中国科学院大学
University of Chinese Academy of Sciences

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# (Towards) Photon Production in the Early Stage of uRHICs

*Dr. Marco Ruggieri*
University of Chinese Academy of Sciences, Beijing, China
*marco.ruggieri@ucas.ac.cn*

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

# Plan of the talk

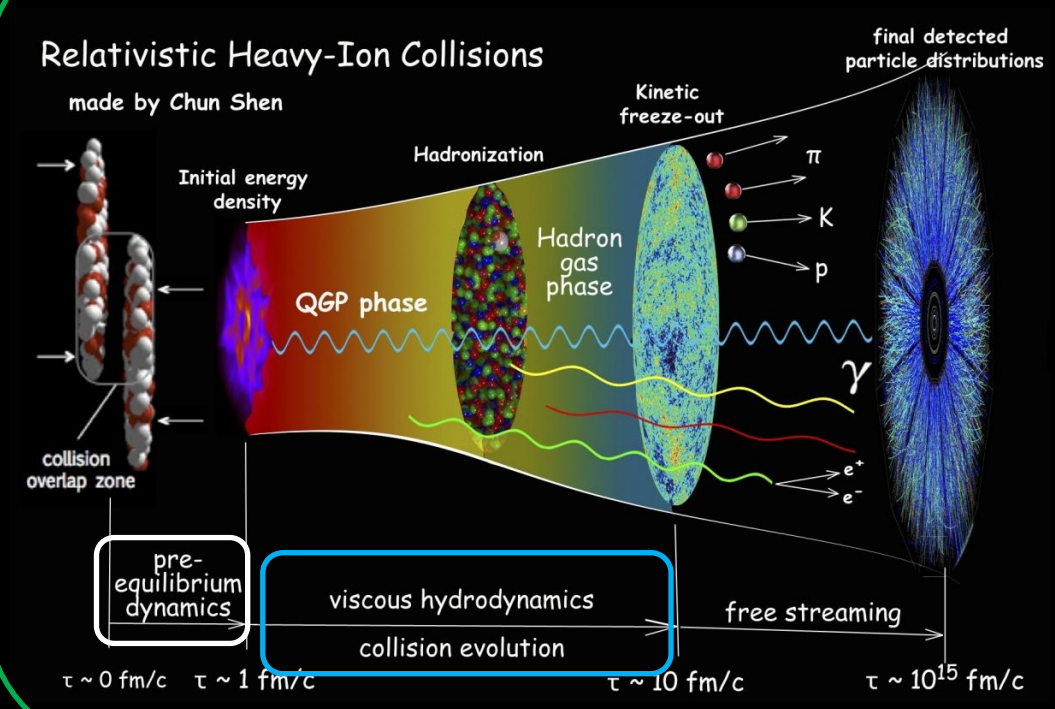
- Statement of the problem
- Abelian Flux Tubes model for early stages
- Relativistic Transport Theory for HICs *See also Greco's talk*
- ***Results***
  - ❖*Initial fields decay*
  - ❖*Timescale for QGP production*
  - ❖***Photon production in the early stage of HICs***
- Conclusions

# Direct photons in HICs

Photons are produced during *all the lifetime* of the fireball produced in HICs.

Photons are good candidate for representing:

- *Thermometer of QGP* [Heinz *et al.*, PRL]
- *Clock of QGP* [Liu *et al.*, PRC79 (2009), Liu and Liu, PRC89 (2014)]




## Some sources

*Pre-equilibrium stage*

- Prompt
- ***Pre-eq parton scattering***

*Viscous qgp+hadron phase evolution*

- ***Thermal QGP***
- Thermal hadrons

*see also Moritz Greif's talk*
*Jean F. Paquet's talk*


# Direct photons in HICs

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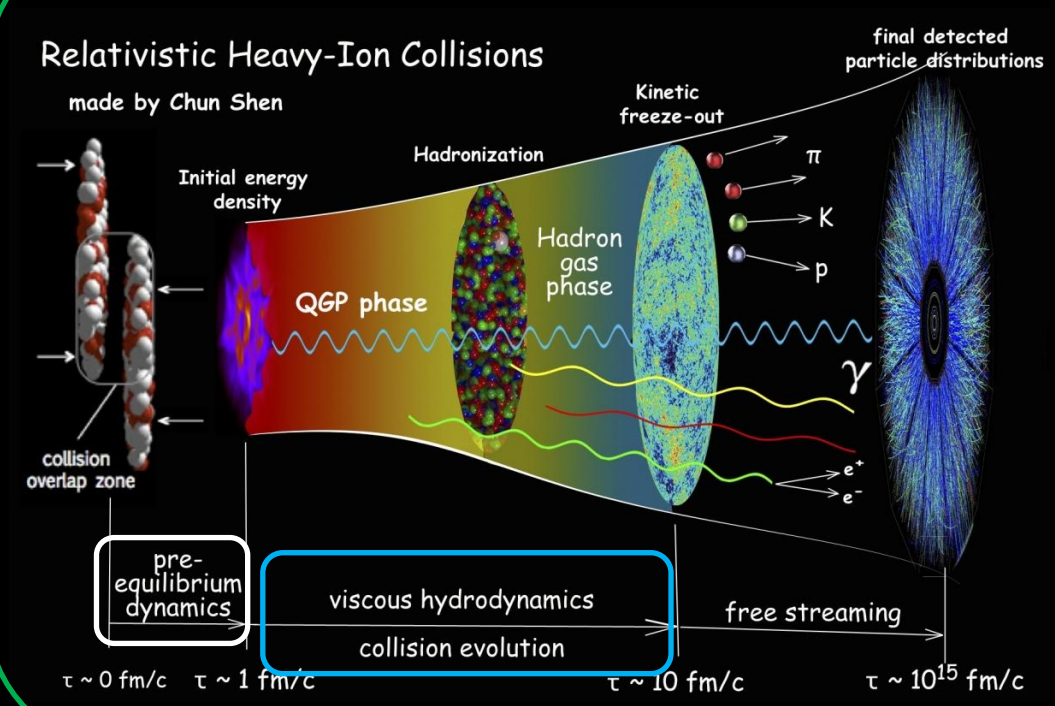



## Our sources

- ***Pre-eq photons***
  Partons arising from the initial classical color fields

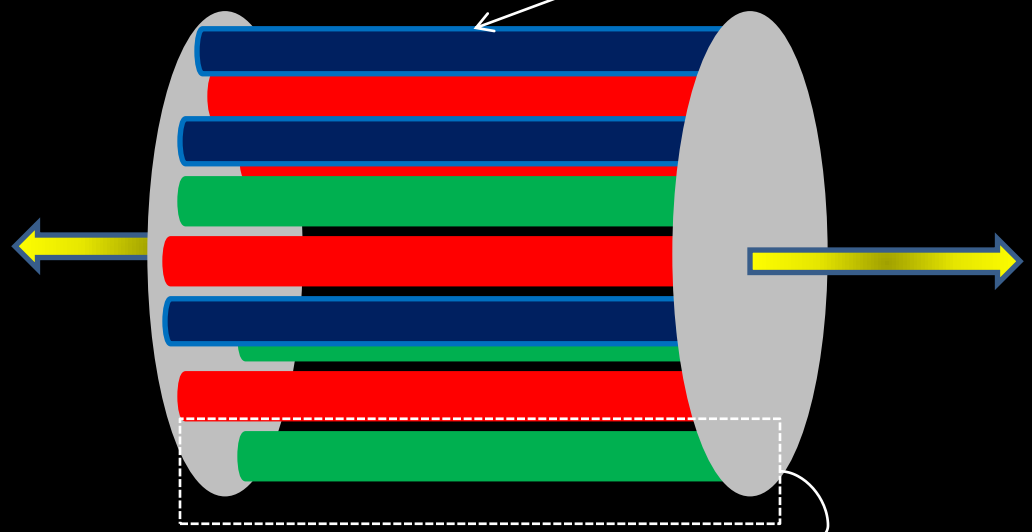
- ***Thermal QGP photons***
  Produced during the thermalized QGP phase

Florkowski and Ryblewski, PRD 88 (2013)

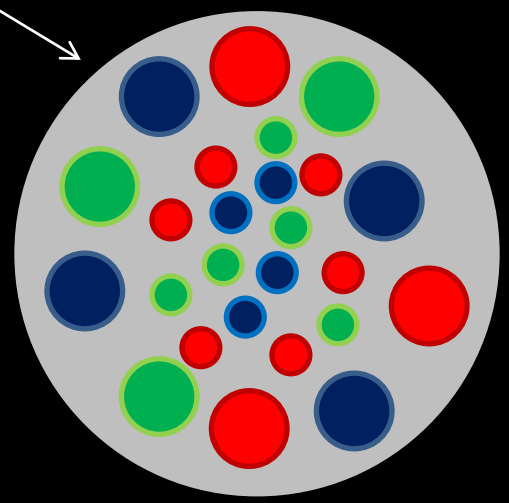
# Abelian flux tube model

*Color flux tubes*

*Longitudinal view*



*Transverse plane view*



Focus on a single flux tube:

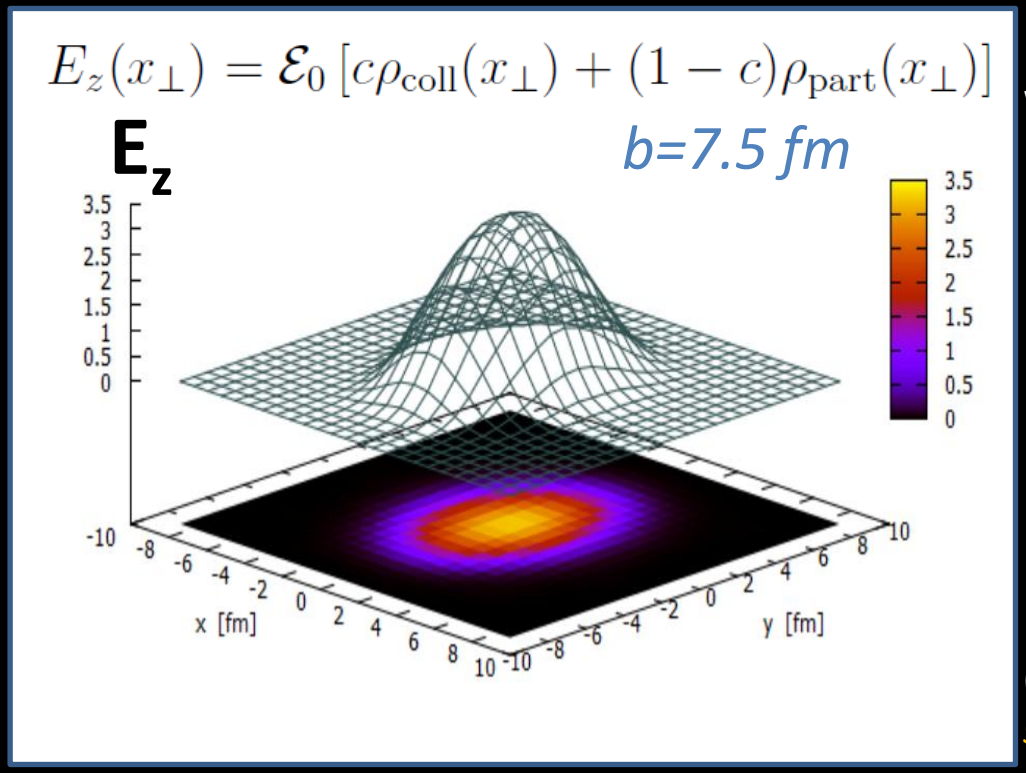
(.) neglect magnetic part of Glasma fields;
(.) assume ***chromoelectric fields*** evolve as ***classical abelian fields***;
(.) initial field is ***longitudinal:*** $E_x(t=0) = E_y(t=0) = 0$
(.) assume ***Schwinger effect*** takes place:
*Color-eletric field decays into quark-antiquark as well as gluon pairs*

***Abelian Flux Tube Model***

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

# The initial condition

*Initial chromo-electric field: <u>smooth in transverse plane</u>*




***What we do***

We prepare a fireball such that:

- ❖Has some classical color field dynamics
- ❖Matches MCGlauber fireball at t=0.6 fm/c:
  - ▪*Eccentricity*
  - ▪*Multiplicity*
- ❖Has a pre-equil. evolution from $t=0^+$

***What we do not***

Prepare a more realistic initial condition (IP-Glasma, Schenke *et al.* 2013 *see also Raju Venugopalan's talk*)

*Although a bit far from Glasma, picture arising agrees qualitatively (and to some extent quantitatively) with results obtained from Glasma+CYM when phsyical quantities are computed.*

Florkowski and Ryblewski, PRD 88 (2013)
M. R. *et al.*, PRC 92 (2015)

*See also Greco's talk*

# Boltzmann equation for QGP and fields

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

$$\left(p_\mu \partial^\mu + gQ F^{\mu\nu} p_\mu \partial^p_\nu\right) f = \mathcal{C}[f]$$

***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***).
*Responsible for deviations from ideal hydro (non vanishing $\eta/s$).*

# Boltzmann equation for QGP and fields

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

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

Florkowski and Ryblewski, PRD 88 (2013)
M. R. *et al.*, PRC 92 (2015)

***Field interaction***

***Invariant source term***

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

***Invariant source term***
***Field interaction*** } Link *parton distribution function* and *classical color field* evolutions

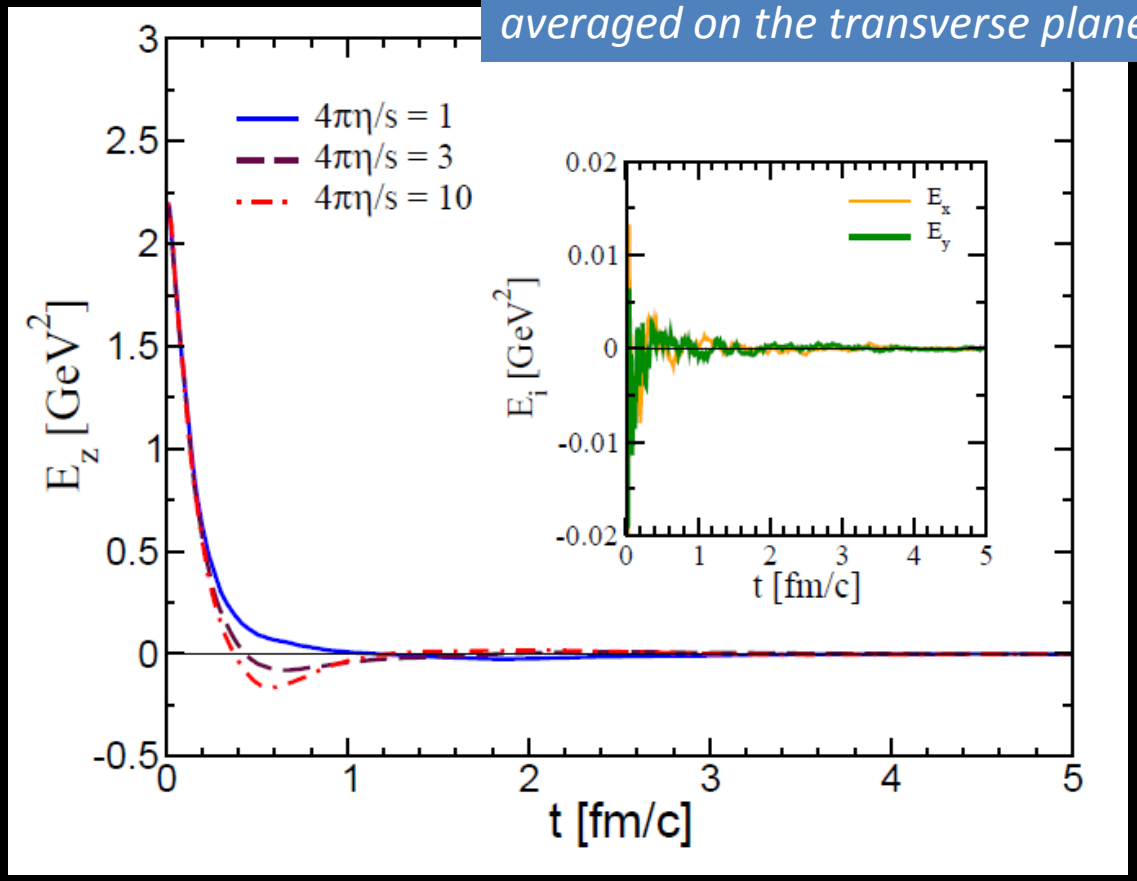
*We have to solve self-consistently Boltzmann and field equations*

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

# From field to QGP

***3+1D***

*Fields at midrapidity averaged on the transverse plane*

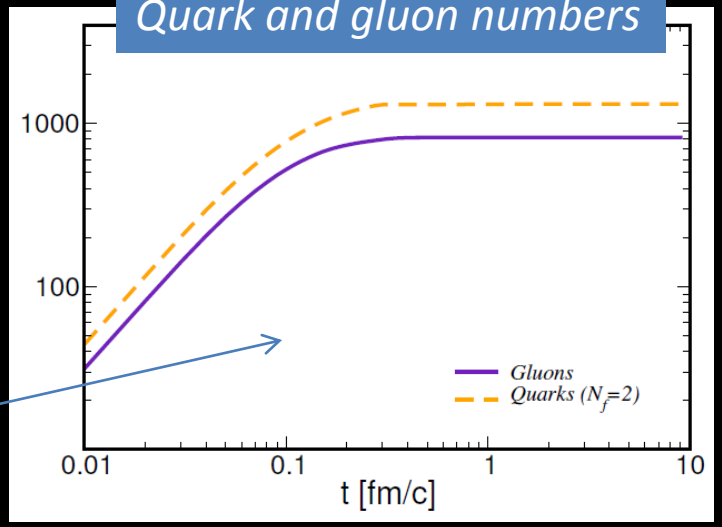



Decay times about 0.4 fm/c

Florkowski and Ryblewski, PRD 88 (2013)
M. R. *et al.*, PRC 92 (2015)

*Field decay timescale sets qgp formation time:*

*Quark and gluon numbers*




Timescale and quark abundance in agreement with:
Lappi *et al.*, PRL96 (2006)
Scardina *et al.*, PLB 724 (2013)
M. R. *et al.*, NPA 941 (2015)

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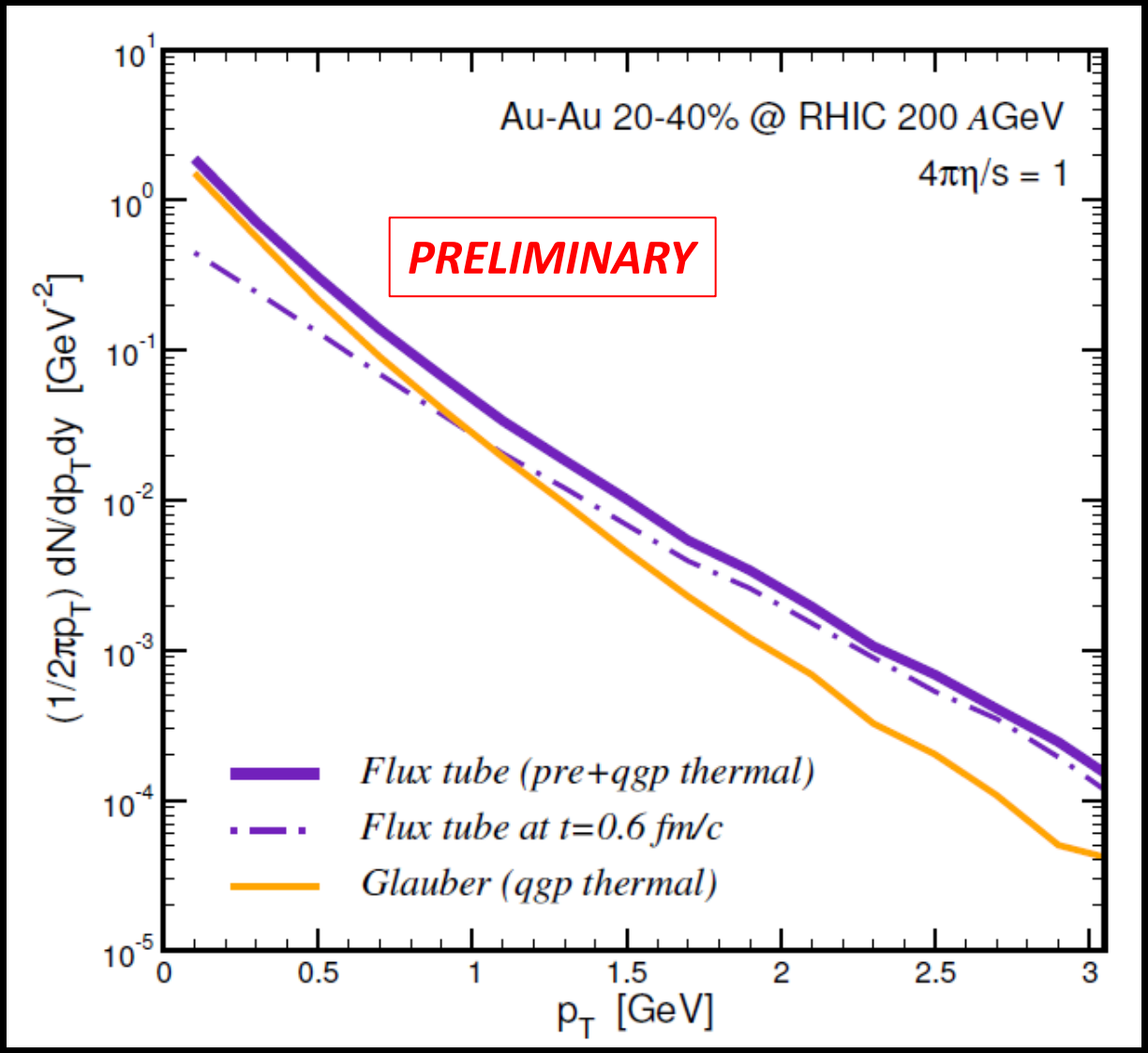
# Partonic photon spectra: contributions



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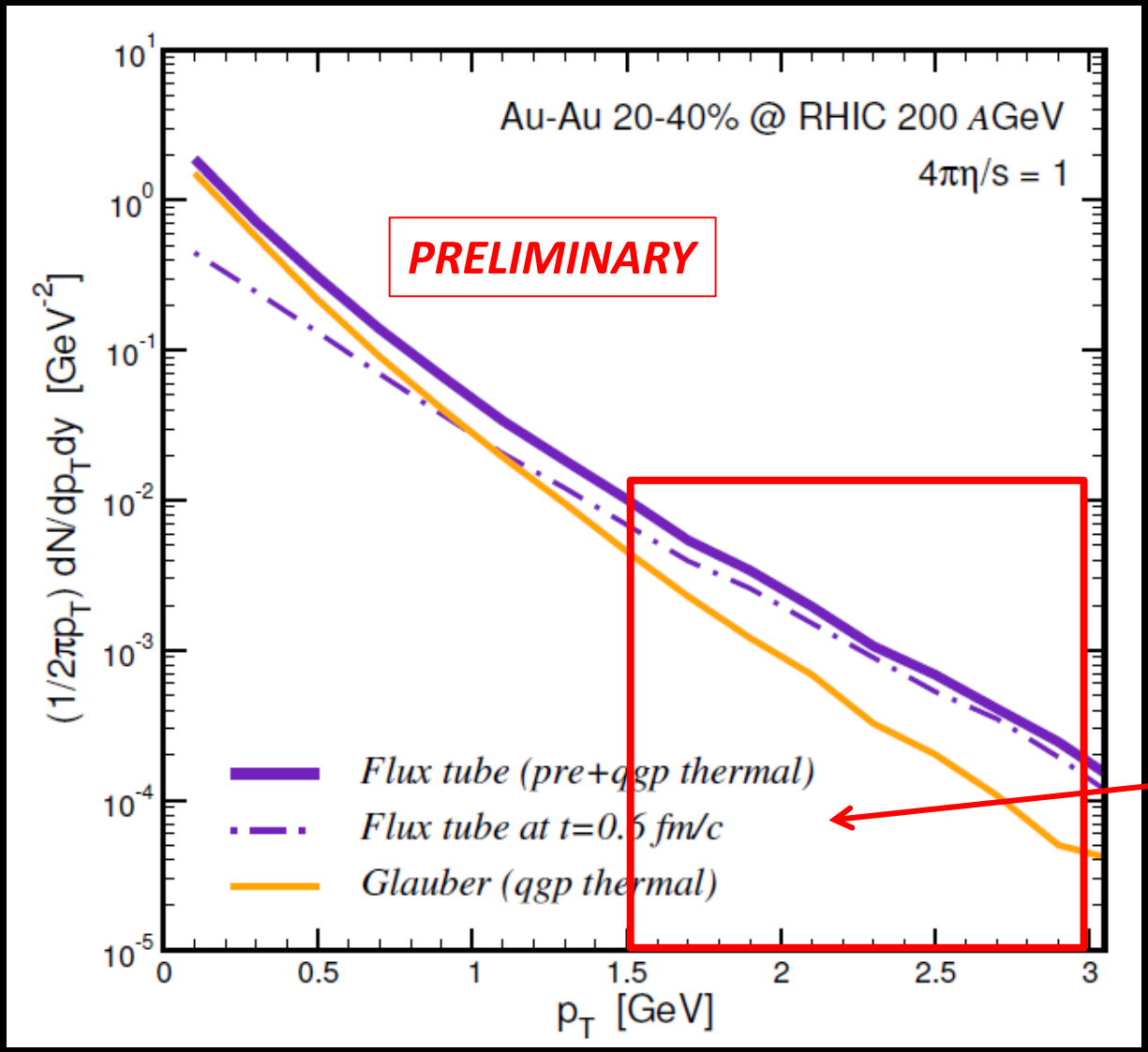


***Main contribution of pre-eq***

$p_T \geq 1.5$ GeV

giving a result *at least*:
2 x thermal qgp
20 x hadron thermal gas

Produced by a medium with

$$\langle p_T^2 \rangle \propto gE$$
$$\approx (2-3\ \mathrm{GeV})^2$$

but missing in the Th-QGP

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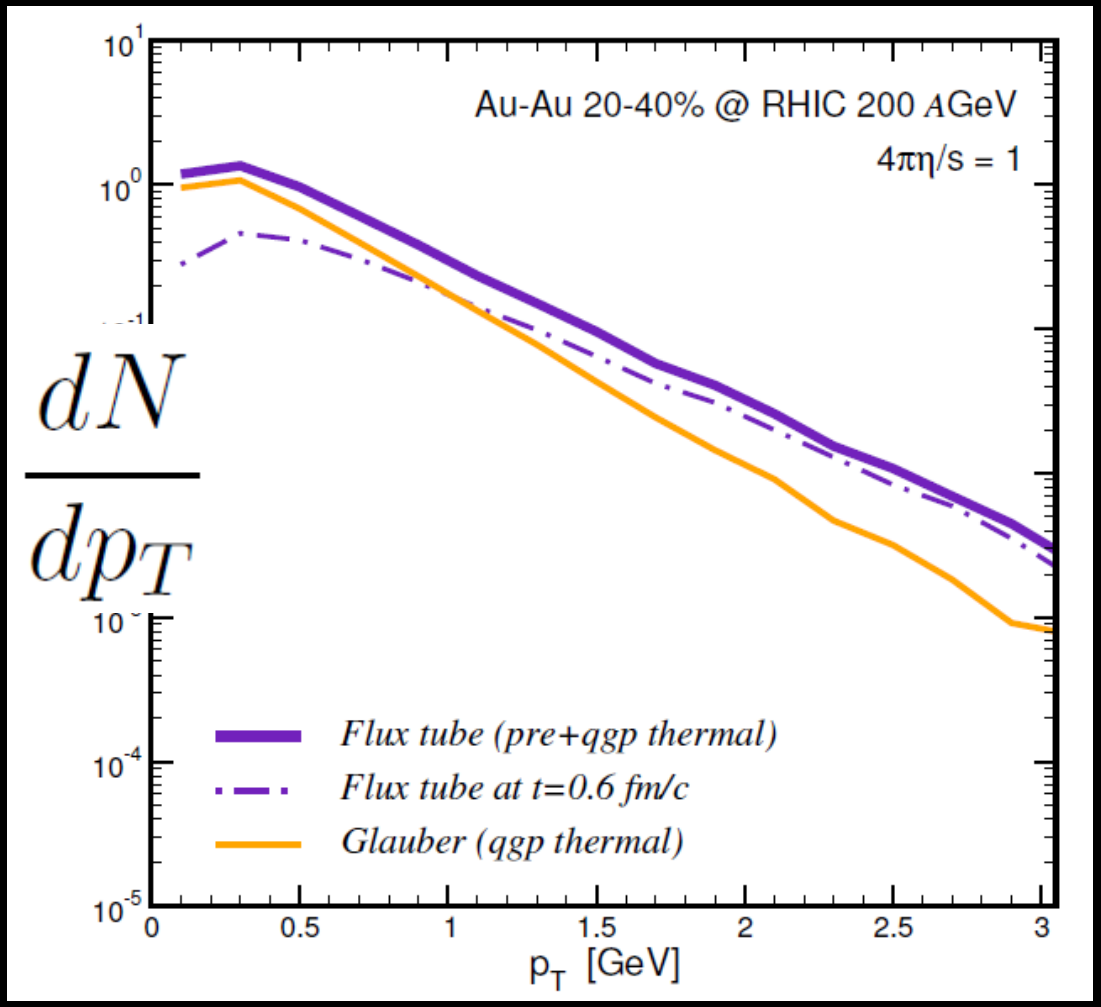
# Partonic photons from pre-eq stage



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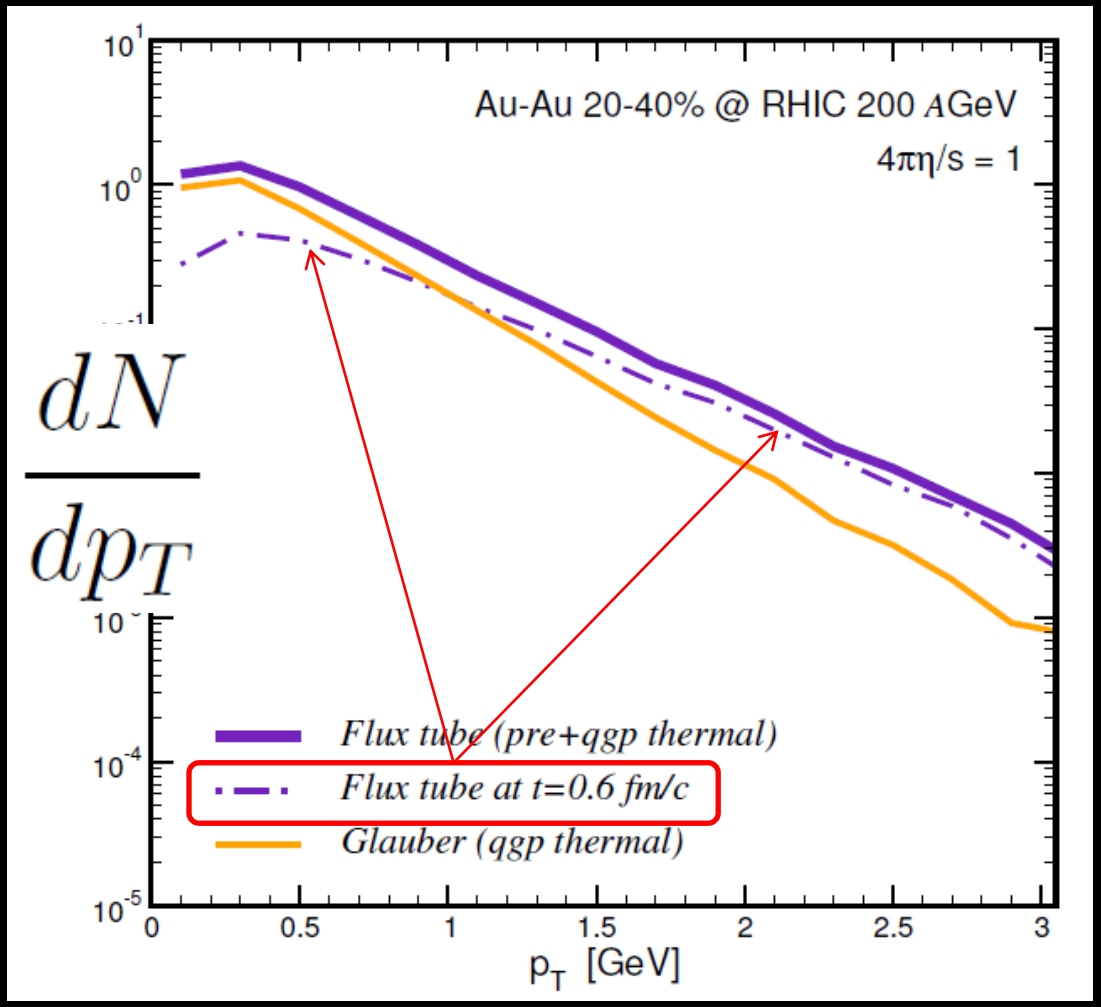
# Partonic photons from pre-eq stage




About **35%** of partonic photons is produced in the first 0.6 fm/c

Typical lifetime of RHIC fireball: approx 5-6 fm/c

In ≈ one/tenth of fireball lifetime, partons produce ≈ 1/3 of the photons they can produce in the full lifetime.

*but*

less than the ones produced assuming $T \propto \tau^{-1/3}$

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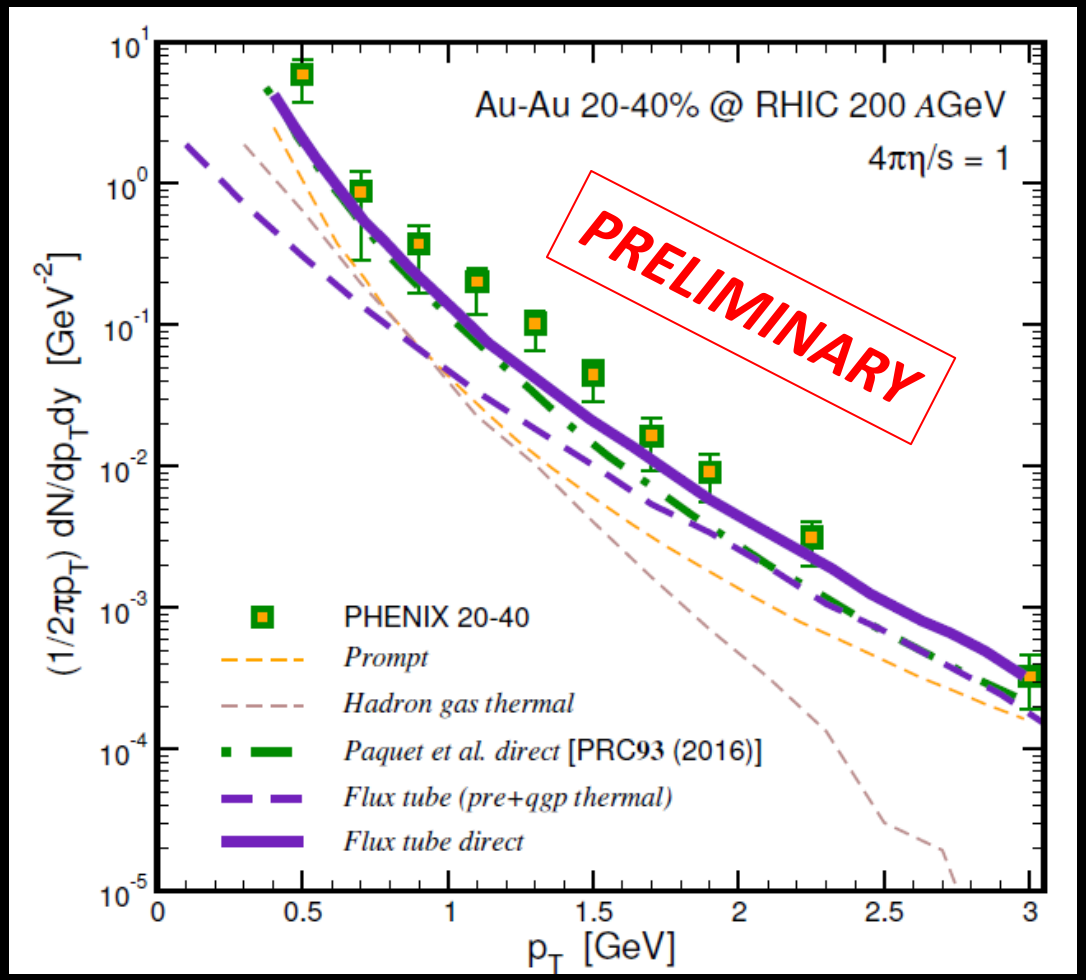
# Direct photon spectra

We can check how the pre-eq contribution changes photon spectrum:




***Contributions added***

1) *Prompt photons*
from Paquet *et al.* [PRC93 (2016)]

2) *Hadrons thermal*
from Paquet *et al.* by a subtraction:
*Paquet's thermal – our Glauber qgp*

***The message***

Photons from pre-eq:

- Signature in 1.5 GeV < $p_T$ < 3 GeV
- *Might be important to understand data in the intermediate $p_T$ region*

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

# Direct photon spectra

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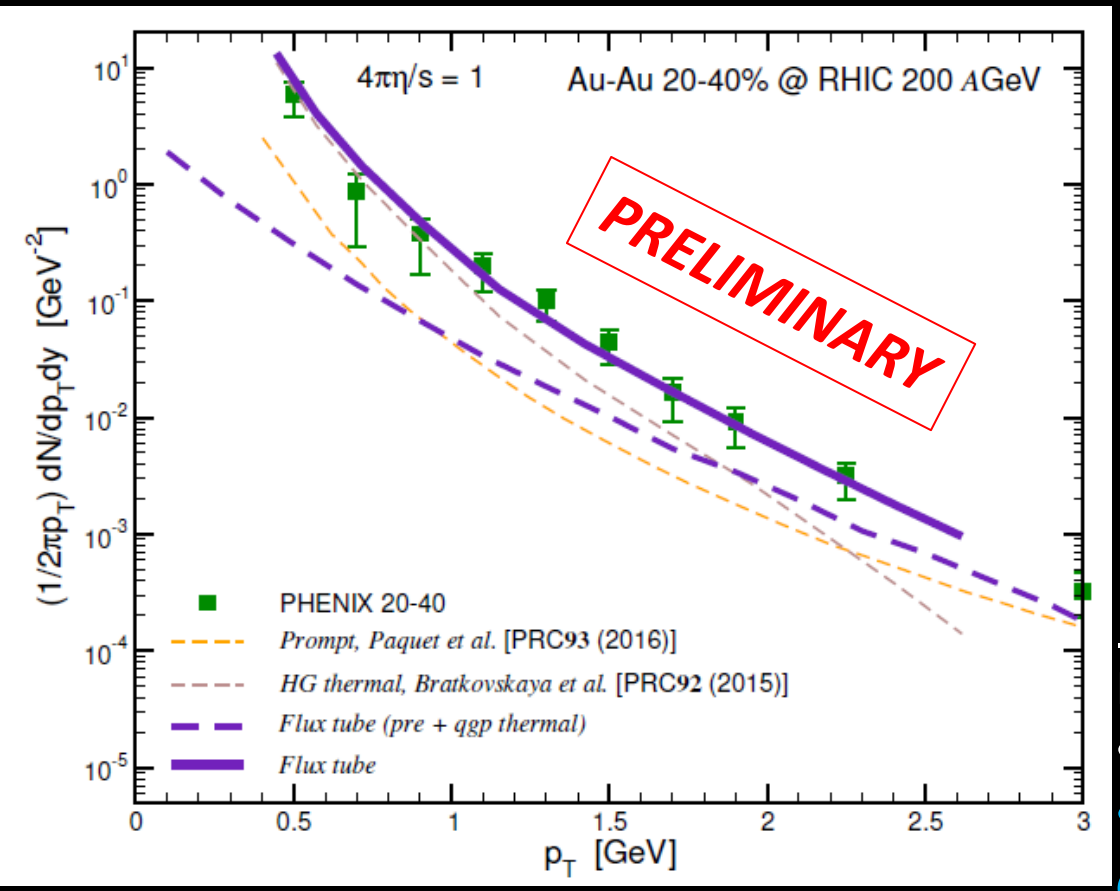



***Contributions added***

1) *Prompt photons*
from Paquet *et al.* [PRC93 (2016)]

2) *Hadrons thermal*
from E. Bratkovskaya *et al.* [PRC92 (2015)]

***The message***

Photons from pre-eq:

- Signature in 1.5 GeV < $p_T$ < 3 GeV
- *Might be important to understand data in the intermediate $p_T$ region*

# Conclusions

- ***Relativistic Transport Theory,*** coupled to a ***decay mechanism for initial color fields,*** permits to study early time dynamics of heavy ion collisions.
- ***Schwinger tunneling*** *allows a* ***fast QGP production,*** *typically a small fraction of fm/c.*

# Conclusions

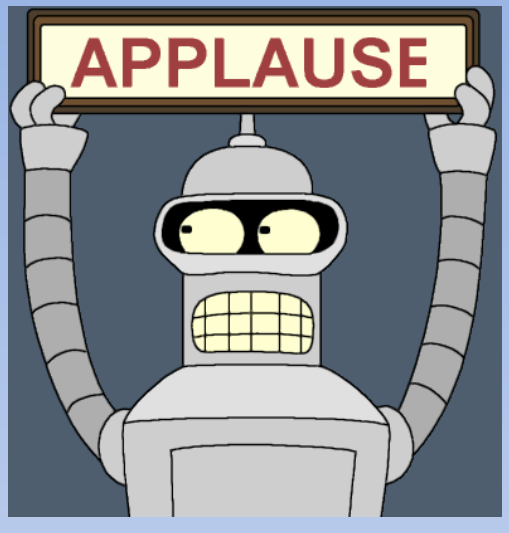
- ***Relativistic Transport Theory,*** coupled to a ***decay mechanism for initial color fields,*** permits to study early times dynamics of heavy ion collisions.
- ***Schwinger tunneling*** *allows a* ***fast QGP production,*** *typically a small fraction of fm/c.*
- ***No dark age for QGP***

  Pre-equilibrium partons produce abundantly photons, comparable in number with those produced by equilibrated QGP during the whole fireball lifetime.
- ***Domain of pre-equilibrium photons***

  Substantial contribution in the range 1.5 GeV < $p_T$ < 3 GeV where both *thermal hadrons* and *thermal QGP* do not contribute significantly.

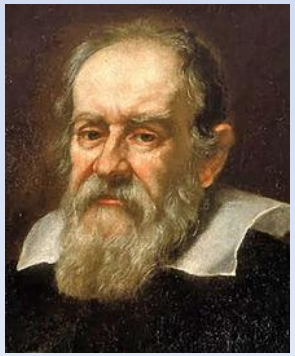
***Pre-equilibrium photons might be important to understand experimental data at RHIC in the aforementioned $p_T$ domain***

# *Thanks for your attention*




*Acknowledgements*
This work has been partly supported by:

- ❑CAS President International Fellowship Initiative (Grant No. 2015PM008)
- ❑NSFC Projects (11135011 and 11575190)



*Io stimo più il trovar un vero, benché di cosa leggiera,*
*che 'l disputar lungamente delle massime*
*questioni senza conseguir verità nissuna.*

Appendix

# APPENDIX

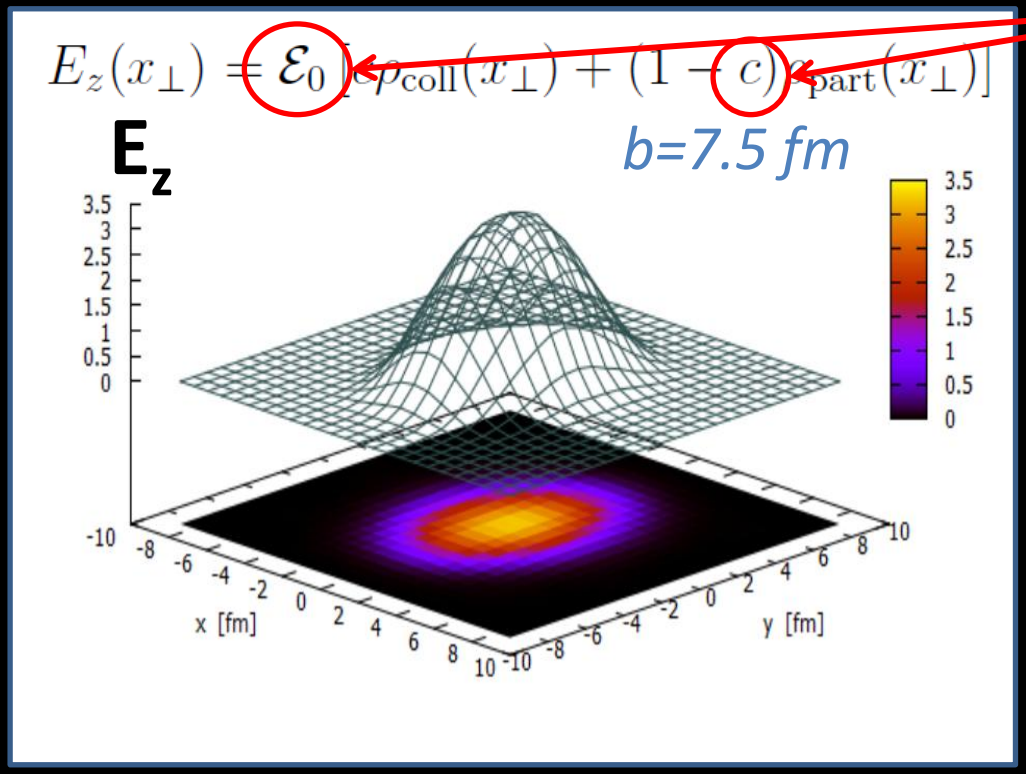
M. R. *et al.*, in preparation

# The initial condition

*Initial chromo-electric field:*

- *Boost invariant in the longitudinal direction*
- *Smooth in transverse plane:*

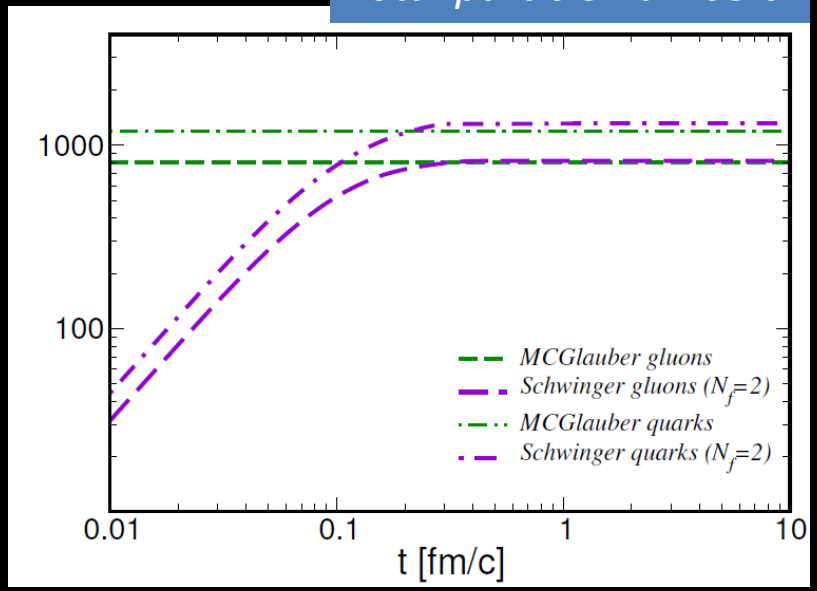
$$E_z(x_\perp) = \mathcal{E}_0 \left[ c\,\rho_{\rm coll}(x_\perp) + (1-c)\,\rho_{\rm part}(x_\perp) \right]$$




Set up to match *MCGlauber* for RHIC collision at b=7.5 fm:

- *Eccentricity at $\tau$= 0.6 fm/c*
- *Multiplicity*

*Total particle numbers*



# Our problem: partonic photons

Among the many photon sources in uRHICs, in our fireball we consider the ***partonic*** ones:

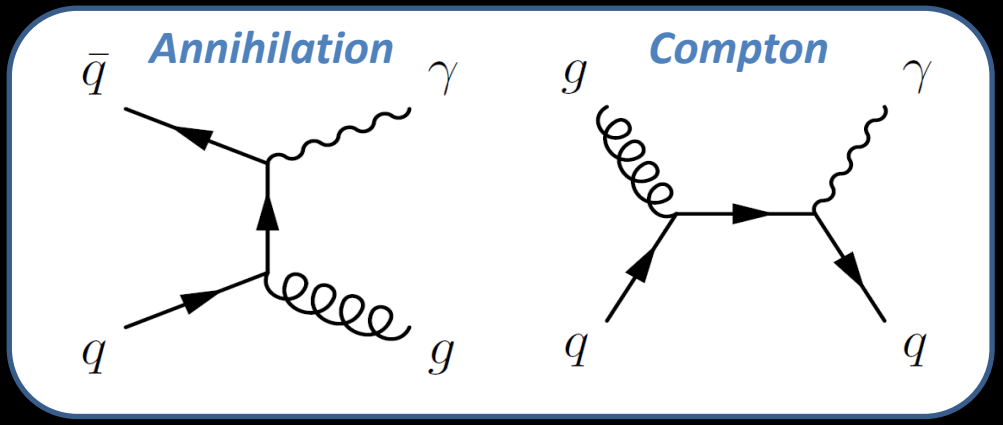
***Partonic photons***

- *Pre-eq stage*

During classical field decay

- *Thermal QGP*

During QGP evolution




*What we do not have in the present implementation*

- *Thermal hadrons contribution*. However notice that:

1. Thermal hadrons contribute to a different $p_T$ region in the photon spectrum
2. We add by hand thermal hadrons contribution, see final figure

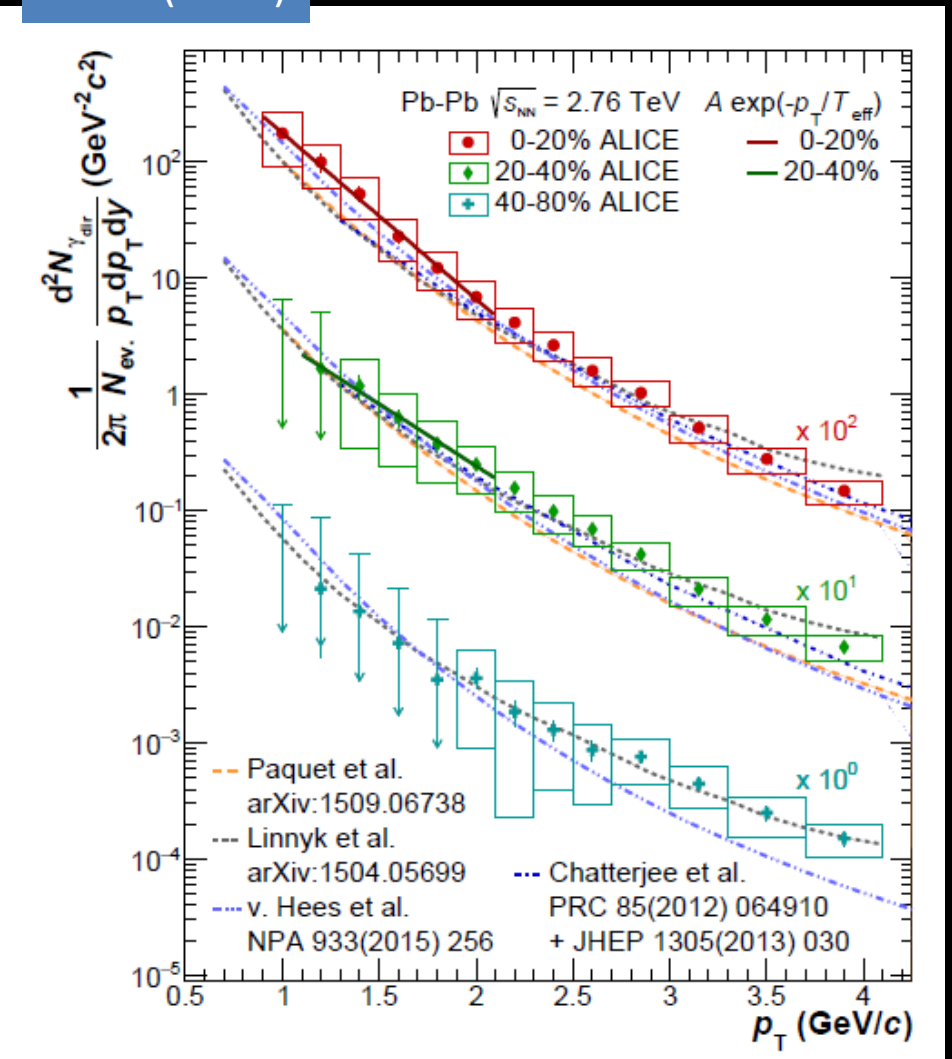
- *Bremstrahlung* [AMY, JHEP 0112 (2001)]
- *Photons from anomaly* [Kharzeev *et al.* (2012)]
- *Gluon fusion* [Ayala *et al.* (2016)]

} Might be important for large magnetic field

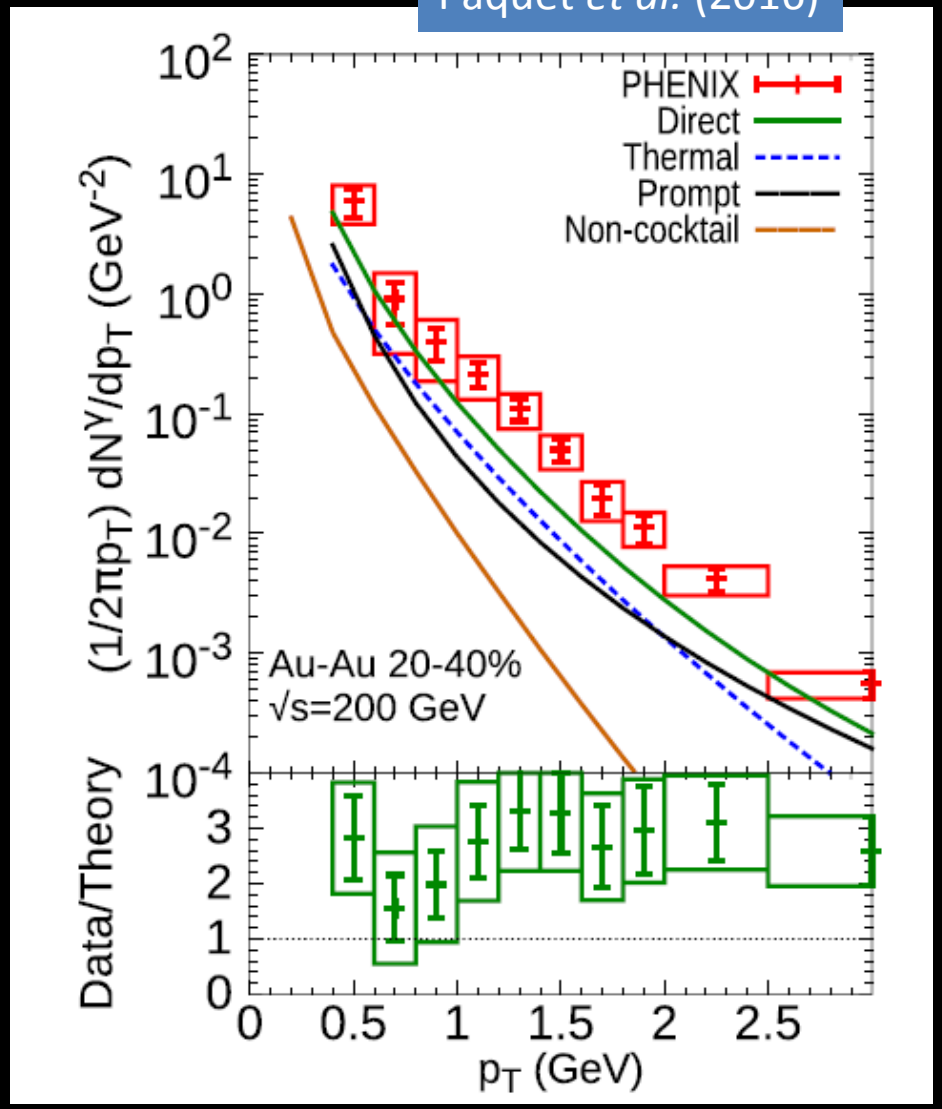
- *Classical EM photon production* [Tanji (2016)]

# Direct photon spectra

ALICE (2016)

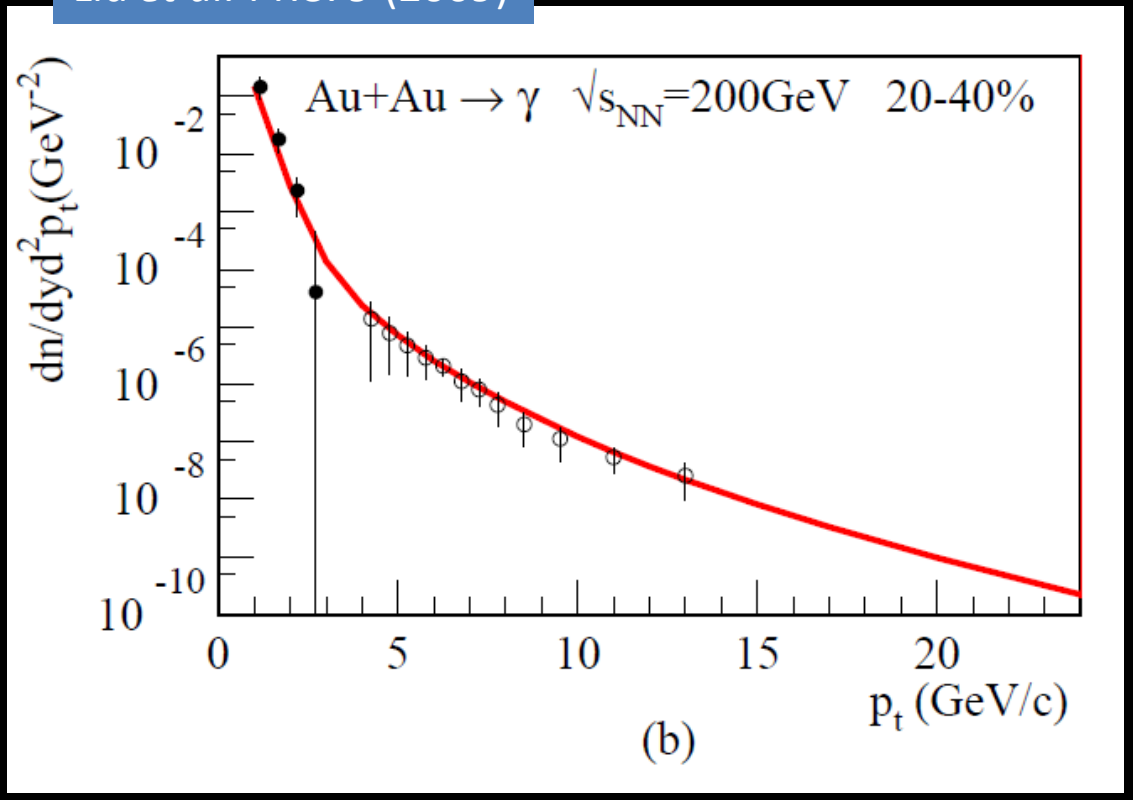



Paquet *et al.* (2016)

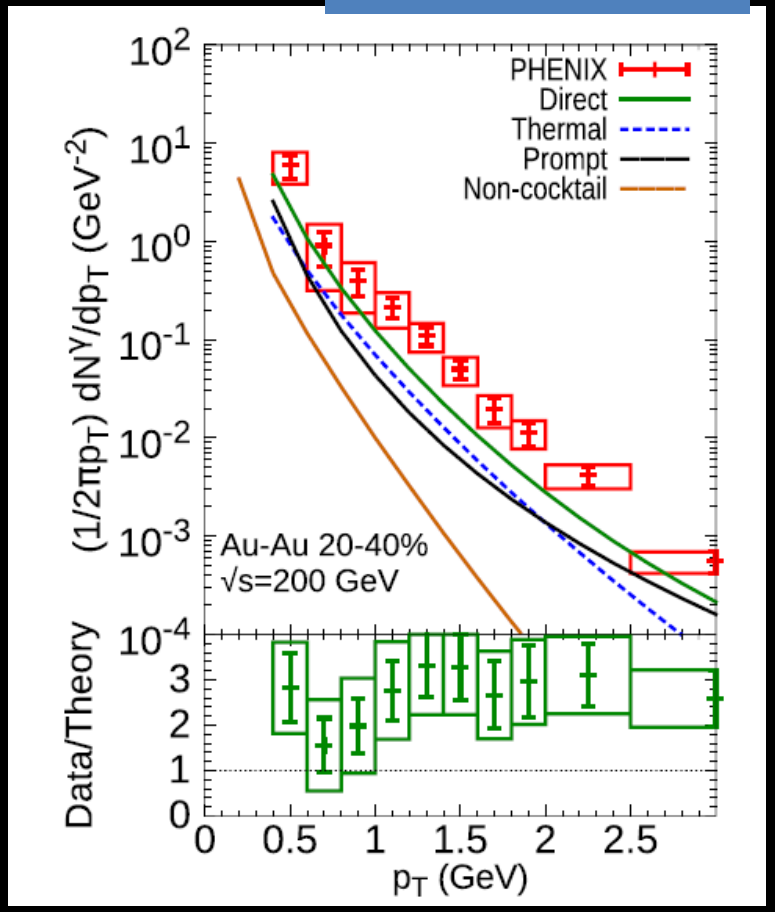


# Direct photon spectra

Liu *et al.* PRC79 (2009)



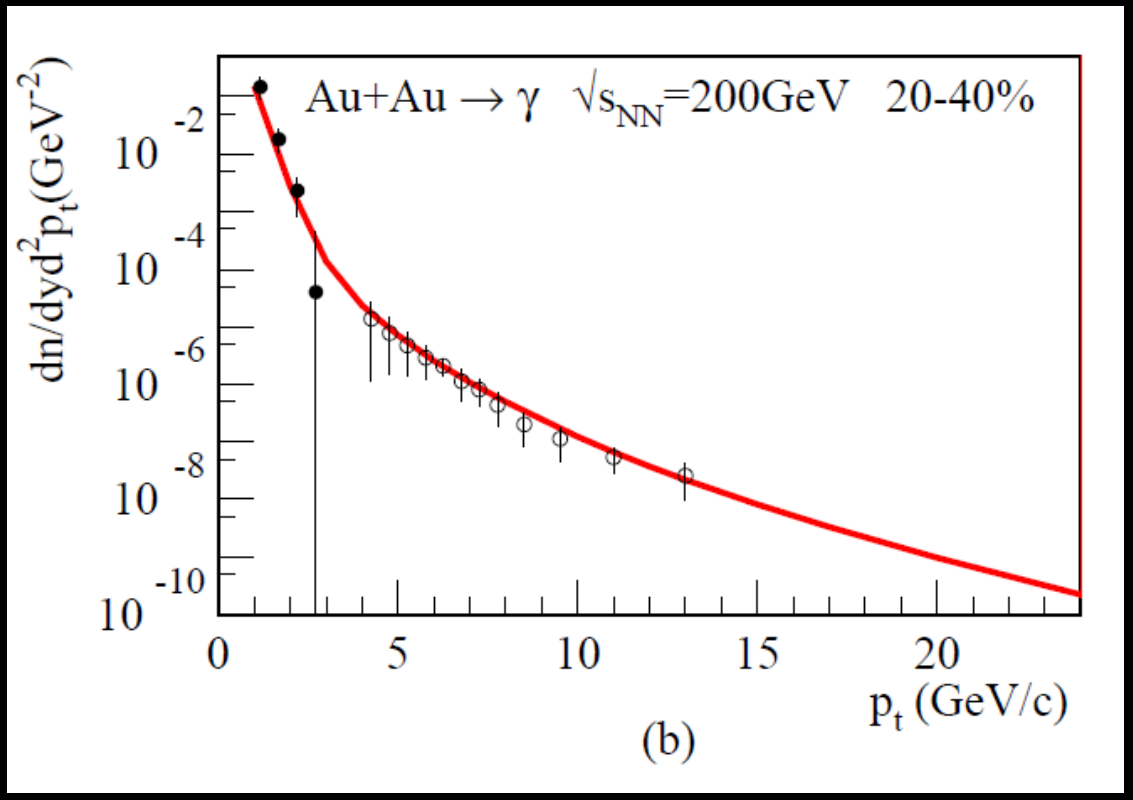

Paquet *et al.* (2016)



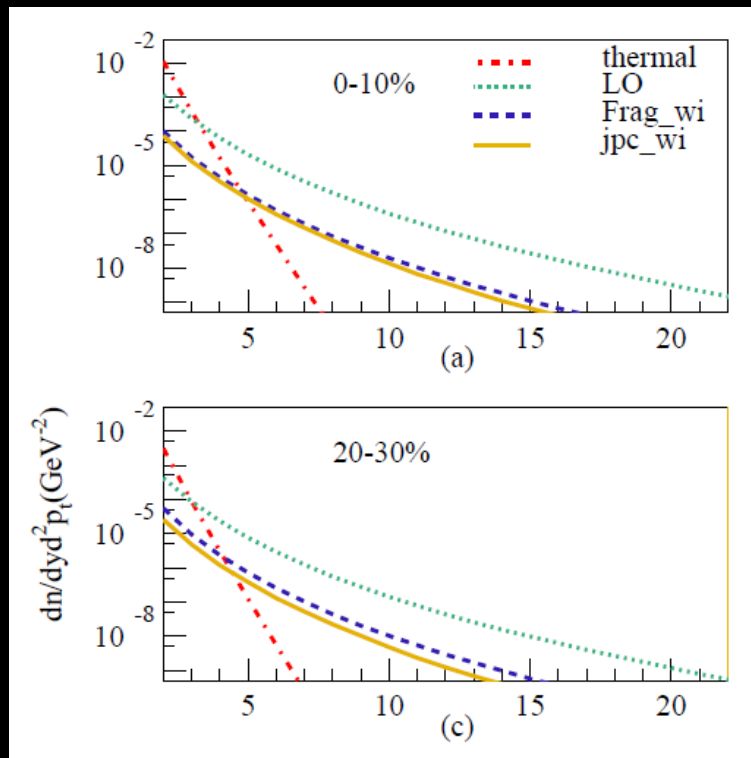
Liu *et al.* PRC79 (2009)

# Direct photon spectra

*Direct photon spectrum*



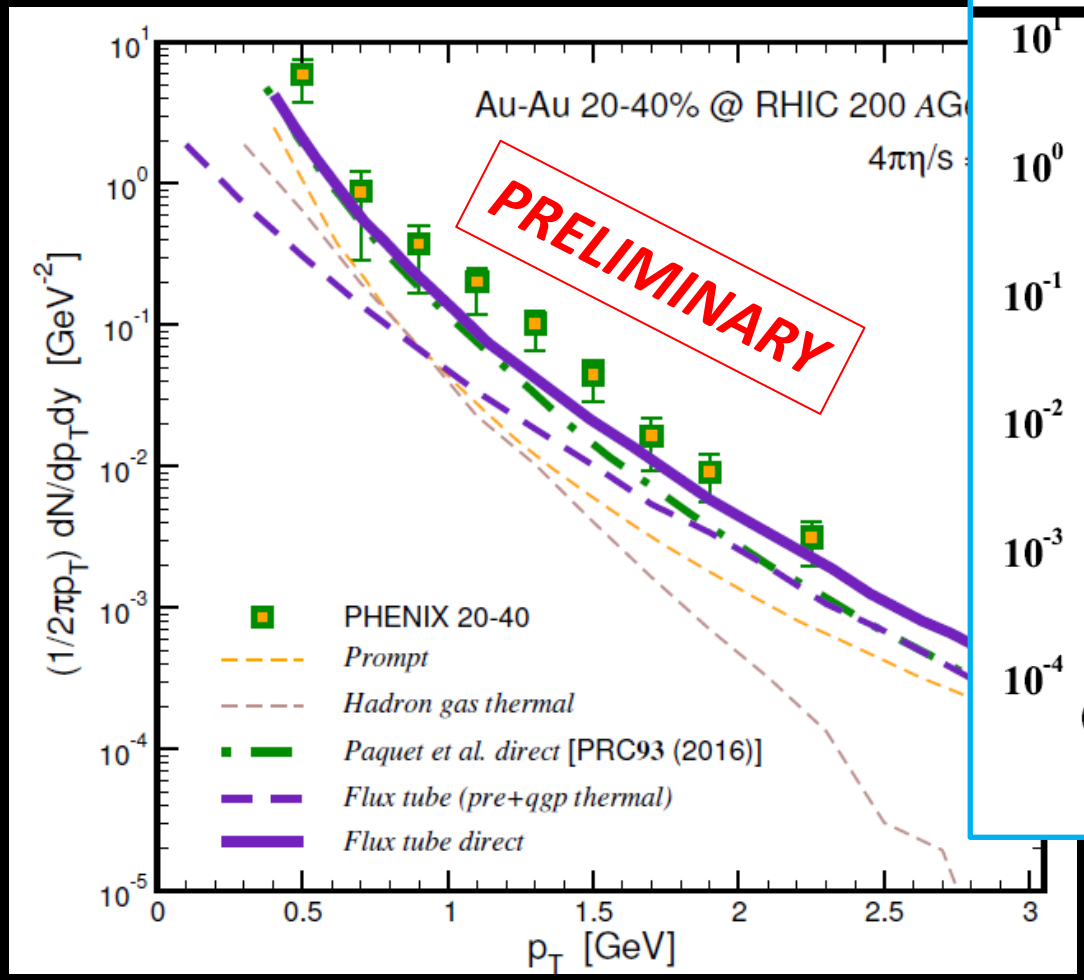

*Contributions*

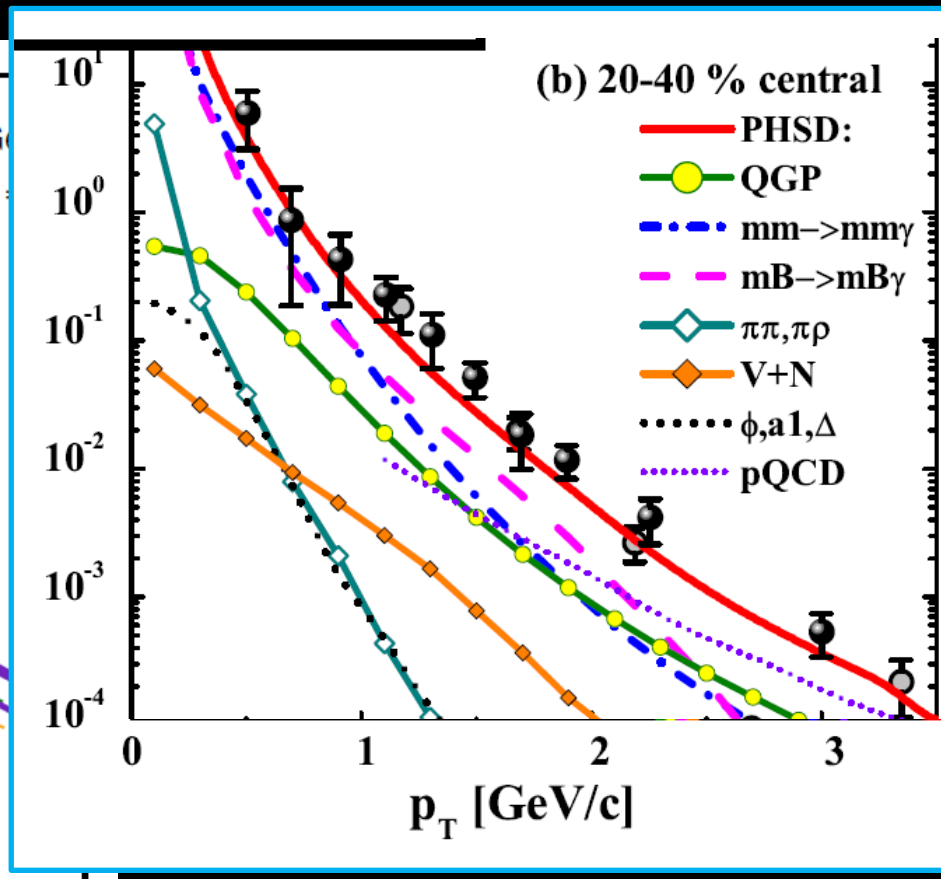


M. R. *et al.*, in preparation

# Direct photon spectra

Nice agreement with PHSD calculation:




E. Bratkovskaya *et al.*, PRC**92** (2015)

# Schwinger effect in Chromodynamics

## *Non abelian and time effects*

It is quite remarkable that the Schwinger effect, that we have discussed for the case of an abelian classical field, can be derived also in the case of

(.) ***non-abelian gauge theory***

(.) ***time-dependent color-electric field***

$$\frac{dW_{q(\bar{q})}}{dt d^3x d^2p_T} = -\frac{1}{4\pi^3} \sum_{j=1}^{3} |g\Lambda_j(t)| \ln[1 - e^{-\frac{\pi(p_T^2+m^2)}{|g\Lambda_j(t)|}}]$$

*quark-antiquark pairs*

$$C_1(t) = [E^a(t)E^a(t)]$$

$$C_2(t) = [d_{abc}E^a(t)E^b(t)E^c(t)]^2$$

$$\frac{dW_{g(\bar{g})}}{dt d^3x d^2p_T} = \frac{1}{4\pi^3} \sum_{j=1}^{3} |g\Lambda_j(t)| \ln[1 + e^{-\frac{\pi p_T^2}{|g\Lambda_j(t)|}}]$$

*gluon pairs*

In the abelian limit the above equations agree with the ones quoted before.


Nayak and Nieuwenhuizen, PRD 71 (2005)
Nayak and Cooper, PRD 73 (2006)
G. Nayak, EJTP 8 (2011)
G. Nayak, EPJ C59 (2009)
G. Nayak, IJMP A25 (2010)

# Schwinger effect in Chromodynamics

## *Abelian Flux Tube Model*

Focus on a single flux tube:

(.) neglect color-magnetic fields;
(.) assume abelian dynamics for ***color-electric fields***;
(.) assume ***Schwinger effect*** takes place:
*Color-eletric color field decays into quark-antiquark as well as gluon pairs*

***Abelian Flux Tube Model***

***Particle spectrum***

$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x d^2p_T dp_z} = \mathcal{R}_{jc}(p_T)\delta(p_z)p_0$$

$$\mathcal{R}_{jc}(p_T) = \frac{\mathcal{E}_{jc}}{4\pi^3}\left|\ln\left(1 \pm e^{-\pi p_T^2/\mathcal{E}_{jc}}\right)\right|$$

$$\mathcal{E}_{jc} = \left(g|Q_{jc}E| - \sigma_j\right)\theta\left(g|Q_{jc}E| - \sigma_j\right)$$

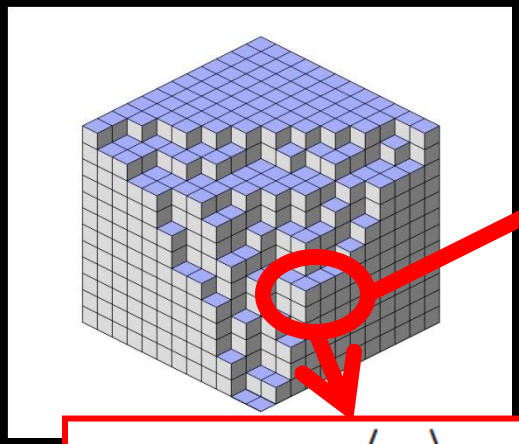
*String tension*

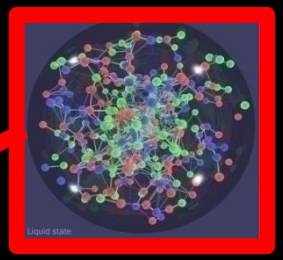
(.) Energy per unit length has to be larger than the QCD string tension
(.) Effective electric field is smaller due to string tension effect

*See also Greco's talk*

# Transport rephrased to hydro

***Total Cross section*** is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of $\eta/s$***.





$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho} \frac{1}{\sigma}$$

(.) Collision integral is gauged in each cell to assure that the fluid dissipates according to the desired value of $\eta/s$.

(.) Microscopic details are not important: the specific microscopic process producing $\eta/s$ is not relevant, only macroscopic quantities are, in analogy with hydrodynamics.

***Transport***

Description in terms of parton distribution function

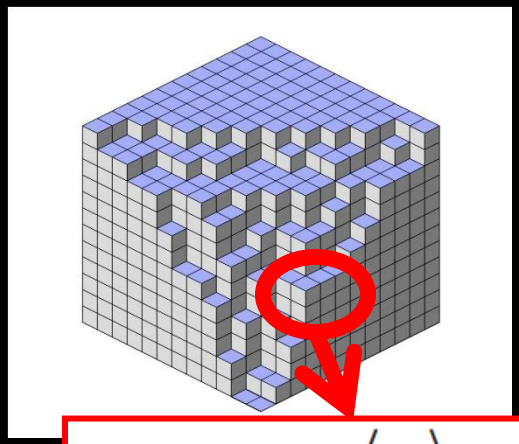
***Hydro***

Dynamical evolution governed by macroscopic quantities

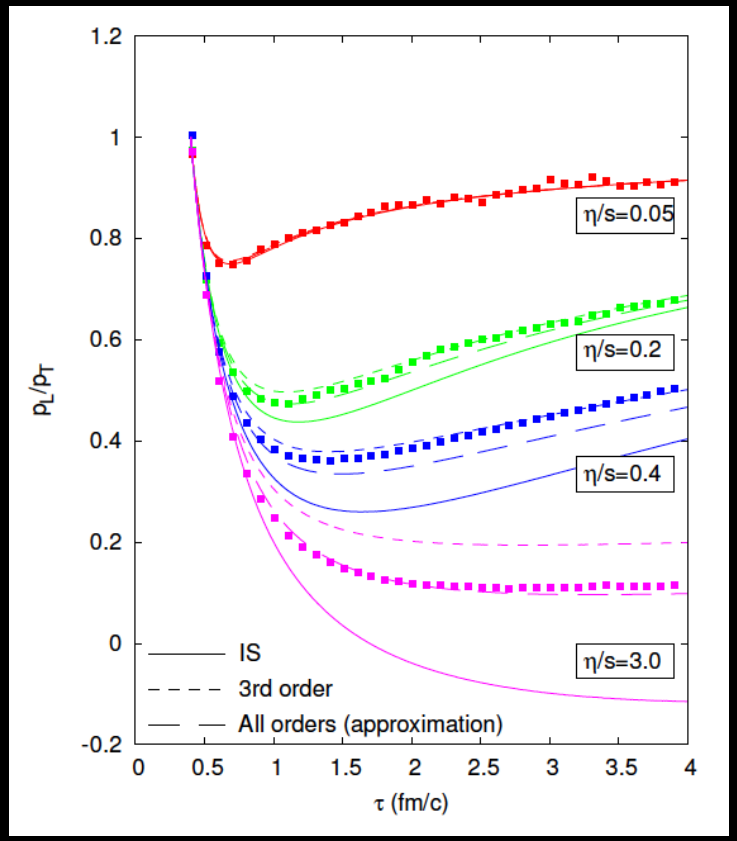
# Transport *gauged* to hydro

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.

***Total Cross section*** is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.



$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho} \frac{1}{\sigma}$$



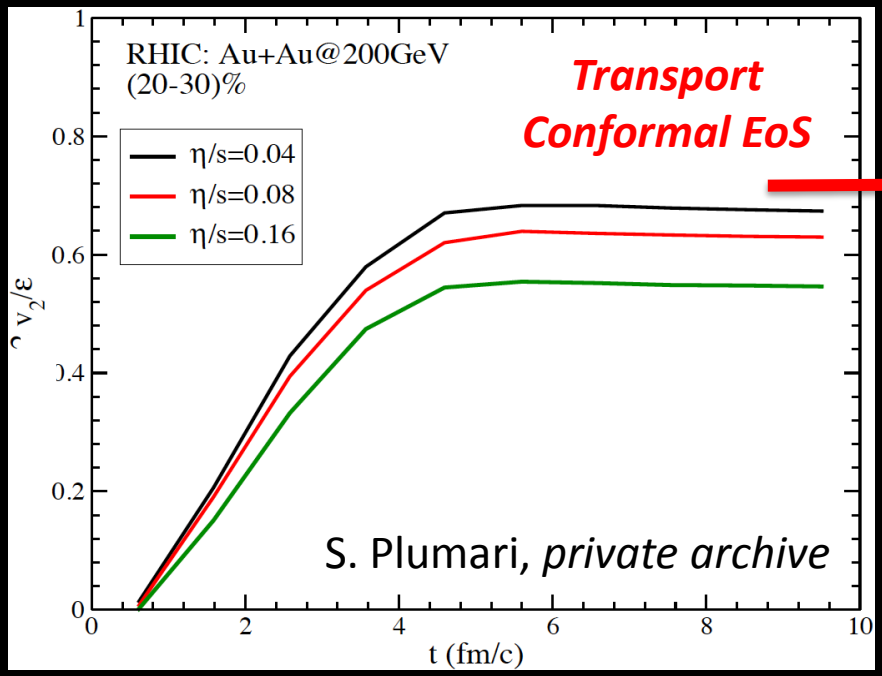

El, Xu, Greiner, Phys.Rev. C81 (2010) 041901

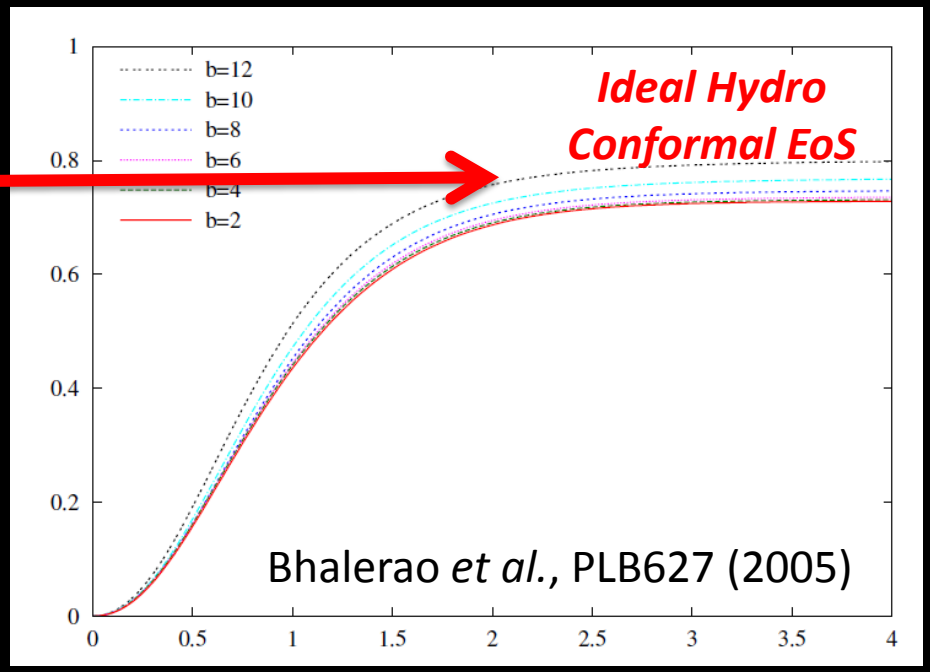
***There is agreement of hydro with transport also in the non dilute limit***

# Transport *gauged* to hydro, again

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.

***Total Cross section*** is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.




***There is agreement of hydro with transport also in the non dilute limit***

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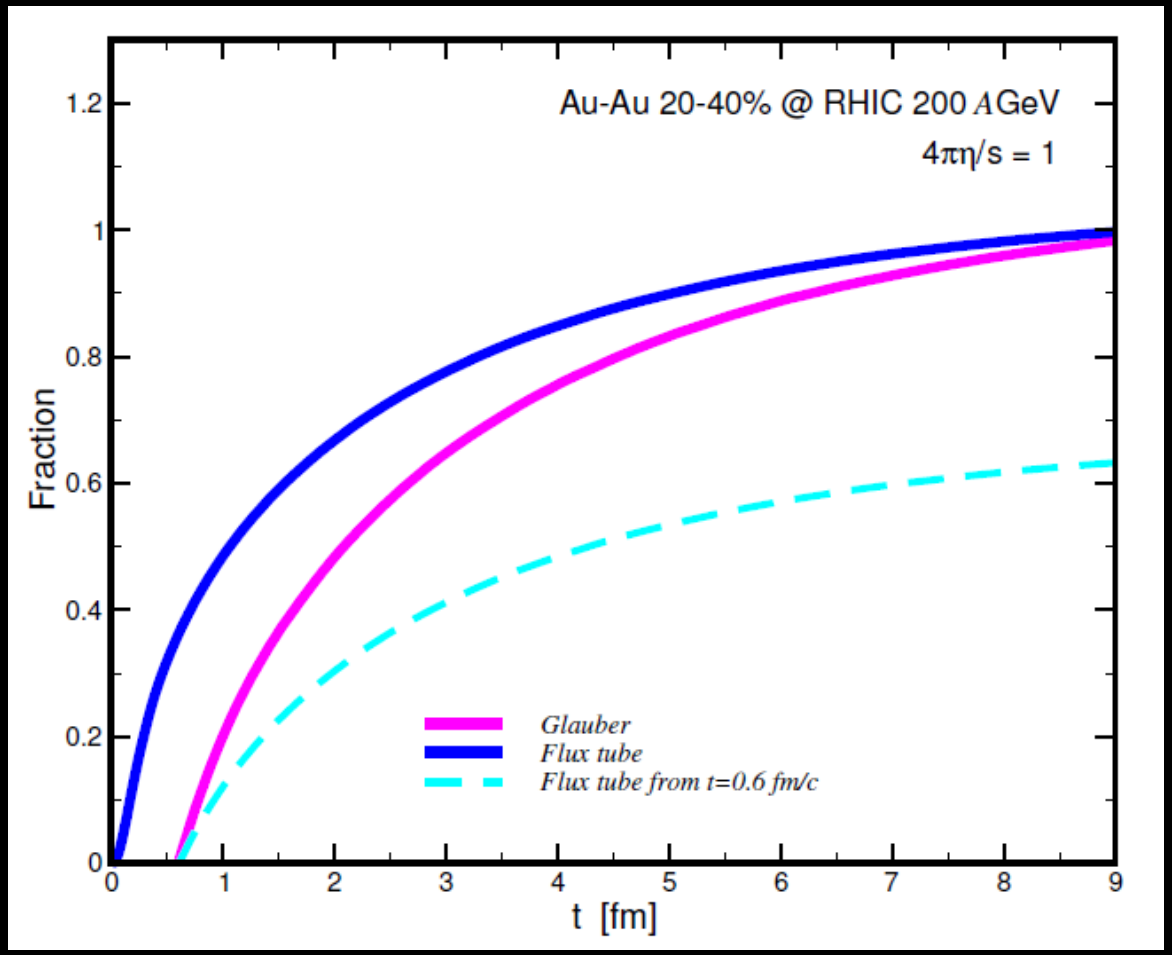
# Photon number fraction versus time




≈ 40%

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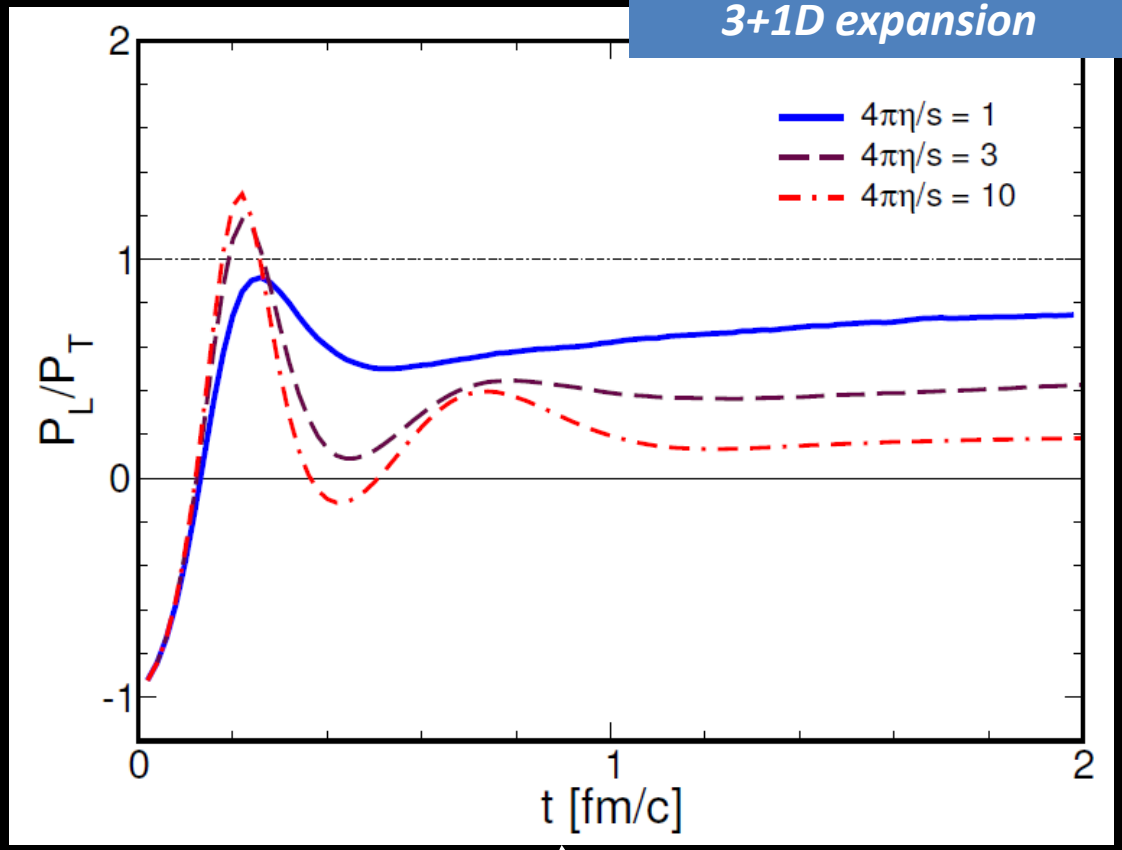
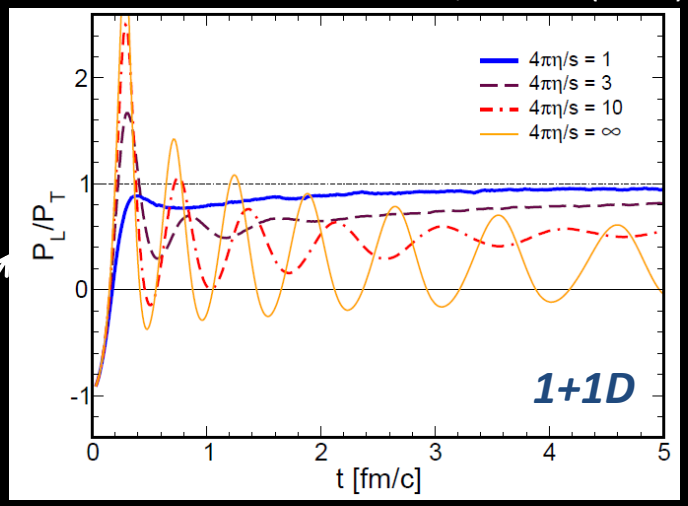
# Isotropization for a 3+1D expansion

***Pressure isotropization***
***3+1D expansion***




Florkowski and Ryblewski, PRD 88 (2013)
M. R. *et al.*, PRC 92 (2015)




*Qualitative agreement with the 1+1D calculation*

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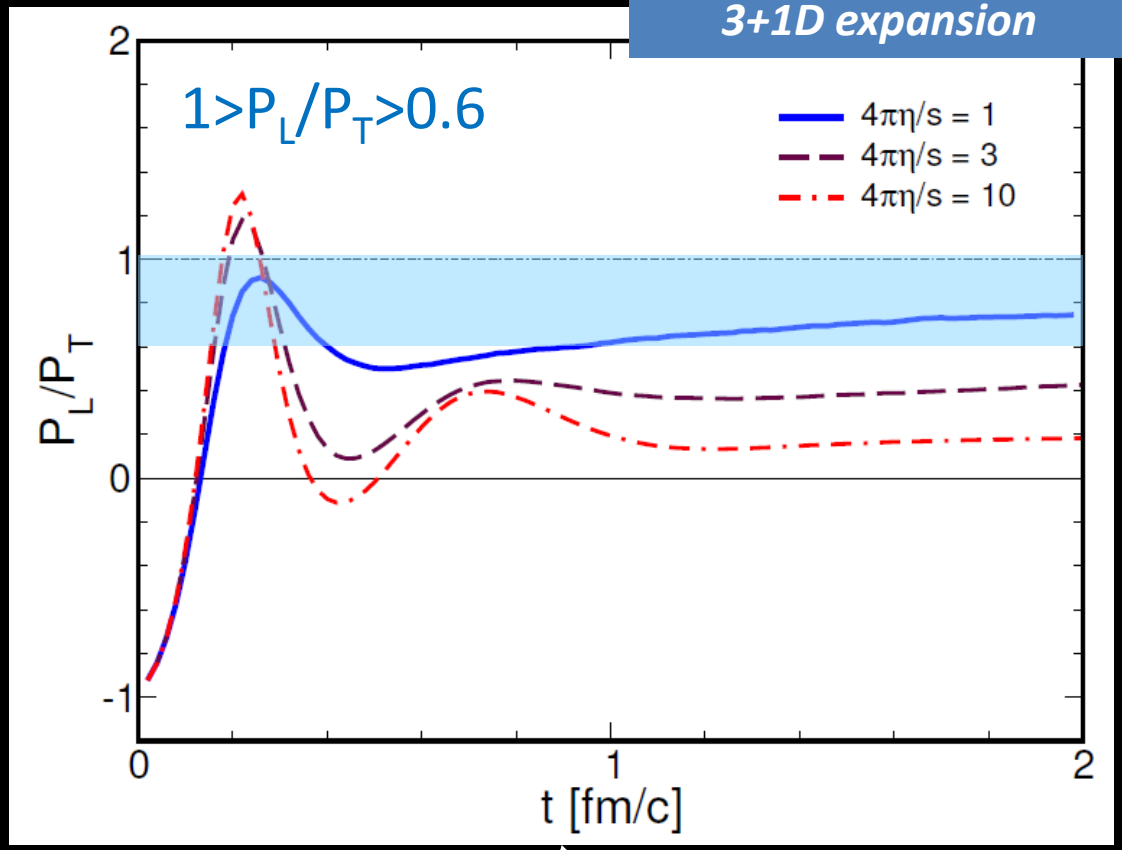
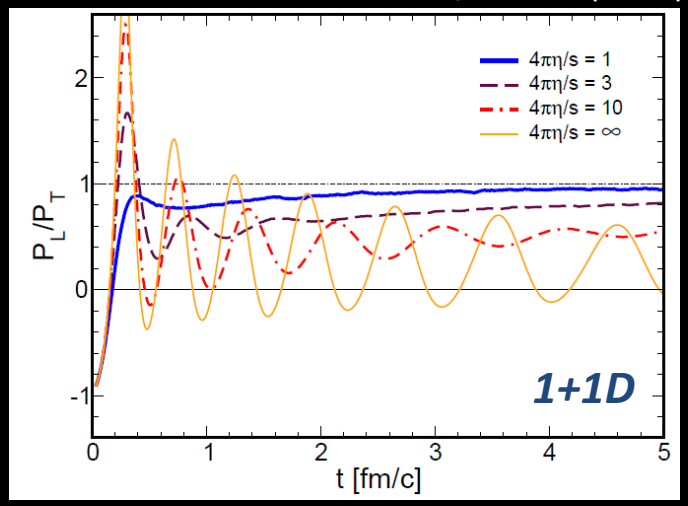
# Isotropization for 3+1D expansion

***Pressure isotropization***
***3+1D expansion***




Small $\eta/s$
Almost isotropic
in 1 fm/c

Florkowski and Ryblewski, PRD 88 (2013)
M. R. *et al.*, PRC 92 (2015)




*Nice agreement with the 1+1D calculation*

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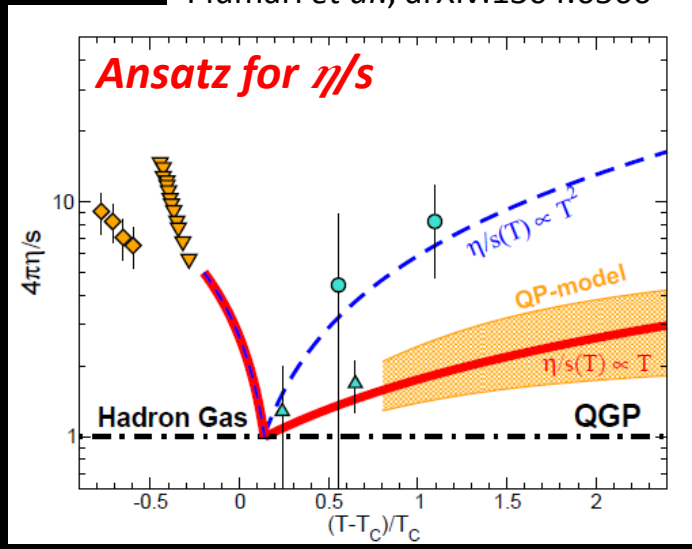
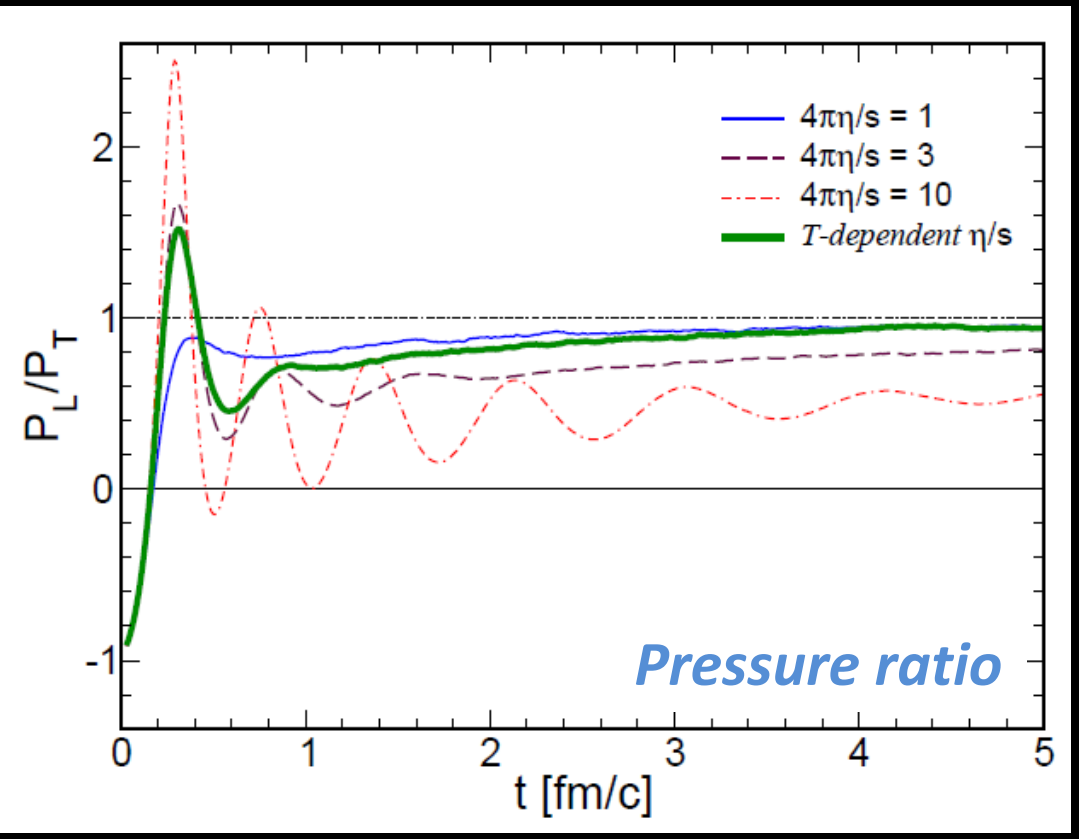
# Isotropization for T-dependent $\eta/s$

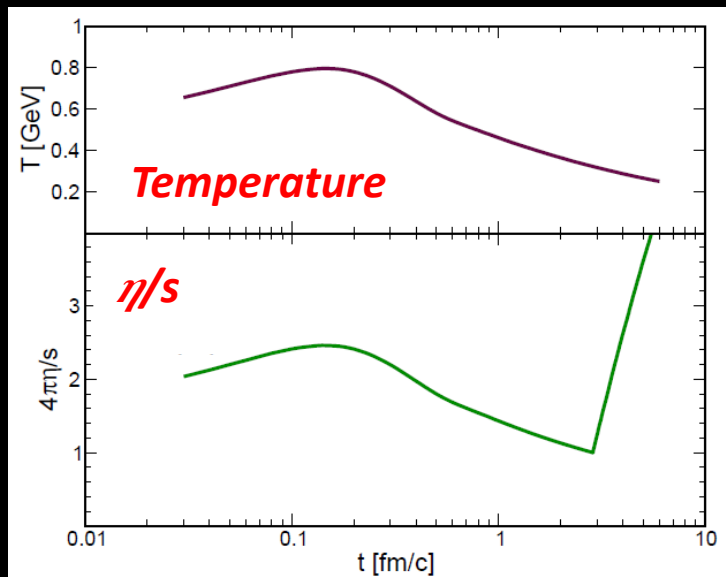
Local temperature in realistic collisions evolves in time:

***$\eta/s$ should be time-dependent***

Plumari *et al.*, arXiv:1304.6566

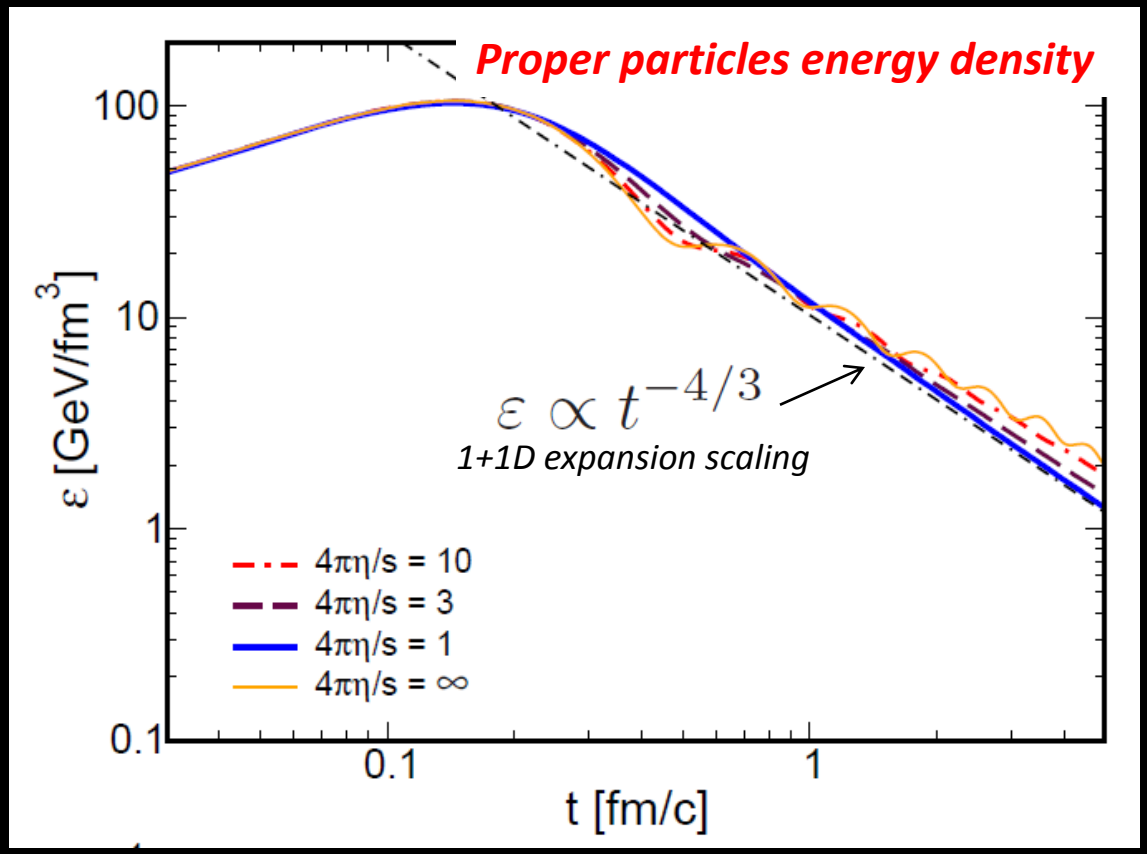


M. R. *et al.*, PRC 92 (2015)
M. R. *et al.*, in preparation

# 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)

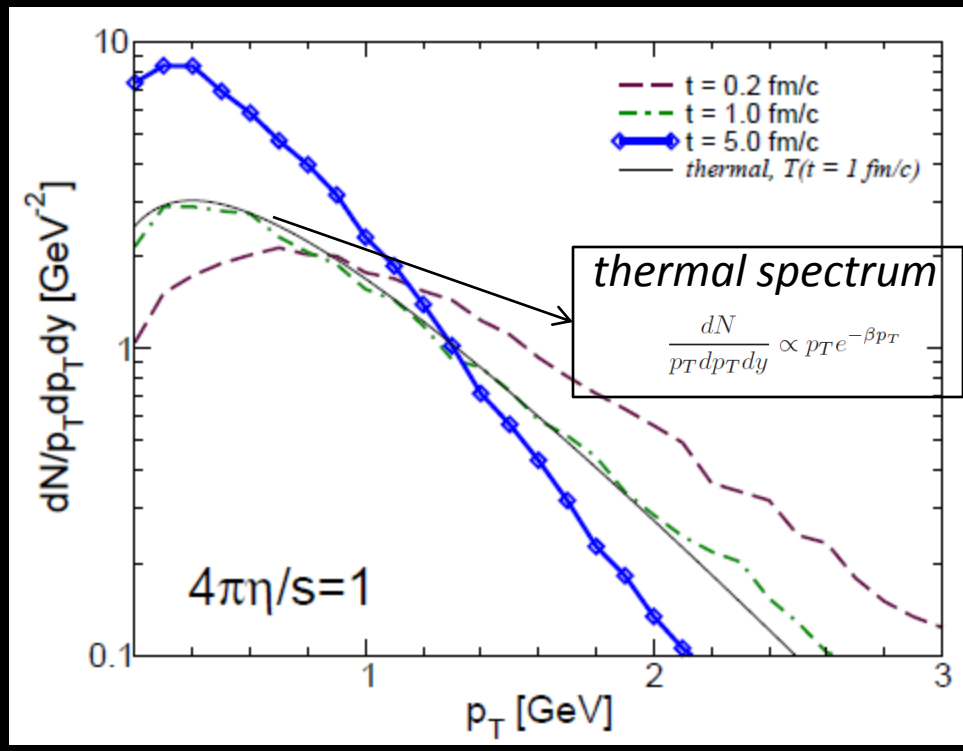
*This is quite interesting because it proves that transport theory is capable to describe, even in conditions of quite strong coupling (small η/s), the evolution of physical quantities in agreement with calculations based on hydrodynamics, once the microscopic cross section is put aside in favor of fixing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

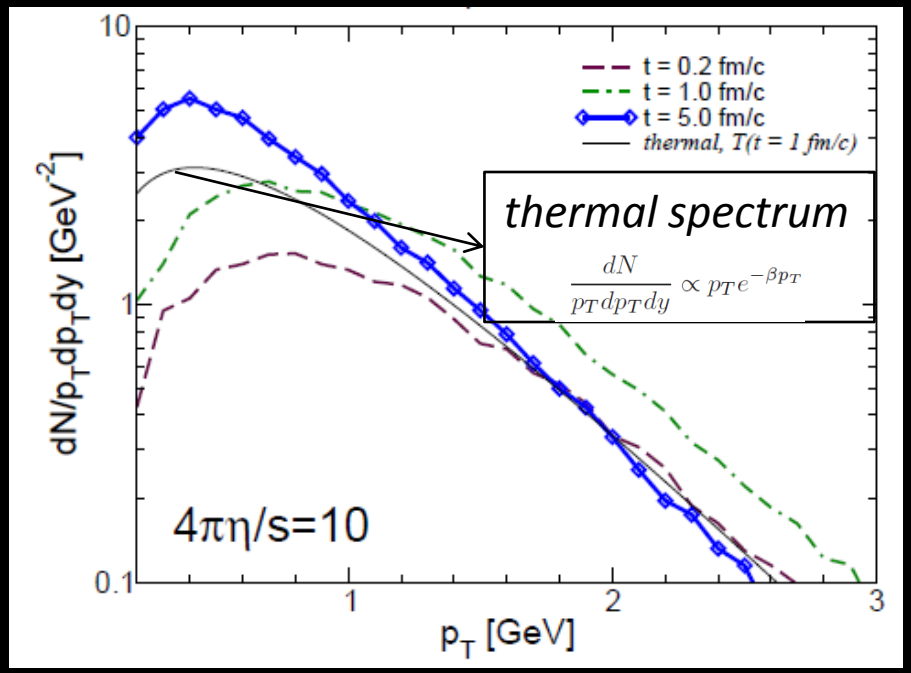
M. R. *et al.*, PRC 92 (2015)
M. R. *et al.*, in preparation

# 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

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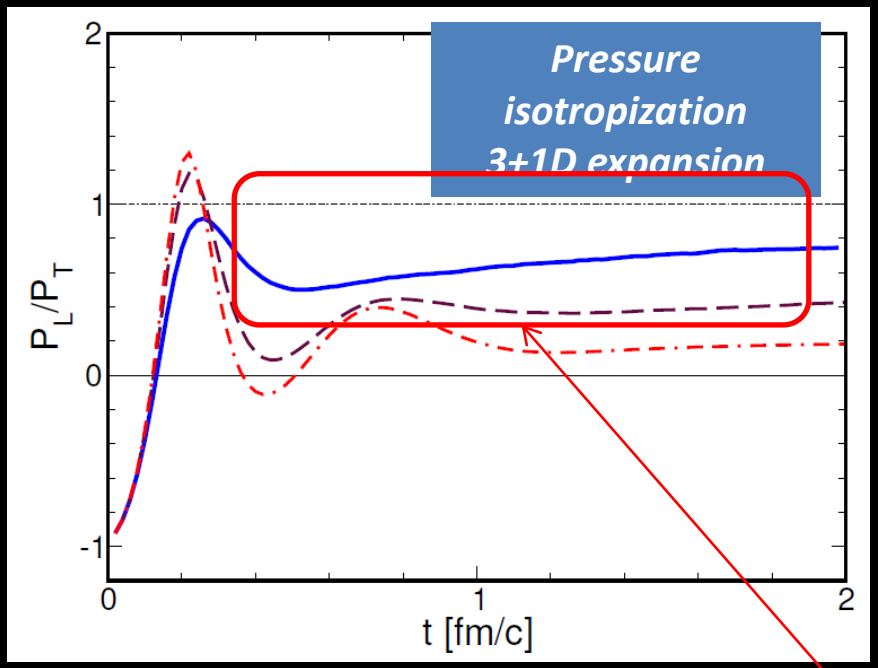
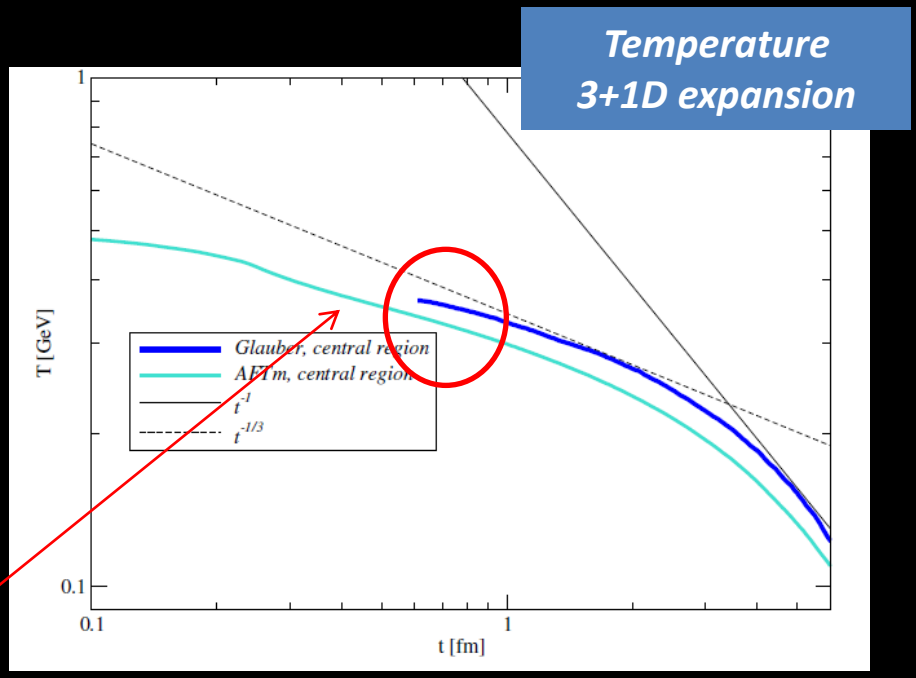
# Abelian flux tube model

(.) neglect magnetic part of Glasma fields;
(.) assume ***chromoelectric fields*** evolve as ***classical abelian fields***;
(.) initial field is ***longitudinal:*** $E_x(t=0) = E_y(t=0) = 0$
(.) assume ***Schwinger effect*** takes place:
*Color-eletric field decays into quark-antiquark as well as gluon pairs*

***Abelian Flux Tube Model***




*A path to hydrodynamization*

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

# Temperature evolution