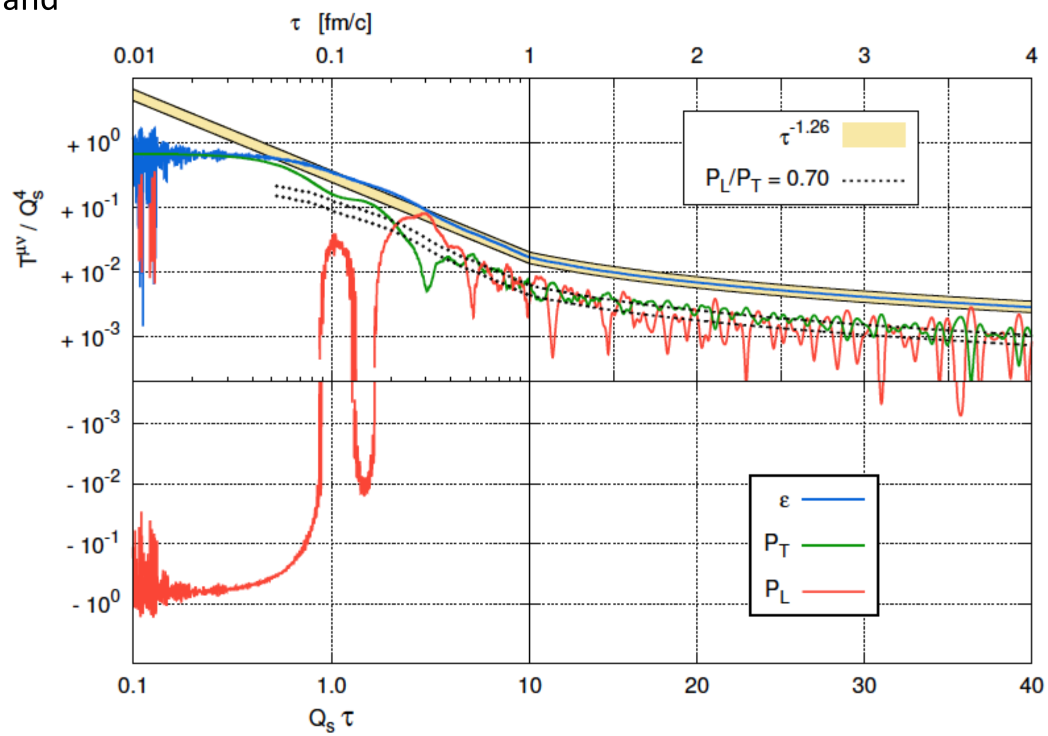
Recent results of Gelis and Eppelbaum using spectrum of initial fluctuations derived from QCD:

Find hydrodynamic behaviour a good approximation as coupling constant gets bigger, but even for

It is a good approximation.
For RHIC and LHC energy the coupling is even larger

$$\eta/S \sim 0.25 \qquad t_{hydro} \sim 3/Q_{sat}$$

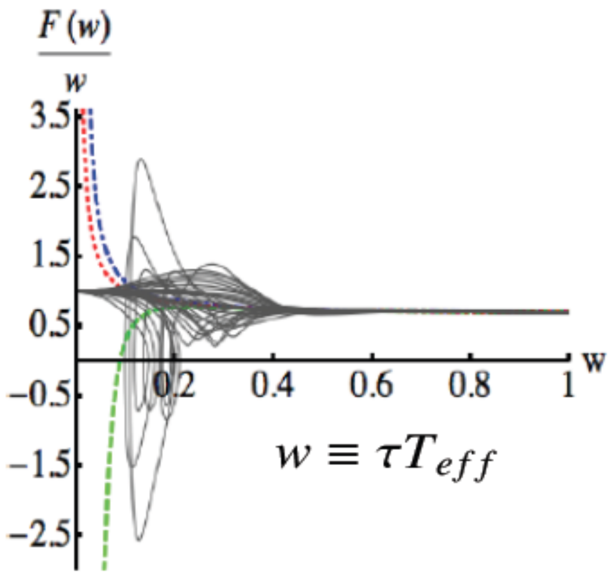
Gelis and Epelbaum;
Berges, Schlichtin, Sexty and Venugopalan

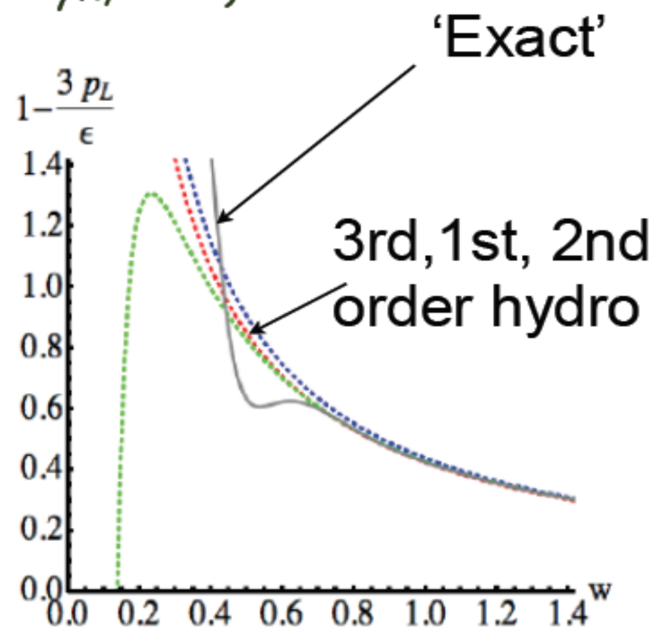


The perfect fluid might not be a thermally equilibrated system!

Holographic description of a boost invariant plasma

(Heller, Janik, Witaszczyk, 2011)





Viscous hydro can cope with partial thermalization, and large differences between longitudinal and transverse pressures

In fact, there is little experimental evidence that complete local equilibrium is reached in nuclear collisions

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The Glasma may be a nearly perfect fluid, even though it is not a thermalized sQGP. It is certainly a sQGP

Distinctive Feature of the Glasma: Not Many Quarks

In the Glasma,

$$N_{gl} \sim \Lambda_s \Lambda^2 / \alpha_s$$

$$N_{quark} \sim \Lambda^3$$

At thermalization

$$\alpha_s \Lambda = \Lambda_s$$

Initially, gluons dominate but at thermalization the number of quarks is of the order of the number of gluons

Some enhancement of flow but probably not enough

How do the Quarks Appear in Time:

Scattering time

$$t \sim \Lambda/\Lambda_s^2$$

Energy Density:

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

$$\delta < 1/3$$

$$N_q/N_{glue} \sim \alpha_s \Lambda/\Lambda_s$$

Is suppressed until the thermalization time.

The only scale for the distribution is the saturation momentum

Geometric scaling of photon distributions:

Hemmick, Kharchatryan, Leonidov, McLerran

$$\frac{1}{\sigma}\ \frac{dN}{d^2 p_T} = F(Q_{sat}/p_T)$$

σ Is the geometrical overlap area $\sim N_{part}^{2/3}$

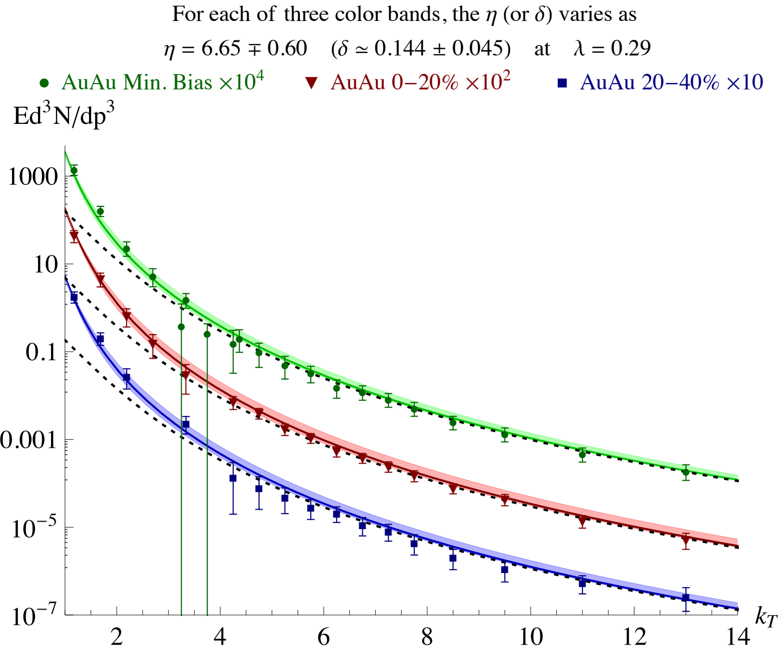
$$Q_{sat} \sim N_{part}^{1/3}\ (\Lambda_{QCD}/p_T)^\lambda \qquad \lambda \sim .3$$

Power law fit to pT spectrum give a power of about 8, and therefore roughly a N_{part}^2 dependence on centrality
Fit is shown on previous figure

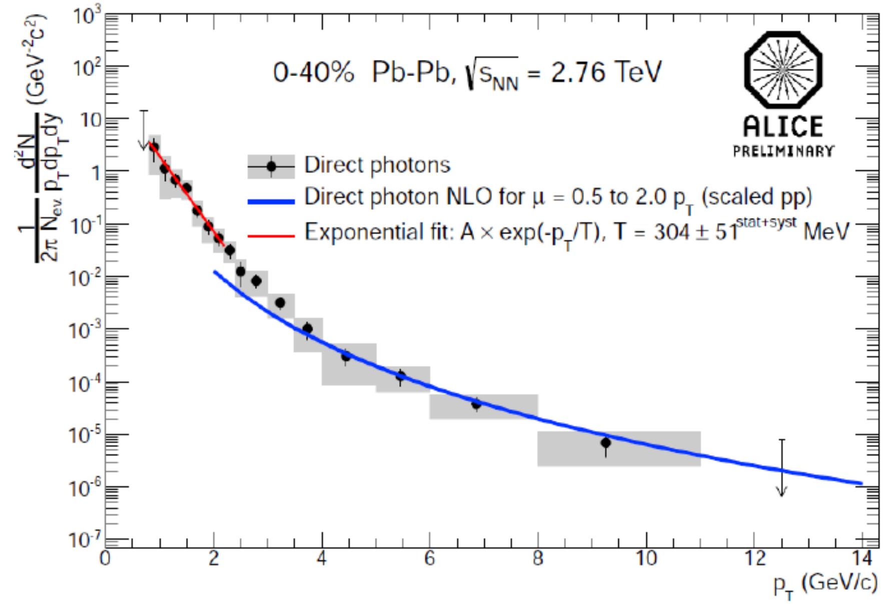
Rate for Glasma emission is

$$\frac{dN}{d^4x dy d^2 k_T} = \frac{\alpha}{\pi} \Lambda_s \Lambda g(E/\Lambda)$$

Integrating ovr space time history generates a power law for k_T distribution and preserves geometric scaling as does hydrodynamics



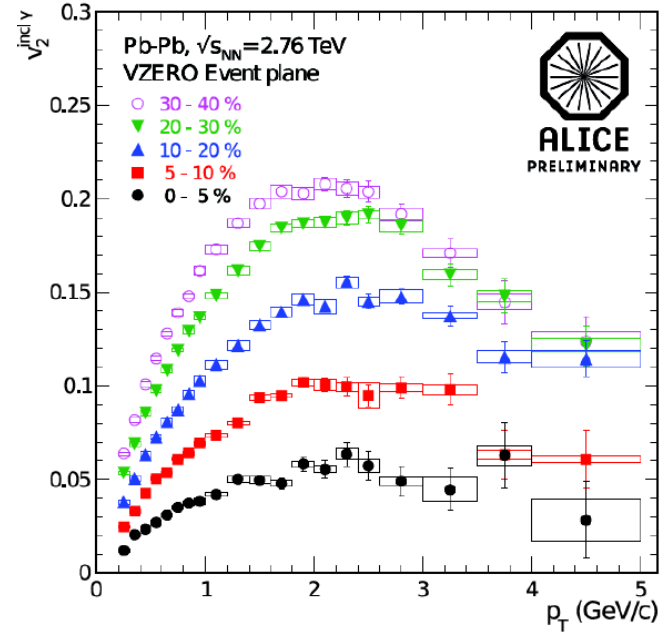
Photon excess in Phenix as function of centrality and pT



Similar photon excess seen in Pb-Pb at Alice

Confirmed
High pT suggests photons comes from early time
V2
and
geometric scaling of multiplicity dependence seen in Phenix suggest photons did not arise from a very hot thermalized QGP

Large Flow seen in both Phenix and Alice



Bzdak, McLerran

Can the Glasma generate initial state flow?

Free scalar field theory with a source:

$$(p^2 + M^2)\phi = \rho$$

$$dN/dyd^2k_T \sim \rho(k,\omega)\rho(-k,-\omega)$$

Moments in space are converted into moments in coordinate space, no interaction required

For delta function in time, odd moments vanish, so odd moments are generated in time evolution; Even moments are genuine initial conditions

V_2(n) \sim v_2(2) is satisfied

Effect is biggest for smallest systems, since this is fluctuation dominated

How does this effect Glasma and Thermalized QGP evolution?

Schenke, Tribedy and Venugopalan

Questions:

Can we argue that the flow from photon comes at late times?

Can we argue it needs a component for early times?

Is there geometric scaling in the photon data?

What do we know about v_n[m] and is what is observed similar to hadronic data

Perhaps we are learning about early times from the photon flow data, but perhaps this is telling us something about the Glasma?