The chiral medium of the early stage of relativistic heavy ion collisions

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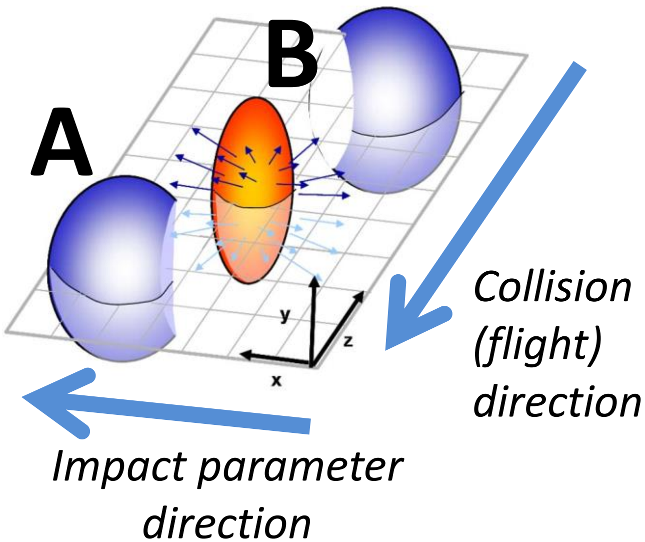
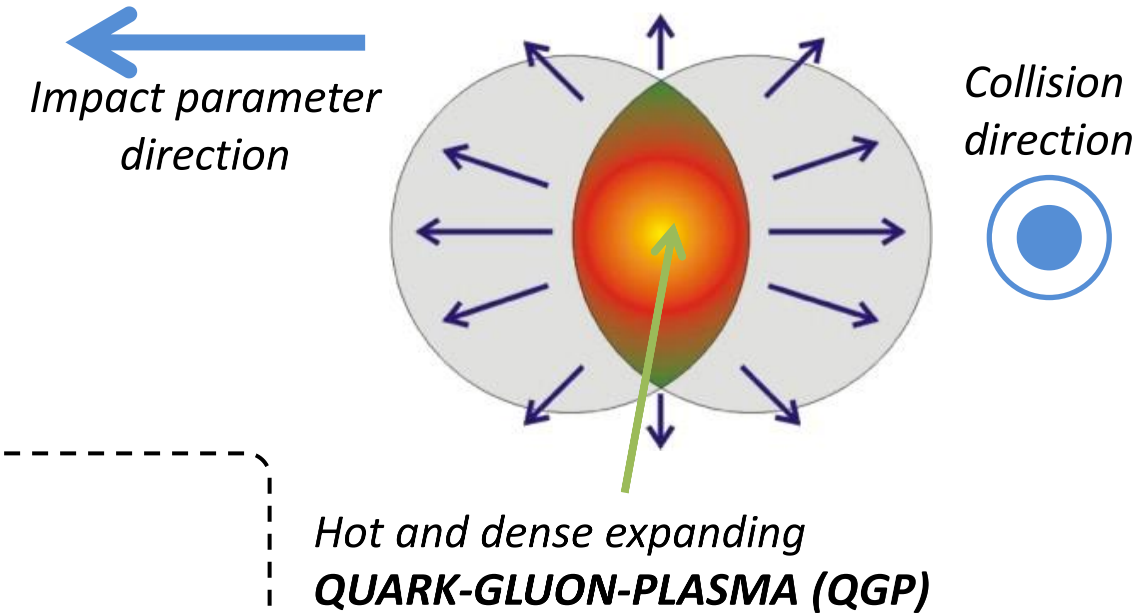
Plan of the talk

- *Relativistic heavy ion collisions (RHICs)*
- *Glasma and its evolution (Ev-Glasma)*
- *Production of chiral density in the pre-hydro stage of RHICs*
- *Photons from the Chiral Magnetic Effect in the Ev-Glasma*
- *Conclusions and Outlook*

Relativistic Heavy Ion Collisions (RHICs)





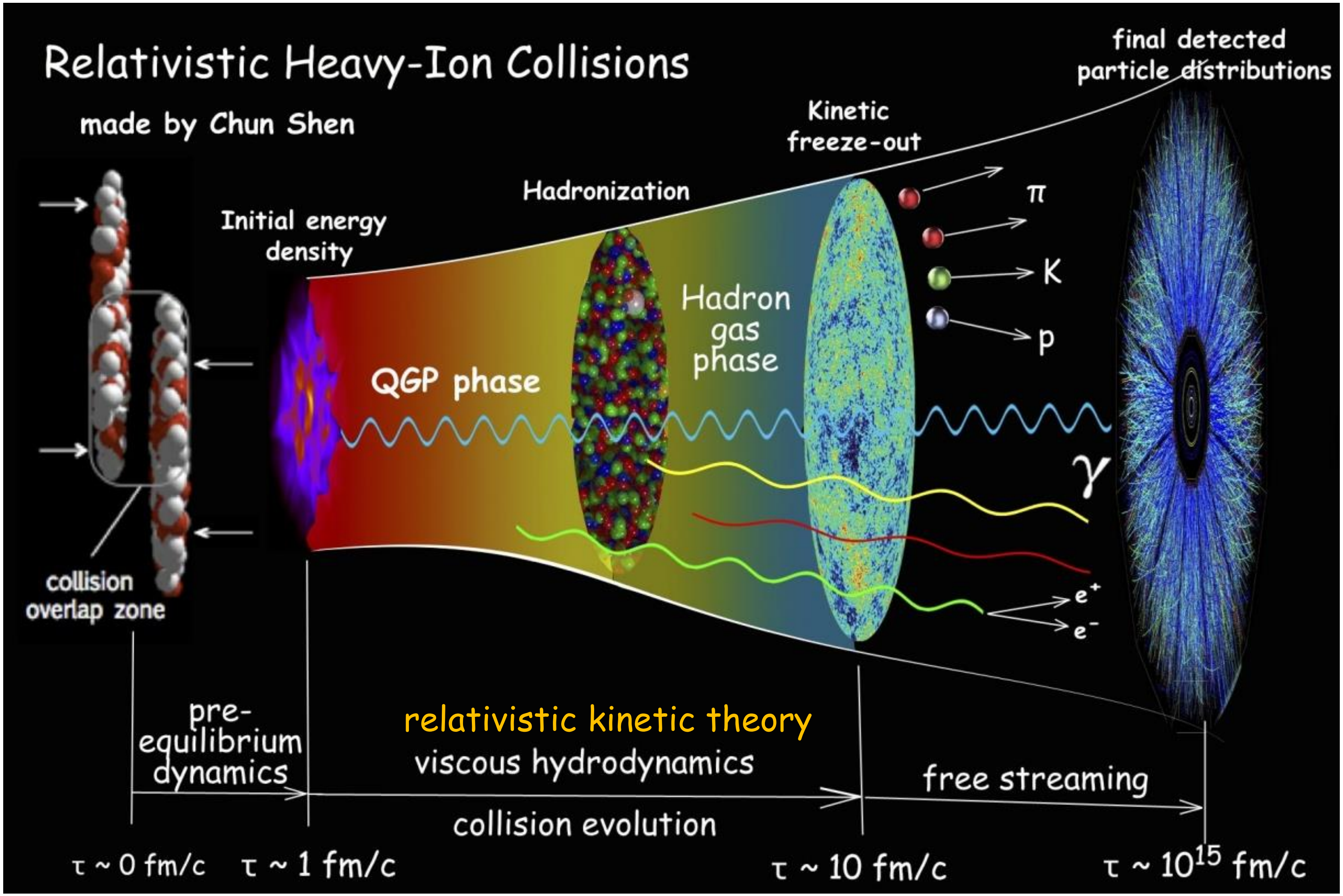
A,B: Cu, Au (RHIC@BNL)
Pb (LHC@CERN)
p (LHC@CERN)
p-Pb collisions (LHC@CERN)
d-Au collisions (LHC@CERN)

$$\mathrm{Au-Au}: \sqrt{s} = 200 \times A \text{ GeV} \quad \text{at RHIC}$$
$$\mathrm{Pb-Pb}: \sqrt{s} = 2.76 \times A \text{ TeV} \quad \text{at LHC}$$
$$\mathrm{p-Pb}: \sqrt{s} = 5.02 \text{ TeV} \quad \text{at LHC}$$
$$\mathrm{p-p}: \sqrt{s} = 5,\ 7 \text{ and } 13 \text{ TeV} \quad \text{at LHC}$$

QGP formation time
- RHIC $\approx$ 0.6 fm/c
- LHC $\approx$ 0.2 fm/c

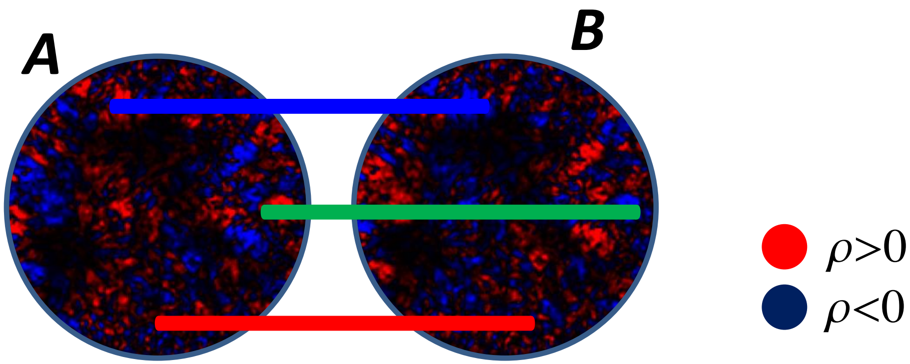
QGP lifetime
- RHIC $\approx$ 5 fm/c
- LHC $\approx$ 10 fm/c

Medium evolution in RHICs

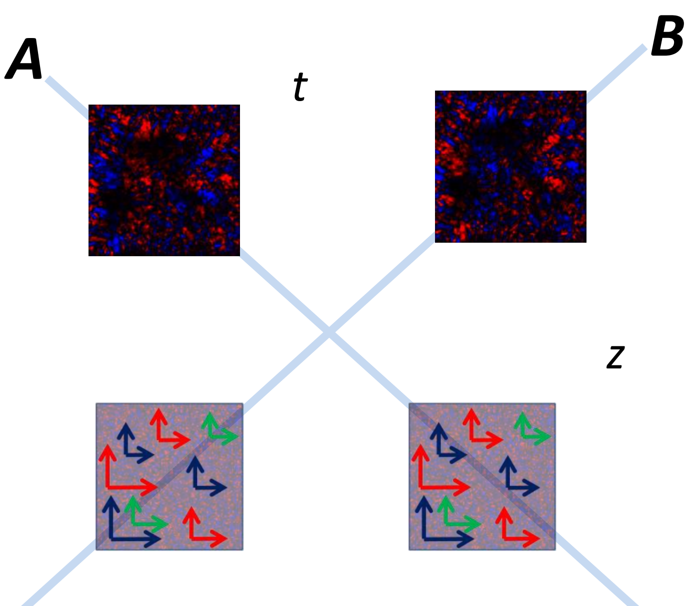


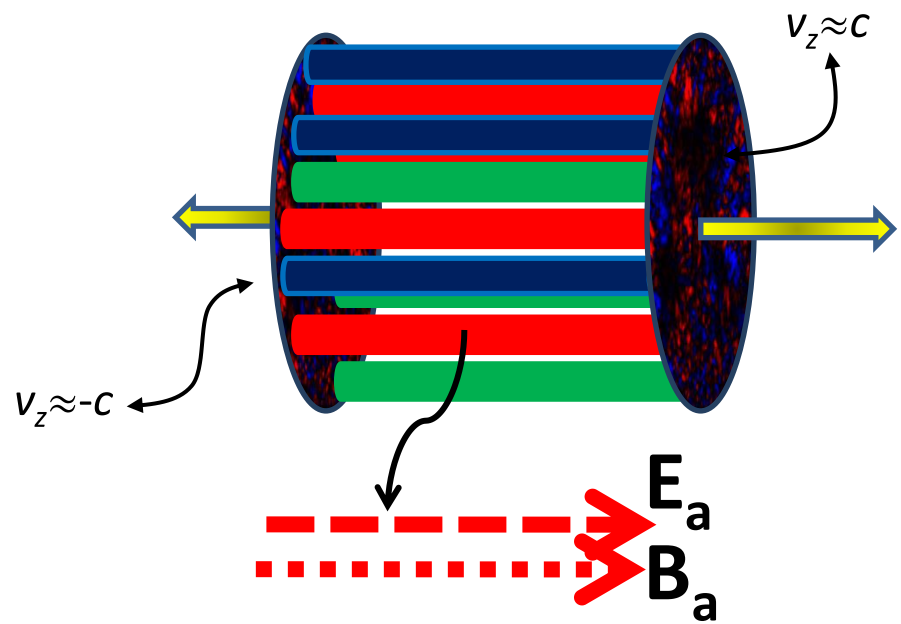
Glasma: the initial condition of RHICs

Dense gluons ***interact*** and form two sets of opposite ***effective color charges*** on the light cone of the two nuclei.



$$\nabla \cdot \boldsymbol{E} = ig\left[\mathcal{A}^i, \mathcal{E}^i\right]$$
$$\nabla \cdot \boldsymbol{B} = ig\left[\mathcal{A}^i, \mathcal{B}^i\right]$$

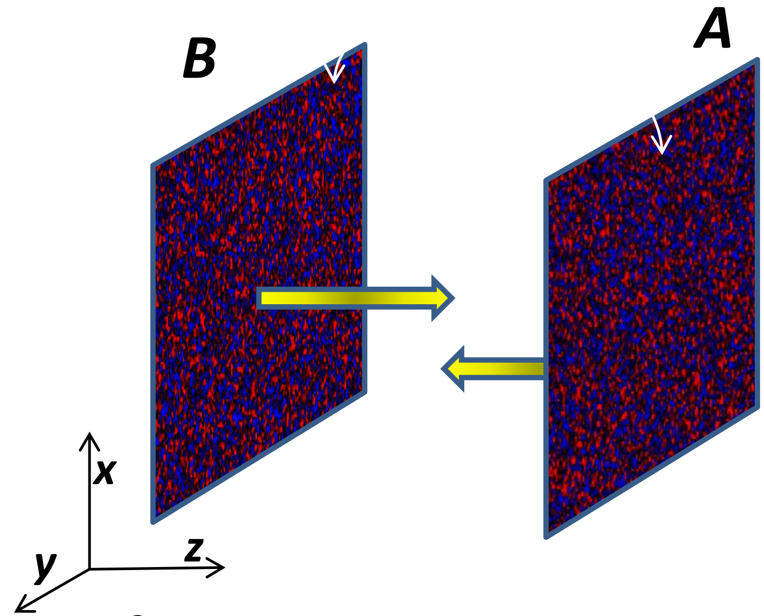




Lappi and McLerran (2006)

The MV model of color sources

"Colliding nuclei"

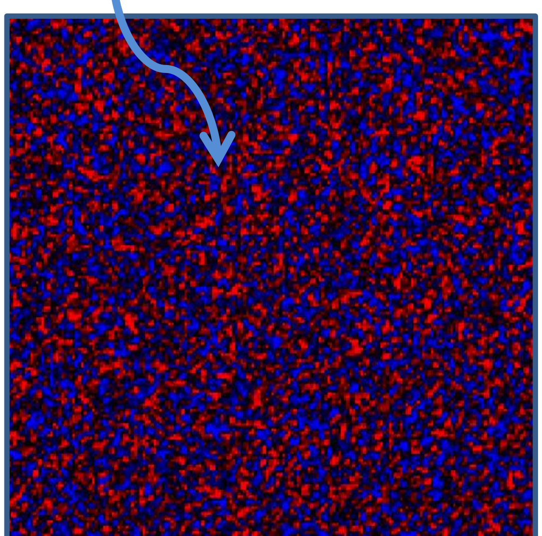


$g^2\mu \approx$ *Qs: saturation scale*

• *Fast (large momentum) partons*
Their dynamics in the Lab frame is slowed down due to time dilation: ***static sources of color fields.***

Model of static sources (MV model)
Uncorrelated color density fluctuations on the two nuclei.

$$\langle \rho^a(\boldsymbol{x}_T) \rangle = 0,$$
$$\langle \rho^a(\boldsymbol{x}_T) \rho^b(\boldsymbol{y}_T) \rangle = (g^2\mu)^2 \delta^{ab} \delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T)$$



$\rho>0$
$\rho<0$

From the correlators of Wilson lines:

$$g^2\mu = O(Q_s)$$

Lappi (2008)

$g^2\mu_{Pb} \approx$ 3.6 GeV – 5.3 GeV

McLerran and Venugopalan (1996)
Kovchegov (1996)

Classical Yang-Mills equations

Due to the large density the gluon field behaves like a classical field:
Dynamics is governed by classical EoMs, namely the classical Yang-Mills (CYM) equations.

$$\partial_\tau E_i = \tfrac{1}{\tau}\mathcal{D}_\eta F_{\eta i} + \tau \mathcal{D}_j F_{ji}, \qquad E_i = \tau \partial_\tau A_i,$$

$$\partial_\tau E_\eta = \tfrac{1}{\tau}\mathcal{D}_j F_{j\eta}, \qquad E_\eta = \frac{1}{\tau}\partial_\tau A_\eta.$$

$$\tau = \sqrt{t^2 - z^2}$$

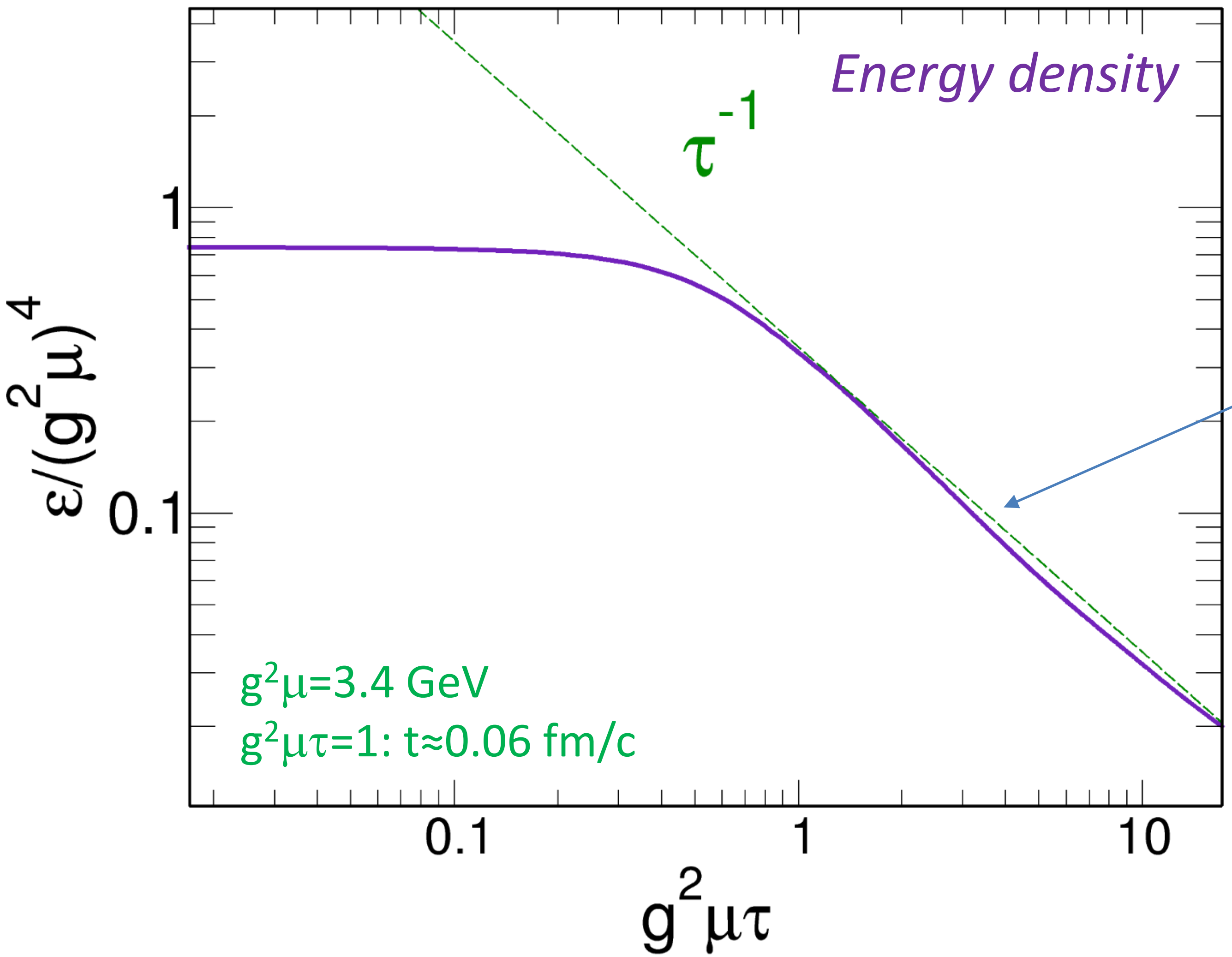
$$\eta = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$$

and the **chromo-magnetic field** is defined as

$$B_i = -\epsilon^{ij} F_{j\eta} \qquad B_\eta = -\tfrac{1}{2}\epsilon^{ij} F_{ij}$$

Evolution of the system is studied assuming the Glasma initial condition, and evolving this condition by virtue of the CYM equations.

Ev-Glasma: energy density



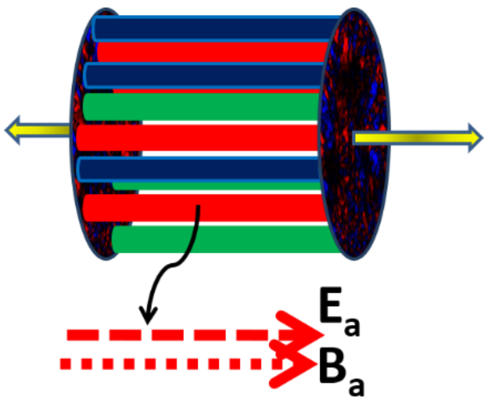
Longitudinal expansion with zero pressure:

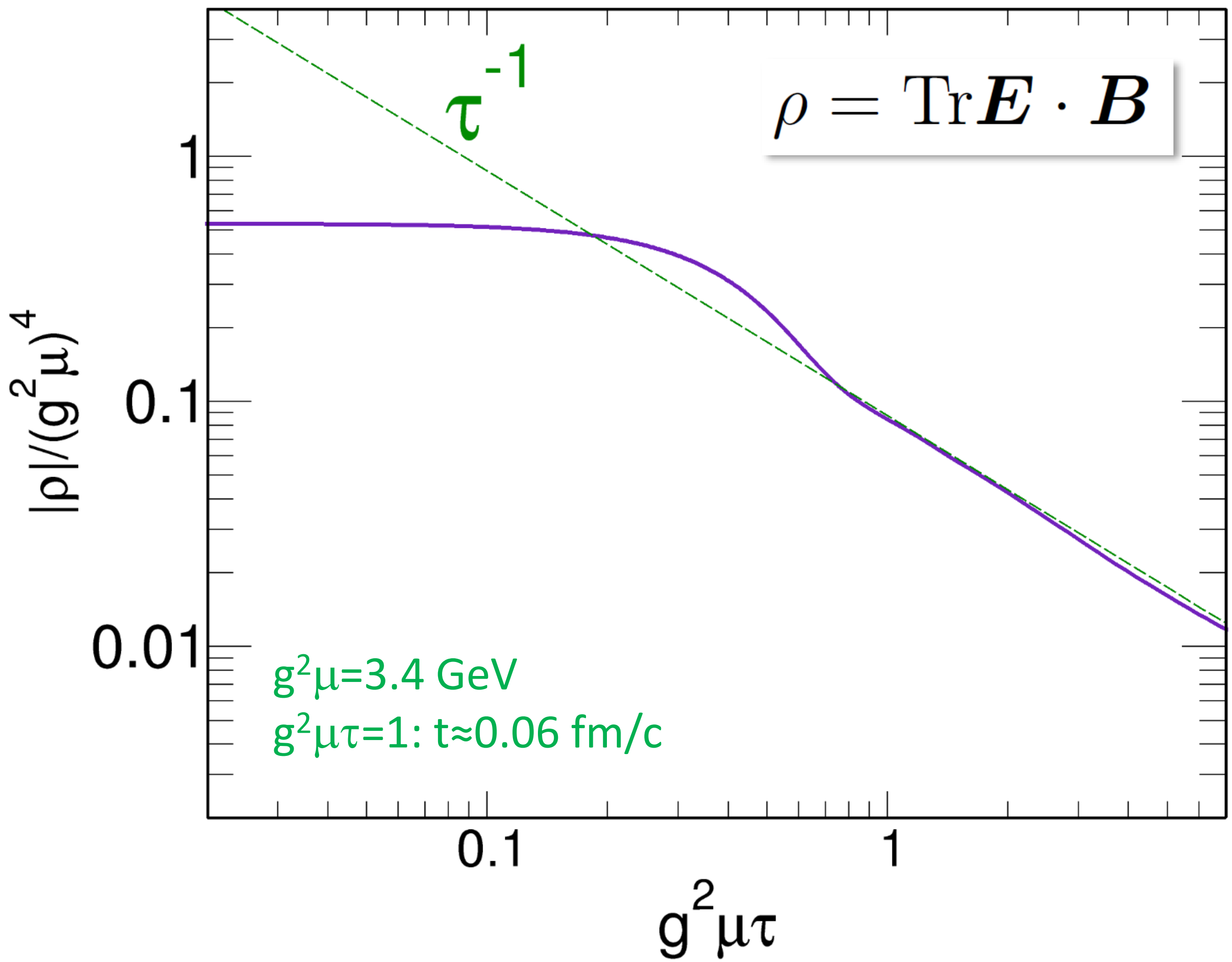
$$\frac{d\varepsilon}{\varepsilon} = -\frac{d\tau}{\tau}$$

Description based on kinetic theory can start in this free streaming regime.

- *Dilute fields regime within* $g^2\mu\tau=O(1)$
- *Free streaming in the longitudinal direction in the dilute fields regime*

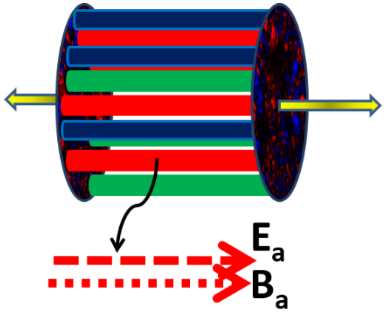
Ev-Glasma: ***EB***





- **E** *parallel to* **B** *at initial time: large fluctuations of* ρ.
- *Evolution and longitudinal expansion dilute* $|\rho|$.

Chiral medium in the Ev-Glasma



$$\left(\partial_\tau + \frac{1}{\tau}\right) j_5^\tau = \frac{1}{8\pi^2}\mathrm{Tr}[\boldsymbol{E}\cdot\boldsymbol{B}]$$

Chiral (ABJ) QCD anomaly
[Adler (1969), Bell and Jackiw (1969), Warringa (2012)]

Ev-Glasma fields

$$\tau = \sqrt{t^2 - z^2}$$
$$\eta = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$$

Because of chiral anomaly, the chiral density is produced in the early stage of RHICs (Ev-Glasma stage).

(Volumetric) Chiral density

$$j_5^\tau(\tau, x_\perp) = \frac{dN_5}{\tau d\eta d^2 x_\perp}$$

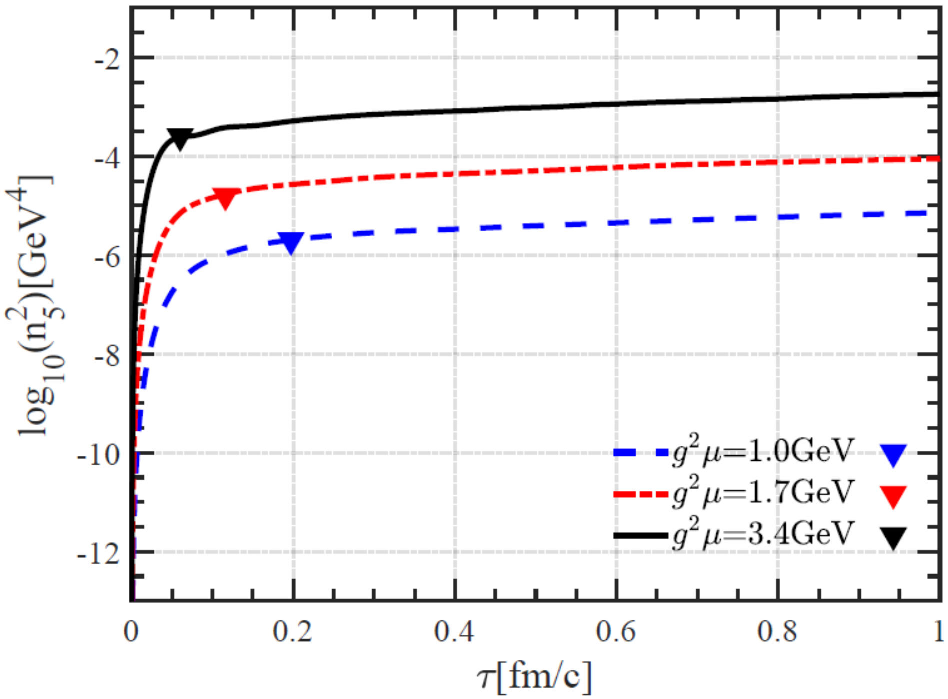
Chiral density per unit rapidity

$$n_5(\tau, x_\perp) \equiv \frac{dN_5}{d\eta d^2 x_\perp} = \tau j_5^\tau(\tau, x_\perp).$$

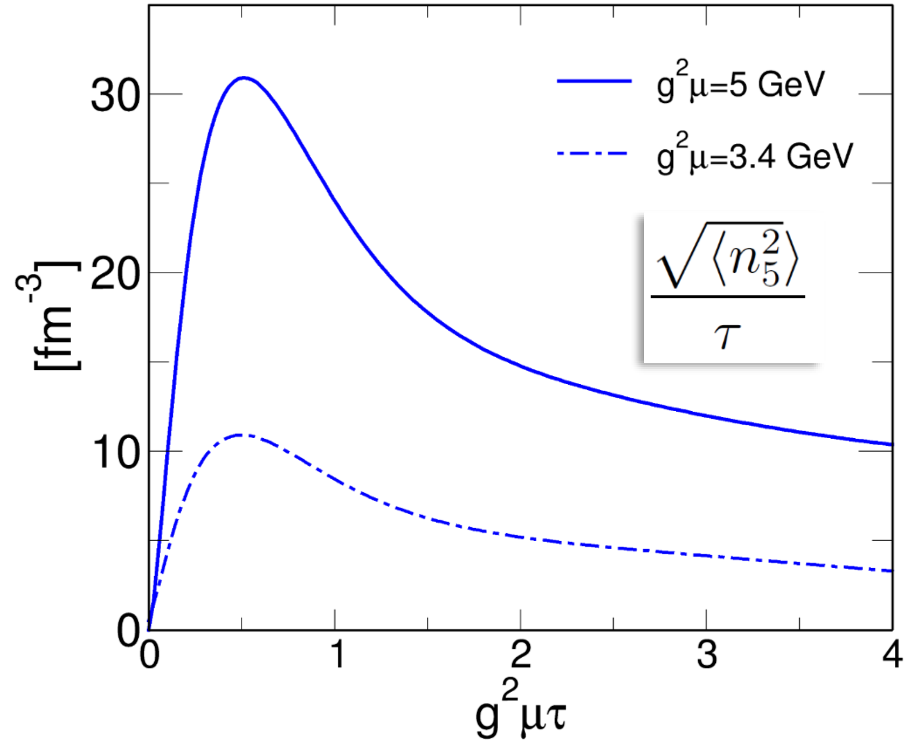
M.R. et al., arXiv:2006.01090
Lappi et al. (2018), Lappi and McLerran (2006), Venugopalan (2016)

Production of chiral density: formation time

Density in transverse plane



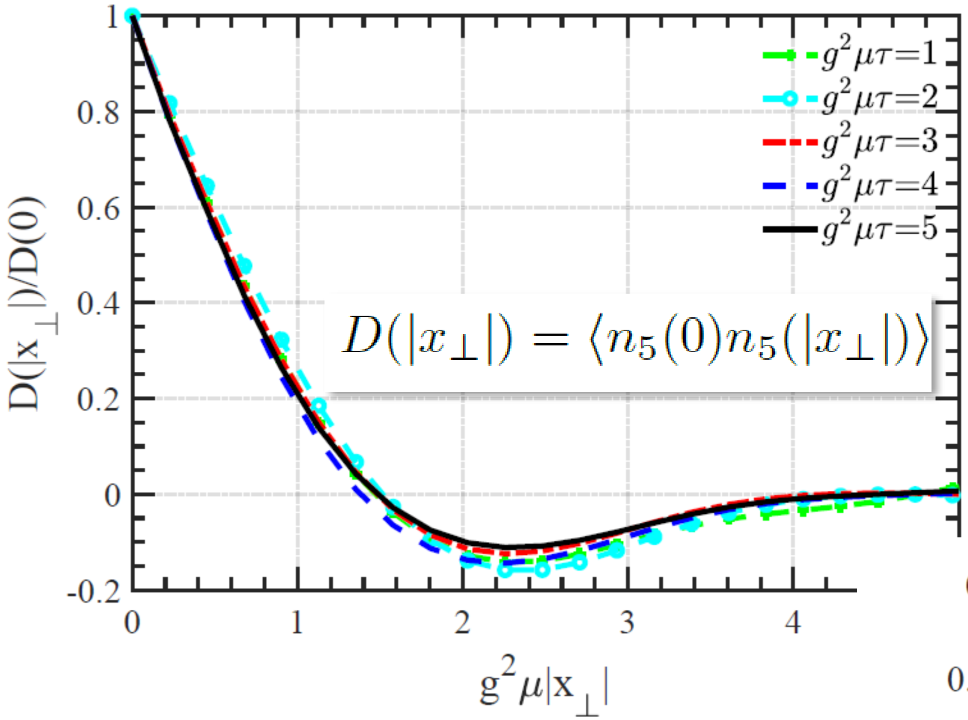
Density in 3D-volume



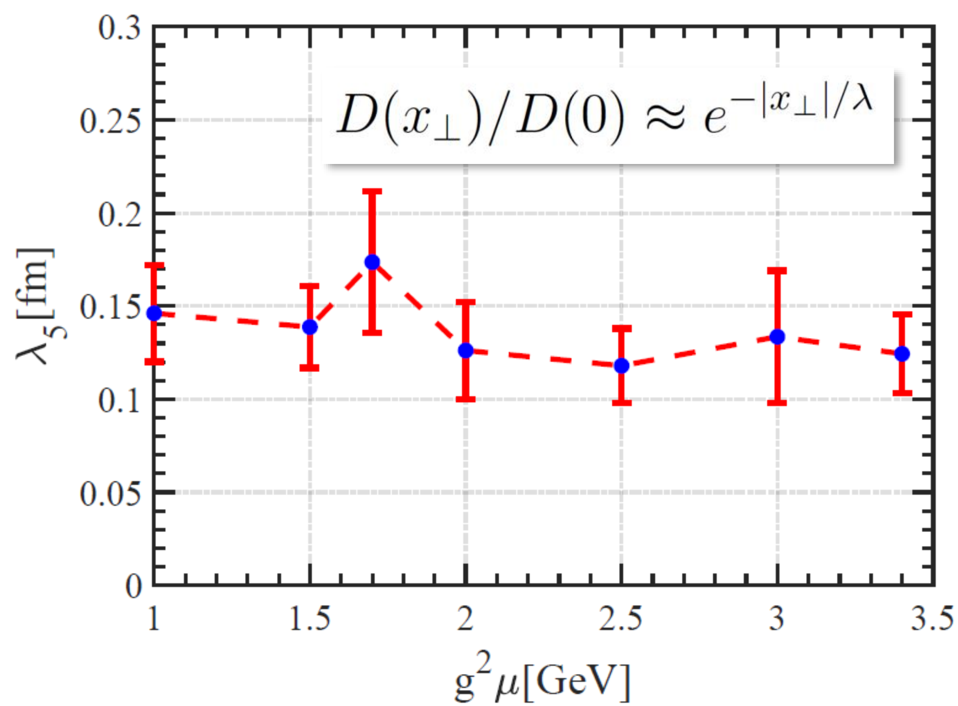
Steady state for time ***≤ 0.2 fm/c≈1/g² μ****,*
namely, when bulk enters the dilute fields regime.

M.R. et al., arXiv:2006.01090
See also Lappi et al. [2018], Venugopalan et al. [2016]

Transverse size of correlation domains



Correlator of the chiral density

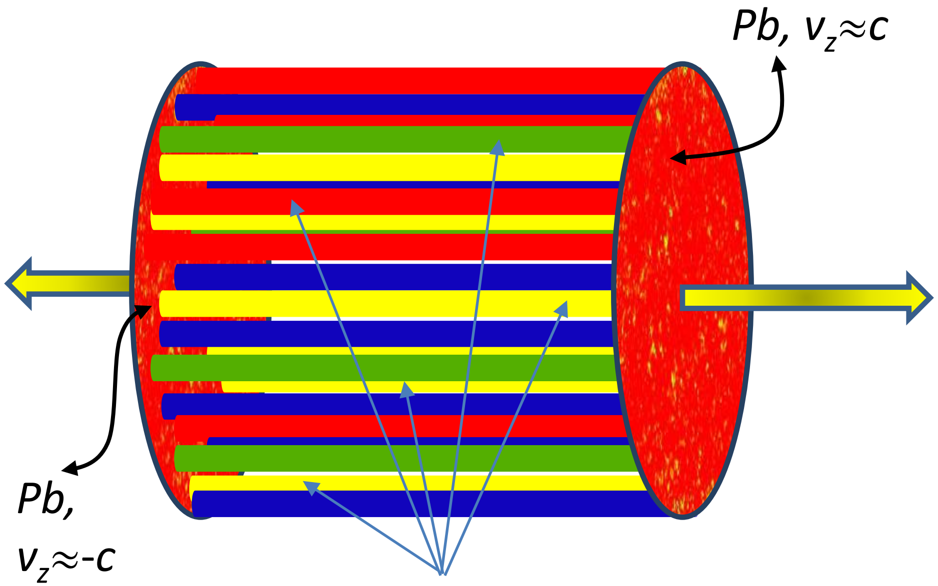


From the exponential decay:
Correlation length

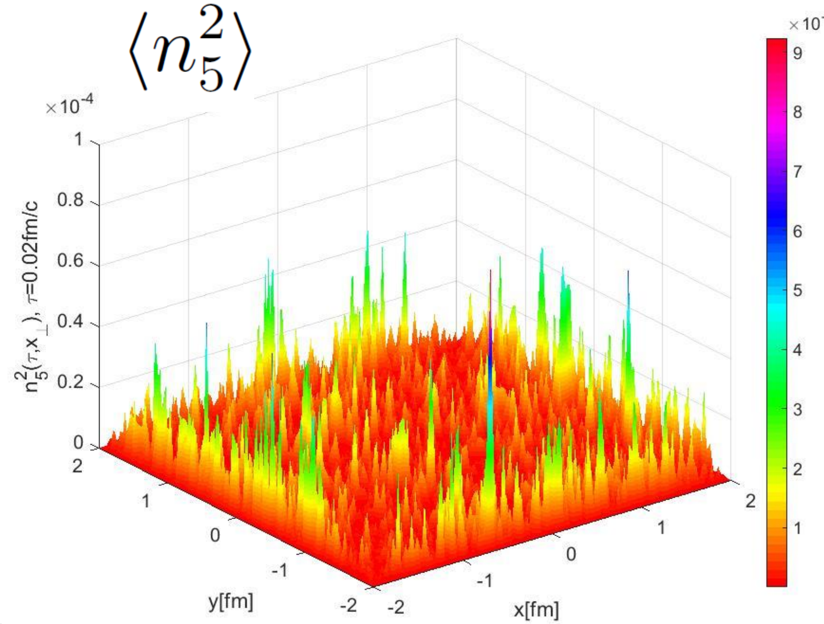
Microscopic domains (λ≈0.1 fm) of chiral density form in the transverse plane

M.R. et al., arXiv:2006.01090

Summary: the chiral medium of pre-hydro stage



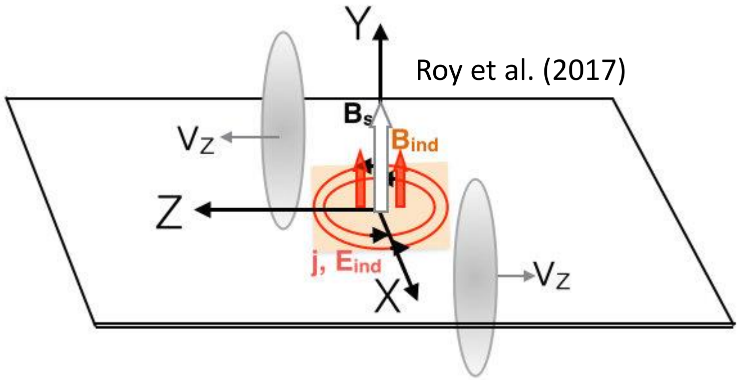
Filaments of chiral density, stretched by expansion along the longitudinal direction

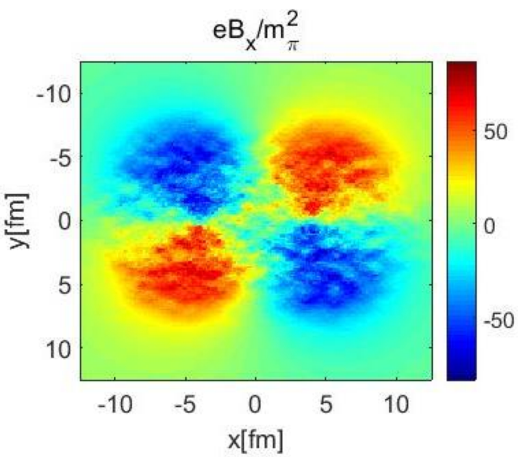


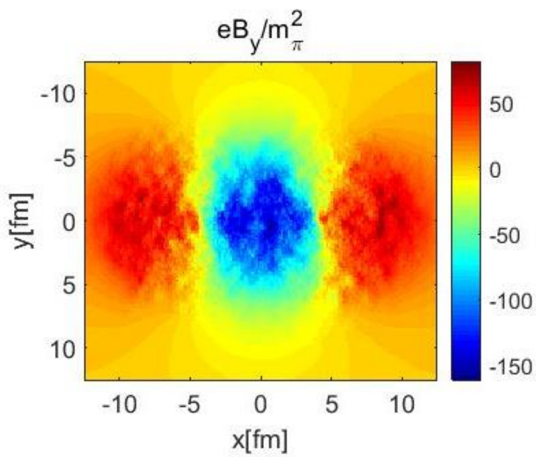
- *Chiral anomaly plus Ev-Glasma fields produce chiral density,* n_5
- n_5 *arranges in <u>filaments</u> of transverse size* $\lambda = O(1/g^2\mu) = O(1/Q_s)$
- *Time scale of formation of the medium* $\tau = O(1/g^2\mu) = O(1/Q_s)$

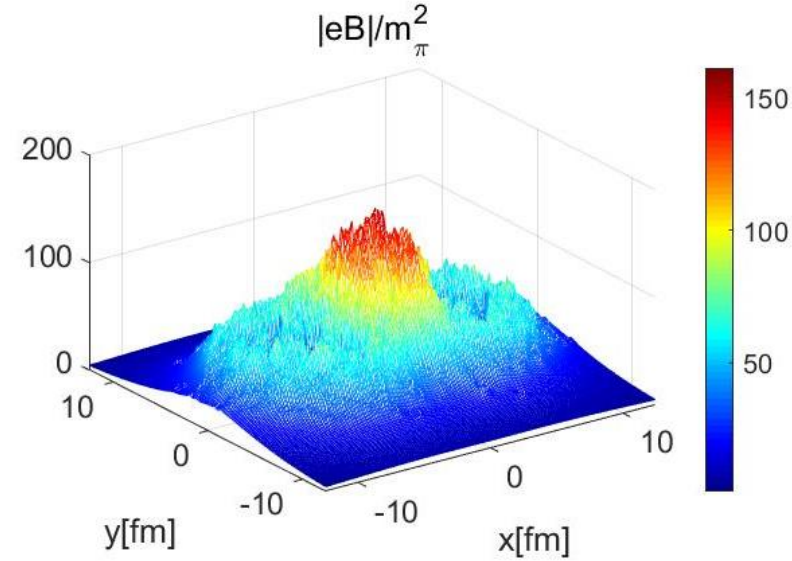
M.R. et al., arXiv:2006.01090

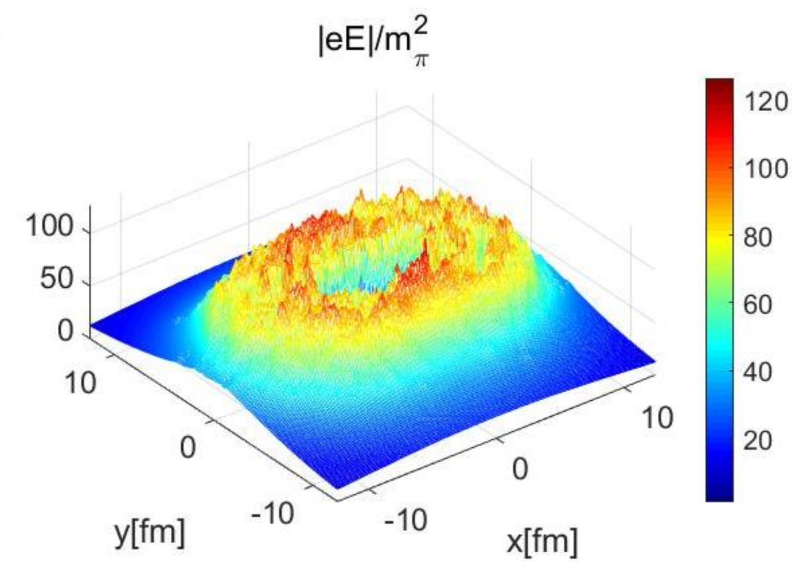
EM fields at initial time of [Pb-Pb@2.76A]() TeV









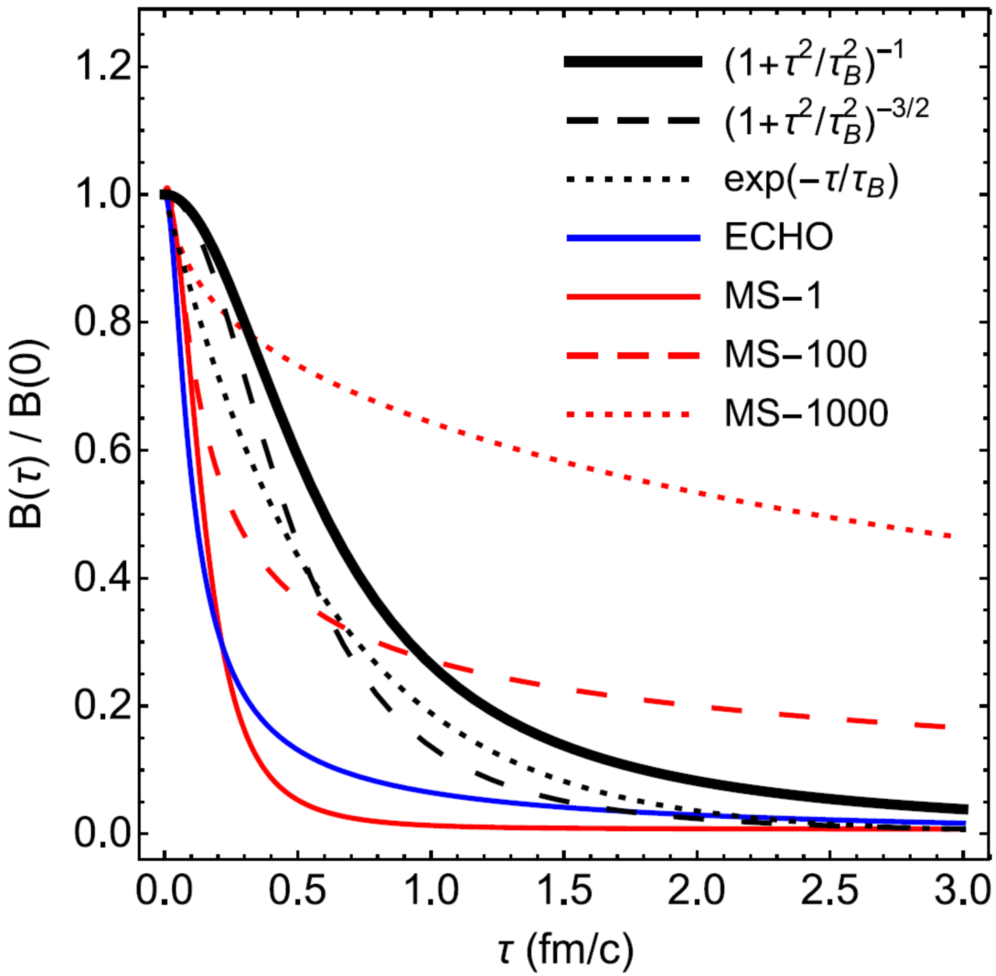


- *Fields in vacuum are well known*
- ***Medium effects (out of equilibrium, QGP) hard to compute***

Plots compiled by Moran Jia

Electromagnetic fields in RHICs

Figure from:
Shi, Jiang,Lilleskov and Liao (2018)



Uncertainty comes from medium effects that are poorly known

Optimistic view

$\tau_B \approx \tau_{thermalization} \approx$ *0.3-0.6 fm/c*

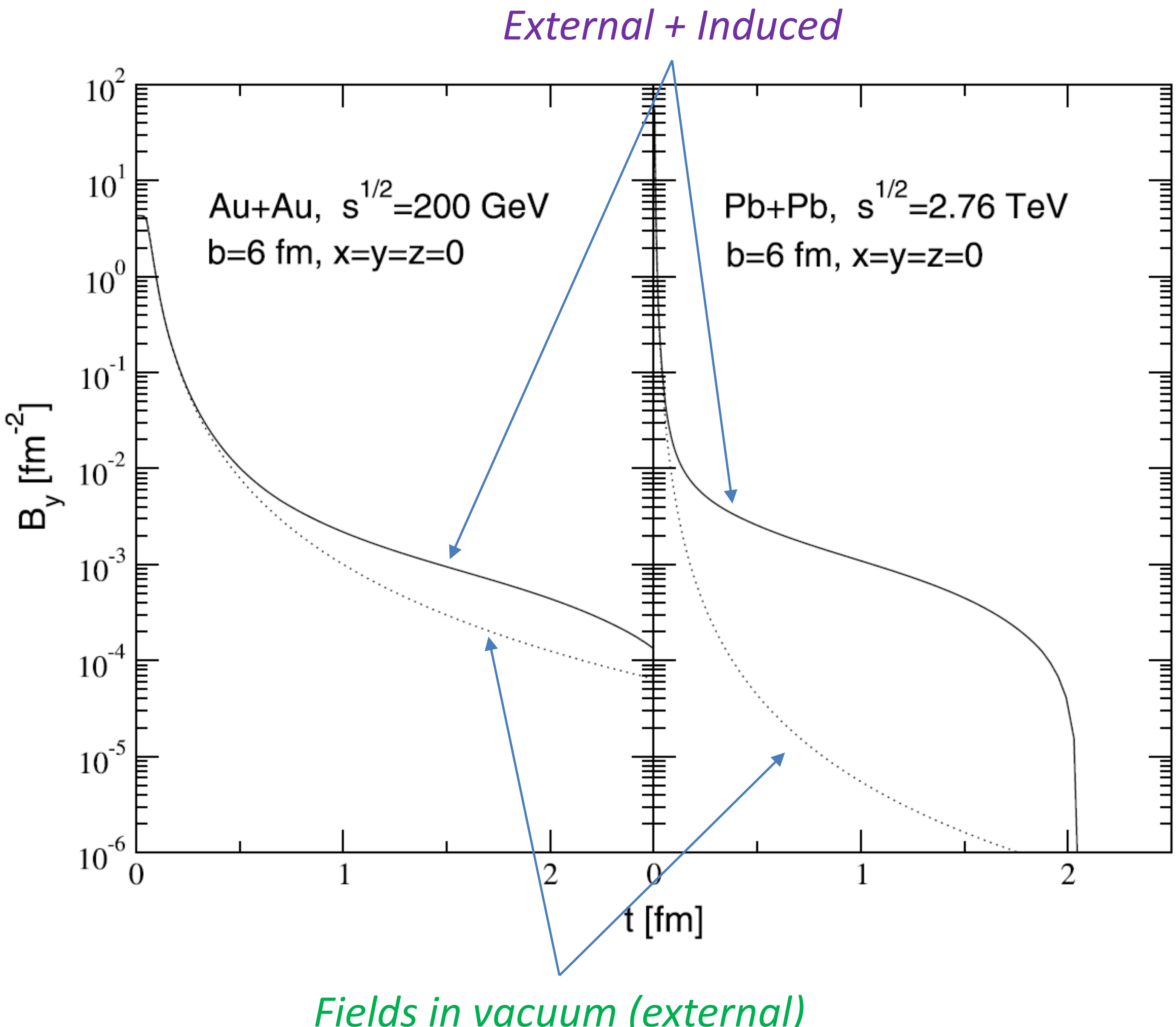
Pessimistic view

$\tau_B \approx \tau_{vacuum} \approx$ *0.02 fm/c*

For other calculations at RHIC and LHC: *PHSD [2011], Li-Sheng-Wang [2016], Gursoy [2014], Kharzeev [2008], Skokov [2008], Das [2017], McLerran-Skokov [2014], Sun [2020], Liao [2018], Zakharov [2014], Deng-Huang [2014], Zakharov [2018], Holliday [2016], She [2017]*

For reviews
Liao [2018], Oliva [2020]

Electromagnetic fields in RHICs

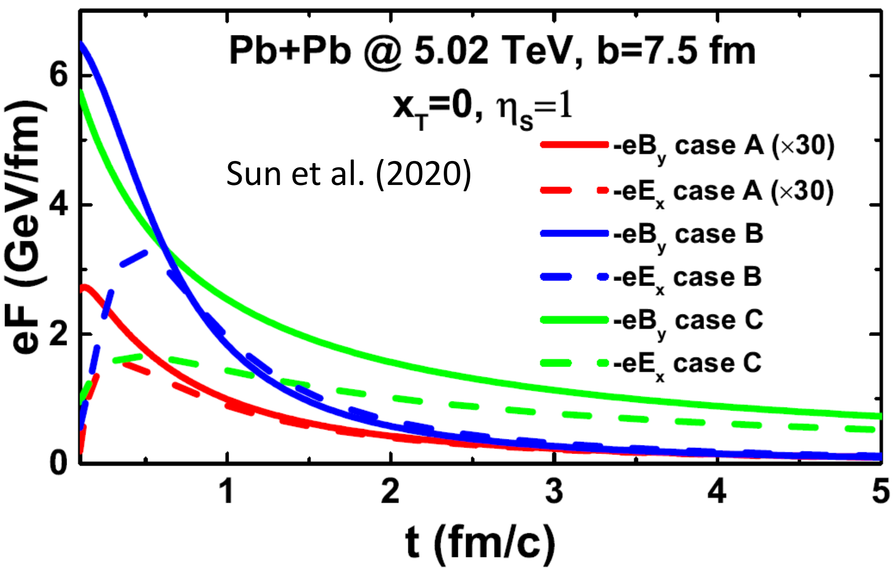


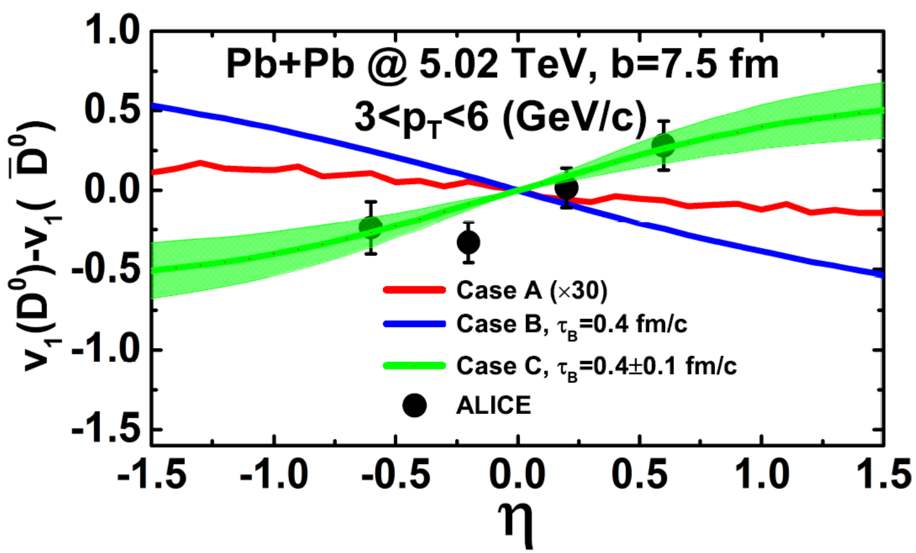
Zakharov (2014)

The choice of B(τ,η)

We adopt the optimistic point of view and assume $\tau_B \approx \tau_{thermalization}$.
After all, we found that a (chiral) medium is formed quickly.

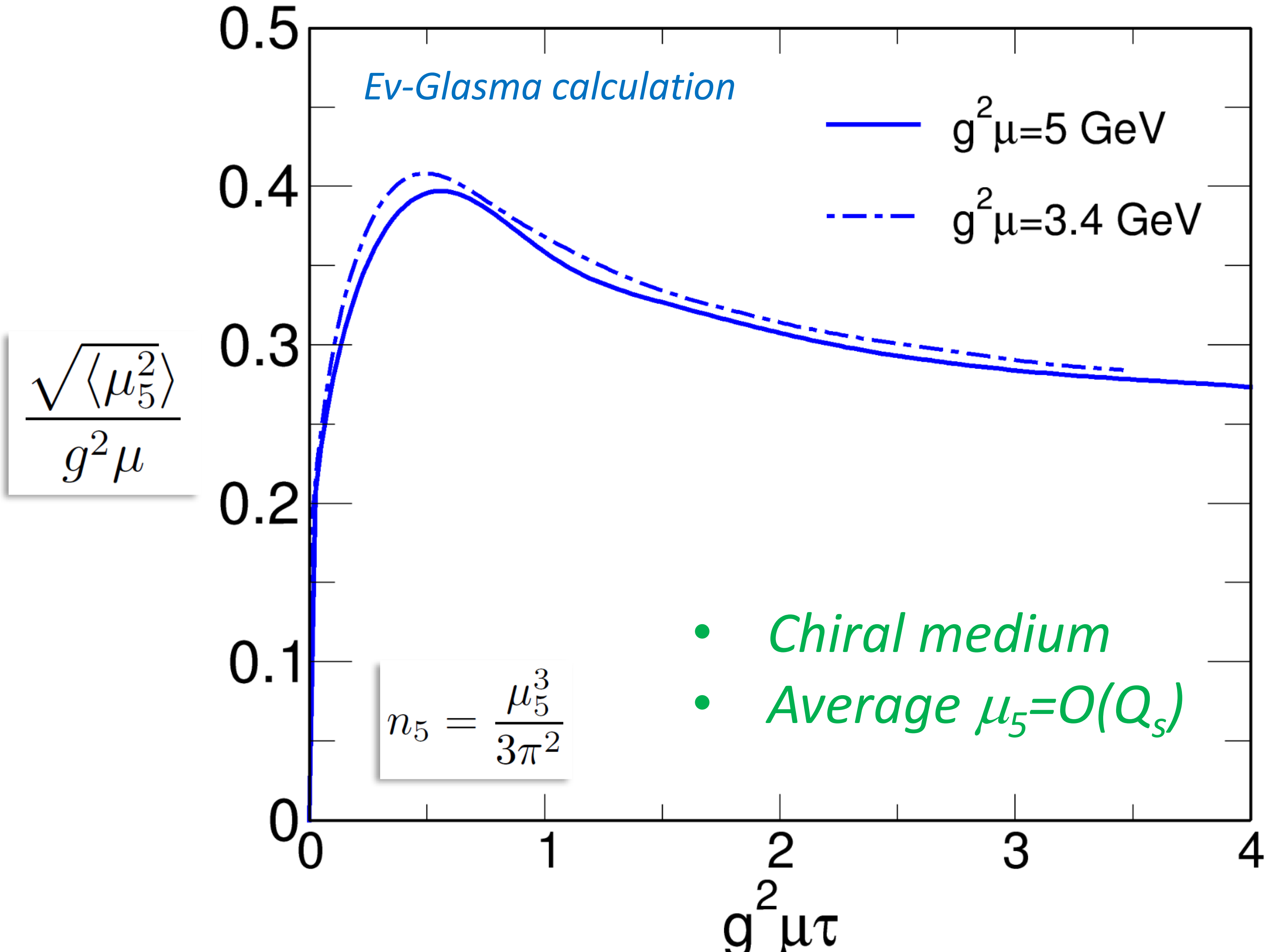
$$B_y = \frac{B_0 \cosh \eta}{1 + \tau/\tau_B}$$





This form of B_y called case C in Sun et al 2020, explains the v_1-splitting of neutral D mesons at LHC (not explained by other calculations).

The chiral chemical potential, μ_5, in the early stage



- *Chiral medium*
- *Average μ_5=O(Q_s)*

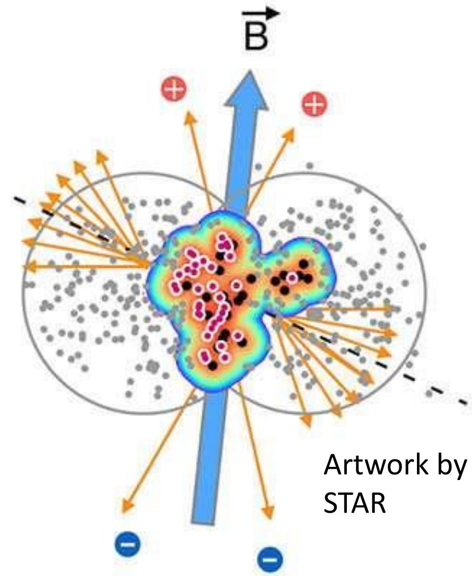
M.R. et al., in preparation

Chiral Magnetic Effect (CME) in the early stage

- *Chiral medium*
- *Strong magnetic field*

CME current

$$\boldsymbol{J}_V = \frac{N_c}{2\pi^2}\mu_5 e\boldsymbol{B}$$

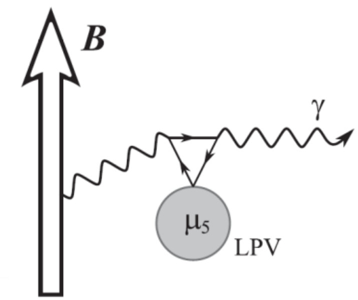


Artwork by STAR

Chiral Magnetic Effect
in the early stage of RHICs

For references on CME in RHICs see:
Kharzeev, McLerran and Warringa (2008)
Fukusima, Kharzeev, and Warringa (2008)
Zakharov (2012), Skokov et al (2016)
Ongoing experimental search of CME in RHICs:
STAR 2010, PHENIX 2010, ALICE 2014, STAR 2015, ALICE 2016, ALICE 2020

Photons from the chiral magnetic effect



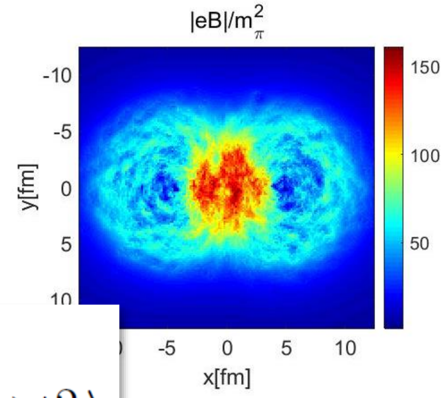
$$\frac{dN}{d^2q_T dy} = \frac{25\alpha}{2(2\pi)^3 9\pi^3}\left(1 - \frac{q_y^2}{\boldsymbol{q}^2}\right)\left\langle|\zeta(\boldsymbol{q})|^2\right\rangle$$

$$\left\langle|\zeta(\boldsymbol{q})|^2\right\rangle = e^2 \int \tau_1 d\tau_1 d\eta_1 \int \tau_2 d\tau_2 d\eta_2 \; e^{-iq_\perp(\tau_1 \cosh\eta_1 - \tau_2\cosh\eta_2)} B(\tau_1,\eta_1)B(\tau_2,\eta_2) \times \int d^2x_\perp d^2y_\perp e^{i\boldsymbol{q}_\perp\cdot(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)} \left\langle \mu_5(\tau_1,\boldsymbol{x}_\perp)\mu_5(\tau_2,\boldsymbol{y}_\perp)\right\rangle .$$

Fukusima-Mameda (2012)

Photons from the chiral magnetic effect

$$\boxed{B_y = \frac{B_0 \cosh\eta}{1+\tau/\tau_B}}$$



$$\frac{dN}{d^2q_T dy} = \frac{25\alpha}{2(2\pi)^3 9\pi^3}\left(1-\frac{q_y^2}{\boldsymbol{q}^2}\right)\langle|\zeta(\boldsymbol{q})|^2\rangle$$

$$\begin{aligned}\langle|\zeta(\boldsymbol{q})|^2\rangle \;=\; & e^2\int \tau_1 d\tau_1 d\eta_1 \int \tau_2 d\tau_2 d\eta_2\; e^{-iq_\perp(\tau_1\cosh\eta_1-\tau_2\cosh\eta_2)}\boxed{B(\tau_1,\eta_1)B(\tau_2,\eta_2)}\\ & \times\int d^2x_\perp d^2y_\perp e^{i\boldsymbol{q}_\perp\cdot(\boldsymbol{x}_\perp-\boldsymbol{y}_\perp)}\langle\mu_5(\tau_1,\boldsymbol{x}_\perp)\mu_5(\tau_2,\boldsymbol{y}_\perp)\rangle\,.\end{aligned}$$

<u>Consider B independent of coordinates</u>

- *Reasonable for calculating over a small portion of the transverse plane*
- ***Con: neglects correlations of B in the transverse plane***

M.R. et al., in preparation

Photons from the chiral magnetic effect

$$\frac{dN}{d^2q_T dy} = \frac{25\alpha}{2(2\pi)^3 9\pi^3}\left(1 - \frac{q_y^2}{\boldsymbol{q}^2}\right)\langle|\zeta(\boldsymbol{q})|^2\rangle$$

$$\langle|\zeta(\boldsymbol{q})|^2\rangle = e^2 \int \tau_1 d\tau_1 d\eta_1 \int \tau_2 d\tau_2 d\eta_2 \; e^{-iq_\perp(\tau_1\cosh\eta_1 - \tau_2\cosh\eta_2)} B(\tau_1,\eta_1)B(\tau_2,\eta_2)$$
$$\times \int d^2x_\perp d^2y_\perp e^{i\boldsymbol{q}_\perp\cdot(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)} \boxed{\langle\mu_5(\tau_1,\boldsymbol{x}_\perp)\mu_5(\tau_2,\boldsymbol{y}_\perp)\rangle} .$$

from Ev-Glasma

M.R. et al., in preparation

CME photons: ansatz for the μ_5-correlator

For an estimate of the magnitude of the CME photon spectrum:

$$\langle \mu_5(\tau_1, \boldsymbol{x}_T)\mu_5(\tau_2, \boldsymbol{y}_T)\rangle = \left\langle \mu_5^2\left(\frac{\tau_1+\tau_2}{2}\right)\right\rangle \frac{|\boldsymbol{x}_T - \boldsymbol{y}_T|}{\lambda} K_1\left(|\boldsymbol{x}_T - \boldsymbol{y}_T|/\lambda\right) e^{-|\tau_1-\tau_2|/\lambda_\tau}$$

$$\left.\frac{dN}{2\pi q_t dq_T}\right|_{y=0} = \frac{1}{2}\frac{25\alpha}{2(2\pi)^3 9\pi^3} e^2 B_0^2 A_T \left[\frac{4\pi\lambda^2}{(1+q_T^2\lambda^2)^2}\right] \times (2\lambda_\tau)\int_0^\tau \tau^2 d\tau \left(\frac{1}{1+\tau/\tau_B}\right)^2 \langle\mu_5^2\rangle |\mathcal{I}(q_T\tau)|^2 \left(1 - \frac{e^{-\tau_1/\lambda_\tau}}{2} - \frac{e^{(\tau_1-\tau)/\lambda_\tau}}{2}\right)$$

$$\left.\frac{dN}{2\pi q_t dq_T}\right|_{y=0} \approx \frac{a}{q_T^2}, \quad q_T\tau \ll 1$$

$$\left.\frac{dN}{2\pi q_t dq_T}\right|_{y=0} \approx \frac{c}{q_T^5}, \quad q_T\tau \gg 1$$

$$B_y = \frac{B_0 \cosh\eta}{1+\tau/\tau_B}$$

$$\int d^2u \frac{u}{\lambda} K_1(u/\lambda) e^{i\boldsymbol{q}_T\cdot\boldsymbol{u}} = \frac{4\pi\lambda^2}{(1+q_T^2\lambda^2)^2};$$

$$\mathcal{I}(q_T\tau) = 2\int_0^\infty e^{iq_T\tau\cosh\eta}\cosh\eta\, d\eta = 2K_1(-iq_T\tau)$$

M.R. et al., in preparation

CME photons: ansatz for the μ_5-correlator

For an estimate of the magnitude of the CME photon spectrum:

$$\langle \mu_5(\tau_1, \boldsymbol{x}_T)\mu_5(\tau_2, \boldsymbol{y}_T)\rangle = \left\langle \mu_5^2\left(\frac{\tau_1+\tau_2}{2}\right)\right\rangle \frac{|\boldsymbol{x}_T - \boldsymbol{y}_T|}{\lambda} K_1\left(|\boldsymbol{x}_T - \boldsymbol{y}_T|/\lambda\right) e^{-|\tau_1-\tau_2|/\lambda_\tau}$$

$$\left.\frac{dN}{2\pi q_t dq_T}\right|_{y=0} = \frac{1}{2}\frac{25\alpha}{2(2\pi)^3 9\pi^3} e^2 B_0^2 A_T \left[\frac{4\pi\boxed{\lambda^2}}{(1+q_T^2\lambda^2)^2}\right] \times (2\boxed{\lambda_\tau}) \int_0^\tau \tau^2 d\tau \left(\frac{1}{1+\tau/\tau_B}\right)^2 \boxed{\langle\mu_5^2\rangle} |\mathcal{I}(q_T\tau)|^2 \left(1 - \frac{e^{-\tau_1/\lambda_\tau}}{2} - \frac{e^{(\tau_1-\tau)/\lambda_\tau}}{2}\right)$$

from Ev-Glasma

For estimating the CME photon spectrum

- *Borrow λ, λ_τ and averaged-μ_5^2 from Ev-Glasma calculations*
- *Use the K1-ansatz to get the spectrum*

M.R. et al., in preparation

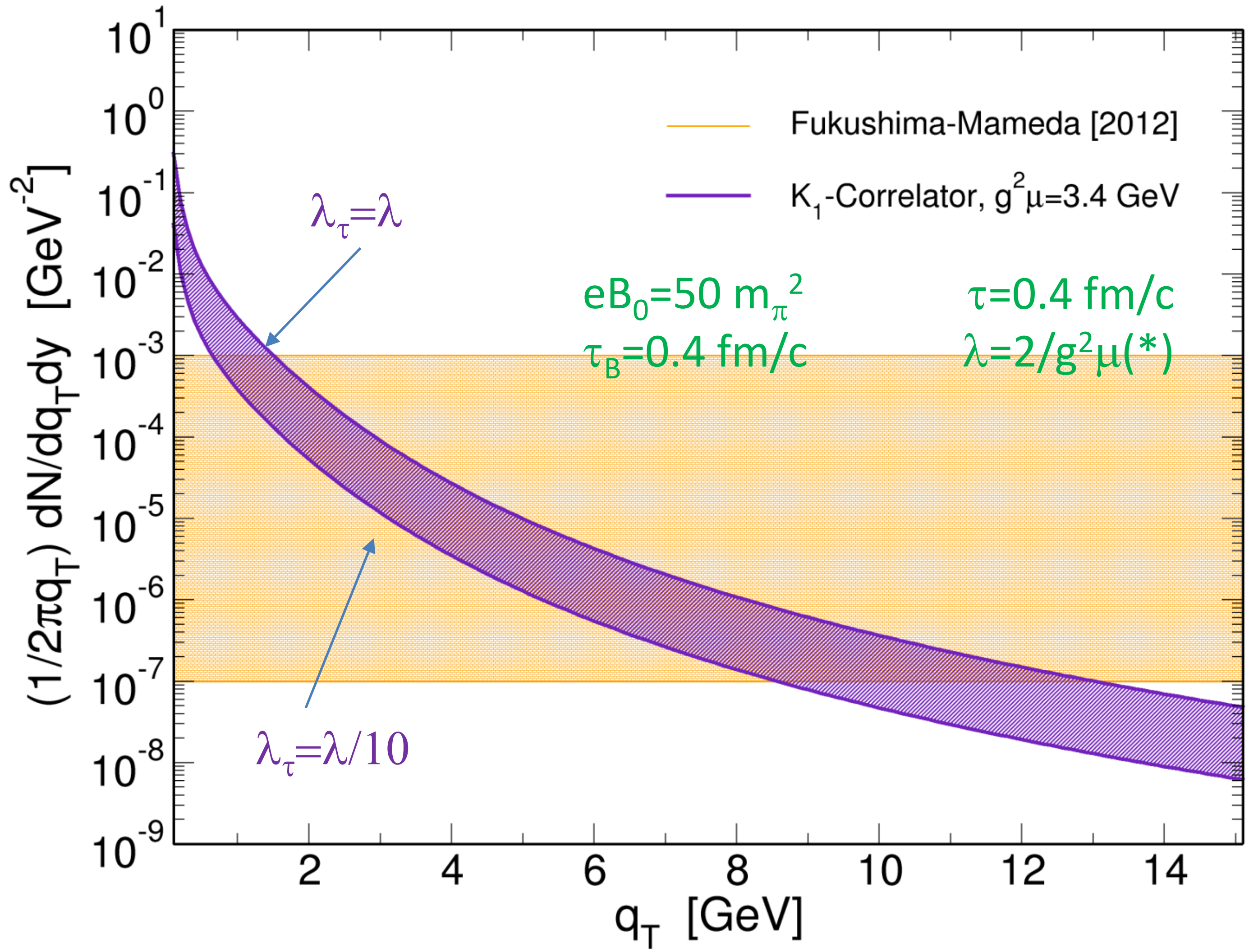
CME photons: estimates with the K_1-correlator

$$\langle \mu_5(\tau_1, \boldsymbol{x}_T)\mu_5(\tau_2, \boldsymbol{y}_T)\rangle = \left\langle \mu_5^2\left(\frac{\tau_1+\tau_2}{2}\right)\right\rangle \frac{|\boldsymbol{x}_T - \boldsymbol{y}_T|}{\lambda} K_1\left(|\boldsymbol{x}_T - \boldsymbol{y}_T|/\lambda\right) e^{-|\tau_1-\tau_2|/\lambda_\tau}$$

$$B_y = \frac{B_0 \cosh\eta}{1+\tau/\tau_B}$$

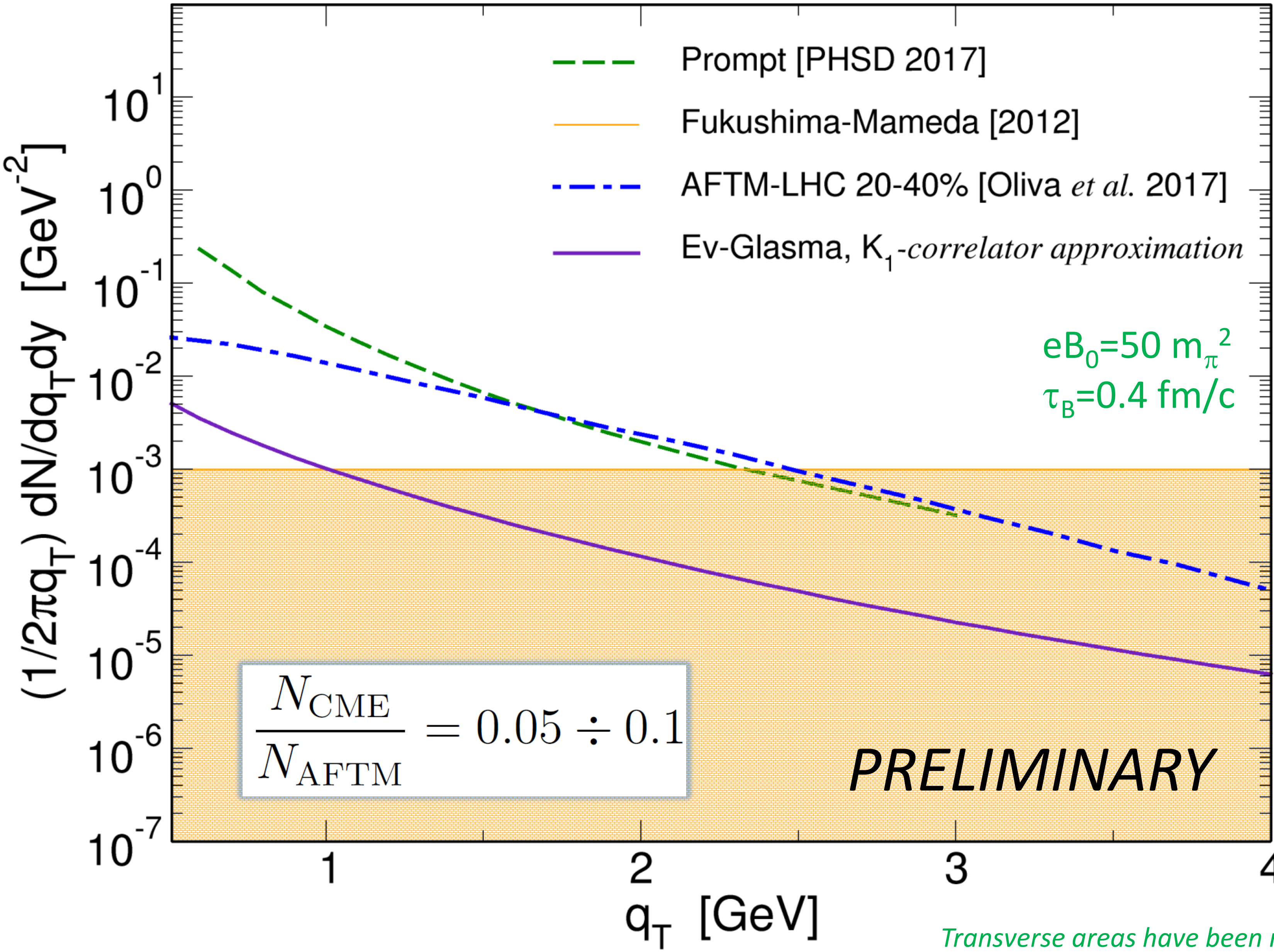
$$\frac{\langle q_T\rangle}{g^2\mu} = O(1)$$

Most CME photons produced within $g^2\mu\tau \leq 1$



(*) From M.R. et al., arXiv:2006.01090

Comparison with other early stage contributions



Transverse areas have been rescaled to match the AT of the Ev-Glasma calculations

M.R. et al., in preparation

Elliptic flow of the CME photons

$$\frac{dN}{d^2q_T dy} = \frac{25\alpha}{2(2\pi)^3 9\pi^3}\left(1-\frac{q_y^2}{\boldsymbol{q}^2}\right)\left\langle|\zeta(\boldsymbol{q})|^2\right\rangle$$

Anisotropic distribution

Isotropic in transverse plane(*)

Source of anisotropy

$$\frac{dN}{d^2q_T dy} = \frac{dN}{2\pi q_T dq_T dy}\left[1+2v_1(q_T,y)\cos\phi+2v_2(q_T,y)\cos 2\phi+\dots\right]$$

Elliptic flow

Direct flow

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(*)*B distribution in transverse plane can add some anisotropy*

Elliptic flow of the CME photons

$$\frac{dN}{d^2q_T dy} = \frac{25\alpha}{2(2\pi)^3 9\pi^3}\left(1-\frac{q_y^2}{\boldsymbol{q}^2}\right)\left\langle|\zeta(\boldsymbol{q})|^2\right\rangle$$

Anisotropic distribution

Isotropic in transverse plane(*)

Source of anisotropy

$$1-\frac{q_y^2}{\boldsymbol{q}^2} = \cos^2\phi = \frac{1+2\cos 2\phi}{2} \to v_2 = \frac{1}{2}$$ (*)

CME photons have a large elliptic flow

$$v_2 = \frac{v_2^{\rm CME} N_\gamma^{\rm CME} + v_2^{\rm noCME} N_\gamma^{\rm noCME}}{N_\gamma^{\rm CME} + N_\gamma^{\rm noCME}} \approx v_2^{\rm noCME} + \frac{N_\gamma^{\rm CME}}{N_\gamma^{\rm noCME}} v_2^{\rm CME}$$

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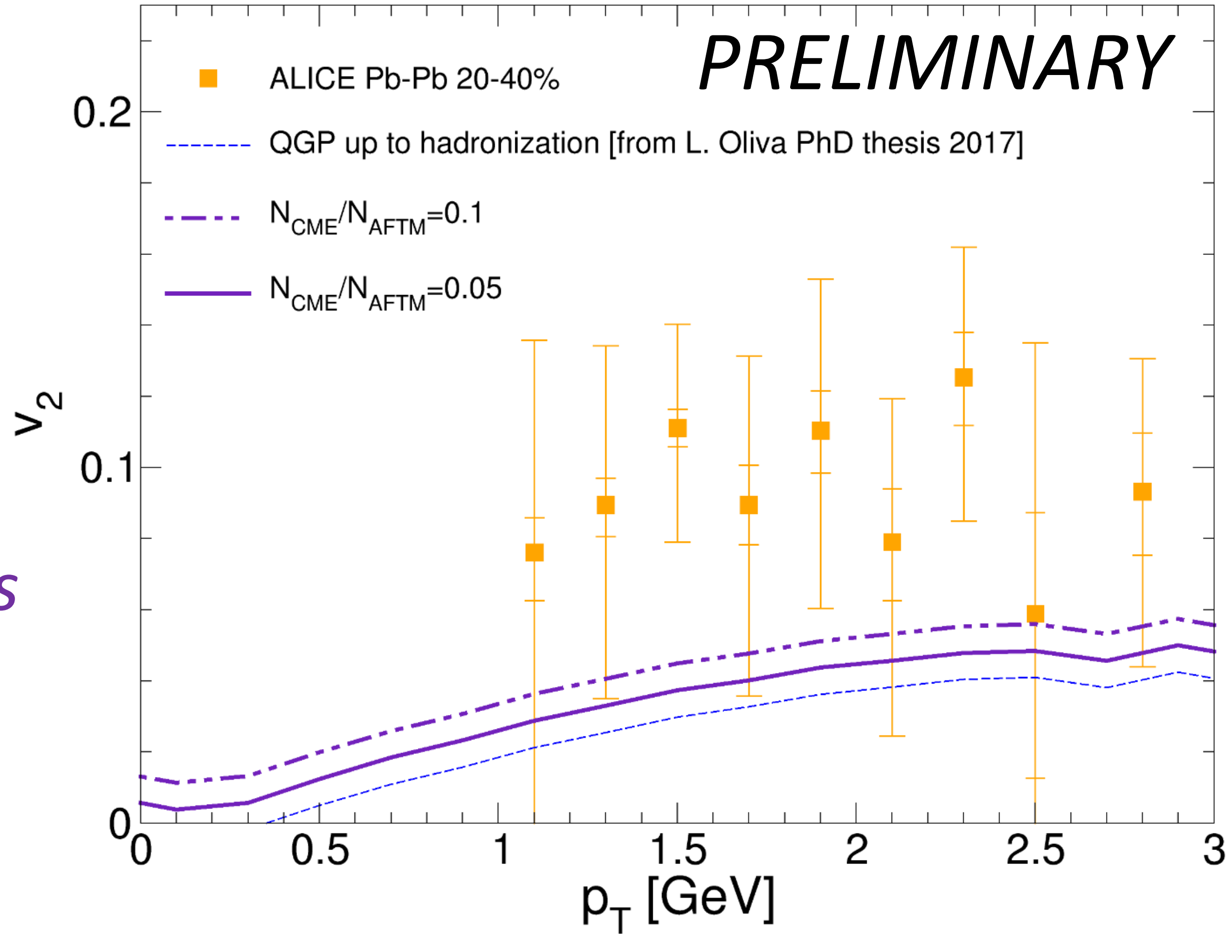
(*)(*)*Correlations of B in transverse plane can add some* q_T *dependence*

Elliptic flow of the CME photons

$$N_{\mathrm{AFTM,\ early}} \approx 0.3 \times N_{\mathrm{QGP}}$$ [Oliva et al. 2017]

$$N_{\mathrm{CME}} \approx (0.05 \div 0.1) \times 0.3 \times N_{\mathrm{QGP}}$$

$$\Delta v_2 \approx \frac{N_{\mathrm{CME}}}{N_{\mathrm{QGP}}} v_2^{\mathrm{CME}} \approx (0.015 \div 0.03) \times \frac{1}{2}$$



Effect of CME photons on v_2 is sizable

M.R. et al., in preparation

Conclusions and Outlook

- *Chiral anomaly produces filaments of chiral density, n_5, that stretch with the expanding medium in the early stages of RHICs*
- *Structures of correlated n_5 form in the transverse plane* **$\lambda=O(1/Q_s)$**
- *Time scale of formation of the medium* **$\tau=O(1/Q_s)$**
- ***CME in the early stage*** *due to presence of n_5 and* ***magnetic field***
- ***CME photons in the early stage****: minor contribution to spectrum but potentially sizable contribution to v_2*

- *CME photons in Weyl semimetals (?)*
- *Relation between n_5 and μ_5 for matter in flux tubes (strong fields, finite sizes,……)*
- *RHIC vs LHC: weaker but longer lived magnetic fields*

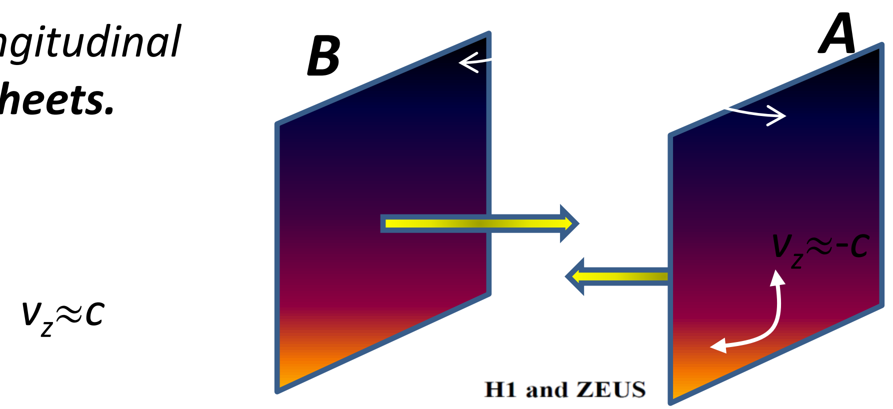
Thank you for your attention!

Appendix

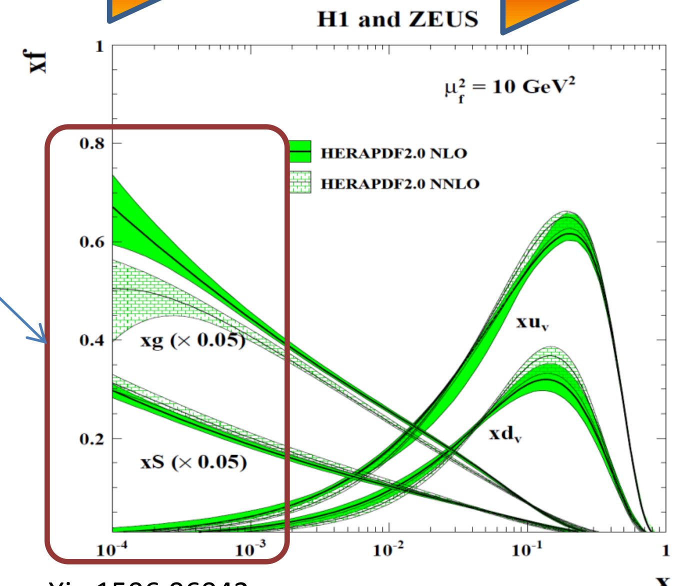
Slow versus fast partons

"Colliding nuclei"

*The two nuclei are Lorentz contracted along the longitudinal direction: **in Lab frame they appear like two thin sheets.***



The small-x proton wave function is dominated by the sea of virtual gluons.

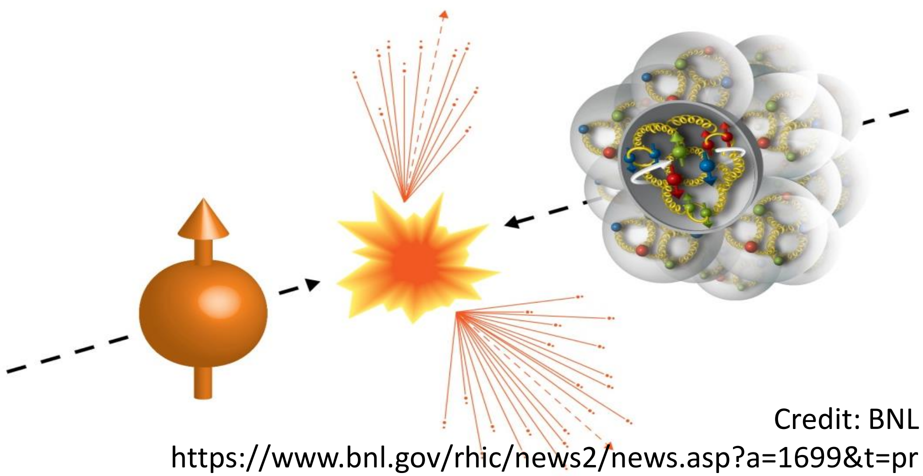


arXiv:1506.06042

$$x \approx \frac{\langle p_T \rangle}{\sqrt{s}}$$

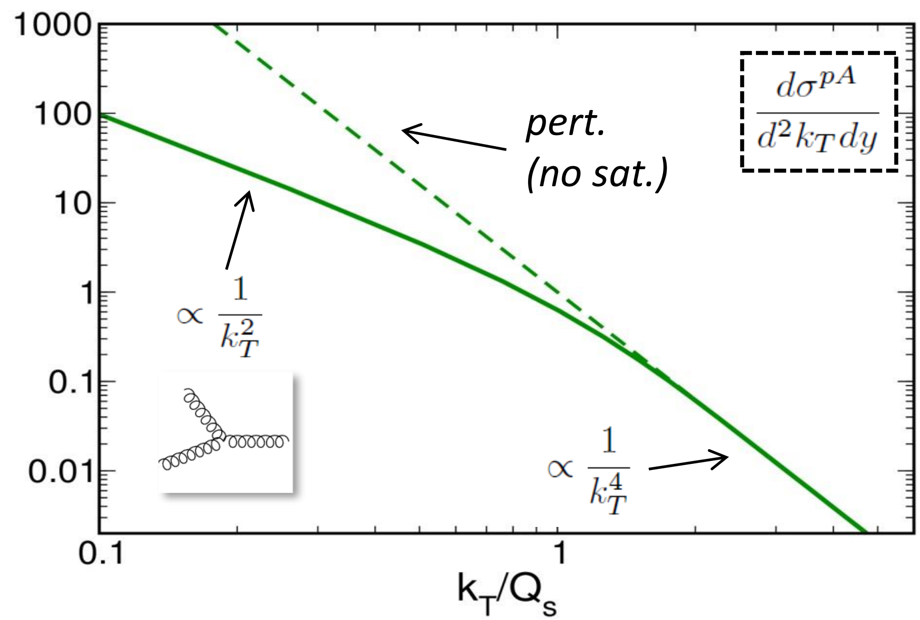
High energy collisions probe small-x regions

Gluon recombination might imply saturation



Credit: BNL
https://www.bnl.gov/rhic/news2/news.asp?a=1699&t=pr

High gluon density:
Gluon recombination

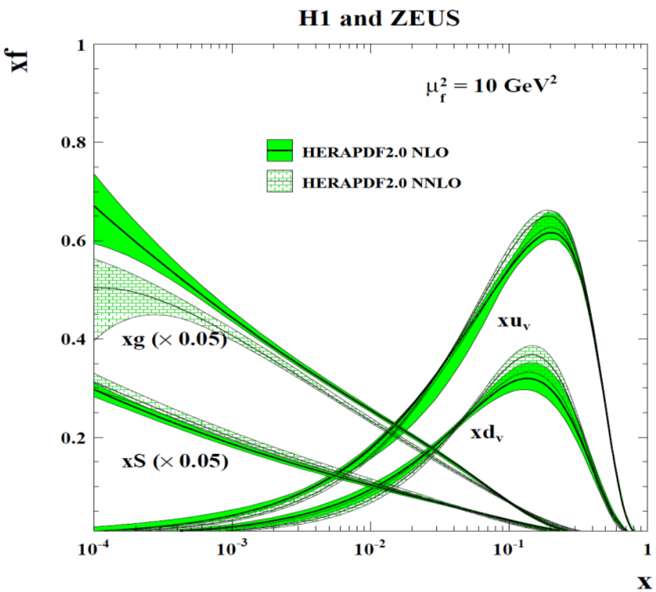


<u>Saturation</u>
Gluon production is suppressed due to the abundance of the 2 → 1 processes.

<u>Saturation scale, **Qs**</u>
Momentum scale at which saturation becomes important

McLerran and Venugopalan (1994)
and many others

The Colored Glass



Color

Gluons carry a color

Condensate

Many small-x gluons: *classical field* like in a condensate

Glass

Partons (quarks and gluons) with x ≈ 1 are very fast (v ≈ c):

Substantial Lorentz time dilation

Dynamics in the lab system slows down

The x ≈ 1 appear frozen in lab, like molecules in glasses

The dynamical evolution of the CGC: Yang-Mills equation

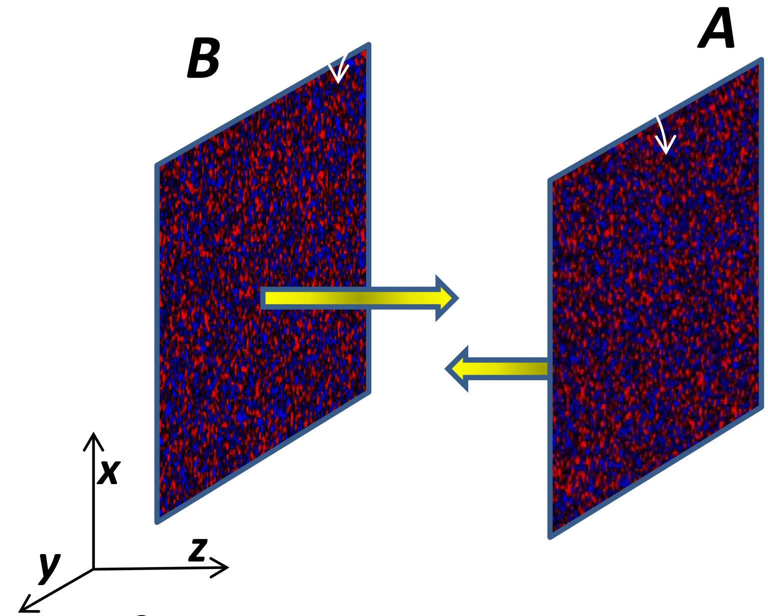
$$D^{\mu} F_{\mu\nu} = -J_{\nu}$$

Condensate (x ≈ 0)

Glass (x ≈ 1)

The MV model of color sources

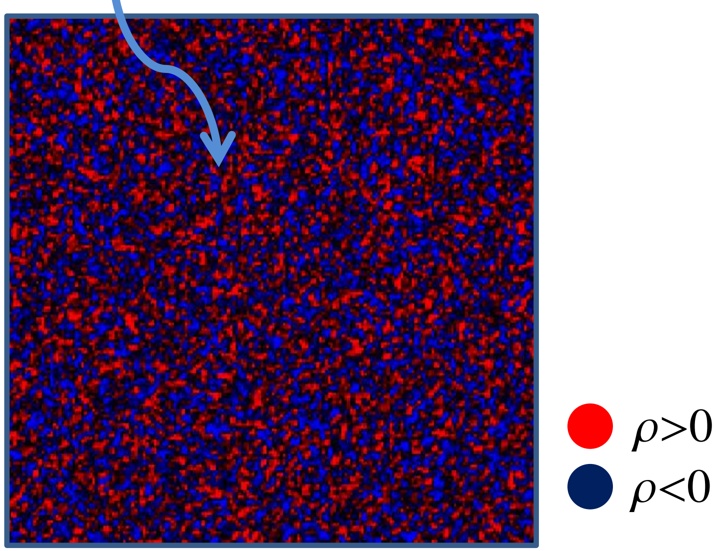
“Colliding nuclei”



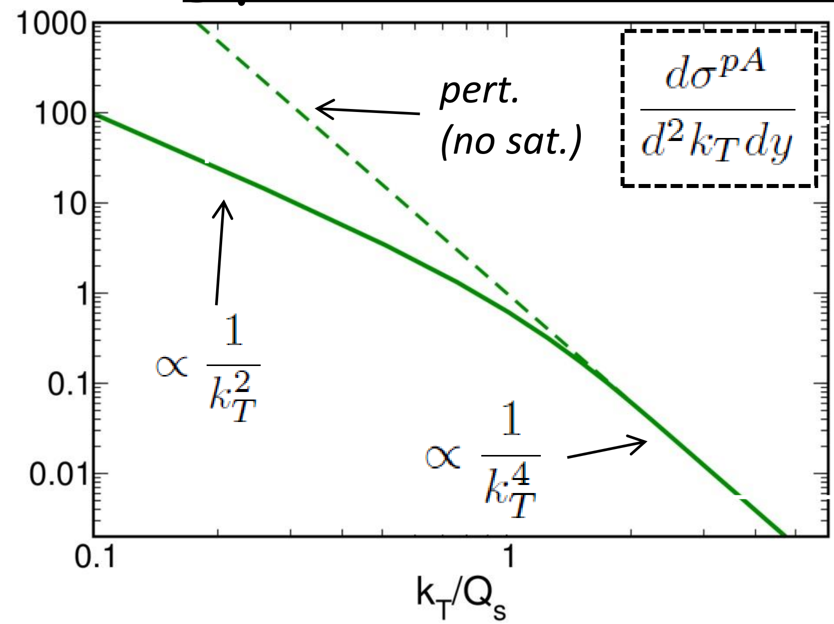
• *Fast (large momentum) partons*
Their dynamics in the Lab frame is slowed down due to time dilation: ***static sources of color fields.***

Model of static sources (MV model)
Uncorrelated color density fluctuations on the two nuclei.

$$\langle \rho^a(\boldsymbol{x}_T) \rangle = 0,$$
$$\langle \rho^a(\boldsymbol{x}_T) \rho^b(\boldsymbol{y}_T) \rangle = (g^2\mu)^2 \delta^{ab} \delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T)$$



$g^2\mu \approx$ *Qs: saturation scale*



Fixing the saturation scale and $g^2\mu$

Modified GBW fit controlla Lappi 2008

Freund *et al.* (2002)
Albacete *et al.* (2004)
Armesto *et al.* (2005)
Kowalski *et al.* (2006)
Kowalski *et al.* (2008)
Lappi (2008)

$$Q_s^2 = f(A) Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

$f(A) = A^{1/3}$, *naive*
$f(A) = cA^{1/3}\log(A)$, *IP-Sat*

naive
- $x \approx 10^{-2}$ RHIC energy: $Q_s \approx 1.7$ GeV, $g^2\mu \approx 3$ GeV
- $x \approx 10^{-4}$ LHC energy: **$Q_s \approx 3$ GeV, $g^2\mu \approx 5.3$ GeV**

IP-Sat
- $x \approx 10^{-2}$ RHIC energy: $Q_s \approx 1.1$ GeV, $g^2\mu \approx 2$ GeV
- $x \approx 10^{-4}$ LHC energy: **$Q_s \approx 2$ GeV, $g^2\mu \approx 3.6$ GeV**

We consider
$g^2\mu_{Pb} \approx$ in the range 3.6 GeV – 5.3 GeV

This is for Appendix only

Glasma: building up the initial condition

$$-\nabla \cdot \alpha^{(A)}(\mathbf{x}_\perp) = \rho^{(A)}(\mathbf{x}_\perp),$$
$$-\nabla \cdot \alpha^{(B)}(\mathbf{x}_\perp) = \rho^{(B)}(\mathbf{x}_\perp)$$

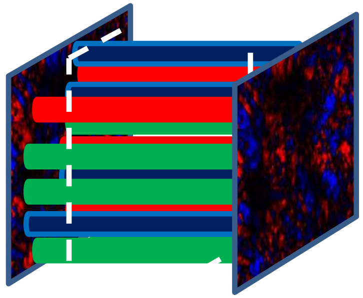
$$\alpha_i^{(A)}(\mathbf{x}_\perp) = iU^{(A)}(x_\perp)\partial_i U^{(A)\dagger}(x_\perp),$$
$$\alpha_i^{(B)}(\mathbf{x}_\perp) = iU^{(B)}(x_\perp)\partial_i U^{(B)\dagger}(x_\perp)$$

$$A_i = \alpha_i^{(A)} + \alpha_i^{(B)}, i = x, y,$$
$$A_\eta = 0,$$

$$E_\eta = i\sum_i [\alpha_i^{(A)}, \alpha_i^{(B)}],$$
$$B_\eta = i([\alpha_x^{(A)}, \alpha_y^{(B)}] + [\alpha_x^{(B)}, \alpha_y^{(A)}]).$$

This is for Appendix only

Glasma: the energy density profile

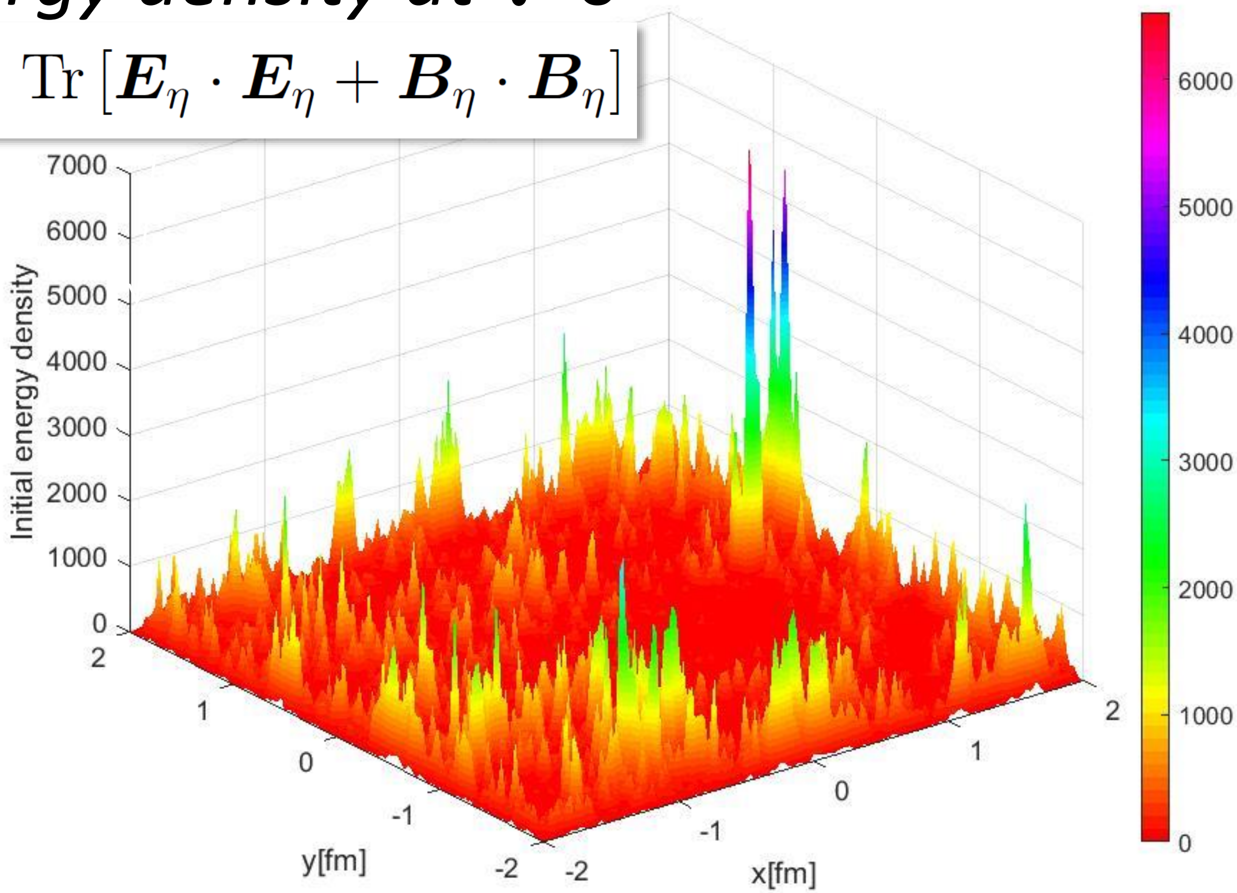


Distribution on the *transverse plane at the initial time*.

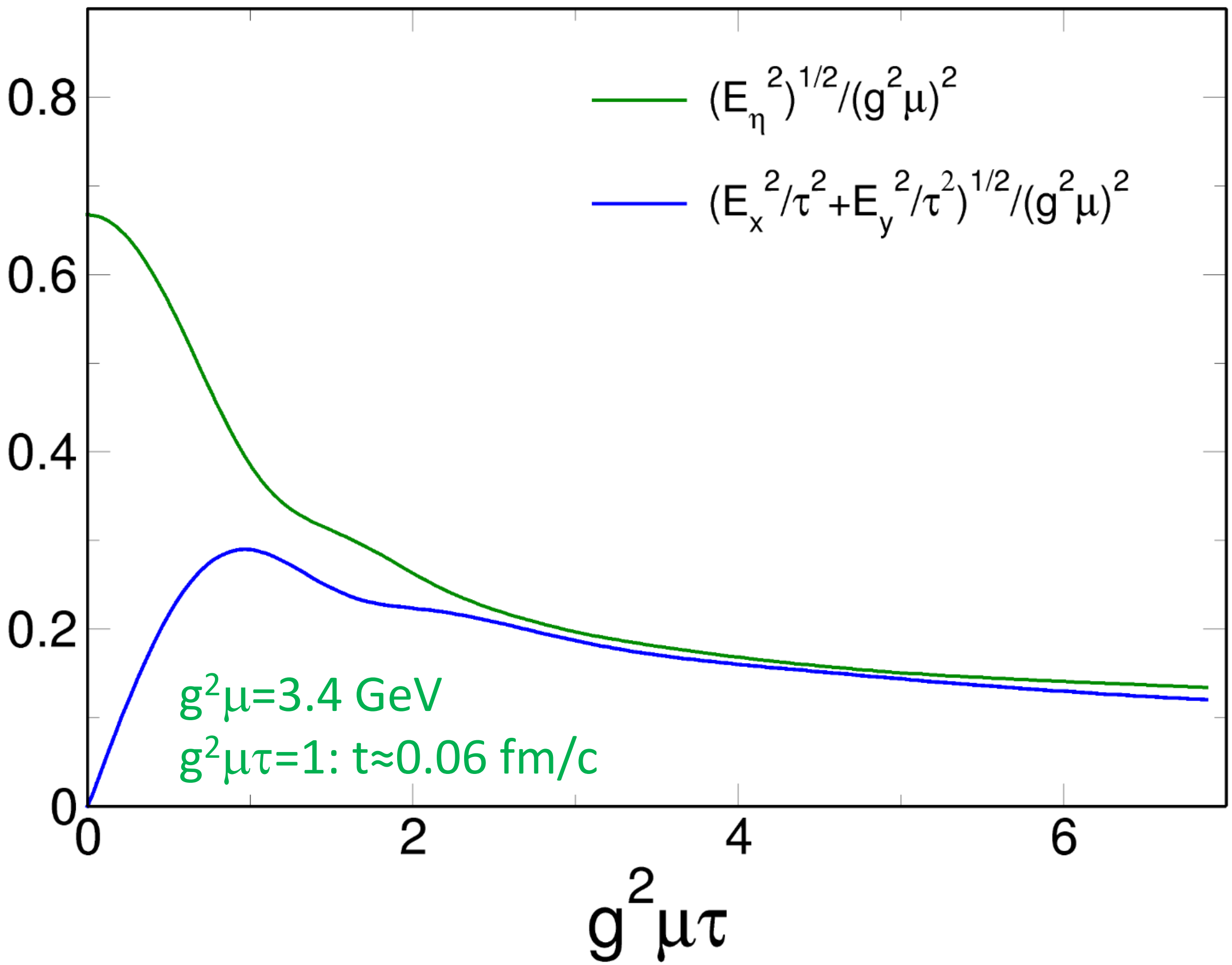
Fields are *invariant* for *longitudinal boosts.*

Energy density at τ=0

$$\mathcal{H} = \mathrm{Tr}\left[\boldsymbol{E}_\eta \cdot \boldsymbol{E}_\eta + \boldsymbol{B}_\eta \cdot \boldsymbol{B}_\eta\right]$$



Ev-Glasma: color fields

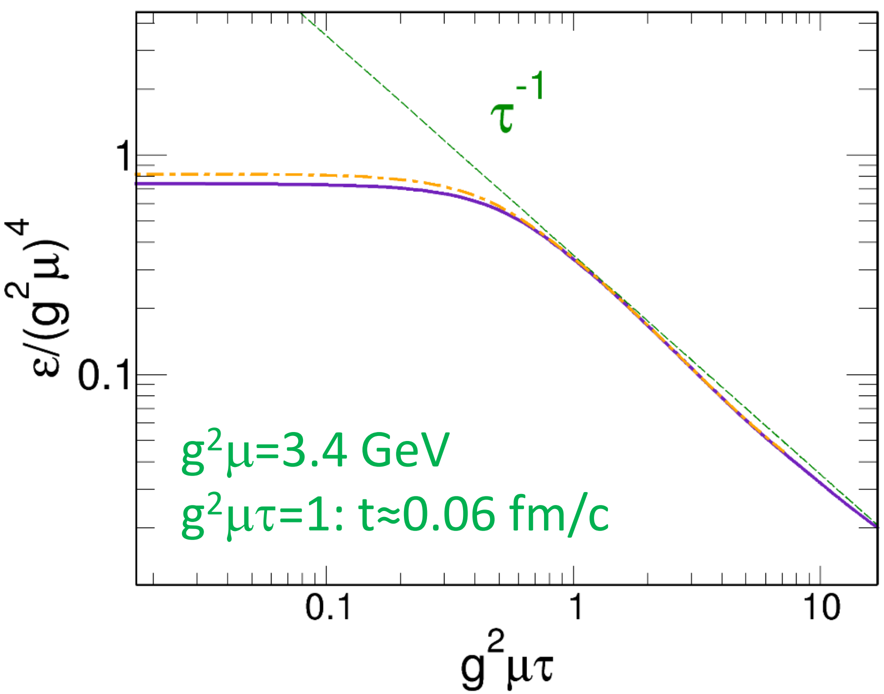


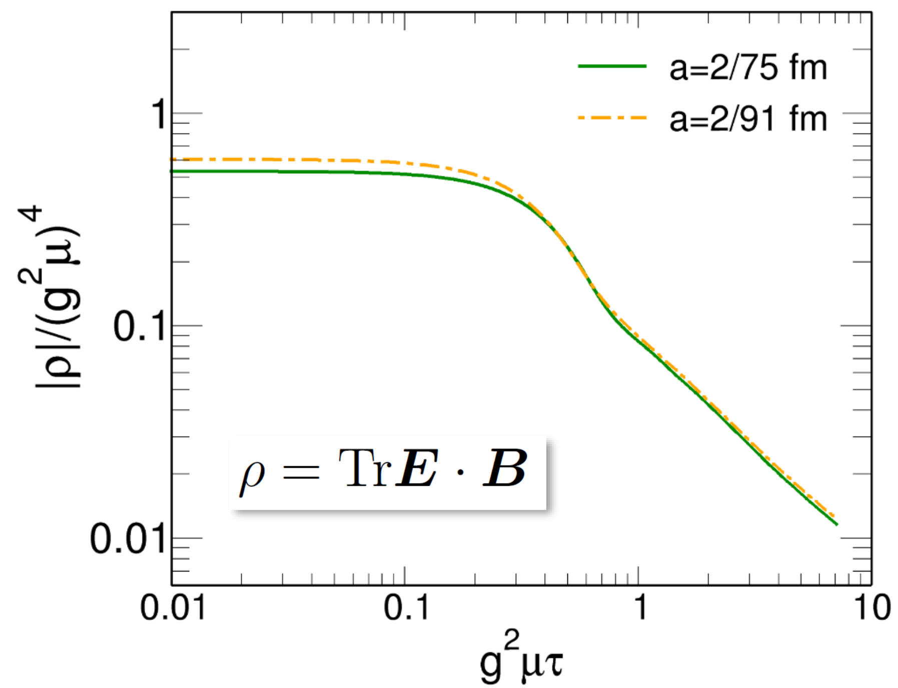
See also
M. Ruggieri *et al.* (2019)
M. Ruggieri and S. K. Das (2018)
Fukushima and Gelis (2011)
Ohnishi *et al.* (2011)
Lappi and McLerran (2006)

$$\left.\frac{dE_a^x}{dt}\right|_{t=0^+} = \partial_y B_z^a + f_{abc} A_y^b B_z^c$$

Formation time of transverse fields:
$g^2\mu\tau\approx 1$ namely $\tau\approx 0.1$ fm/c

Check lattice spacing



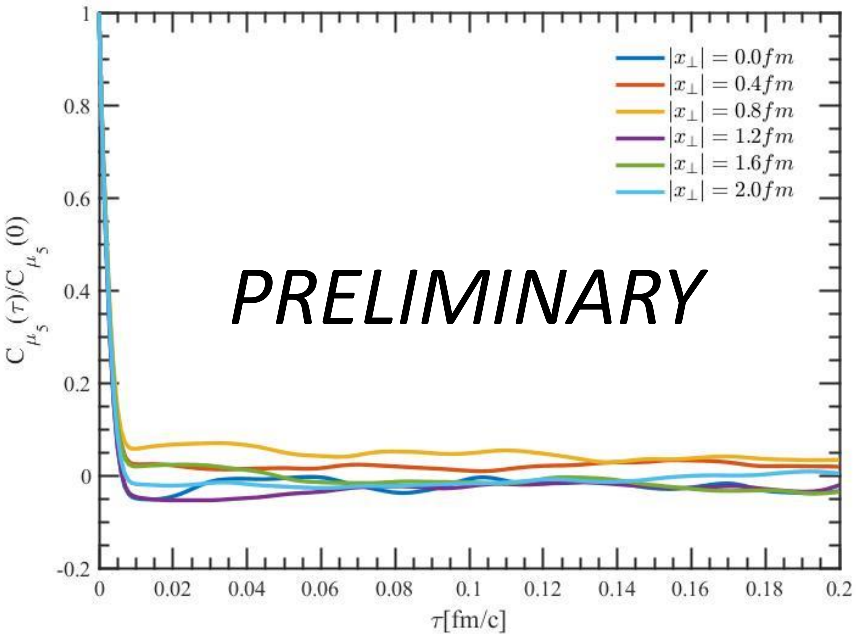


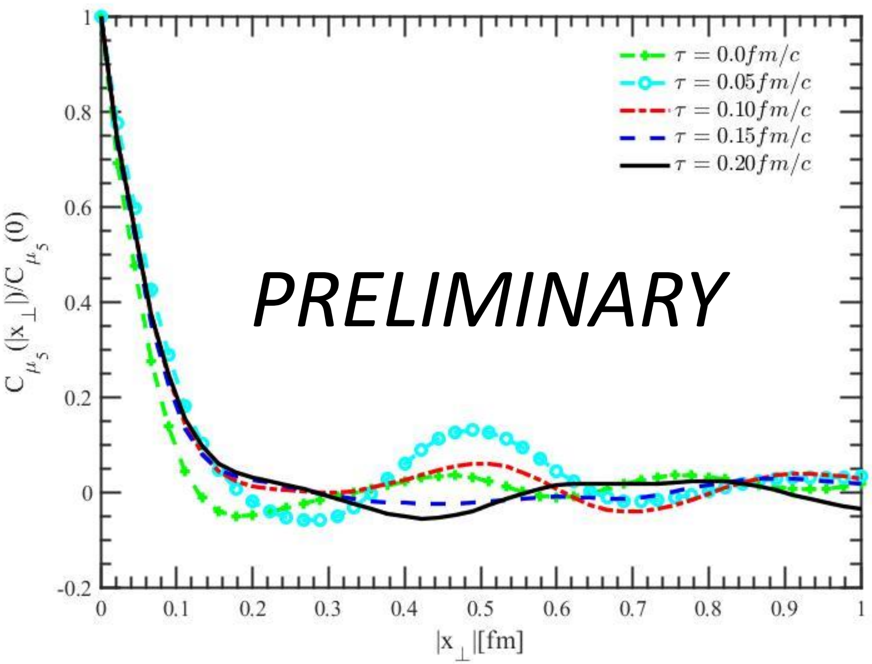
This is for Appendix only

Space and time correlators of μ_5

For an estimate of the magnitude of the CME photon spectrum:

$$\langle \mu_5(\tau_1, \boldsymbol{x}_T)\mu_5(\tau_2, \boldsymbol{y}_T)\rangle = \langle \mu_5^2\rangle(2\lambda_\tau)e^{-|\boldsymbol{x}_T - \boldsymbol{y}_T|/\lambda}\delta(\tau_1 - \tau_2)$$





M.R. et al., in preparation

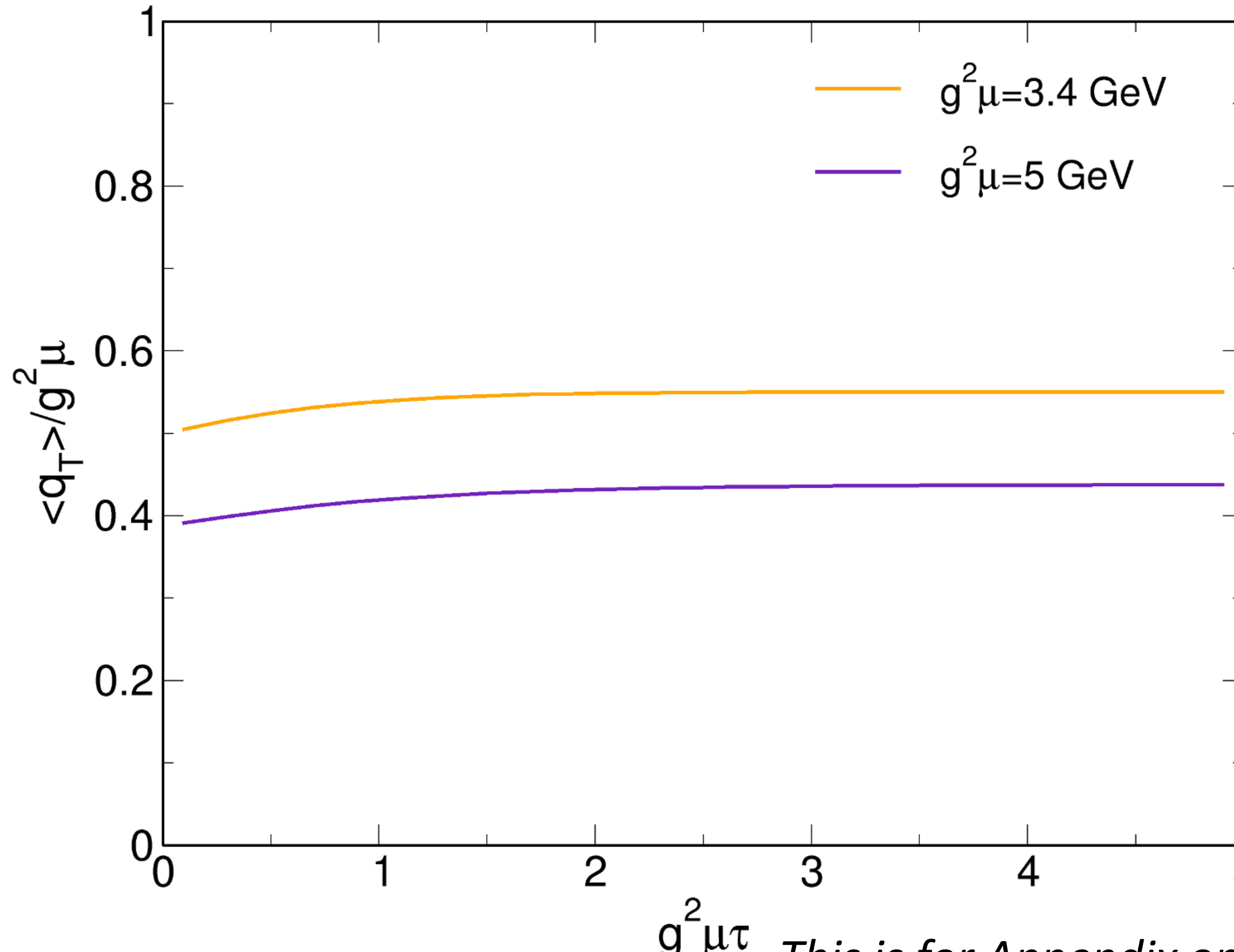
This is for Appendix only

CME photons: estimates with the K_1-correlator

K_1-correlator

$$\langle \mu_5(\tau_1, \boldsymbol{x}_T)\mu_5(\tau_2, \boldsymbol{y}_T)\rangle = \left\langle \mu_5^2\left(\frac{\tau_1+\tau_2}{2}\right)\right\rangle \frac{|\boldsymbol{x}_T-\boldsymbol{y}_T|}{\lambda} K_1\left(|\boldsymbol{x}_T-\boldsymbol{y}_T|/\lambda\right) e^{-|\tau_1-\tau_2|/\lambda_\tau}$$

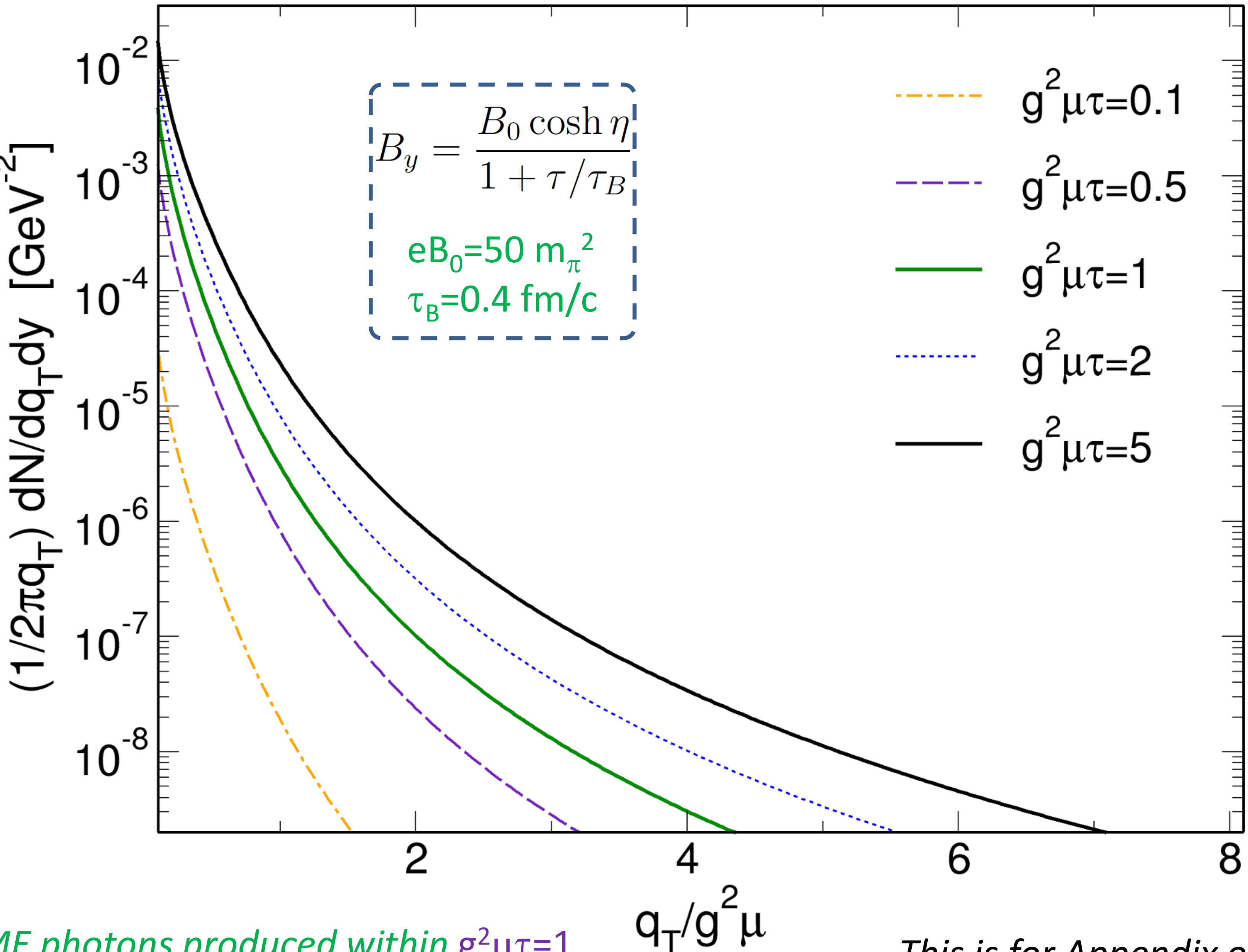
$$\frac{\langle q_T\rangle}{g^2\mu} = O(1)$$



This is for Appendix only

(*) From M.R. et al., arXiv:2006.01090

CME photons: spectrum at several times



Most CME photons produced within $g^2\mu\tau=1$

This is for Appendix only

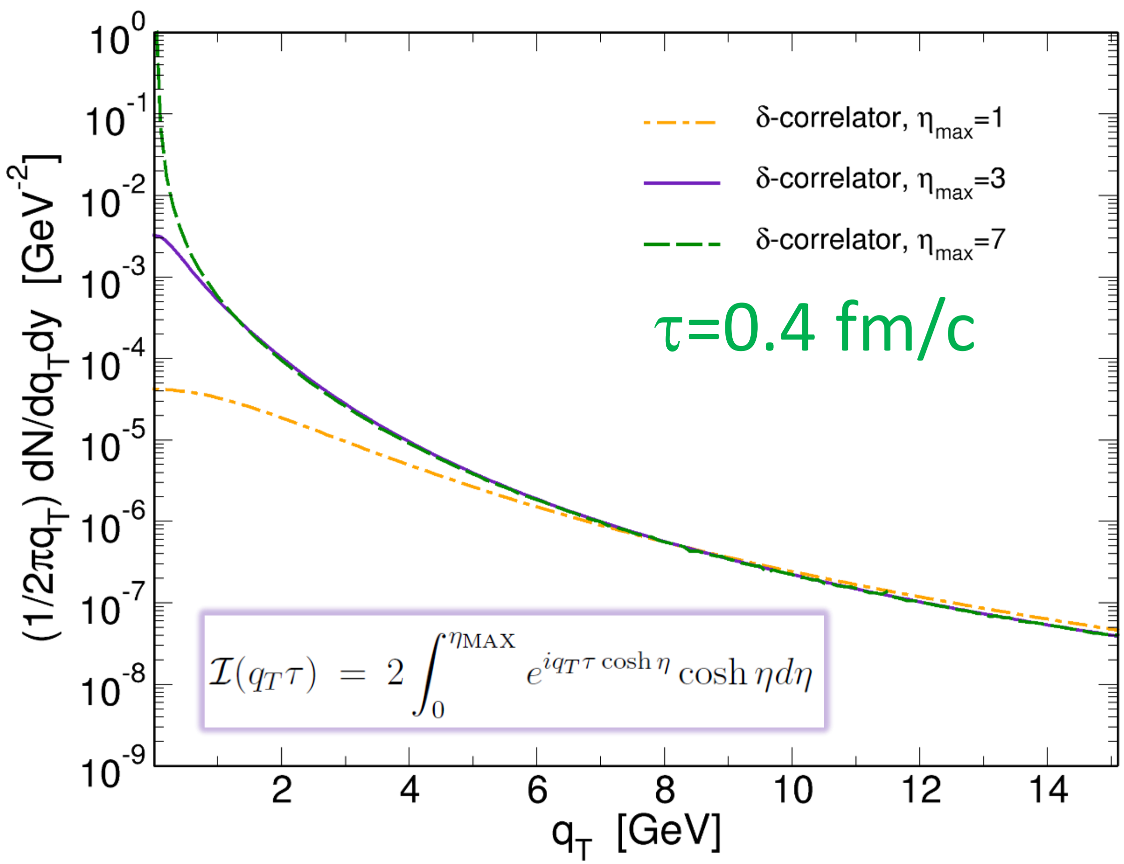
CME photons: rapidity cutoff effect

δ-correlator

$$\left.\frac{dN}{2\pi q_t dq_T}\right|_{y=0} = \frac{1}{2}\frac{25\alpha}{2(2\pi)^3 9\pi^3} e^2 B_0^2 A_T \left[\frac{2\pi\lambda^2}{(1+q_T^2\lambda^2)^{3/2}}\right](2\lambda_\tau)\int_0^\tau \tau^2 d\tau e^{-2\tau/\tau_B}\langle\mu_5^2\rangle |\mathcal{I}(q_T\tau)|^2$$

$I(q_T\tau)$ *takes most contribution from*
$1<\cosh\eta<1+1/q_T\tau$
due to oscillations at larger values of η.

$\eta_{MAX}=3$ is well above $1+1/q_T\tau$ for $q_T=0.5$ GeV:
no strong dependence on the cutoff η_{MAX}.



This is for Appendix only