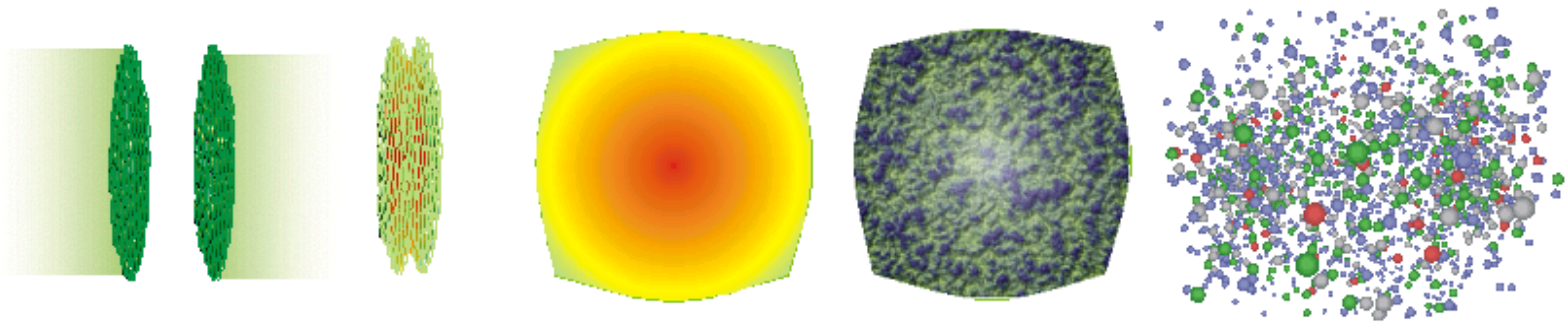
The Glasma and Photons

L. McLerran, RBRC, BNL 2014

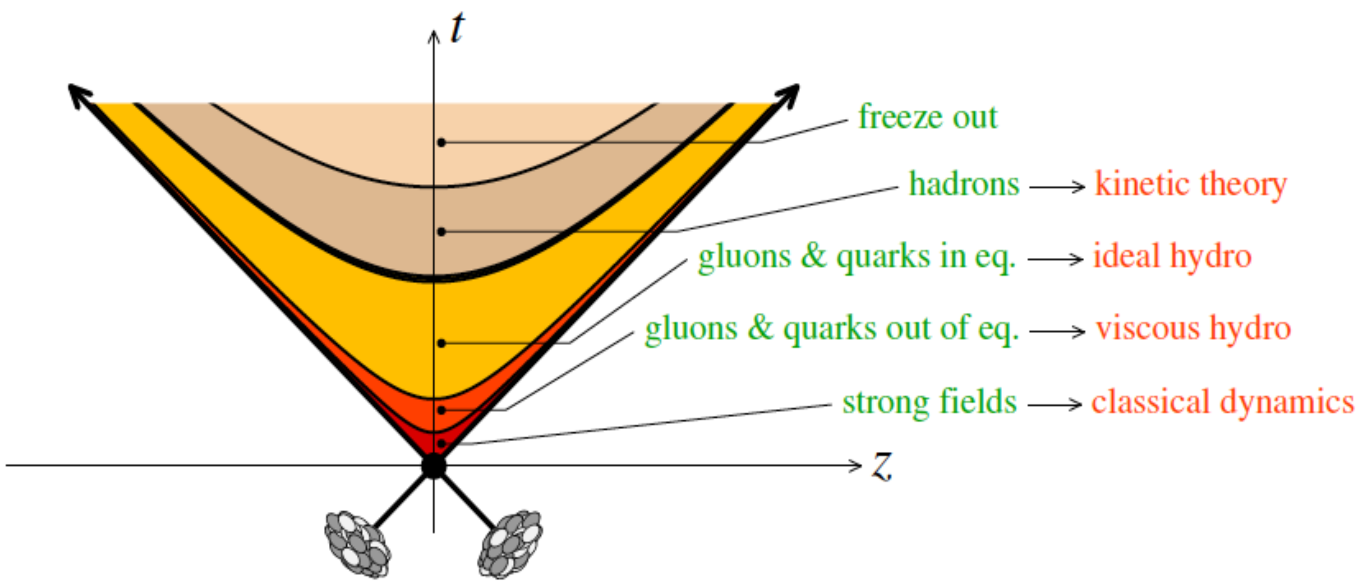


CGC | Initial Singularity | Glasma | Thermalized QGP | Hadron Gas

$\leftarrow$ Strongly Interacting QGP $\rightarrow$

The Glasma are highly coherent colored fields evolving to a thermalized QGP
The Glasma is weakly coupled but strongly interacting

$$\alpha_S << 1 \qquad A \sim \frac{1}{g} Q_{sat} \qquad \frac{dN}{dyd^2r_T} \sim \frac{Q^2_{sat}}{\alpha_S}$$

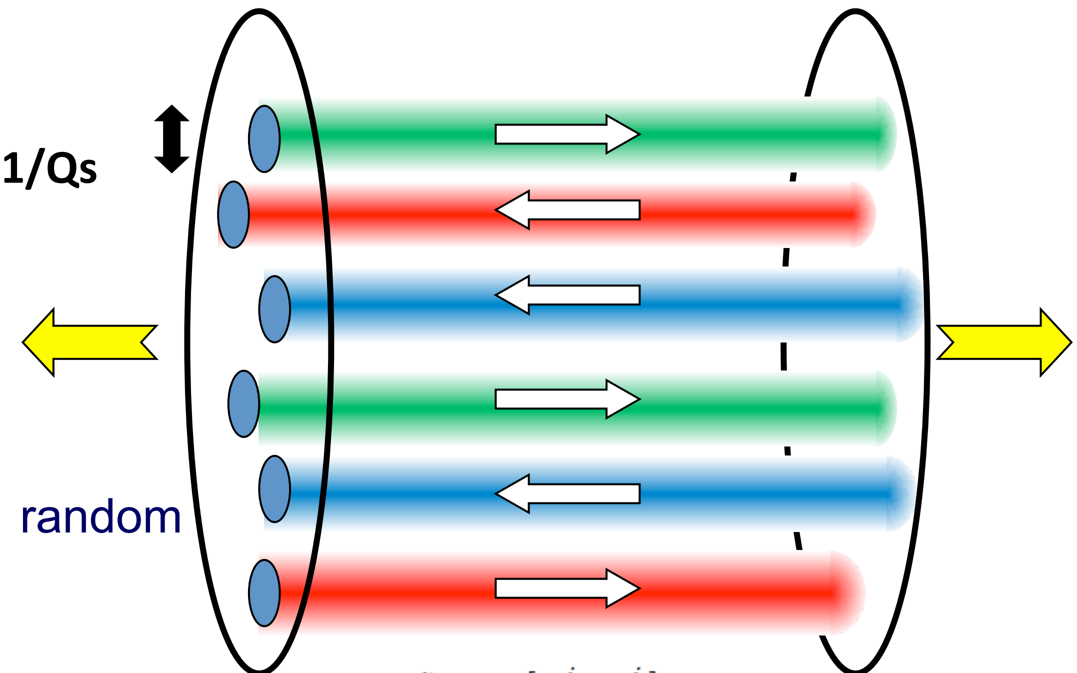


Color Glass Condensate:
The High Density Gluonic States of a high energy hadron that dominate high energy scattering.

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

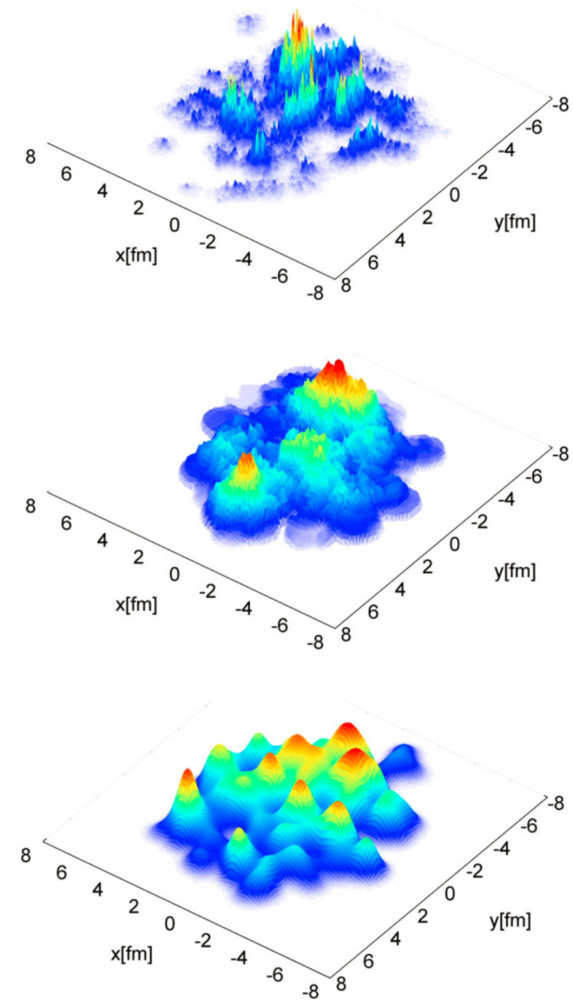
Thermalized sQGP:
Largely incoherent quark and gluons that are reasonably well thermalized

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

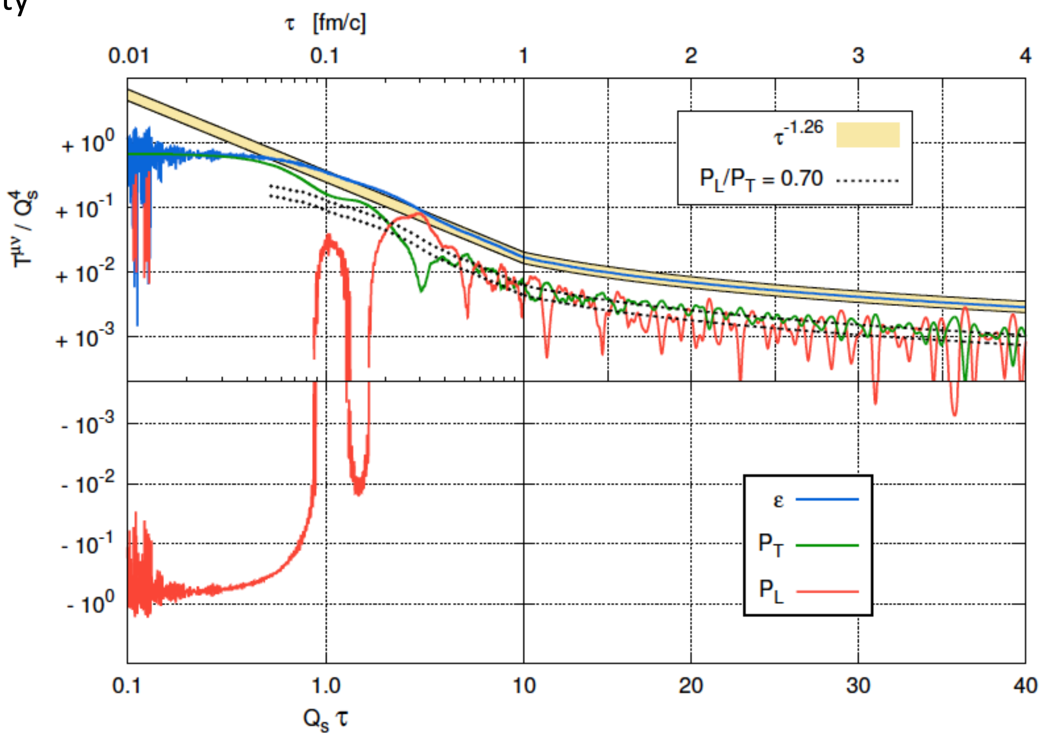
Recent results of Gelis and Eppelbaum using spectrum of initial fluctuations derived from QCD:

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

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

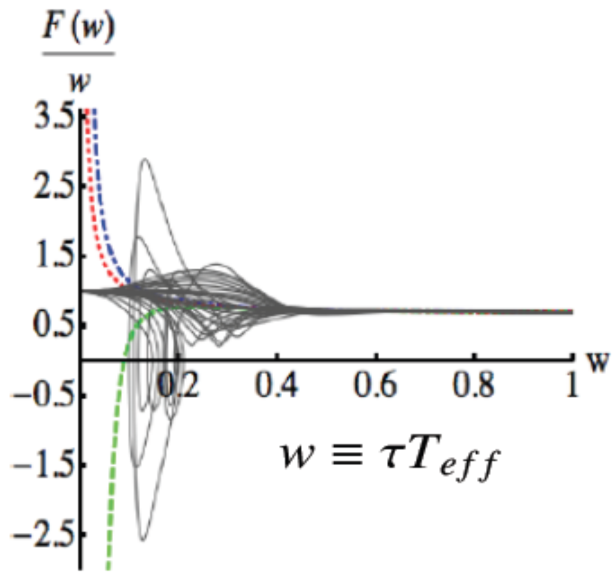
Gelis and Epelbaum;
Berges, Schlichting, Sexty
and Venugopalan

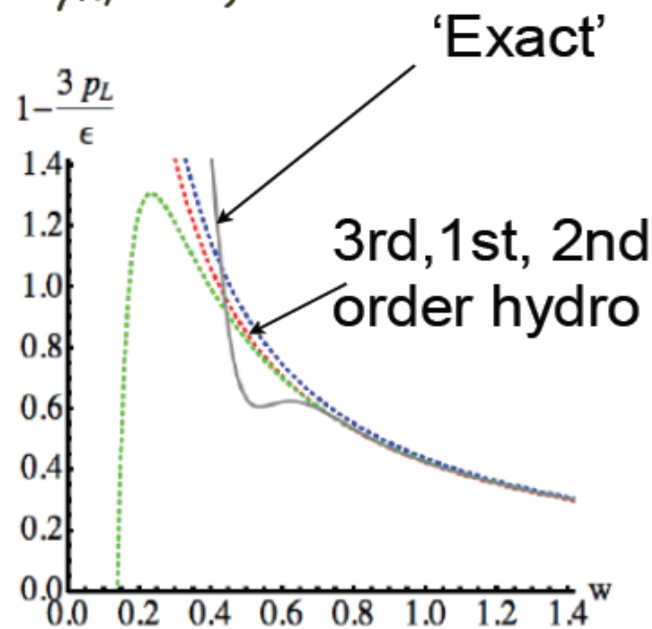


The perfect fluid might not be a thermally equilibrated system!

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

How Does the Glasma Evolve:

At an early time:

$$\frac{1}{\tau \pi R^2} \frac{dN}{d^3 p_T} = f(p)$$

$$f(p) \sim \frac{1}{\alpha_s}, \quad p \leq Q_{sat}$$

$$f(p) \leq 1, \quad p \geq Q_{sat}$$

System evolves by scattering and two scales emerge

$$\Lambda_{IR}, \quad f(\Lambda_{IR}) \sim \frac{1}{\alpha_S}$$

$$\Lambda_{UV}, \quad f(\Lambda_{UV}) \sim 1$$

How do these scales evolve?

In transport equation:

$$df/dt \sim \alpha^2 f^3$$

The term with four factors of f cancels in the difference between backwards and forward going processes

If the process is dominated in the infrared:

$$df/dt \sim \frac{1}{\tau_{scat}} f$$

The scattering time can be evaluated in terms of the two scales by explicitly evaluating the phase space integrals in the transport equations

$$\tau_{scat} \sim \frac{\Lambda_{UV}}{\Lambda_{IR}} \frac{1}{\Lambda_{IR}}$$

Assumes not dominated by a condensate

Note that factors of coupling strength have disappeared. The scattering time is the Lorentz time dilation of the infrared scattering scale when the coherence is maximal. This result is true also when including inelastic scattering.

The equation:

$$\tau_{scat} \sim \frac{\Lambda_{UV}}{\Lambda_{IR}} \frac{1}{\Lambda_{IR}}$$

Is true except close to a thermal fixed point. Near a thermal fixed point, the right hand side of the transport equation vanishes. Near the thermal fixed point, the evolution of the system slows as one has approached equilibrium.

Far from equilibrium, we expect

$$\tau \sim \tau_{scat}$$

We will soon see that the time evolution of both scales is determined by this condition and the condition of energy conservation, assuming that in the infrared, the distributions functions are classical thermal distribution functions

$$f \sim \frac{1}{\alpha_S} \frac{\Lambda_{IR}}{E} \qquad \epsilon \sim \int d^3p \; pf \sim \frac{1}{\alpha_S} \Lambda_{IR} \Lambda_{UV}^3$$

A simple model, assuming local equilibration in the infrared is

$$f(p) = \frac{\kappa \Lambda_{IR}}{\alpha_S \Lambda_{UV}} \; \frac{1}{e^{E/\Lambda_{UV}} - 1}$$

This distribution is a classical thermal distribution in the infrared

$$f \sim \frac{1}{\alpha_S} \frac{\Lambda_{IR}}{E}$$

and goes to zero when $E \sim \Lambda_{UV}$

It is like a thermal; distribution with a temperature $T \sim \Lambda_{UV}$

It becomes a thermal distribution function when the over-occupation factor $\frac{\kappa \Lambda_{IR}}{\alpha_S \Lambda_{UV}} \rightarrow 1$

Or when $\kappa \Lambda_{IR} = \alpha_S \Lambda_{UV}$

Then the infrared scale is that of the magnetic mass and the UV scale is the temperature

Note that the entropy of the gluon distribution is

$$s \sim \int d^3p\{(1+f)ln(1+f) - fln(f)\} \ \sim \Lambda_{UV}^3 ln\frac{\Lambda_{IR}}{\alpha_S \Lambda_{UV}}$$

But the number of gluons is

$$\rho \sim \frac{1}{\alpha_S}\Lambda_{IR}\Lambda_{UV}^2$$

So the entropy to particle ratio is less than one until thermalization due to the coherence

$$s/n \sim \alpha_S \Lambda_{UV}/\Lambda_{IR}$$

For fermions we can use

$$q = \frac{1}{e^{E/\Lambda_{UV}} + 1}$$

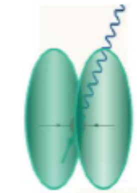
The ratio of the number of quarks to gluons is suppressed until thermalization due to the over-occupation of gluonic states

$$q/g \sim \alpha_S \Lambda_{UV}/\Lambda_{IR}$$

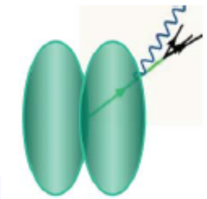
The advantage of this parameterization of the gluon distribution functions is that thermal results can be reproduced simply by replacing the temperature with the ultraviolet scale, and multiplying the gluon distribution function by the over-occupation factor. An example of how this works is with photon production.

The Problem with Photons at RHIC and LHC

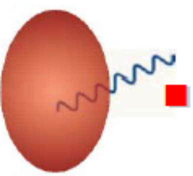
- **Decay photons** (in pp and AA):
  $m \rightarrow \gamma + X$, $m = \pi^0, \eta, \omega, \eta', a_1, \ldots$



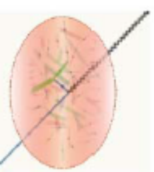
- **Direct photons:** (inclusive(=total) – decay) – measured experimentally



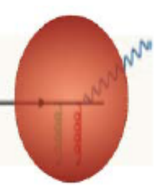
- **hard photons**: (large p_T, in pp and AA)
  - **prompt** (pQCD; initial hard N+N scattering)
  - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)



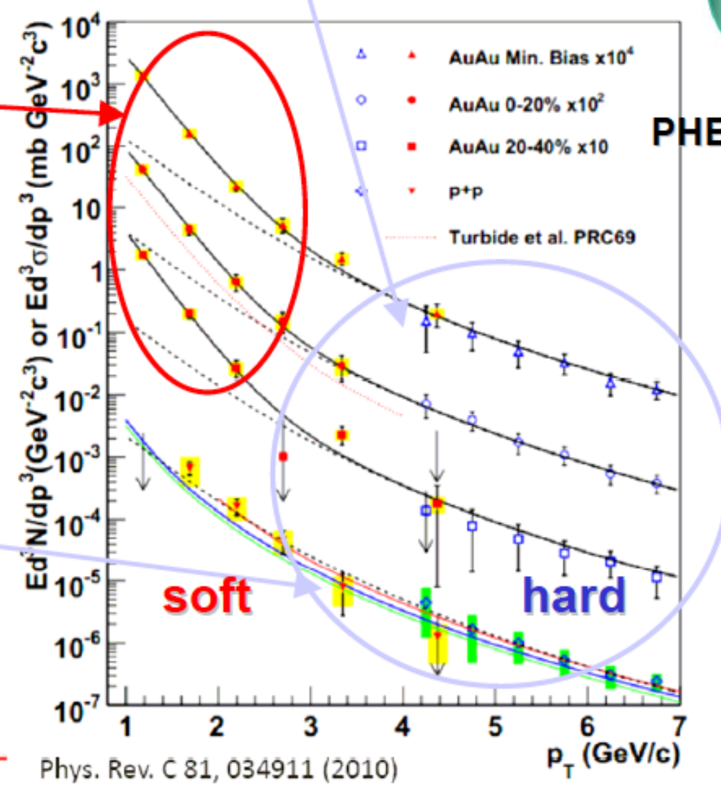
- **thermal photons**: (low p_T, in AA)
  - **QGP**
  - **Hadron gas**



- **jet-γ-conversion** in plasma (large p_T, in AA)



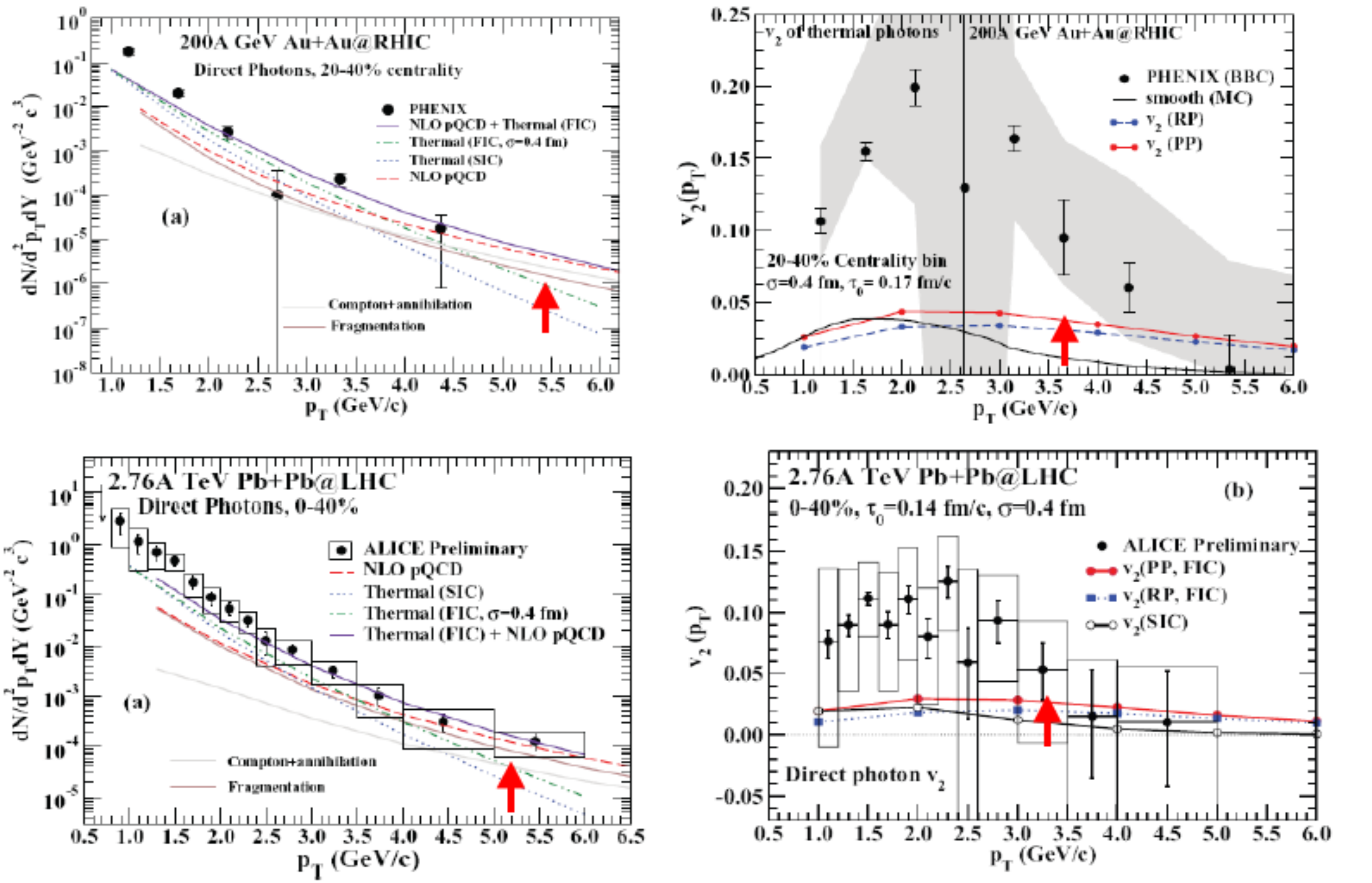
- **jet-medium photons** (large p_T, in AA) - scattering of hard partons with thermalized partons $q_{hard}+g_{QGP} \rightarrow \gamma+q$,
  $q_{hard}+qbar_{QGP} \rightarrow \gamma+q$



Bratkovskaya: QM2014

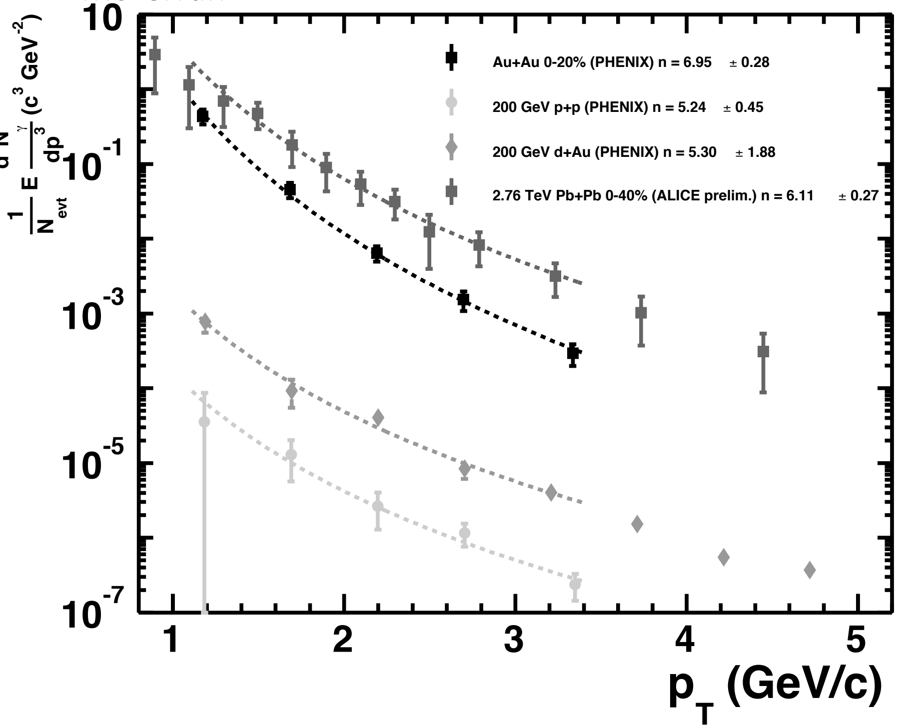
It is not clear whether the photons seen are emitted early or late, nor the source of these photons: misidentified hadron decays, jet fragmentation, QGP or hadron gas. The photons also have a large flow that is problematic. There are problems both with absolute rates and with the magnitude of v2

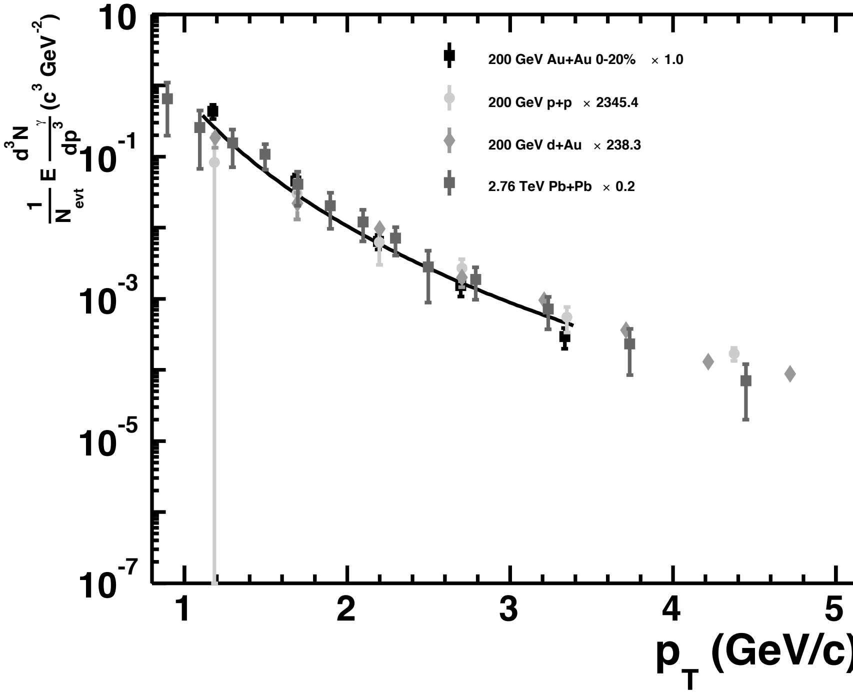
Eskola et al



There is geometric scaling of the p_t spectrum for pp, dAu, A-A at RHIC and LHC

Golec- Biernat, Statso Kwieczinski; Praszalowicz and McLerran



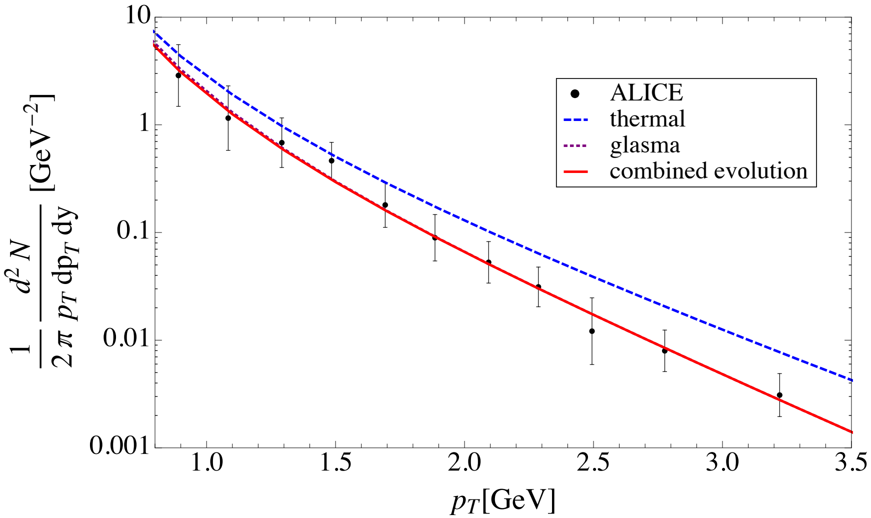


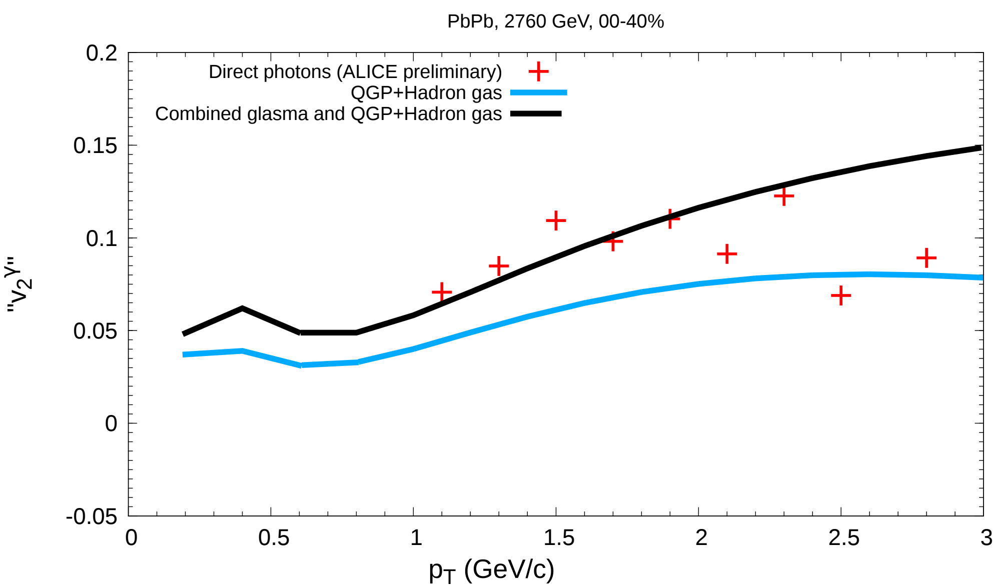
$$Q^2_{sat} = \frac{\kappa}{\pi R^2} \frac{dN}{dy}$$

$$\frac{1}{\pi R^2} \frac{dN_\gamma}{dy d^2 p_T} = F\left(\frac{Q_{sat}}{p_T}\right)$$

We also agree with the multiplicity dependence seen in Phenix
LDM and Christian Klein -Boesing

With Bjoern Schenke we computed spectrum of photons in 1+1 hydro. Shape fits well, but the rate requires a large k factor of about 7





Because the Glasma decays more slowly than the thermalize QGP, we get acceptable flow from Glasma + QGP

The rate problem remains, but perhaps is solved by properly doing jet quenching plus fragmentation photons. A large uncertainty here is associated with how the jet contribution is computed.

Paquet, McLerran and Schenke