TNPI 2017 – Cortona
XVI Conference on Theoretical Nuclear Physics in Italy

The pre-equilibrium stage of ultra-relativistic heavy ion collisions and its impact on photon production

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Francesco Scardina

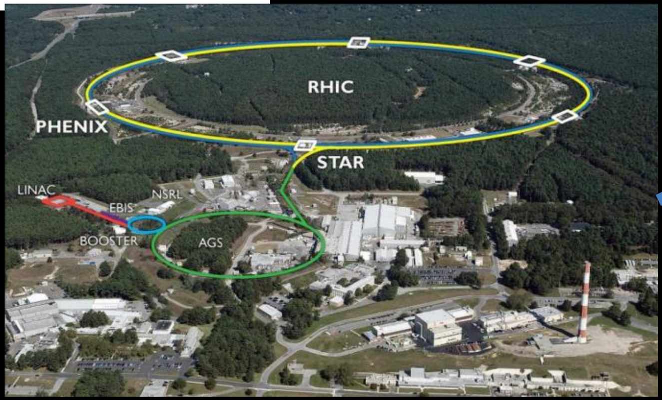
RELATIVISTIC HEAVY ION COLLISIONS

Large Hadron Collider (LHC) at CERN

E = 0.9–5.5 *A* TeV

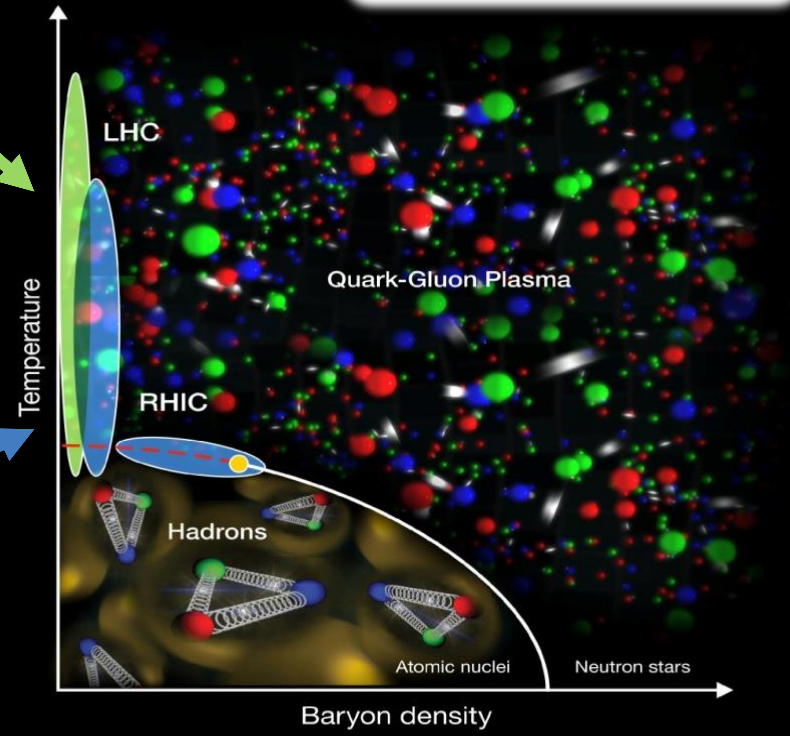
Relativistic Heavy Ion Collider (RHIC) at BNL

E = 9–200 *A* GeV

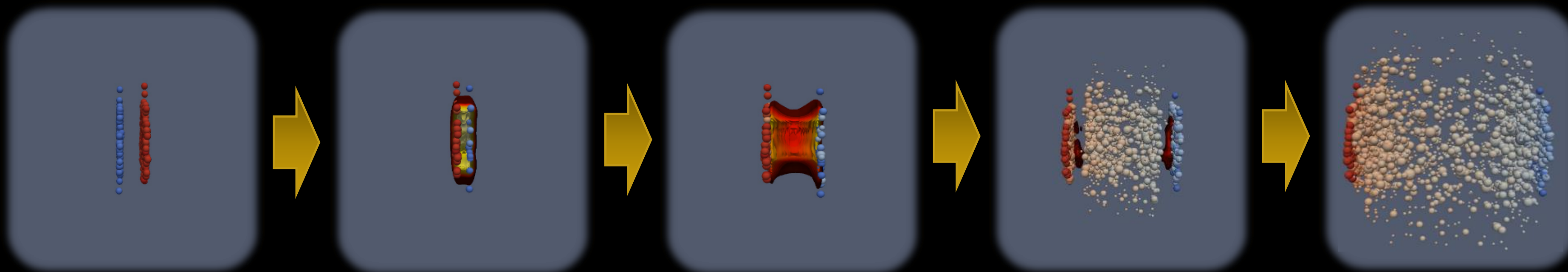


allow to experimentally investigate the high temperature and small baryon density region of the nuclear matter phase diagram

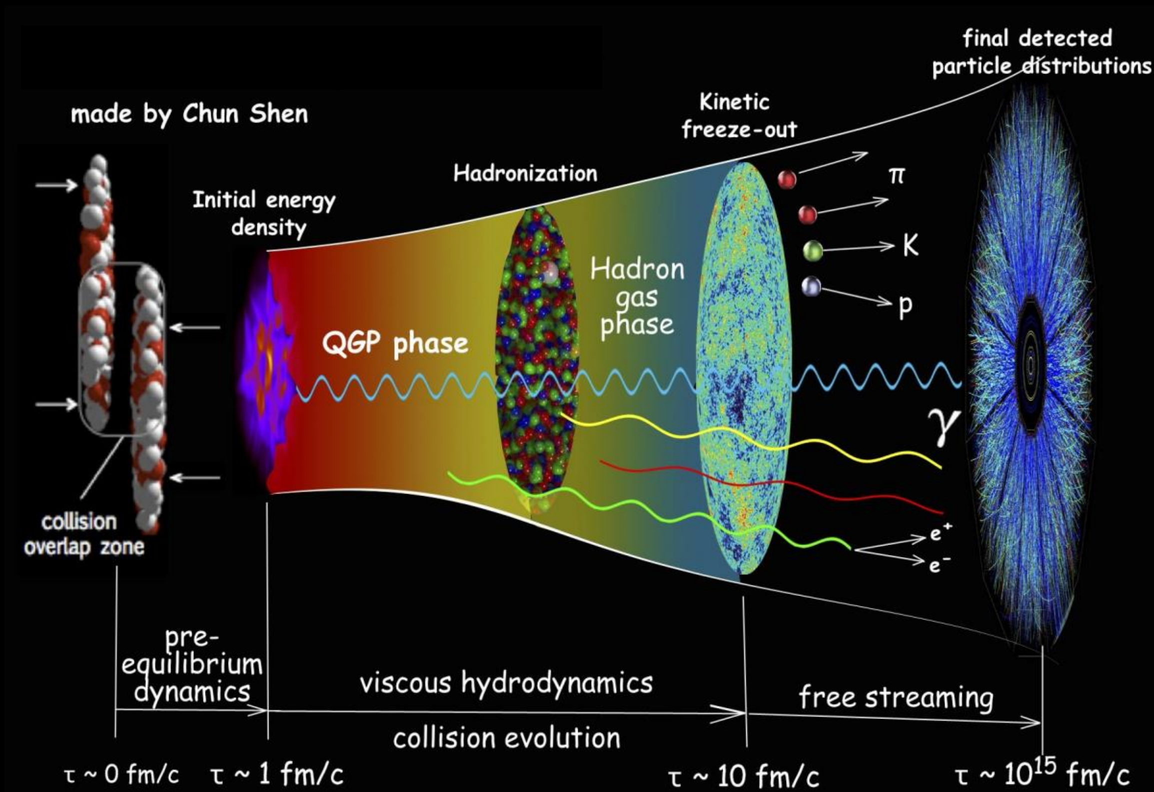
QUARK GLUON PLASMA



RELATIVISTIC HEAVY ION COLLISIONS



made by Jonah Bernhard



EXPANDING FIREBALL

the evolution lasts about

$t \sim 10\text{-}20$ fm/c $\sim 10^{-23}$ s

initial temperature is about

$T \sim 300\text{-}600$ MeV $\sim 10^{12}$ K

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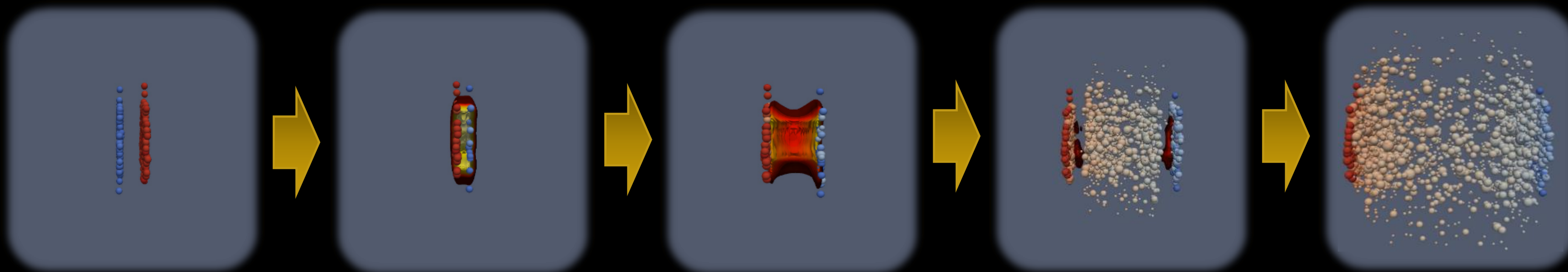

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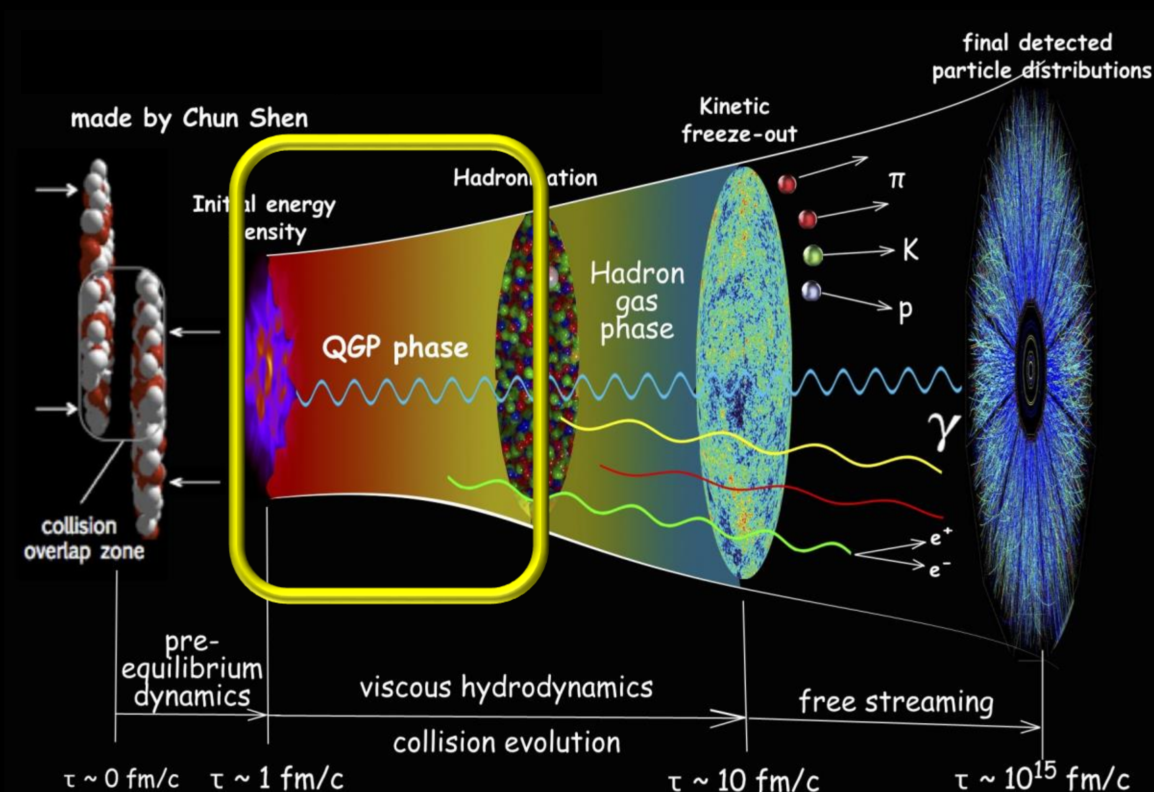

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Quark-Gluon Plasma

hydrodynamical behaviour with very low viscosity and collective flows formation

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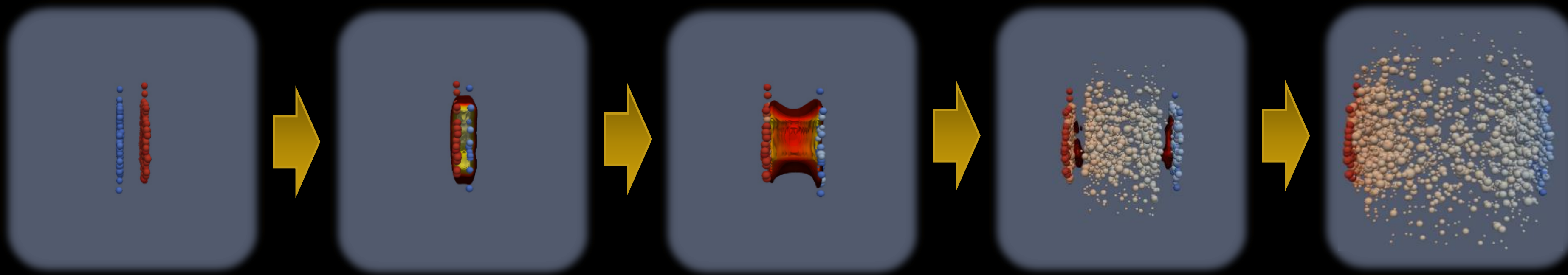

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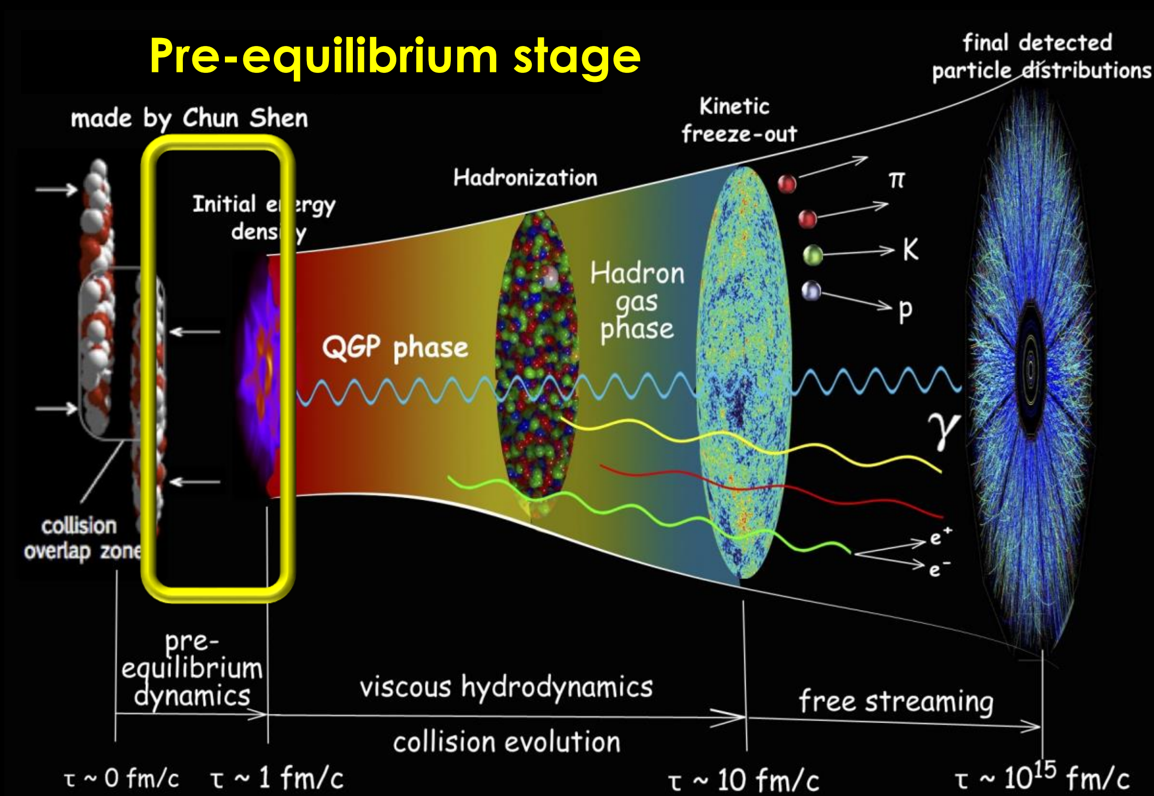

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Quark-Gluon Plasma

hydrodynamical behaviour with very low viscosity and collective flows formation

BOLTZMANN TRANSPORT EQUATION

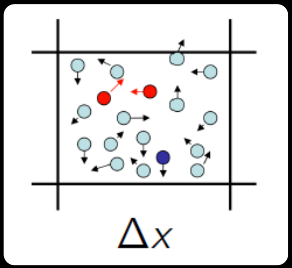
In order to **simulate** the temporal evolution of the fireball we solve the **Boltzmann equation** for the parton distribution function **f(x,p)**

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

Free streaming

Field interaction
e.g. color-electric field

Collision integral
deviations from ideal hydro



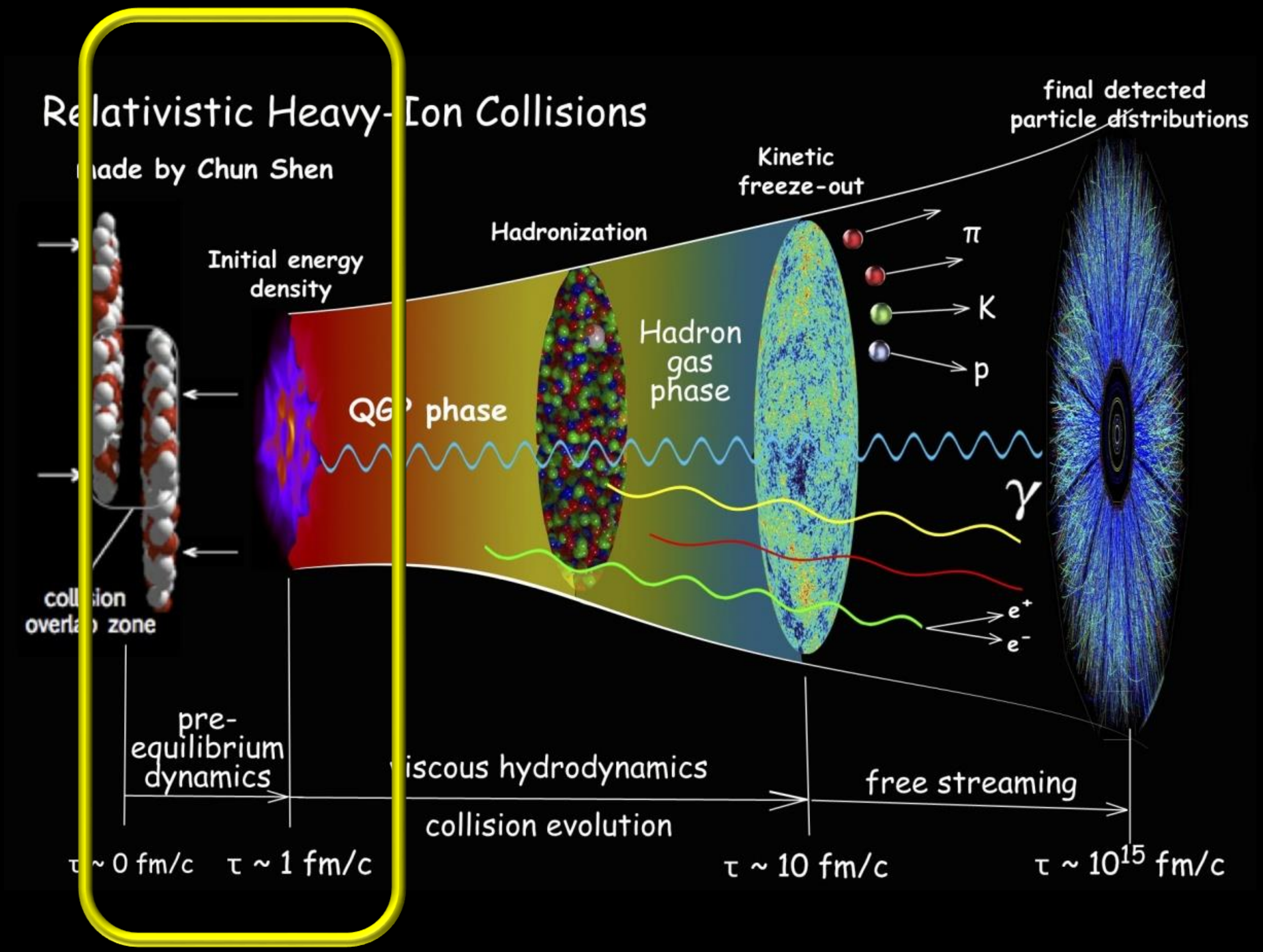
$$\mathcal{C}[f] = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2}(f'_1 f'_2 - f_1 f_2) \times |\mathcal{M}_{12\to 1'2'}|\,(2\pi)^4 \delta^{(4)}(p'_1 + p'_2 - p_1 - p_2)$$

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

Follow the entire dynamical fireball evolution within one single theoretical approach

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

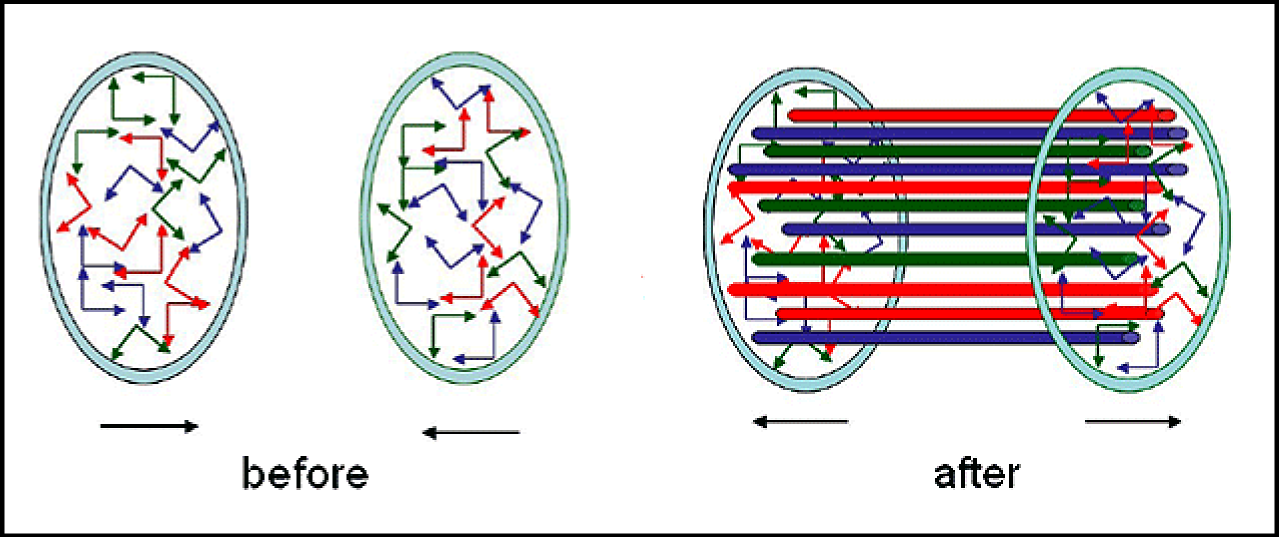
EARLY TIME DYNAMICS



Picture credit: Chun Shen (McGill University, Montreal QC, Canada)

PRE-EQUILIBRIUM DYNAMICS: GLASMA

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



ASSUMPTIONS of HYDRO SIMULATIONS

- ❖ Isotropization
- ❖ Thermalization
- ❖ QGP formation

achieved within $T_{eq} \leq 1$ fm/c

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

Oliva et al., PRC 92 (2015) 064904
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

Vacuum with an electric field is unstable towards pair creation

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

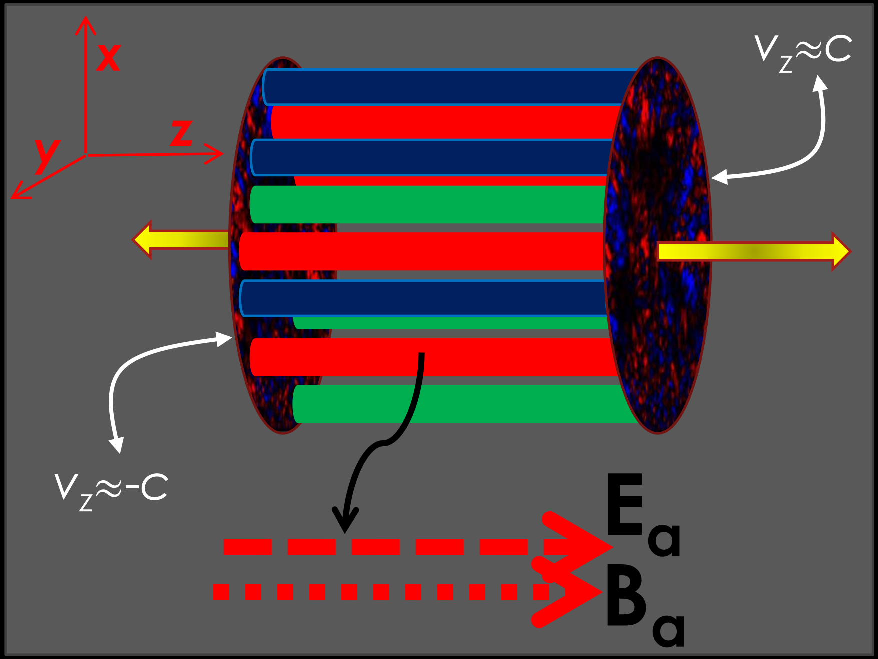
LONGITUDINAL CHROMO-ELECTRIC FIELDS DECAY IN GLUON PAIRS AND QUARK-ANTIQUARK PAIRS

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

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

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

Casher, Neuberger and Nussinov, PRD 20 (1979) 179
Glendenning and Matsui, PRD 28 (1983) 2890
Florkowski and Ryblewski, PRD 88 (2013) 034028



made by Marco Ruggieri

ABELIAN FLUX TUBE MODEL

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

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

$$\underbrace{\left(p_\mu \partial^\mu + g Q_{jc} F^{\mu\nu} p_\mu \partial_\nu^p\right)}_{\text{Field interaction}} f_{jc} = \underbrace{p_0 \frac{\partial}{\partial t} \frac{d N_{jc}}{d^3 x d^3 p}}_{\text{Source term}} + \mathcal{C}[f]$$

Florkowski and Ryblewski, PRD 88 (2013) 034028

$$\frac{dE}{d\tau} = \underbrace{\underbrace{-j_M}_{\text{conductive current}} \underbrace{- j_D}_{\text{polarization current}}}_{\text{Currents depend on distribution function}}$$

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

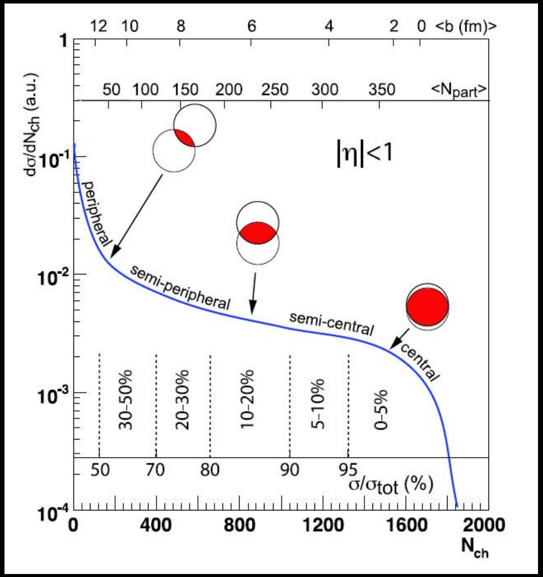
Field interaction* + *Source term

Link between parton distribution function and classical color fields evolution

WE SOLVE SELF-CONSISTENTLY BOLTZMANN AND MAXWELL EQUATIONS

3+1D EXPANSION simulating RHIC and LHC collisions

EQUILIBRIUM INITIAL CONDITIONS
given by
Glauber distribution in x_T-space
thermal spectrum in p_T-space
Th-Glauber simulations



Miller et al., ARNPS 57 (2007) 205

RHIC **Starting time: t_0 = 0.6 fm/c**

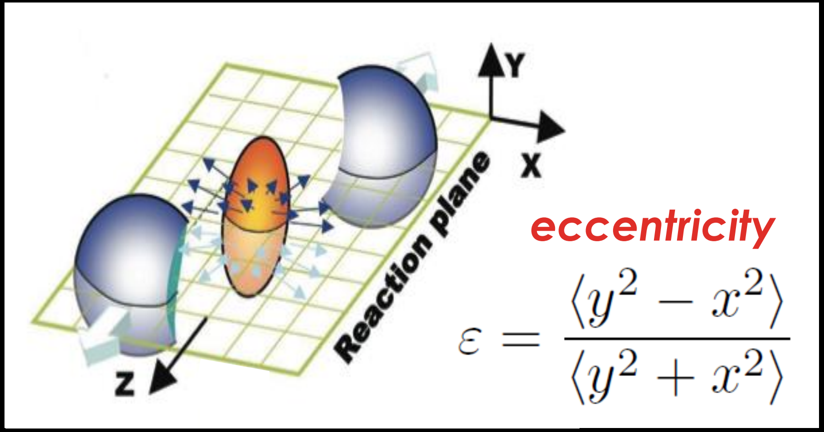
For 20-40% centrality class

- Multiplicity of about 1700 particles
- Initial eccentricity of about 0.33

LHC **Starting time: t_0 = 0.3 fm/c**

For 20-40% centrality class

- Multiplicity of about 3600 particles
- Initial eccentricity of about 0.33



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

3+1D EXPANSION simulating RHIC and LHC collisions

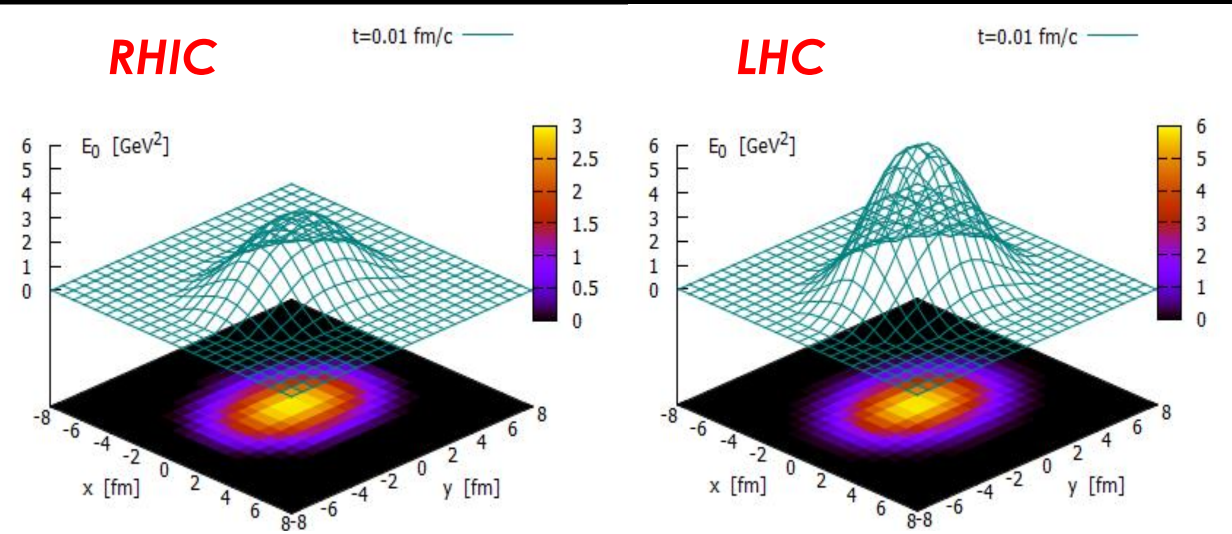
PRE-EQUILIBRIUM DYNAMICS
given by
initial chromo-electric field
smooth in transverse plane

AFTm simulations

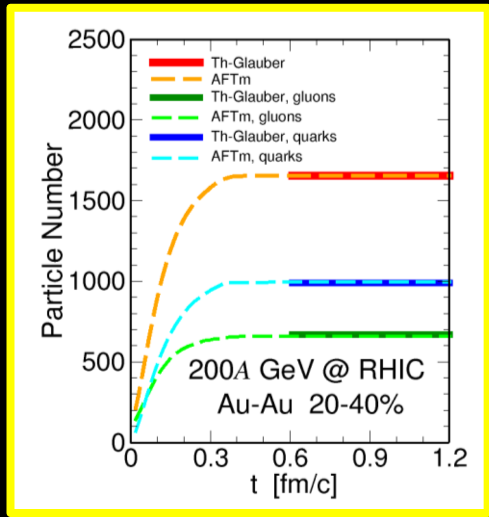
$$E_z^0(\boldsymbol{x}_T) = E^0_{\max}[\alpha\,\rho_{\rm coll}(\boldsymbol{x}_T) + (1-\alpha)\,\rho_{\rm part}(\boldsymbol{x}_T)]$$

Parameters fixed matching multiplicity and eccentricity of the bulk medium with the Th-Glauber ones

RHIC/LHC **Starting time: $t_0 = 0^+$ fm/c**

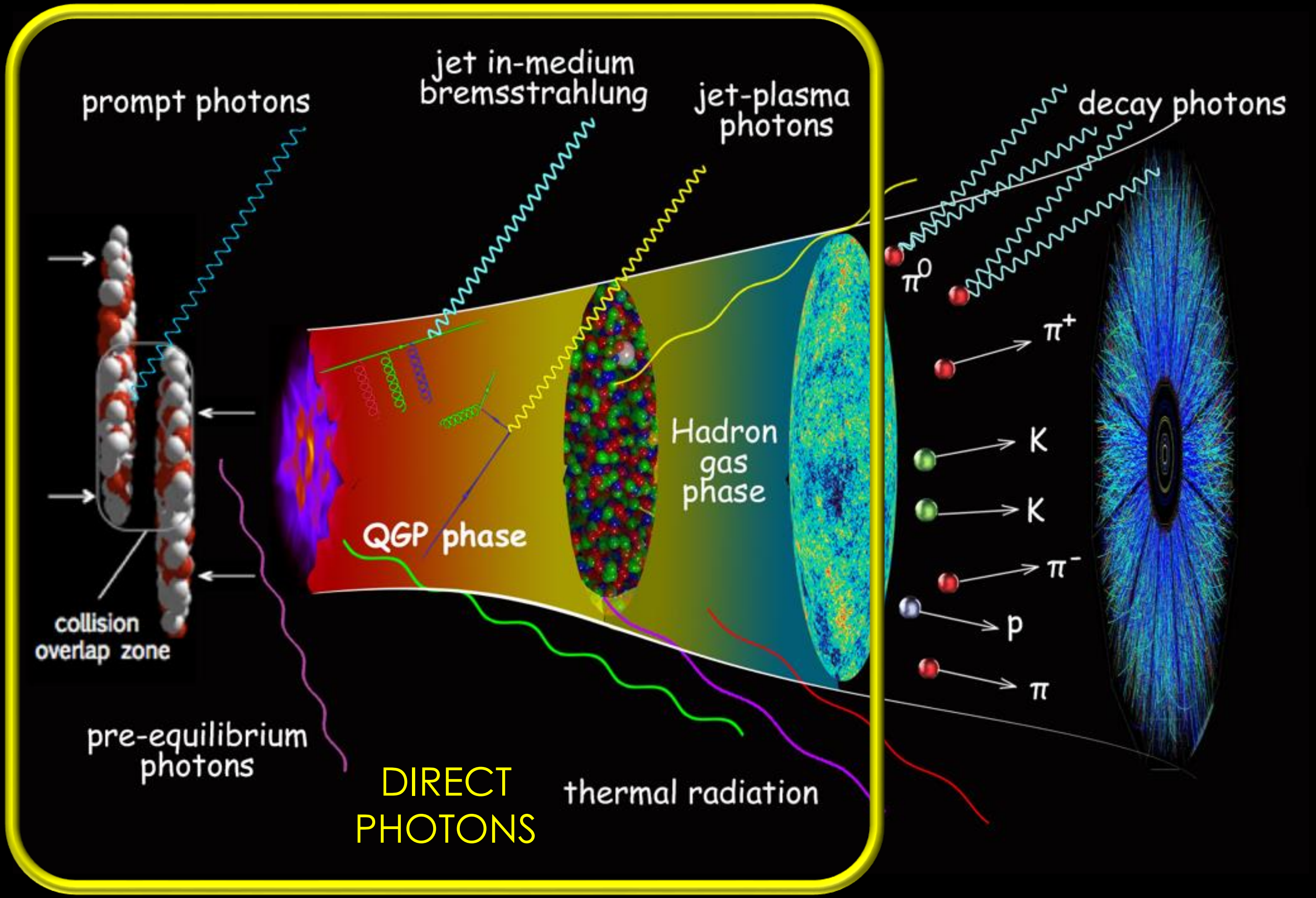


initial fields for 20-40% centrality class



QGP formation time about 0.3 fm/c

PHOTON PRODUCTION



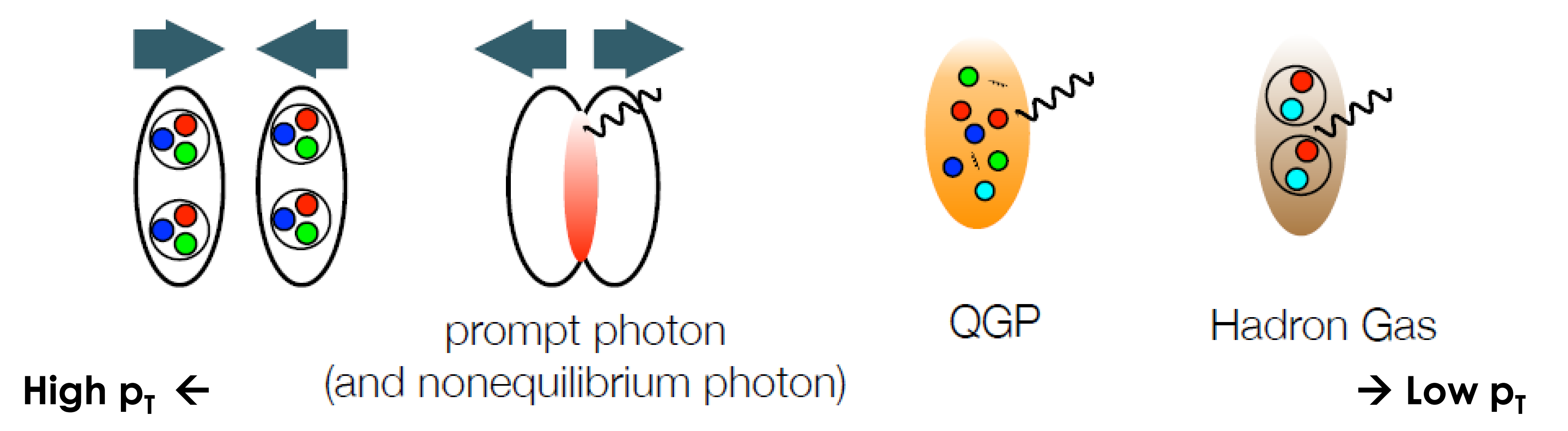
[Source: C. Shen, talk at ECT*, Trento 12/2015]

ELECTROMAGNETIC PROBES

Once produced, **photons** do not suffer further interaction with the medium due to their **electromagnetic nature** ($\alpha \ll \alpha_S$)

DIRECT PHOTONS

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



Experiments can not distinguish among the different sources

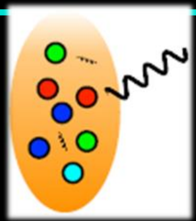
Theoretical models can be used to identify these sources and their relative importance in the spectrum

QGP AND HADRONIC PHOTONS

fireball evolution

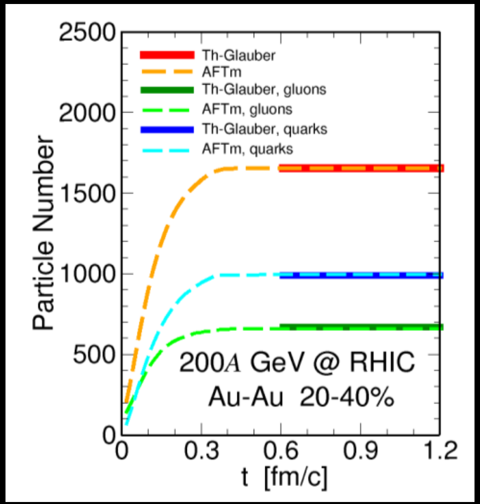
Pre-equilibrium photons
During classical field decay

Thermal QGP photons
During thermal QGP evolution



Thermal hadronic photons
During thermal HG evolution

In our fireball we consider the QGP photons produced in the pre-equilibrium stage and after thermalization
NO NET DISTINCTION WITHIN AFTM



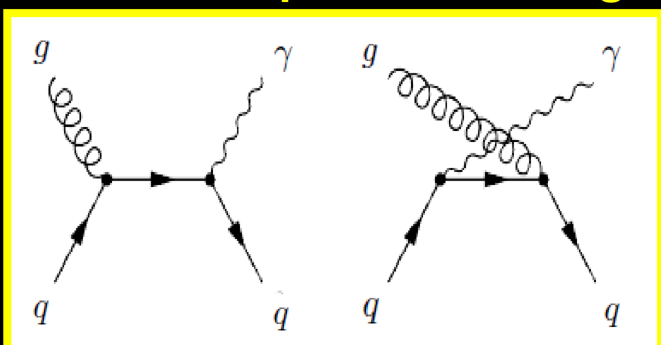
BOLTZMANN TRANSPORT EQUATION

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

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

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

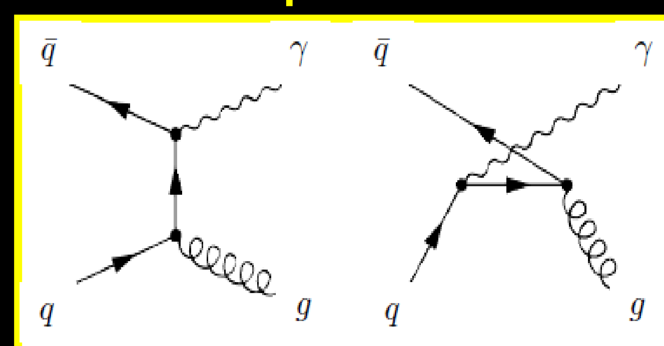
QCD Compton scattering



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

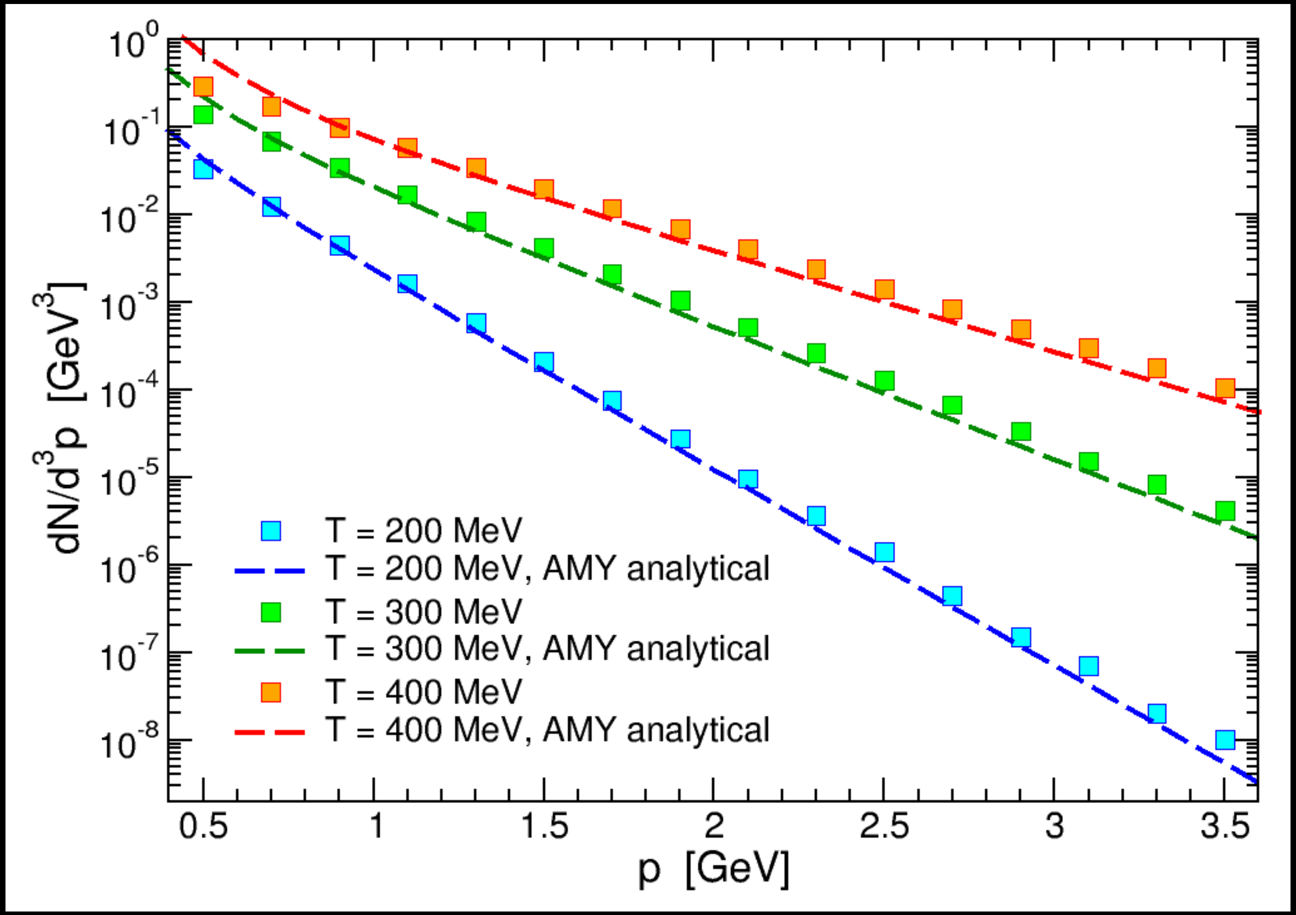
$$\frac{d\sigma^{annihil}}{dt} = \frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

Quark-antiquark annihilation

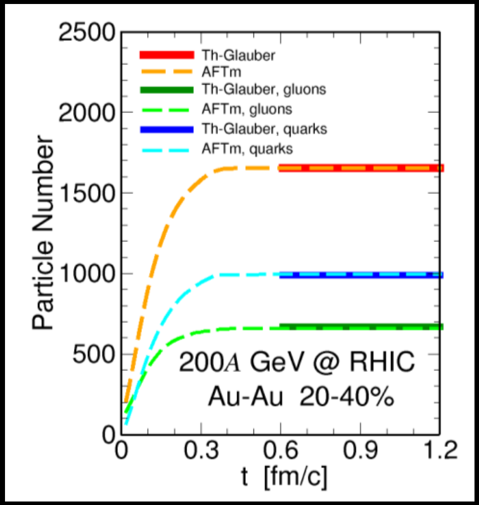


TEXT IN A STATIC BOX AT FIXED T

We reproduce full photon production rates fairly well in the temperature range that is relevant for relativistic heavy ion collisions

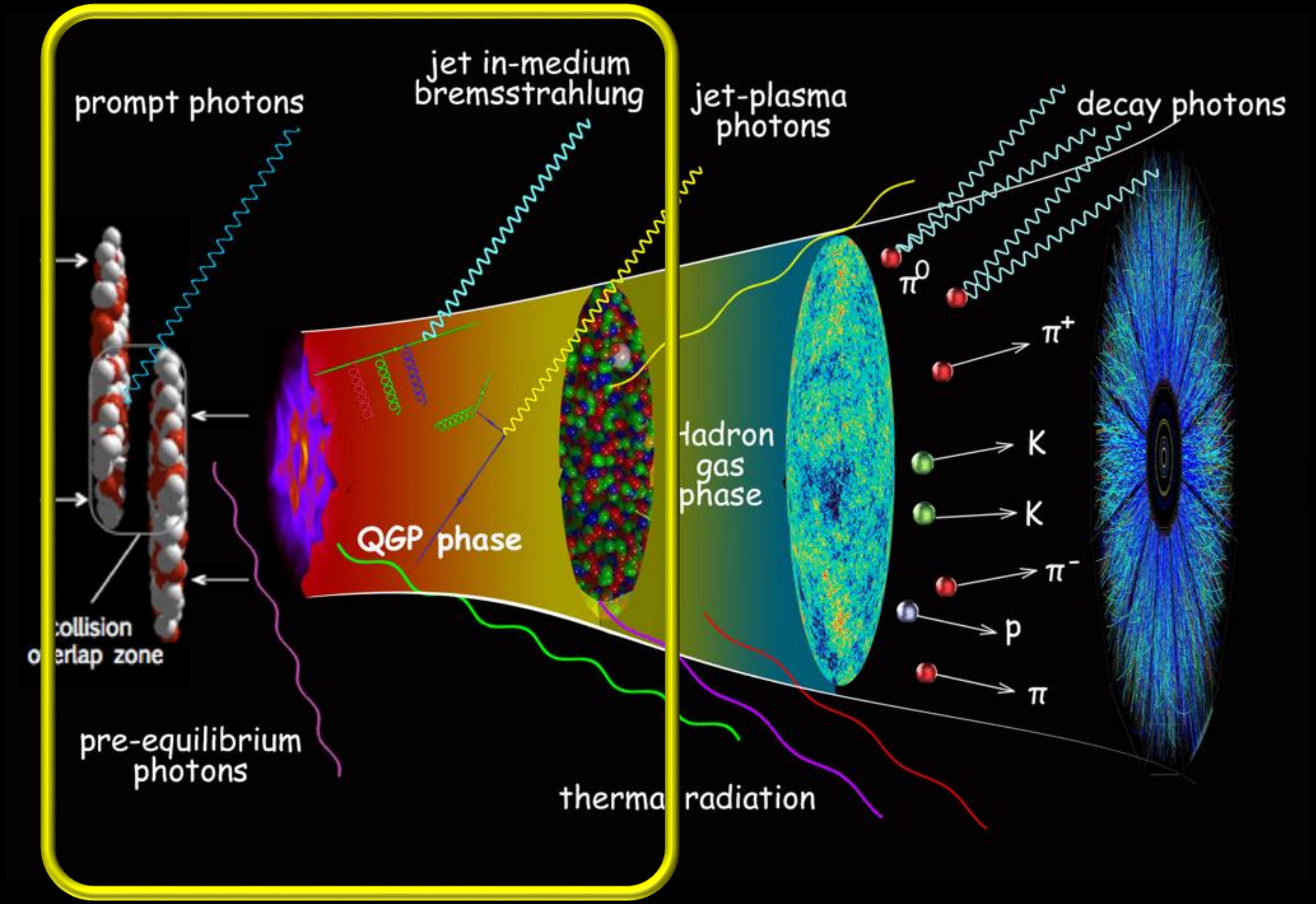


We describe photon emission consistently since the very early stage up to the hadronization time



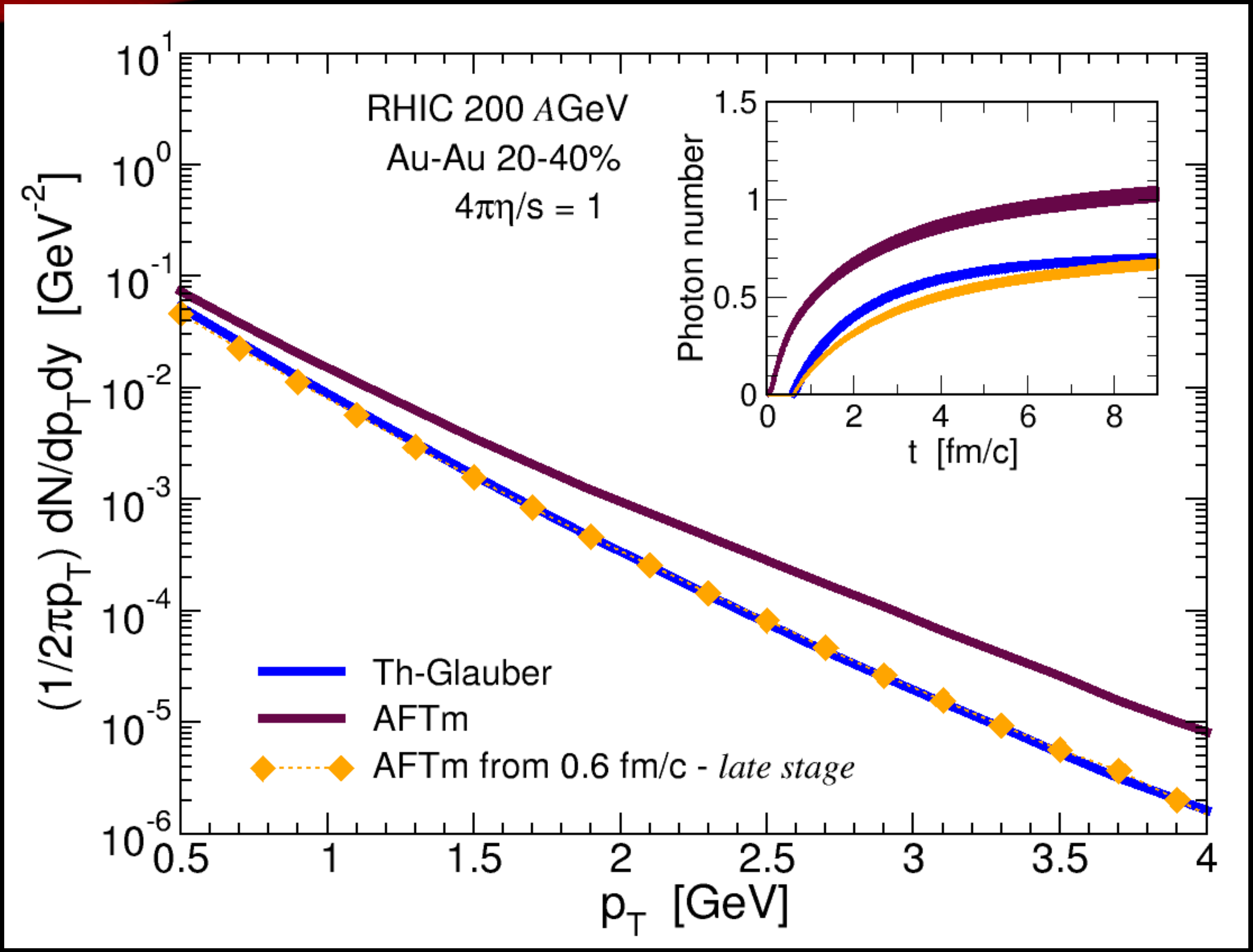
Oliva *et al.*, PRC 96 (2017) 014914
AMY: Arnold, Moore and Yaffe, JHEP 0112 (2001) 009

PRE-EQUILIBRIUM CONTRIBUTION TO PHOTON PRODUCTION



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

PHOTONS at RHIC: impact of pre-equilibrium



Th-Glauber:
$t_0 = 0.6$ fm/c
hydro-like evolution

AFTm:
$t_0 = 0^+$ fm/c
pre-equilibrium dynamics

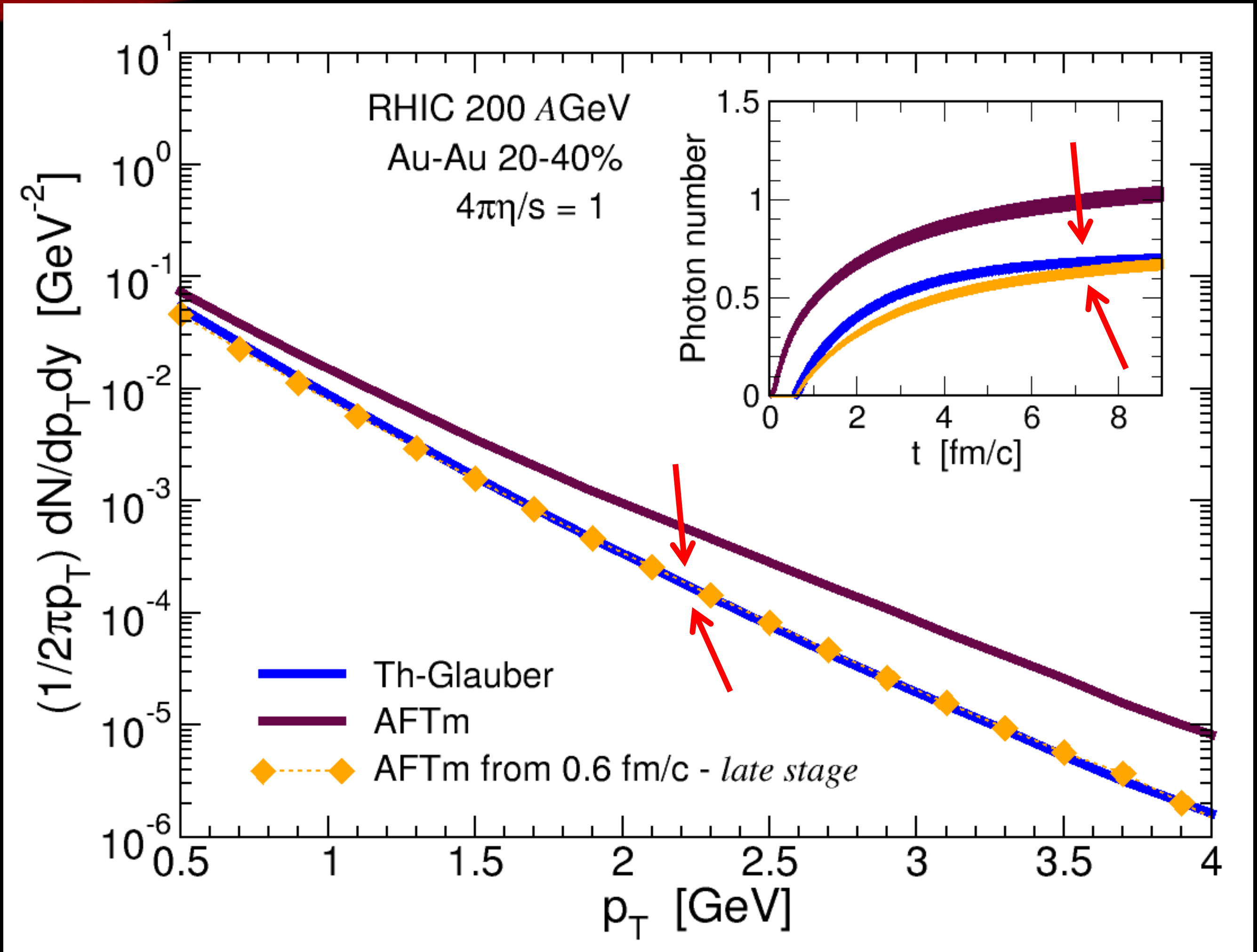
AFTm, *late stage:*
AFTm after thermalization time $t = 0.6$ fm/c

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

Photon abundancy enhanced of about 40% by the early stage

Oliva *et al.*, PRC 96 (2017) 014914

PHOTONS at RHIC: impact of pre-equilibrium



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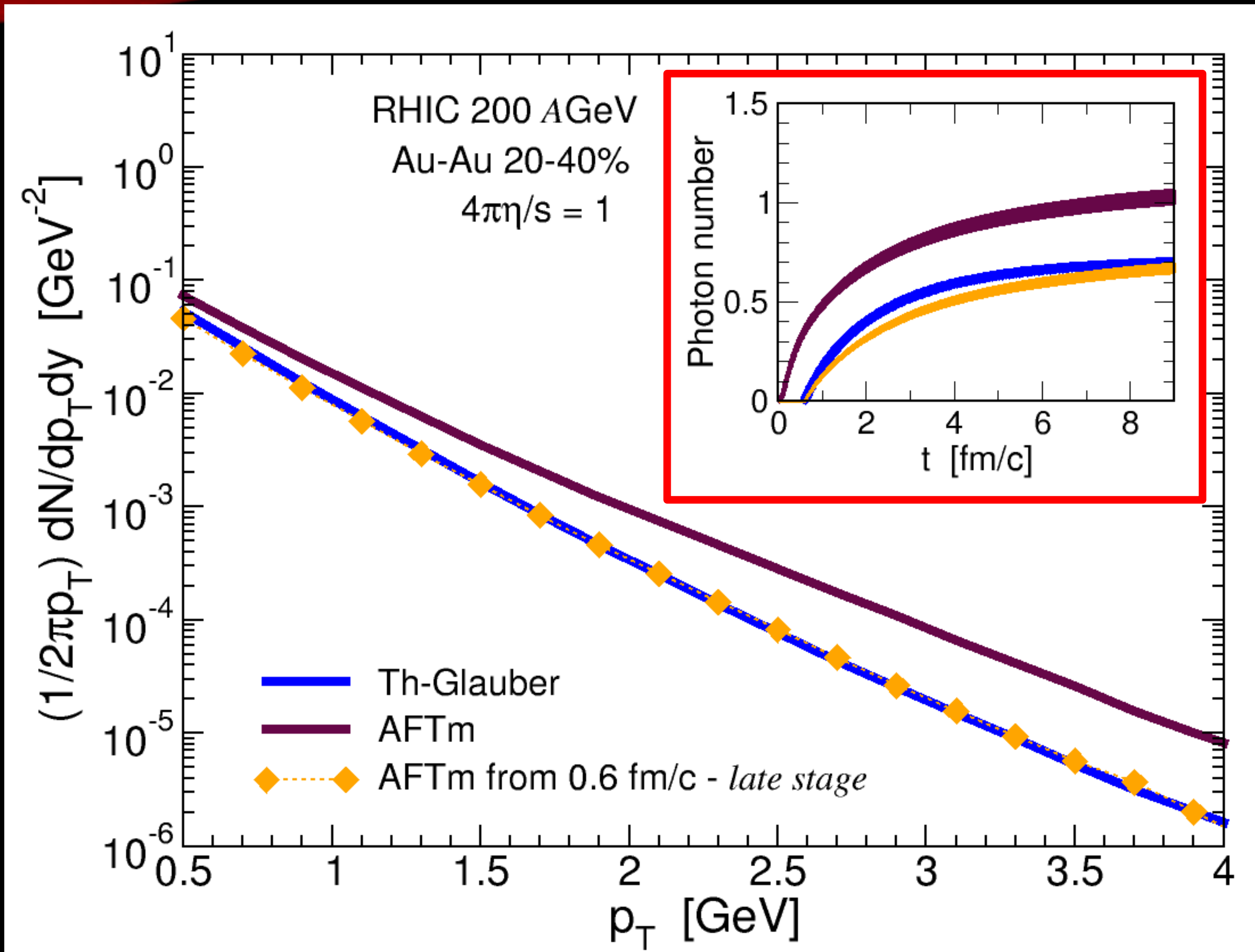

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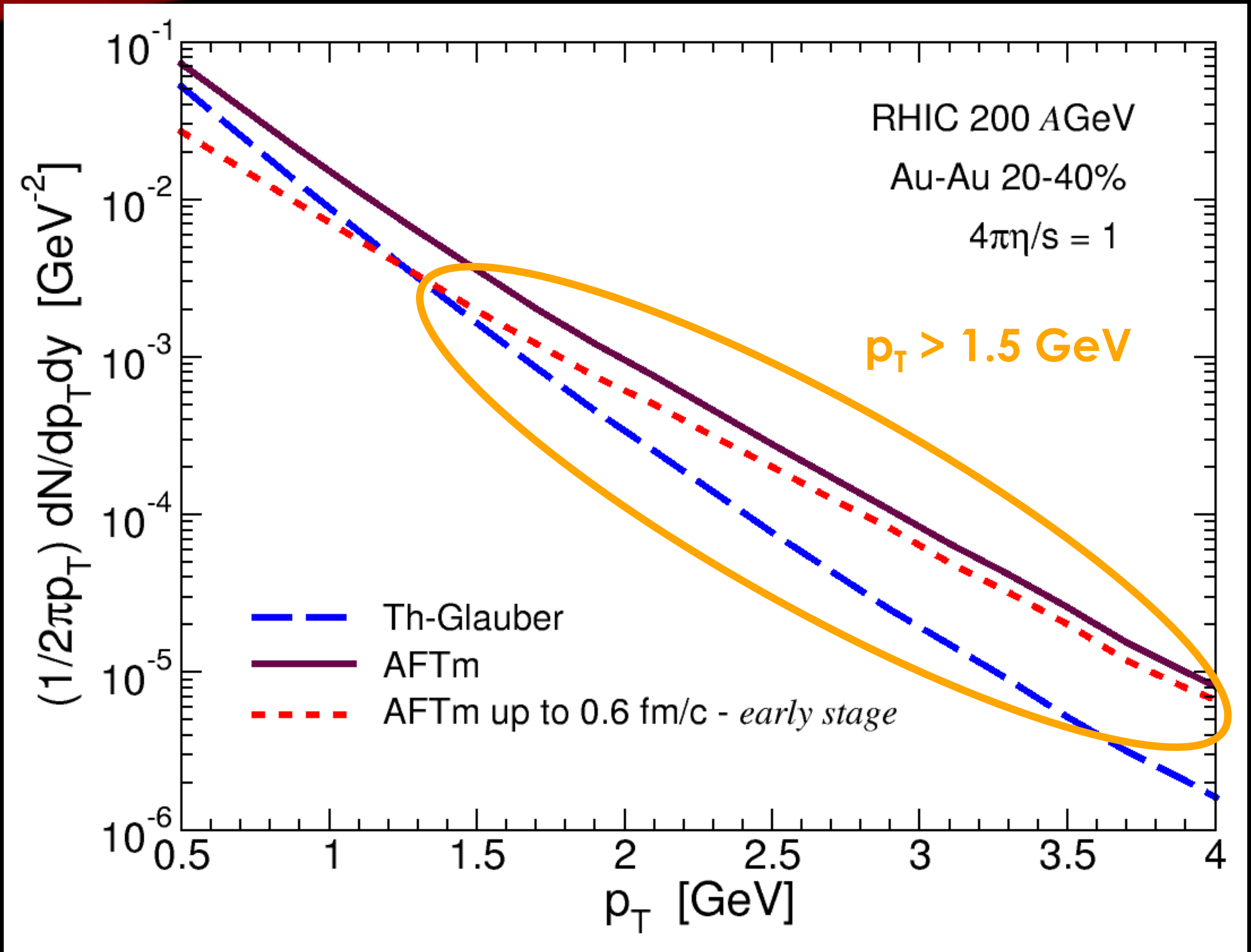


Th-Glauber:
$t_0 = 0.6$ fm/c
hydro-like evolution

AFTm:
$t_0 = 0^+$ fm/c
pre-equilibrium dynamics

AFTm, *early stage*:
AFTm before thermalization time
$t = 0.6$ fm/c

Photon spectrum from QGP is dominated by the early stage photons in the transverse momentum region p_T > 1.5 GeV

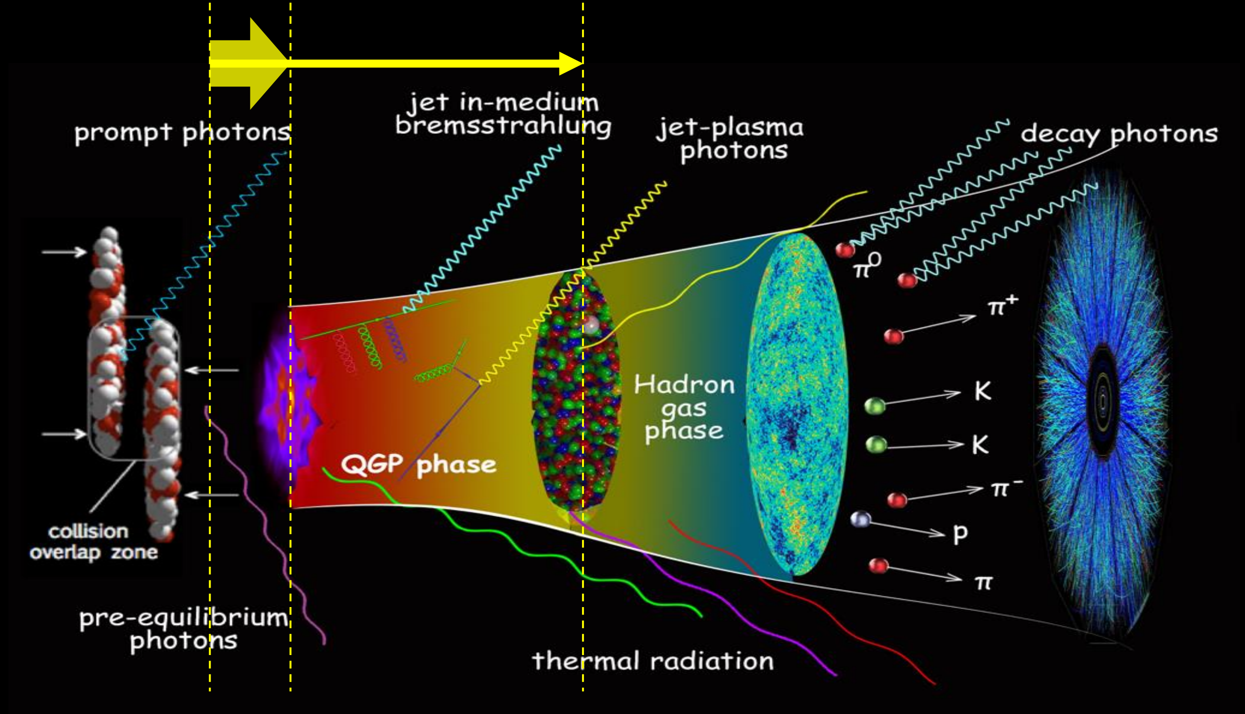
Oliva *et al.*, PRC 96 (2017) 014914

PHOTONS at RHIC: impact of pre-equilibrium

The EARLY STAGE is QUITE BRIGHT

NO DARK AGE in uRHICs

the lifetime of the early stage is at most one tenth of the full QGP lifetime in the fireball

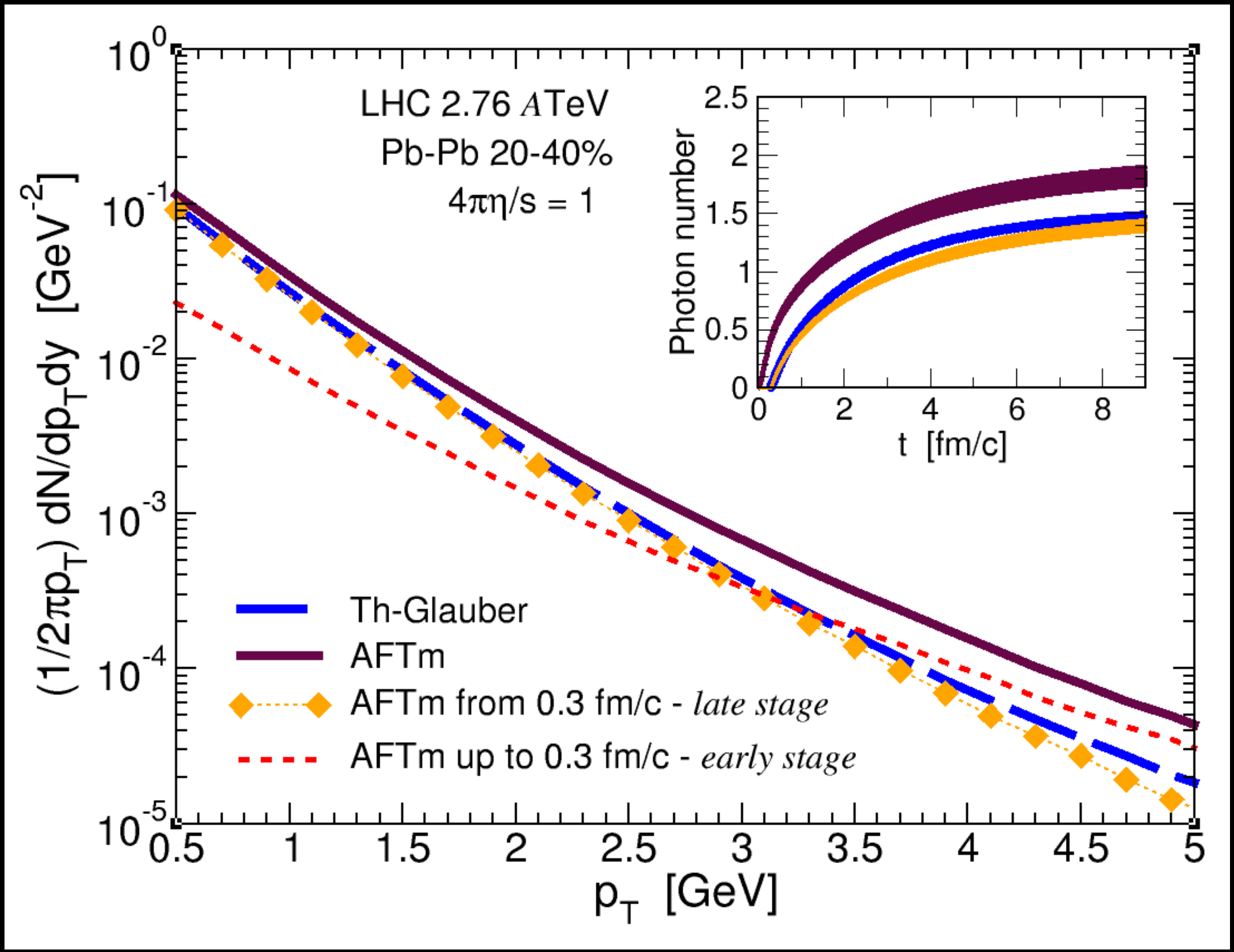


At RHIC
Lifetime of QGP lasts about 5-6 fm/c

In ~ 1/10 of its lifetime QGP produces ~ 1/3 of the photons it produces during the full evolution

PHOTONS at LHC: impact of pre-equilibrium

Oliva *et al.*, PRC 96 (2017) 014914



Th-Glauber:

t_0 = 0.3 fm/c

hydro-like evolution

AFTm:

$t_0 = 0^+$ fm/c

pre-equilibrium dynamics

AFTm, *late stage:*

AFTm after thermalization time t = 0.3 fm/c

AFTm, *early stage:*

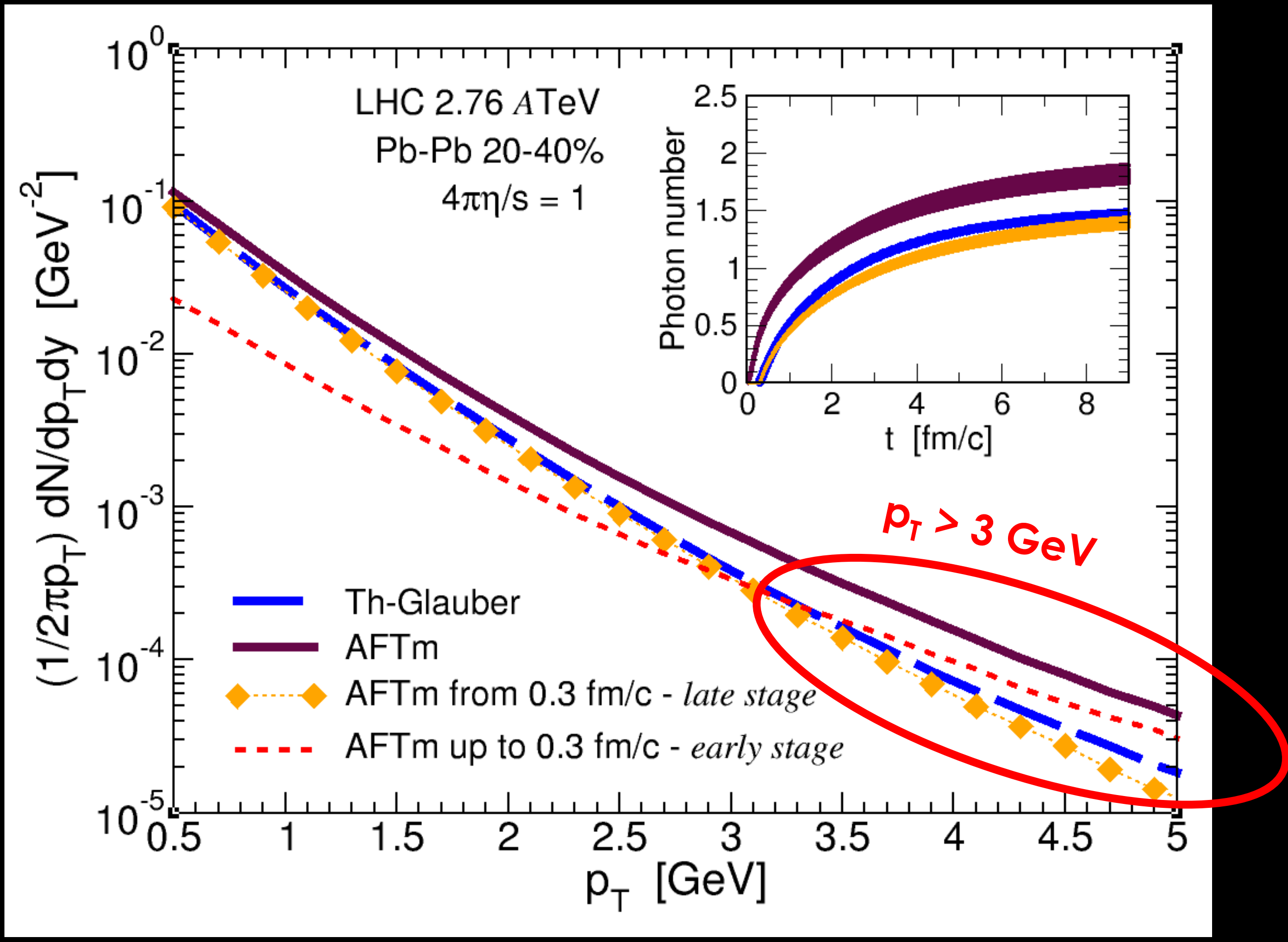
AFTm before thermalization time t = 0.3 fm/c

Pre-equilibrium enhances photon abundancy of about 30%

Early stage photons dominate for p_T > 3 GeV

PHOTONS at LHC: impact of pre-equilibrium

Oliva *et al.*, PRC 96 (2017) 014914



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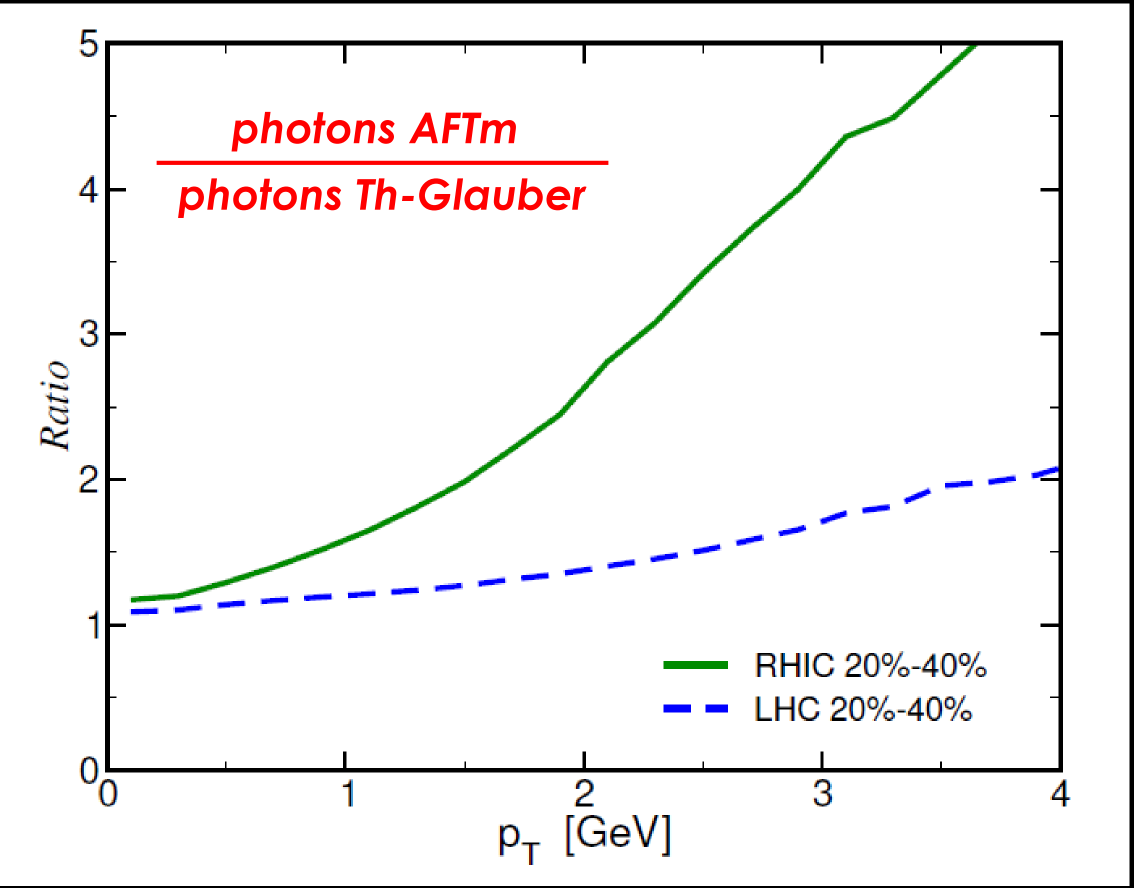
PHOTONS: impact of pre-equilibrium

QGP photons produced by the AFTm (with pre-eq.) relatively to Th-Glauber (without pre-eq.)



Oliva *et al.*, PRC 96 (2017) 014914

Early stage lifetime:

- RHIC ~ 0.6 fm/c
- LHC ~ 0.3 fm/c

Thermalized QGP lifetime:

- RHIC ~ 5-6 fm/c
- LHC ~ 10-12 fm/c

Relative contribution of the early stage respect to the thermalized QGP phase smaller at LHC

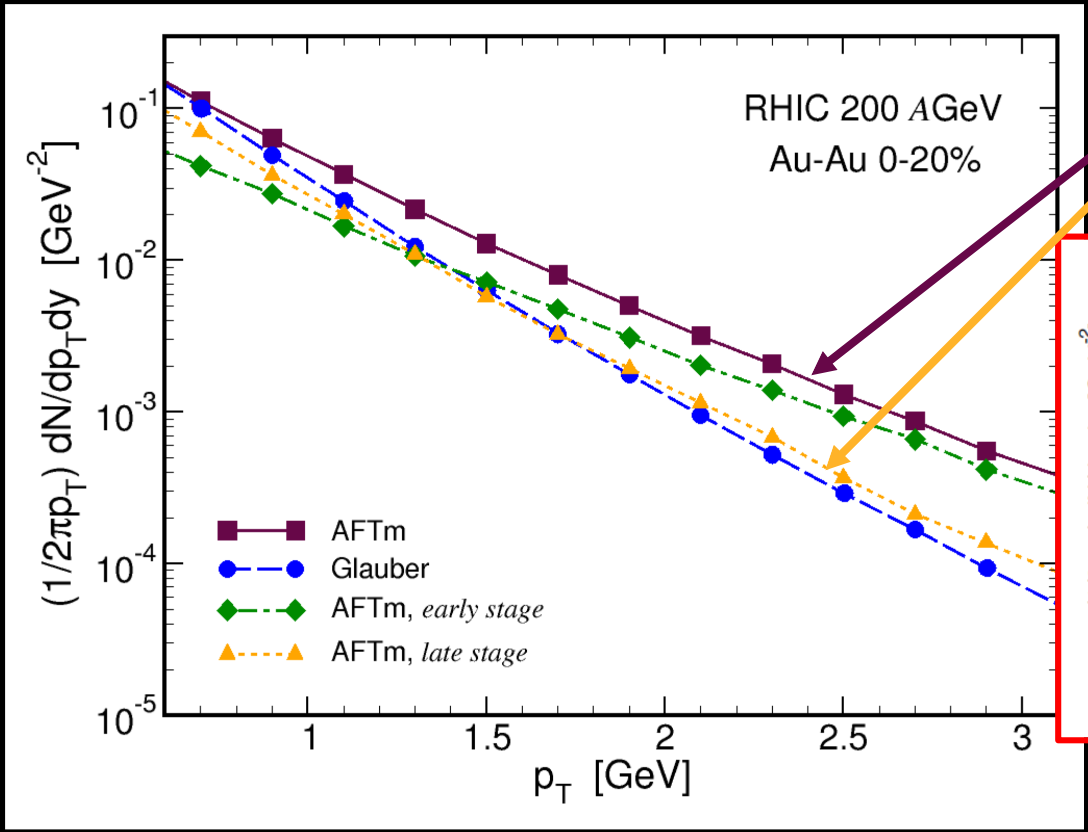
LHC early stage is less shiny than the RHIC one when both are compared with a thermal QGP

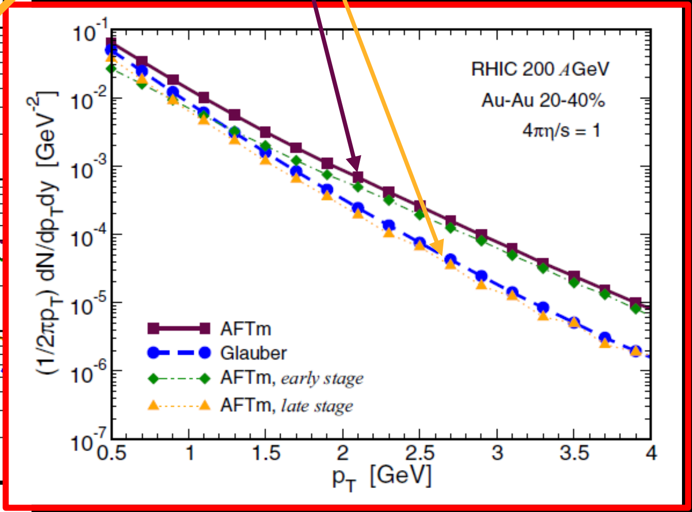
In agreement with Berges et al., PRC 95 (2017) 054904

Comparison between different centralities

RHIC COLLISIONS at
0-20% CENTRALITY CLASS
b ≈ 4.5 fm

QUALITATIVELY:
similar impact of pre-equilibrium on photon spectrum



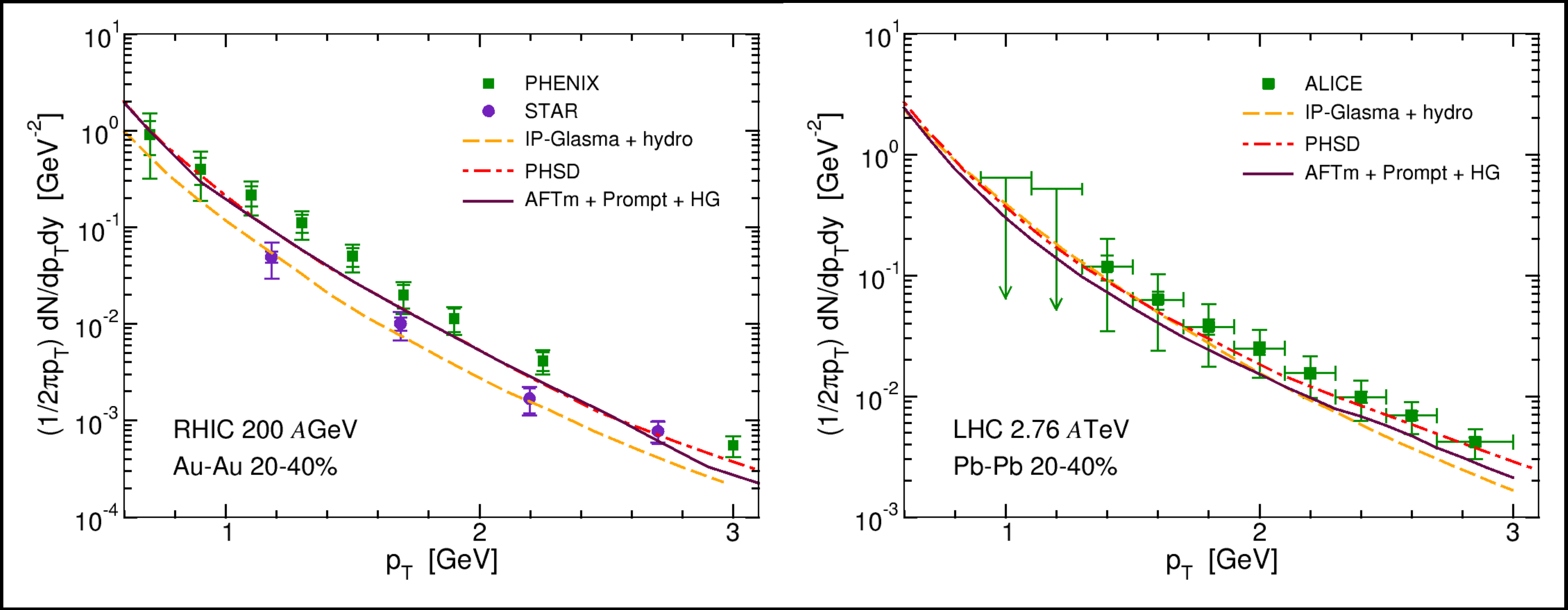


RHIC COLLISIONS
0-20% CENTRALITY CLASS
b ≈ 8.1 fm

QUANTITATIVELY: enhanced photon production due to the larger number of participants

DIRECT PHOTON SPECTRUM in uRHICs

Exploratory comparison with experimental data
Our simulations do not include any hadronization process

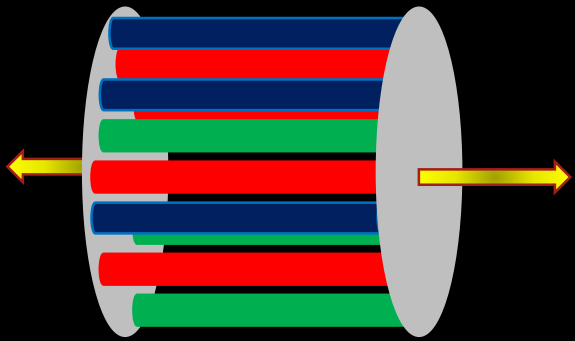


Contributions added to AFTm:

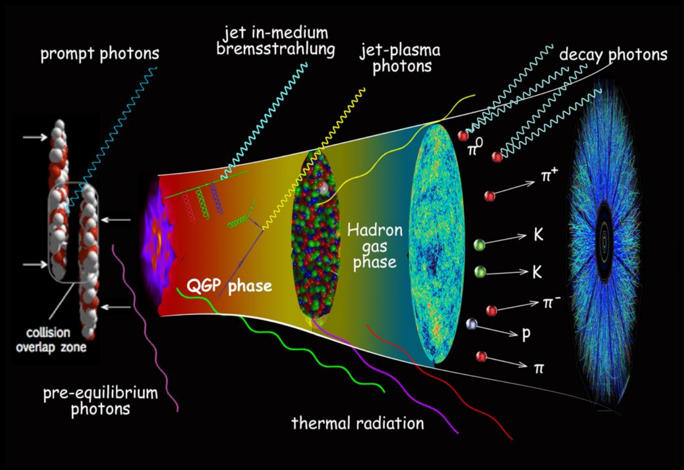
- Prompt photons from Paquet *et al*. PRC 93 (2016) 044906 (IP-Glasma+hydro)
- Hadronic thermal photons from Linnyk *et al*., PRC 92 (2015) 054914 (PHSD)

PHENIX Collaboration, PRC 91 (2015) 064904
STAR Collaboration, PLB 770 (2017) 451
ALICE Collaboration, PLB 754 (2016) 235

CONCLUSIONS



- ✓ **Relativistic Transport Theory** allows to study **early times dynamics of heavy ion collisions.**
- ✓ **Schwinger tunneling** provides a **fast production of both quarks and gluons,** typically in a small fraction of fm/c.



- ✓ The **early stage shines:** pre-equilibrium photons comparable in number with those emitted from the equilibrated QGP during its whole lifetime.
- ✓ **Substantial contribution** of pre-equilibrium photons **in the intermediate transverse momentum range.**
- ✓ **LHC early stage is less shiny than the RHIC one** when both are compared with a thermal QGP.

Thank you
for your attention!

BACKUP SLIDES

BOLTZMANN TRANSPORT EQUATION
Numerical implementation

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

Test particle method to map the phase space

$$f(\boldsymbol{r}, \boldsymbol{p}, t) = \omega \sum_{i=1}^{N_{test}} \delta^{(3)}(\boldsymbol{r} - \boldsymbol{r}_i(t))\delta^{(3)}(\boldsymbol{p} - \boldsymbol{p}_i(t))$$

$$\frac{\omega}{(2\pi)^3} N_{test} = N_{real}$$

Stochastic method to simulate collisions

$$\begin{aligned}\mathcal{C}[f] &= \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2}(f'_1 f'_2 - f_1 f_2) \\ &\times |\mathcal{M}_{12\to 1'2'}| (2\pi)^4 \delta^{(4)}(p'_1 + p'_2 - p_1 - p_2),\end{aligned}$$

$$P_{22} = \frac{\Delta N^{2\to 2}_{coll}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x} \qquad v_{rel} = \frac{s}{2E_1 E_2}$$

$$\sigma \to \sigma / N_{test}$$

BOLTZMANN TRANSPORT EQUATION

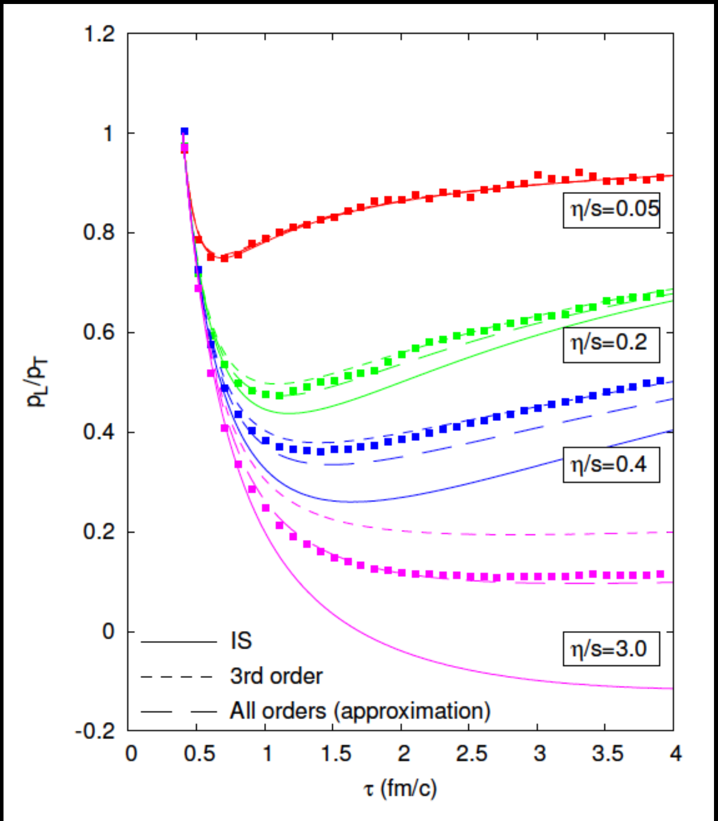
Instead of starting from cross sections we simulate a fluid at **fixed η/s**

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

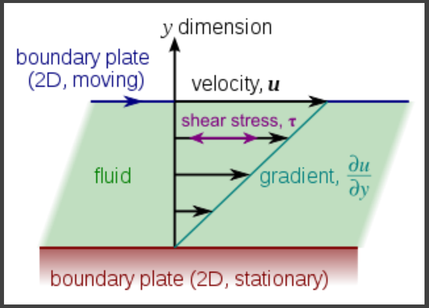
Making a bridge between TRANSPORT and HYDRO



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

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

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



$$\frac{F_x}{A_{yz}} = -\eta\frac{\partial u_x}{\partial y}$$

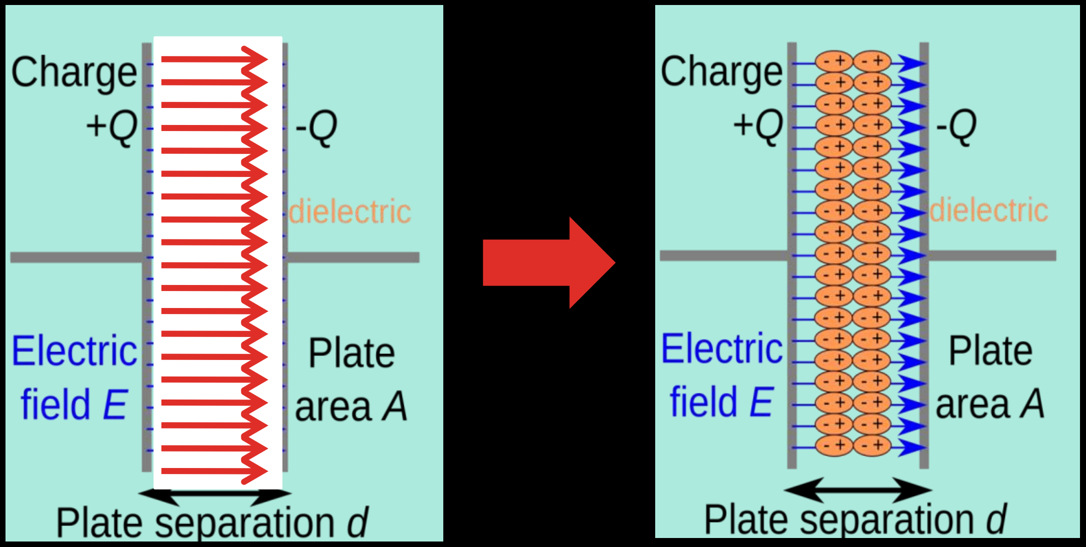
FROM GLASMA TO QUARK-GLUON PLASMA

SCHWINGER MECHANISM

Classical electric 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

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

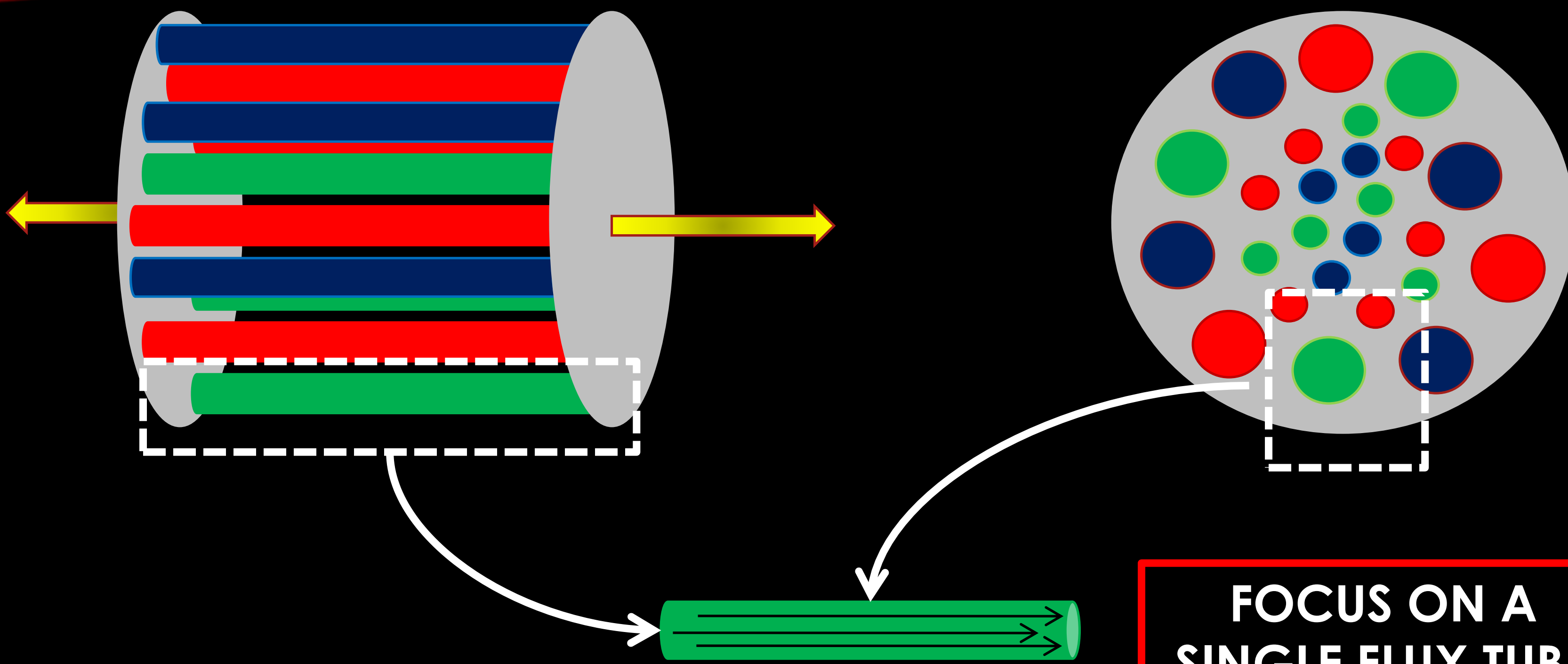
IN CHROMODYNAMICS

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

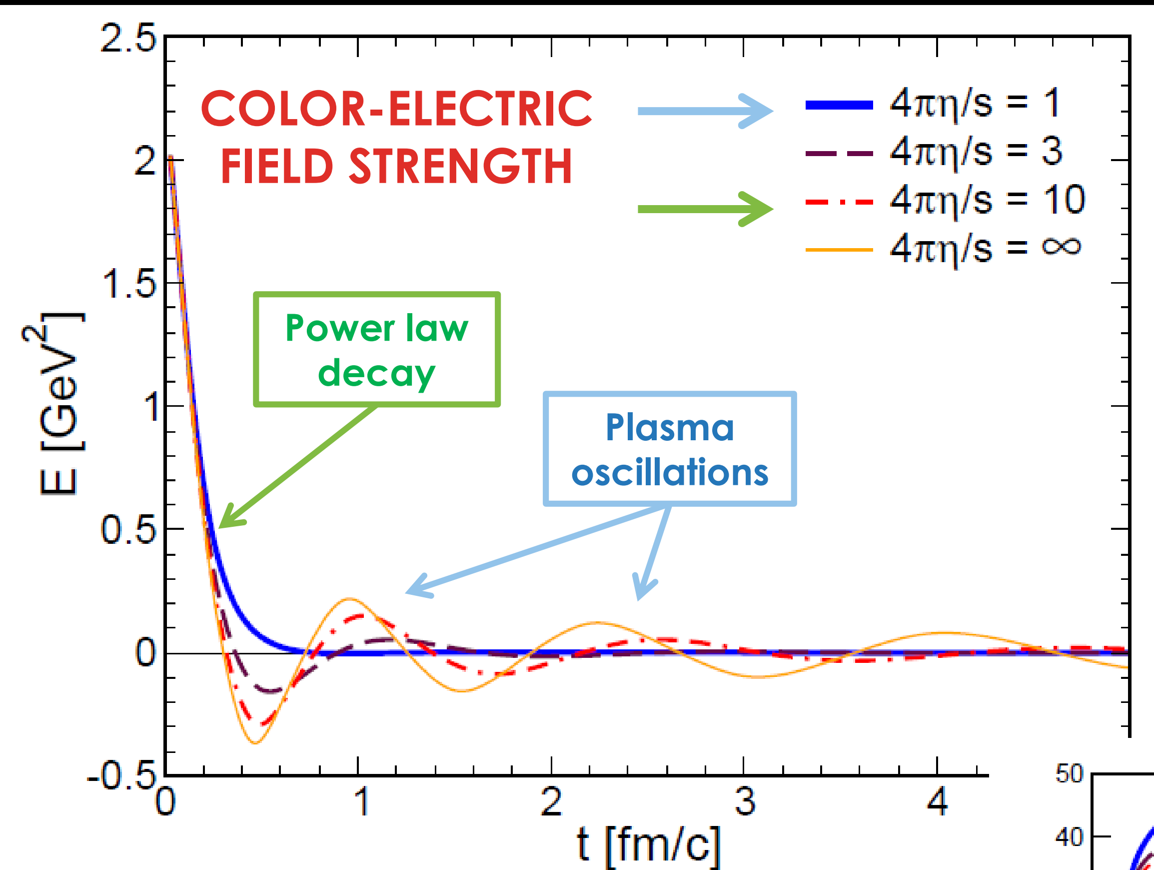


FOCUS ON A SINGLE FLUX TUBE

Initial chromo-electric field longitudinal and homogeneous in transverse plane

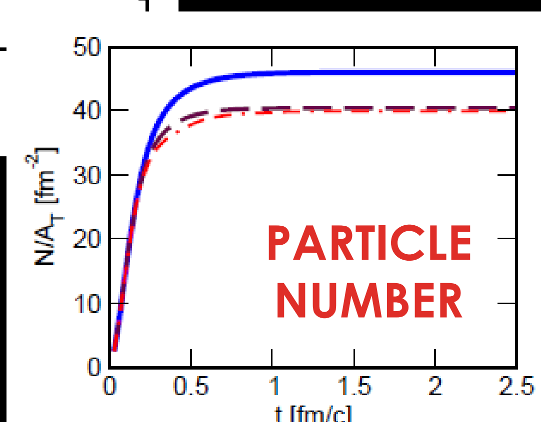
We can investigate the time scales and the mechanisms responsible of the isotropization of the fluid produced in the initial out-of-equilibrium stage of the collision

1+1D EXPANSION
electric field decay and particle formation



Small viscosity → Large scattering rate → Strong current dumping

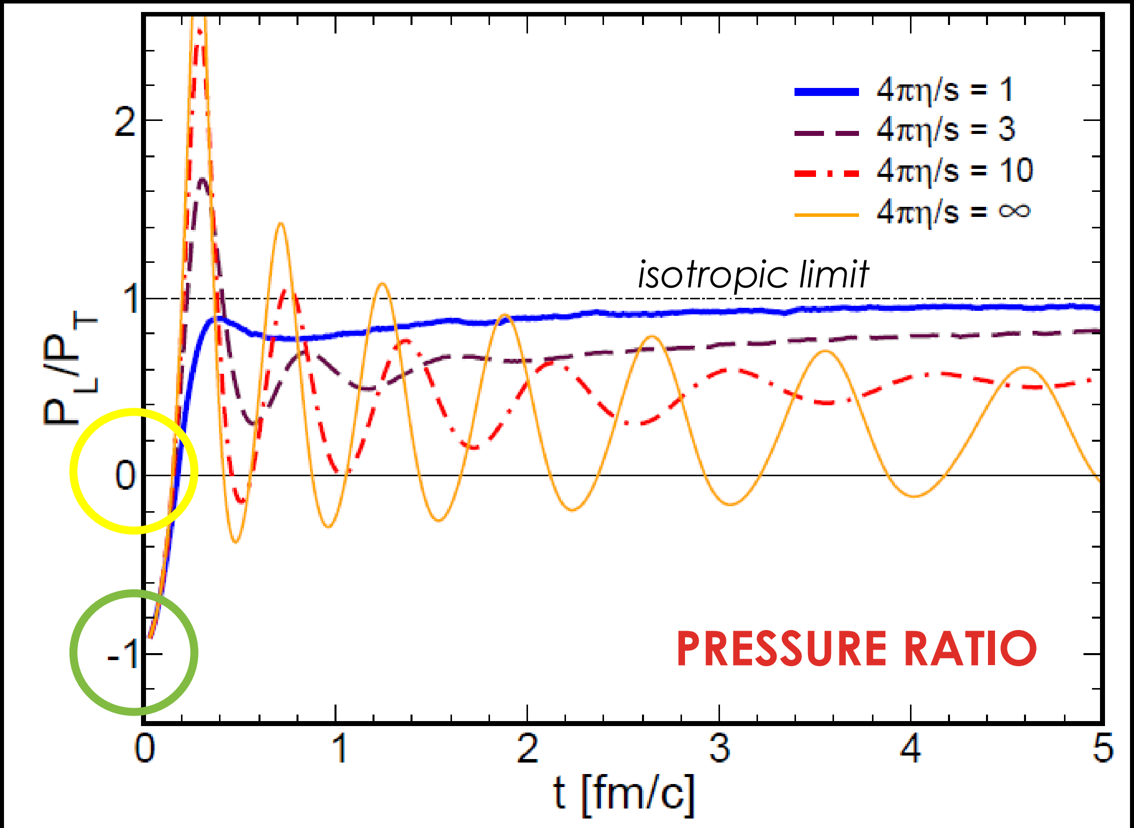
Large viscosity → Small scattering rate → Weak current dumping → Field oscillations



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

Oliva et al., PRC 92 (2015) 064904

1+1D EXPANSION isotropization



Oliva et al., PRC 92 (2015) 064904

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

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

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

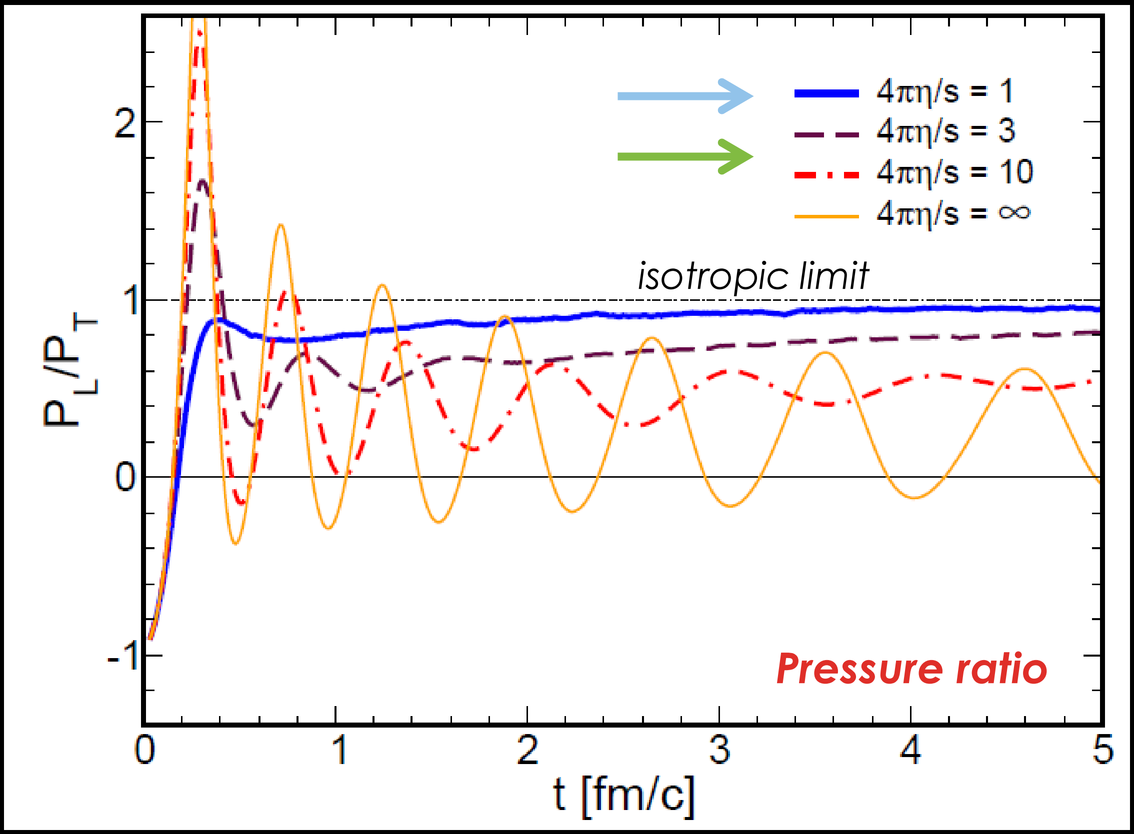
$$P_L = T_{zz}$$
$$P_T = \frac{T_{xx} + T_{yy}}{2}$$

Isotropic system if $P_L = P_T$

High anisotropy: pure field with negative longitudinal pressure

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

1+1D EXPANSION
isotropization



Oliva et al., PRC 92 (2015) 064904

Small viscosity
Quick isotropization in about 1 fm/c

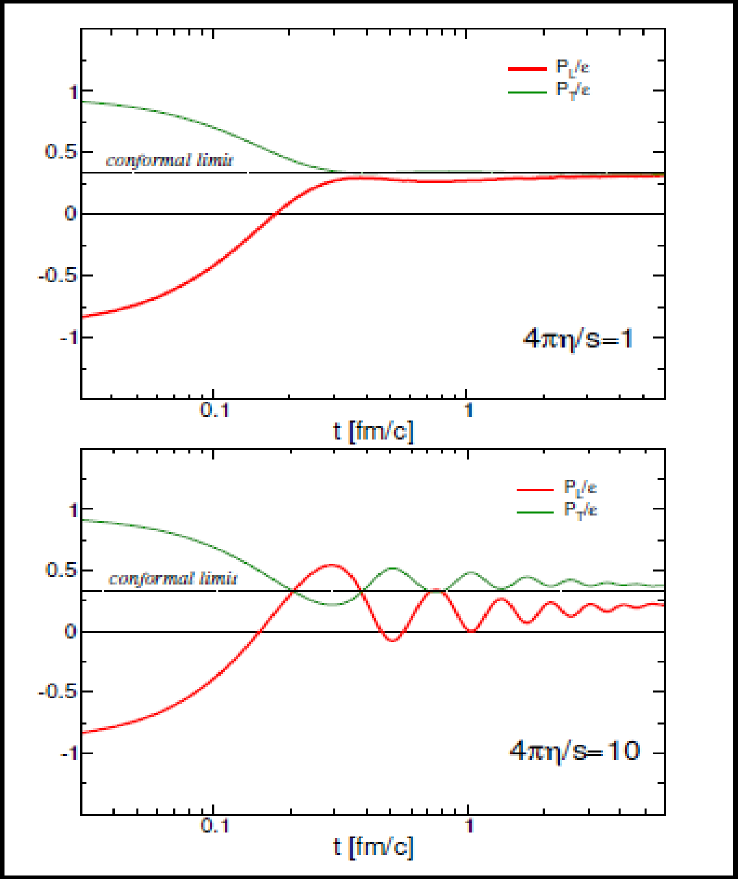
Large viscosity
Less efficient isotropization

Quick isotropization justifies use of viscous hydrodynamics with an initial time of 0.6 fm/c, in which pressure ratio is about 0.7

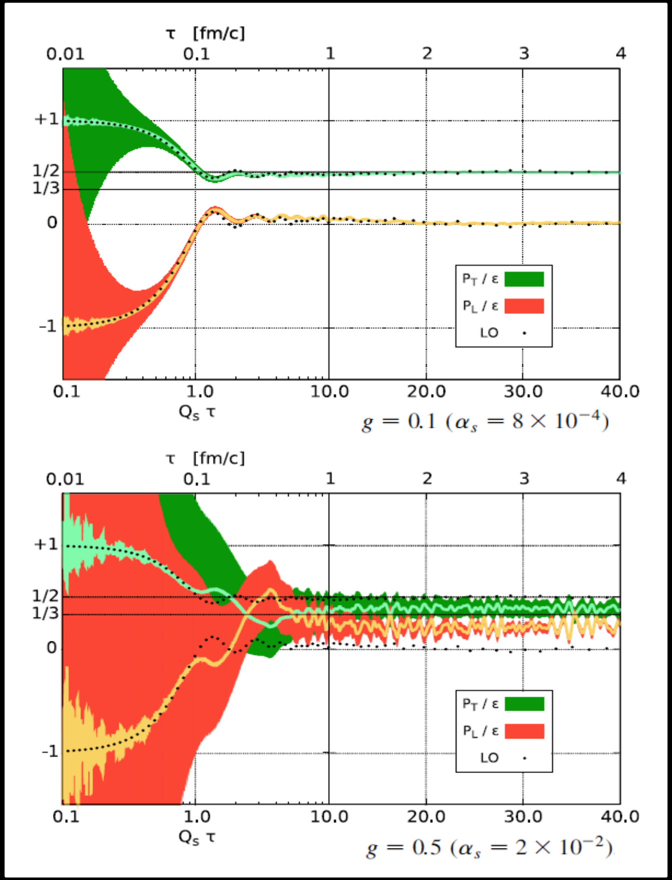
Initial phase is strongly anisotropic and not thermalized.
Which is its impact on observables?

1+1D EXPANSION
isotropization

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



Oliva et al., PRC 92 (2015) 064904

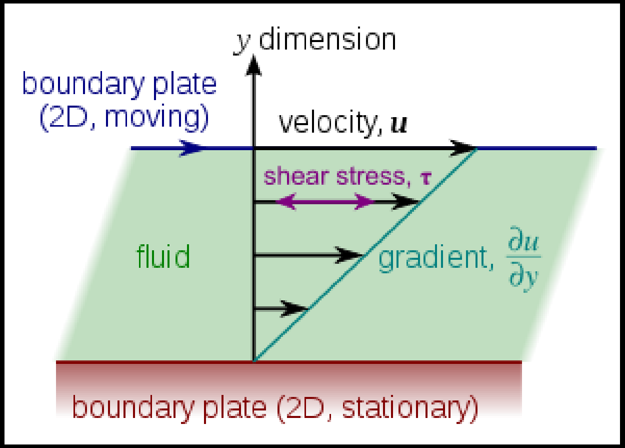


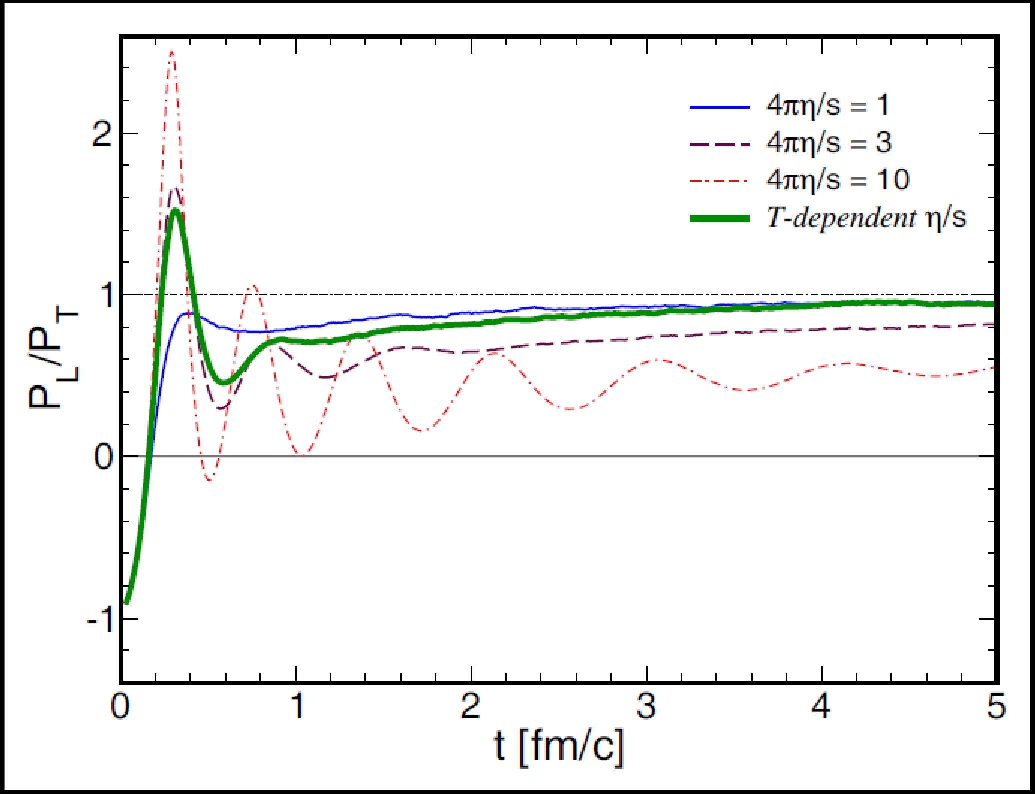
Epelbaum and Gelis, PRL 111 (2013) 232301

1+1D EXPANSION
isotropization

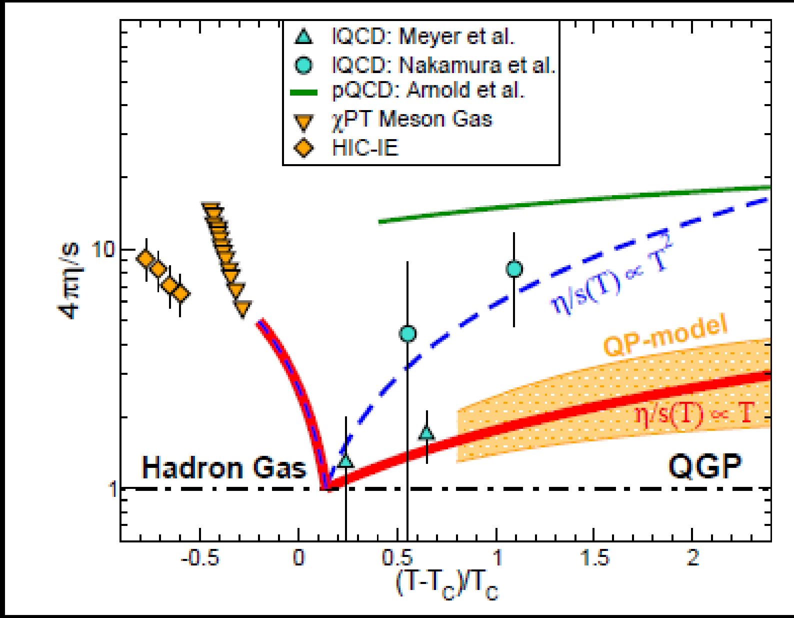
$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial u_x}{\partial y}$$

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





T-dependent viscosity

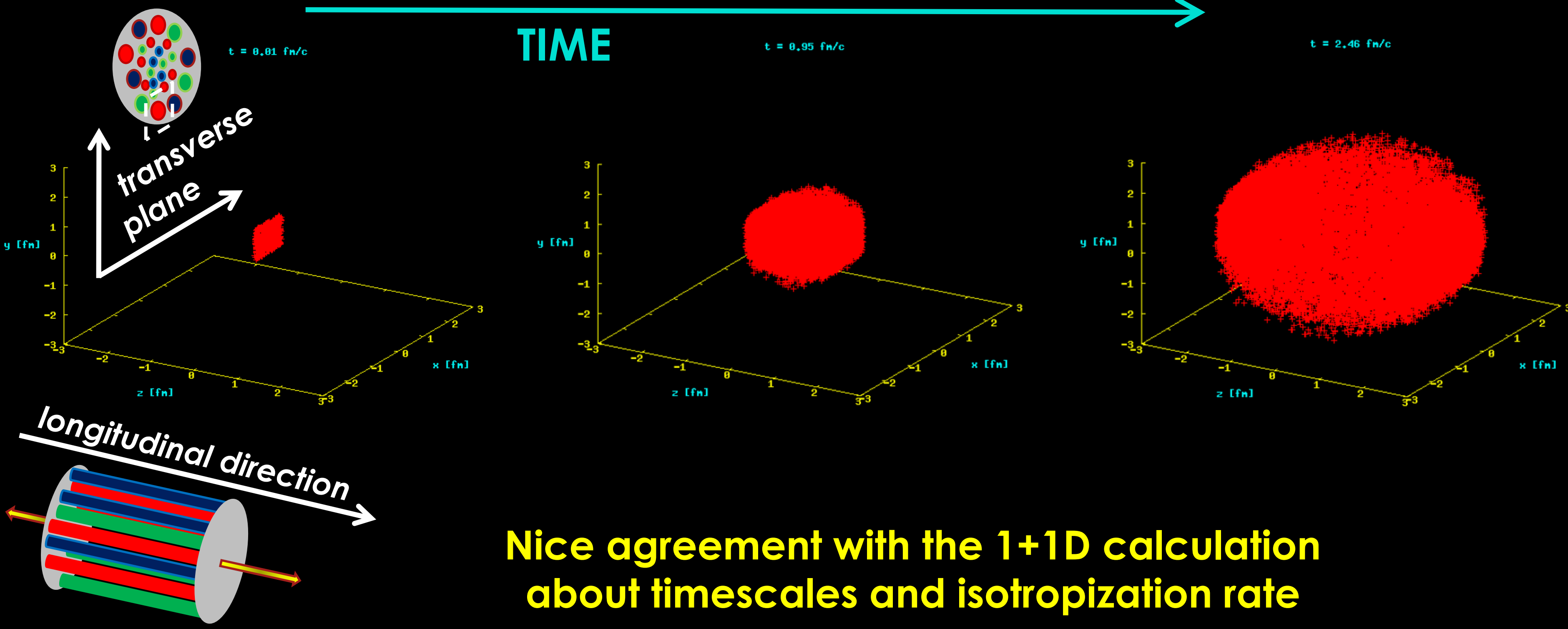


Plumari et al., J.Phys.Conf.Ser. 420 (2013) 012029

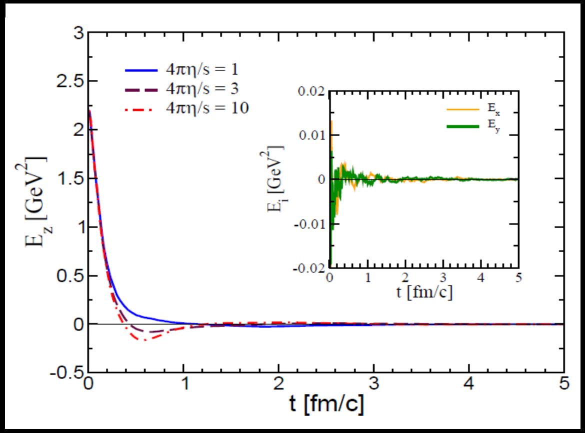
3+1D EXPANSION

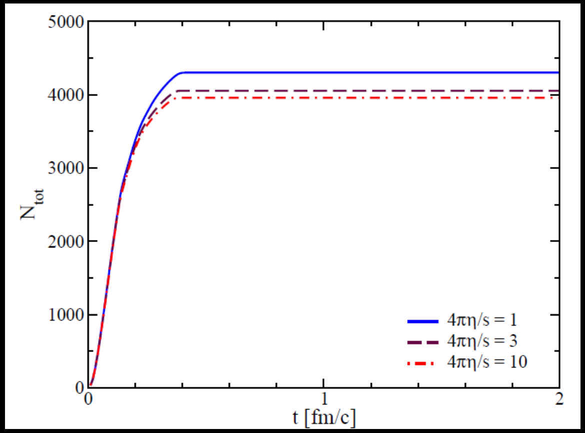
Initial field is longitudinal but a realistic 3D expansion leads to transverse fields

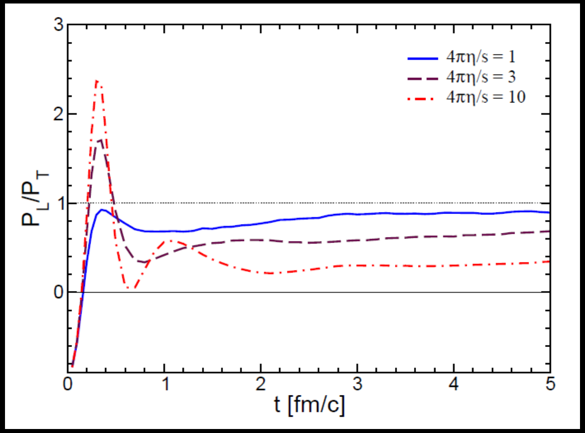
TIME



Nice agreement with the 1+1D calculation about timescales and isotropization rate



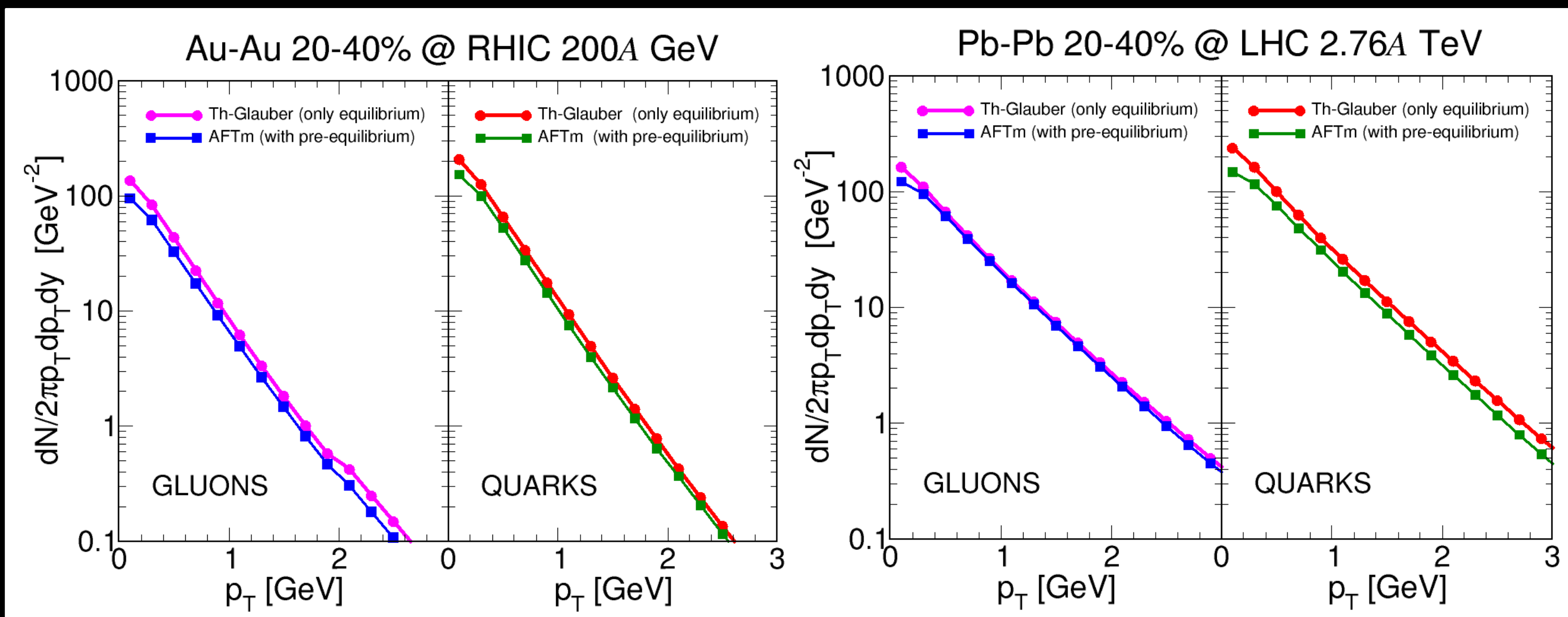




QUARK-GLUON PLASMA: SPECTRUM

INITIAL SPECTRA OF BULK MEDIUM

- Th-Glauber (t_0=0.6/0.3 fm/c) → thermal distribution for p_T < 2/3 GeV + minijets for p_T > 2/3 GeV
- AFTm (t_0=0$^+$ fm/c) → only minijets for p_T > 2/3 GeV



Quark and gluon spectra

Oliva *et al.*, PRC 96 (2017) 014914

Simulations with Glauber and non-equilibrium initializations give very similar **final spectra** of quarks and gluons

QGP AND HADRONIC PHOTONS

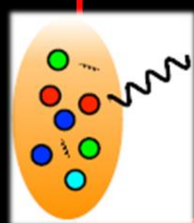
fireball evolution

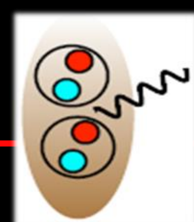
Pre-equilibrium photons

During classical field decay

Thermal QGP photons

During thermal QGP evolution





Thermal hadronic photons

During thermal HG evolution

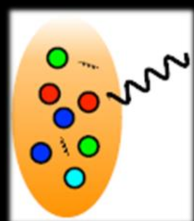
- **QGP is a strongly coupled system**
  Gale at al., PRL 114 (2015) 072301
  Iatrakis et al., JHEP 1704 (2017) 035
- **Enhancement of thermal photon emission**
  Chatterjee *et al*., PRC 85 (2012) 064910
  Van Hees, He and Rapp, NPA 933 (2015) 256
- **Rates for thermalized QGP and thermalized hadron gas (HG)**
  Arnold, Moore and Yaffe, JHEP 0112 (2001) 009
  Ghiglieri et al., JHEP 05 (2013) 010
  Turbide, Rapp and Gale, PRC 69 (2004) 014903
  Heffernan, Hohler and Rapp, PRC 91 (2015) 027902
  Holt, Hohler and Rapp, NPA 945 (2016) 1

QGP AND HADRONIC PHOTONS

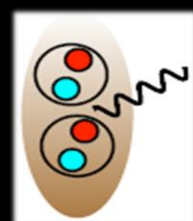
fireball evolution

Pre-equilibrium photons
During classical field decay

Thermal QGP photons
During thermal QGP evolution



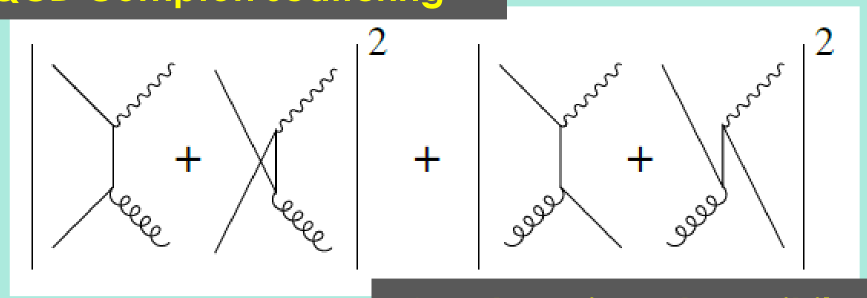
Thermal hadronic photons
During thermal HG evolution



- **Rates in pre-equilibrium stage are still under investigation**
  Berges *et al.*, PRC 95 (2017) 054904
  McLerran *et al.*, NPA 900 (2013) 16
  Başar, Kharzeev and Skokov, PRL 109 (2012) 202303
  Vovchenko *et al.* - PRC 94 (2016) 024906
  Liu and Liu, PRC 89 (2014) 034906
- **Photons from classical currents in the early stage**
  Tanji, PRD 92 (2015) 125012

Implementing the full photon production rate

QCD Compton scattering



Quark-antiquark annihilation

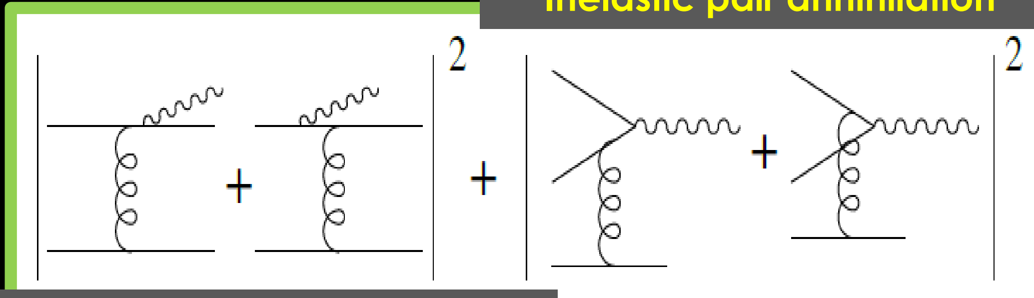
We implement photon production by adding the 2 → 2 standard processes in the collision integral

$$\frac{d\sigma^{Compton}}{dt} = -\frac{\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$
$$\frac{d\sigma^{annihil}}{dt} = \frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

NLO processes give important contribution to the rate because of collinear enhancements

Arnold, Moore and Yaffe, JHEP 0112 (2001) 009

Inelastic pair annihilation



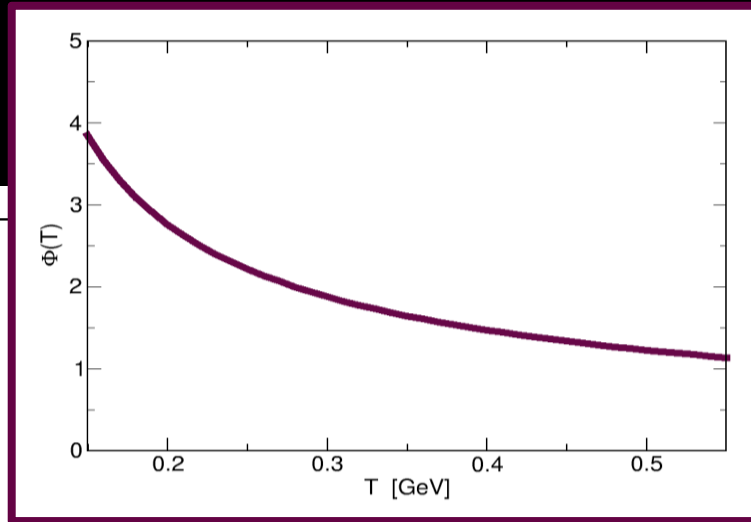
Bremsstrahlung

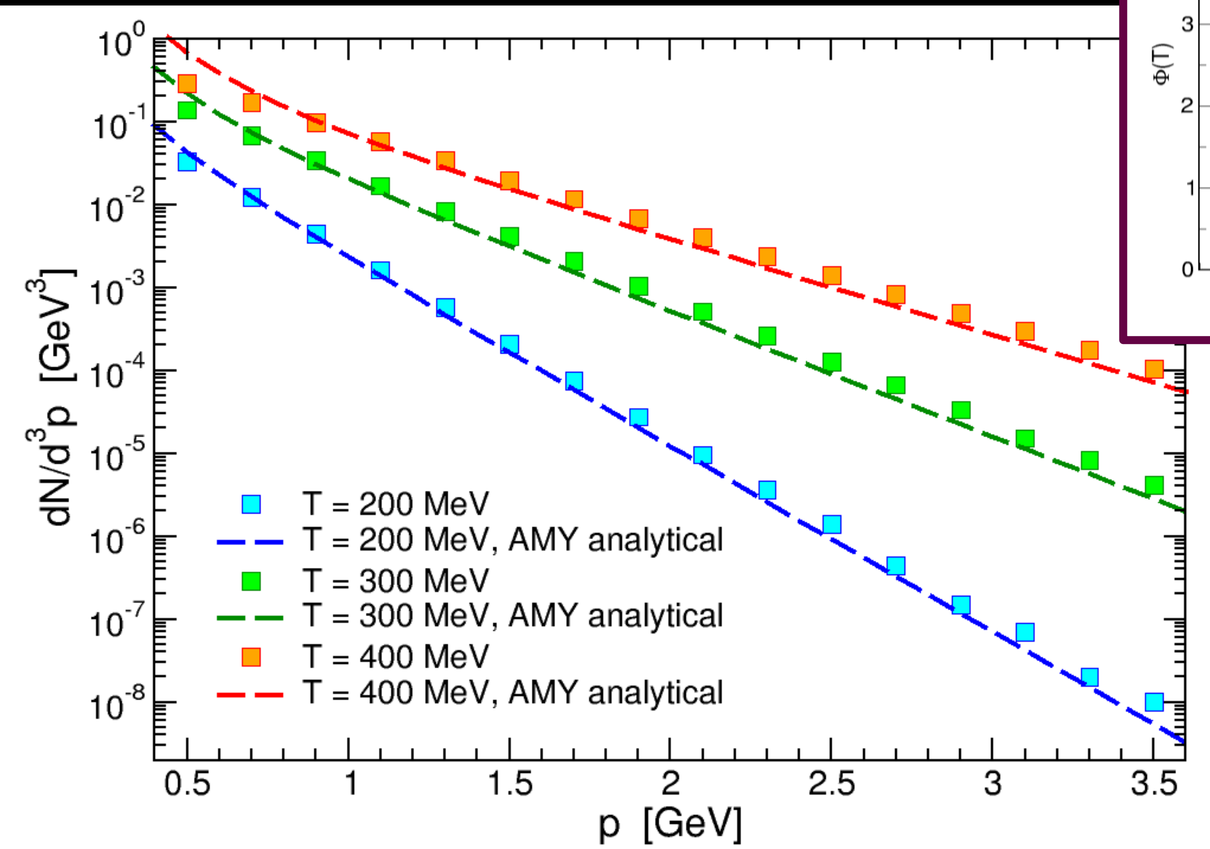
$$\frac{d\sigma^{Compton}}{dt} = -\Phi(T)\frac{\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$
$$\frac{d\sigma^{annihil}}{dt} = \Phi(T)\frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

We use a model function, Φ(T), tuned in order to reproduce the AMY rate at a given temperature

Implementing the full photon production rate

$\Phi(T)$: model function tuned to reproduce the AMY rate at a given temperature





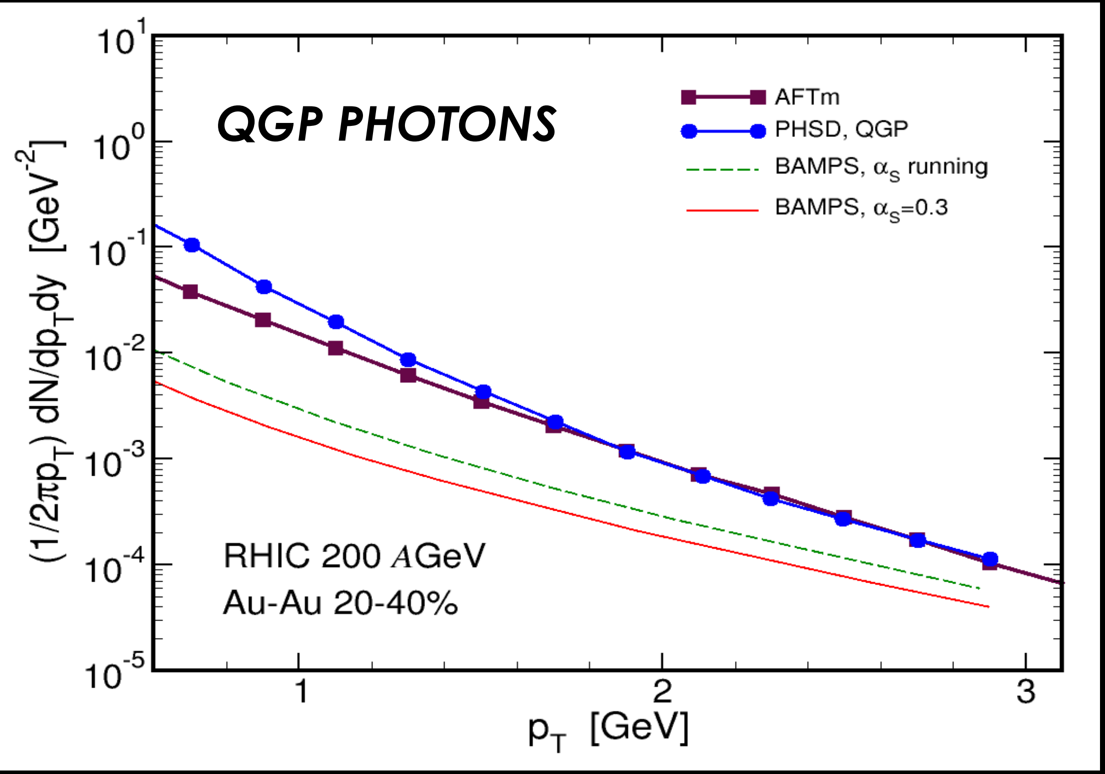
Fair agreement between AMY rate and the one implemented in our collision integral in a broad range of temperature and photon momentum

AMY: Arnold, Moore and Yaffe, JHEP 0112 (2001) 009

We can follow photon production consistently since the very first moments after the collision regardless of the fact that the system is in local equilibrium or not

Comparison with PHSD and BAMPS

Oliva *et al.*, PRC 96 (2017) 014914



AFTm

both quarks and gluons are produced by gluon field decay

PHSD

partons produced by the decay of initial strings

Linnyk *et al.*, PRC 92 (2015) 054914

BAMPS

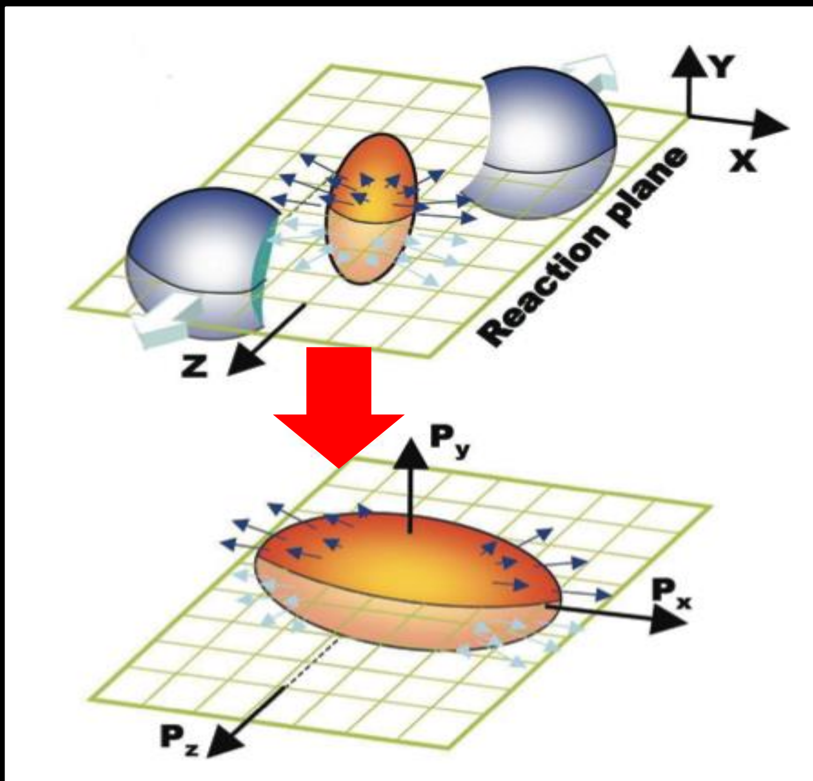
initial state made of gluons, quarks are produced by inelastic QCD scatterings

Greif *et al.*, PRC 95 (2017) 054903

DIFFERENT MECHANISMS AND TIMESCALES OF QUARKS AND GLUONS FORMATION

theoretical uncertainty on QGP production time in HICs → uncertainty on photon abundancy from QGP

COLLECTIVE FLOW



ECCENTRICITY

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

transport properties

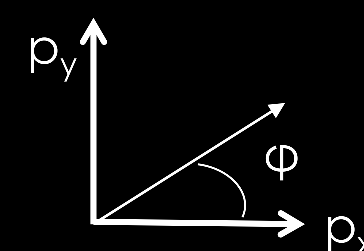
equation of state

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

ELLIPTIC FLOW

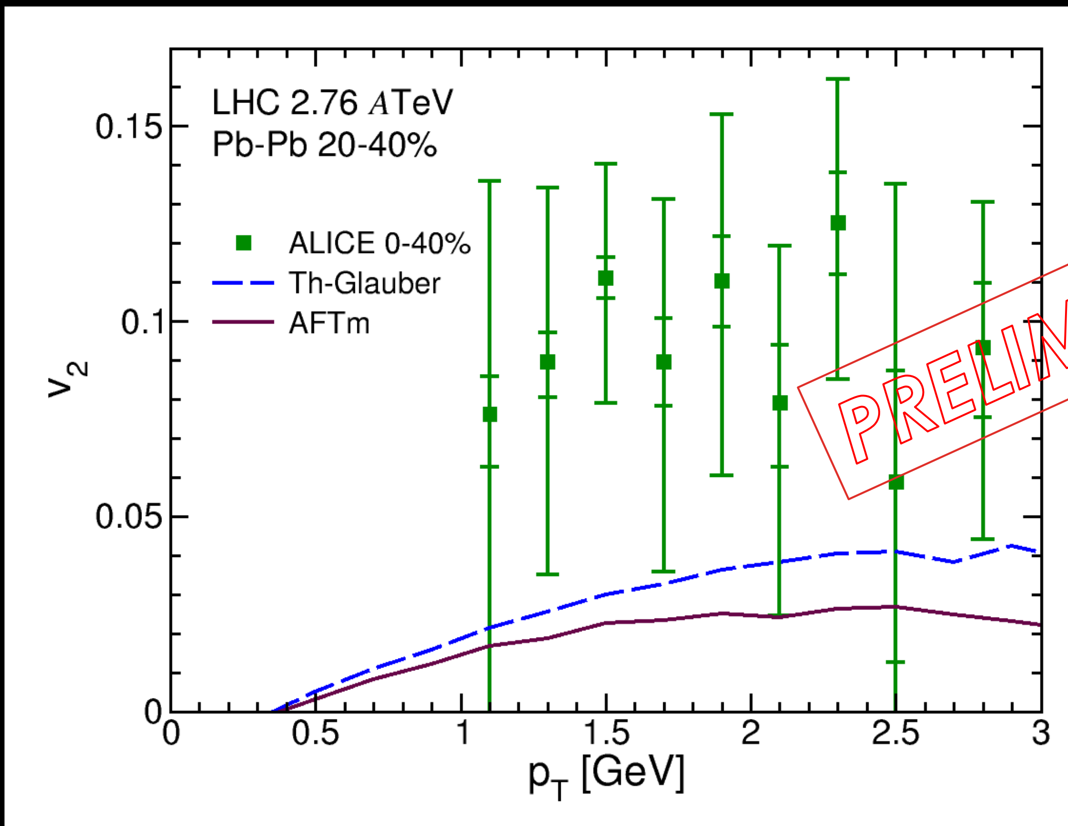
Anisotropic radial flow is described by the Fourier coefficients of the azimuthal particle distributions w.r.t. the reaction plane

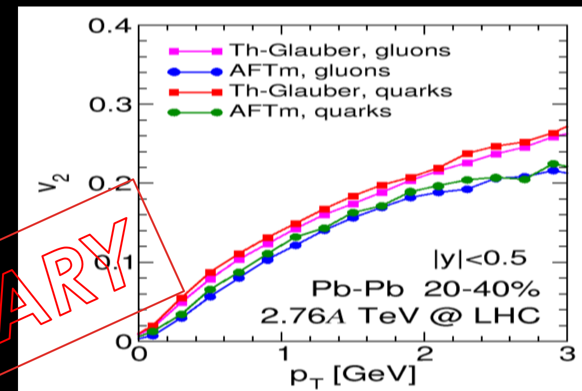
$$\frac{dN}{dp_T d\phi} = \frac{dN}{dp_T}\left[1 + v_2 \cos(2\phi) + 2v_4 cos(4\phi) + \ldots\right]$$



DIRECT PHOTON ELLIPTIC FLOW in uRHICs

Lower $v_2(p_T)$ in the AFTm simulation w.r.t. the Th-Glauber case





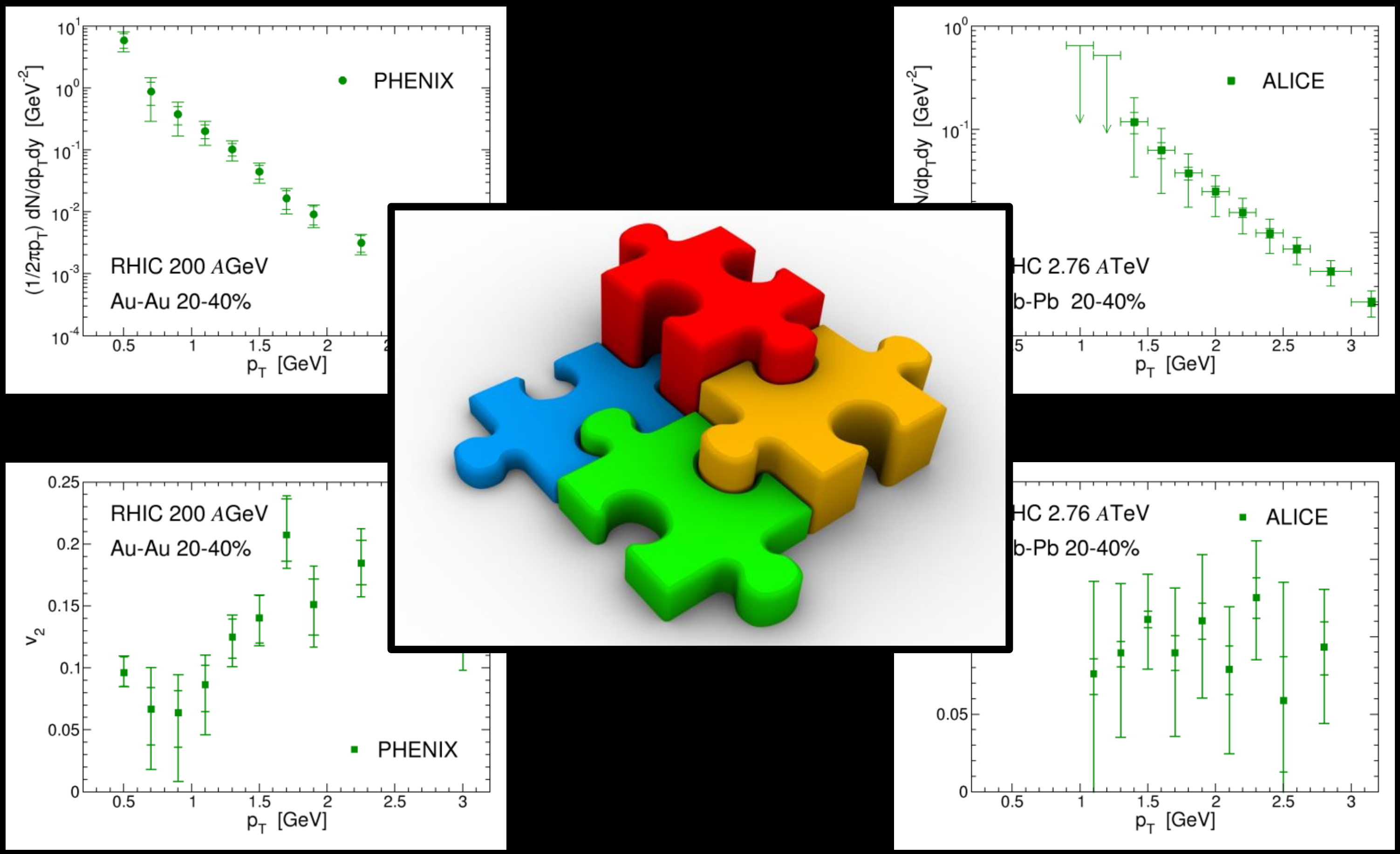
Our simulations do not include any hadronization process

Photon elliptic flow reflects the azimuthal asymmetry of the system at emission time:

- early stage photons suppress the momentum anisotropy brought by QGP thermal photons
- thermal hadronic photons would give a substantial contribution to the final photon elliptic flow

ALICE Collaboration, JPCS 446 (2013) 012028

DIRECT PHOTON "PUZZLE" in uRHICs



The tension in reproducing consistently both spectrum and elliptic flow of direct photons is a common issue of all current theoretical approaches

PHENIX Collaboration, PRC 91 (2015) 064904
PHENIX Collaboration, arXiv:nucl-ex/1509.07758 (2015)
ALICE Collaboration, PLB 754 (2016) 235
ALICE Collaboration, JPCS 446 (2013) 012028