Workshop on Chirality, Vorticity and Magnetic Field
in Heavy Ion Collisions
GGI, Arcetri, Firenze
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Impact of the vortical pre-equilibrium stage of relativistic heavy ion collision on photon production

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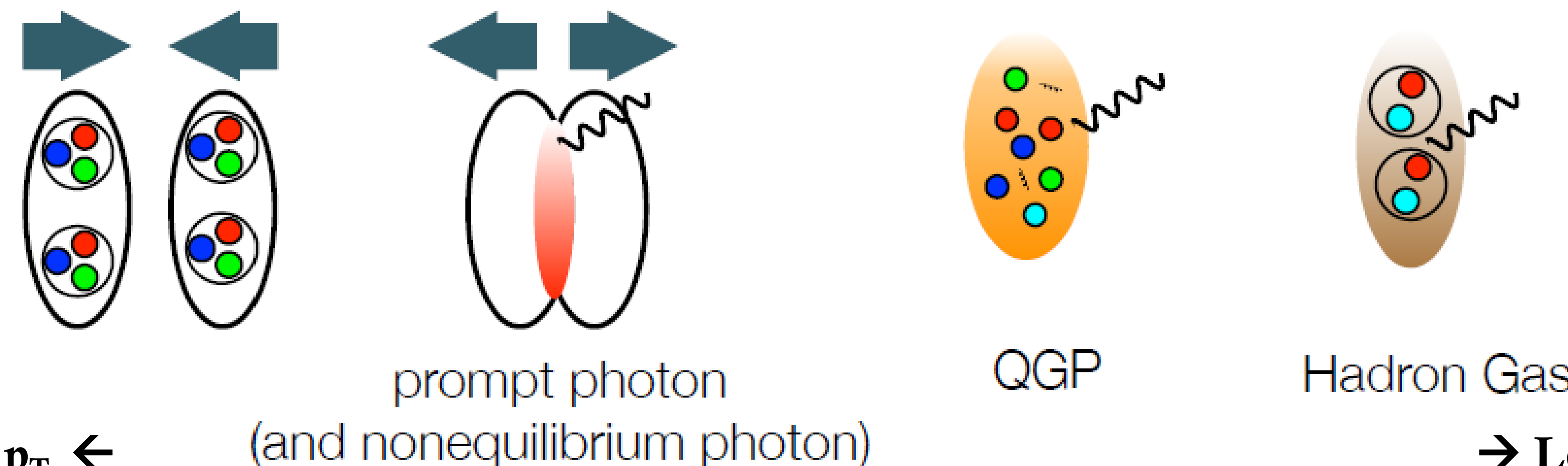
ELECTROMAGNETIC PROBES

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



High p_T ← **→ Low p_T**

Experiments can not distinguish among the different sources

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

BOLTZMANN TRANSPORT EQUATION

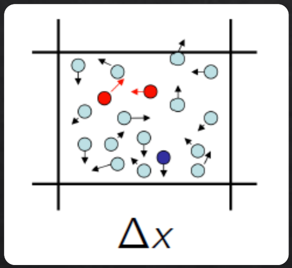
In order to **simulate** the temporal evolution of the fireball
we solve the **Boltzmann equation** for the parton distribution function **f(x,p)**

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

Free streaming

Field interaction
e.g. color-electric field

Collision integral
deviations from ideal hydro



$$\mathcal{C}[f] = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2}(f'_1 f'_2 - f_1 f_2) \times |\mathcal{M}_{12\to1'2'}|\,(2\pi)^4 \delta^{(4)}(p'_1 + p'_2 - p_1 - p_2)$$

- **<u>TEST PARTICLES METHOD</u> to map the phase space**
- **<u>STOCHASTIC METHOD</u> to simulate collisions**

Follow the entire dynamical fireball evolution within one single theoretical approach

Xu and Greiner, PRC 79 (2009) 014904
Greco et al., PLB 670 (2009) 325
Bratkovskaya, et al., NPA 856 (2011) 162
Ruggieri et al., PRC 89 (2014) 054914
Plumari et al., PRC 92 (2015) 054902

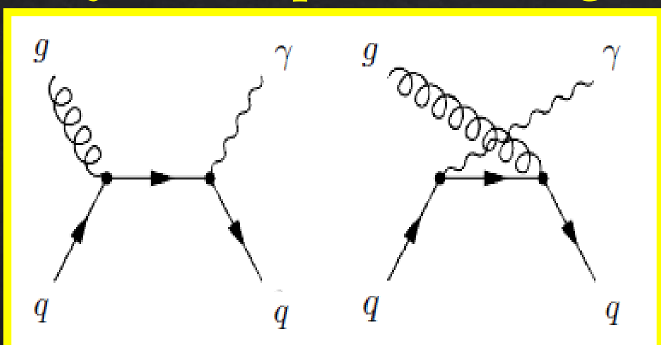
BOLTZMANN TRANSPORT EQUATION

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

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

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

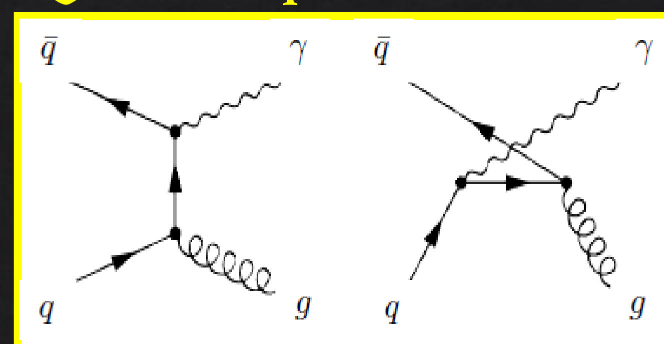
QCD Compton scattering



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

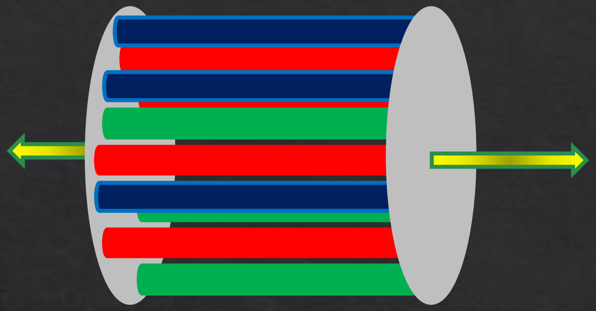
$$\frac{d\sigma^{annihil}}{dt} = \frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

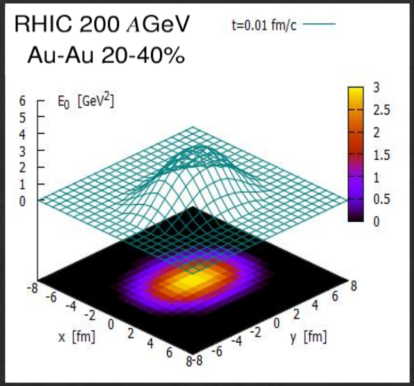
Quark-antiquark annihilation



MOTIVATIONS

GLASMA





Starting time

$t_0 = 0^+$ fm/c

SELF-CONSISTENT SOLUTION OF BOLTZMANN AND MAXWELL EQUATIONS

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

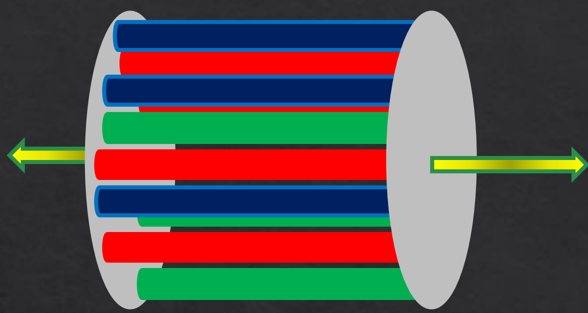
+

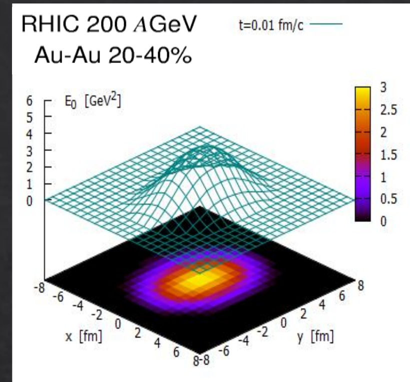
$$\frac{dE}{d\tau} = -j_M - j_D$$

Florkowski and Ryblewski, PRD 88 (2013) 034028
Ruggieri, Puglisi, Oliva, Plumari, Scardina and Greco, PRC 92 (2015) 064904

MOTIVATIONS

GLASMA





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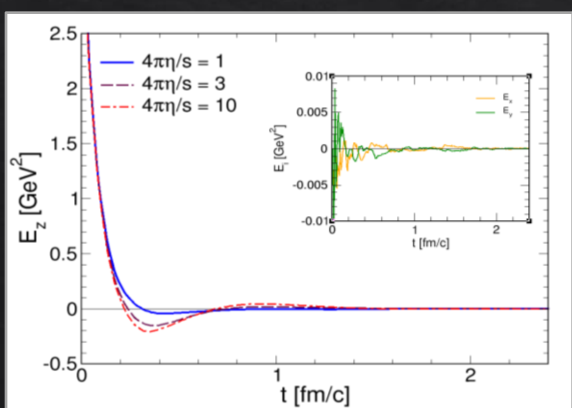
SELF-CONSISTENT SOLUTION OF BOLTZMANN AND MAXWELL EQUATIONS

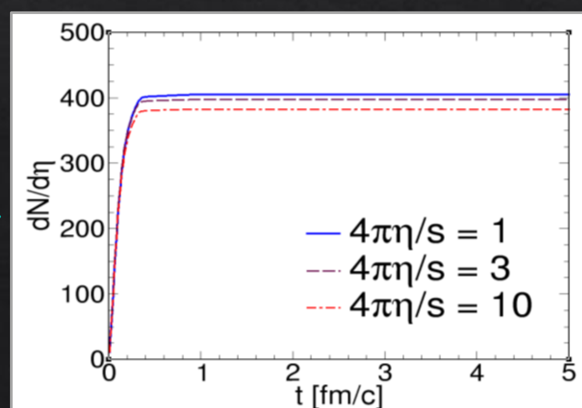
$$(p_\mu \partial^\mu + gQ_{jc}F^{\mu\nu}p_\mu \partial_\nu^p) f_{jc} = p_0 \frac{\partial}{\partial t}\frac{dN_{jc}}{d^3x d^3p} + \mathcal{C}[f]$$

+

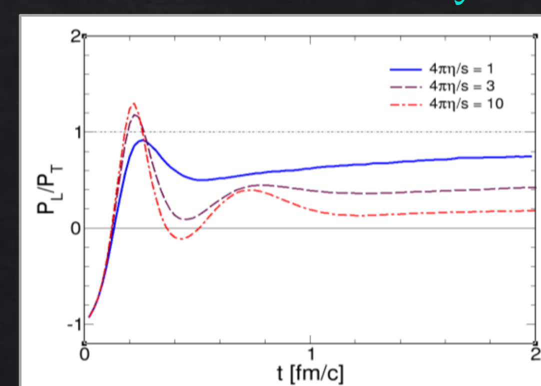
$$\frac{dE}{d\tau} = -j_M - j_D$$

longitudinal chromo-electric fields decay in gluon pairs and quark-antiquark pairs by SCHWINGER MECHANISM





fast isotropization for small viscosity



Florkowski and Ryblewski, PRD 88 (2013) 034028

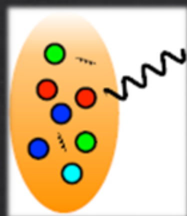
Ruggieri, Puglisi, Oliva, Plumari, Scardina and Greco, PRC 92 (2015) 064904

MOTIVATIONS

Pre-equilibrium photons
During classical field decay

fireball evolution

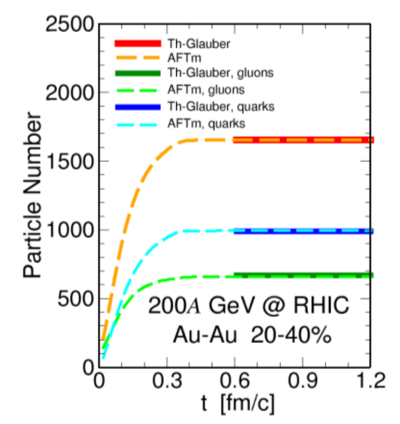
Thermal QGP photons
During thermal QGP evolution



Starting time

$t_0 = 0^+$ fm/c

No net distinction between photons produced in the pre-equilibrium stage and after thermalization



Oliva, Ruggieri, Plumari, Scardina, Peng and Greco, PRC 96, 014914 (2017)

MOTIVATIONS

Starting time

$t_0 = 0^+$ fm/c

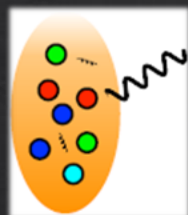
Pre-equilibrium photons

During classical field decay

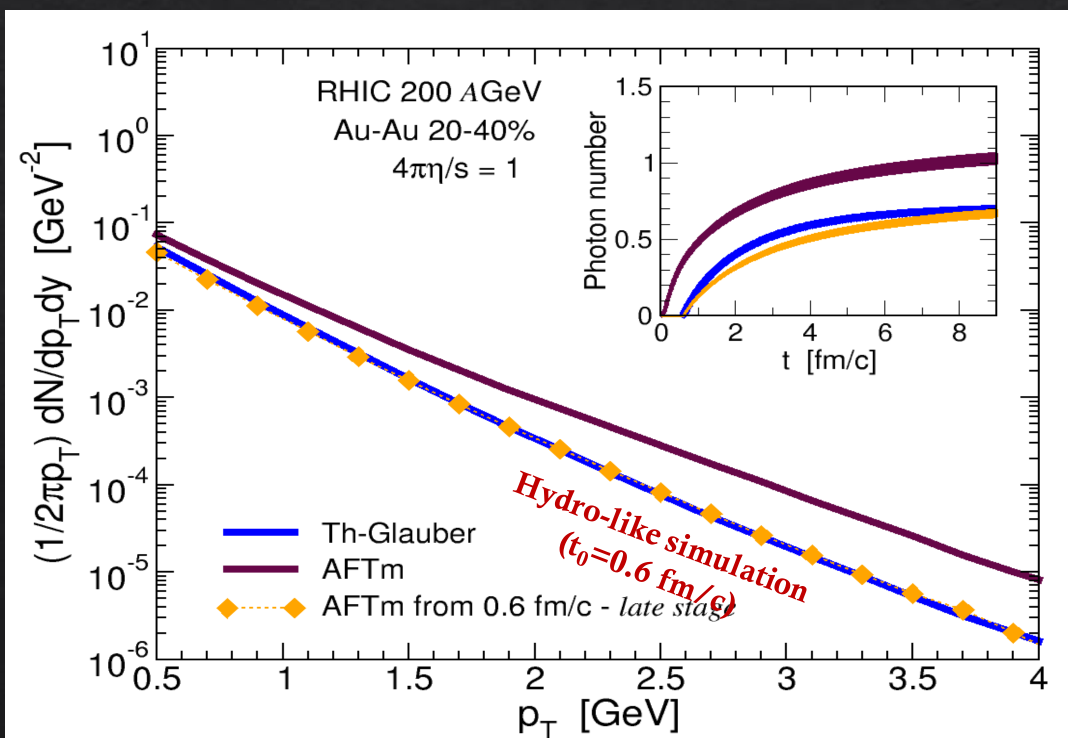
fireball evolution

Thermal QGP photons

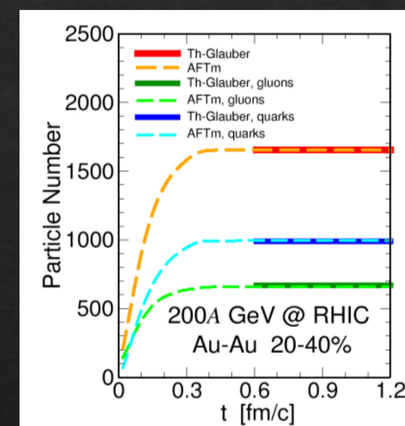
During thermal QGP evolution



No net distinction between photons produced in the pre-equilibrium stage and after thermalization

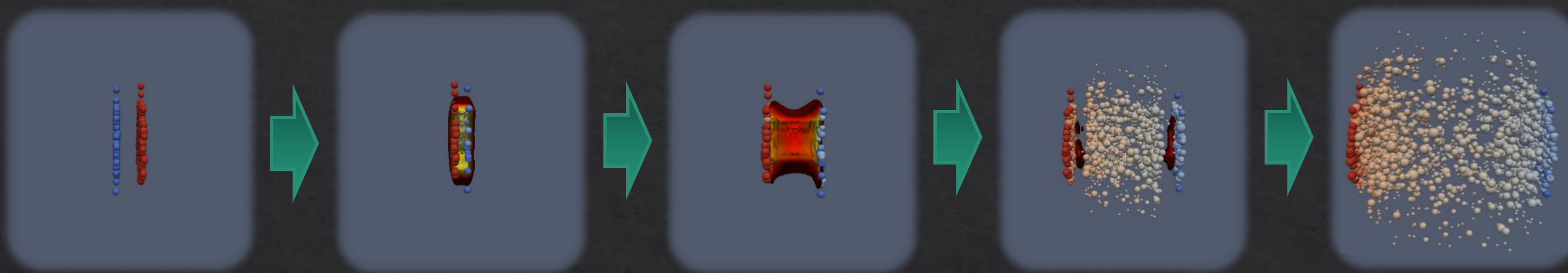


Oliva, Ruggieri, Plumari, Scardina, Peng and Greco, PRC 96, 014914 (2017)

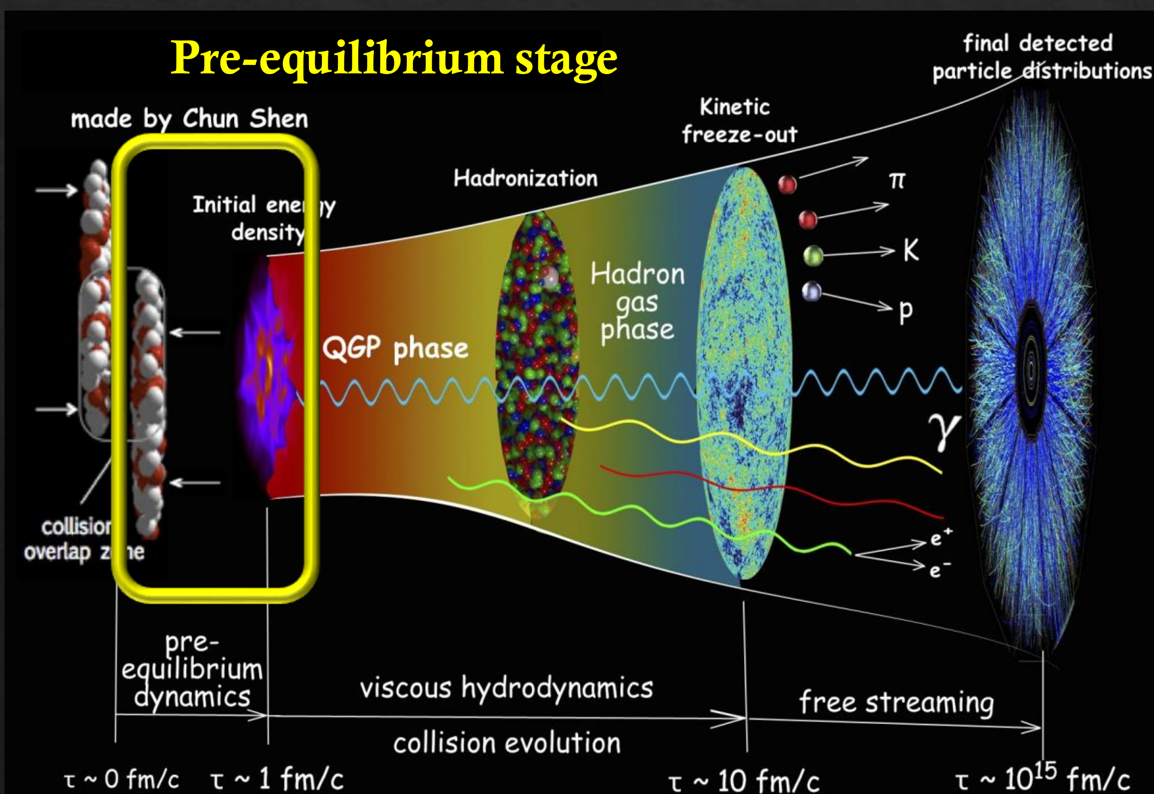


The **early stage shines:**
pre-equilibrium photons comparable in number with those emitted from the equilibrated QGP during its whole lifetime.

RELATIVISTIC HEAVY ION COLLISIONS



made by Jonah Bernhard

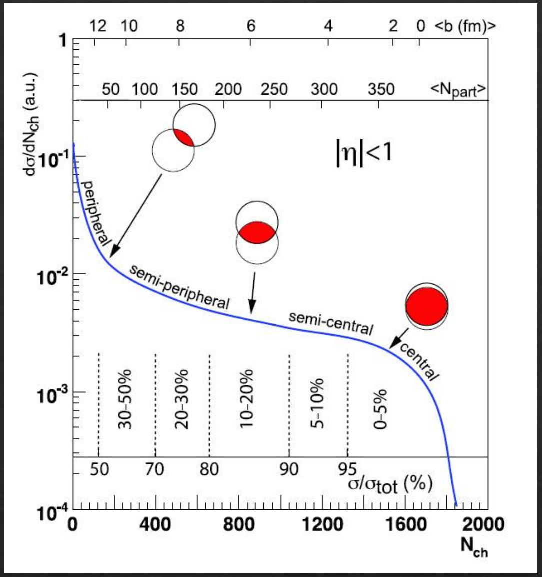


- ❖ Initial phase strongly anisotropic and not thermalized
- ❖ Intense magnetic field $eB_y \sim 5\text{-}50\ m_\pi^2$
- ❖ Vorticity due to the large orbital angular momentum $J_y \sim 10^5\text{-}10^6\ \hbar$

WHICH IS ITS IMPACT ON PHOTON OBSERVABLES?

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

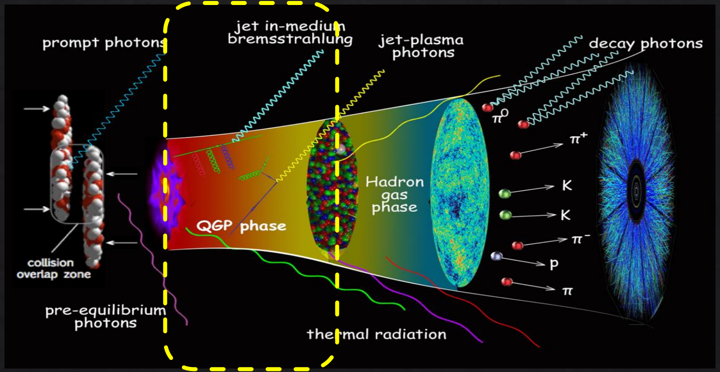


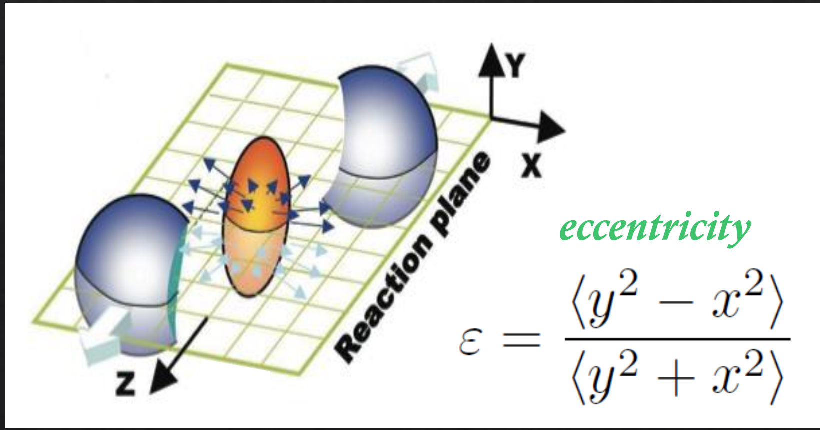
Miller et al., ARNPS 57 (2007) 205

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

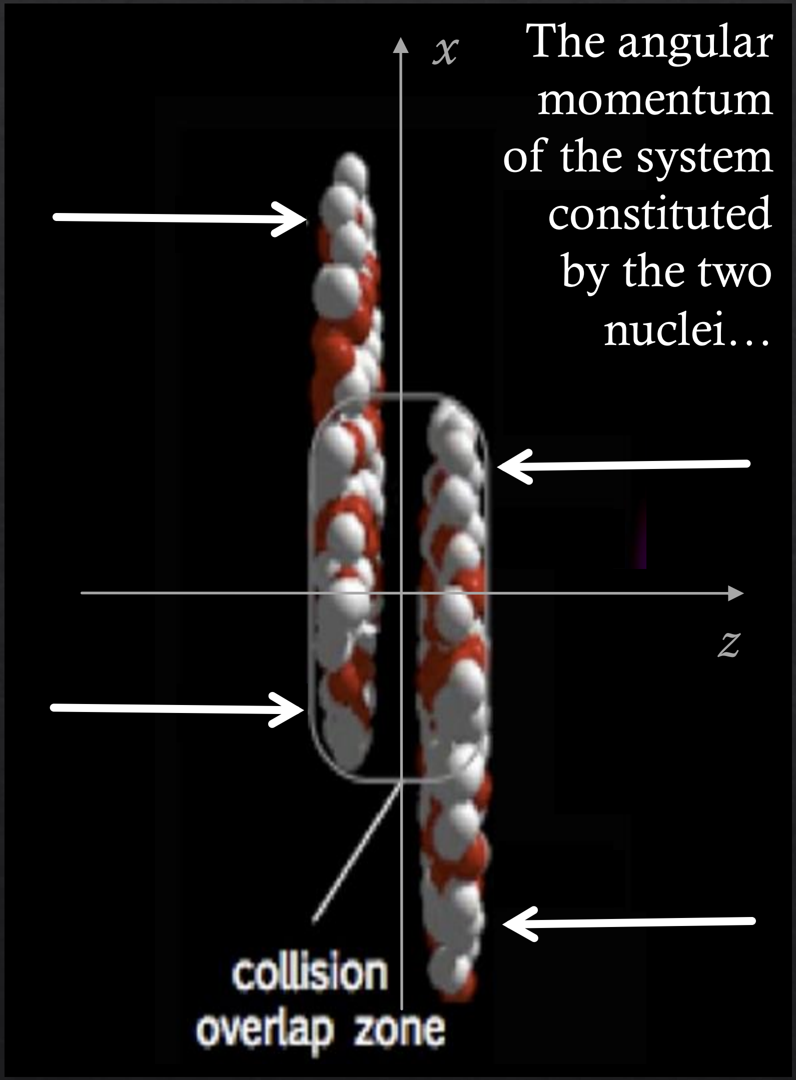
For 20-40% centrality class

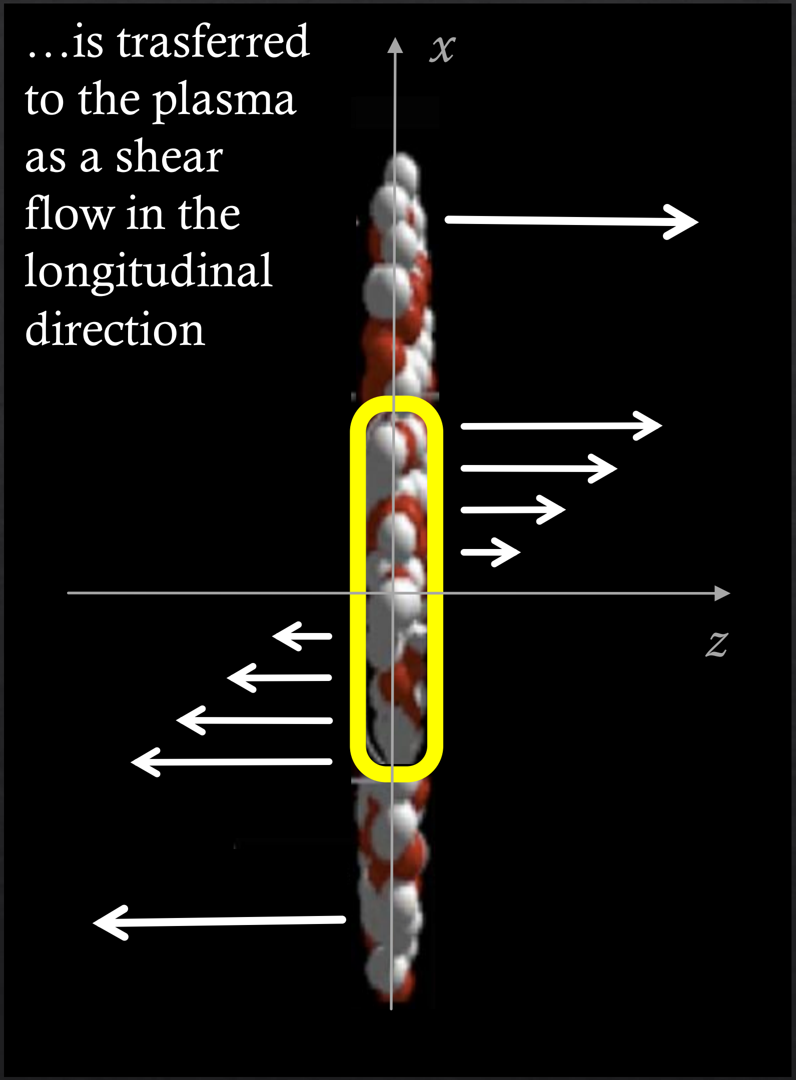
- Multiplicity of about 1700 particles
- Initial eccentricity of about 0.33





VORTICITY IN HEAVY ION COLLISIONS



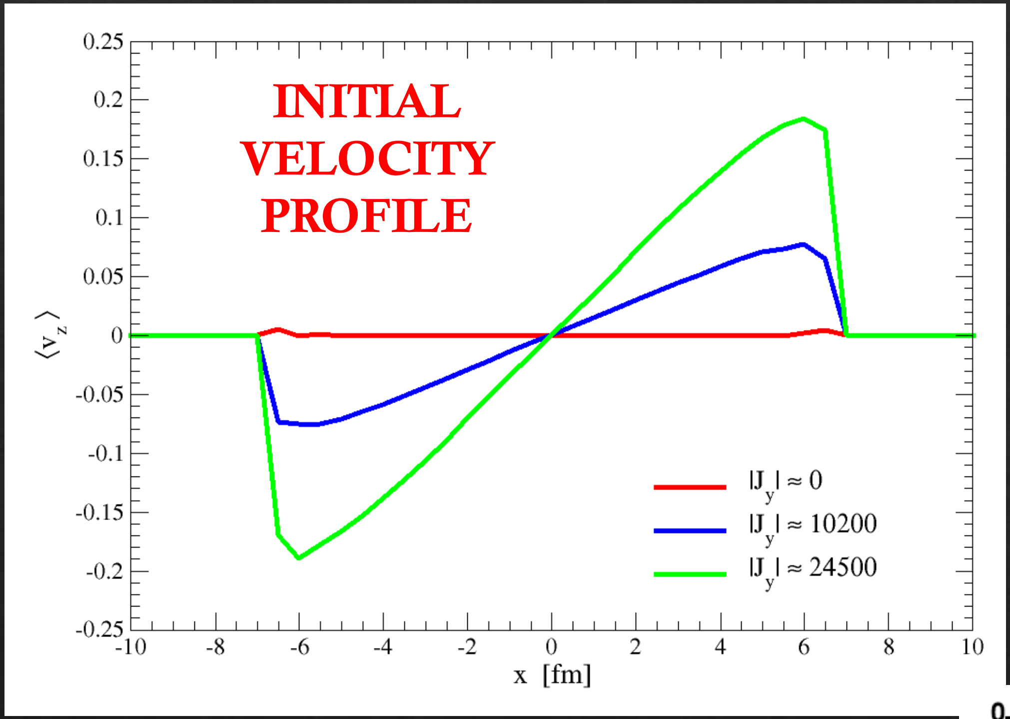


Snellings, Sorge, Voloshin, Wang and Xu, PRL 84, 2803 (2000)
Becattini, Piccinini e Rizzo, PRC 77, 024906 (2008)
Csernai, Magas and Wang, PRC 87, 034906 (2013)

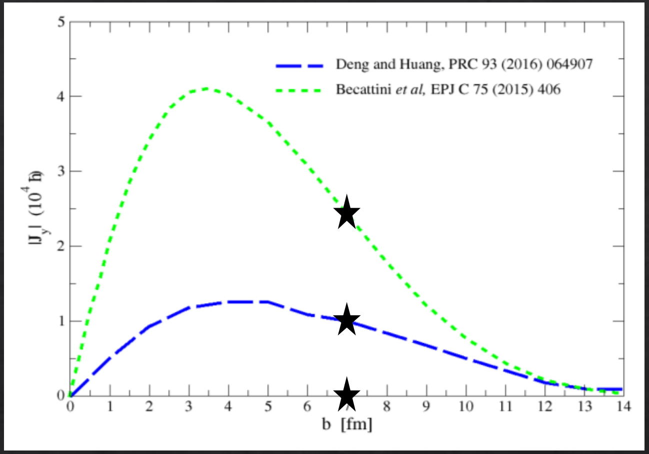
Becattini et al, EPJ C 75, 406 (2015)
Deng and Huang, PRC 93, 064907 (2016)
Jiang, Lin and Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)

VORTICITY IN HEAVY ION COLLISIONS

Au-Au collisions @ RHIC 200 AGeV - b=7 fm

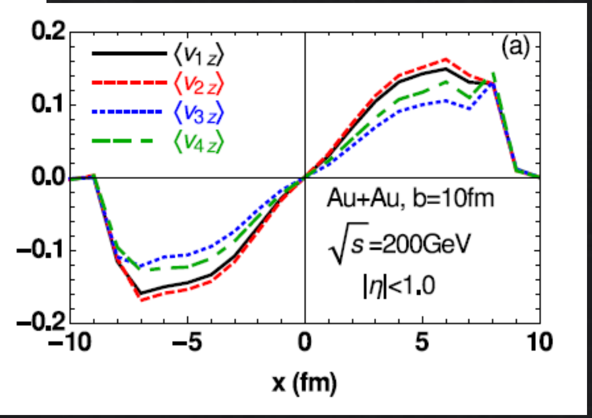


ESTIMATED ANGULAR MOMENTUM OF THE PLASMA



Longitudinal velocity profile at $|\eta_s|<1$ and averaged over all y-layers

In qualitative agreement with Deng and Huang, PRC 93, 064907 (2016)

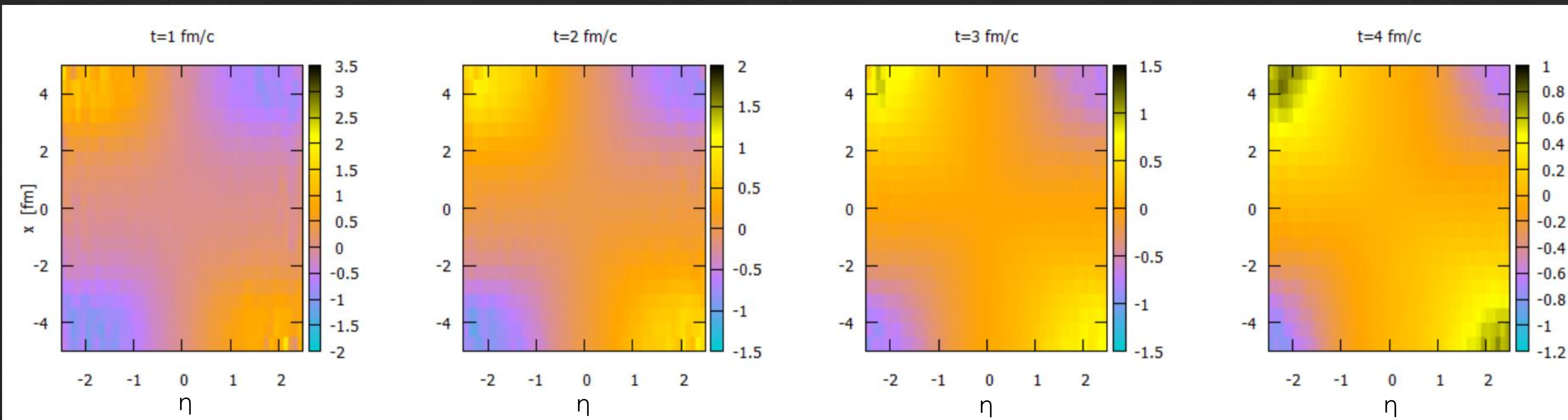


VORTICITY IN HEAVY ION COLLISIONS

Au-Au collisions @ RHIC 200 AGeV - b=7 fm

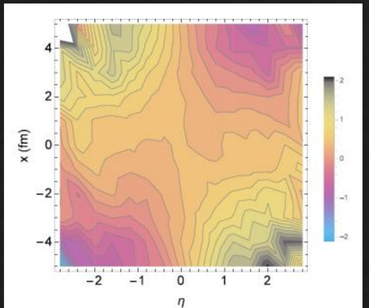
$$\omega_y(\boldsymbol{x},t) = \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x} \quad [\mathrm{fm}^{-1}]$$

VORTICITY FIELD



y-component of the classical vorticity field in the reaction plane (y=0)

In agreement with Jiang, Lin and Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)



VORTICITY FIELD IN THE FIREBALL DECREASES DURING TEMPORAL EVOLUTION

VORTICITY IN HEAVY ION COLLISIONS

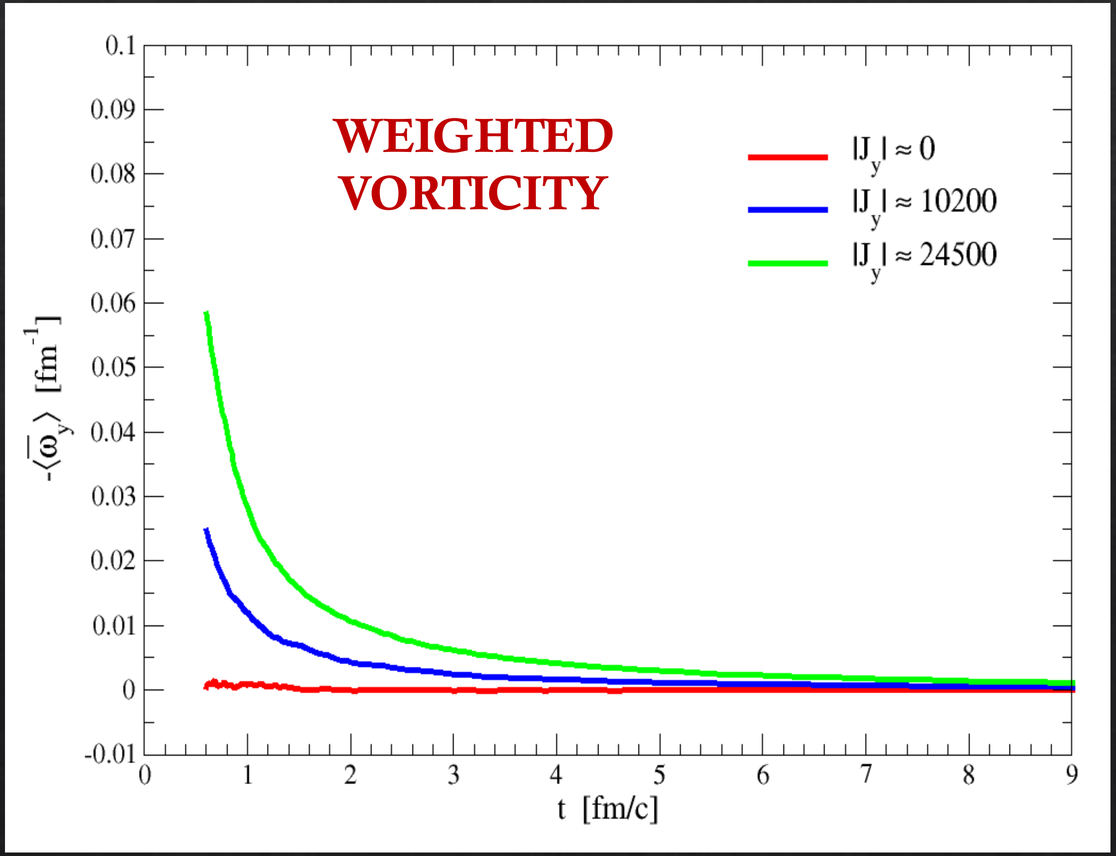
Au-Au collisions @ RHIC 200 AGeV - b=7 fm

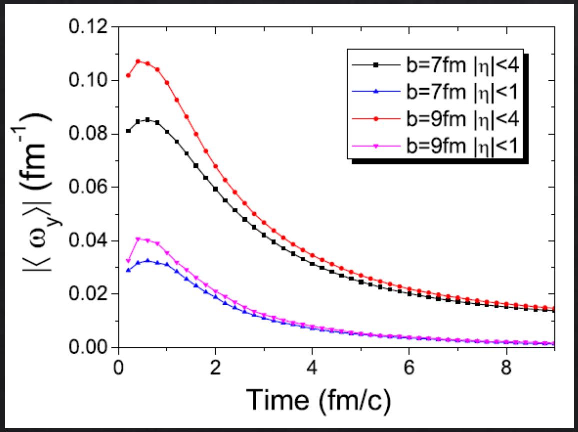
$$\overline{\omega_y}(\boldsymbol{x},t) = \frac{\int d^3x\, w(\boldsymbol{x},t)\omega_y(\boldsymbol{x},t)}{\int d^3x\, w(\boldsymbol{x},t)}$$

y-component of the vorticity averaged in $|\eta_s|<1$ and over the full transverse plane with the weighting function w

$$w(\boldsymbol{x},t) = \rho^2(\boldsymbol{x})\varepsilon(\boldsymbol{x},t)$$

moment-of-inertia density





Jiang, Lin and Liao, PRC 94, 044910 (2016); PRC 95, 049904 (2017)

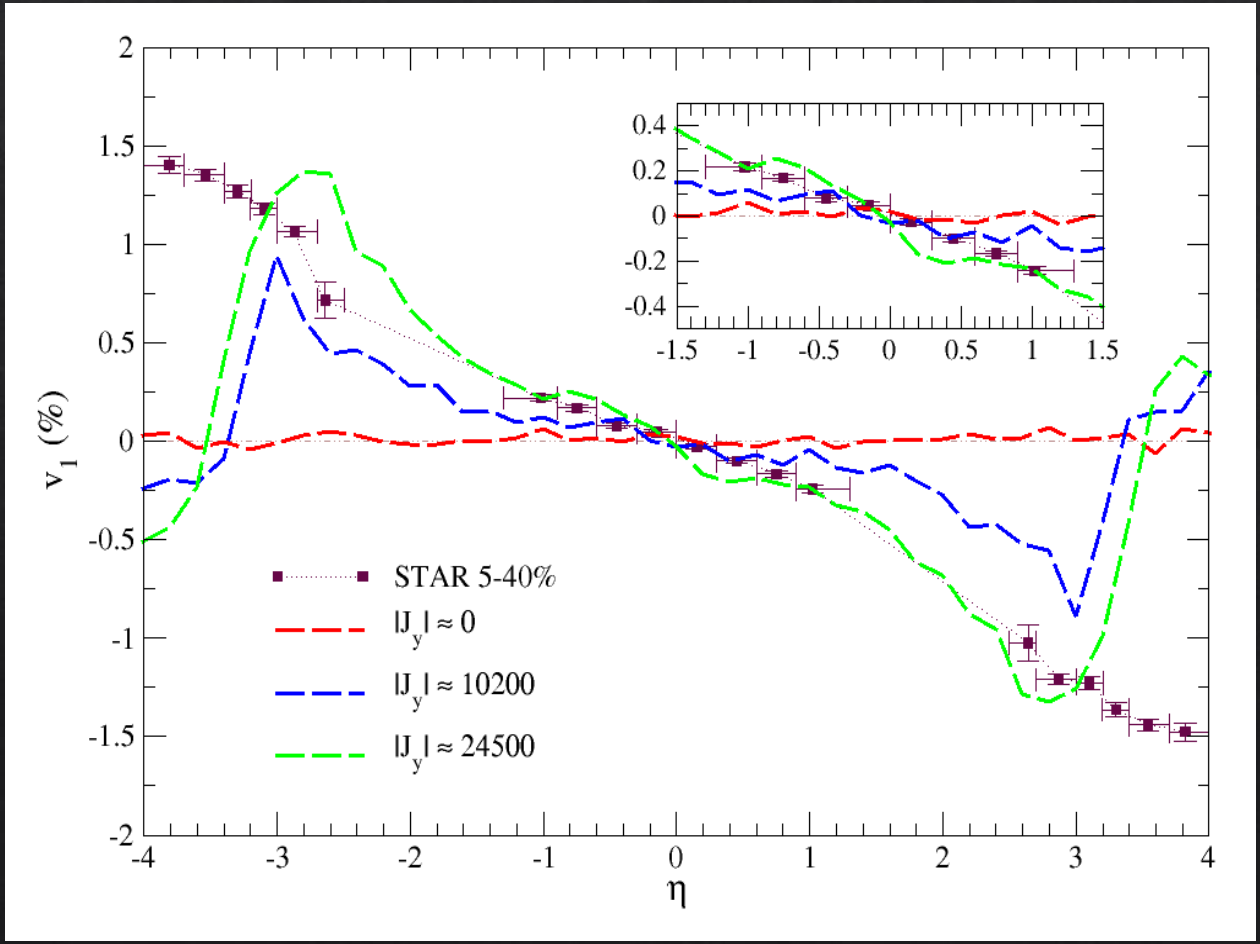
VORTICITY IN HEAVY ION COLLISIONS

Au-Au collisions @ RHIC 200 AGeV - b=7 fm

Inclusion of vorticity necessary to reproduce the measured $v_1(\eta)$ of charged particles

QGP DIRECTED FLOW

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

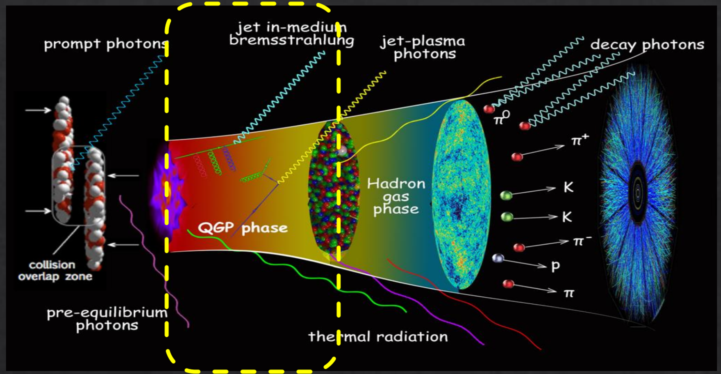


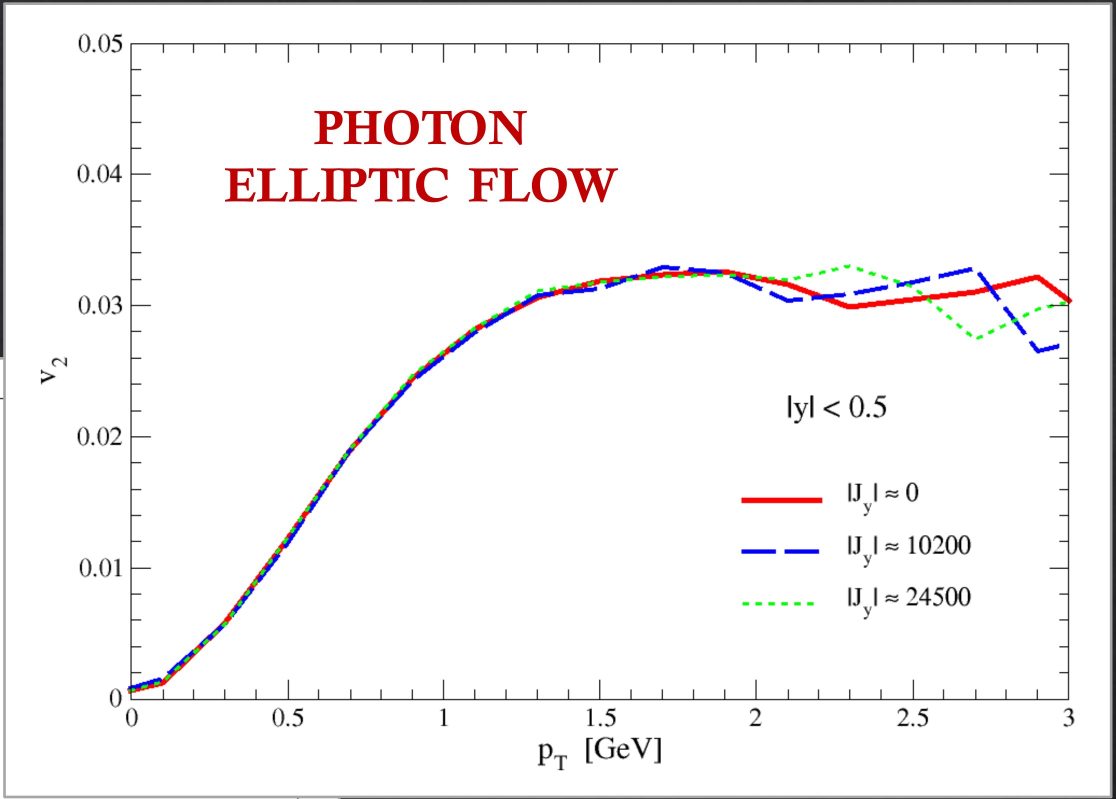
ARE PHOTONS INFLUENCED BY THE VORTICAL STRUCTURE OF QUARK-GLUON PLASMA?

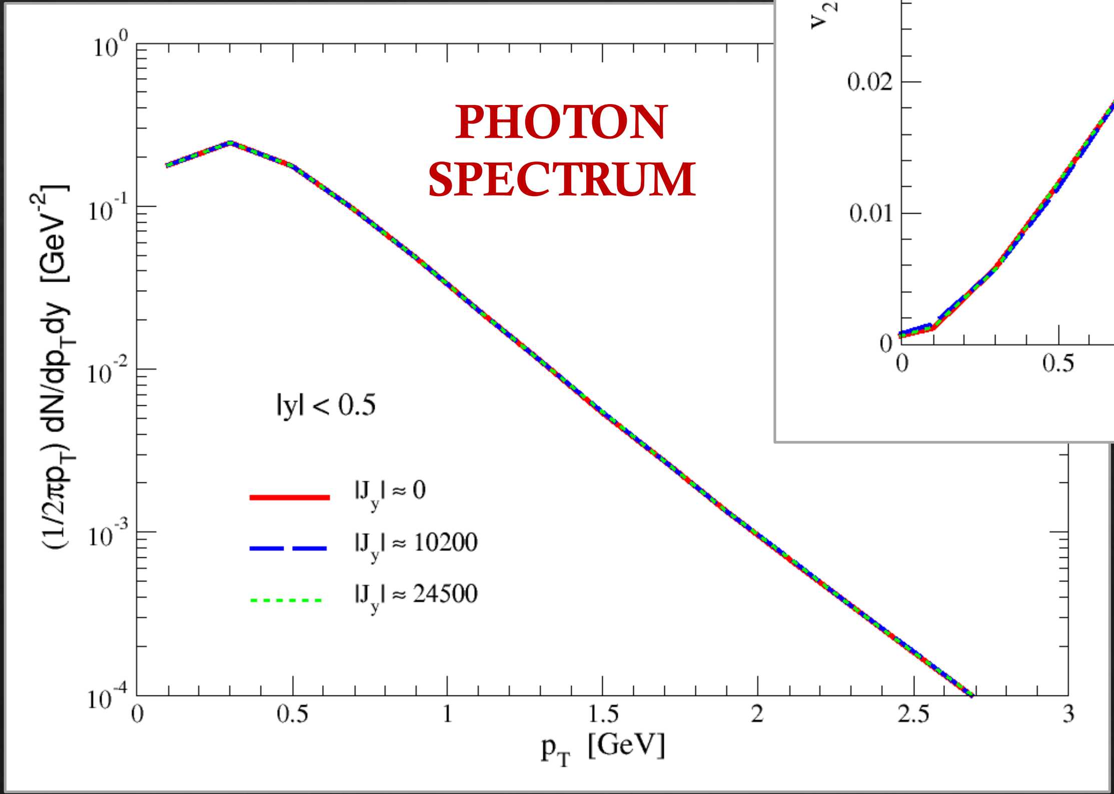
Experimental data: STAR Collaboration, PRL 101 (2008) 252301

IMPACT OF VORTICITY ON PHOTONS

Au-Au collisions @ RHIC 200 AGeV - b=7 fm





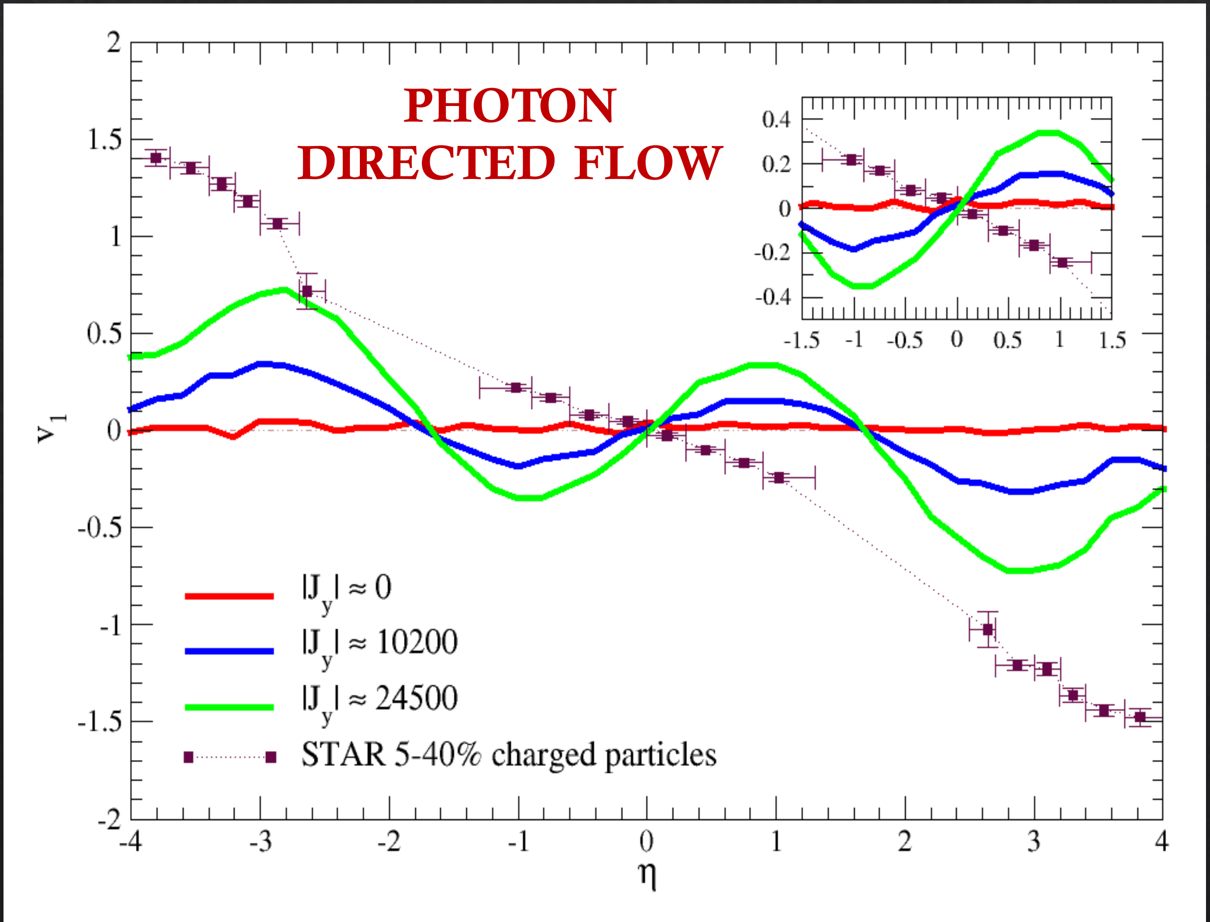


Vorticity does not affect momentum-spectrum and elliptic flow of photons emitted from QGP

VORTICITY IN HEAVY ION COLLISIONS

Au-Au collisions @ RHIC 200 AGeV - b=7 fm

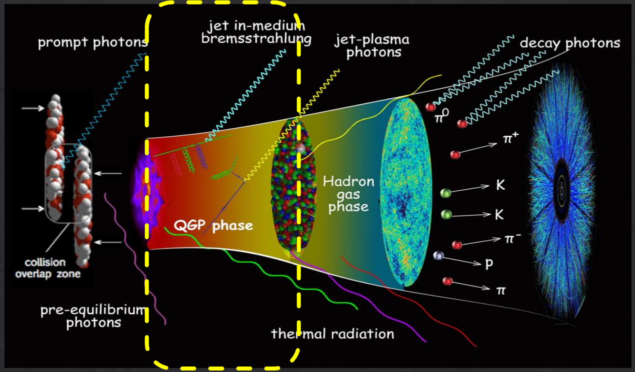
PRELIMINARY



Photon directed flow reflects the asymmetry of the system at emission time

CLEAR EFFECT OF VORTICITY ON PHOTON DIRECTED FLOW

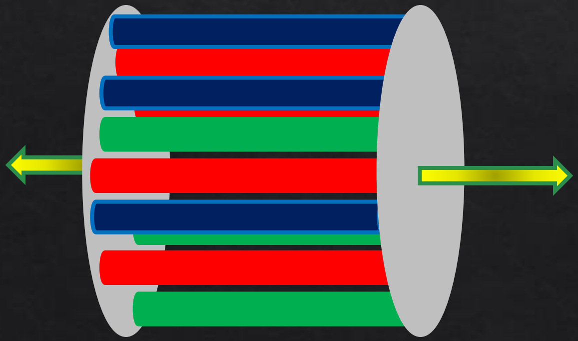
CONCLUSIONS…



Fireball evolution described by means **of relativistic kinetic theory** including the effect of a **finite angular momentum**.

Impact of vorticity on photon production from the quark-gluon plasma:

- ✓ no visible effect in momentum spectrum and in elliptic flow of photons,
- ✓ **photon directed flow comparable in magnitude to that of charged particles.**



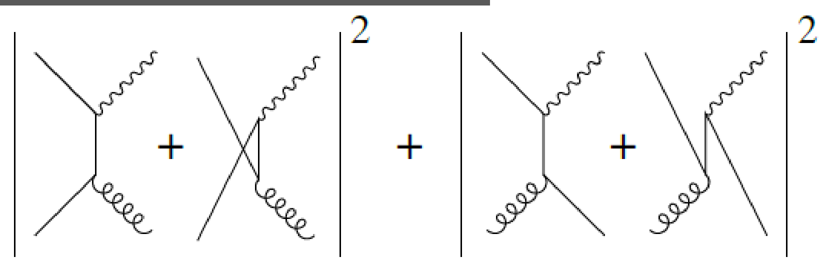
…AND OUTLOOKS

- ✓ Extend the description of vorticity in the early stage before quark-gluon plasma equilibration.
- ✓ Investigate the effect of the initial electromagnetic fields on photon production.

Thank you
for your attention!

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

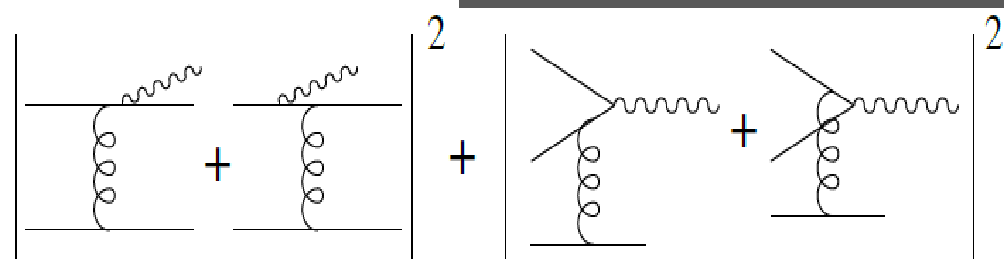
$$\frac{d\sigma^{Compton}}{dt} = -\frac{\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$

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

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

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

Inelastic pair annihilation



Bremsstrahlung

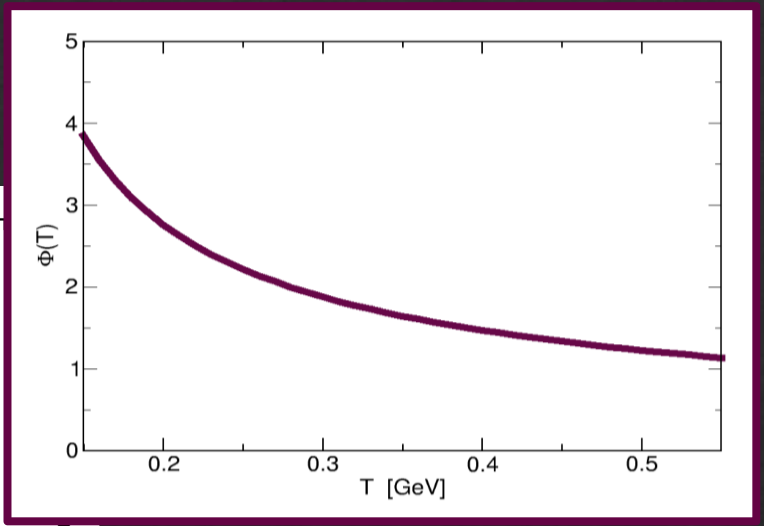
$$\frac{d\sigma^{Compton}}{dt} = -\Phi(T)\frac{\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$

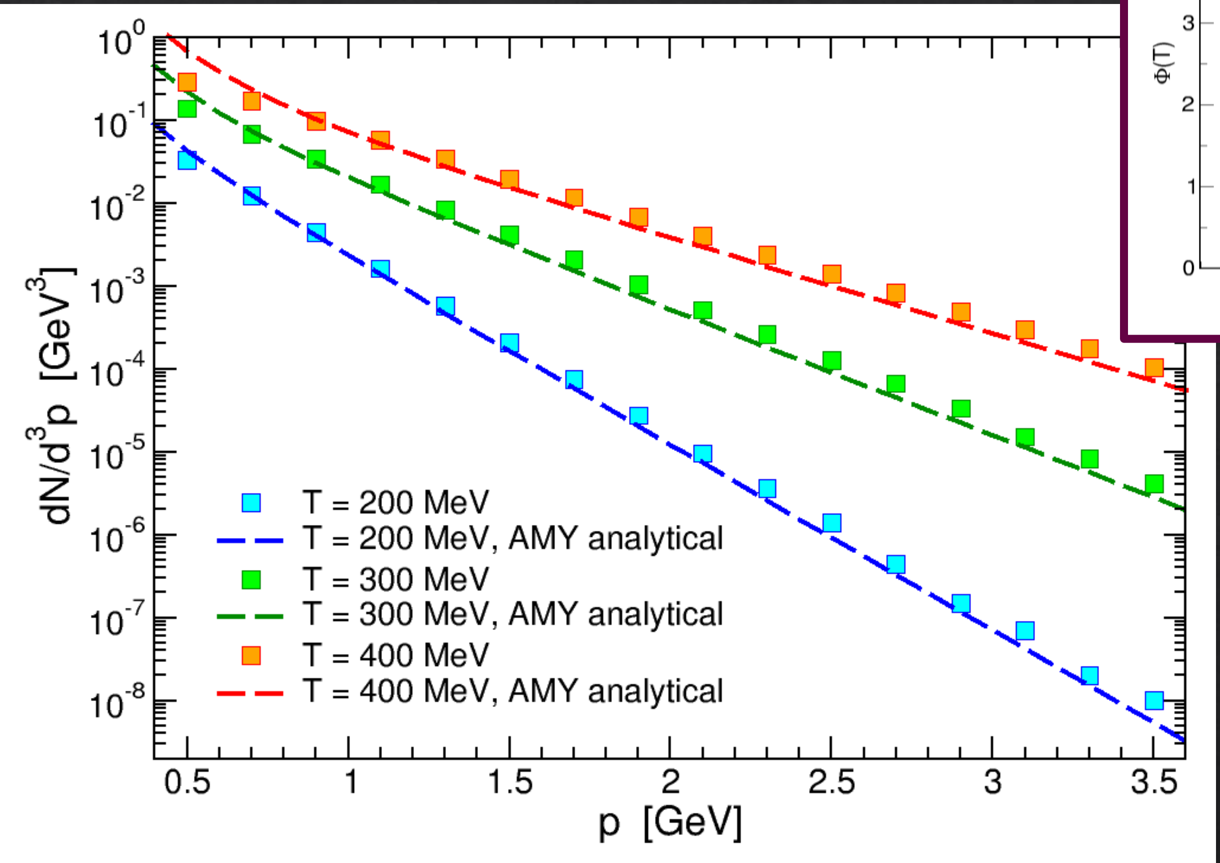
$$\frac{d\sigma^{annihil}}{dt} = \Phi(T)\frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

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

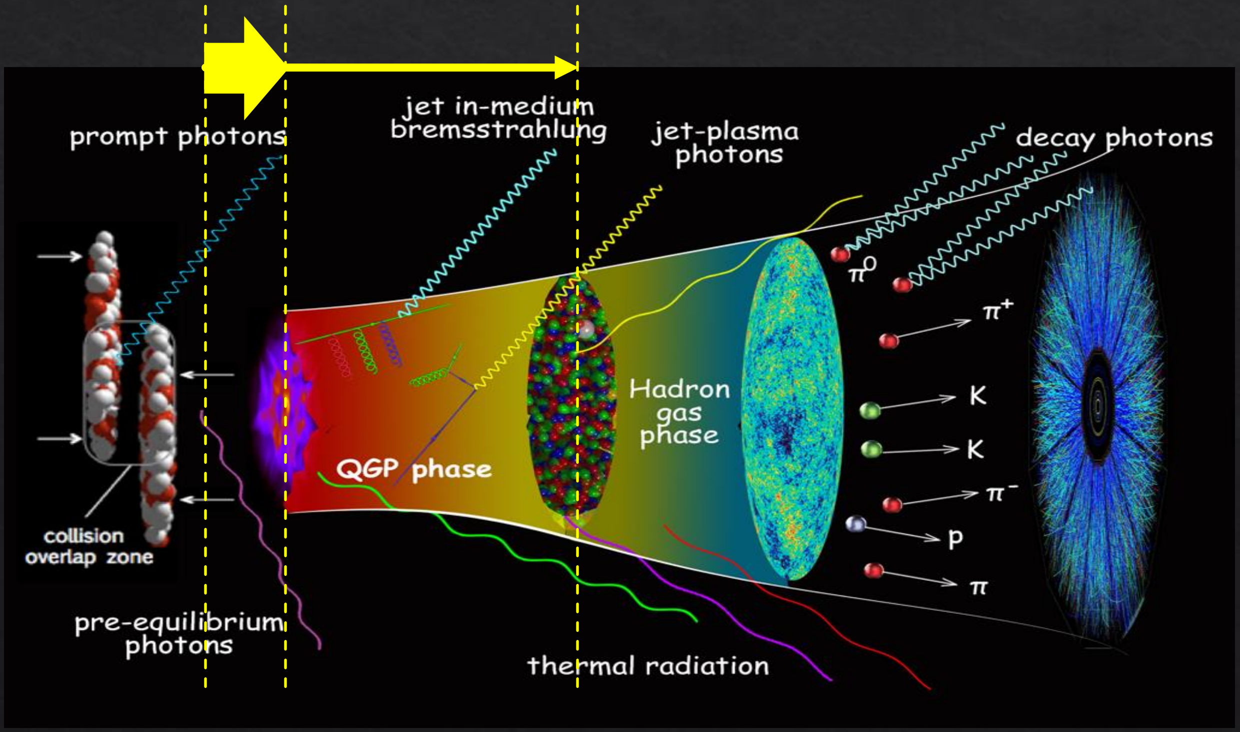
We can follow photon production consistently since the very first moments after the collision regardless of the fact that the system is in local equilibrium or not

PHOTONS at RHIC: impact of pre-equilibrium

The EARLY STAGE is QUITE BRIGHT

NO DARK AGE in uRHICs

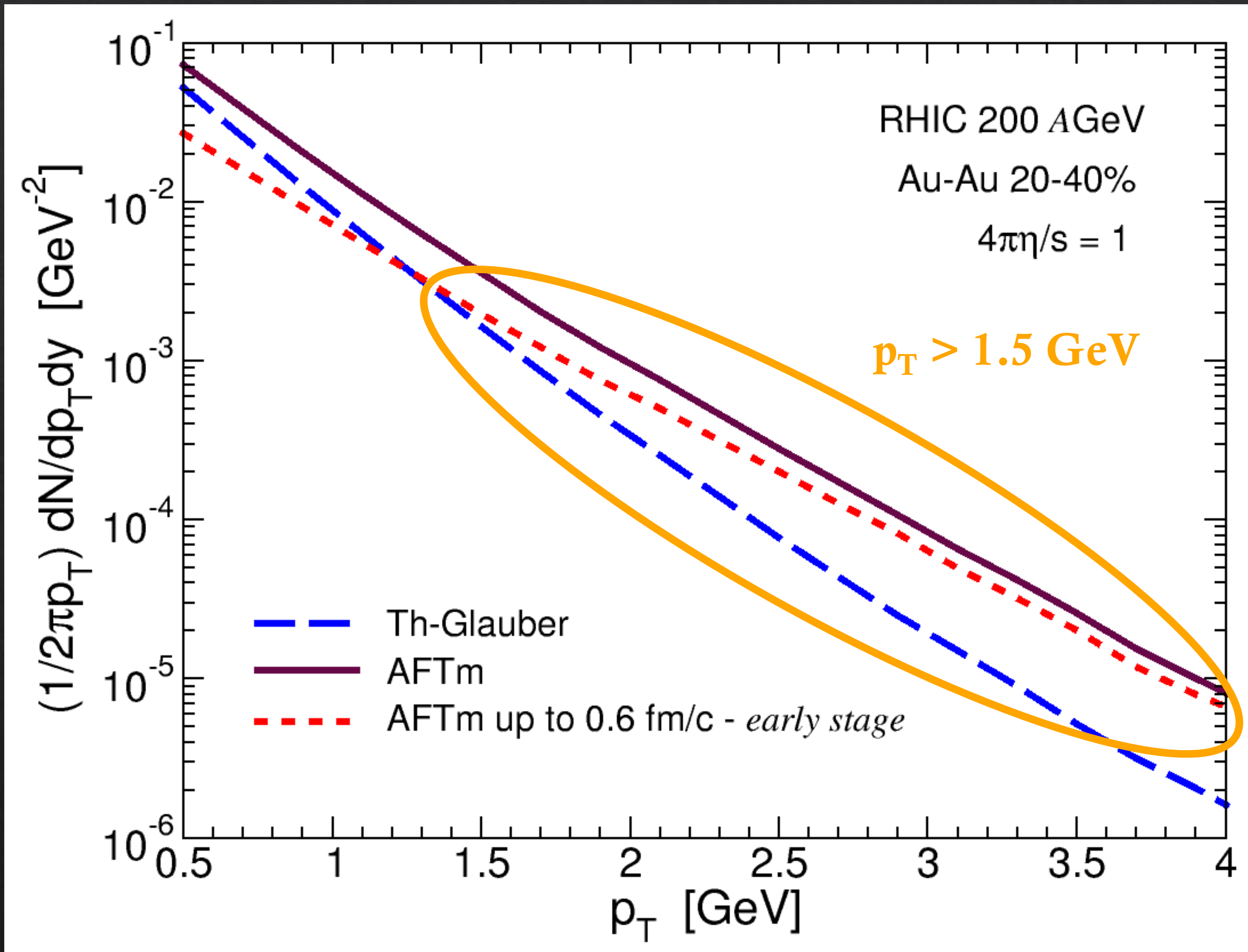
the lifetime of the early stage is at most one tenth of the full QGP lifetime in the fireball



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 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, *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