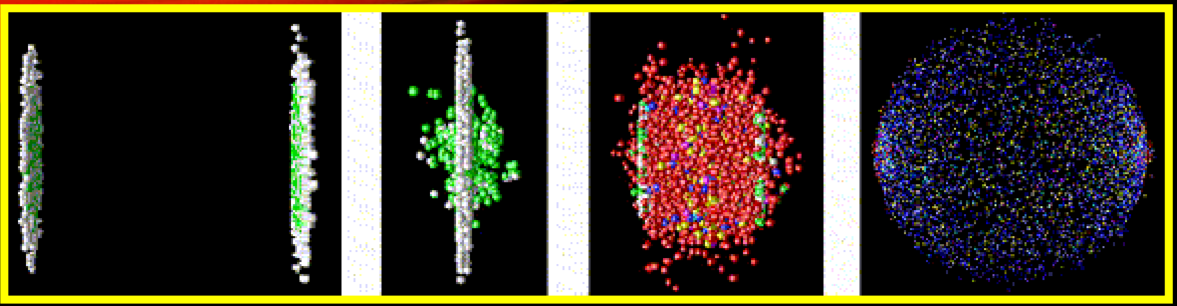
Hot Quarks 2016 – South Padre Island
September 18, 2016

IMPACT OF EARLY STAGE NON-EQUILIBRIUM DYNAMICS ON PHOTON PRODUCTION IN RELATIVISTIC HEAVY ION COLLISIONS

Lucia Oliva

in collaboration with
Vincenzo Greco
Salvo Plumari
Armando Puglisi
Marco Ruggieri
Francesco Scardina



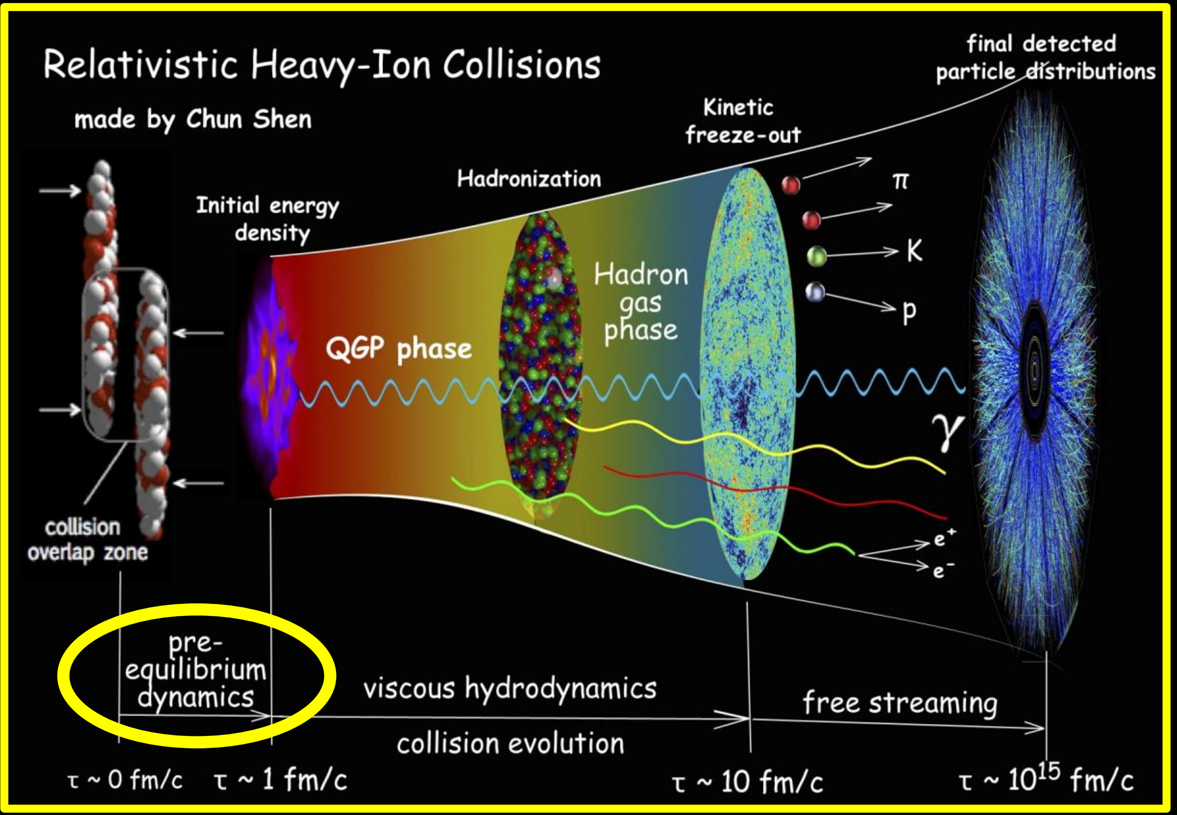
initial stage

pre-equilibrium

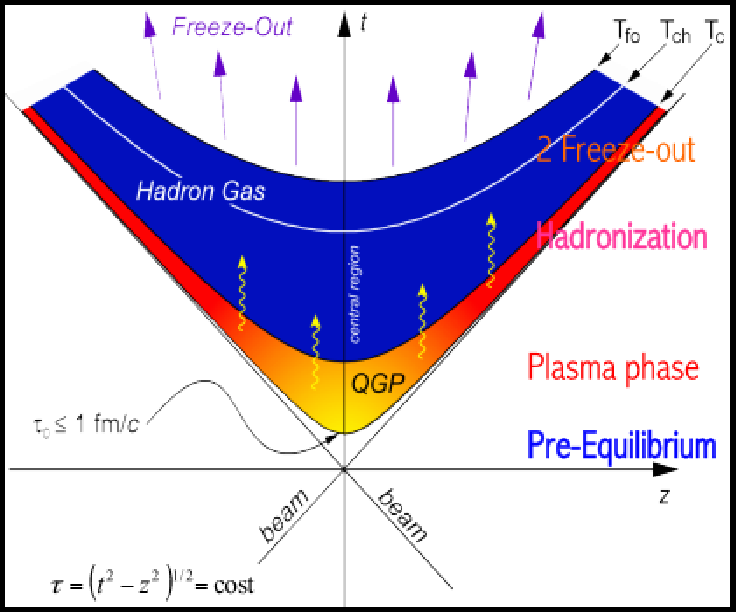
hydrodynamical evolution

hadronization

freeze-out



[Source: http://snelling.web.cern.ch/snelling/img/little_bang.jpg]



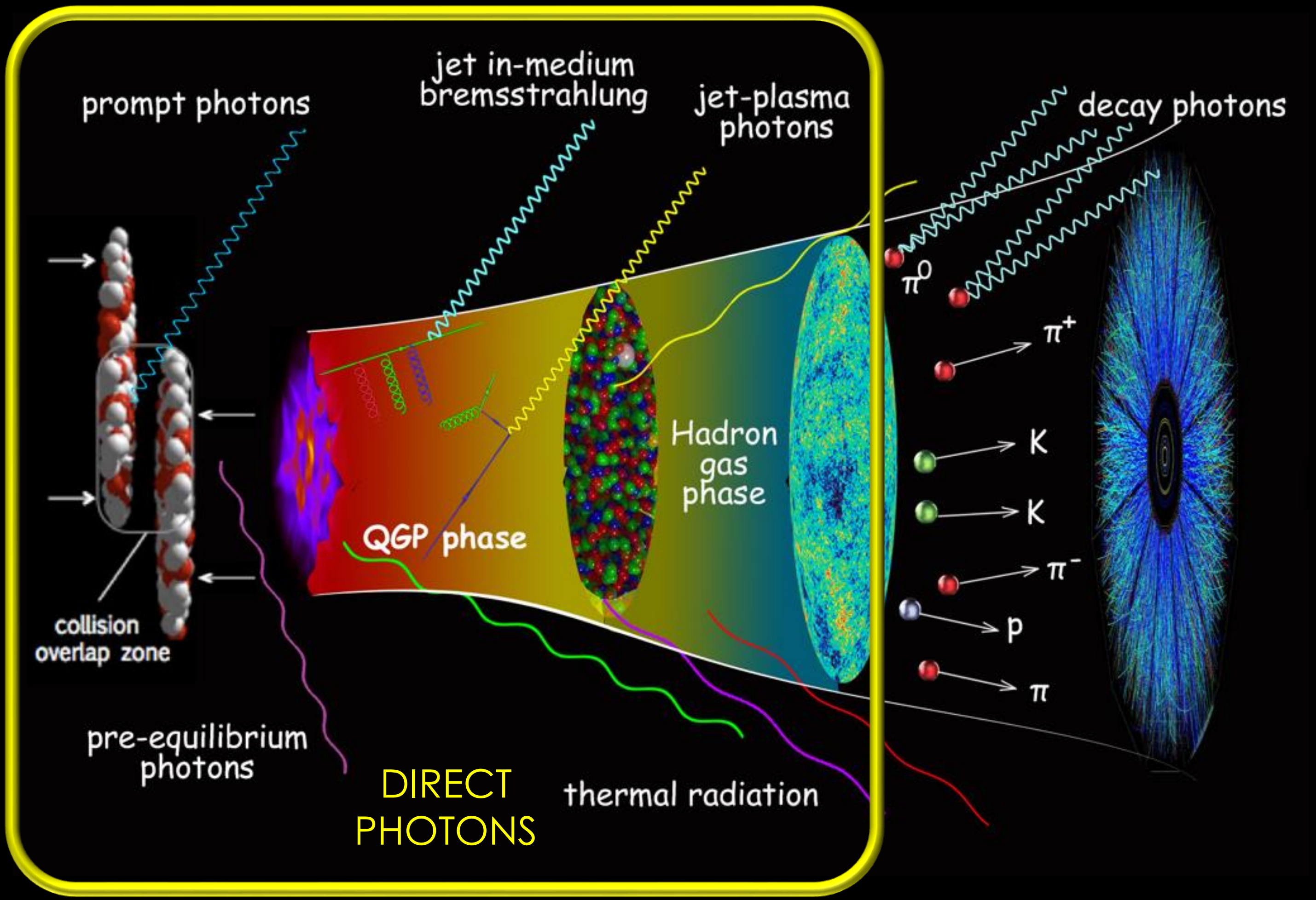
IMPACT OF PRE-EQUILIBRIUM ON SEVERAL OBSERVABLES

Ruggieri et al., PLB 727 (2013) 177

Ruggieri et al., PRC 89 (2014) 054914

Liu et al., PRC 91 (2015) 064906; PRC 92 (2015) 049904

PHOTON PRODUCTION



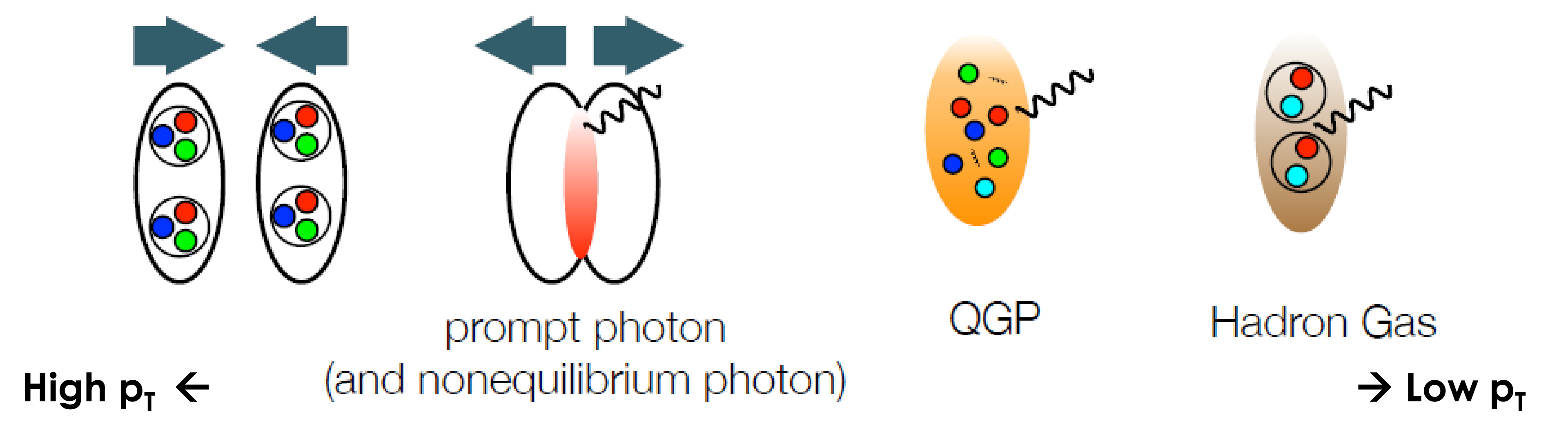
[Source: C. Shen, talk at ECT*, Trento 12/2015]

ELECTROMAGNETIC PROBES

Radiation of photons and dileptons has been proposed as a promising tool to characterize the initial state of heavy ion collisons

DIRECT PHOTONS

- emerge directly from a particle collison
- represent less than 10% of all detected photons



Experiments can not distinguish between the different sources

Theoretical models can be used to identify these sources and their relative importance in the spectrum

Peitzmann and Thoma, Phys. Rep. 364 (2002) 175
Chatterjee, et al., Lect. Notes Phys. 785 (2010) 219
Chauduri, arXiv: 1207.7028 (2012)

BOLTZMANN TRANSPORT EQUATION

In order to **simulate** the temporal evolution of the fireball we solve the **Boltzmann equation** for the parton distribution function **f(x,p)**

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

Free streaming

Field interaction

Collision integral
$\eta/s \neq 0$

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 (**$\eta/s \neq 0$**).*

$$\mathcal{C}[f] = \int \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_{1'}}{2E_{1'}(2\pi)^3} \frac{d^3p_2'}{2E_2'(2\pi)^3} (f_{1'}f_{2'} - f_1 f_2) \times |\mathcal{M}|^2 \delta^4(p_1 + p_2 - p_{1'} - p_{2'})$$

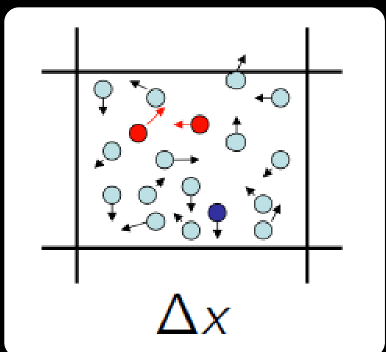
Xu and Greiner, PRC 79 (2009) 014904
Bratkovskaya, et al., NPA 856 (2011) 162
Greco et al., PLB 670 (2009) 325
Plumari and Greco, AIP CP 1422 (2012) 56
Ruggieri et al., PRC 89 (2014) 054914

BOLTZMANN TRANSPORT EQUATION

In order to **simulate** the temporal evolution of the fireball we solve the **Boltzmann equation** for the parton distribution function **f(x,p)**

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

Collision integral
$\eta/s \neq 0$



$$\mathcal{C}[f] = \int \frac{d^3p_2}{2E_2(2\pi)^3}\,\frac{d^3p_{1'}}{2E_{1'}(2\pi)^3}\,\frac{d^3p'_2}{2E'_2(2\pi)^3}\,(f_{1'}f_{2'} - f_1 f_2) \times |\mathcal{M}|^2 \delta^4(p_1+p_2-p_{1'}-p_{2'})$$

- **TEST PARTICLES METHOD** **to map the phase space**
- **STOCHASTIC METHOD** **to simulate collisions**

Transport approach is useful to obtain information about early times evolution

Within one single theoretical approach one can follow the entire dynamical evolution of system produced in RHICs

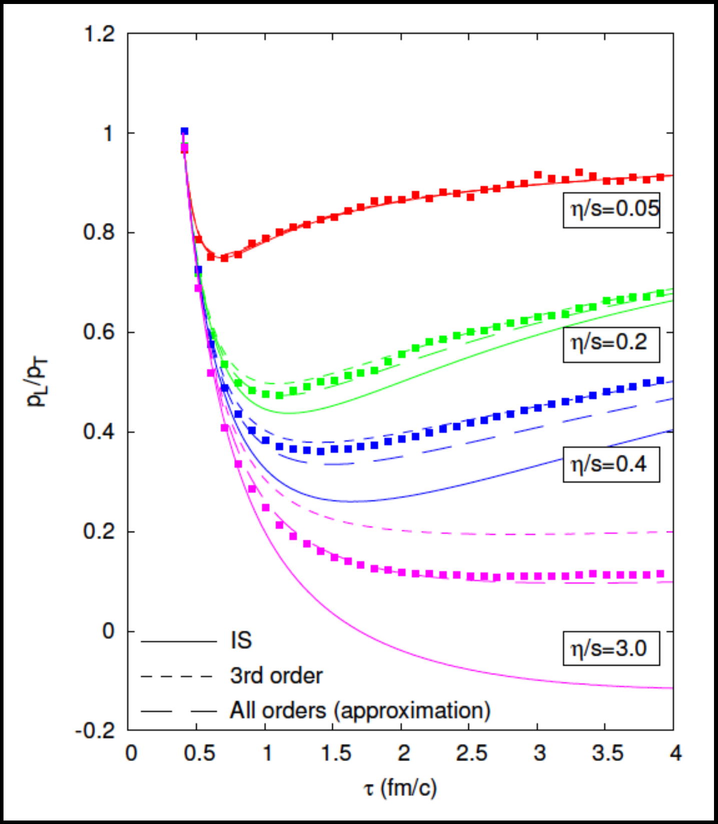
BOLTZMANN TRANSPORT EQUATION

Instead of starting from cross sections we simulate a fluid at **fixed η/s**

Total cross section computed to give the wished value of η/s according to CHAPMAN-ENSKOG EQUATION

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

Plumari, Puglisi, Scardina and Greco, PRC 86 (2012) 054902



El, Xu and Greiner, PRC 81 (2010) 041901

Convergence for small η/s of transport approach at fixed η/s with viscous hydrodynamics

Transport

Description in terms of parton distribution function

Hydro

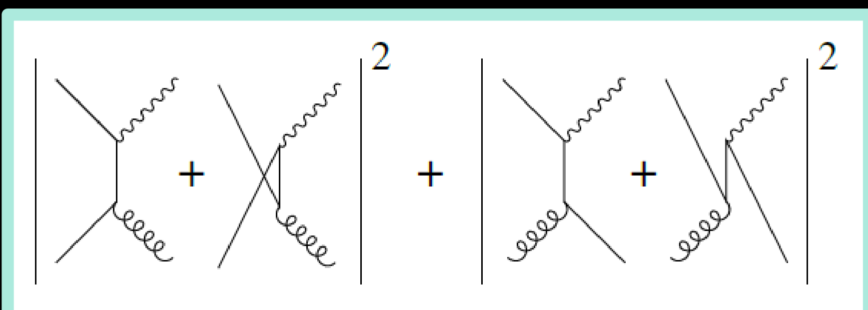
Dynamical evolution governed by macroscopic quantities

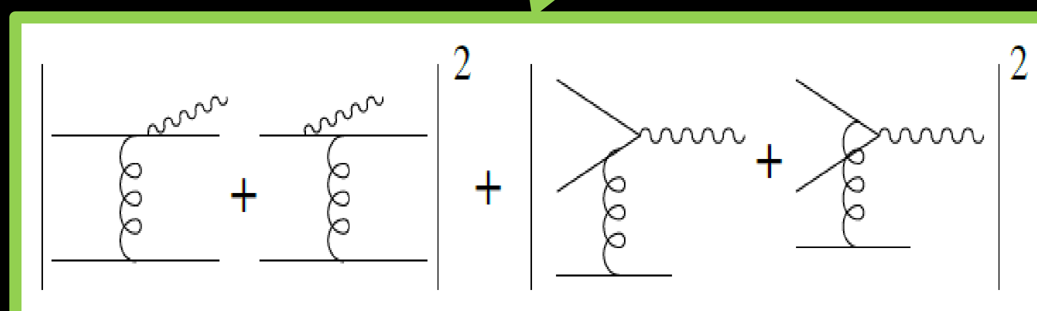
BOLTZMANN TRANSPORT EQUATION

In order to permit photon production we add to the collision integral of the Boltzmann equation processes with a photon in the final state

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

$$C[f] = C_{22}[f] + C_{23}[f] + \dots$$





Aurenche et al., PRD 58 (1998) 085003
ib., PRD 61 (2000) 116001
ib., PRD 62 (2000) 096012
Arnold, Moore and Yaffe, JHEP 0112 (2001) 009

QCD Compton and annihilation reactions

These are the 2 → 2 particles Feynman diagrams contributing to O(α_S)

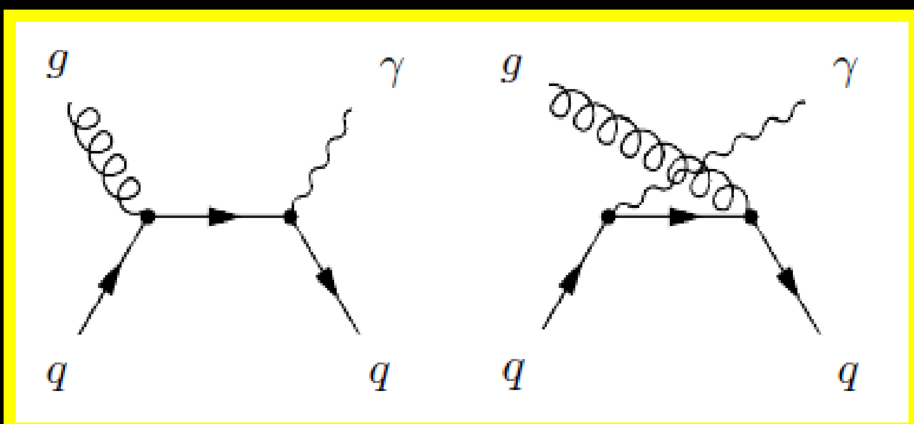
$$q/\bar{q} + g \rightarrow q/\bar{q} + \gamma$$

$$\frac{d\sigma}{dt} = \frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

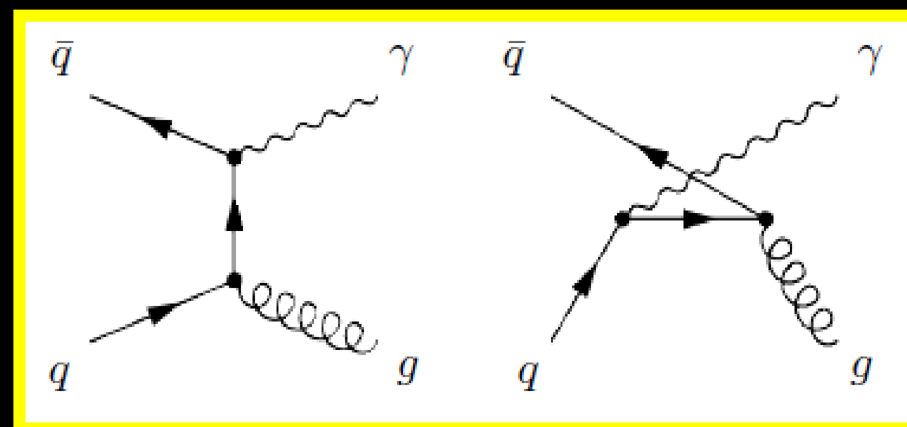
$$q + \bar{q} \rightarrow g + \gamma$$

$$\frac{d\sigma}{dt} = \frac{-\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$

QCD Compton scattering



Quark-antiquark annihilation



$$P_{22} = \frac{\Delta N_{coll}^{2\to 2}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

$$v_{rel} = \frac{s}{2E_1E_2}$$

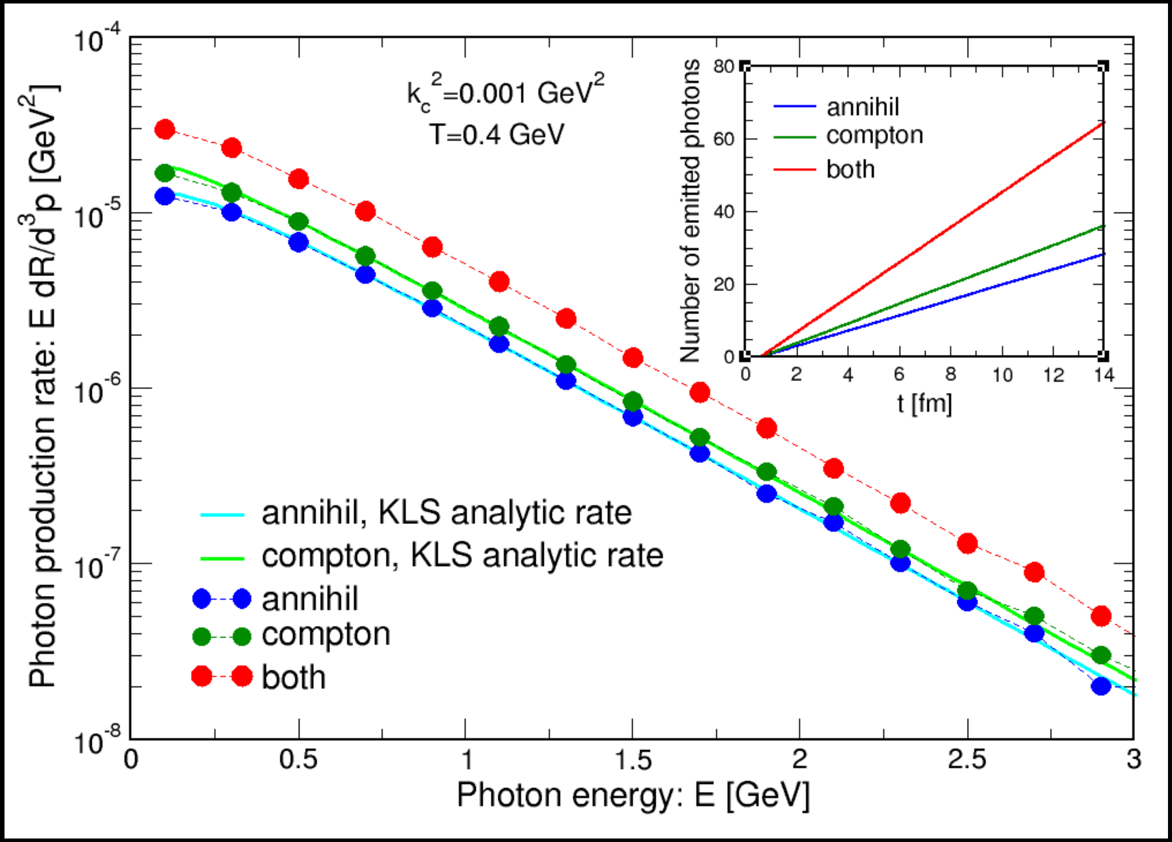
For each processes we have computed the rate *R*
(number of reactions per unit time per unit volume which produce a photon)

Box at fixed T: photon production rates

The thermal emission rates of photons with energy E and momentum **p** were analytically computed by Kapusta, Lichard and Seibert, PRD 44 (1991) 2774

$$E\frac{dR^{\rm Compton}}{d^3p} = \frac{5}{9}\frac{2\alpha\alpha_s}{\pi^4}T^2e^{-E/T} \times\left[\ln(4ET/k_c^2)+\tfrac{1}{2}-C_{\rm Euler}\right]$$

$$E\frac{dR^{\rm annihilation}}{d^3p} = \frac{5}{9}\frac{2\alpha\alpha_s}{\pi^4}T^2e^{-E/T} \times\left[\ln(4ET/k_c^2)-1-C_{\rm Euler}\right]$$

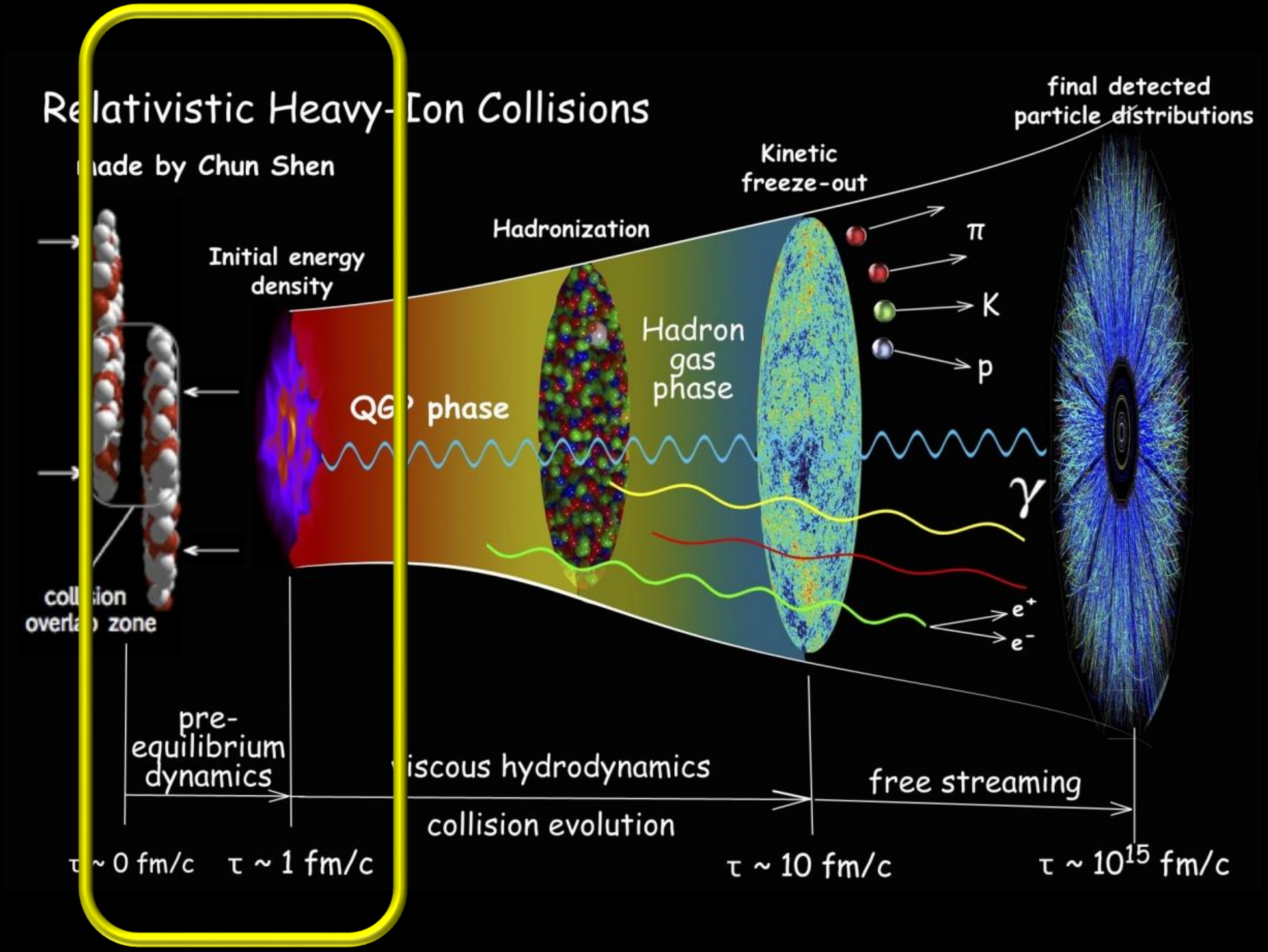


R = dN/d^{4}x

T = 400 MeV

Our transport code results (points) agree with KLS analytic rates.

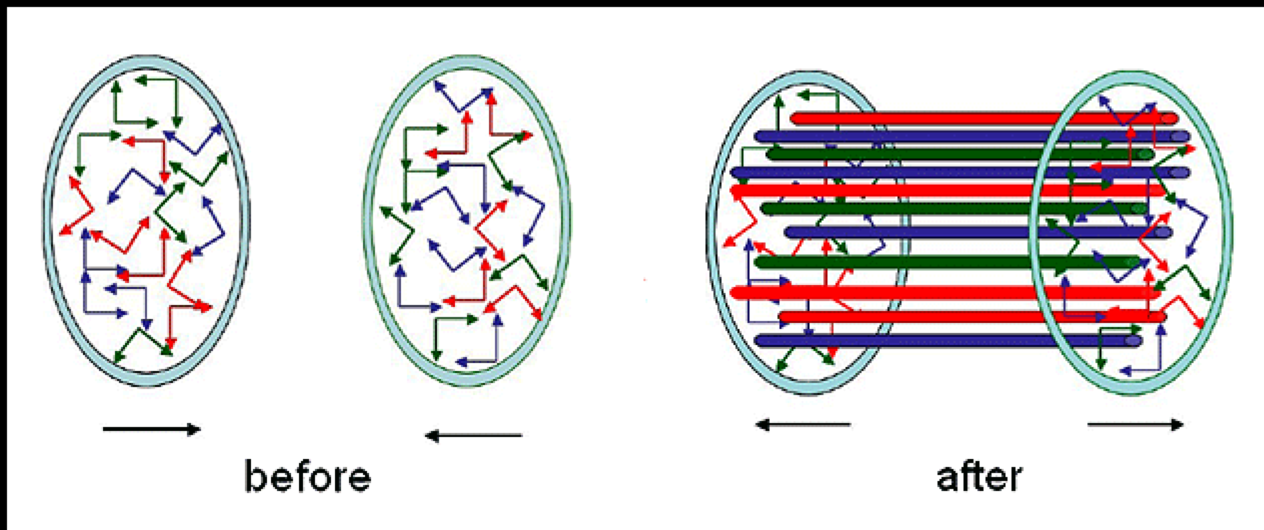
EARLY TIMES DYNAMICS



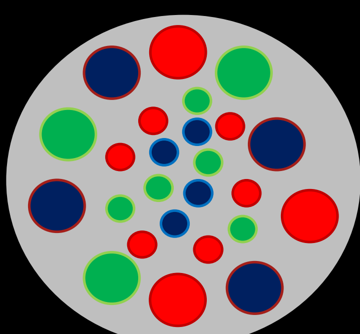
[Source: http://snelling.web.cern.ch/snelling/img/little_bang.jpg]

PRE-EQUILIBRIUM DYNAMICS: GLASMA

Immediately after the collision a peculiar configuration of **strong longitudinal chromo-electric and chromo-magnetic fields** is produced



Transverse plane



How does this configuration of classical color fields become a thermalized and isotropic QGP?

Lappi and McLerran, NPA 772 (2006) 200
Gelis, Lappi and McLerran, NPA 828 (2009) 149
Fukushima and Gelis, NPA 874 (2012) 108

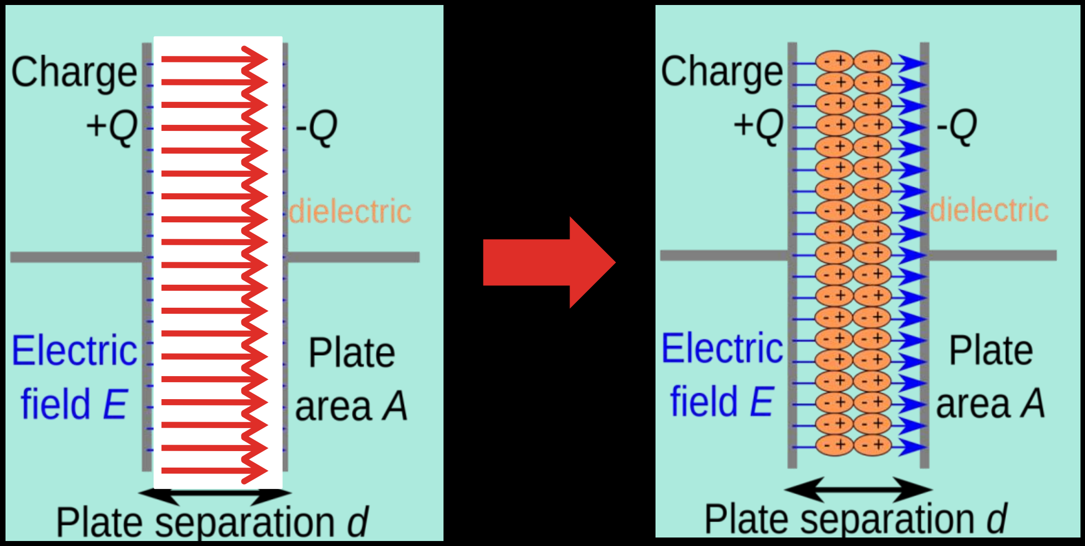
FROM GLASMA TO QUARK-GLUON PLASMA

SCHWINGER MECHANISM

Classical fields decay to particles pairs via tunneling due to vacuum instability

Vacuum with an electric field is unstable towards pair creation

Schwinger effect in QED



Schwinger effect in Electrodynamics

Vacuum decay probability per unit of spacetime to create an electron-positron pair from the vacuum

$$\mathcal{W}(x) = \frac{e^2E^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n\pi m^2}{|eE|}\right)$$

Euler-Heisenberg (1936)
Schwinger, PR 82 (1951) 664

FROM GLASMA TO QUARK-GLUON PLASMA

SCHWINGER MECHANISM

Classical fields decay to particles pairs via tunneling due to vacuum instability

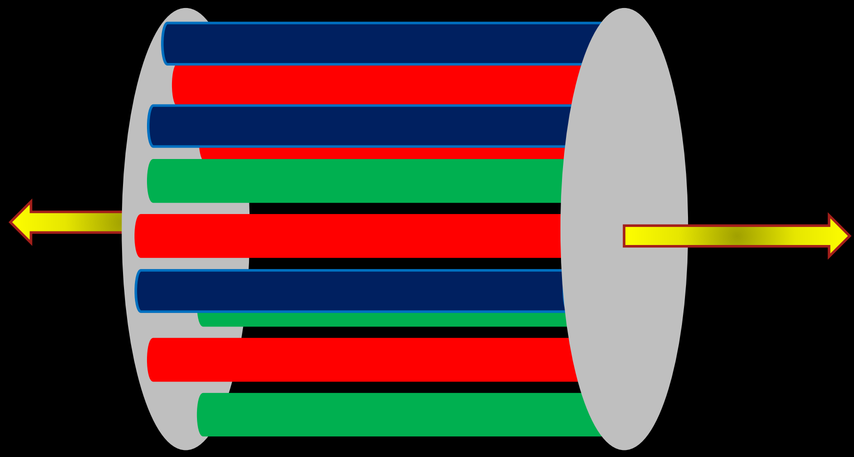
$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x d^2 p_T dp_z} = \mathcal{R}_{jc}(p_T)\delta(p_z)p_0$$

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

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

LONGITUDINAL CHROMO-ELECTRIC FIELDS DECAY IN GLUON PAIRS AND QUARK-ANTIQUARK PAIRS

Schwinger effect in QCD



ABELIAN FLUX TUBE MODEL

- color-magnetic field neglected
- abelian dynamics for the color-electric field
- longitudinal initial field

Casher, Neuberger and Nussinov, PRD 20 (1979) 179
Glendenning and Matsui, PRD 28 (1983) 2890

BOLTZMANN TRANSPORT EQUATION

In order to permit particle creation from the vacuum we need to add a source term to the right-hand side of the Boltzmann equation

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

Florkowski and Ryblewski, PRD 88 (2013) 034028

Field interaction

Source term

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

BOLTZMANN TRANSPORT EQUATION

In order to permit particle creation from the vacuum we need to add a source term to the right-hand side 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) 034028

Field interaction

Source term

$$\frac{dE}{d\tau} = -j_M - j_D$$

conductive current

polarization current

Currents depend on distribution function

Field interaction* + *Source term

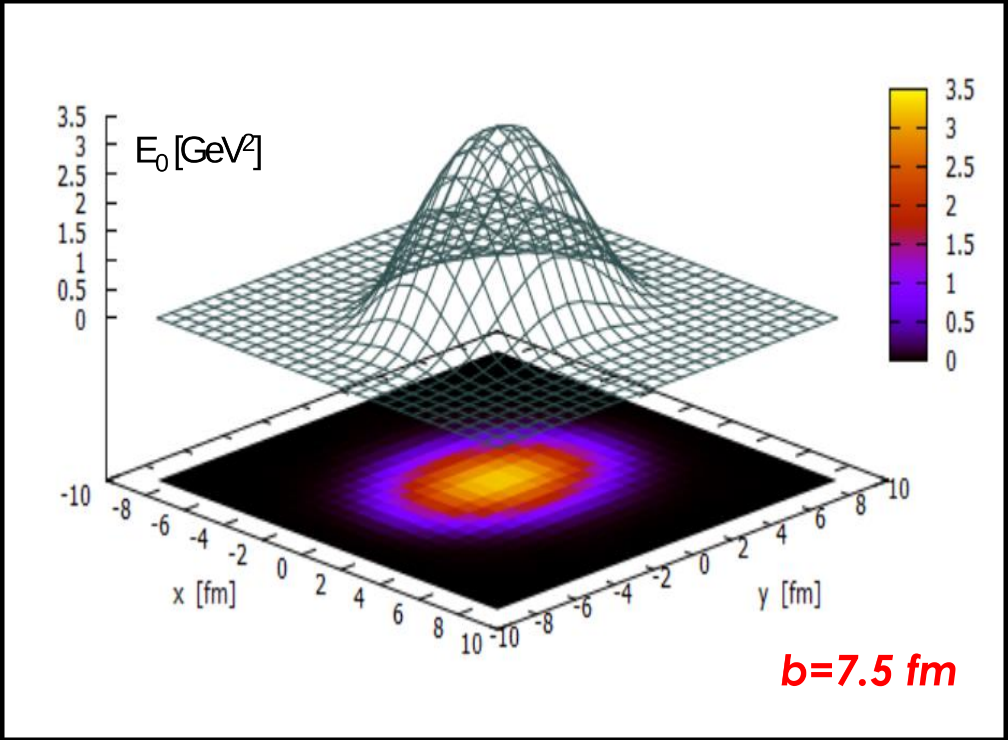
Link between parton distribution function and classical color fields evolution

WE SOLVE SELF-CONSISTENTLY BOLTZMANN AND MAXWELL EQUATIONS

3+1D EXPANSION

Initial color-electric field is obtained matching eccentricity and multiplicity at 0.6 fm/c with those of Th-Glauber simulations.

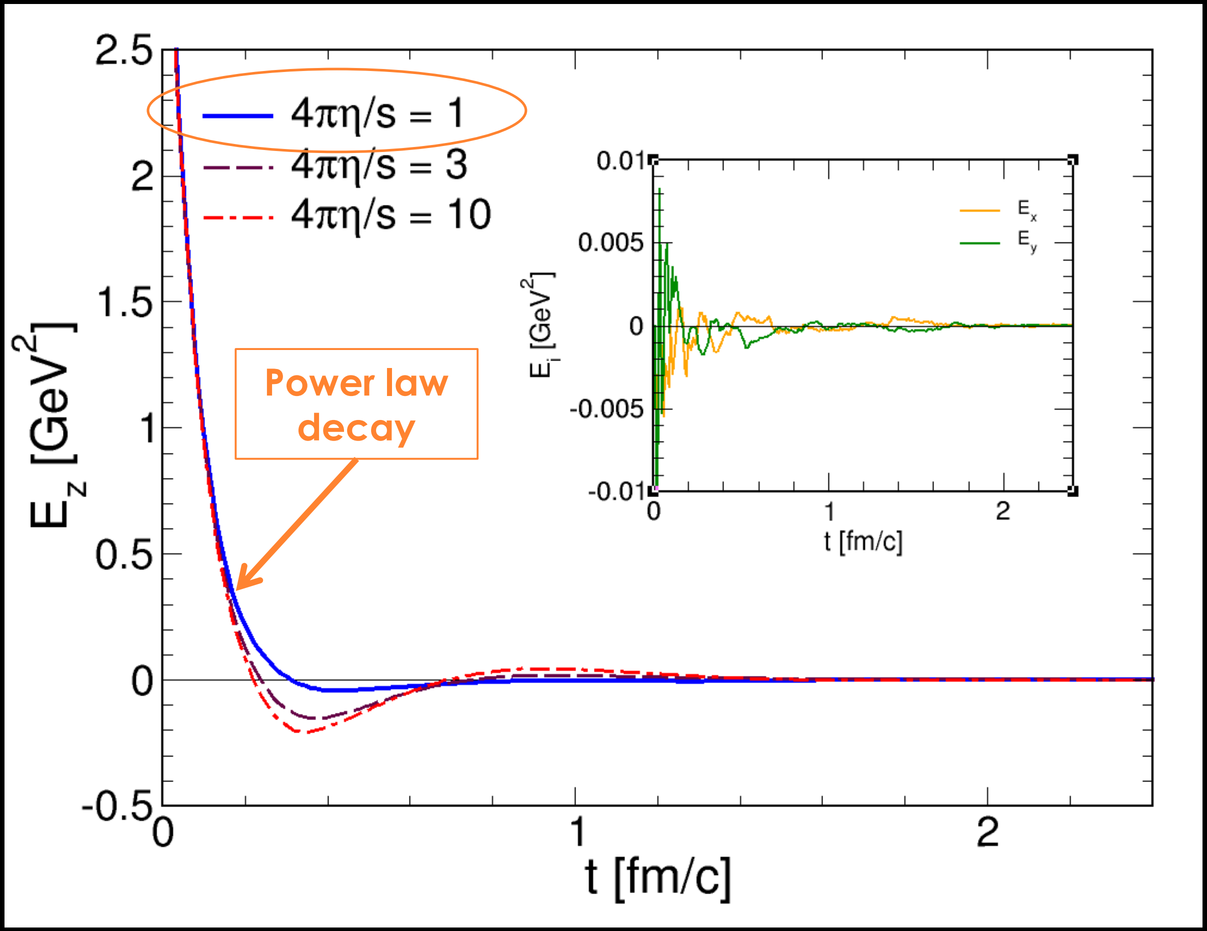
Initial longitudinal field



- ✓ **Electric field with an eccentricity**
  b = 7.5 fm
- ✓ **R-Glauber distribution in transverse plane**
  $E_0 = E_{0,max}\,(0.6\ N_{coll} + 0.4\ N_{part})$
  $E_{0,max} = 3.3\ \mathrm{GeV}^2$
- ✓ **Initial state fluctuations neglected**

By means of one theoretical framework we describe the dynamics from initial state (classical fields) up to final stage (flows production)

ELECTRIC FIELD DECAY



Small viscosity

↓

Large scattering rate

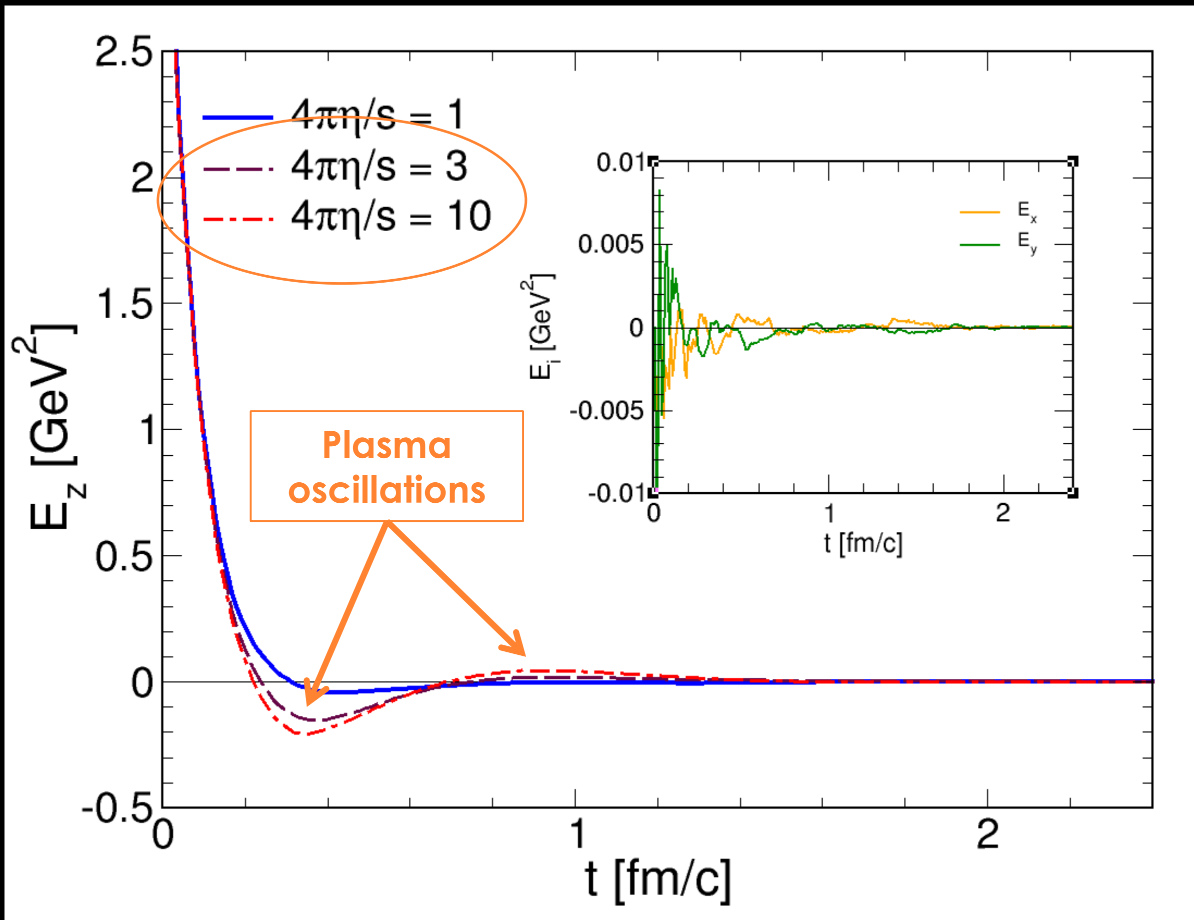
↓

Efficient isotropization

SMALL VISCOSITY
field decays quickly

$$\frac{dE}{d\tau} = -j_M - j_D$$

ELECTRIC FIELD DECAY

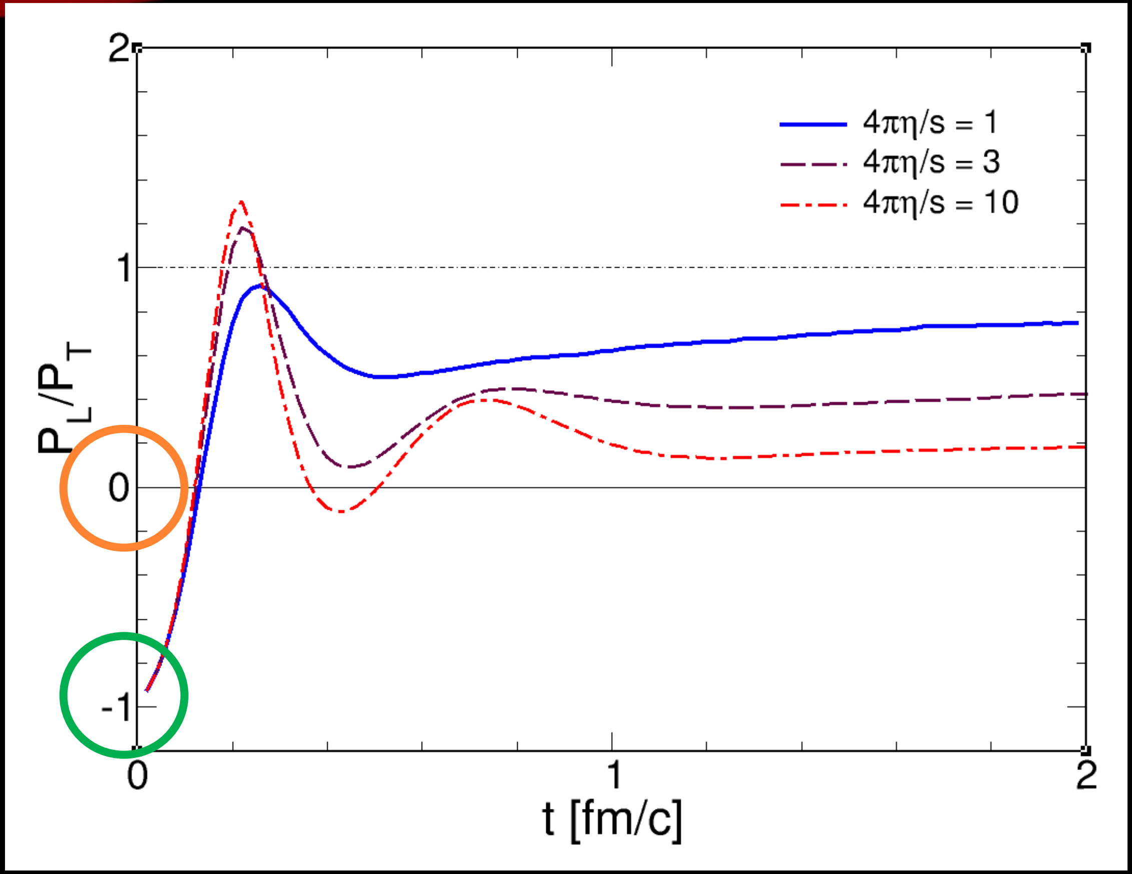


Large viscosity
↓
Small scattering rate
↓
Smaller isotropization efficiency

LARGE VISCOSITY
field is affected by oscillations after a faster initial times decay

$$\frac{dE}{d\tau} = -j_M - j_D$$

ISOTROPIZATION: PRESSURE RATIO



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

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

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

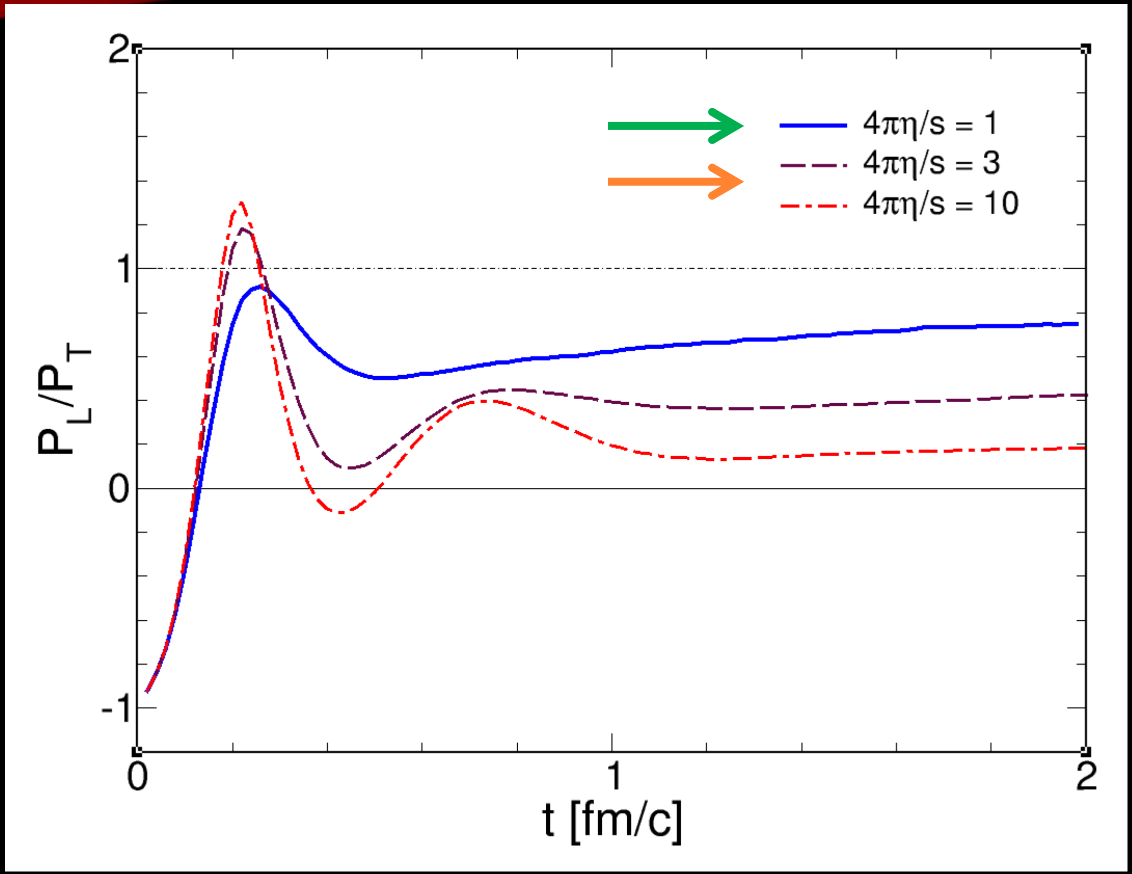
$$P_L = T_{zz}$$
$$P_T = \frac{T_{xx} + T_{yy}}{2}$$

Isotropic system if $P_L = P_T$

High anisotropy: pure field with negative longitudinal pressure

Longitudinal pressure becomes positive due to particles creation within 0.2 fm/c independently of η/s

ISOTROPIZATION: PRESSURE RATIO



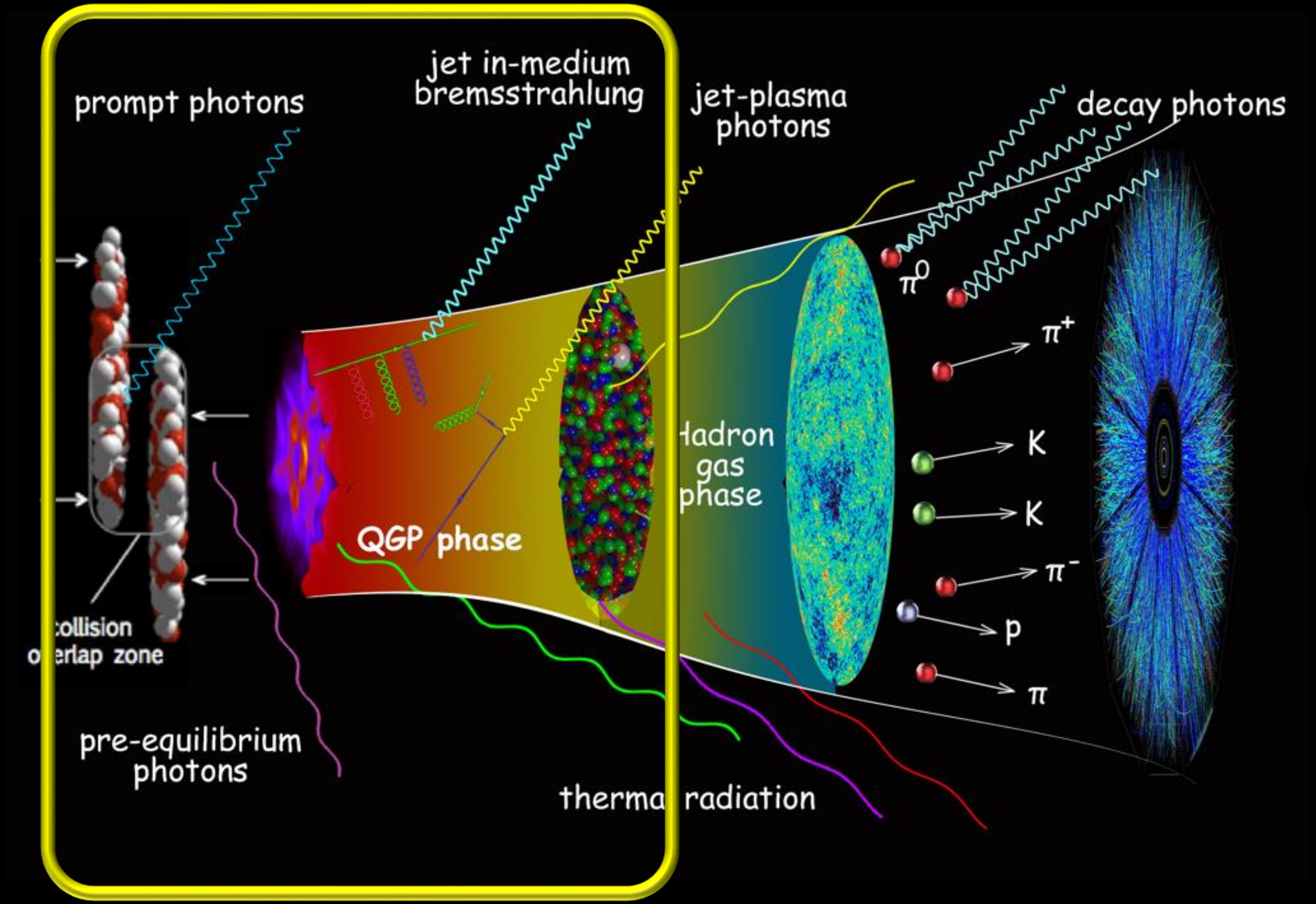
Small viscosity
Quick isotropization in about 1 fm/c

Large viscosity
Less efficient isotropization

Quick isotropization justifies use of viscous hydrodynamics with an initial time of 0.6 fm/c, in which pressure ratio is about 0.5

Initial phase is strongly anisotropic, not thermalized and with negative pressure. Which is its impact on observables?

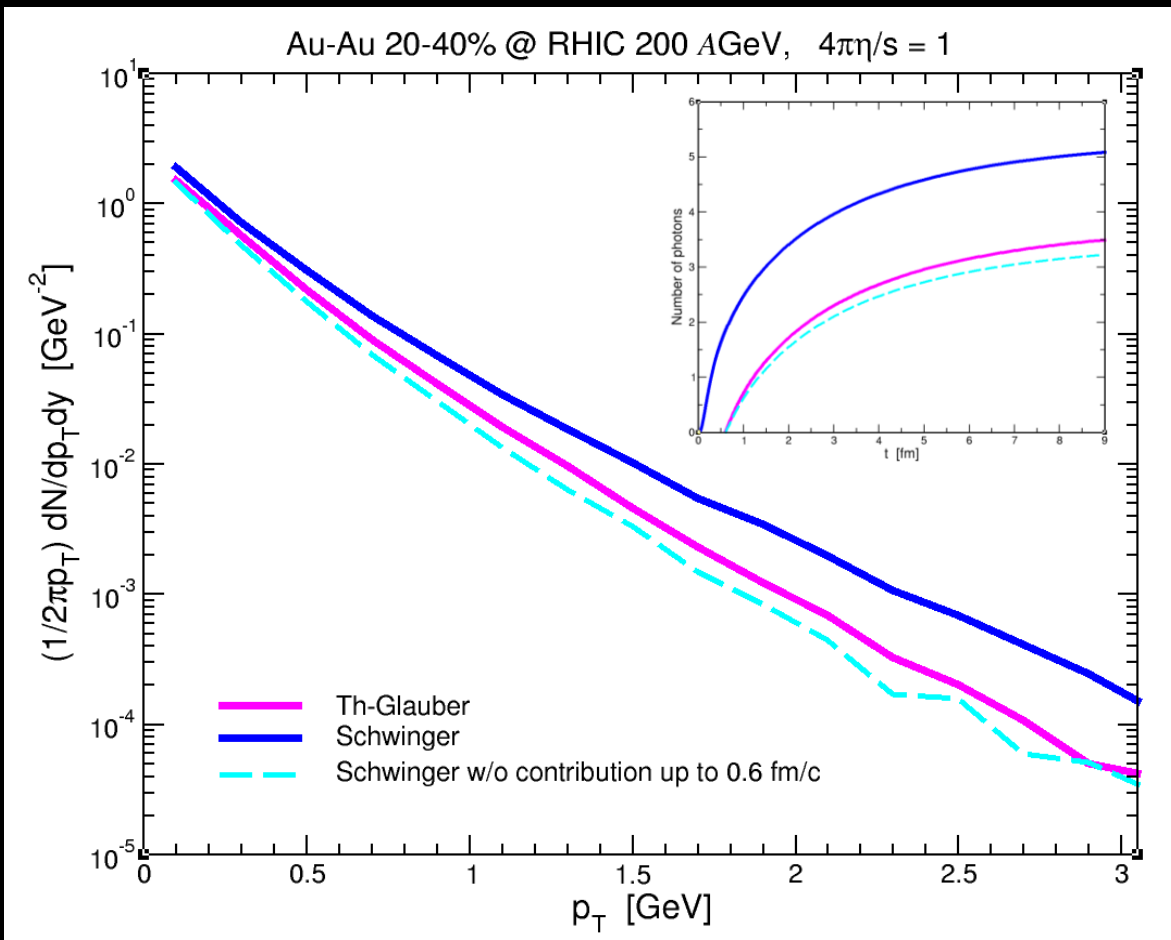
PHOTON PRODUCTION FROM NON-EQUILIBRIUM INITIAL CONDITION



[Source: C. Shen, talk at ECT*, Trento 12/2015]

Results at RHIC: impact of pre-equilibrium

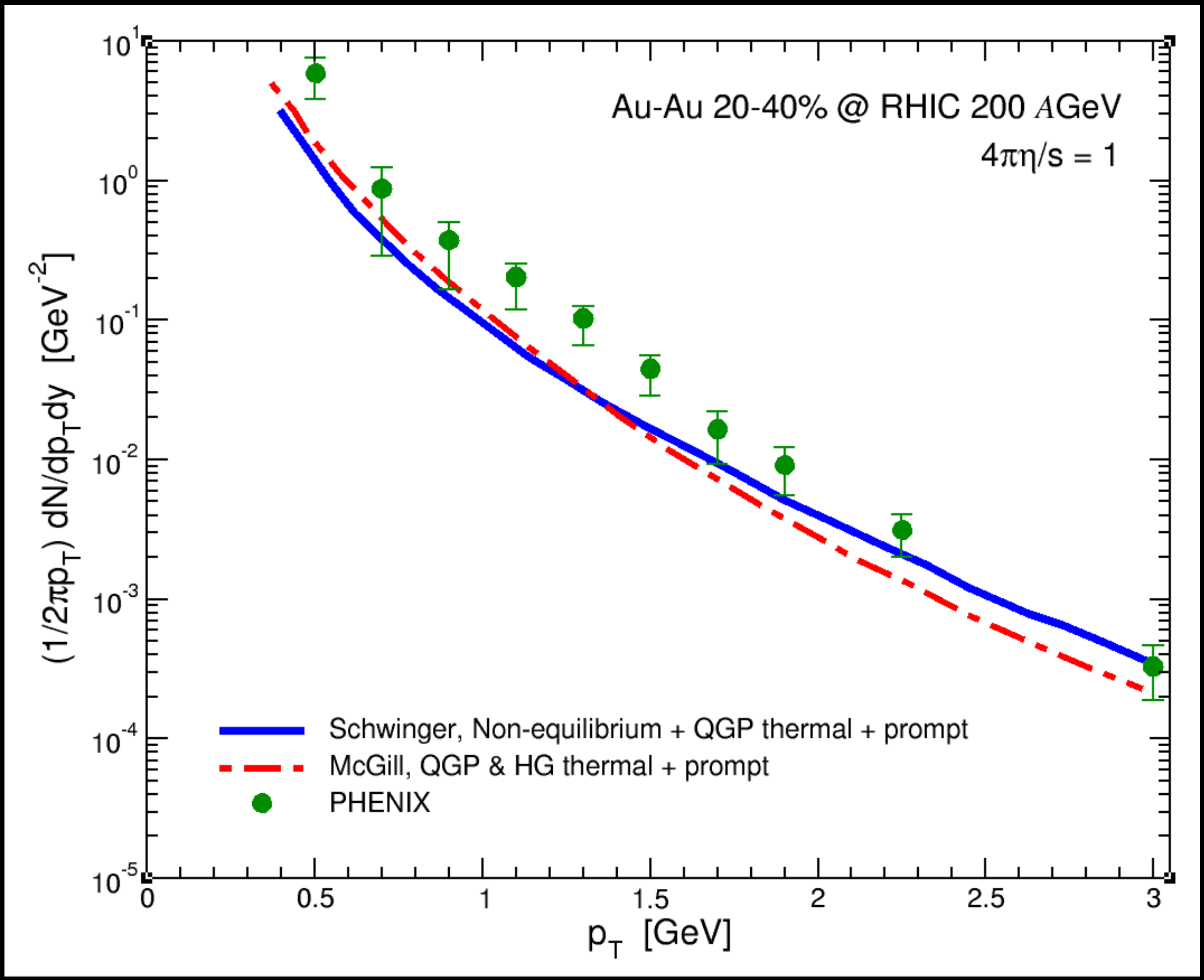
Same evolution after 0.6 fm/c with Glauber and non-equilibrium initial conditions



Schwinger simulations take account of pre-equilibrium effects

Total photon number enhanced of ~30% mainly at high p_T

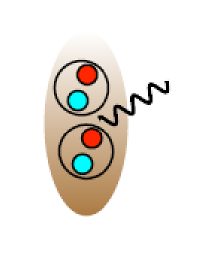
Results at RHIC: photon spectra



Better understanding of high p_T photons

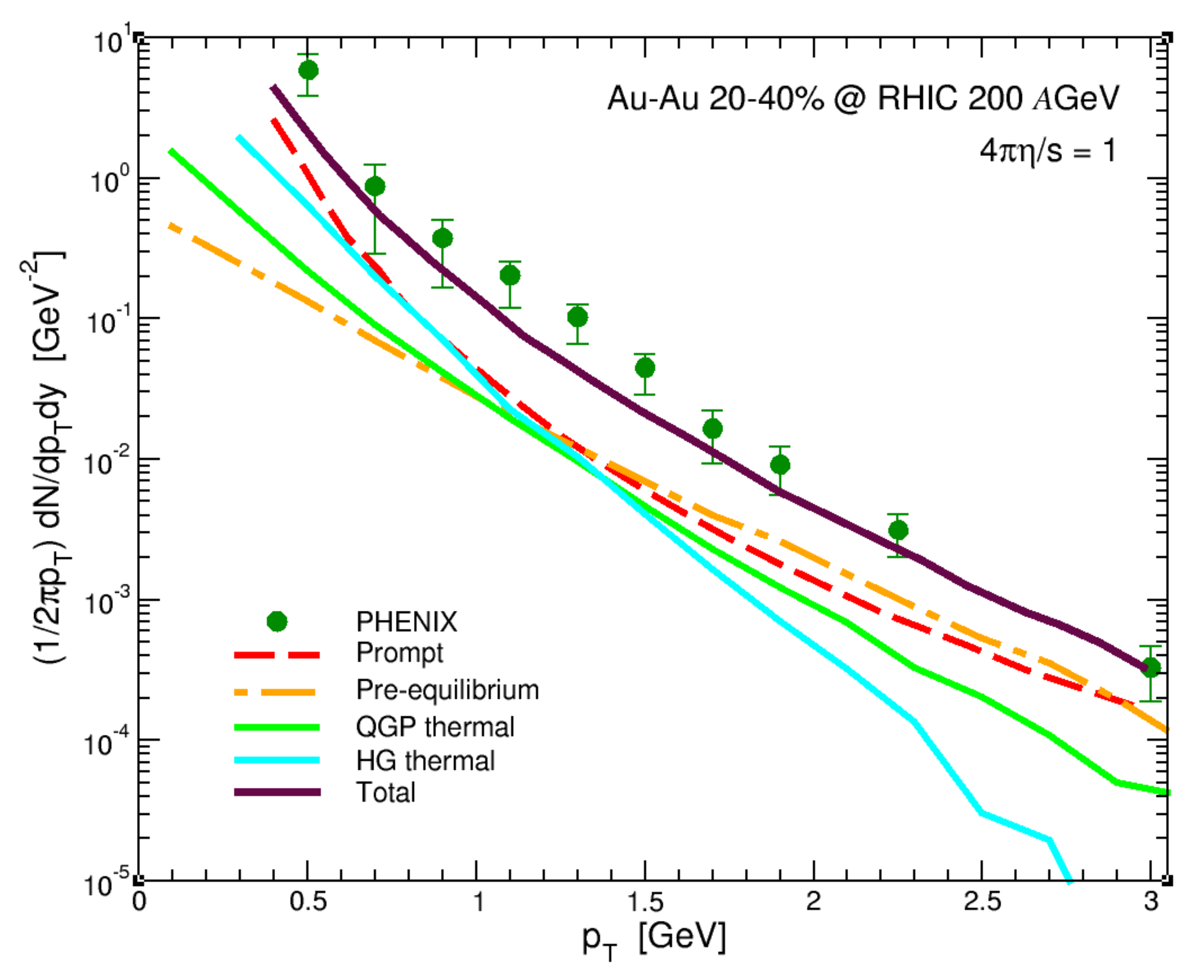
Underestimate of photon emission up to ~1.5 GeV

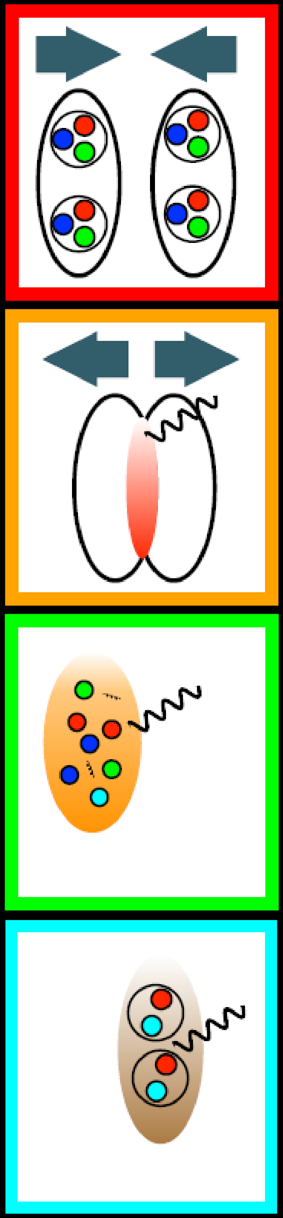
NEED TO CONSIDER HADRONIC THERMAL PRODUCTION



Adare et al. (PHENIX Collaboration), PRC 91 (2015) 064904
Paquet et al., PRC 93 (2016) 044906
Turbide, Rapp and Gale, PRC 69 (2004) 014903

Results at RHIC: different photon sources





By means of one theoretical approach we can identify the different sources of photon production and their relative importance in the spectrum

CONCLUSIONS and OUTLOOKS

- ✓ **Relativistic Transport Theory** allows to study **early times dynamics of heavy ion collisions.**
- ✓ **Schwinger tunneling** provides a **fast particle production**, typically a small fraction of fm/c.
- ✓ **High viscous plasma** is characterized by plasma **oscillations** along the entire evolution of the system, whereas **plasma with small viscosity** reaches the **hydro regime** quickly, within 1 fm/c.
- ✓ **Electromagnetic probes** are an efficient tool to investigate the initial state of heavy ion collisions and the properties of quark-gluon plasma.
- ✓ Impact of pre-equilibrium stage on **photon spectrum** is remarkable.

- ✓ Improve the description of photon emission processes of different sources.
- ✓ Study the impact of early stage dynamics on elliptic flow of direct photons.

Thank you for your attention!

BACK SLIDES

SCHWINGER EFFECT: numerical estimates

IN ELECTRODYNAMICS

Given exponential suppression, probability for tunneling to occur becomes non negligible as soon as

$$|\boldsymbol{E}| \approx m_e^2 \approx 10^{18}\ \mathrm{Volt/m}$$

QED critical field: 2.6×10^{-7} GeV^2

Particles pop up is similar to dielectric breakdown.

Thunderbolt
3×10^{6} Volt/m

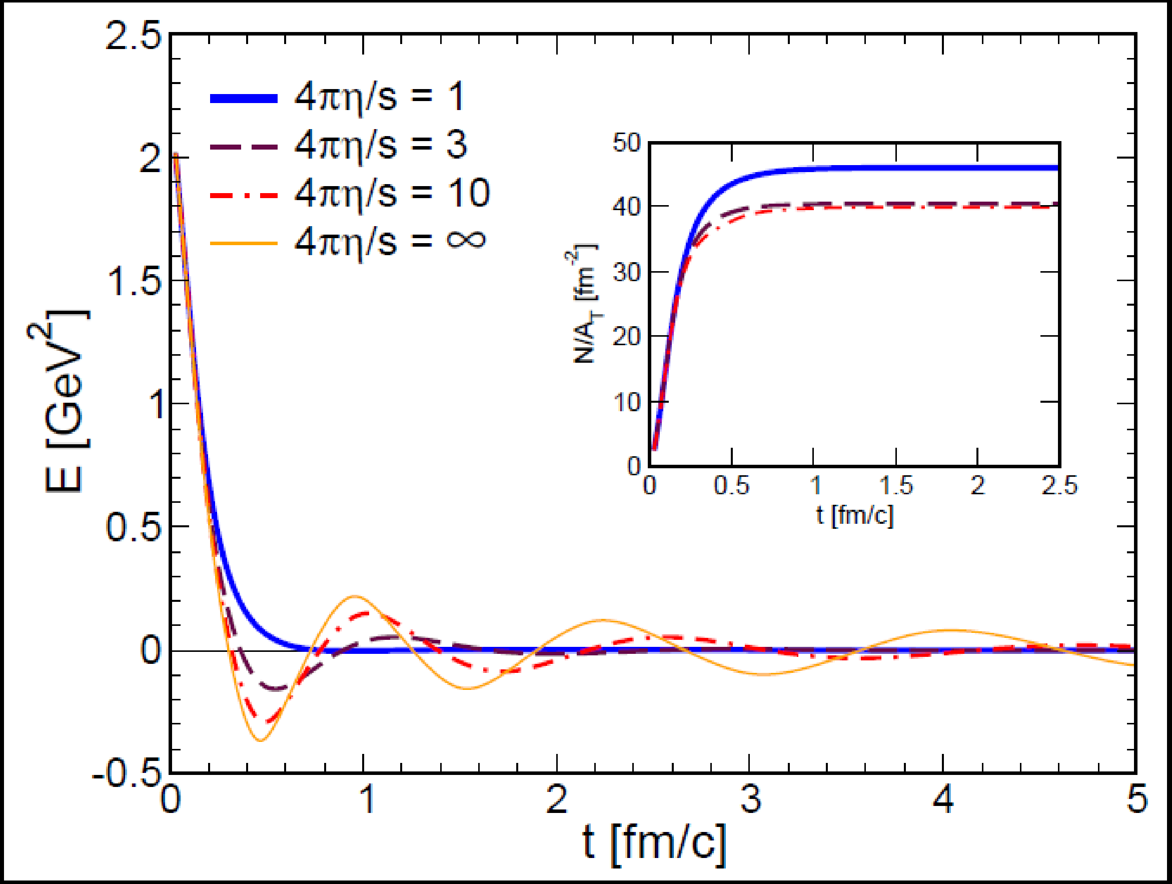
IN CHROMODYNAMICS

In QCD the critical field is given by the string tension: the energy per unit length carried by the field has to be larger of that required to produce a deconfined pair

QCD critical field: 0.2-0.6 GeV^2

Initial color-electric field in HICs:
gE: 1-10 GeV^2

1+1D EXPANSION: ELECTRIC FIELD DECAY



Oliva et al., PRC 92 (2015) 064904

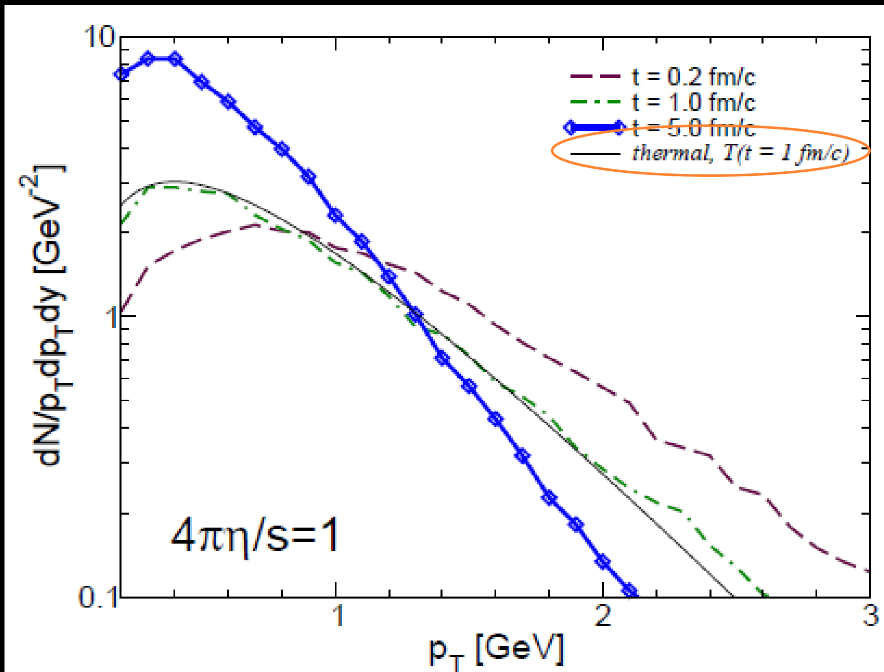
Small viscosity → **Plasma oscillations**

Large viscosity → **Power law decay**

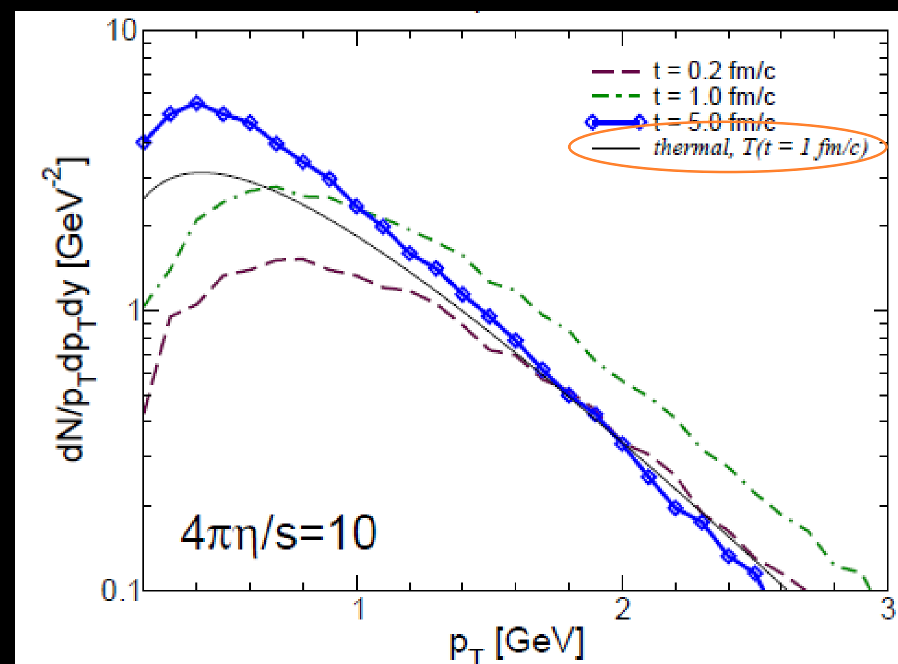
1+1D EXPANSION: THERMALIZATION

$$\frac{dN}{p_T dp_T dy} \propto p_T e^{-\beta p_T}$$

Thermal spectrum



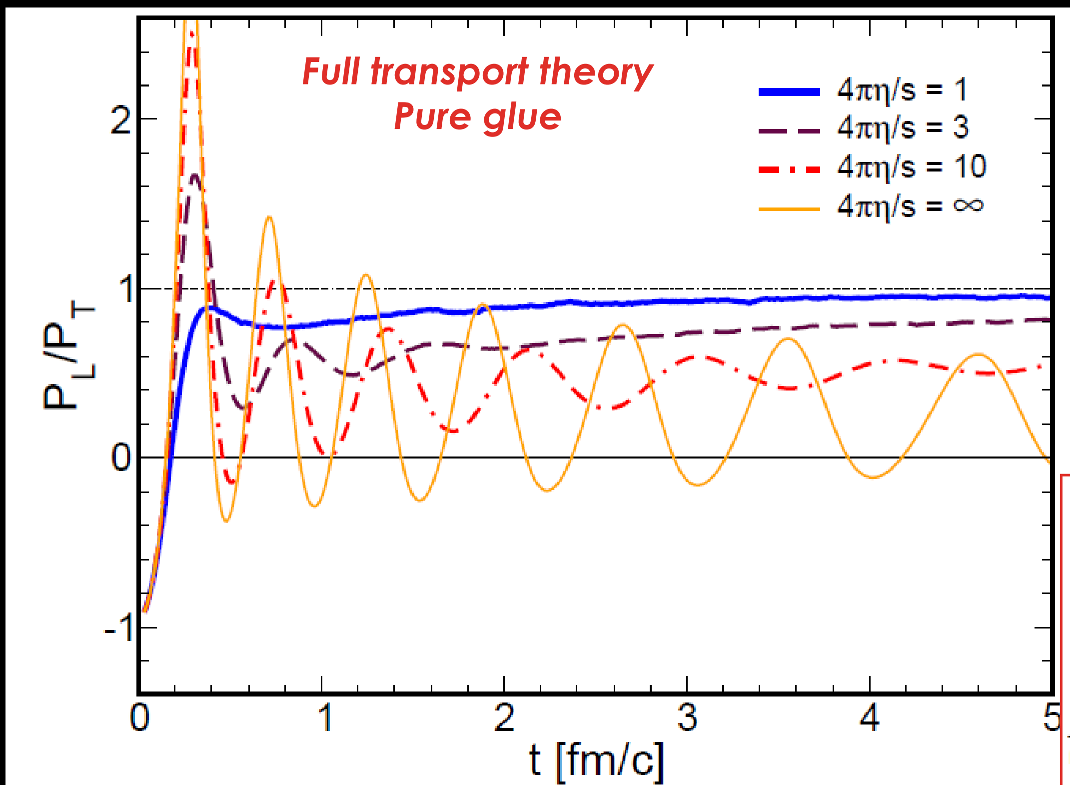
SMALL VISCOSITY
Thermalized plasma within 1 fm/c
Efficient cooling



LARGE VISCOSITY
Plasma non completely thermalized in 1 fm/c
Small cooling efficiency

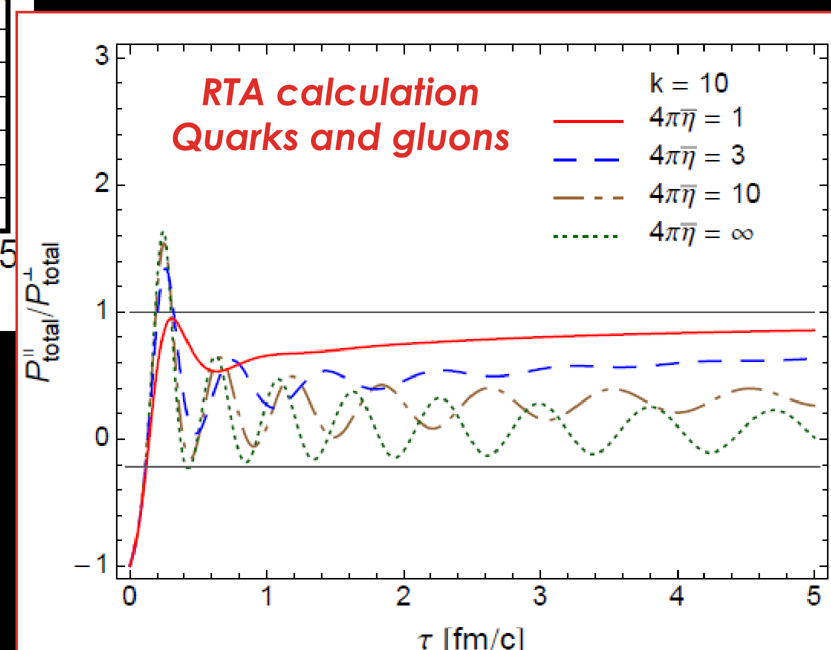
Oliva et al., PRC 92 (2015) 064904

1+1D EXPANSION isotropization



Oliva et al., PRC 92 (2015) 064904

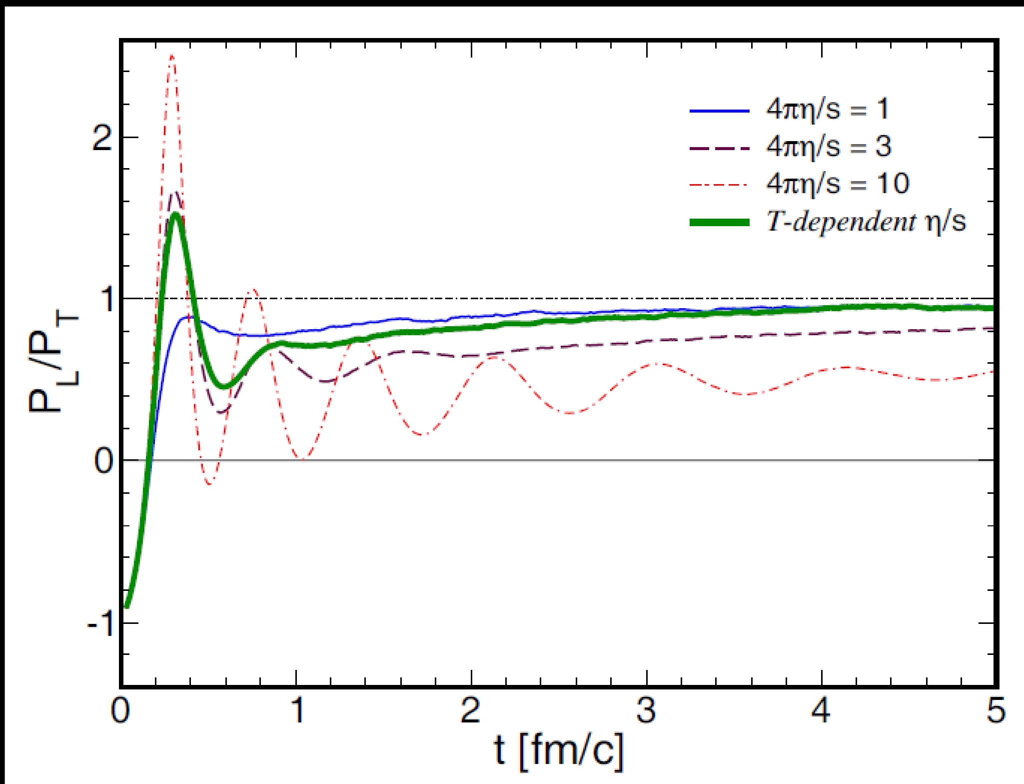
COMPARISON WITH PRESSURE RATIO FROM Florkowski and Ryblewski, PRD 88 (2013)



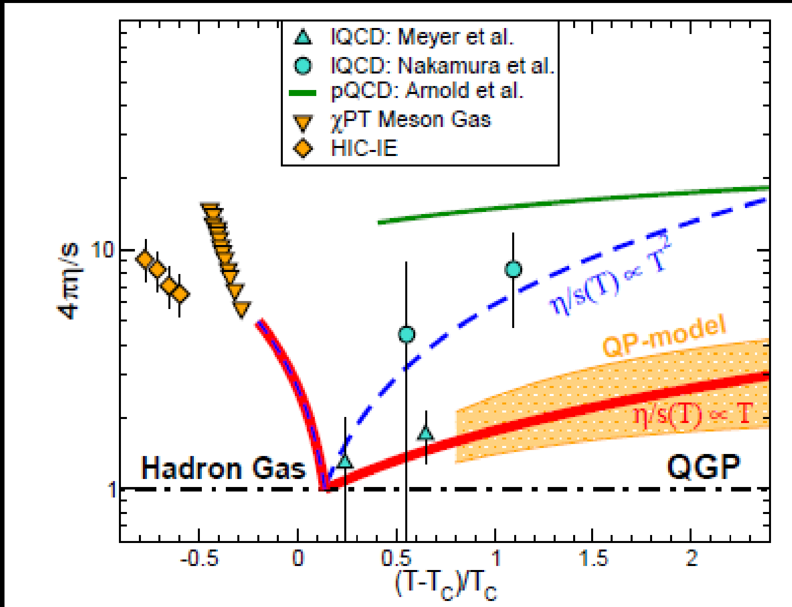
- ❑ **Excellent qualitative agreement**
- ❑ **Quantitative difference due to the different calculation schemes**

1+1D EXPANSION isotropization

SHEAR VISCOSITY η
is a measure of how velocity of fluid changes with depth



TEMPERATURE DEPENDENT VISCOSITY



Plumari et al., J.Phys.Conf.Ser. 420 (2013) 012029

Results at RHIC evolution of photon spectrum from non-equilibrium initial condition