Kyoto, 2015/10/05

Modelling Early Time Dynamics of Relativistic Heavy Ion Collisions

Dr. Marco Ruggieri

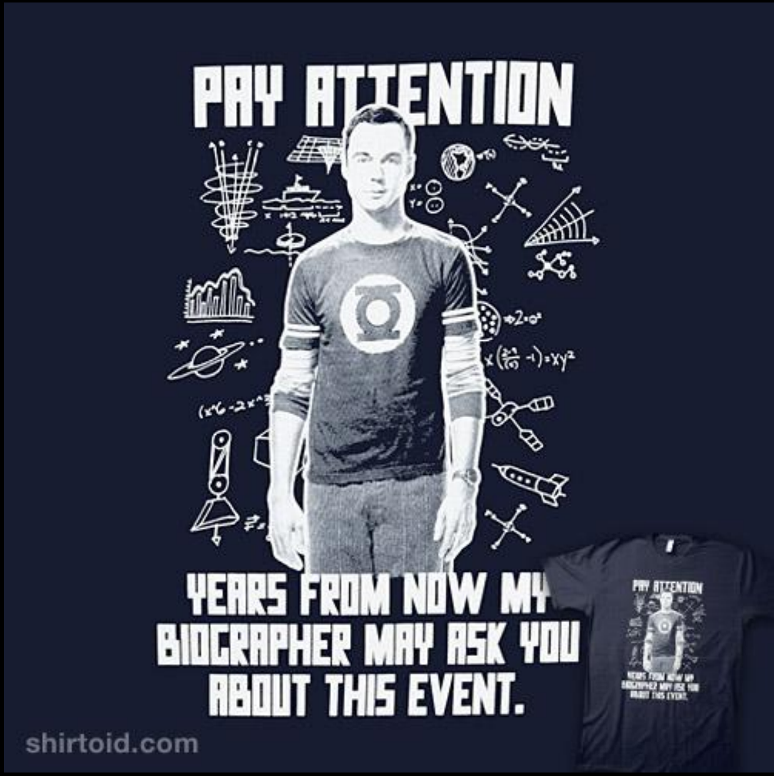
Physics and Astronomy Department, Catania University, Catania (Italy)

Collaborators:
Vincenzo Greco
Lucia Oliva
Salvatore Plumari
Armando Puglisi
Francesco Scardina

(part of)
Catania Transport Group

Plan of the talk

- Relativistic Transport Theory for HICs
- Flux Tube model for early stages
- ***Selected results***
- Conclusions



More on: ***Plumari's*** *talk*
Puglisi's *talk*

Boltzmann equation and QGP

In order to ***simulate*** the temporal evolution of the fireball we solve the ***Boltzmann equation*** for the parton distribution function ***f***:

$$(p_\mu \partial^\mu + gQF^{\mu\nu} p_\mu \partial^p_\nu)\, f = \mathcal{C}[f]$$

Field interaction

Collision integral

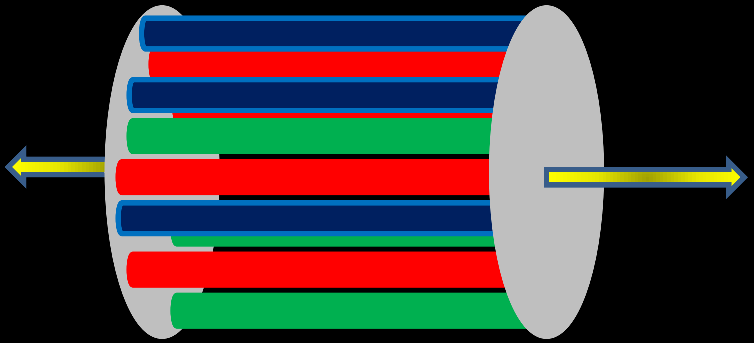
Field interaction: change of ***f*** due to interactions of the partonic plasma with a field (*e.g.* color-electric field).

Collision integral: change of ***f*** due to collision processes in the phase space volume centered at (***x***,***p***).

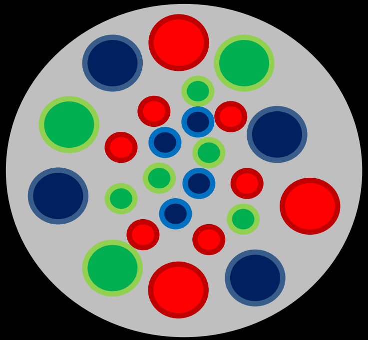
We use the ***stochastic method*** to compute the collision integral:
.) phase space is mapped by test particles
.) collisions are simulated by means of a probabilistic algorithm

From Glasma to QGP: Schwinger effect

Glasma: Longitudinal view



Glasma: Transverse plane



Problem:

how does the QCD dynamics leads to a thermalized and isotropic QGP, starting from a Glasma?

Schwinger effect + collisions

Based on the assumption that classical color fields decay to a QGP via vacuum tunneling, namely via the ***Schwinger effect*** (Schwinger, 1951).

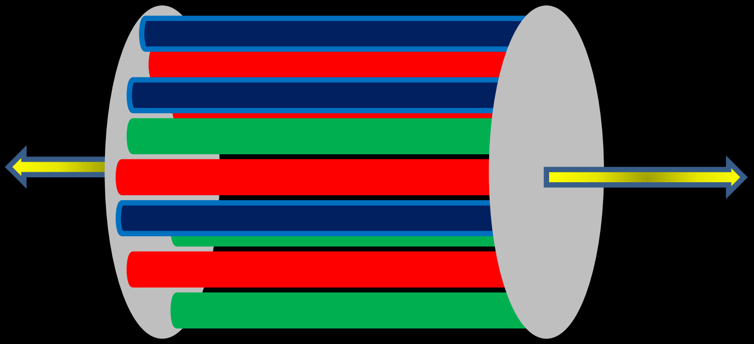
$$\boxed{\frac{dE}{dt} = -j_D - j_M}$$

$$j_M = \sum_{species} g \int \frac{d^3\boldsymbol{p}}{|\boldsymbol{p}|} p_z f(|\boldsymbol{p}|, t)$$

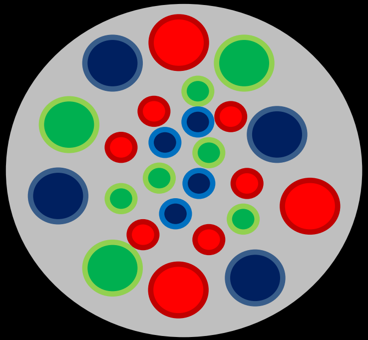
$$j_D \equiv \frac{\partial P}{\partial t} = \int d^3p g \frac{2E_T}{gE} \times \frac{dN}{d^4x d^3p}$$

From Glasma to QGP: Schwinger effect

Glasma: Longitudinal view



Glasma: Transverse plane



Problem:
how does the QCD dynamics leads to a thermalized and isotropic QGP, starting from a Glasma?

Schwinger effect + collisions

Based on the assumption that classical color fields decay to a QGP via vacuum tunneling, namely via the ***Schwinger effect*** (Schwinger, 1951).

$$\boxed{\frac{dE}{dt} = -j_D - j_M}$$

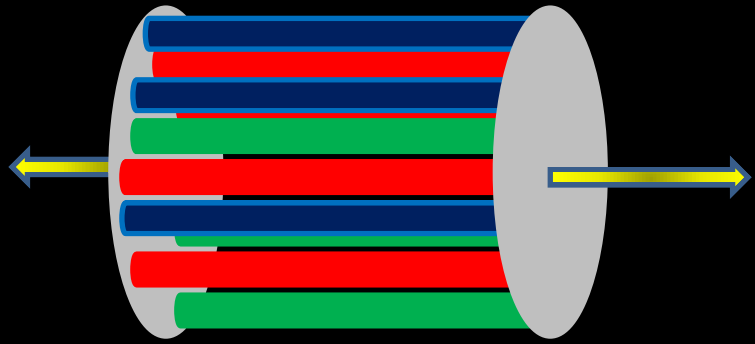
Schwinger effect

$$j_M = \sum_{species} g \int \frac{d^3\boldsymbol{p}}{|\boldsymbol{p}|} p_z f(|\boldsymbol{p}|, t)$$

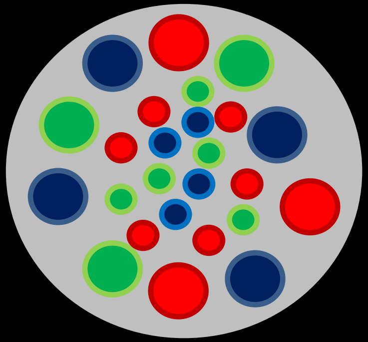
$$j_D \equiv \frac{\partial P}{\partial t} = \int d^3p g \frac{2E_T}{gE} \times \frac{dN}{d^4x d^3p}$$

From Glasma to QGP: Schwinger effect

Glasma: Longitudinal view



Glasma: Transverse plane



Problem:

how does the QCD dynamics leads to a thermalized and isotropic QGP, starting from a Glasma?

Schwinger effect + collisions

Based on the assumption that classical color fields decay to a QGP via vacuum tunneling, namely via the ***Schwinger effect*** (Schwinger, 1951).

$$\boxed{\frac{dE}{dt} = -j_D - j_M}$$

Conduction

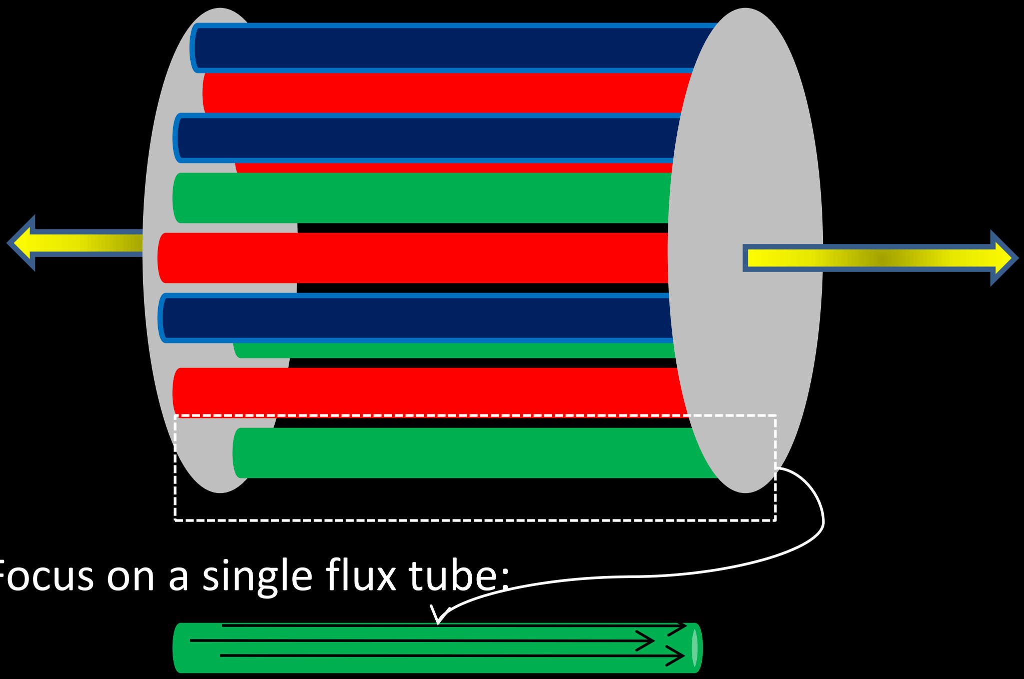
$$j_M = \sum_{species} g \int \frac{d^3\boldsymbol{p}}{|\boldsymbol{p}|} p_z f(|\boldsymbol{p}|, t)$$

$$j_D \equiv \frac{\partial P}{\partial t} = \int d^3p g \frac{2E_T}{gE} \times \frac{dN}{d^4x d^3p}$$

Schwinger effect in Chromodynamics

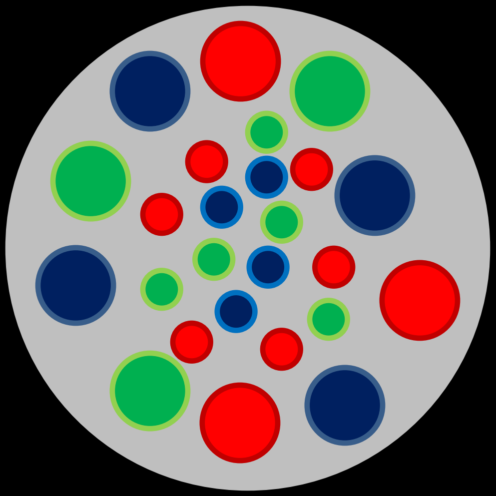
Abelian Flux Tube Model

Longitudinal view



Focus on a single flux tube:

Transverse plane view



(.) neglect color-magnetic fields;

(.) assume ***color-electric fields*** evolve as ***classical abelian fields***;

(.) initial field is ***longitudinal;***

(.) assume ***Schwinger effect*** takes place:

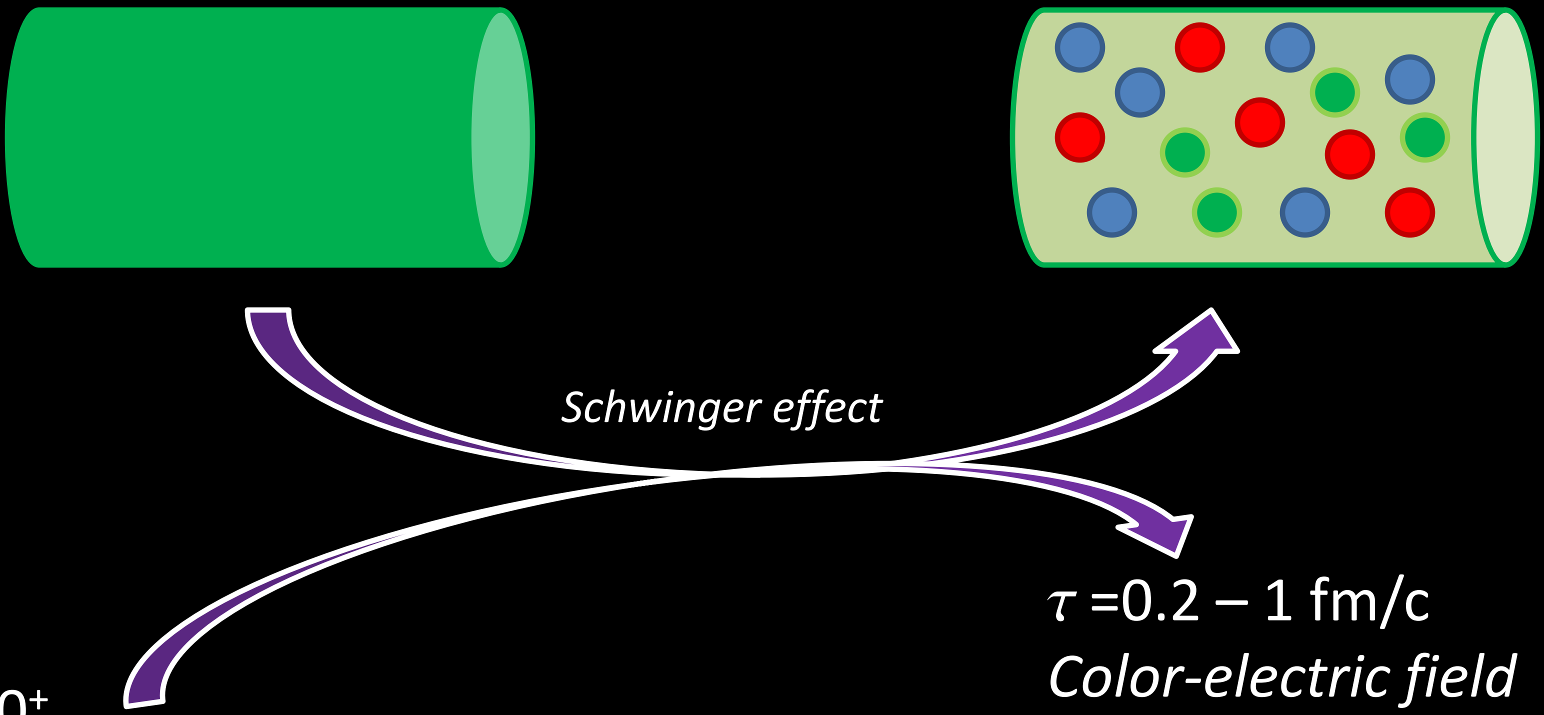
Color-eletric color field decays into quark-antiquark as well as gluon pairs

Abelian Flux Tube Model

Schwinger effect in Chromodynamics

Summary of the dynamics involved

Longitudinal view of a single expanding flux tube



Schwinger effect

$\tau = 0^+$

Strong color-electric field

$\tau = 0.2 - 1$ fm/c

Color-electric field

\+

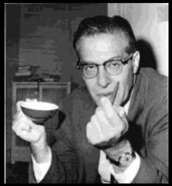
Particle quanta:

quarks and gluons (QGP)

Boltzmann equation and QGP

In order to permit ***particle creation*** from the vacuum we need to add a ***source term*** to the rhs of the Boltzmann equation:

$$\left(p_\mu \partial^\mu + g Q_{jc} F^{\mu\nu} p_\mu \partial_\nu^p\right) f_{jc} = p_0 \frac{\partial}{\partial t} \frac{dN_{jc}}{d^3x\, d^3p} + \mathcal{C}[f]$$



Florkowski and Ryblewski, PRD 88 (2013)

Field interaction

Invariant source term

Invariant source term: change of ***f*** due to particle creation in the volume at ***(x,p).***
IST is implemented stochastically.

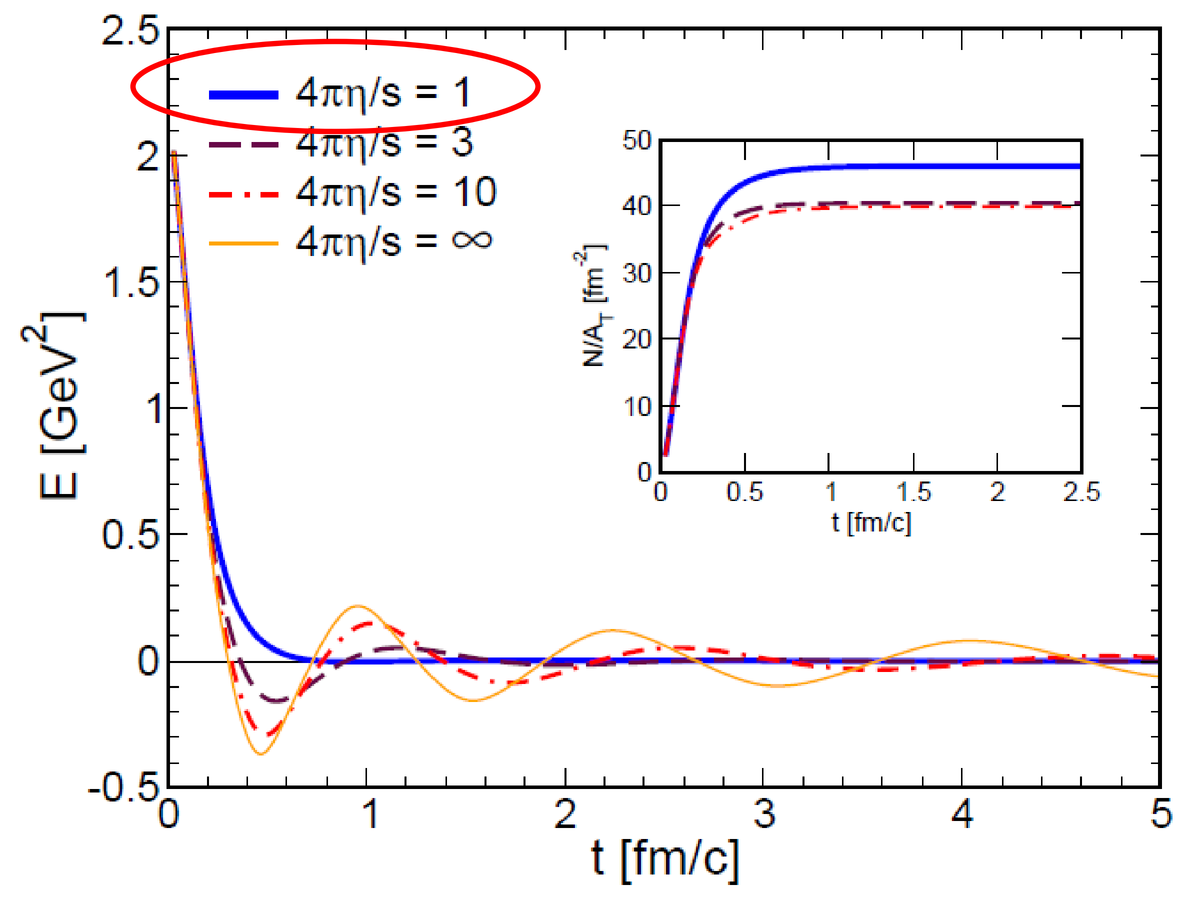
Invariant source term
Field interaction

Link *parton distribution function* and *classical color field* evolutions

We have to solve self-consistently Boltzmann and Maxwell equations

M. R. et al., arXiv:1505.08081

Field decay in 1+1D expansion



ρ	*electric charge density*
j_M	*electric current*
j_D	*polarization current*

Schwinger production of plasma

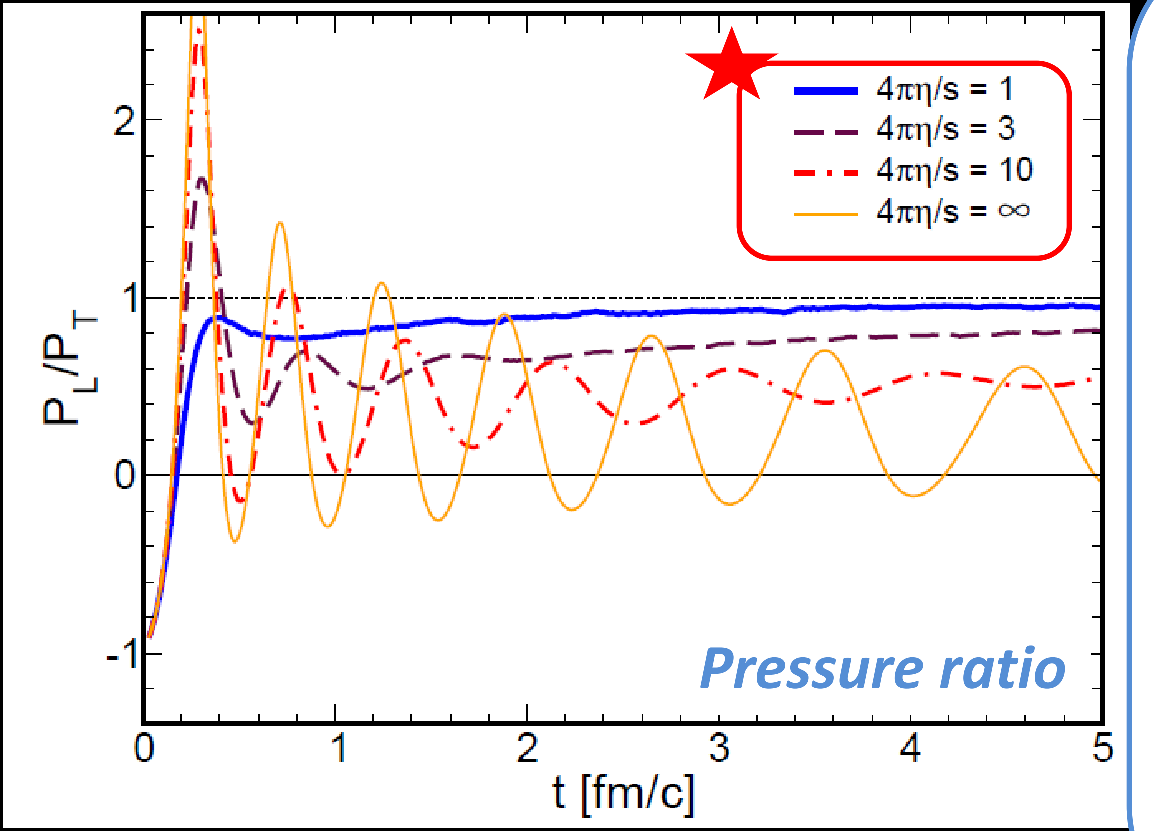
Small η/s
(.) Field decays quickly (power law)

Small η/s implies *large scattering rate*, meaning *efficient randomization* of particles momenta in each cell, thus damping ordered particle flow along the field direction (electric current).

Decay controlled by Schwinger effect

M. R. et al., arXiv:1505.08081

Pressure isotropization



$$T^{\mu\nu}_{field} = \mathrm{diag}\,(\varepsilon, P_T, P_T, P_L)$$
$$\propto \mathrm{diag}\left(\mathcal{E}^2, \mathcal{E}^2, \mathcal{E}^2, -\mathcal{E}^2\right)$$

$$T^{\mu\nu}_{particles} = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(\boldsymbol{x}, \boldsymbol{p})$$

$$T^{\mu\nu} = T^{\mu\nu}_{particles} + T^{\mu\nu}_{field}$$

$$P_L = T_{zz}$$
$$P_T = \frac{T_{xx} + T_{yy}}{2}$$

★

Strong coupling: isotropization time of about 1 fm/c

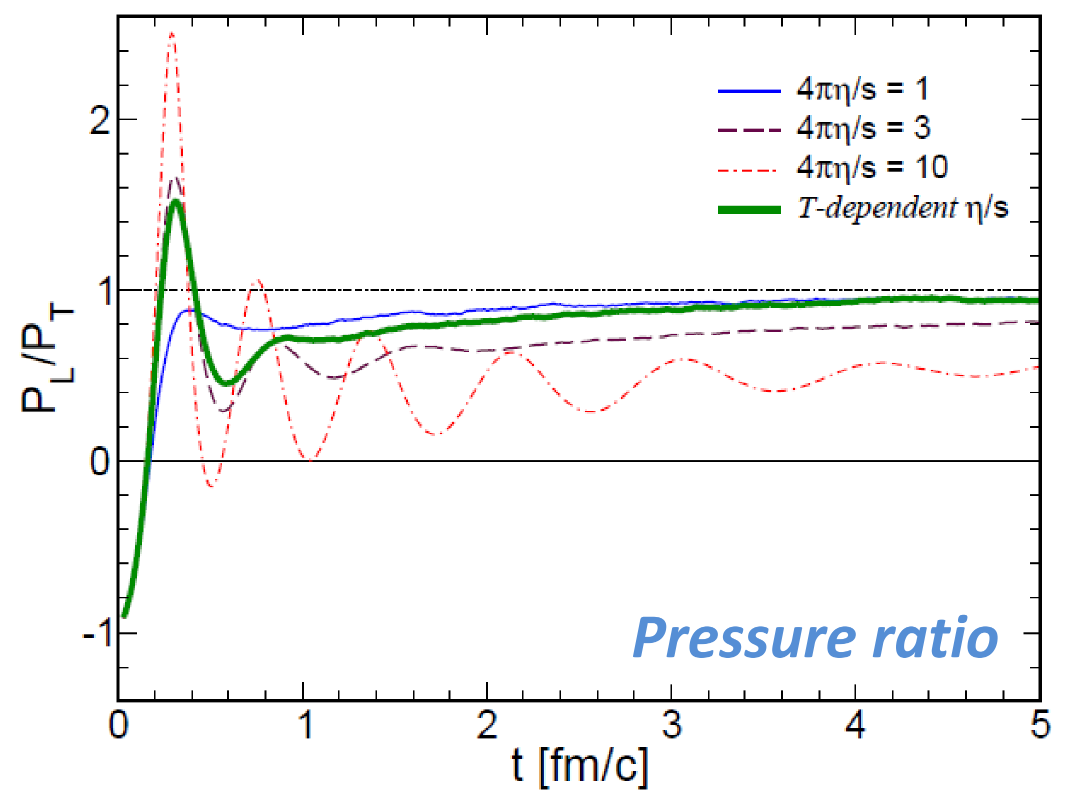
Weak coupling: less efficient isotropization

M. R. et al., *in preparation*

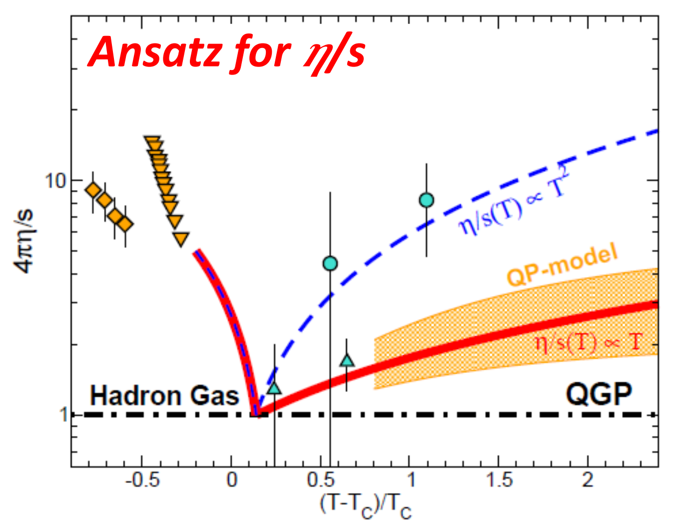
Isotropization for T-dependent η/s

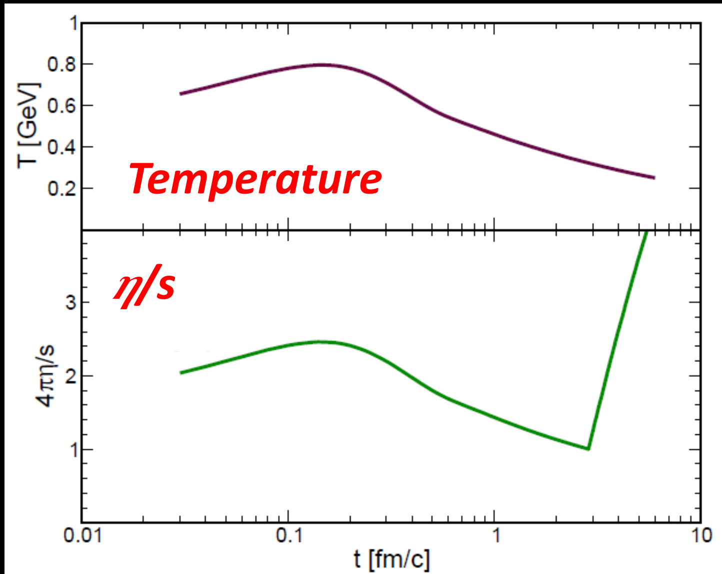
Local temperature in realistic collisions evolves in time:

η/s should be time-dependent



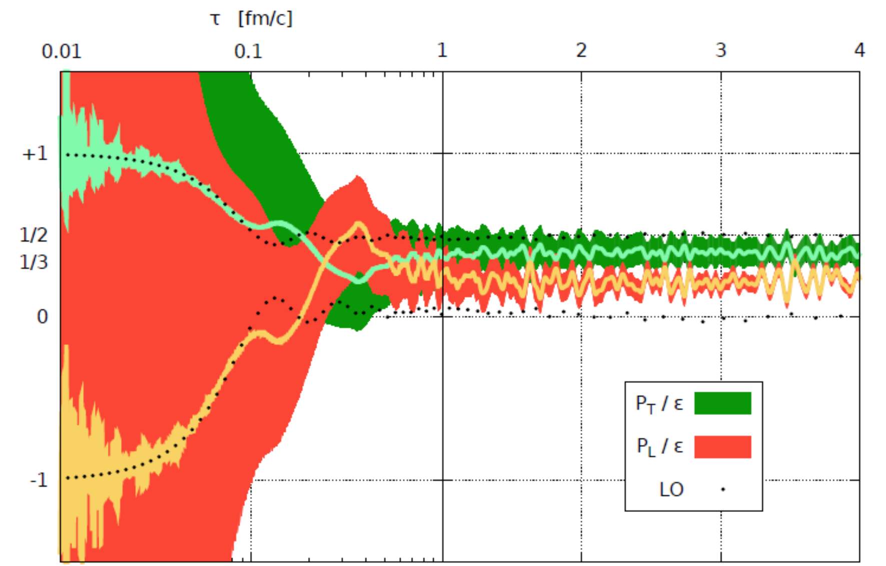
Plumari *et al.*, arXiv:1304.6566





Comparison

Classical Yang-Mills dynamics

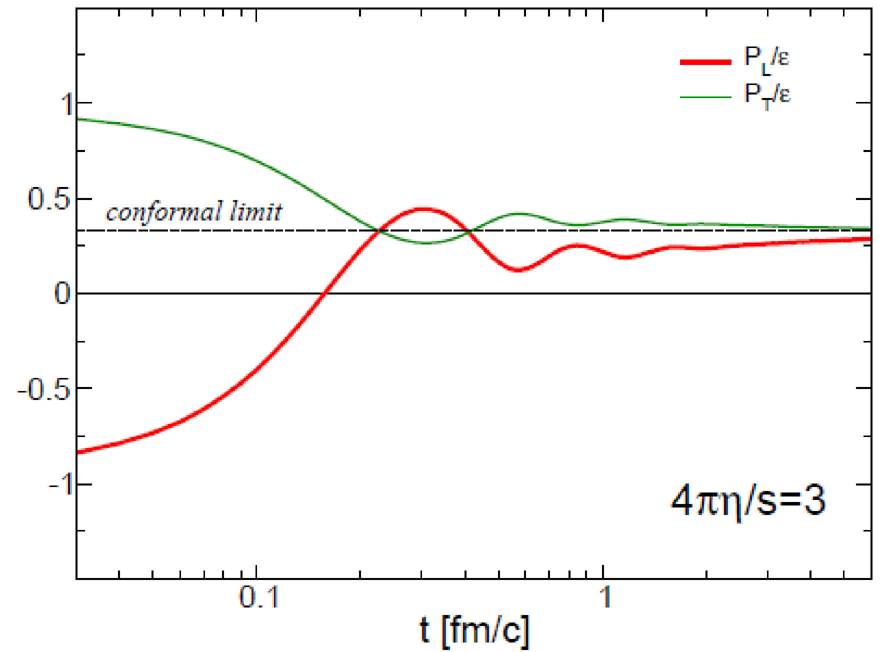


Epelbaum and Gelis, PRL 88 (2013)

(.) Classic Yang-Mills calculation, 3+1D

(.) Quantum fluctuations rather than Schwinger effect

Transport + Abelian fields dynamics



M. R. et al., arXiv:1505.08081

(.) Relativistic Transport+Abelian fields, 1+1D

(.) Schwinger effect to produce particle quanta

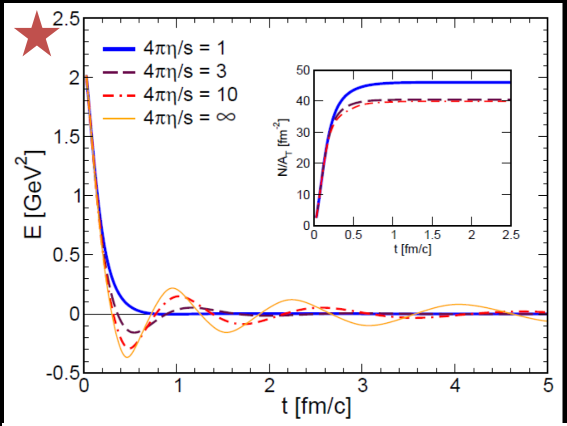
Physical mechanism producing isotropy is different,
nevertheless final result are in semi-quantitative agreement

Supporting viscous hydro assumptions

Standard assumptions in HICs viscous hydro calculations:

*Isotropic, thermalized and chemically equilibrated QGP is formed **within 1 fm/c***

P. Romatschke, **Int.J.Mod.Phys. E19 (2010)**
D. Teaney, e-Print: arXiv:0905.2433 **[nucl-th]**
L. Csernai et al, **Lett.Nuovo Cim. 27 (1980)**
Kolb and Heinz, **In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 634-714**



Our results:

★) *Initial strong color field decays in 0.2-1 fm/c*

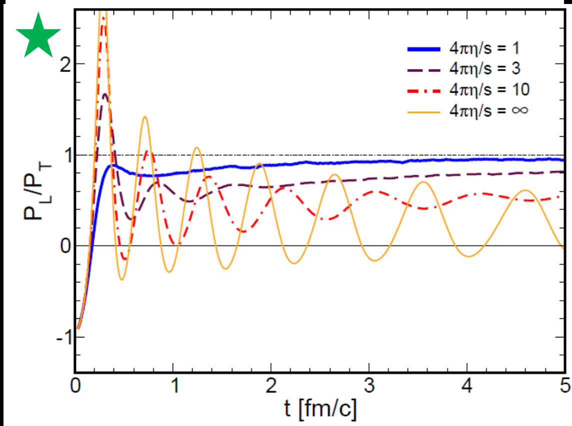
★) *Isotropization and thermalization is achieved within 1 fm/c*

.) *Chemical equilibration achieved within 1 fm/c*

M. R. *et al.*, e-Print: arXiv:1502.04596 **[nucl-th]**

.) *Proper energy density scaling achieved within 1 fm/c*

M. R. *et al.*, e-Print: arXiv:1505.08081 **[hep-ph]**
In agreement with ideal hydro calculations:
Gatoff *et al.*, PRD 36 (1987)



Our results support viscous hydro assumptions:

We obtain, as a result of a calculation, a viscous hydro regime within the appropriate time scale

Conclusions

- ***Relativistic Transport Theory, coupled to a decay mechanism for initial color fields, permits to study early times dynamics of heavy ion collisions.***
- ***Schwinger tunneling*** *allows a* ***fast particle production,*** *typically a small fraction of fm/c.*
- Weakly coupled plasma is characterized by plasma oscillations which are non negligible along the entire evolution of the system.
- ***Strongly coupled plasma*** does not experience important plasma oscillations, rather a ***hydro regime is reached in a very short time***
- Isotropization time is less than 1 fm/c

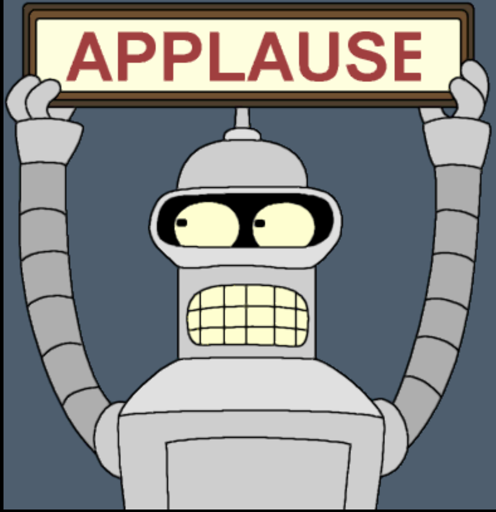
The scenario we obtain for the early stages of heavy ion collision is in agreement with, and dynamically justifies, usual assumptions of viscous hydro about

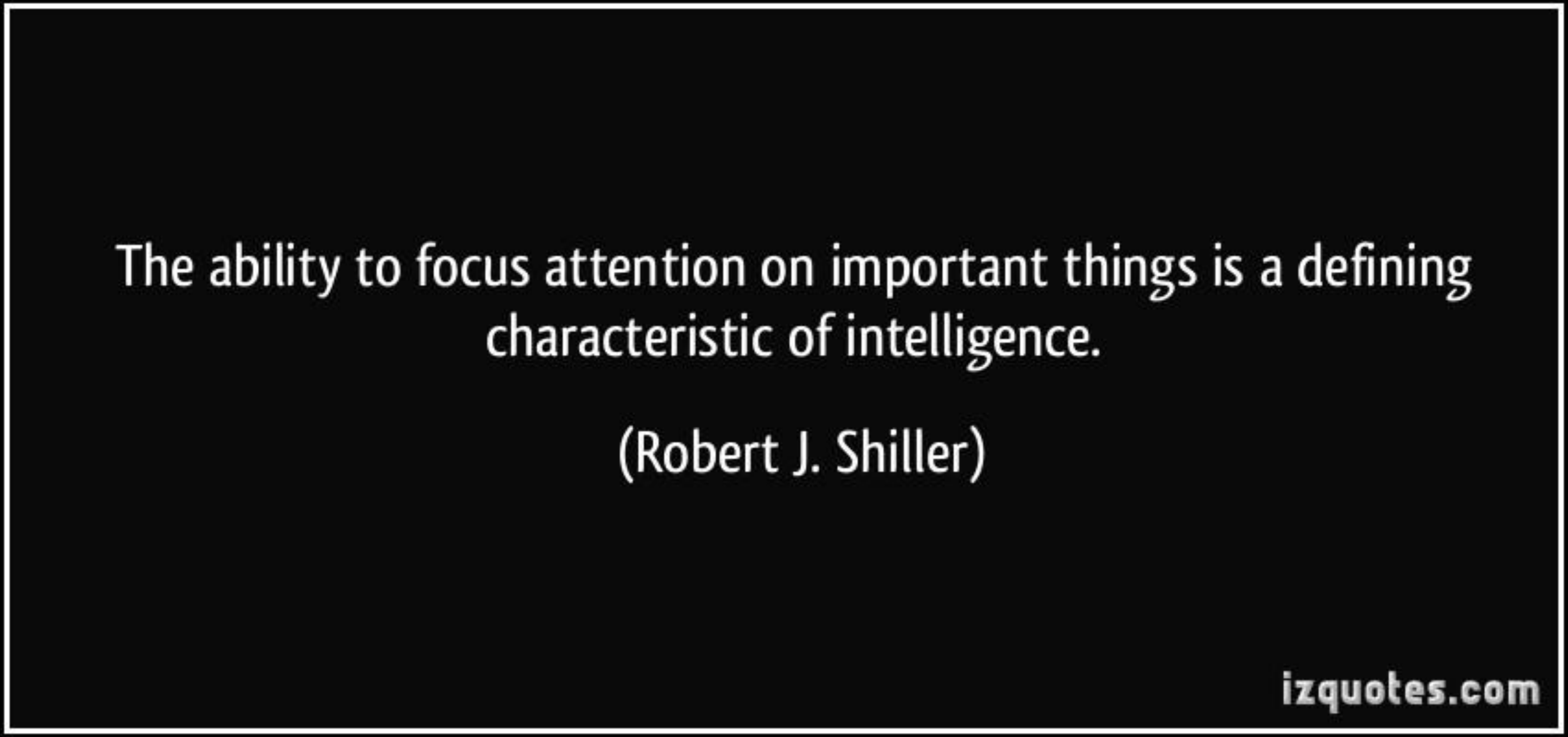
-Isotropization and thermalization
-Chemical equilibration
-QGP time formation

Outlook

- 3+1 dimensional simulations
  - *Isotropization*
  - *Thermalization*
  - *Particle production*
  - *Flows*
- Flux tubes with realistic profiles
- CYM initializations and early time evolution

H. Iida et al., arXiv:1410.7309




The ability to focus attention on important things is a defining characteristic of intelligence.

(Robert J. Shiller)

izquotes.com

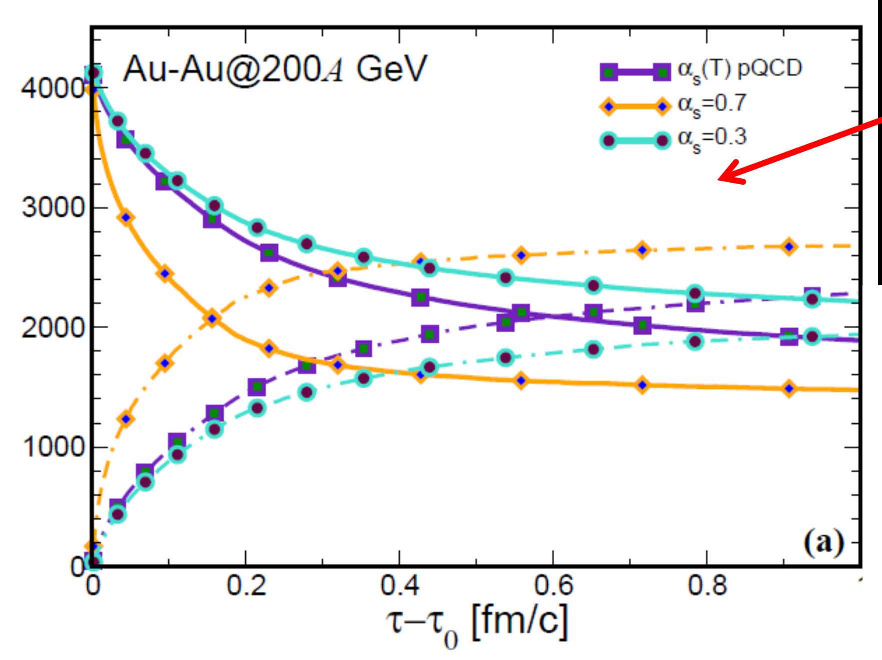
Appendix

APPENDIX

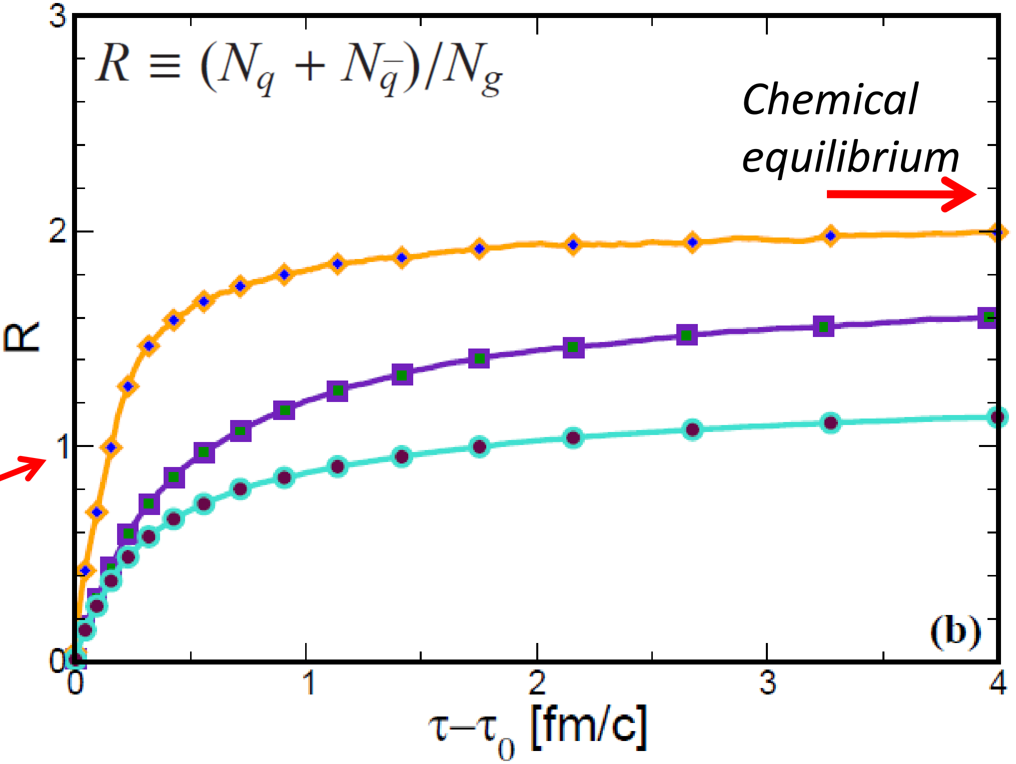
M. R. *et al.*, NPA 941 (2015)
F. Scardina *et al.*, PLB**724** (2013)

Quark production in QGP

Assume no quarks in the initial stage: *how efficient QCD processes are to produce quarks?*



Quark production by QCD inelastic processes is very fast



Chemical equilibrium

Abundant quark production

Pros and cons

(.) Transport theory is appropriate for studying non-equilibrium phenomena.

(.) Within a single, self-consistent theoretical framework we can follow the dynamical evolution of QGP from its early life up to final stages.

(.) It can be easily applied to ***pA*** and ***pp*** collisions.

(.) We can study the effects of the initial dynamics on observables:
  Collective flows
  Rapidity distributions
  Particle spectra

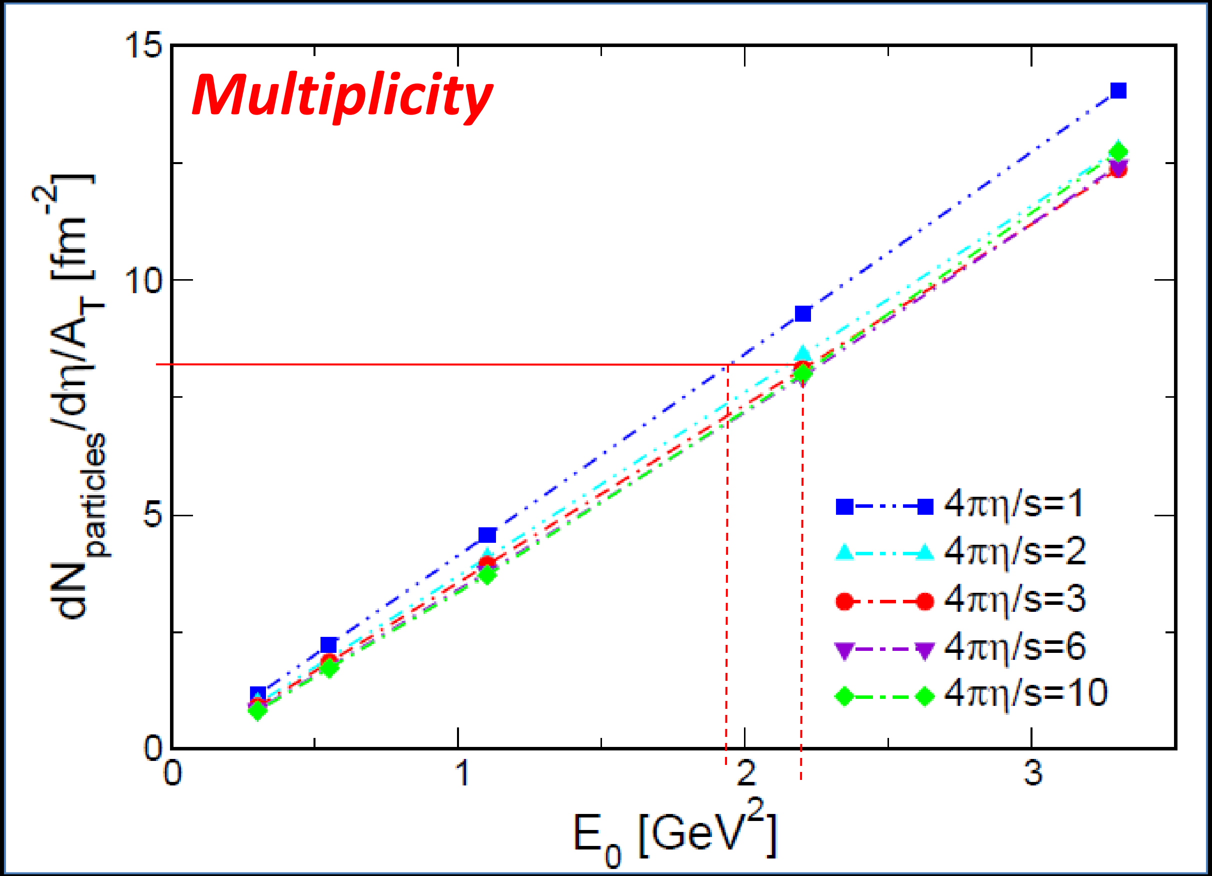
(.) Initial field dynamics ignores the full structure of the glasma flux tubes:
  Color-magnetic fields
  Field fluctuations in rapidity and transverse plane

(.) The model ignores the non abelian interactions in the color field sector.

We have a good starting point at hand, quite under control, which we are improving step by step to obtain a more complete description of early stages.

A rough initial field estimate

Naïve calculation
(rough estimate)



Multiplicity for a RHIC collision, b=2.5 fm:

$$\frac{dN}{dy} = \frac{dN}{d\eta} \approx 1040$$

Transverse area:

$$A_T \approx \pi R^2 \approx \pi (6.5)^2 \approx 137 \text{ fm}^2$$

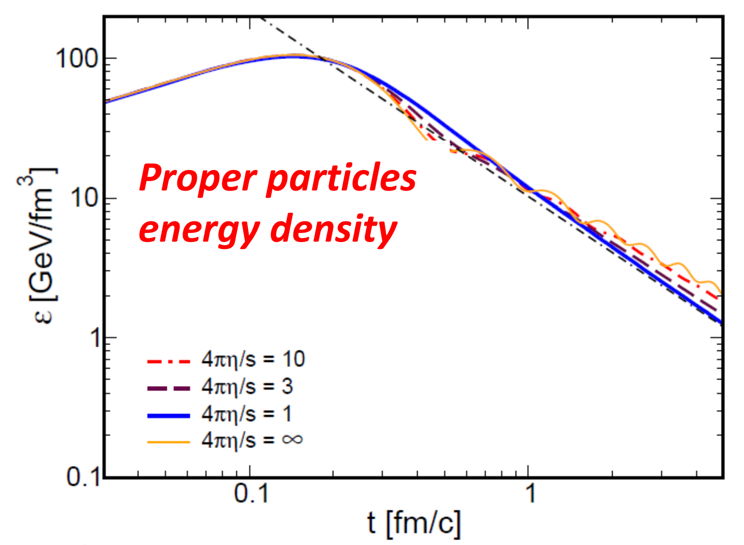
Multiplicity per transverse area:

$$\frac{dN}{A_T d\eta} \approx 8 \text{ fm}^{-2}$$

$$E_0 \approx 1.9 \div 2.2 \text{ GeV}^2$$

Very rough estimate:
it gives the proper order of magnitude,
leaving the exact number determination to a more realistic model of the initial tubes distribution

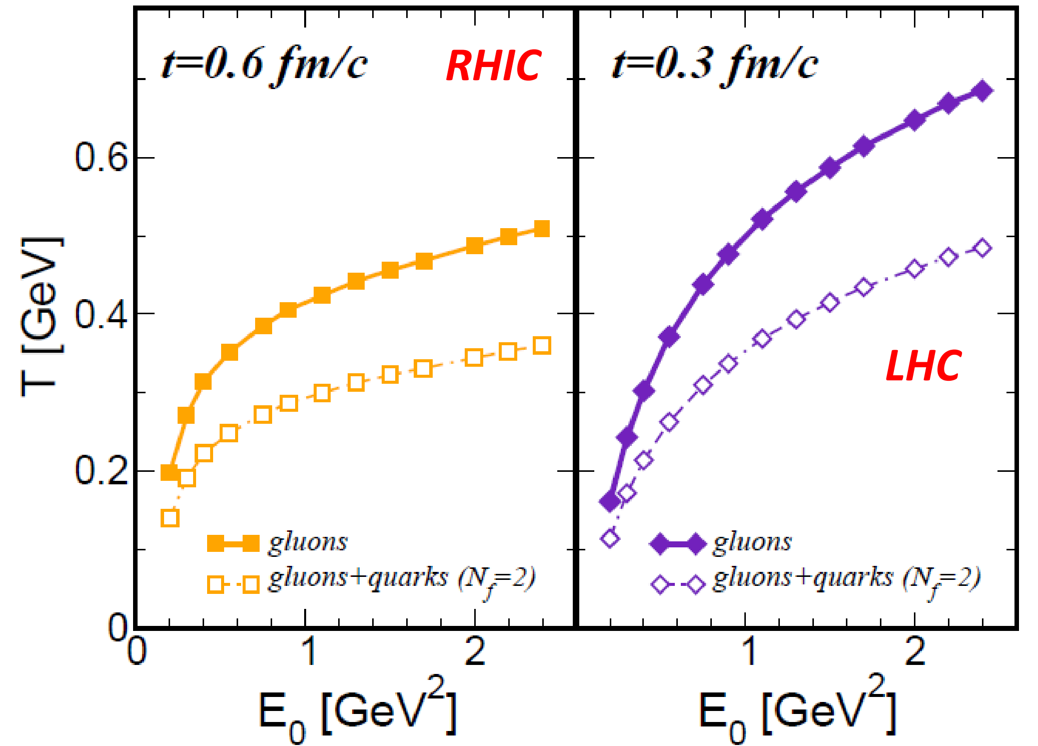
Flux tube evolution: local temperature



Proper particles energy density

$$\varepsilon \propto T^4$$

Temperature estimate



For simulations at RHIC energy:

(.) free streaming up to t=0.6 fm/c

(.) assume a core temperature T=0.34 GeV

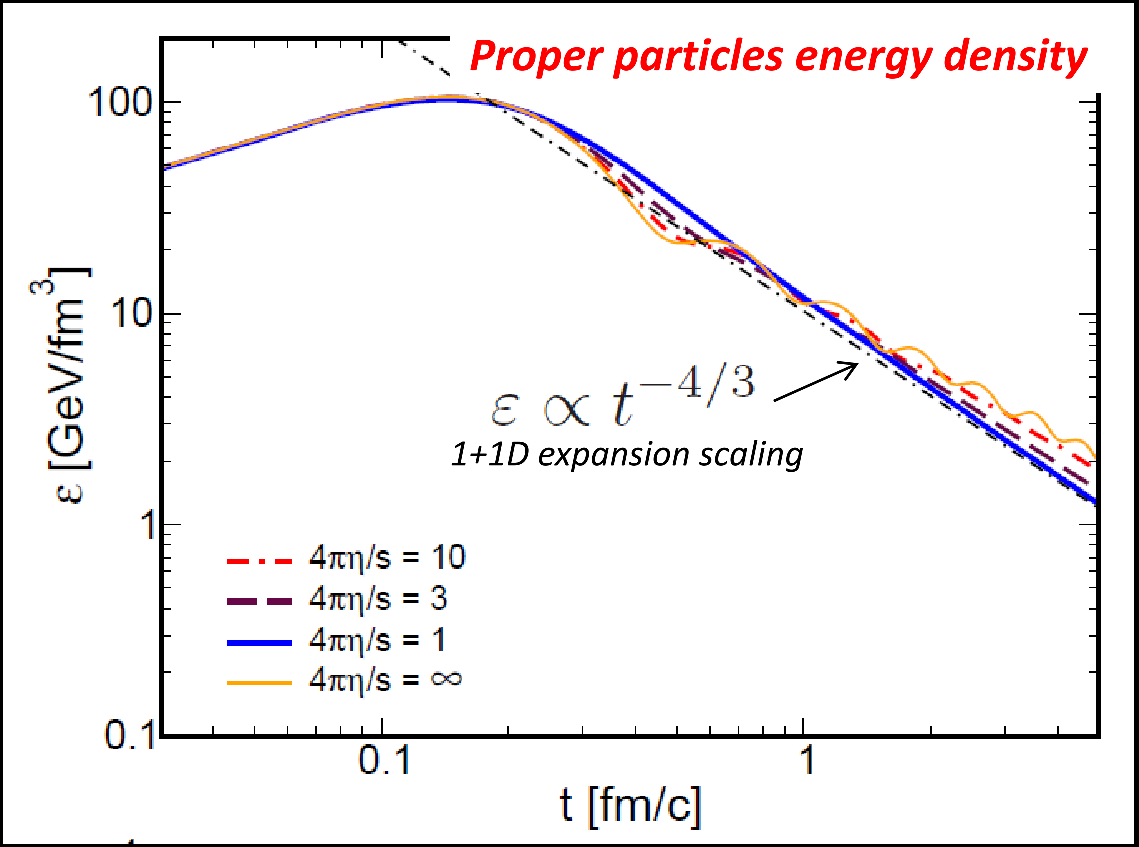
For simulations at LHC energy:

(.) free streaming up to t=0.3 fm/c

(.) assume a core temperature T=0.5 GeV

M. R. et al., arXiv:1505.08081

A hydro regime



Small η/s
After a short transient, the hydro regime begins:

$$\varepsilon \propto t^{-4/3}$$

Large η/s
After a short transient:
(.) dissipation keeps the system temperature higher;
(.) oscillations arising from the field superimpose to power law decay

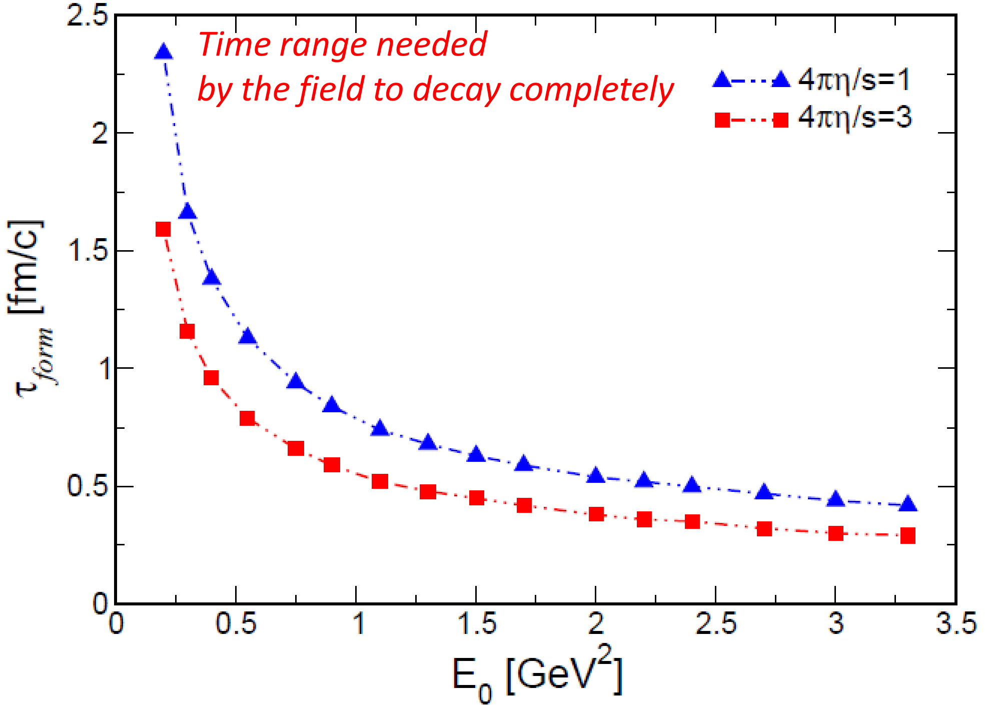
In agreement with *ideal hydro calculations*:
Gatoff *et al.*, PRD 36 (1987)

This is quite interesting because it proves that transport theory is capable to describe, even in conditions of quite strong coupling (small η/s), the evolution of physical quantities in agreement with calculations based on hydrodynamics, once the microscopic cross section is put aside in favor of fixing η/s.

M. R. et al., arXiv:1505.08081

Particles formation for 1+1D expansion

Proper time for conversion to particles



Field evolution satisfies:

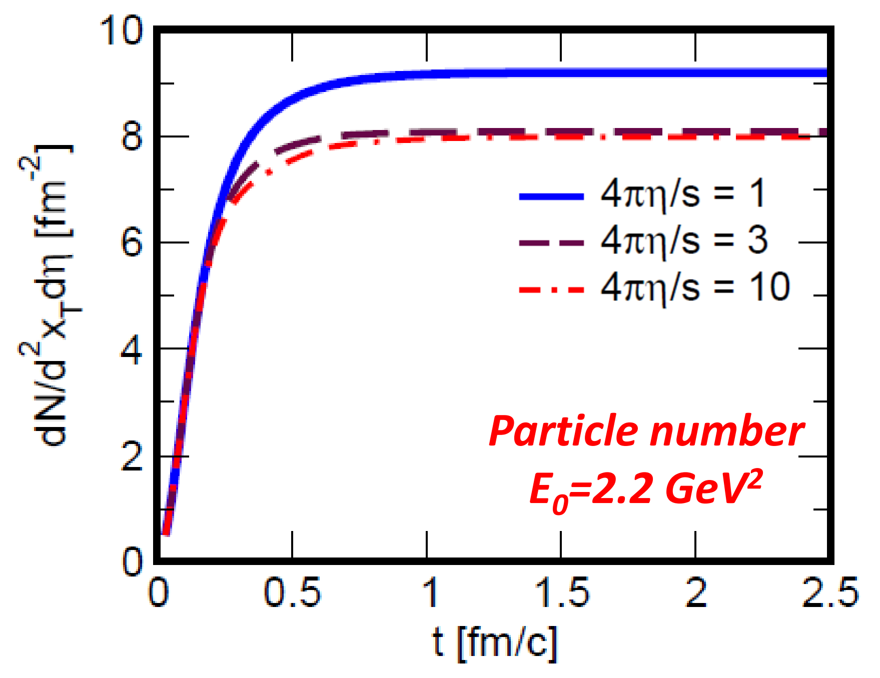
$$\frac{d}{dt}\left(\frac{\boldsymbol{E}^2}{2}\right) = -\boldsymbol{j}\cdot\boldsymbol{E}$$

hence, smaller field implies slower decay.

Unless initial field is very small,

formation time is less than 1 fm/c

Typical fireball lifetime: 5-10 fm/c



Particle number

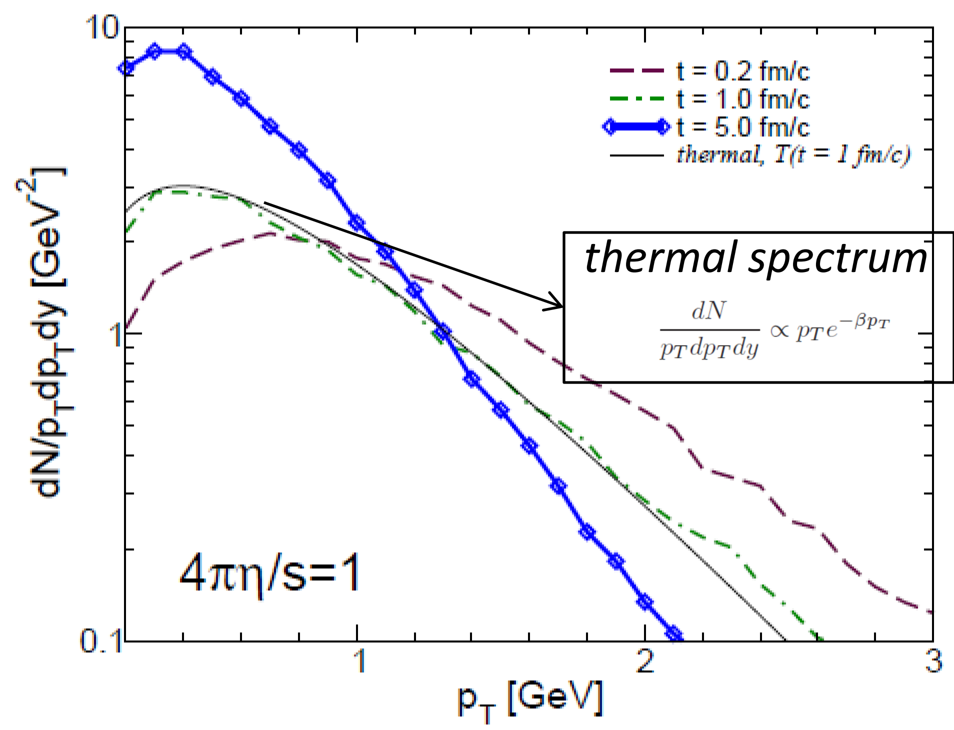
E_0=2.2 GeV²

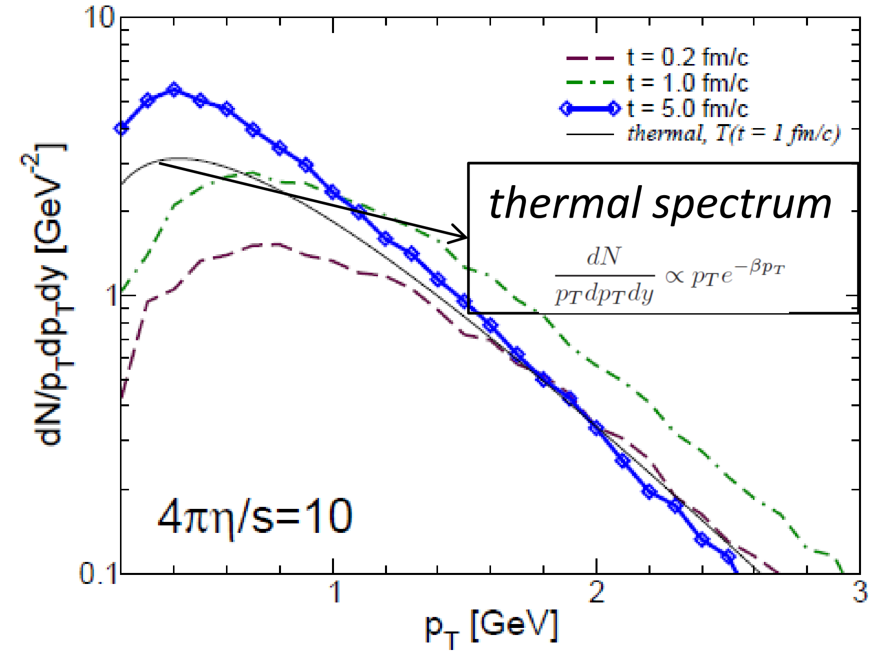
M. R. et al., arXiv:1505.08081

Thermalization

Comparison of *produced particles spectra* with *thermal spectra* at the *same energy density*.

Small viscosity:
Very fast thermalization $\tau < 1$ fm/c

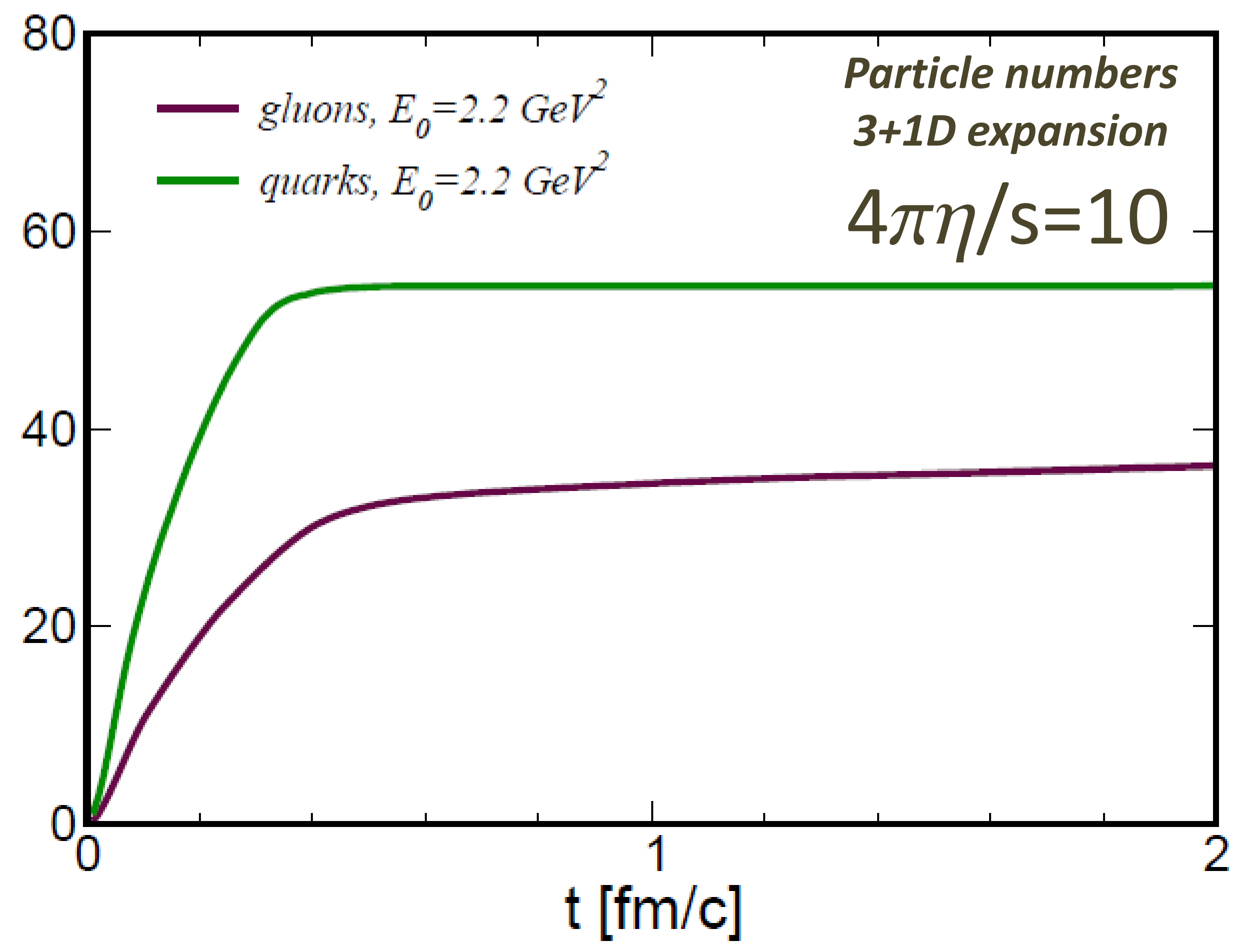




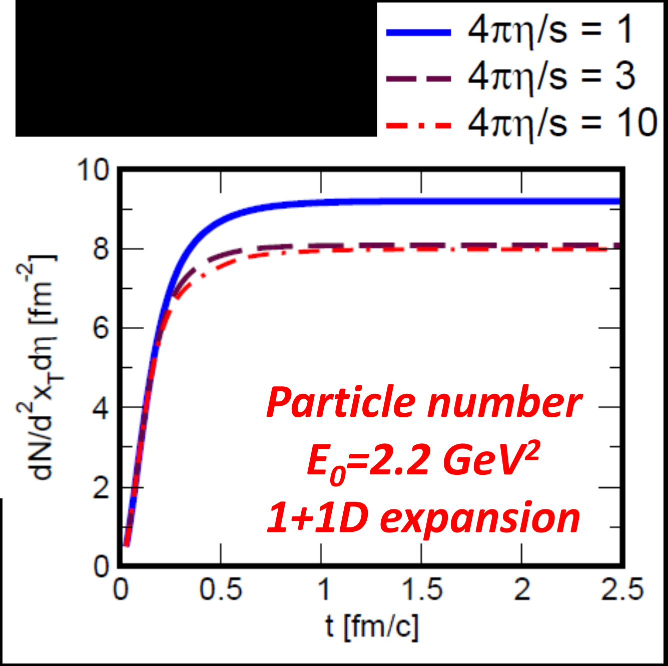
Large viscosity:
Particle spectra is quite different from the thermal spectrum with the same energy density

M. R. et al., *in preparation*

Plasma production for 3+1D expansion



An aside:
abundant quarks are produced by the Schwinger effect



Plasma production occurs within 0.3-1 fm/c