Theoretical Physics Colloquium

hosted by Prof. Igor Shovkovy at the Arizona State University

Online – 27th January 2021

The impact of ***electromagnetic and vortical fields in relativistic nuclear collisions***

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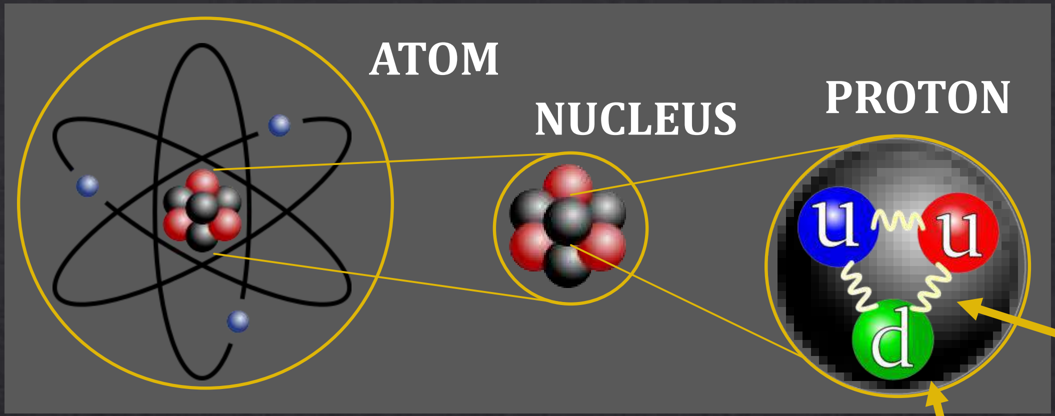
Alexander von Humboldt
Stiftung/Foundation

CRC–TR 211
Strong-interaction matter under extreme conditions



Within hadrons the quarks are bound together by the **STRONG INTERACTION** originating from the exchange of elementay particles called **GLUONS**

HADRONS are composite objects consisting of elementary particles called **QUARKS**

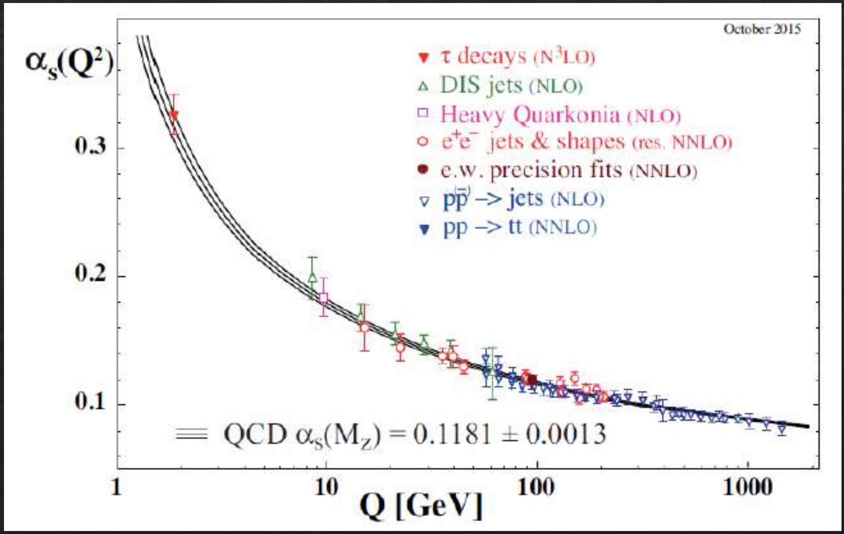
The theory governing the dynamics of quarks and gluons is the Quantum Chromodynamics (QCD)

$$\mathcal{L}_{cl} = \bar{q}_i^{\alpha}\left(i\gamma^{\mu}D_{\mu} - m\right)_{\alpha\beta}^{ij} q_j^{\beta} - \frac{1}{4}F_{\mu\nu}^{a}F_{a}^{\mu\nu}$$

QCD LAGRANGIAN

COLOR CONFINEMENT
isolated colored particles
have never been observed

PDG, Chin. Phys. C 38, 010009 (2014-2015)



Low energy
Long distance

High energy
Short distance

ASYMPTOTIC FREEDOM
the interaction between colored particles become asymptotically weaker as the energy scale increases

QCD predicts the existence of a super-dense and ultra-hot form of matter
in which the color charged particles are deconfined

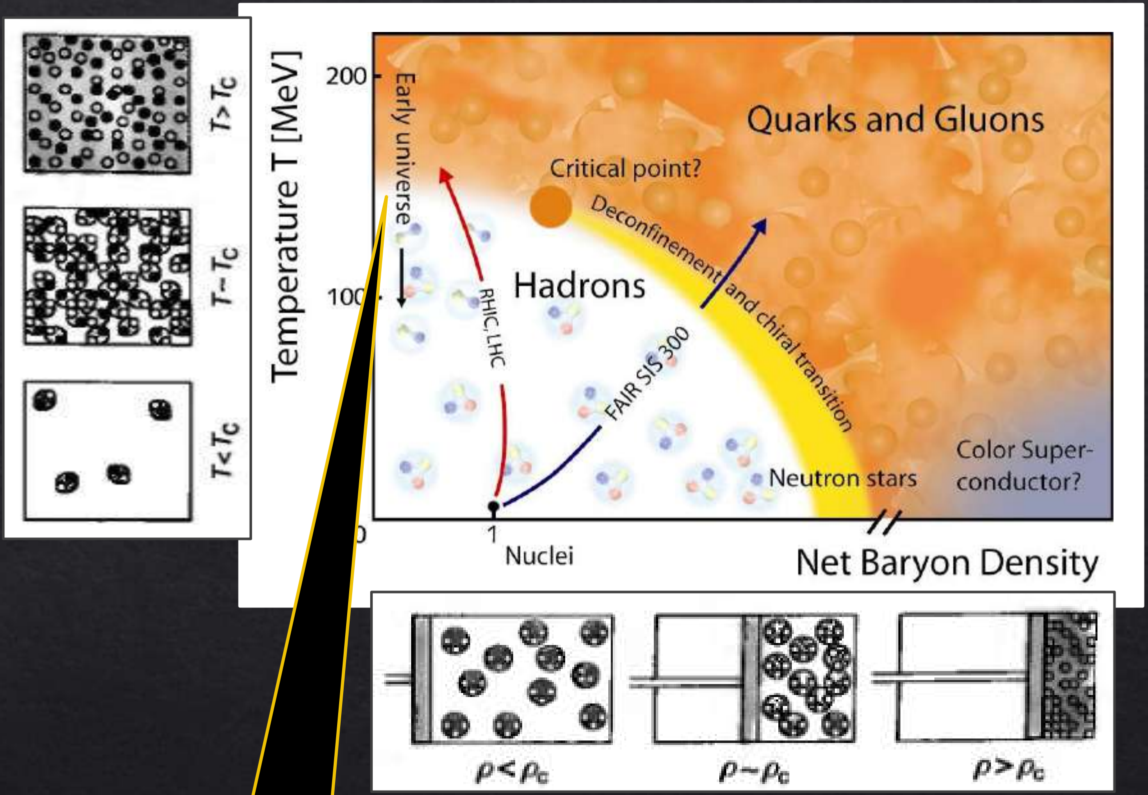
QUARK-GLUON PLASMA (QGP)

Collins and Perry, Phys. Rev. L 34 (1975) 1353

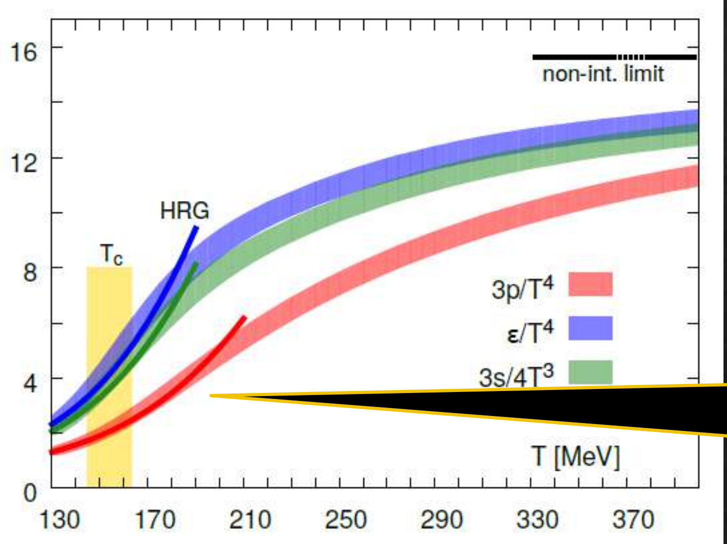
QCD PHASE DIAGRAM

Phenomenological models and lattice QCD calculations indicate the existence of a transition from hadronic matter to QGP at large energy density

$$\varepsilon \sim 0.5 - 1 \text{ GeV/fm}^3$$



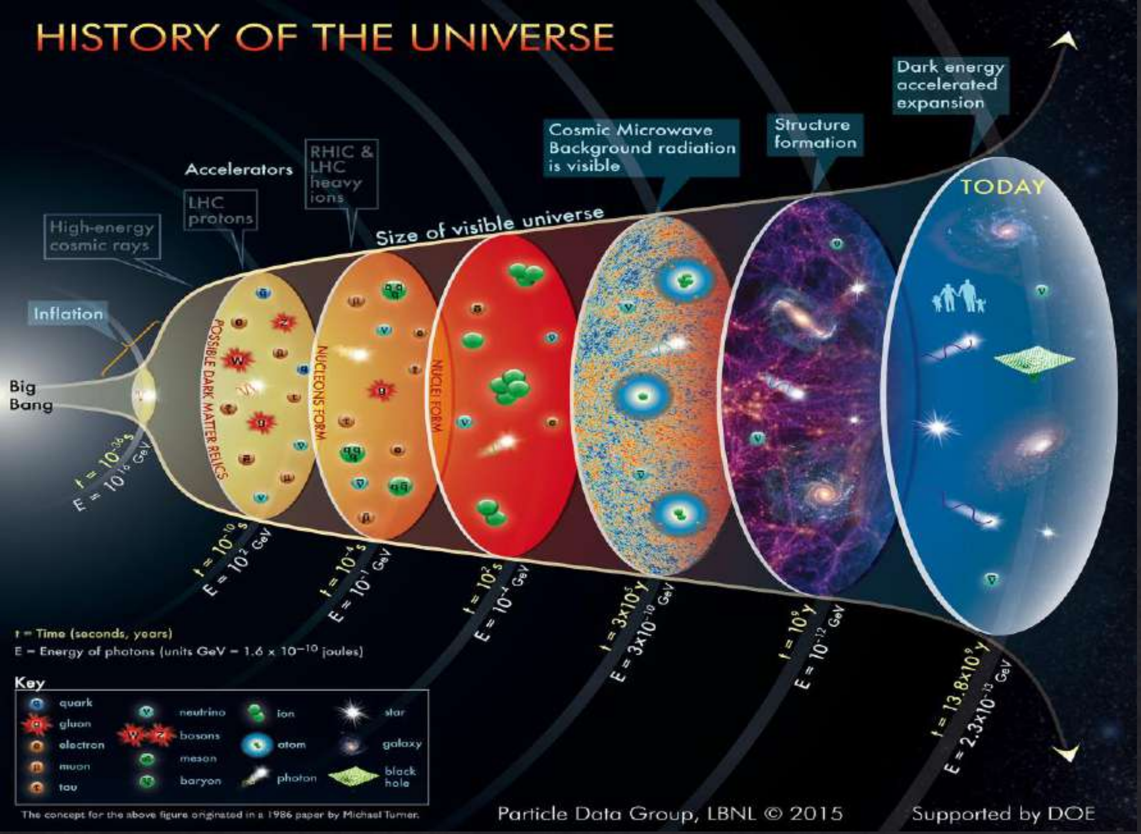
lattice QCD calculations



HotQCD Coll., Phys. Rev. D 90 (2014) 094503

at $\mu = 0$
CROSSOVER
$T_c \approx 155$ MeV

QCD transition for (pseudo)critical values of temperature and density

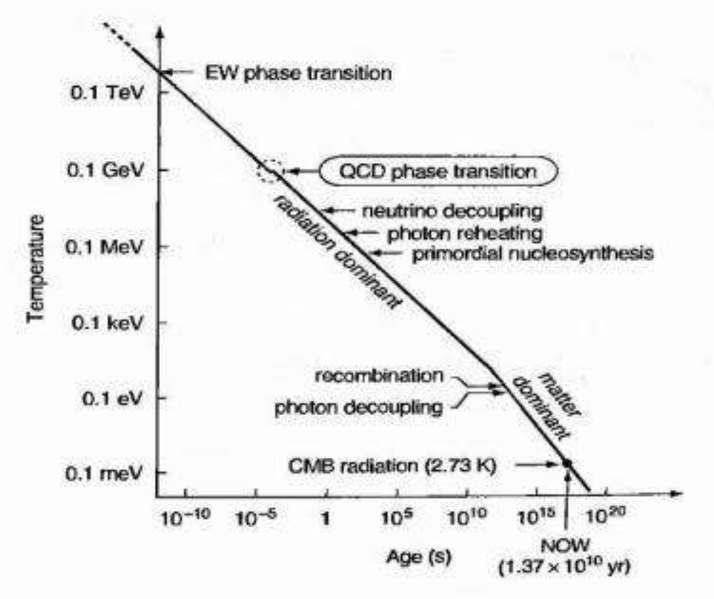


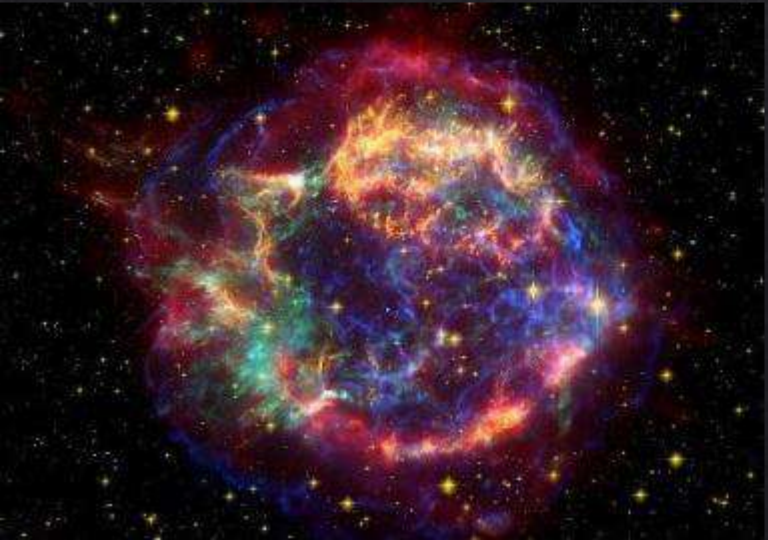
QGP at high temperature and low net baryon density in the

EARLY UNIVERSE

up to ~10 μs after the Big Bang

$T_c \approx 155$ MeV $\approx 2{\cdot}10^{12}$ K

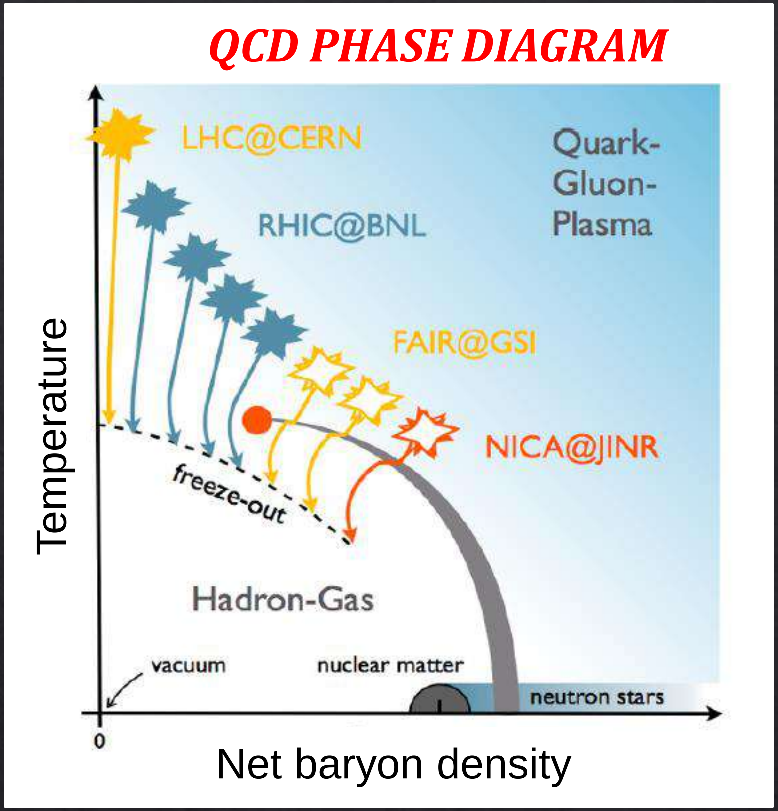




QGP at low temperature and high net baryon density in the core of

NEUTRON STARS

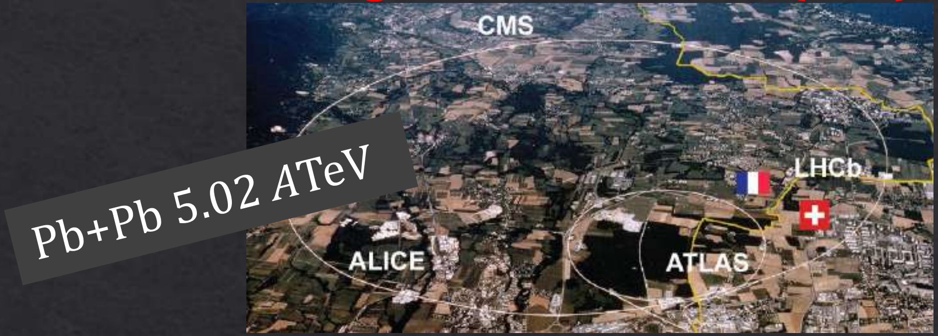
$\rho_c \approx$ 5-10 $\rho_{nm} \approx$ 0.8-1.6 $\text{fm}^{-3} \approx 10^{45}$ particles/m^3



Heavy-Ion Collisions (HICs) at high energy

- ✓ allow to experimentally investigate the QCD phase diagram
- ✓ recreate the extreme condition of temperature and density required to form the QGP

Large Hadron Collider (LHC)



Pb+Pb 5.02 ATeV

Relativistic Heavy Ion Collider (RHIC)

Au+Au 200 AGeV

Au+Au 11 AGeV

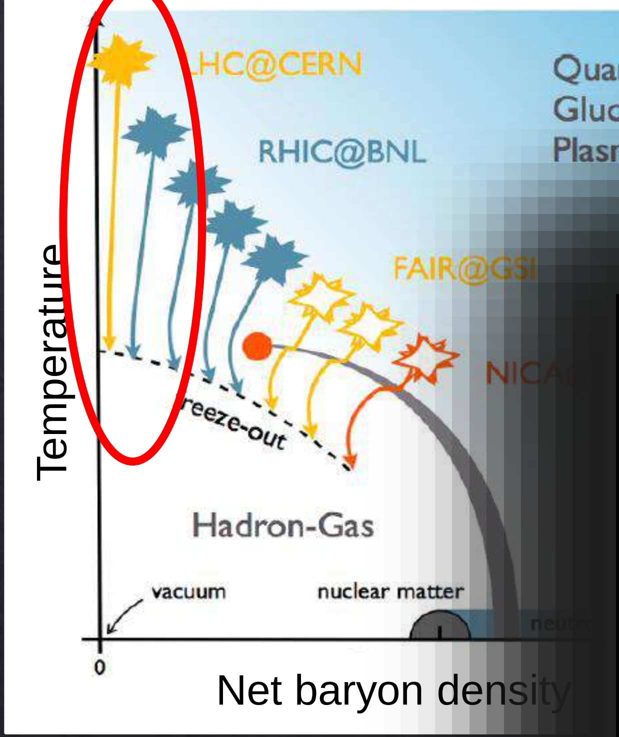
Nuclotron-based Ion Collider fAcility (NICA)

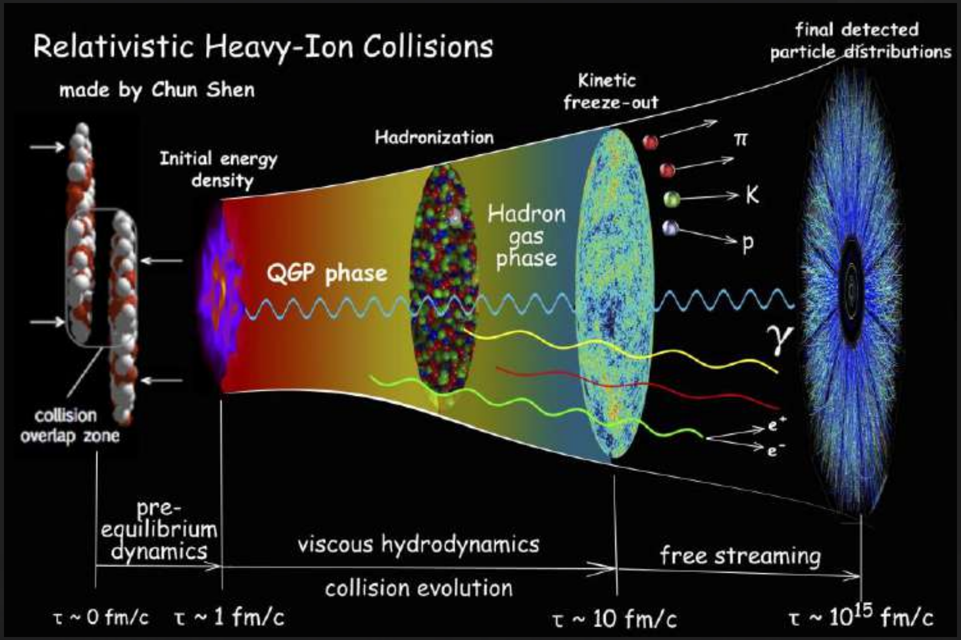
Facility for Antiproton and Ion Research (FAIR)

Au+Au 30 AGeV

EVOLUTION OF A RELATIVISTIC HEAVY-ION COLLISION

QCD PHASE DIAGRAM





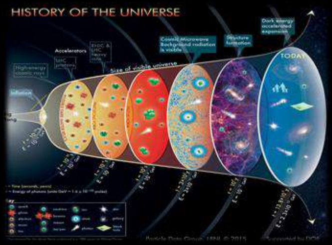
Picture credit: Chun Shen (McGill University, Montreal QC, Canada)

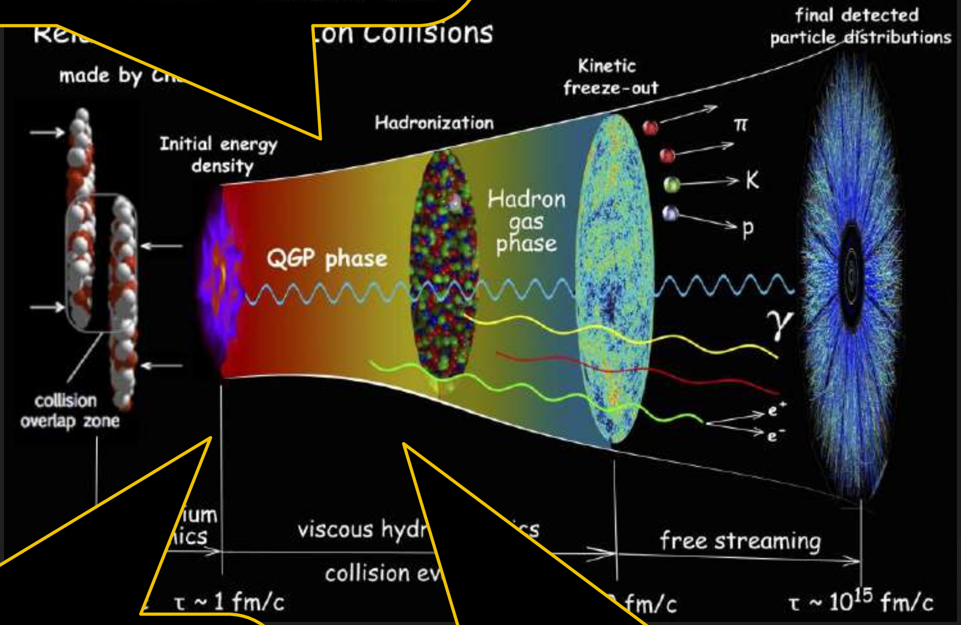
EXPANDING QUARK-GLUON PLASMA FIREBALL

TRANSIENT

$t \sim 10$ fm/c $\sim 10^{-23}$–10^{-22} s

10^{18} times shorter than the QGP lifetime in the early Universe

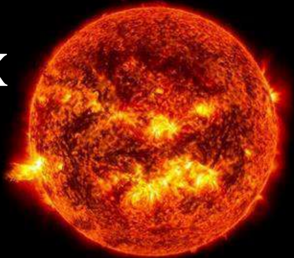




HOT

$T \sim 300$–600 MeV $\sim 10^{12}$ K

10^{5} times hotter than the centre of the sun

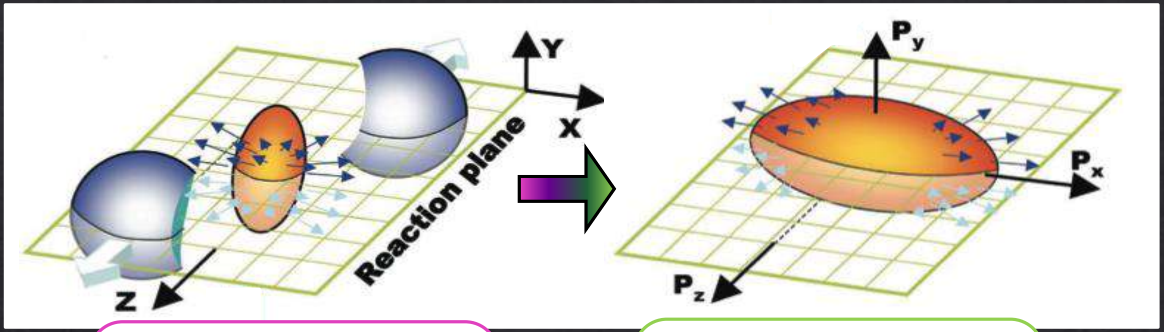


TINY

$x \sim 10$ fm $\sim 10^{-14}$ m

10^{11} times smaller than a typical water droplet

QGP as a nearly perfect fluid

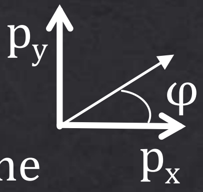


$$\varepsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}$$

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

ECCENTRICITY **ELLIPTIC FLOW**

Anisotropic radial flow described by the Fourier coefficients of the azimuthal particle distributions



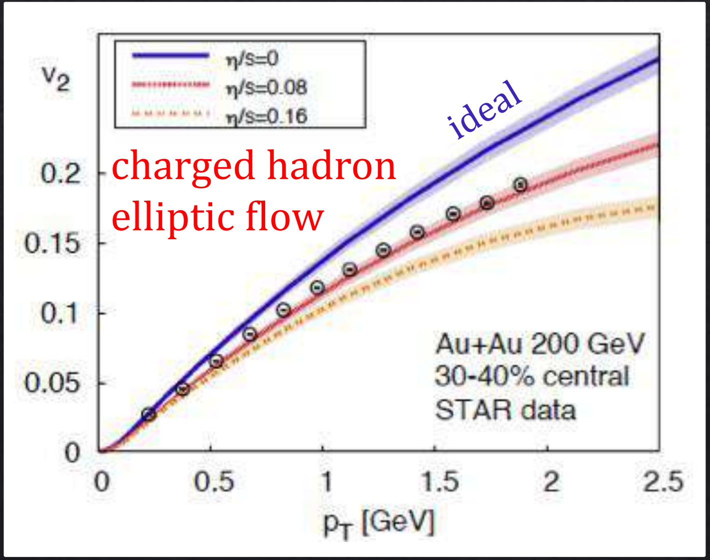
$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2\, v_n \cos[n\varphi]$$

$$\partial_\mu T^{\mu\nu} = 0,$$

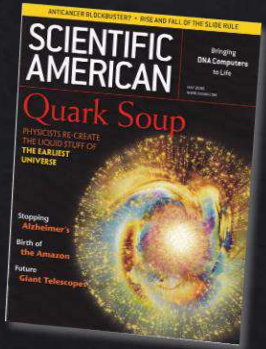
$$T^{\mu\nu} = e\, u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$

RELATIVISTIC (VISCOUS) HYDRODYNAMICS

macroscopic description of the fireball evolution based on conservation laws (with viscous corrections)



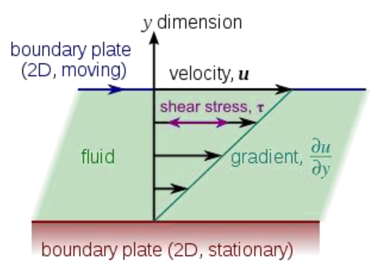
Schenke, Jeon and Gale,
Phys. Rev. Lett. 106, 042301 (2011)



Riordan and Zajc, Sci. Am. 294N5, 24 (2006)

Quark-Gluon Plasma
hydrodynamical behaviour
with collective flows formation

QGP as a nearly perfect fluid

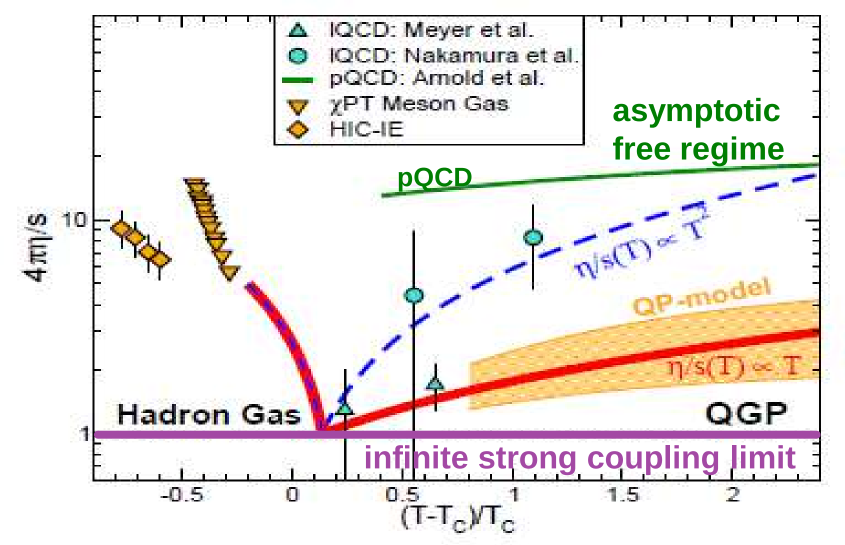


$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial u_x}{\partial y}$$

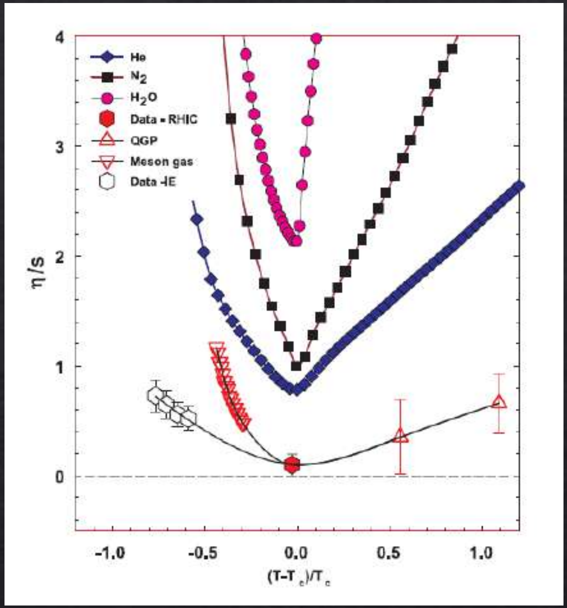
SHEAR VISCOSITY OVER ENTROPY DENSITY RATIO η/s
is a measure of how much
the system is strongly coupled

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

NON-PERTURBATIVE behaviour of QGP



Plumari *et al.*, JPCS 420, 012029 (2013)

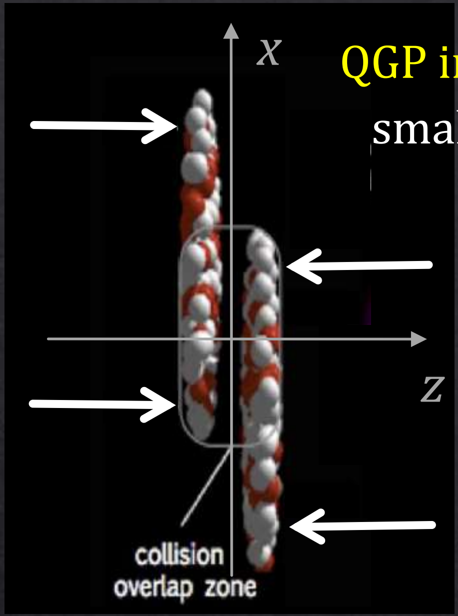


Lacey and Taranenko,
PoS CFRNC2006, 021 (2006)

$$4\pi\eta/s \approx 1 - 2$$

QGP flows like an almost perfect fluid
with the smallest η/s ever observed in nature

QGP droplets in small systems

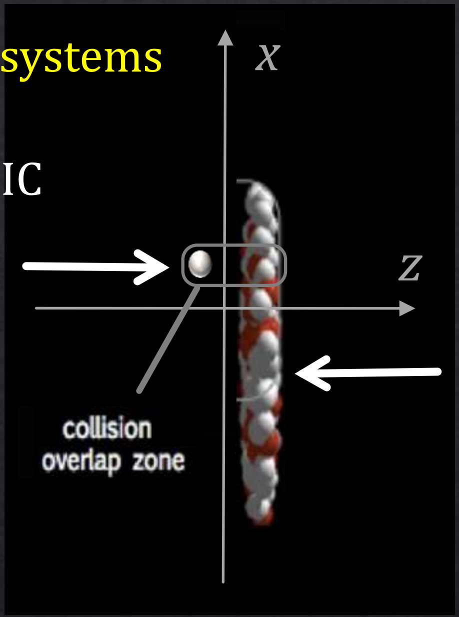


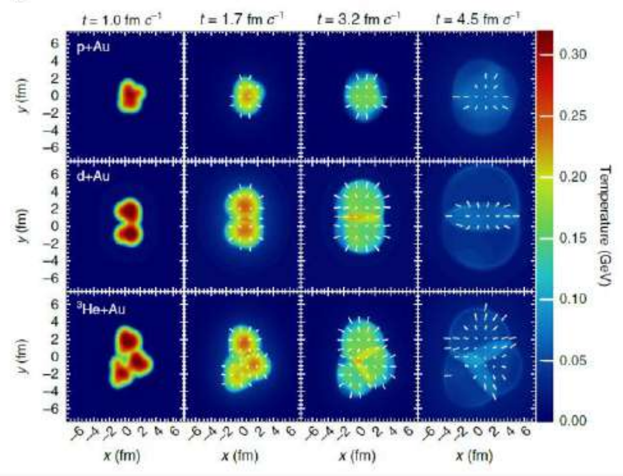
QGP initially expected only in high energy collisions of two heavy ions

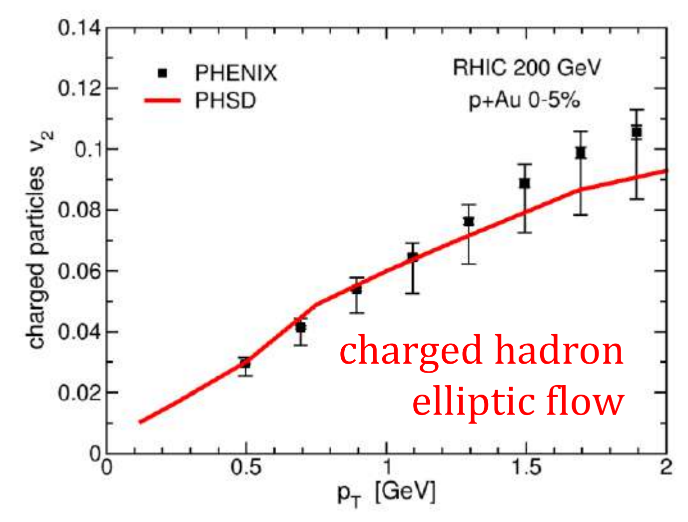
small colliding systems regarded as control measurements

Signatures of collective flow found in small systems

in high-multiplicity events of
p+p, p+Pb at LHC, p/d/^{3}He+Au at RHIC

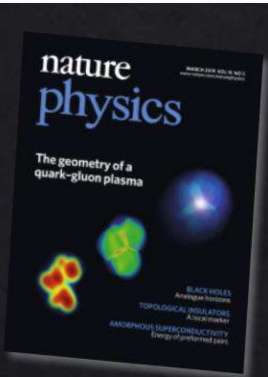






charged hadron
elliptic flow

Oliva, Moreau, Voronyuk and Bratkovskaya,
Phys. Rev. C 101 (2020) 014917



PHENIX, Nature Phys. 15 (2019) 214

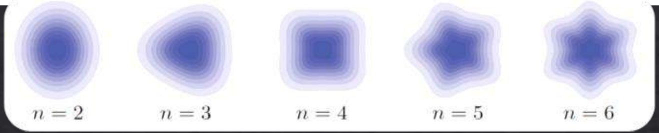
Quark-Gluon Plasma
creation of short-lived
droplets in small systems

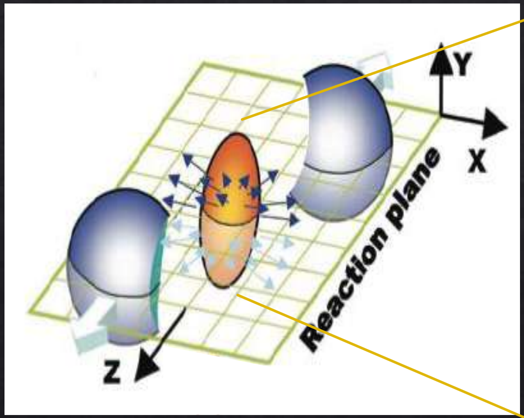
The fluctuating quark-gluon plasma

Initial-state fluctuatons of nucleon positions in the overlap region

- not only flow anisotropies with even parity due to symmetry
- odd harmonics appearing in the azimuthal particle distribution

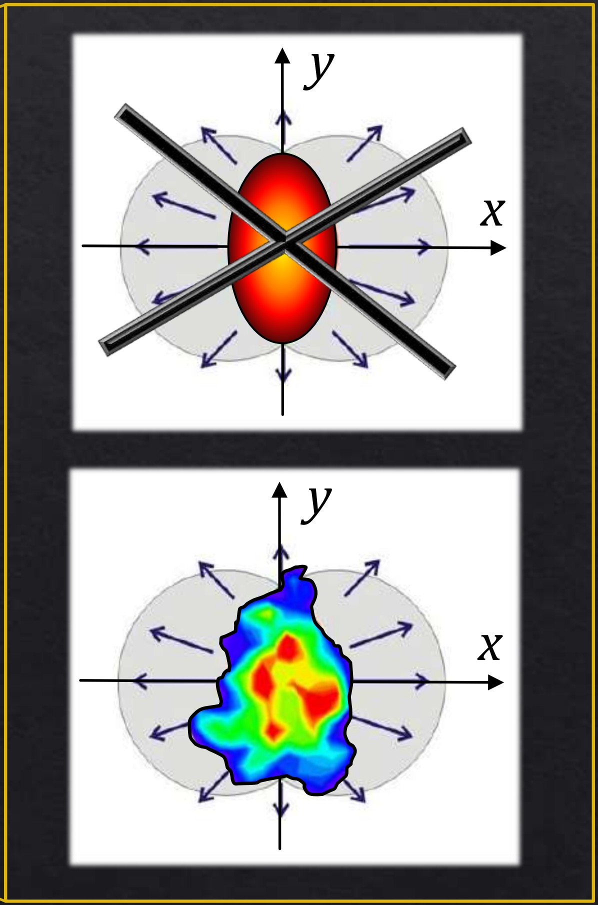
$$\frac{\mathrm{d}n}{\mathrm{d}\phi} \propto 1 + \sum_n 2v_n(p_T)\cos[n(\phi - \Psi_n)]$$





Not a simple almond shape...

...but a LUMPY PROFILE on the transverse plane



UPGRADING THE TRANSVERSE VIEW

Transport kinetic equations

Evolution of the fireball described at a microscopic level by the **transport equations**

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

RELATIVISTIC
BOLZTMANN
EQUATIONS

Free streaming

Field interaction

change of ***f*** due to interactions of the plasma with a field (*e.g.* color and **electromagnetic fields**)

collision integral

change of **f** due to collision processes responsible for deviations from ideal hydro ($\eta/s \neq 0$)

Generalization to off-shell dynamics
Parton-Hadron String Dynamics (PHSD)
instead of Boltzmann eqs. ⟶ Kadanoff-Baym eqs.
instead of particle distribution function ***f*** ⟶ Green functions with complex self-energies

Cassing and Bratkovskaya, Nucl. Phys. A 831, 215 (2009)
Bratkovskaya, et al., Nucl Phys. A 856, 162 (2011)

Xu and Greiner, Phys. Rev. C 79, 014904 (2009)
Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)
Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

Intense electromagnetic and vortical fields

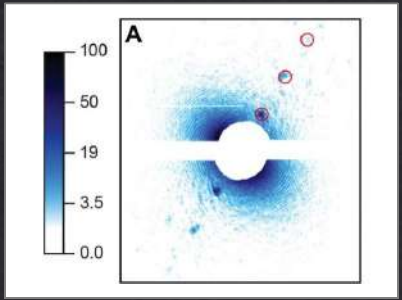
- ✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG VORTICITY

tornado cores

~ $10^{-1}\ s^{-1}$

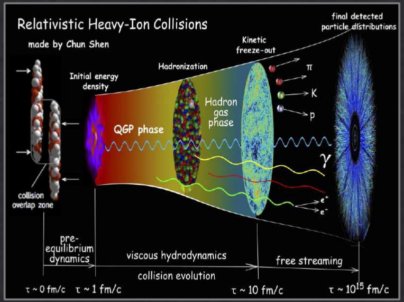
Jupiter’s spot

~ $10^{-4}\ s^{-1}$



He nanodroplets

~ $10^{7}\ s^{-1}$



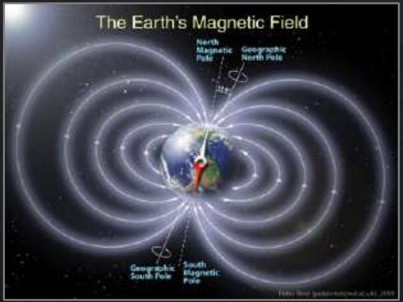
urHICs

~ 10^{22}–$10^{23}\ s^{-1}$

vorticity

ω

- ✓ INTENSE ELECTROMAGNETIC FIELDS (EMF)



Earth’s field

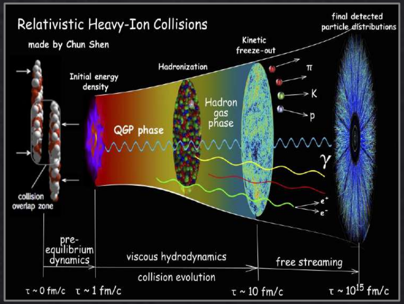
~ 1 G

laboratory

~ 10^{6} G

magnetars

~ 10^{14}–10^{15} G



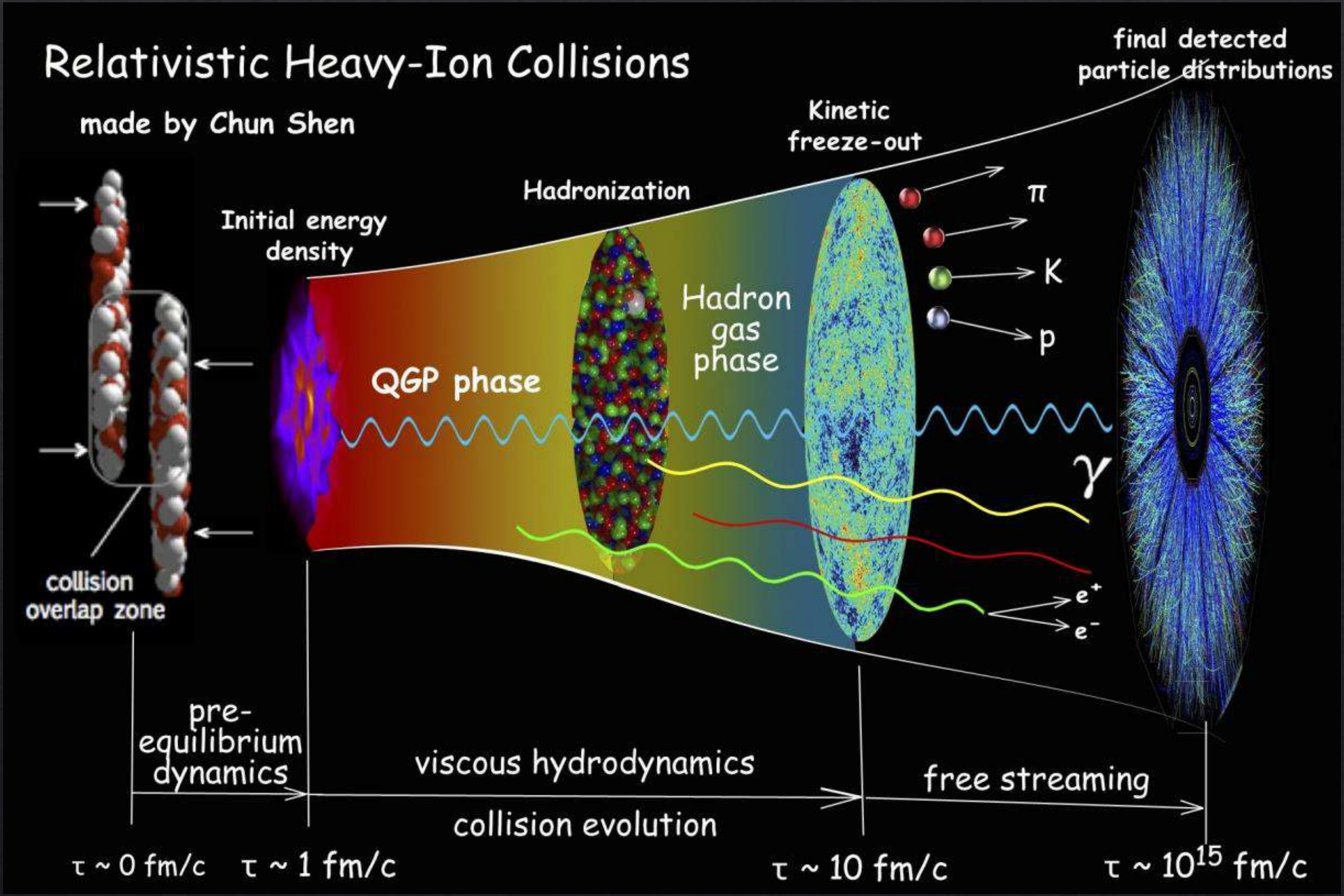
urHICs

~ 10^{18}–10^{19} G

magnetic field

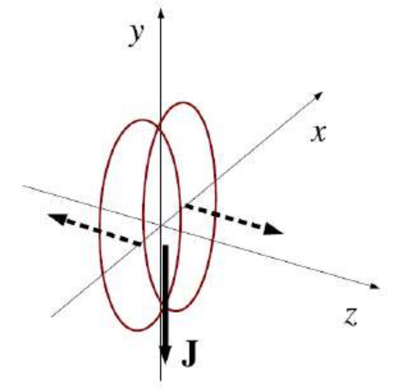
B

VORTICITY AND DIRECTED FLOW



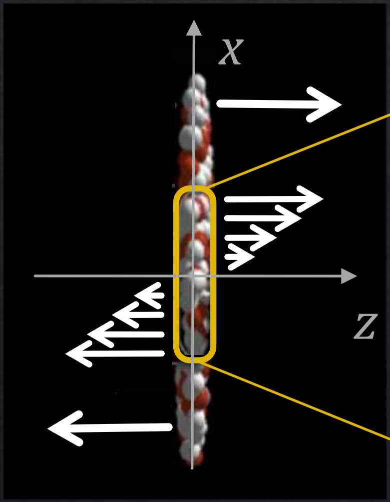
Picture credit: Chun Shen (McGill University, Montreal QC, Canada)

The vortical quark-gluon plasma



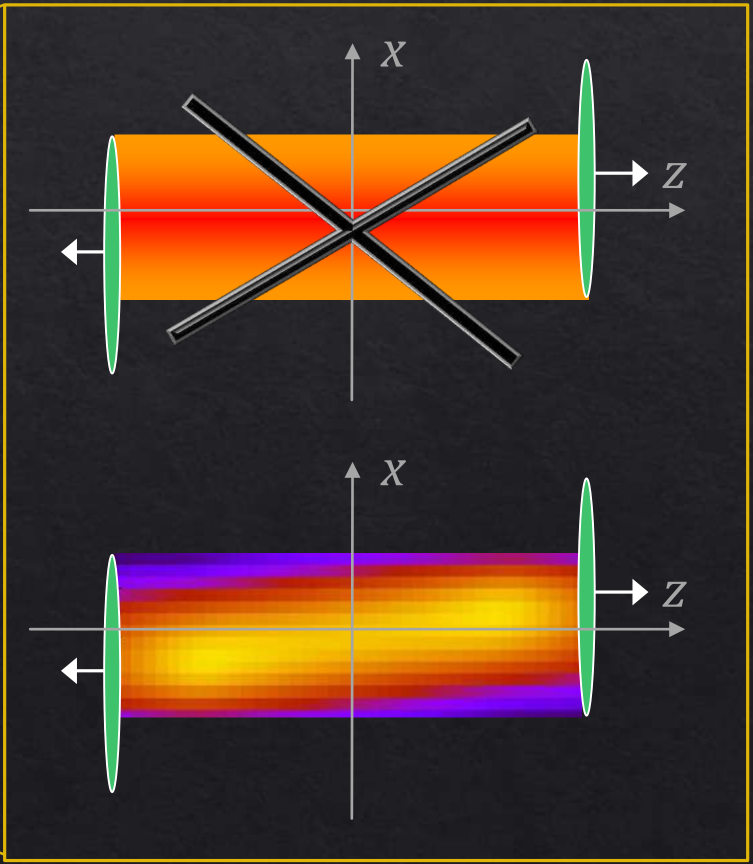
Huge **orbital angular momentum** of the colliding nuclear system

- in ultrarelatvistic HICs $\mathbf{J} \approx \mathbf{10^5 - 10^6}\,\boldsymbol{\hbar}$
- dominated by the y component perpendicular to the reaction plane
- partly trasferred to the plasma



Not a symmetric
energy distribution…

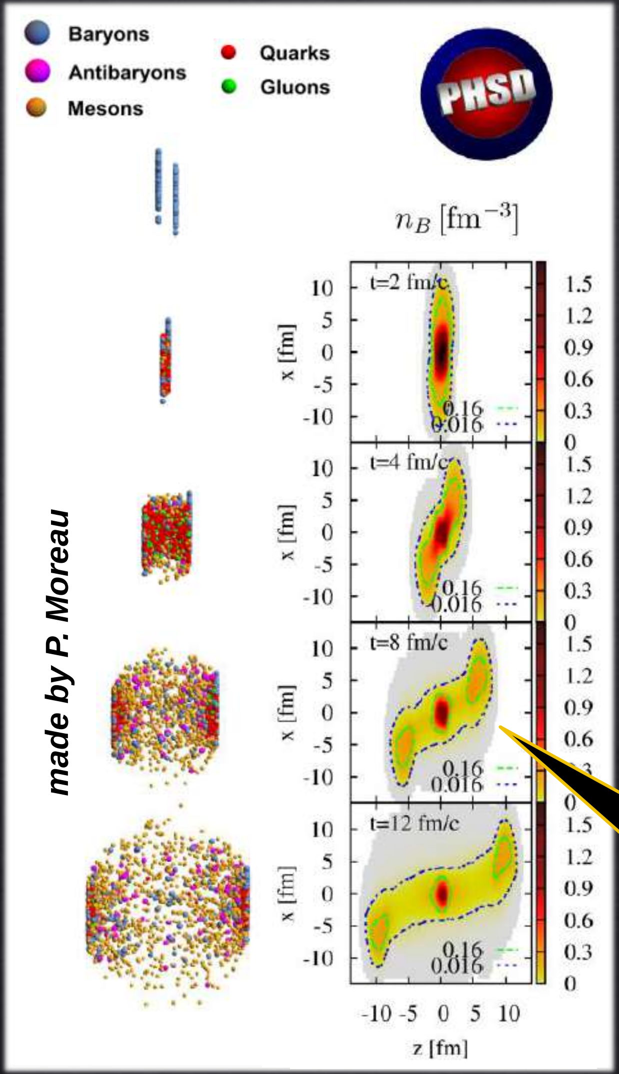
…but a TILTED FIREBALL
on the reaction plane



UPGRADING
THE LONGITUDINAL VIEW

Two approaches: vorticity in HICs

PHSD APPROACH



CATANIA APPROACH

asymmetry in local participant density
from forward and backward going nuclei

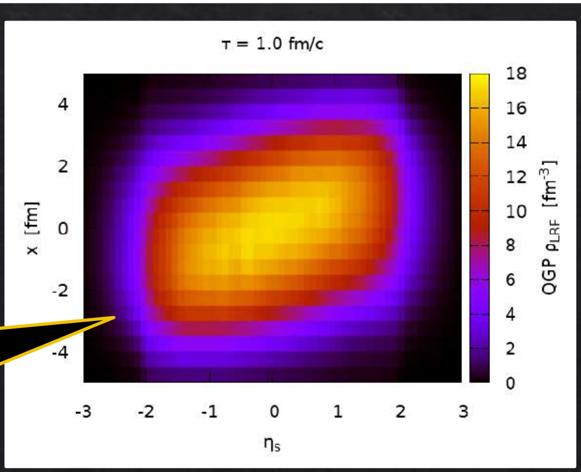
$$\rho(x_\perp,\eta_s) = \rho_0 \frac{W(x_\perp,\eta_s)}{W(0,0)} \exp\left[-\frac{(|\eta_s|-\eta_{s0})^2}{2\sigma_\eta^2}\theta(|\eta_s|-\eta_{s0})\right]$$

$$W(x_\perp,\eta_s) = 2\left(N_A(x_\perp)f_-(\eta_s) + N_B(x_\perp)f_+(\eta_s)\right)$$

$$f_+(\eta_s) = f_-(-\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \frac{\eta_s+\eta_m}{2\eta_m} & -\eta_m \le \eta_s \le \eta_m \\ 1 & \eta_s > \eta_m \end{cases}$$

SPACETIME
RAPIDITY
$\eta_s = \tanh^{-1}\frac{z}{t}$

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



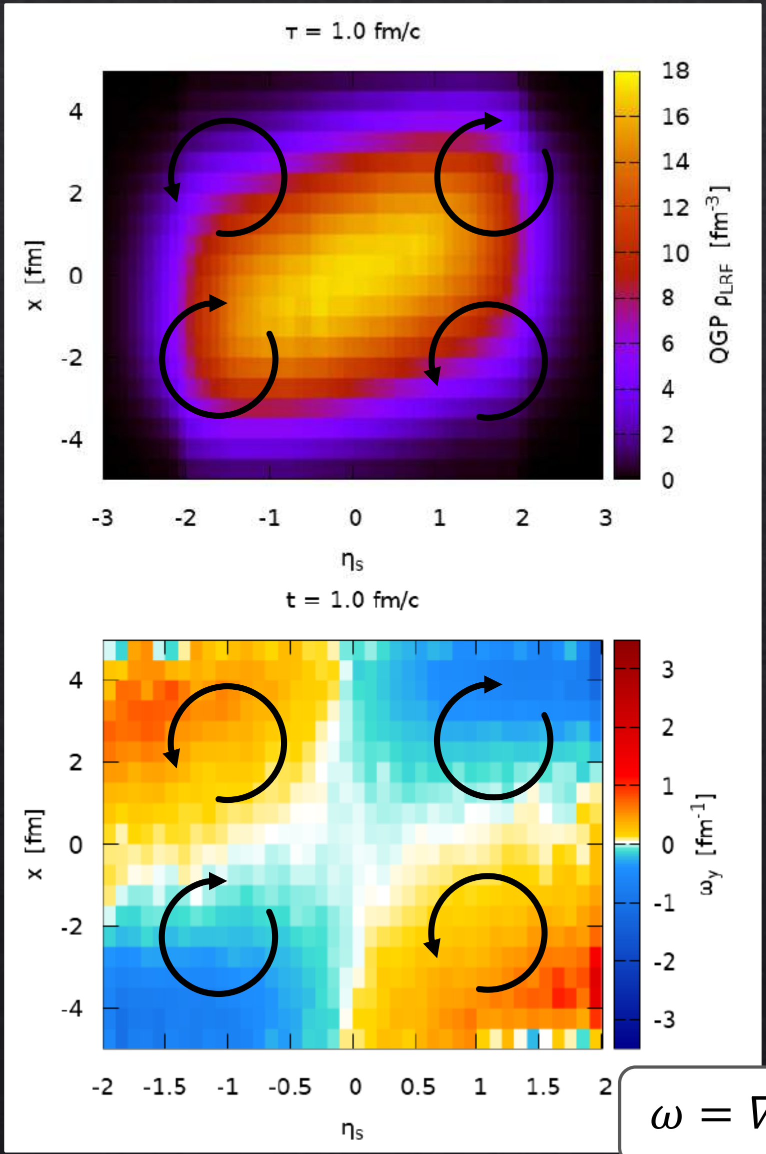
tilted fireball
on the
reaction plane

Cassing and Bratkovskaya, Nucl. Phys. A 831, 215 (2009)
Kolomeitsev, Toneev and Voronyuk, Phys. Rev. C 97, 064902 (2018)

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)
Oliva, Plumari and Greco, 2009.11066

The vortical quark-gluon plasma

Oliva, Plumari and Greco, 2009.11066



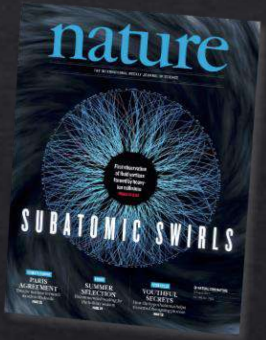
$$\omega = \nabla \times v$$

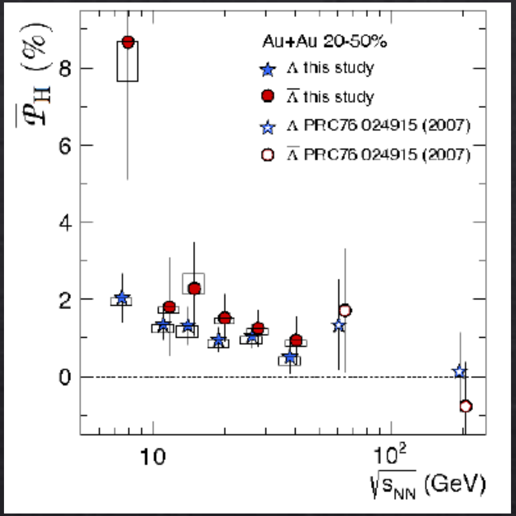
NONRELATIVISTIC VORTICITY

The huge angular momentum and the tilt of the fireball induce in the QGP an intense VORTICITY

The vorticity $\boldsymbol{\omega}$ is a measure of the local angular velocity of the fluid

Vorticity induce polarization of Λ hyperons





STAR Collaboration, Nature 548, 62 (2017)
Becattini and Lisa, arXiv:2003.03640

$$\omega \approx 3\ \mathrm{c/fm} \approx 10^{23}\ \mathrm{s}^{-1}$$

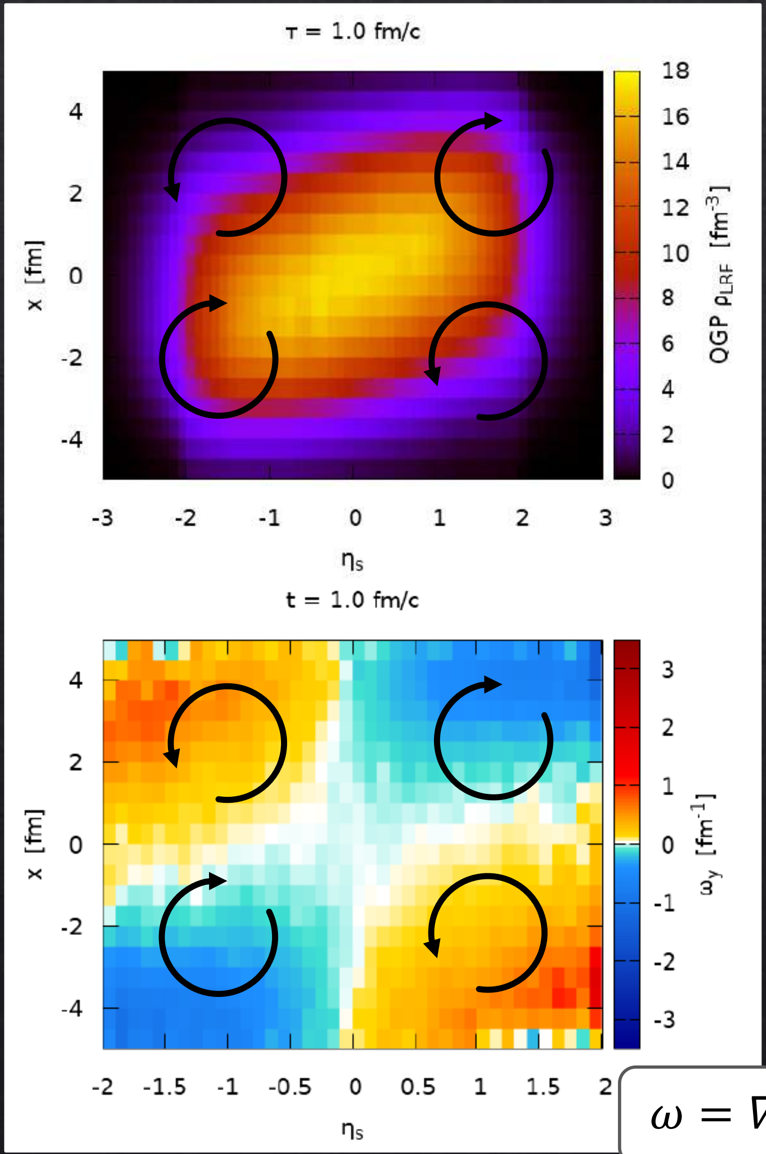
QGP as the most vortical fluid

with the largest ω ever observed in nature

Csernai, Magas and Wang, Phys. Rev. C 87, 034906 (2013)
Deng and Huang, Phys. Rev . C 93, 064907 (2016)
Jiang, Lin and Liao, Phys. Rev. C 94, 044910 (2016)

The vortical quark-gluon plasma

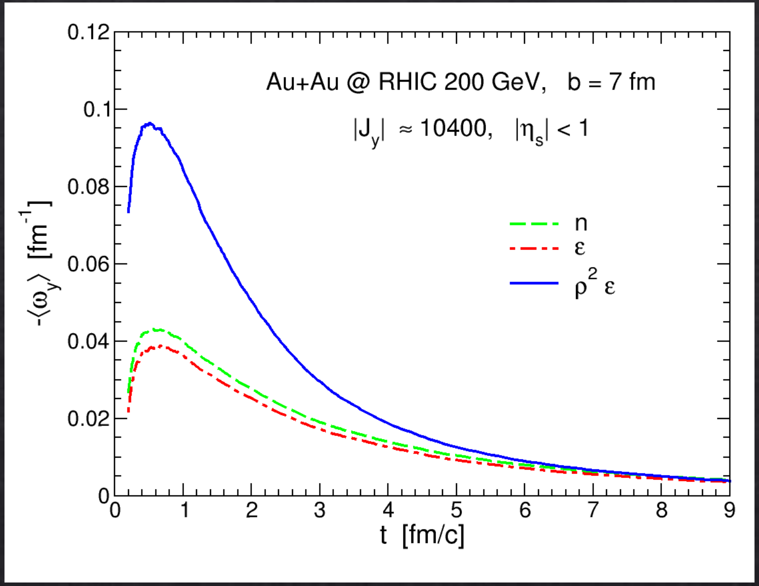
Oliva, Plumari and Greco, 2009.11066



$$\omega = \nabla \times v$$

NONRELATIVISTIC VORTICITY

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



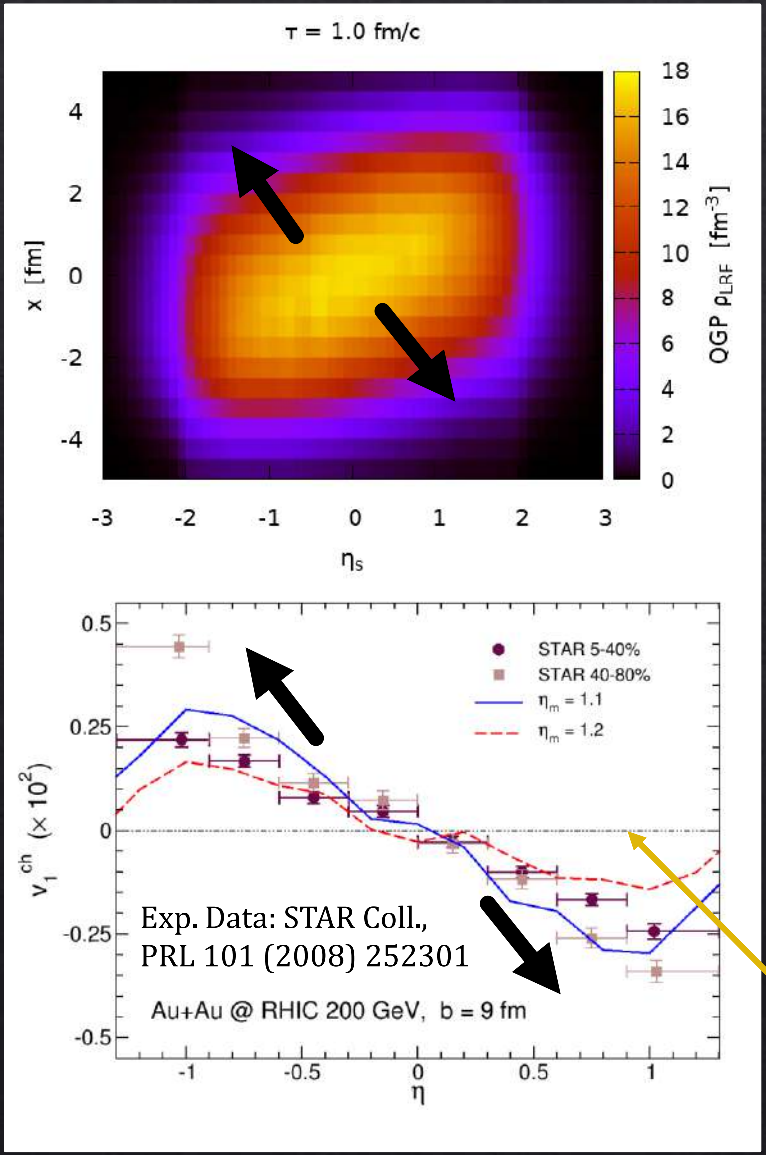
$$\langle \omega_y \rangle(\boldsymbol{x}, t) = \frac{\int d^3x\, w(\boldsymbol{x}, t)\omega_y(\boldsymbol{x}, t)}{\int d^3x\, w(\boldsymbol{x}, t)}$$

moment-of-inertia density $w(\boldsymbol{x}, t) = \rho^2(\boldsymbol{x})\varepsilon(\boldsymbol{x}, t)$

Csernai, Magas and Wang, Phys. Rev. C 87, 034906 (2013)
Deng and Huang, Phys. Rev . C 93, 064907 (2016)
Jiang, Lin and Liao, Phys. Rev. C 94, 044910 (2016)

Charged hadron directed flow

Oliva, Plumari and Greco, 2009.11066



Exp. Data: STAR Coll.,
PRL 101 (2008) 252301

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n} 2\, v_n \cos[n\varphi]$$

The huge angular momentum and the tilt of the fireball induce in the QGP a <u>DIRECTED FLOW</u>

$$v_1 = \langle \cos\varphi \rangle = \langle p_x/p_T \rangle$$

collective sidewards deflection of particles along the *x* direction

The tilt of the fireball induce a negative slope in the η dependence of the v_1 of bulk particles

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)

$v_1 = 0$ *if the fireball is not tilted*

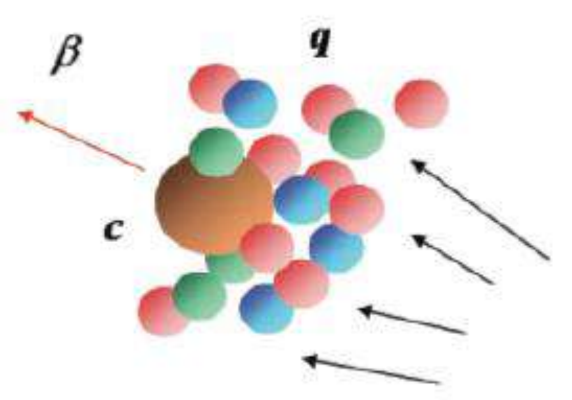
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

PSEUDORAPIDITY

(θ: polar angle of particle momentum)

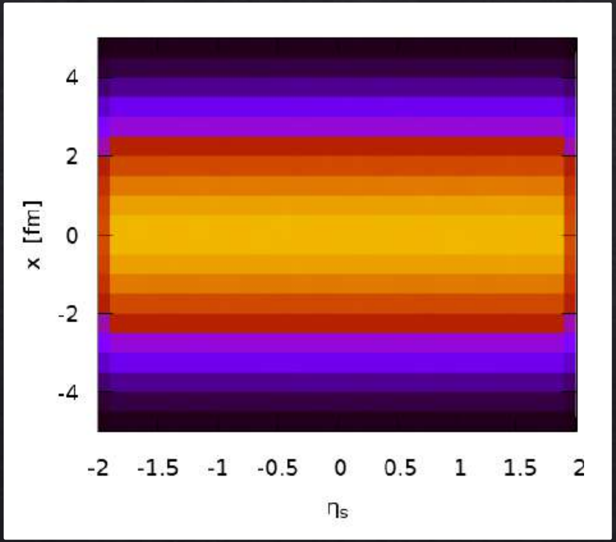
DIRECTED FLOW OF CHARGED PARTICLES

Heavy quarks (HQs)



QGP in relativistic HICs

- ☐ mostly made of light quarks (*u*, *d*, *s*): **$m_q \approx$ 10-100 MeV**
- ☐ few heavy **charm quarks: $m_c \approx$ 1500 MeV**

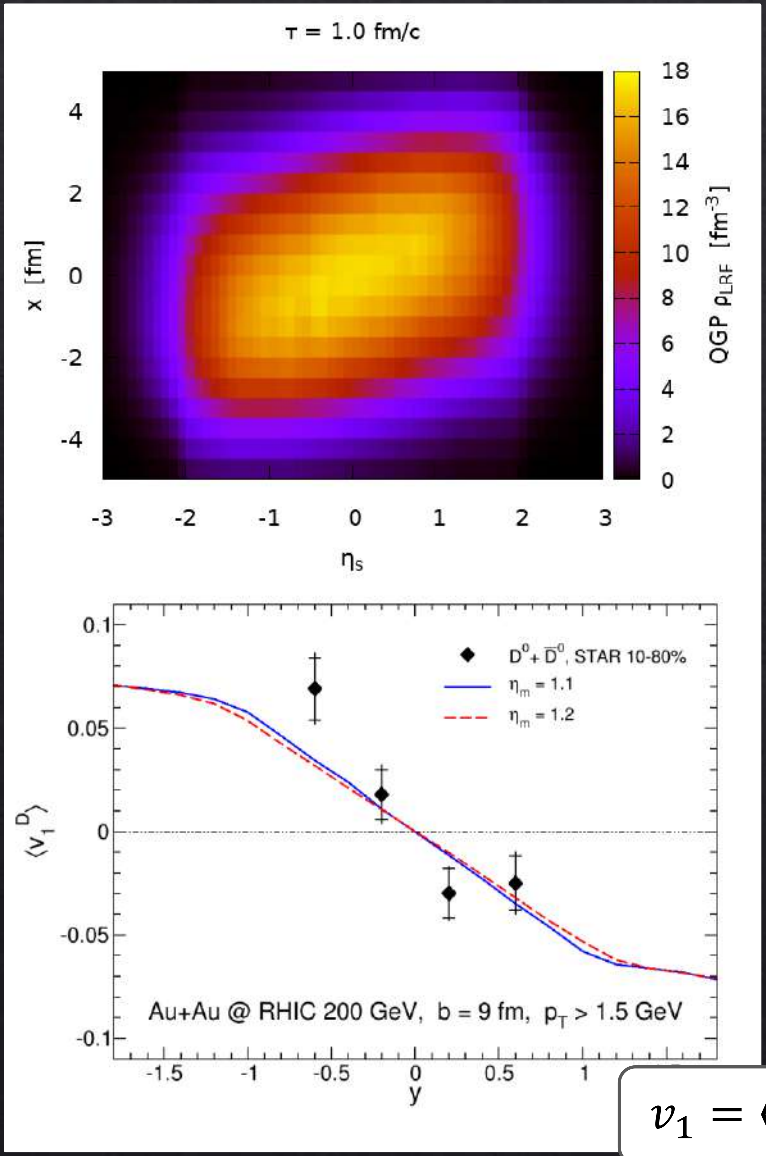


- ➢ **$m_{HQ} \gg \Lambda_{QCD}$**
  HQ produced in pQCD initial hard scatterings
- ➢ **$m_{HQ} \gg T_{HICs}$**
  negligible thermal production of HQ
- ➢ **$\tau_0^{HQ} < 0.1$ fm/c $\ll \tau_0^{QGP}$**
  HQ production much earlier than QGP formation
- ➢ **$\tau_{th}^{HQ} \approx \tau^{QGP} \approx$ 5-10 fm/c $\gg \tau_{th}^{QGP}$**
  HQ thermalization time comparable to QGP lifetime
- ➢ ***production points of HQs symmetric in the forward-backward hemispheres***

the final states of HQs keep traces of both the initial stage
and the subsequent evolution of the thermalized QGP

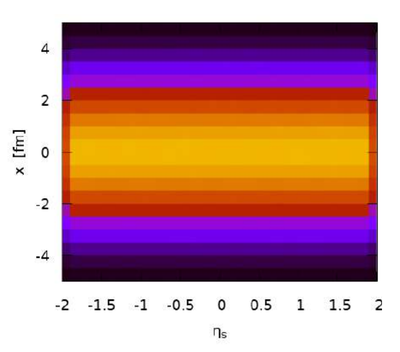
D meson directed flow

Oliva, Plumari and Greco, 2009.11066



Are HEAVY QUARKS affected by the initial tilt of the fireball and the directed flow of bulk medium?

production points of HQs symmetric in the forward-backward hemispheres



The directed flow of neutral *D* mesons is 20-30 times larger than that of light hadrons

Chatterjee and Bozek, Phys. Rev. Lett. 120, 192301 (2018)
STAR Collaboration, Phys. Rev. Lett. 123, 162301 (2019)

v_1 ***(HQs)*** $\gg$ v_1 ***(QGP)***

origin of the large directed flow of HQs different from the one of light particles

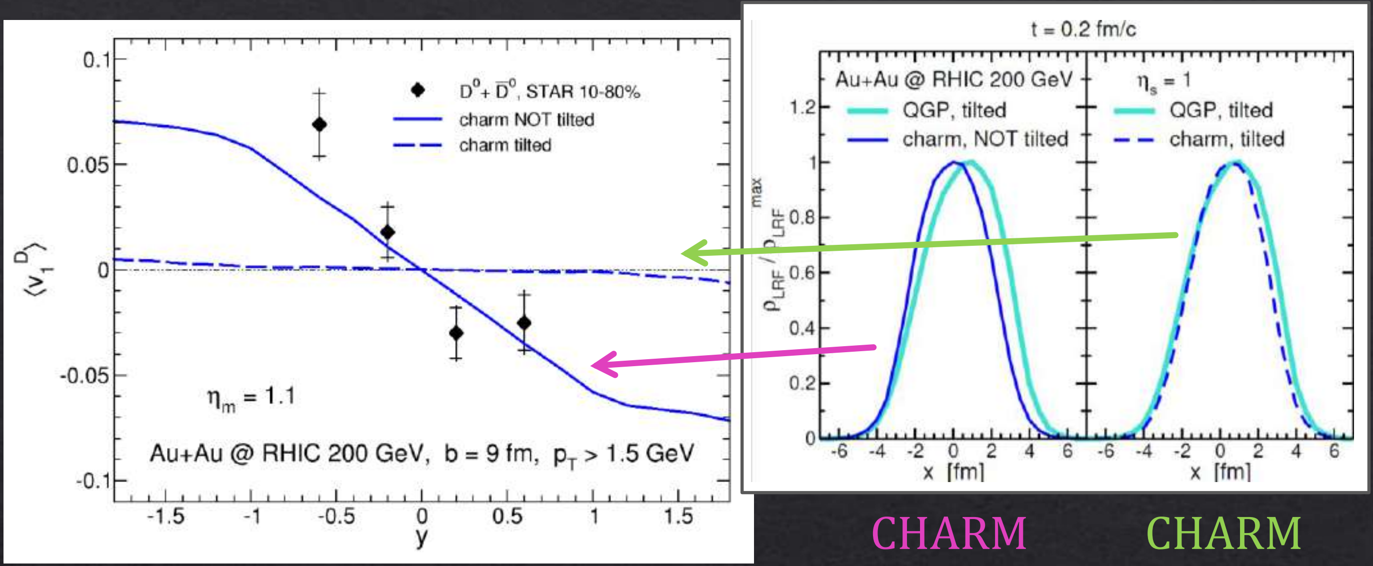
$$v_1 = \langle p_x / p_T \rangle$$

$$y = \tanh^{-1}\frac{v_z}{c}$$

RAPIDITY
relativistic analog
of velocity
(v_z: longitudinal
particle velocity)

DIRECTED FLOW OF NEUTRAL D MESONS

Origin of D meson directed flow



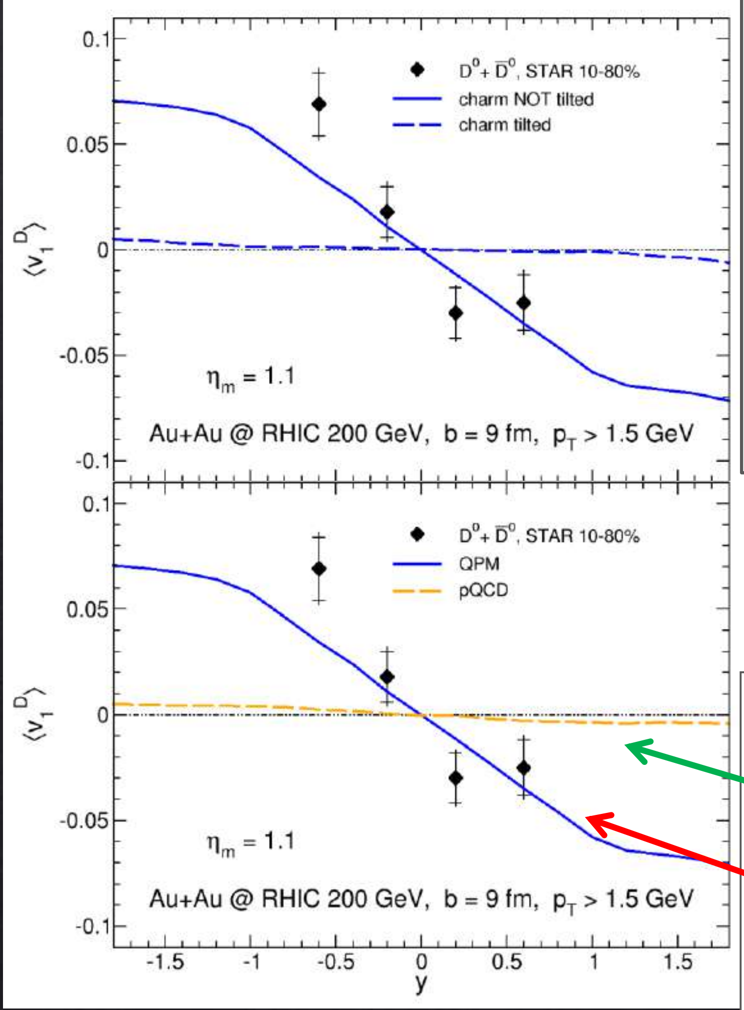
longitudinal asymmetry leads to pressure push of the bulk on the HQs

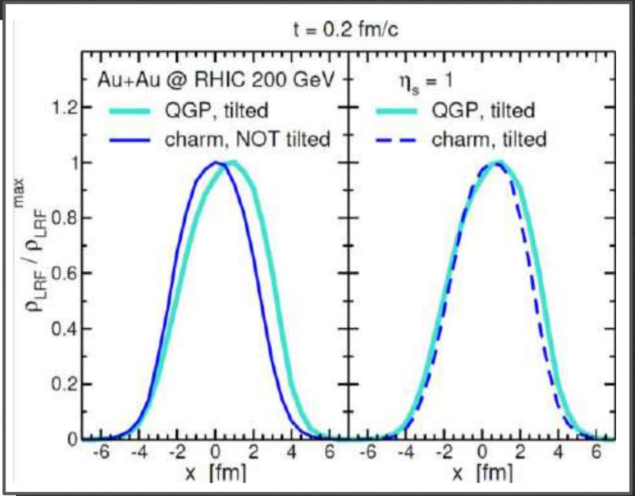
CHARM **NOT** TILTED

CHARM TILTED

Oliva, Plumari and Greco, 2009.11066

Origin of D meson directed flow

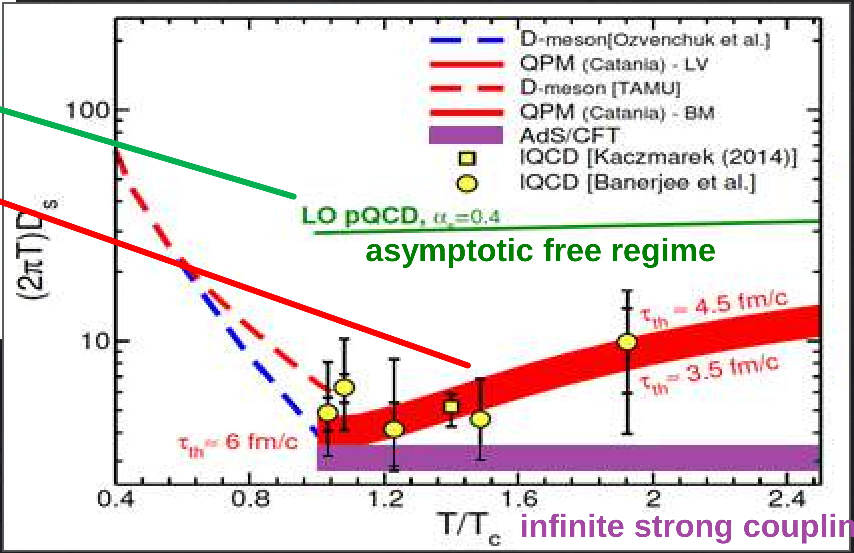




longitudinal asymmetry leads to pressure push of the bulk on the HQs

effective because the HQ interaction in QGP is largely non-perturbative

NON-PERTURBATIVE behaviour of QGP



infinite strong coupling limit

Greco,
NPA 967, 200
(2017)

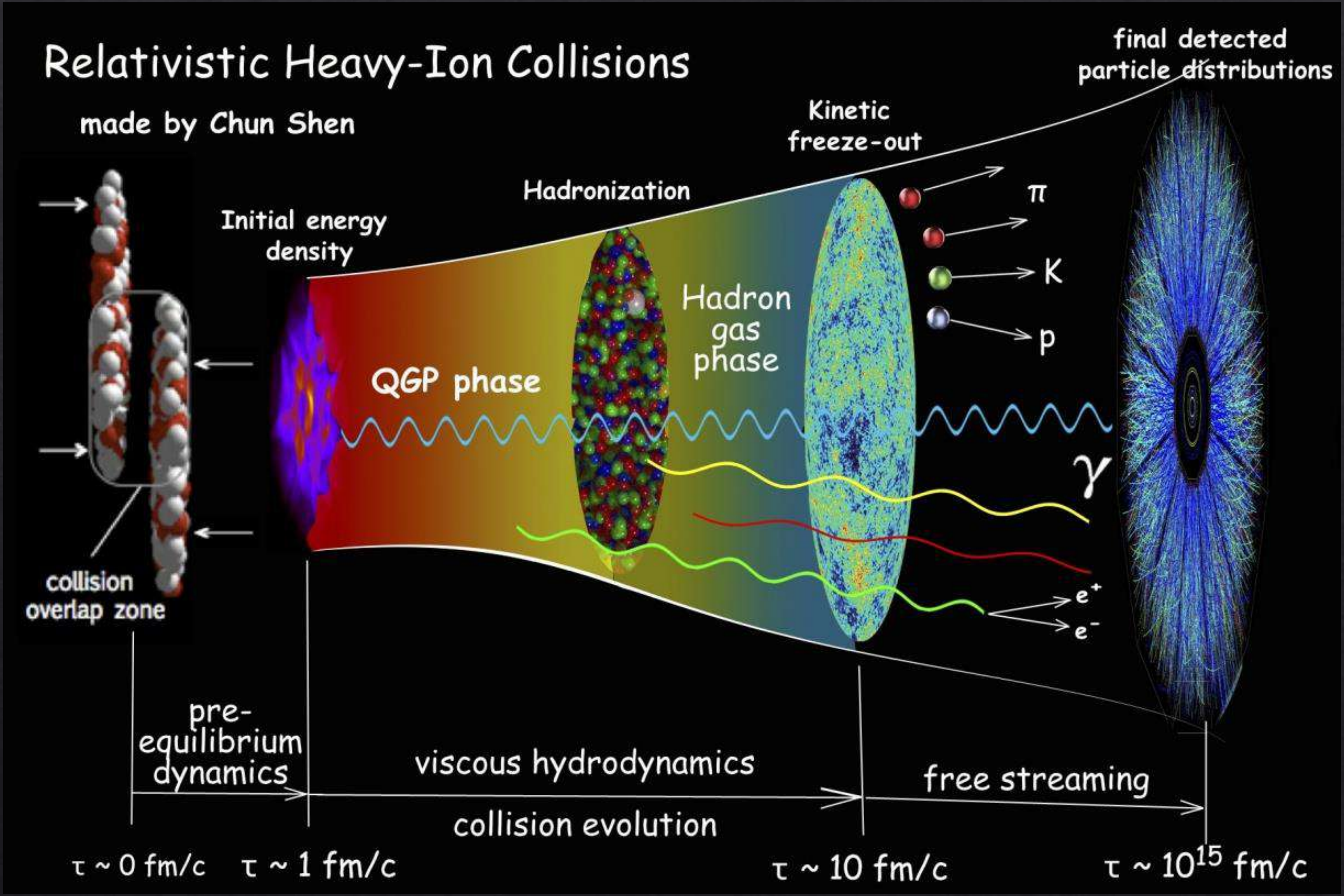
$$2\pi T D_s \approx 3 - 6$$

QGP diffuses charm quarks like an almost perfect fluid

with a very low $2\pi TD_s$

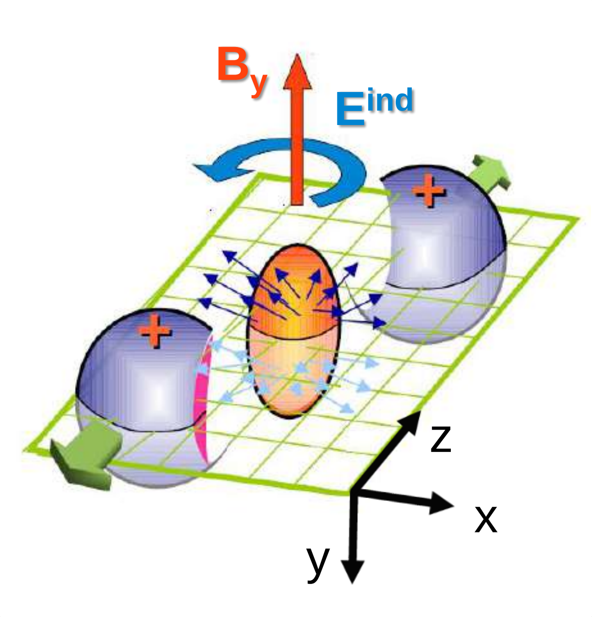
Oliva, Plumari and Greco, 2009.11066

EM FIELDS AND DIRECTED FLOW



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

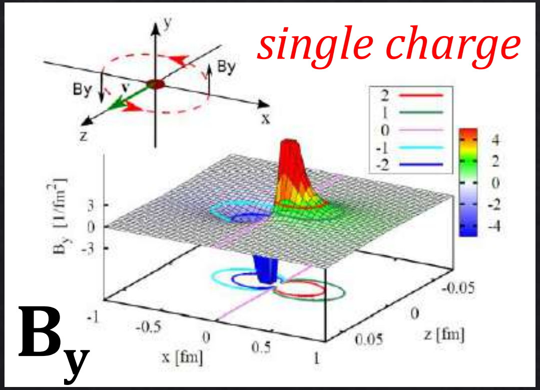
Electromagnetic fields in HICs



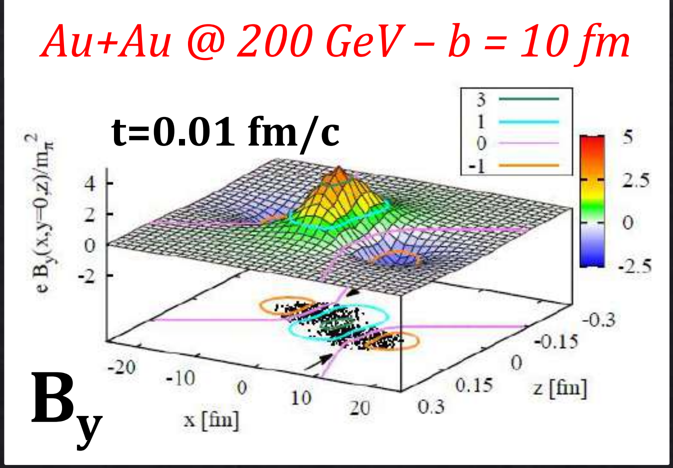
Huge **magnetic field** in the overlapping area of the collision

- in ultrarelatvistic HICs **$eB \approx 5\text{-}50\ m_\pi^2 \sim 10^{18}\text{-}10^{19}$ G**
- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction

Kharzeev, McLerran and Warringa, Nucl. Phys. A 803, 227 (2008)
Skokov, Illarionov and Toneev, Int. J. Mod. Phys. A 24, 5925 (2009)
Voronyuk *et al.* (HSD), Phys. Rev. C 83, 054911 (2011)

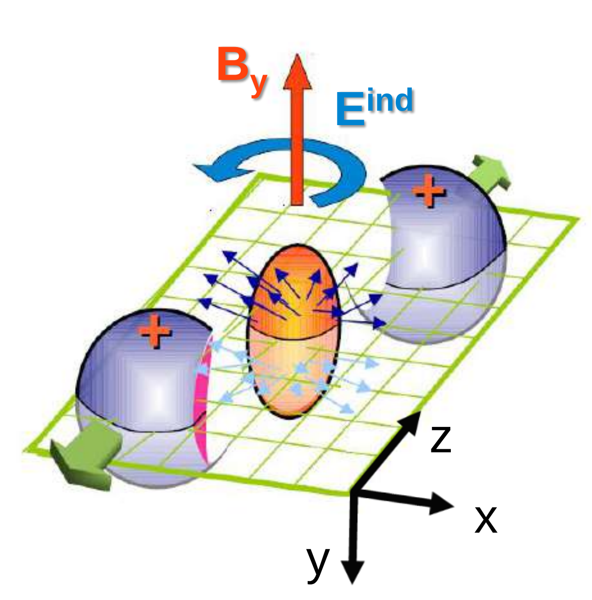

single charge

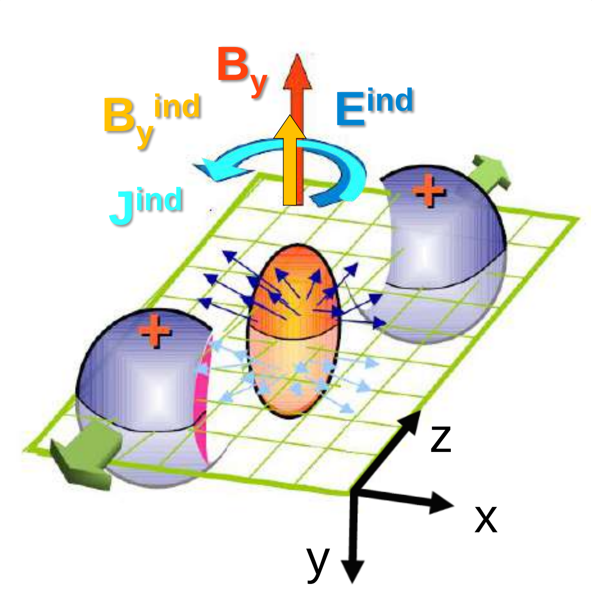
in a nuclear collision the EMF are a superposition of the fields produced by all moving charges


Au+Au @ 200 GeV – b = 10 fm

t=0.01 fm/c

Electromagnetic fields in HICs





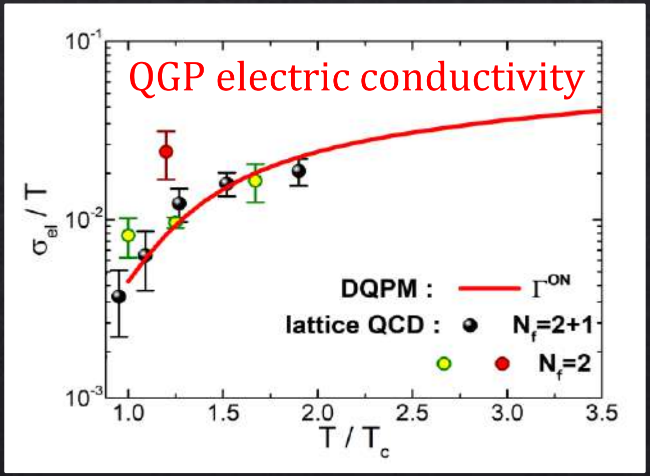
Huge **magnetic field** in the overlapping area of the collision

- in ultrarelatvistic HICs **eB ≈ 5-50 m_π^2 ~ 10^{18}-10^{19} G**
- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction

Theoretical calculations indicates that QGP is a good electric conductor

Ohm's law

$$J = \sigma_{el} E$$



Soloveva, Moreau and Bratkovskaya, Phys. Rev. C 101, 045203 (2020)

Charged currents are induced in the QGP by the Faraday electric field that in turn generates a magnetic field pointing towards the initial one

EMF in tranport approaches

In a kinetic framework the transport equations should be coupled to the Maxwell equations for describing the EMF produced in HICs and their effect on final observables

$$\left\{\frac{\partial}{\partial t} + \left(\frac{\mathbf{p}}{p_0} + \nabla_{\mathbf{p}} U\right)\nabla_{\mathbf{r}} + \left(-\nabla_{\mathbf{r}} U + e\mathbf{E} + e\mathbf{v}\times\mathbf{B}\right)\nabla_{\mathbf{p}}\right\} f = \mathcal{C}[f]$$

TRANSPORT EQUATIONS

Lorentz force

$$\nabla\cdot\mathbf{B} = 0 \qquad \nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \qquad \nabla\cdot\mathbf{E} = 4\pi\rho \qquad \nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}$$

MAXWELL EQUATIONS

charge distribution **electric current**

For a complete description

- nontrivial electromagnetic response of the QGP (electromagnetic conductivity, chiral conductivity, ...)
- consistent solution of evolution equations for the many-particle system and the EMF

Two approaches: EMF in nuclear collisions

Through Liénard-Wiechert potentials one gets the retarded EMF for a moving point-like charge

PHSD APPROACH

$$\mathbf{E}(\mathbf{r},t)=\frac{e}{4\pi}\left[\underbrace{\frac{\mathbf{n}-\boldsymbol{\beta}}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3\gamma^2R^2}}_{\text{Coulomb}}+\underbrace{\frac{\mathbf{n}\times\left((\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right)}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3cR}}_{\text{bremsstrahlung}}\right]_{\mathrm{ret}}\qquad \mathbf{B}(\mathbf{r},t)=[\mathbf{n}\times\mathbf{E}(\mathbf{r},t)]_{\mathrm{ret}}$$

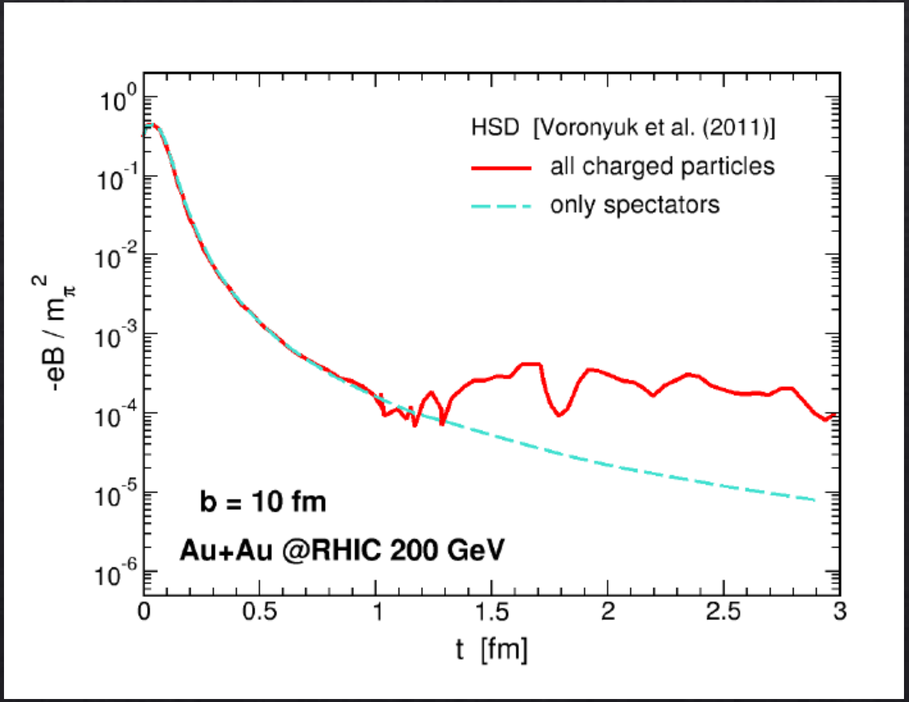
$$\mathbf{R}=\mathbf{r}-\mathbf{r}'\qquad \mathbf{n}=\frac{\mathbf{R}}{R}\qquad \boldsymbol{\beta}=\frac{\mathbf{v}}{c}$$

Neglecting the acceleration one obtains the EMF generted by a charge in uniform motion

$$eE(r,t)=\sum_i\frac{\mathrm{sgn}(q_i)\alpha_{em}R_i(t)(1-\beta_i^2)}{\left\{[R_i(t)\cdot\beta_i]^2+R_i(t)^2\,(1-\beta_i^2)\right\}^{3/2}}$$

$$eB(r,t)=\sum_i\frac{\mathrm{sgn}(q_i)\alpha_{em}\beta_i\times R_i(t)(1-\beta_i^2)}{\left\{[R_i(t)\cdot\beta_i]^2+R_i(t)^2\,(1-\beta_i^2)\right\}^{3/2}}$$

The EMF are obtained summing over all charges in the collisions: spectators and participants protons, newly produced particles (QGP)



Voronyuk *et al.* (HSD), Phys. Rev. C 83, 054911 (2011)
Toneev *et al.* (PHSD), Phys. Rev. C 86, 064907 (2012)

Two approaches: EMF in nuclear collisions

CATANIA APPROACH

$$\rho = \rho_{ext} \qquad \boldsymbol{J} = \boldsymbol{J}_{ext} + \boldsymbol{J}_{ind}$$

$$\rho_{ext} = e\delta(z - \beta t)\delta(\boldsymbol{x}_\perp - \boldsymbol{x'}_\perp)$$

$$\boldsymbol{J}_{ext} = \hat{z}\beta e\delta(z - \beta t)\delta(\boldsymbol{x}_\perp - \boldsymbol{x'}_\perp)$$

external charge and current produced by a point-like charge in longitudinal motion

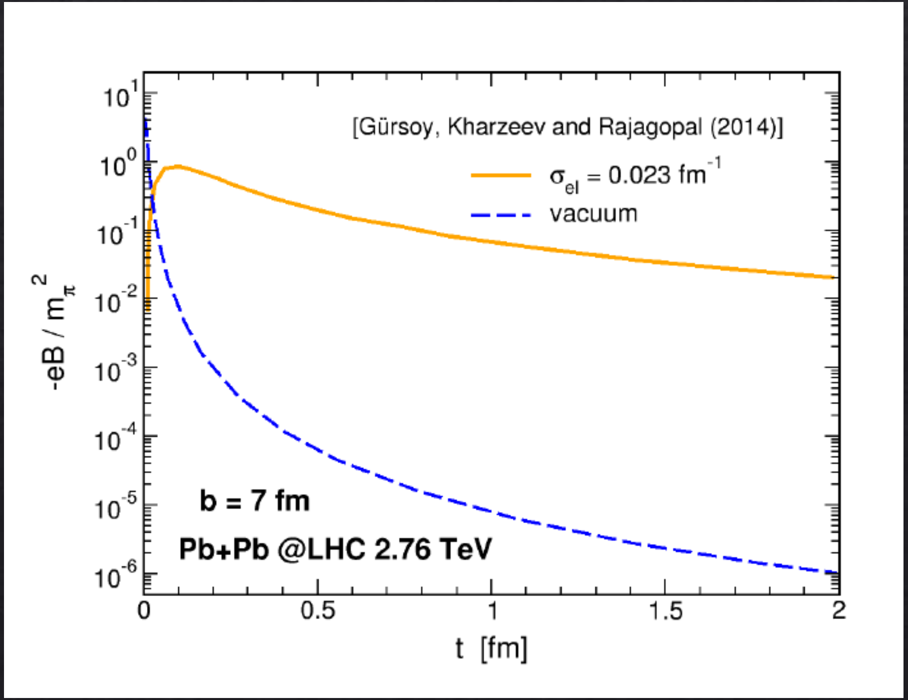
induced current from Ohm's law

$$\boldsymbol{J}_{ind} = \sigma_{el}\boldsymbol{E}$$

From Maxwell equations one obtains wave equations for the EMF that can be solved analytically considering a medium with **constant electric conductivity**

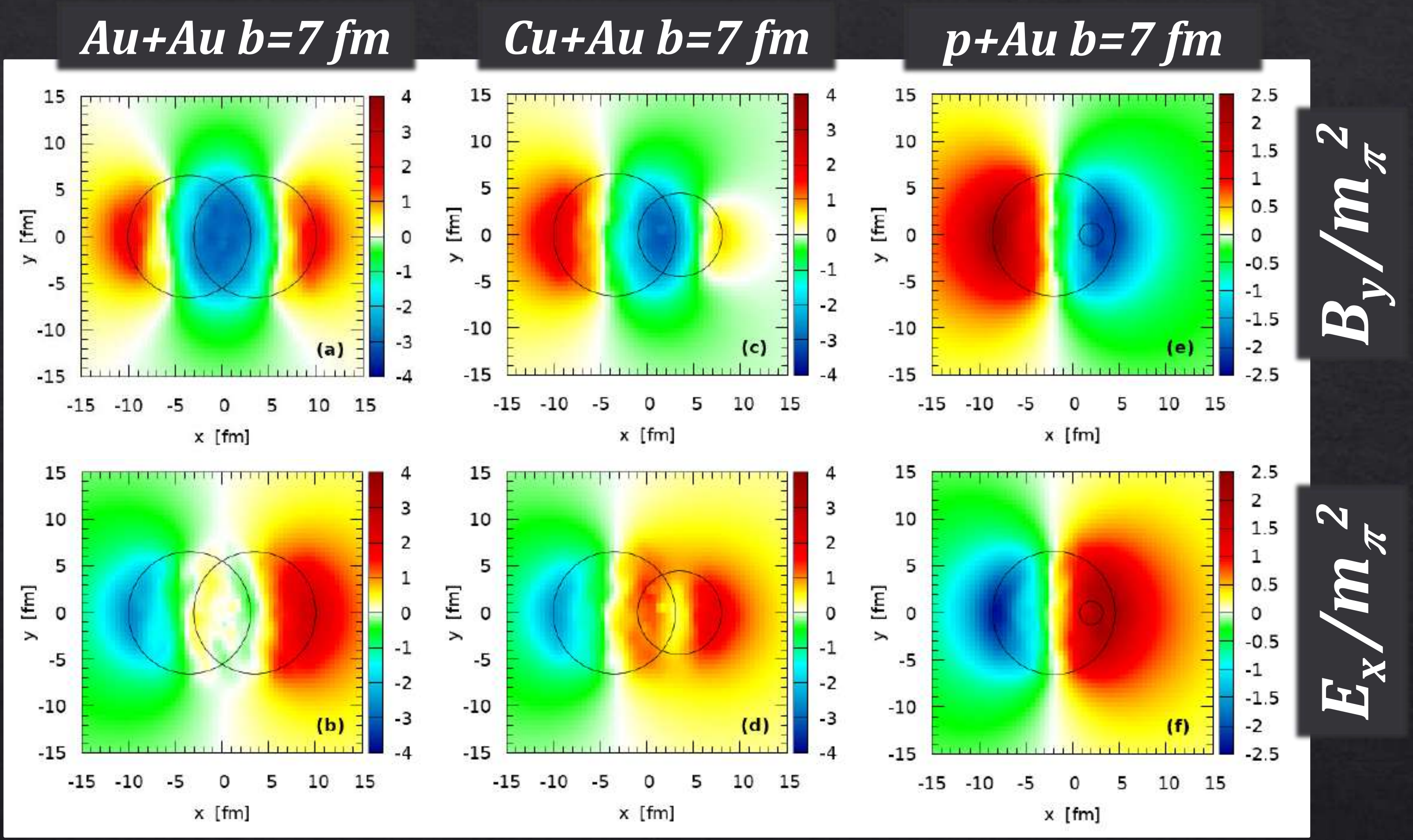
$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{B} = -\nabla \times \boldsymbol{J}_{ext}$$
$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{E} = -\nabla\rho_{ext} + \partial_t\boldsymbol{J}_{ext}$$

Fold the solution with the nuclear transverse density profile of the spectator nuclei and sum forward and backward contributions for obtaining the EMF produced in HICS



Tuchin, Adv. High Energy Phys. 2013, 1 (2013)
Gursoy, Kharzeev, Rajagopal, Phys. Rev. C 89, 054905 (2014)

EMF from large to small systems



Au+Au b=7 fm

Cu+Au b=7 fm

p+Au b=7 fm

B_y/m_π^2

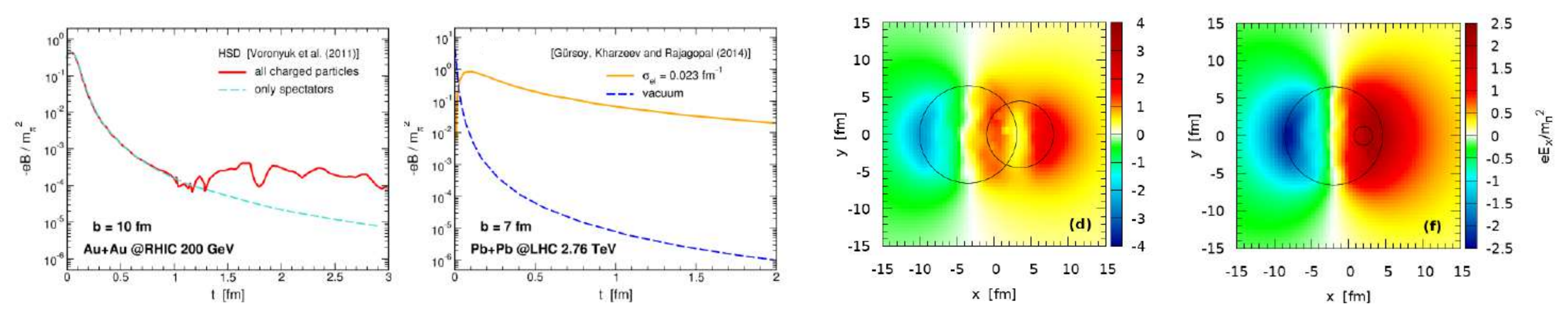
E_x/m_π^2

initial transvese profiles at RHIC 200 GeV

intense electric fields directed from the heavy nuclei to light one
in the overlap region of asymmetric colliding systems
due to the different number of protons in the two nuclei

Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014)
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

EMF and directed flow



presence of charge in the early stage

QGP transport properties

The huge EMF induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge

- ➢ difference in the v_1 of light hadrons $O(10^{-4}\text{–}10^{-3})$

  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014)

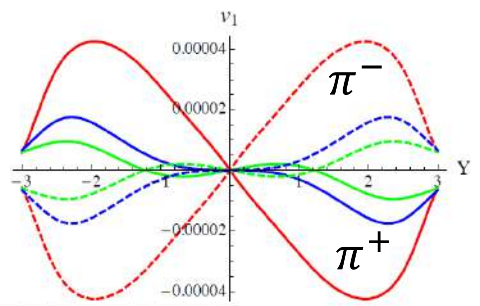
  Toneev, Voronyuk, Kolomeitsev and Cassing,
  Phys. Rev. C 95, 034911 (2017)

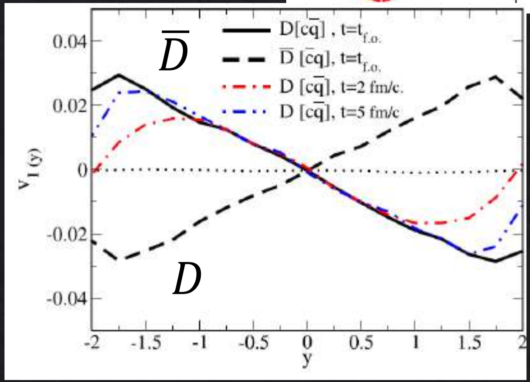
- ➢ difference in the v_1 of heavy mesons $O(10^{-2})$

  Das, Plumari, Chatterjee, Alam, Scardina and Greco,
  Phys. Lett. B 768, 260 (2017)

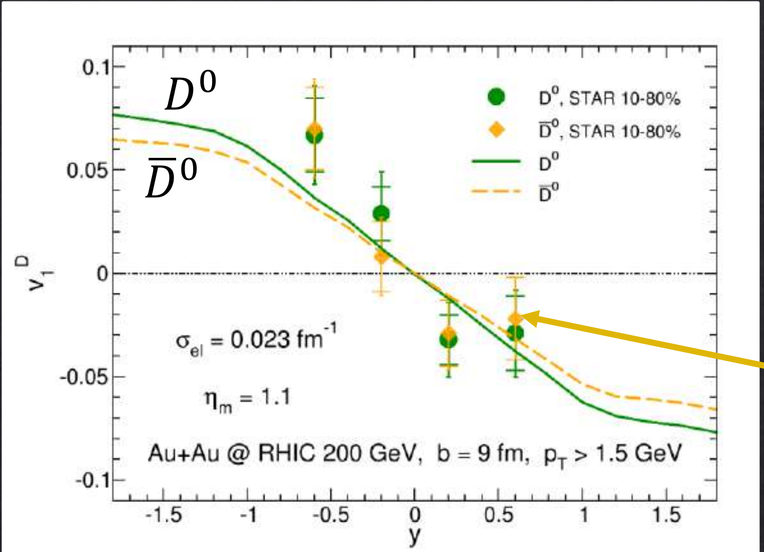
Oliva, Eur. Phys. J. A 56, 255 (2020)
Dubla, Gursoy and Snellings, 2009.09727

reviews

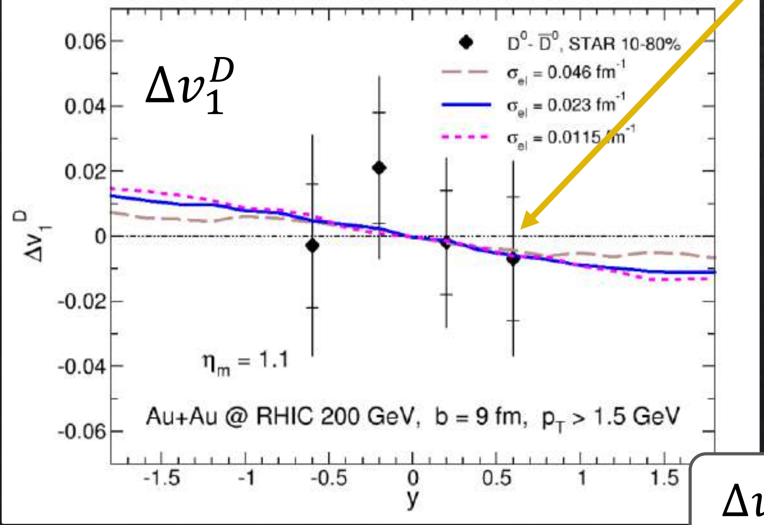




Directed flow in A+A at RHIC energy



Exp. data: STAR Coll., PRL. 123 (2019) 162301

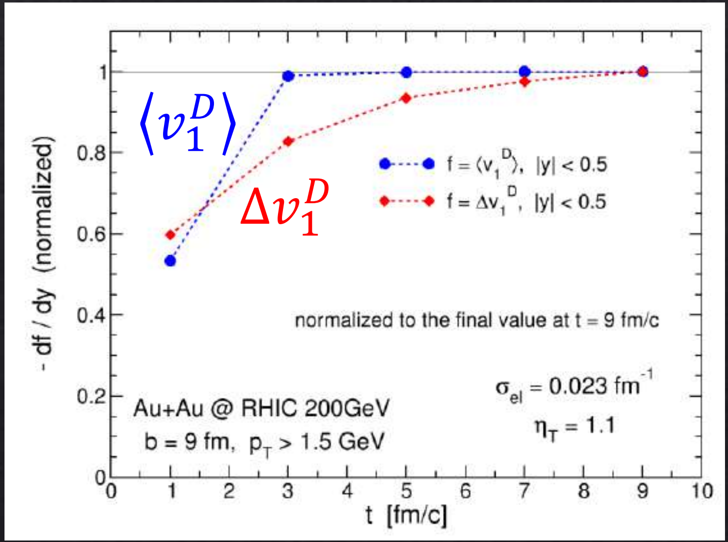


The electromagnetic fields induce a large splitting in the directed flow of HEAVY QUARKS

$$\Delta v_1\ (HQ) \gg \Delta v_1\ (QGP)$$

charm quarks are more sensitive to the EMF due to the early production

but Δv_1^{HQ} at top RHIC energy still consistent with zero due to the large exp. errors



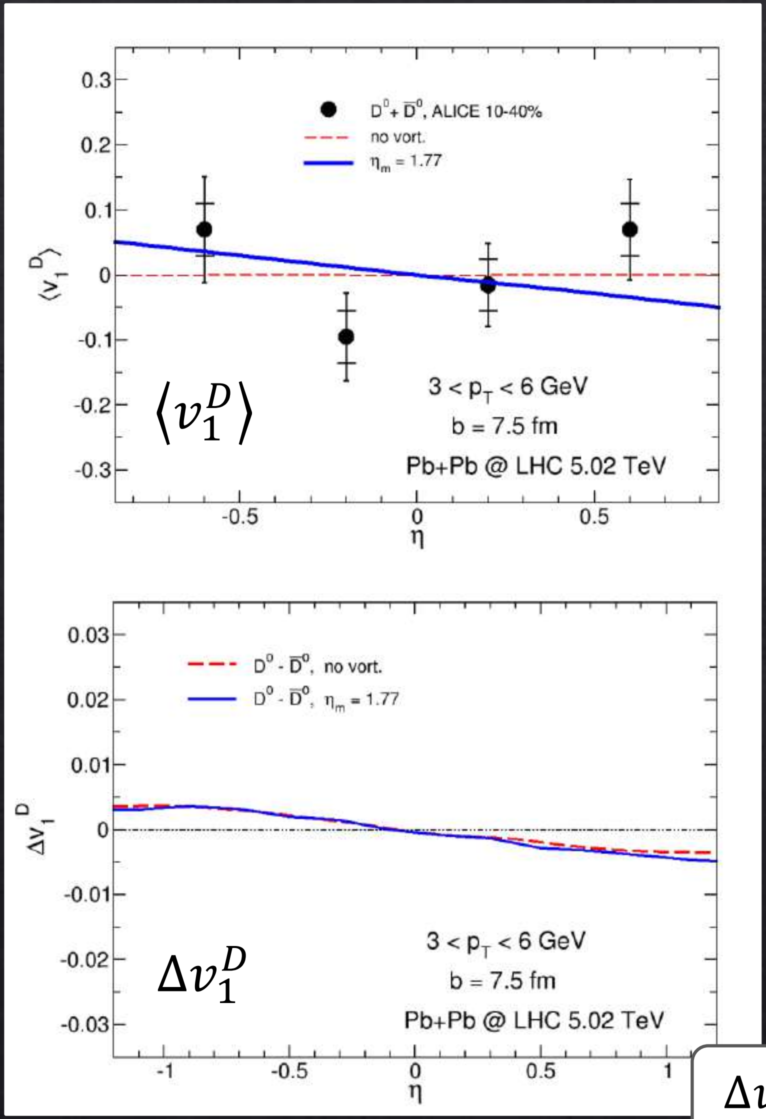
$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

SLOPE TIME EVOLUTION

DIRECTED FLOW OF NEUTRAL D MESONS

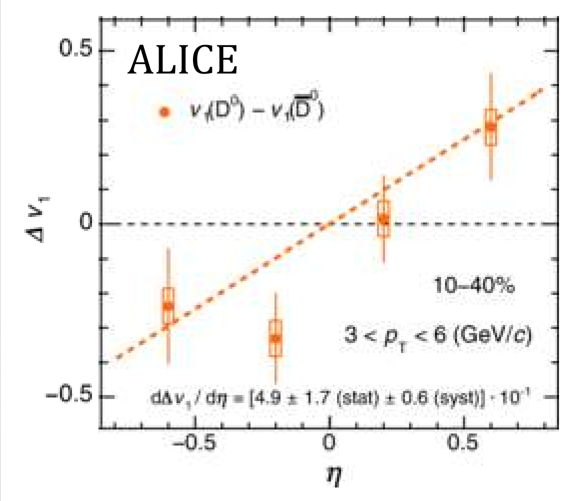
Oliva, Plumari and Greco, 2009.11066

Directed flow in A+A at LHC energy



the slope of the combined v_1 of D^0 and $\bar{D}^0$ indicated by ALICE data is smaller than the one observed at RHIC and is consistent with zero

ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)



$$\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC})$$

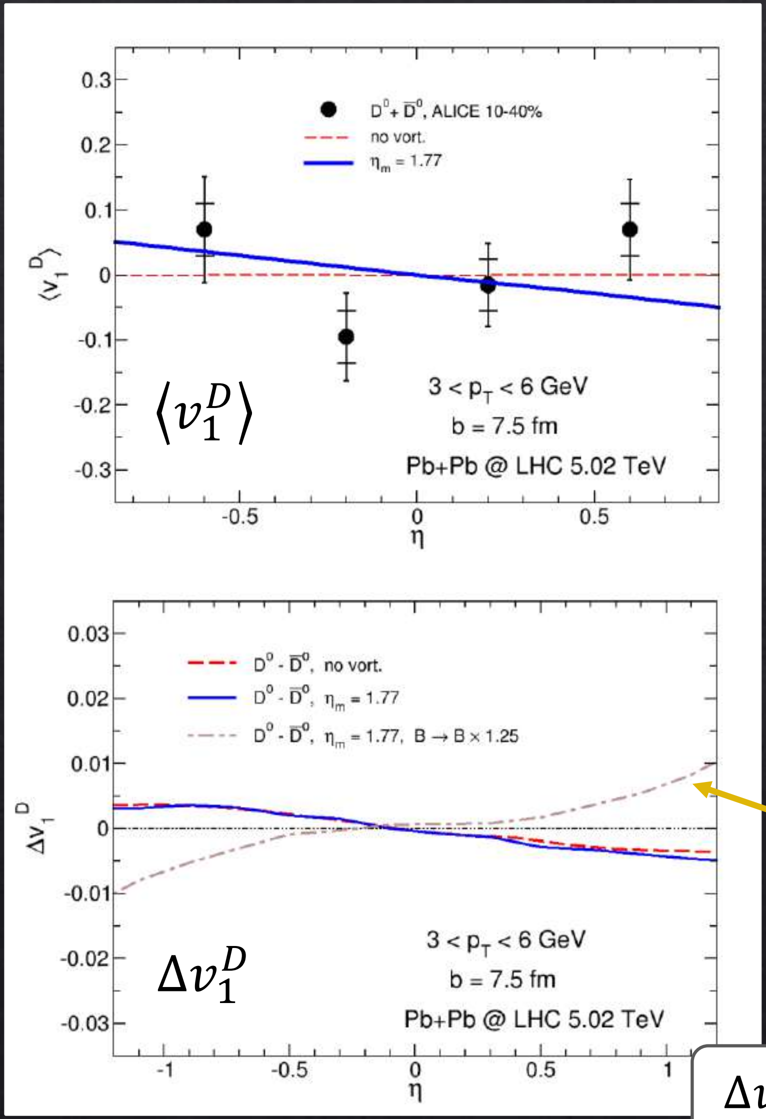
the v_1 splitting between D^0 and $\bar{D}^0$ measured by ALICE has opposite sign and magnitude about 50 times larger

$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

DIRECTED FLOW OF NEUTRAL D MESONS

Oliva, Plumari and Greco, 2009.11066

Directed flow in A+A at LHC energy



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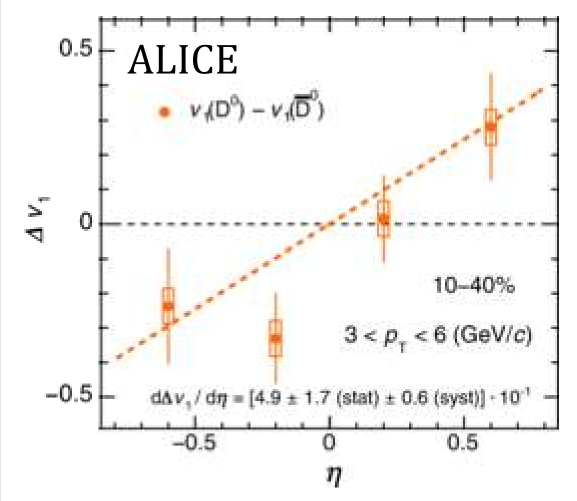
ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)



$$\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC})$$

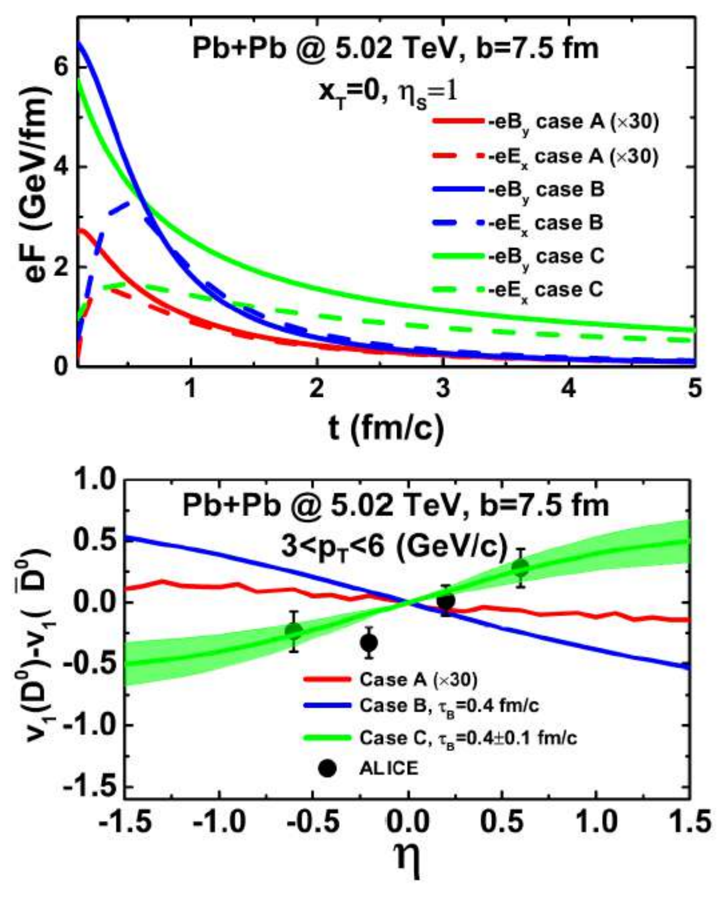
positive slope rising by hand the value of the magnetic field

$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

DIRECTED FLOW OF NEUTRAL D MESONS

Oliva, Plumari and Greco, 2009.11066

Directed flow in A+A at LHC energy



Sun, Plumari and Greco, 2004.09880

- Analytic solution of EMF with constant σ_{el} case A

  Oliva, Plumari and Greco, 2009.11066
  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014)

- Magnetic field parametrized with time evolution between in-vacuum and in-medium decay:

$$B(x,y,\tau) = B(\tau)\rho_B(x,y)$$

electric field from Faraday law:

$$\nabla \times \boldsymbol{E} = -\partial B/\partial t$$

Sun, Plumari and Greco, 2004.09880
Yin and Liao, Phys. Lett. B 756, 42 (2016)

case B

$$B(\tau) = \frac{B_0}{1+(\tau/\tau_B)^2}$$

case C

$$B(\tau) = \frac{B_0}{1+\tau/\tau_B}$$

case C reproduce the ALICE data for the v_1 splitting of neutral *D* meson but it is really a slow time decay of *B*

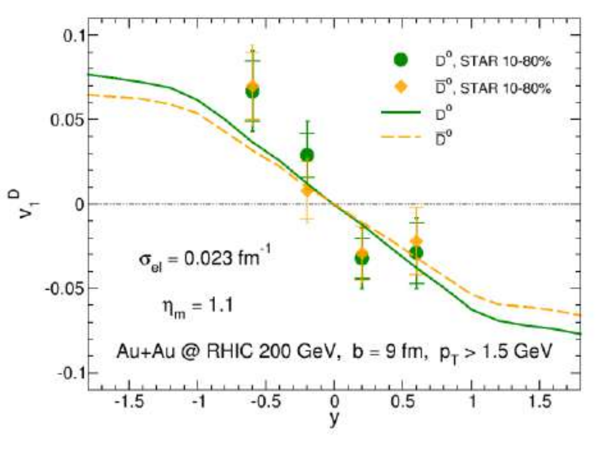
if the v_1 splitting of neutral *D* mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

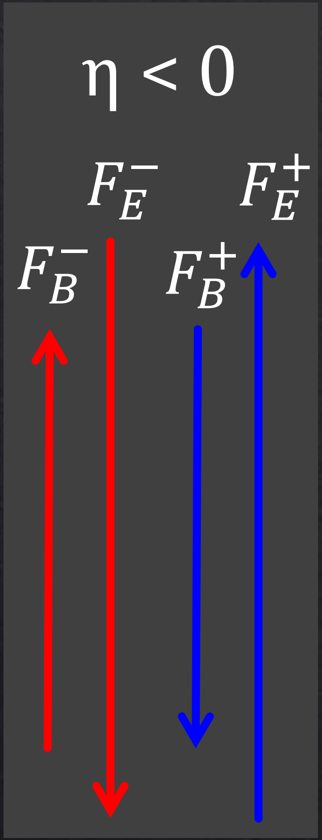
EMF and directed flow in A+A

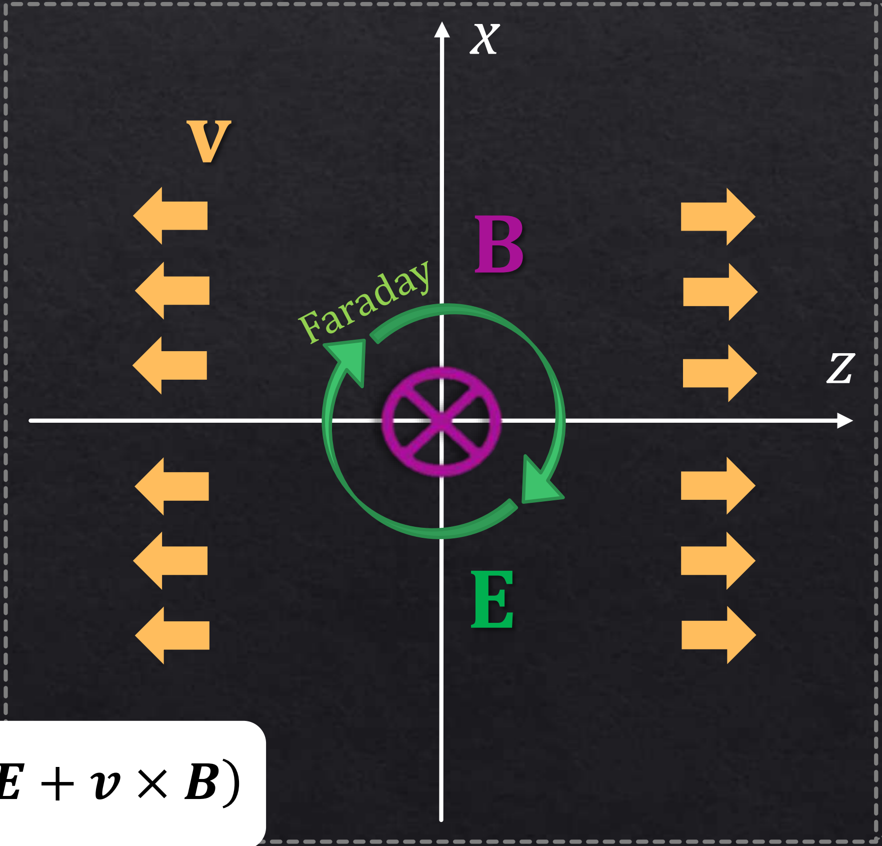
rapidity dependence of the DIRECTED FLOW

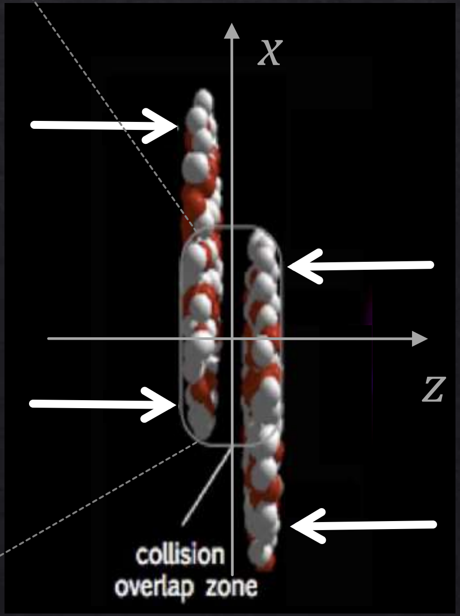
collective sidewards deflection of particles

$$v_1 = \langle \cos\varphi \rangle = \langle p_x/p_T \rangle$$



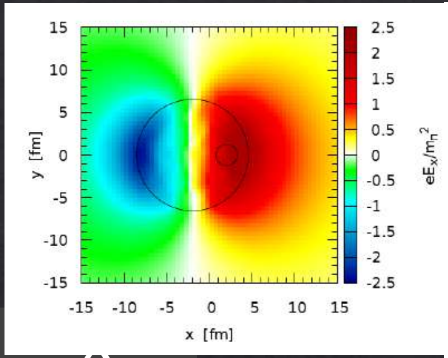


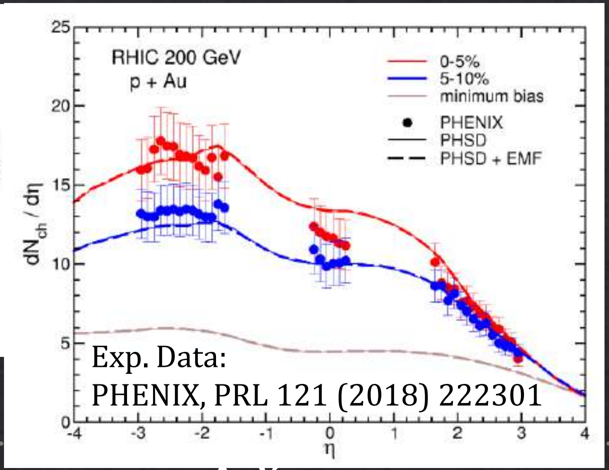




$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

EMF and directed flow in p+A



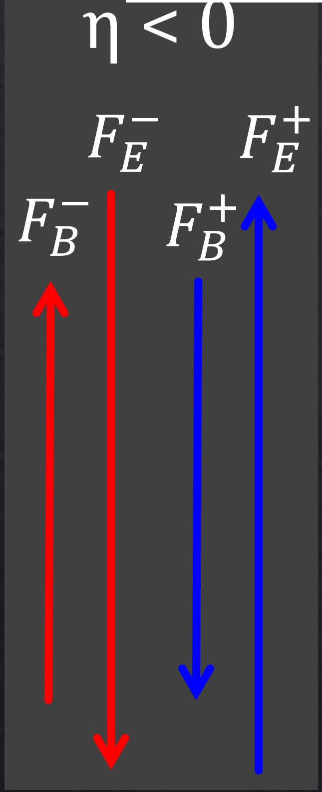


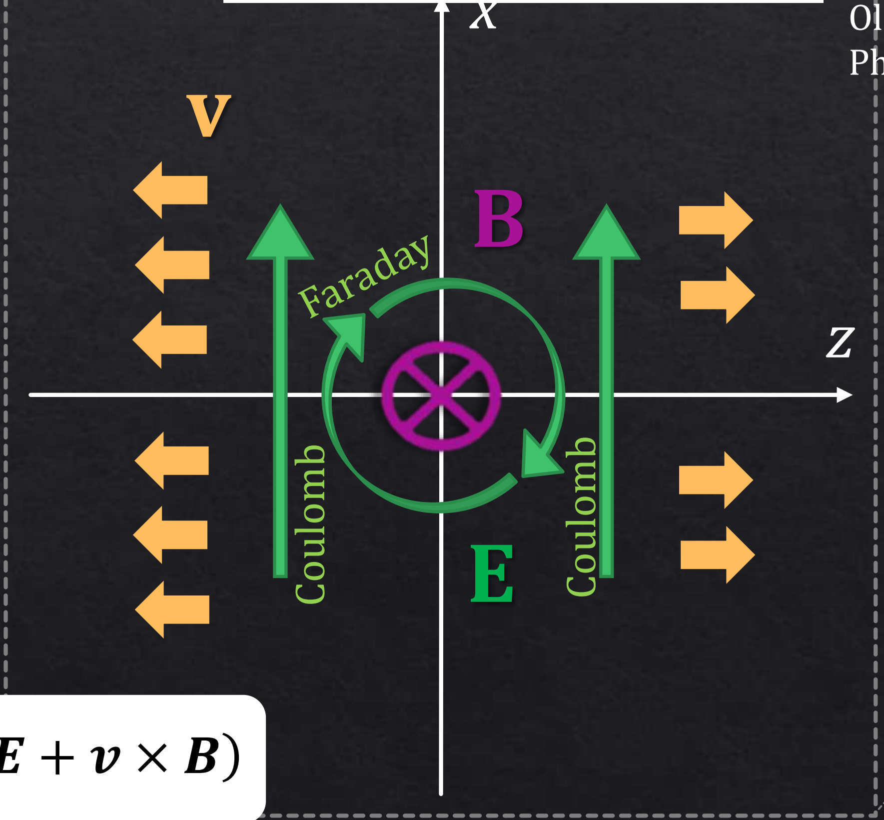
Exp. Data:
PHENIX, PRL 121 (2018) 222301

Asymmetry in charged particle and electric field profiles in p+Au

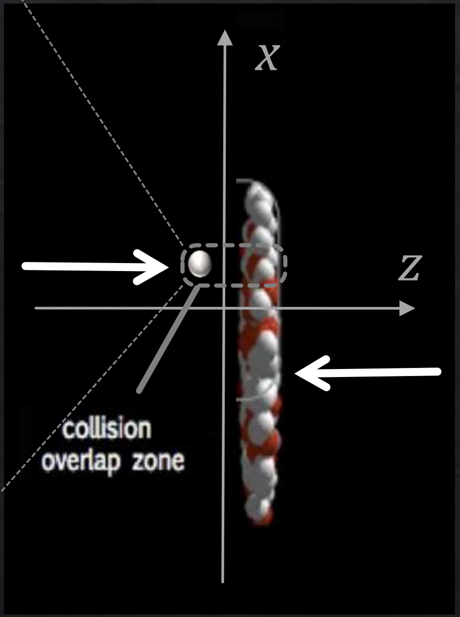
- enhanced particle production in the Au-going direction
- electric field directed from the heavy ion to the proton

Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)





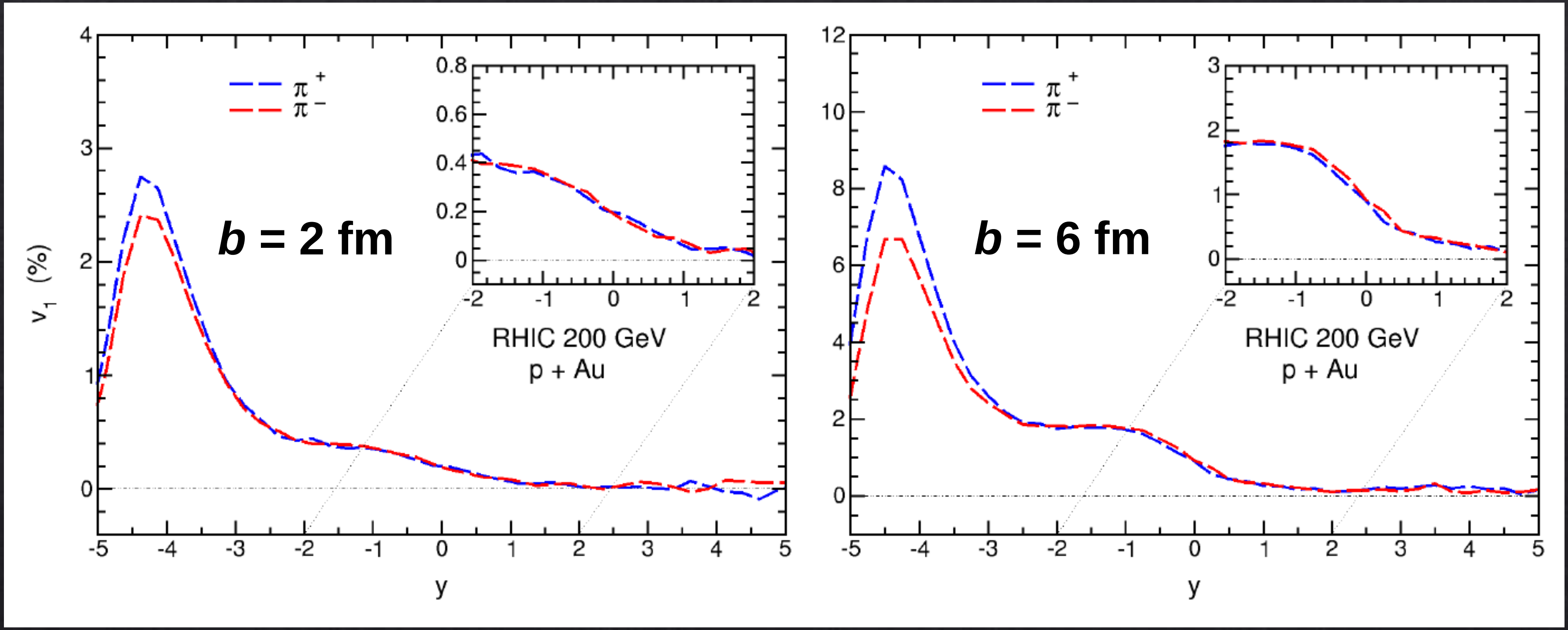
$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$



Directed flow in p+A

rapidity dependence of the
DIRECTED FLOW OF PIONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

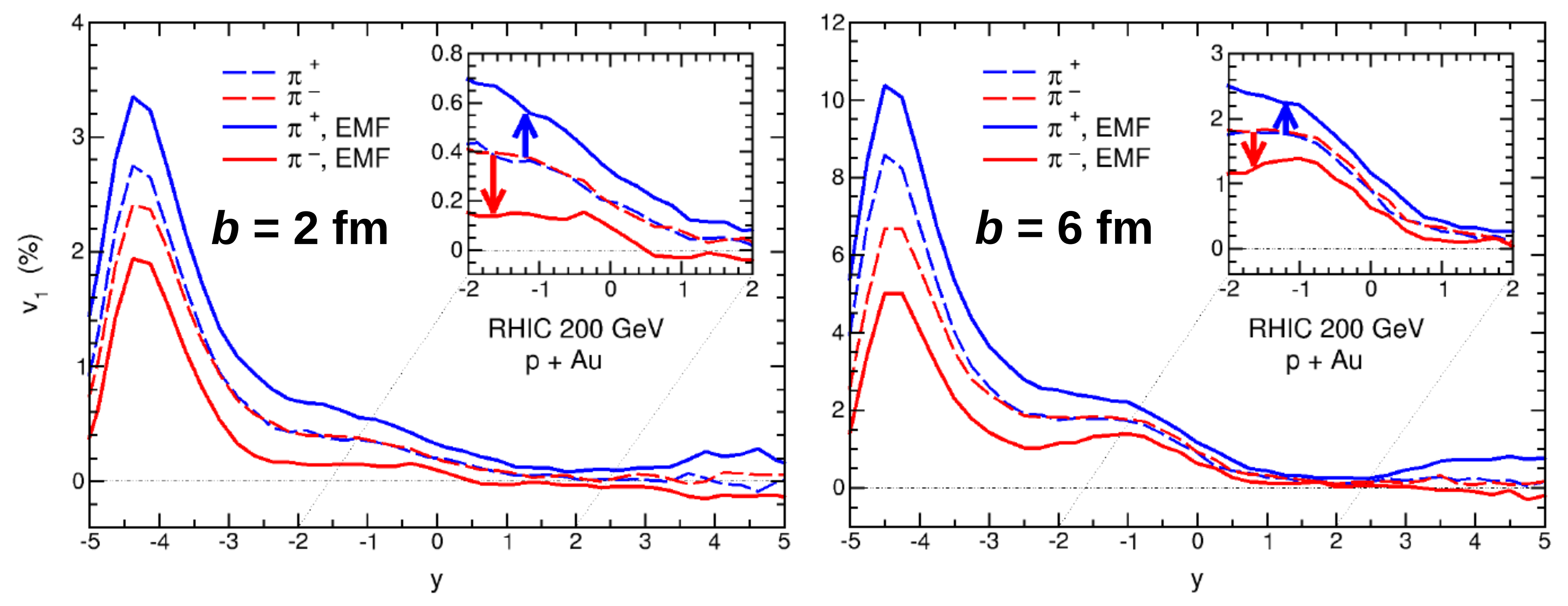
SPLITTING of light mesons

INDUCED BY THE ELECTROMAGNETIC FIELD?

Directed flow in p+A

rapidity dependence of the DIRECTED FLOW OF PIONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



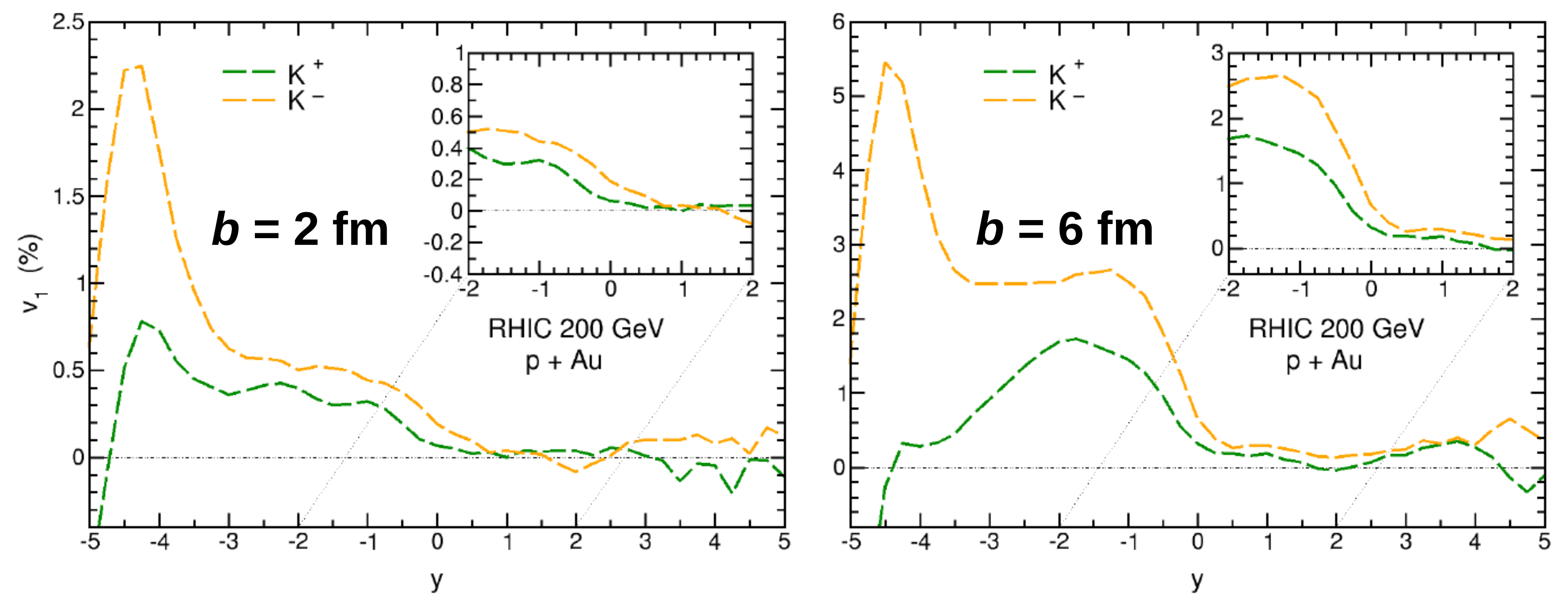
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

Splitting of π$^+$ and π$^-$ induced by the electromagnetic field

Directed flow in p+A

rapidity dependence of the
DIRECTED FLOW OF KAONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$

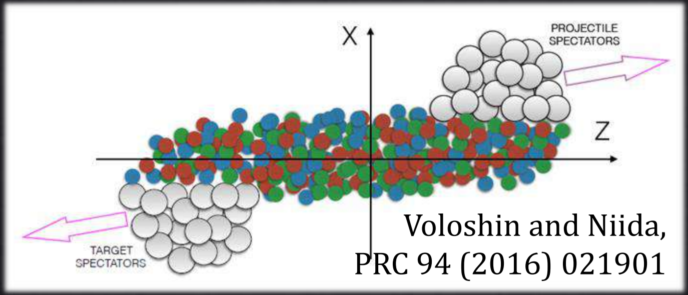


Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

different v_1 also in simulations without EMF

more contributions to K^+ $(\bar{s}u)$ with respect to K^- $(s\bar{u})$ from quarks of the initial colliding nuclei

STAR Coll., PRL 120 (2018) 062301

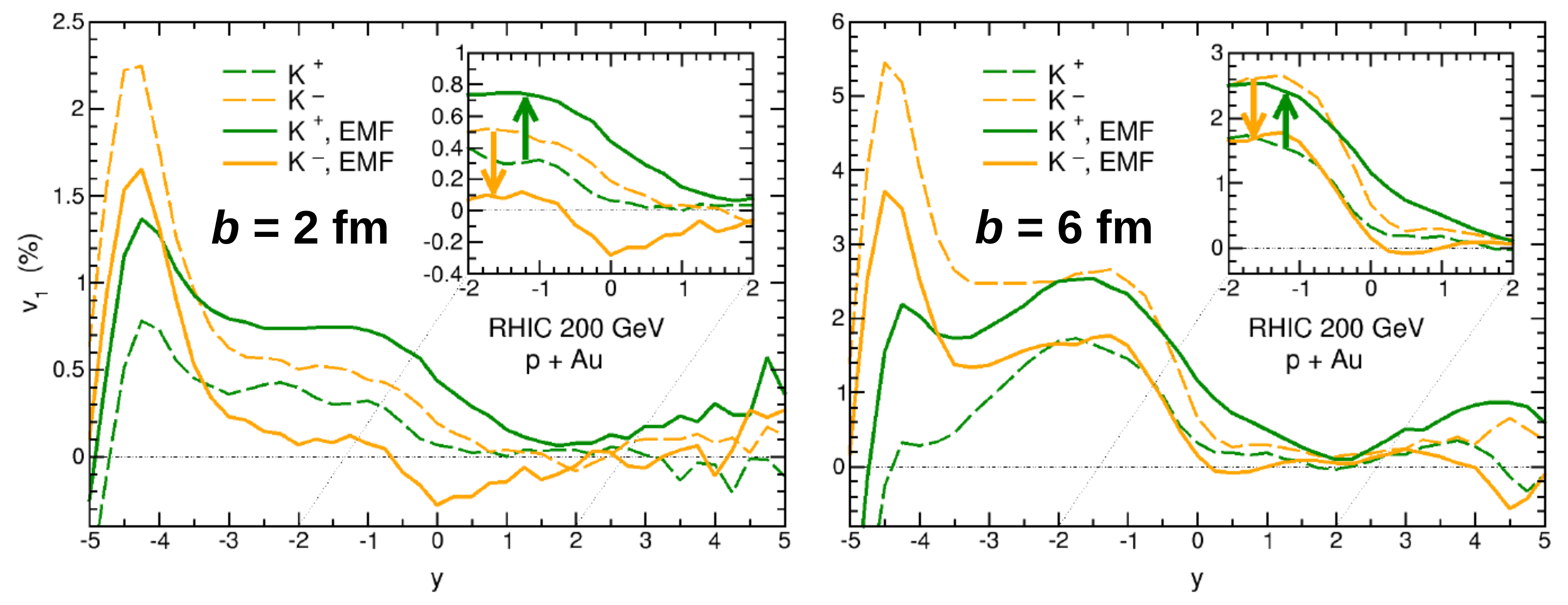


Voloshin and Niida, PRC 94 (2016) 021901

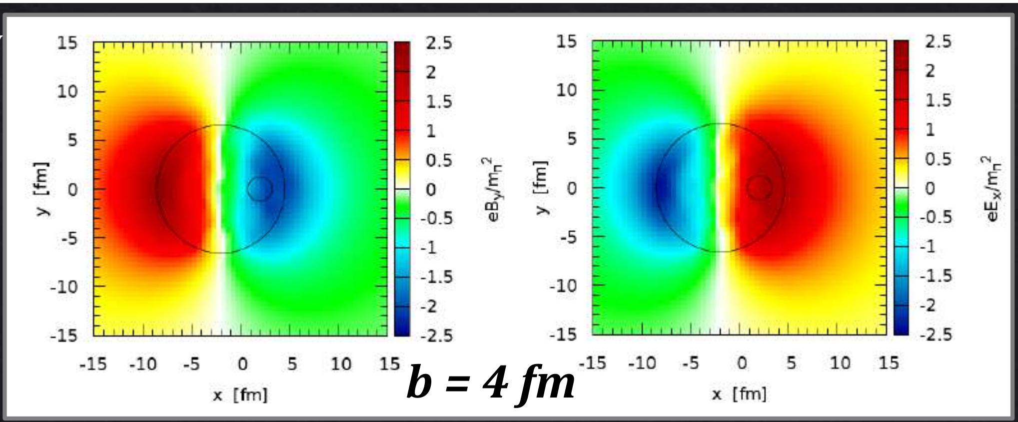
Directed flow in p+A

rapidity dependence of the DIRECTED FLOW OF KAONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



Oliva, Moreau, Voronyuk and Bratkovskaya, Phy



Splitting of K⁺ and K⁻ induced by the electromagnetic field

Directed flow in p+A

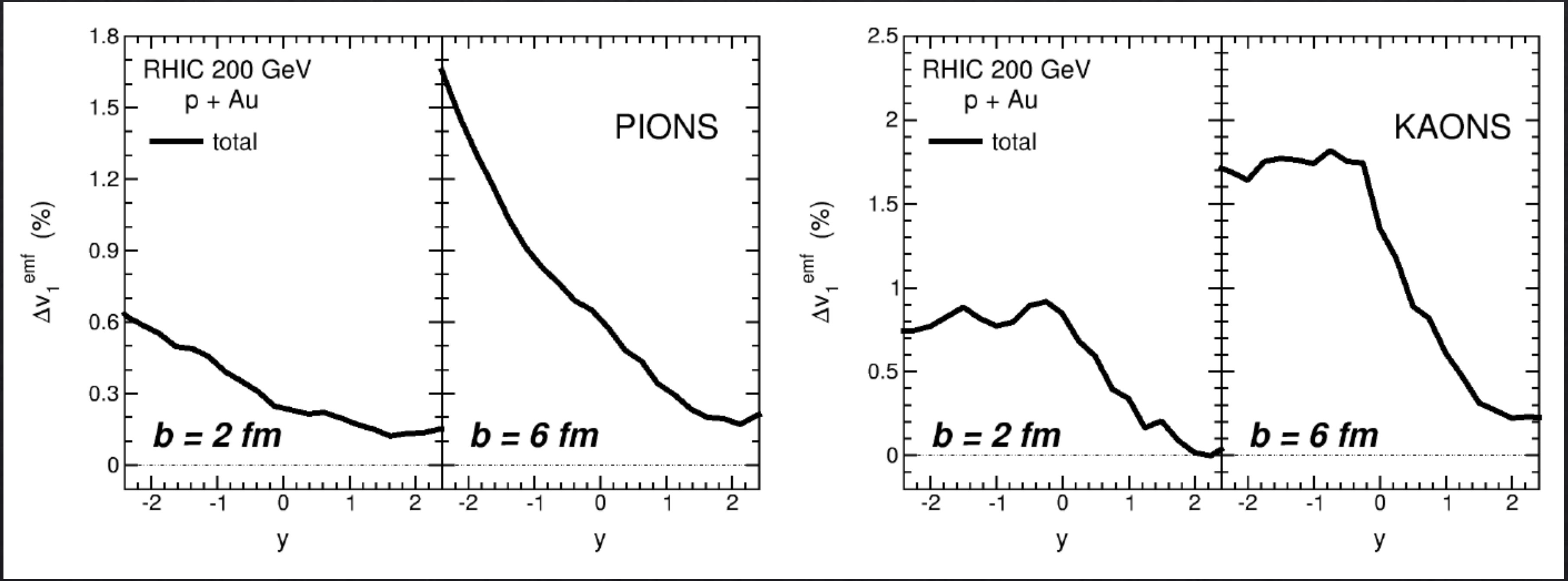
ELECTROMAGNETICALLY-INDUCED SPLITTING in the directed flow of hadrons with same mass and opposite charge

$$\Delta v_1{}^{emf} \equiv \Delta v_1{}^{(PHSD+EMF)} - \Delta v_1{}^{(PHSD)}$$

$$\Delta v_1 \equiv v_1^+ - v_1^-$$

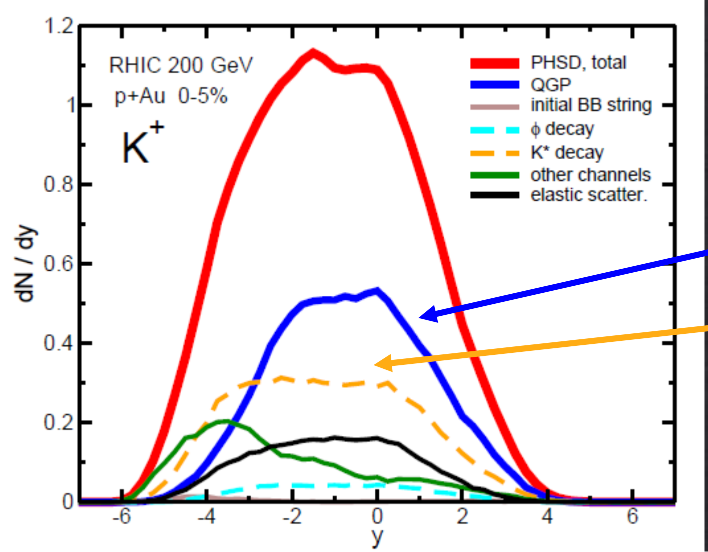
$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- magnitude increasing with impact parameter
- larger splitting for kaons than for pions



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

Directed flow in p+A

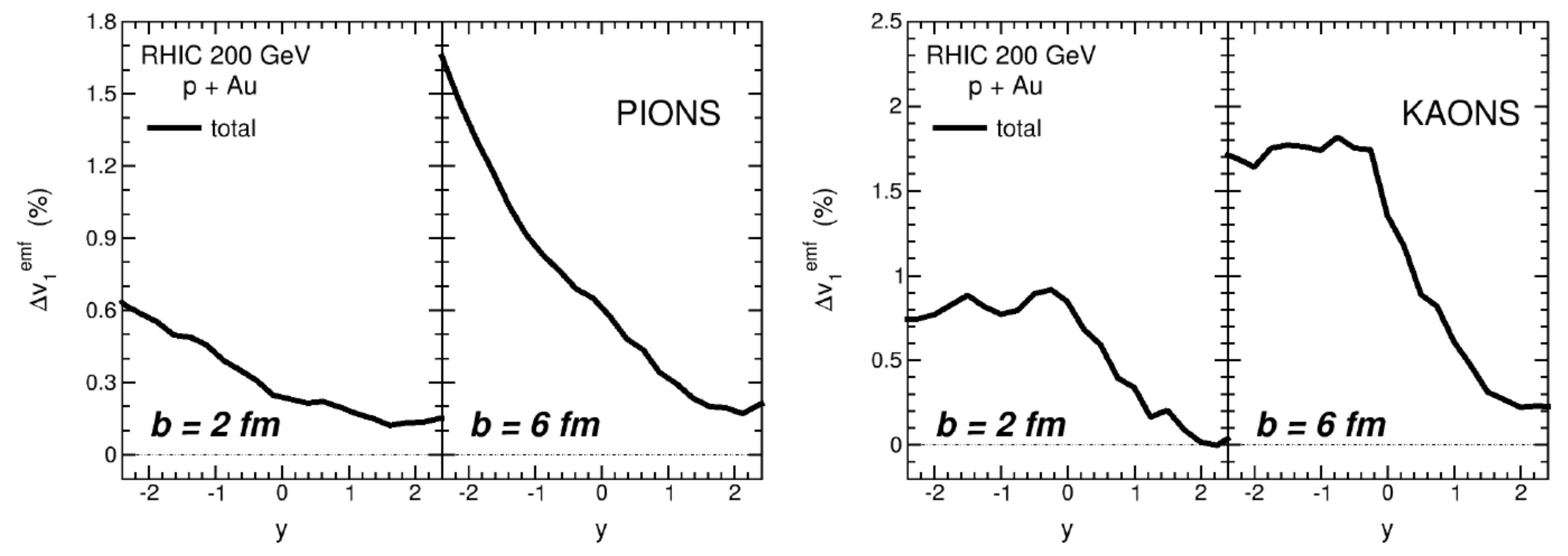


large amount of particles escapes from the medium just after production from QGP hadronization without further rescattering

directly from QGP hadronization

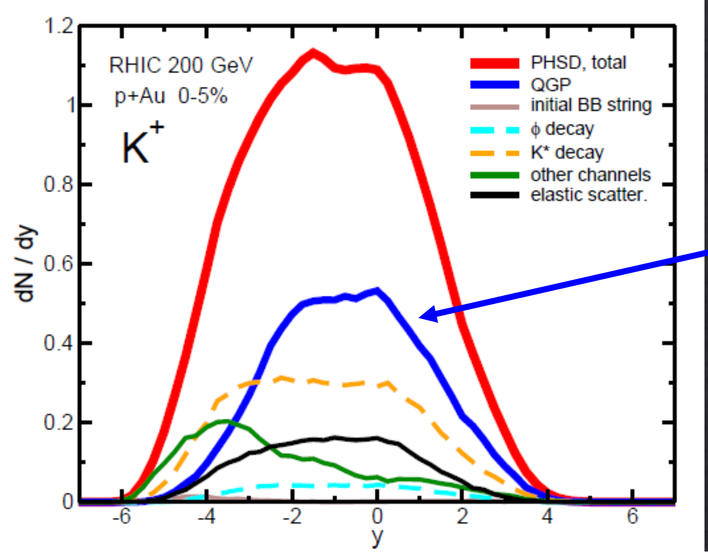
from K* decay

in A+A kaons created by K* decay are about twice those generated directly from QGP



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

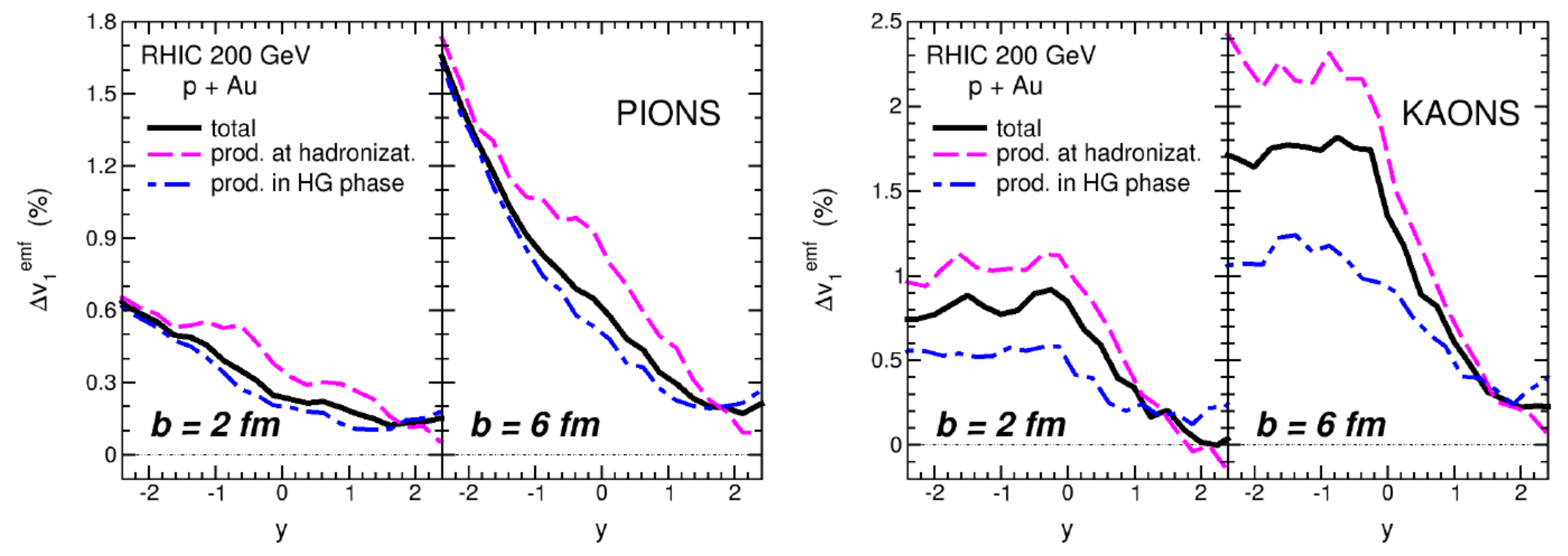
Directed flow in p+A



large amount of particles escapes from the medium just after production from QGP hadronization without further rescattering

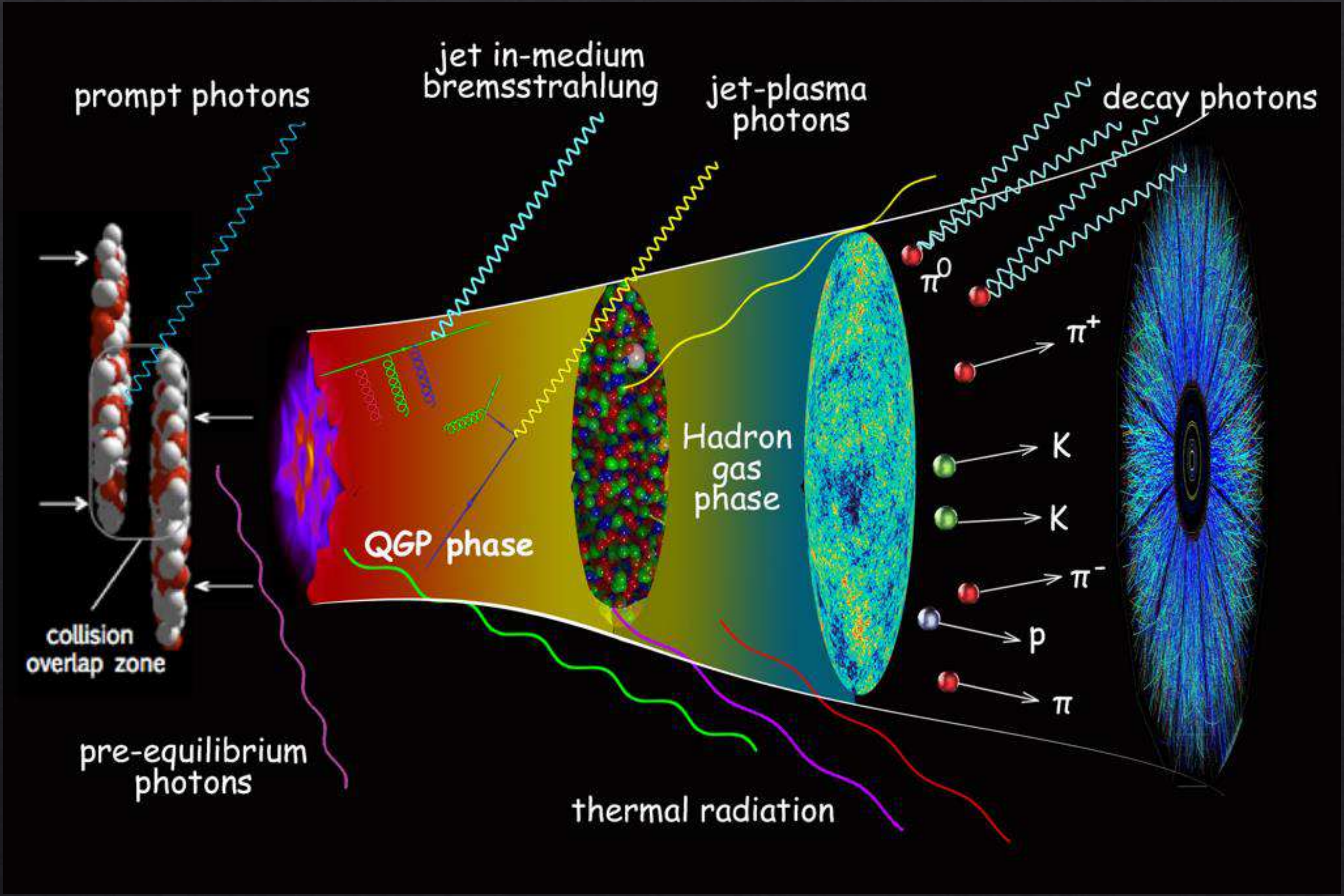
directly from QGP hadronization

v_1 splitting mainly generated at partonic level (especially for kaons)

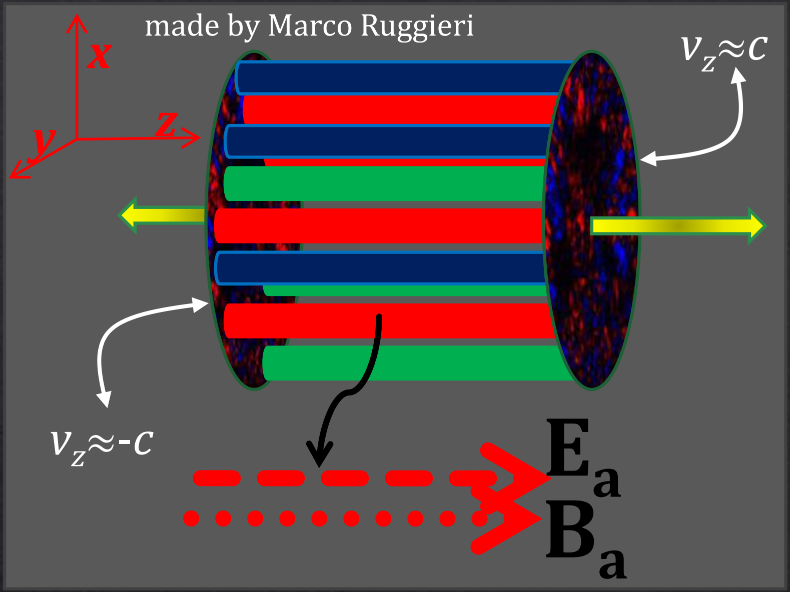


Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101 (2020) 014917

PHOTON EMISSION FROM CME



Not only EMF…but also chromoEMF



GLASMA
just after the collision strong longitudinal color-electric and color-magnetic fields are produced

CLASSICAL YANG-MILLS (CYM) EQUATIONS
due to the large density of the gluon field its dynamics is governed by classical eqs. of motion

Lappi and McLerran, Nucl. Phys. A 772, 200 (2006)

Assuming the Glasma initial condition the system evolves through the CYM equations

color fields from evolving Glasma

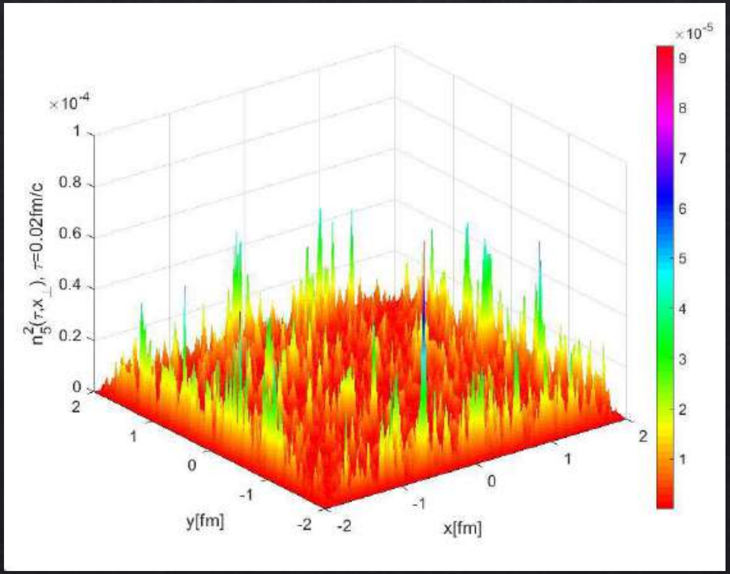
$$\left(\partial_\tau + \frac{1}{\tau}\right) j_5^\tau = \frac{1}{8\pi^2} \mathrm{Tr}\left[\boldsymbol{E} \cdot \boldsymbol{B}\right]$$

chiral QCD anomaly

Adler, Phys. Rev. 177, 2426 (1969)
Bell and Jackiw, Nuovo Cimento A 60, 47 (1969)

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

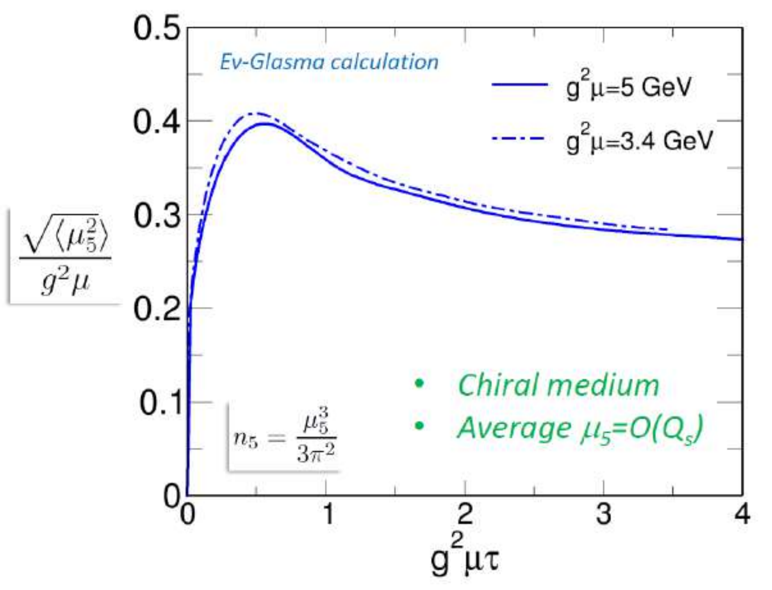
chiral density



Because of chiral anomaly the chiral density is produced in the early stage

Jia, Liu, Zhang and Ruggieri, 2006.01090

Chiral medium and intense magnetic field

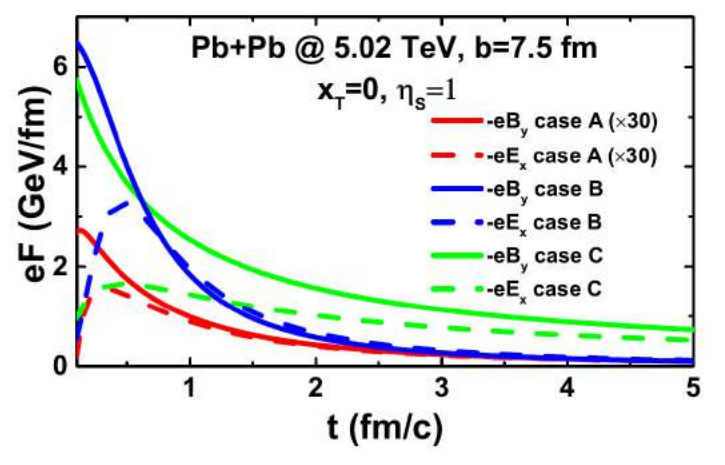


Jia, Liu, Zhang and Ruggieri, 2006.01090

Chiral anomaly plus evolving glasma fields (Ev-Glasma) produce a chiral density n_5 in the early stage

$$n_5 = \frac{\mu_5}{3\pi^2}$$

- a chiral medium formed within 0.2 $\mathrm{fm}/c \approx 1/g^2\mu$
- average chiral chemical potential $\mu_5 \approx \mathrm{O}(Q_s)$



Sun, Plumari and Greco, 2004.09880

case B

$$B_y = \frac{B_0 \cosh\eta}{1 + (\tau/\tau_B)^2}$$

case C

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

☐ “pessimistic” view

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

☐ “optimistic” view

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

case C reproduces the ALICE data for the v_1 splitting of neutral D meson (τ_B = 0.4 fm/c)

Chiral magnetic effect and photon production

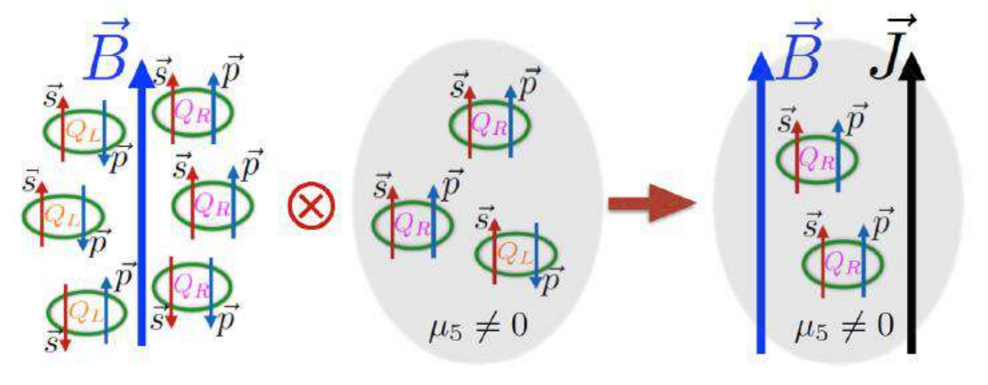
CME current

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

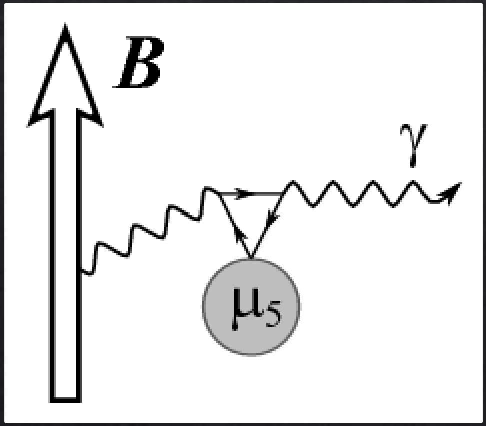
magnetic field

chiral medium

CHIRAL MAGNETIC EFFECT (CME)



Kharzeev, McLerran and Warringa, Nucl. Phys. A 803, 227 (2008)
Kharzeev, Liao, Voloshin and Wang, Prog. Part. Nucl. Phys. 88, 1 (2016) *review*



Fukushima and Mameda, Phys. Rev. D 86, 071501(R) (2012)

$$\frac{dN_\gamma}{d^2q_T dy} = \alpha_{em}\frac{25}{144\pi^6}\left(1 - \frac{q_y^2}{\boldsymbol{q}^2}\right)\langle\zeta(\boldsymbol{q})\rangle$$

$$\zeta(\boldsymbol{q}) \equiv \left|\int d^4x e^{-iq\cdot x} eB_y(x)\mu_5(x)\right|^2$$

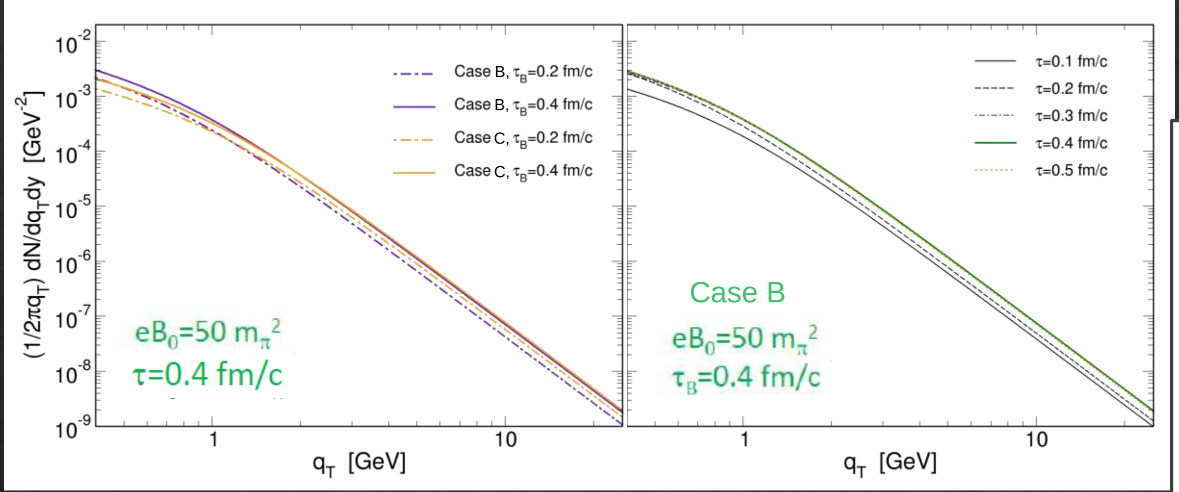
photon production from the CME

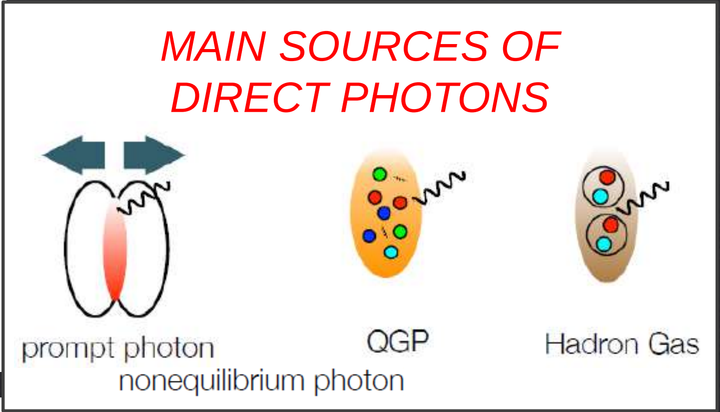
from the optimistic view assuming $\tau_B \approx \tau_{\text{thermalization}}$

from evolving glasma calculations

Jia, Liu, Oliva, Huang, Fukushima and Ruggieri, *in preparation*

CME photons: estimate of the spectrum





Comparison with other
early stage contributions

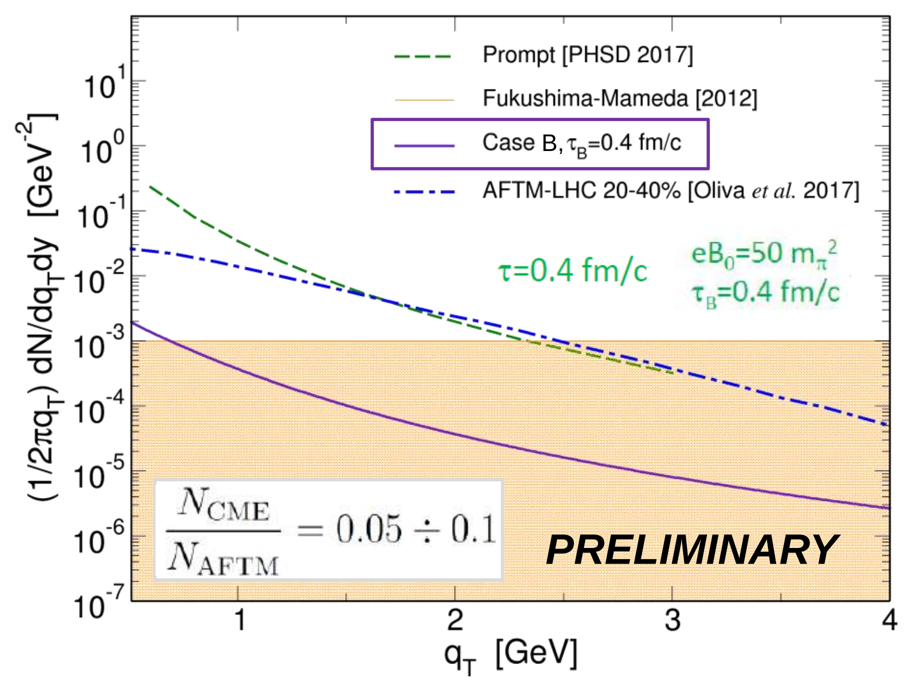
- ☐ prompt photons

Linnyk, Bratkovskaya and Cassing,
Prog. Part. Nucl. Phys. 87, 50 (2016)

- ☐ pre-equilibrium photons from the Abelian Flux Tube model (AFTM)

Oliva, Ruggieri, Plumari, Scardina, Peng and Greco,
Phys. Rev. C 96, 014914 (2017)

CME photons are 5-10% w.r.t.
pre-equilibrium photons



Jia, Liu, Oliva, Huang, Fukushima and Ruggieri, *in preparation*

CME photons: estimate of the elliptic flow

CME photons

$$\frac{dN_\gamma}{d^2 q_T dy} = \alpha_{em} \frac{25}{144\pi^6} \left(1 - \frac{q_y^2}{\boldsymbol{q}^2}\right) \langle \zeta(\boldsymbol{q}) \rangle$$

nearly isotropic

source of anisotropy

anisotropic distribution
in transverse plane

$$1 - \frac{q_y^2}{\boldsymbol{q}^2} = \cos^2\phi = \frac{1 + 2\cos 2\phi}{2} \to v_2^{\mathrm{CME}} = \left\langle \cos 2\phi \right\rangle = \frac{1}{2}$$

$N^{\mathrm{CME}} \approx (0.05 \div 0.01)\, N^{\mathrm{AFTM}}$

$N^{\mathrm{noCME}} \approx N^{\mathrm{AFTMearly}}$

$$v_2 = \frac{v_2^{\mathrm{CME}} \boxed{N_\gamma^{\mathrm{CME}}} + v_2^{\mathrm{noCME}} \boxed{N_\gamma^{\mathrm{noCME}}}}{N_\gamma^{\mathrm{CME}} + N_\gamma^{\mathrm{noCME}}}$$

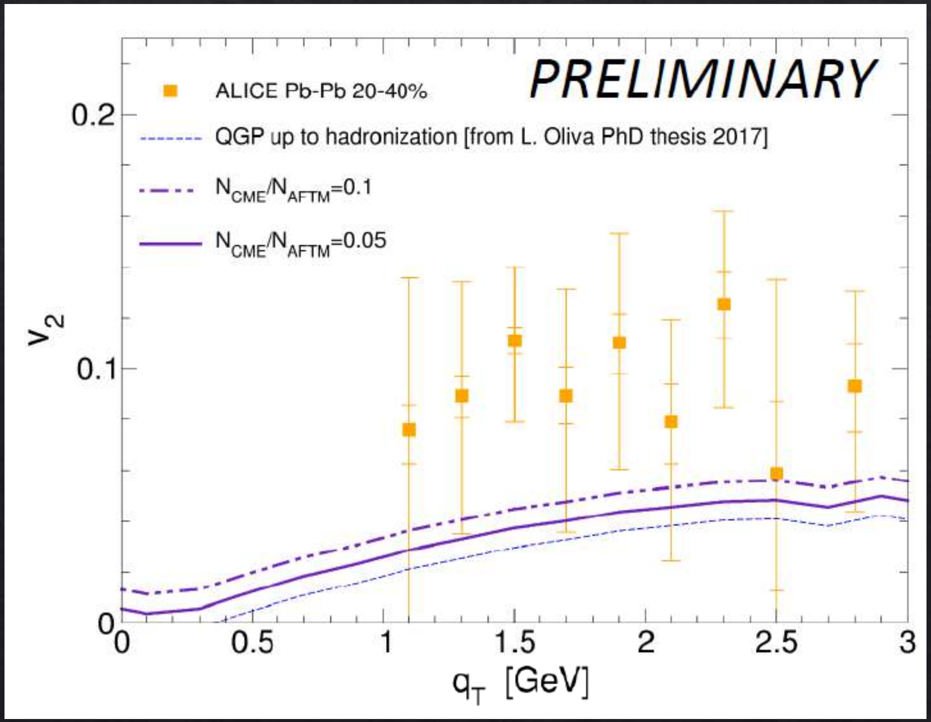
$$\approx v_2^{\mathrm{noCME}} + \frac{N_\gamma^{\mathrm{CME}}}{N_\gamma^{\mathrm{noCME}}} v_2^{\mathrm{CME}}$$

$N^{\mathrm{AFTMearly}} \approx 0.3\, N^{\mathrm{AFTM}}$

Oliva et al., Phys. Rev. C 96, 014914 (2017)

$$\Delta v_2 \approx (0.015 \div 0.03) \times \frac{1}{2}$$

Effect of CME photons on v_2 is sizeable



Jia, Liu, Oliva, Huang, Fukushima and Ruggieri, *in preparation*

CONCLUSIONS

Fascinating dynamics in relativistic nuclear collisions

- ➢ **strong vorticity** induced by the huge angular momentum
- ➢ **intense electromagnetic fields** (EMF)

Relativistic transport theory allows to describe the whole evolution of heavy-ion reactions and small colliding systems at high energy

Many interesting effects of electromagnetic and vortical fields in relativistic collisions

- ✓ The **directed flow** of **light hadrons** and **heavy mesons**
  - o can shed light on the early-time dynamics
  - o heavy quarks are more sensitive than light quarks
  - o small systems are an unexpected laboratory
- ✓ The **photon emission** from the **chiral magnetic effect** (CME) in the early stage
  - o the CME is due to the presence of chiral density and magnetic field
  - o CME photons have minor role to spectrum but sizable contribution to elliptic flow
- ✓ The **polarization** of **hyperons** and **vector mesons**
- ✓ The **anomalous transport phenomena** (not only the CME)

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Thank you
for your attention!

Many thanks to my collaborators

Elena Bratkovskaya (ITP Frankfurt, GSI Darmstadt)
Vincenzo Greco (Catania Uni, INFN-LNS)
Pierre Moreau (Duke Uni)
Salvatore Plumari (Catania Uni, INFN-LNS)
Marco Ruggieri (Lanzhou Uni)
Vadim Voronyuk (JINR Dubna)

Electromagnetic fields effects

Many interesting phenomena in high-energy nuclear collisions driven by the intense EMF

- chiral magnetic effect and related transport phenomena

  Kharzeev, McLerran and Warringa, Nucl. Phys. A 803, 227 (2008); Fukushima, Kharzeev and Warringa, Phys. Rev. D 78, 074033 (2008); Huang, Rept. Prog. Phys. 79, 076302 (2016); Kharzeev, Liao, Voloshin and Wang, Prog. Part. Nucl. Phys. 88, 1 (2016)

- polarization of hadrons

  Becattini, Karpenko, Lisa, Upsal and Voloshin, Phys. Rev. C 95, 054902 (2017); Han and Xu, Phys. Lett. B 786, 255 (2018); Sheng, Wang and Wang, Phys. Rev. D 102, 056013 (2020); Sheng, Oliva and Wang, Phys. Rev. D 101, 096005 (2020)

- early-time emission of photons and dileptons

  Fukushima and Mameda, Phys. Rev. D 86, 071501(R) (2012); Basar, Kharzeev and Skokov, Phys. Rev. Lett. 109, 202303 (2012); Basar, Kharzeev and Shuryak, Phys. Rev. C 90, 014905 (2014); Tuchin, Int. J. Mod. Phys. E 23, 1430001 (2014); **Jia, Liu, Oliva, Huang, Fukushima and Ruggieri., in preparation**

- Schwinger particle production

  Sheng, Fang, Wang and Rischke, Phys. Rev. D 99, 056004 (2019)

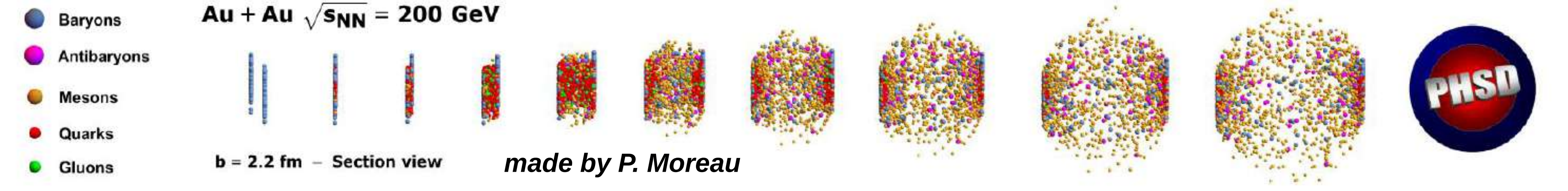
- charge-dependent directed flow

  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014); Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014); Toneev, Voronyuk, Kolomeitsev and Cassing, Phys. Rev. C 95, 034911 (2017); Das, Plumari, Chatterjee, Alam, Scardina and Greco, Phys. Lett. B 768, 260 (2017); Gursoy, Kharzeev, Marcus, Rajagopal and Shen, Phys.Rev.C 98, 055201 (2018); Chatterjee and Bozek, Phys. Lett. B798, 134955 (2019); **Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020); Oliva, Plumari and Greco, 2009.11066**; Oliva, Eur. Phys. J. A 56, 255 (2020); Dubla, Gursoy and Snellings, 2009.09727

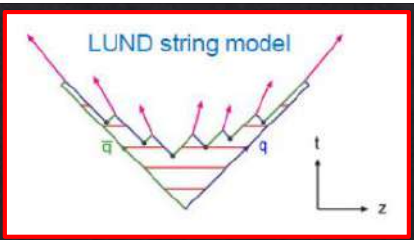
PHSD: Parton-Hadron-String Dynamics

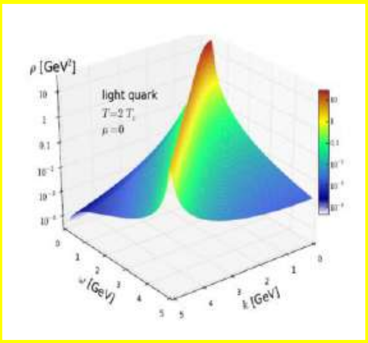
non-equilibrium off-shell transport approach to describe HICs and small systems

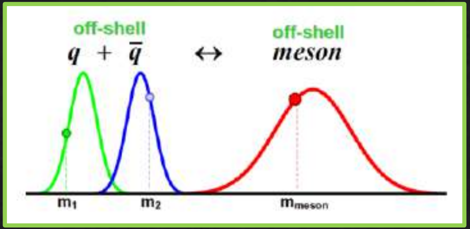
To study the phase transition from hadronic to partonic matter
and QGP properties from a microscopic origin



made by P. Moreau







- INITIAL A+A COLLISIONS: nucleon-nucleon collisions lead to the formation of strings that decay to pre-hadrons
- FORMATION OF QGP: if energy density $\varepsilon > \varepsilon_C$ pre-hadrons dissolve in massive quarks and gluons + mean-field potential
- PARTONIC STAGE: evolution based on off-shell transport equations with the DQPM defining parton spectral functions
- HADRONIZATION: massive off-shell partons with broad spectral functions hadronize to off-shell baryons and mesons
- HADRONIC PHASE: evolution based on the off-shell transport equations with hadron-hadron interactions

Cassing and Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215
Cassing, EPJ ST 168 (2009) 3; NPA856 (2011) 162

Catania transport approach

The temporal evolution of the QGP fireball and the heavy quarks (HQ) in relativistic HICs is described by solving the **relativistic Boltzmann transport equation** for the parton distribution function **f(x,p)**

QGP

$$p^\mu \partial_\mu f_g(x,p) = \mathcal{C}[f_g, f_q]$$

$$p^\mu \partial_\mu f_q(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f_q(x,p) = \mathcal{C}[f_g, f_q]$$

HEAVY QUARKS

$$p^\mu \partial_\mu f_{HQ}(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f_{HQ}(x,p) = \mathcal{C}[f_g, f_q, f_{HQ}]$$

RELATIVISTIC BOLZTMANN EQUATIONS

Collision integral

change of **f** due to collision processes responsible for deviations from ideal hydro (η/s ≠ 0)

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

Field interaction

change of ***f*** due to interactions of the partonic plasma with the external electromagnetic field

Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)
Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

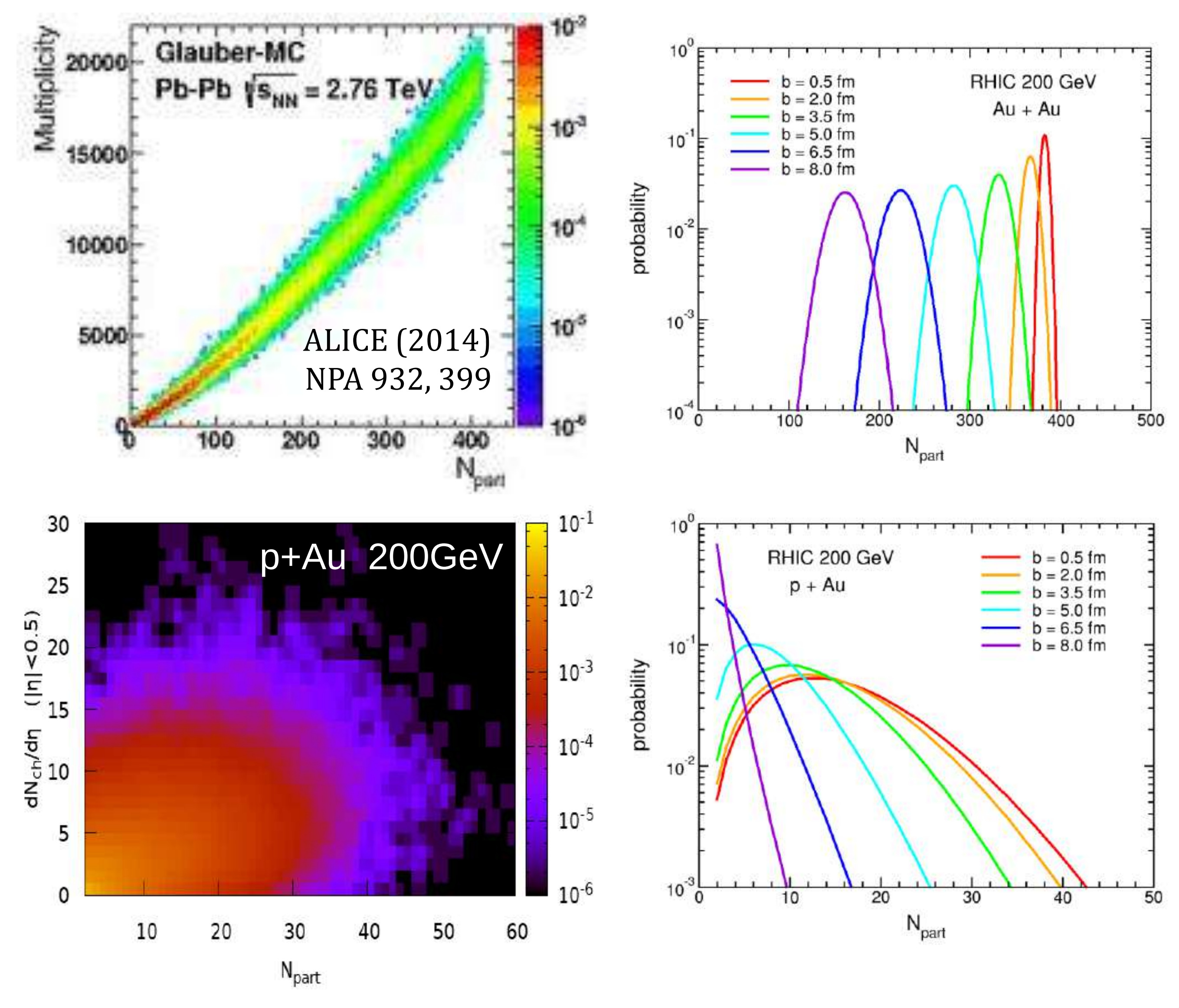
Centrality determination : A+A vs p+A

A+A

centrality characterizes
the amount of overlap
in the interaction area

p+A

multiplicity fluctuation
mixes events
from different
impact parameters



ALICE (2014)
NPA 932, 399

LO, Moreau, Voronyuk and Bratkovskaya, PRC 101 (2020) 014917

Anisotropic radial flow

INITIAL-STATE FLUCTUATIONS AND FINITE EVENT MULTIPLICITY

azimuthal particle distributions
w.r.t. the reaction plane

$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2 v_n(p_T) \cos[n(\varphi - \Psi_n)]$$

n-th order
flow harmonics

$$v_n = \frac{\langle \cos[n(\varphi - \Psi_n)] \rangle}{Res(\Psi_n)}$$

event-plane angle resolution
(three-subevent method)

Important especially for small colliding system, e.g. p+A

n-th order
event-plane angle

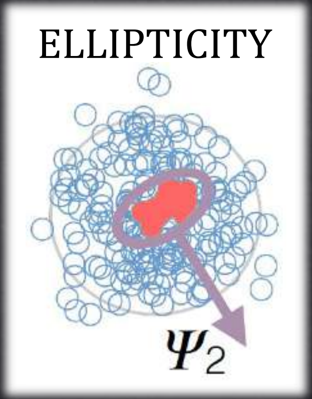
$$\Psi_n = \frac{1}{n} \operatorname{atan2}\left(Q_n^y, Q_n^x\right)$$

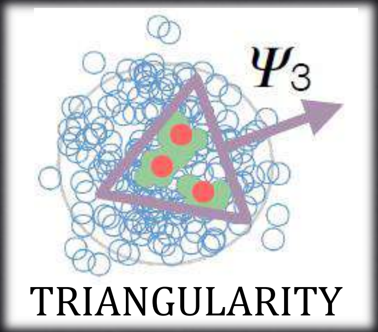
$$Q_n^x = \sum_i \cos[n\varphi_i]$$

$$Q_n^y = \sum_i \sin[n\varphi_i]$$

Since the finite number of particles produces limited resolution in the determination of Ψ_n, the v_n must be corrected up to what they would be relative to the real reaction plane

Poskanzer and Voloshin,
PRC 58 (1998) 1671

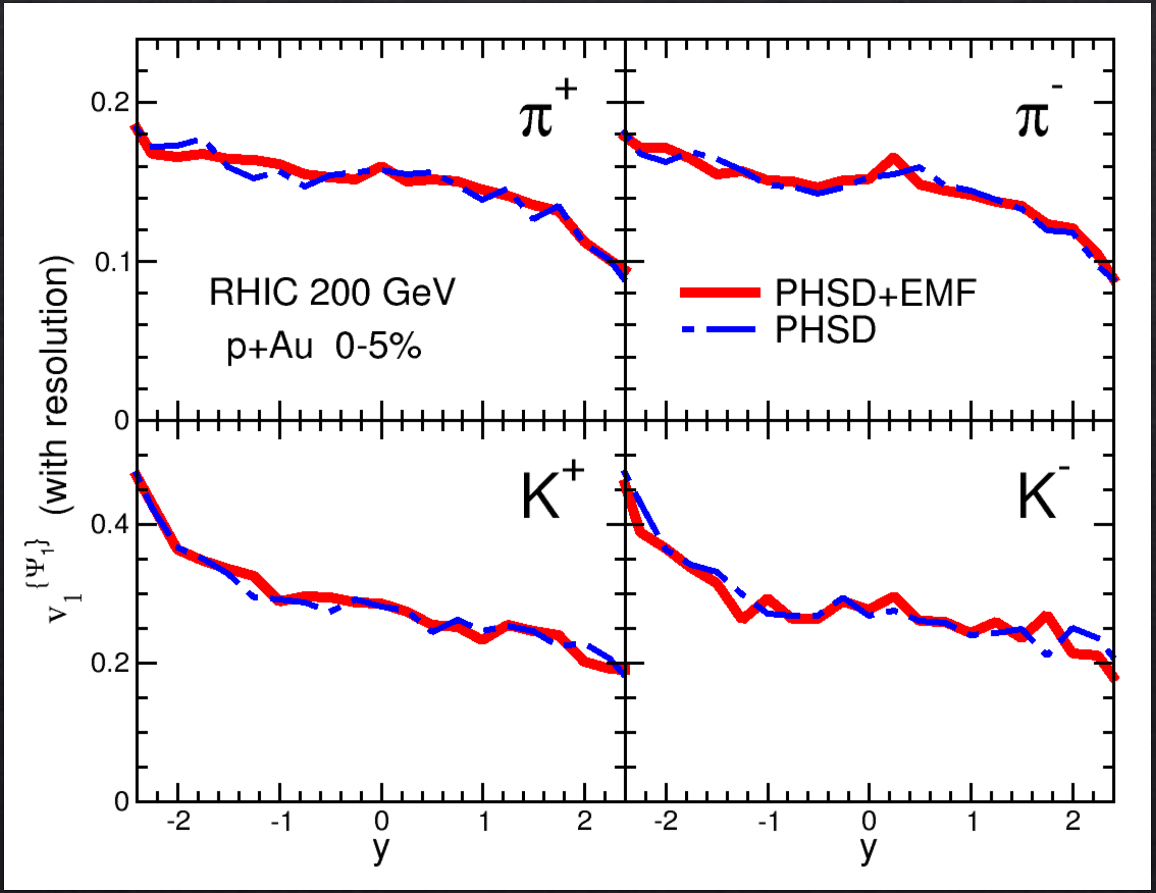




p+Au: directed flow

rapidity dependence of
the DIRECTED FLOW
OF IDENTIFIED PARTICLES

$$v_1(y) = \frac{\langle \cos[\varphi(y) - \Psi_1] \rangle}{Res(\Psi_1)}$$



Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

SPLITTING
of positively and negatively
charged particles
INDUCED BY THE EMF?

5% central collisions

no visible changes
with and without
electromagnetic fields

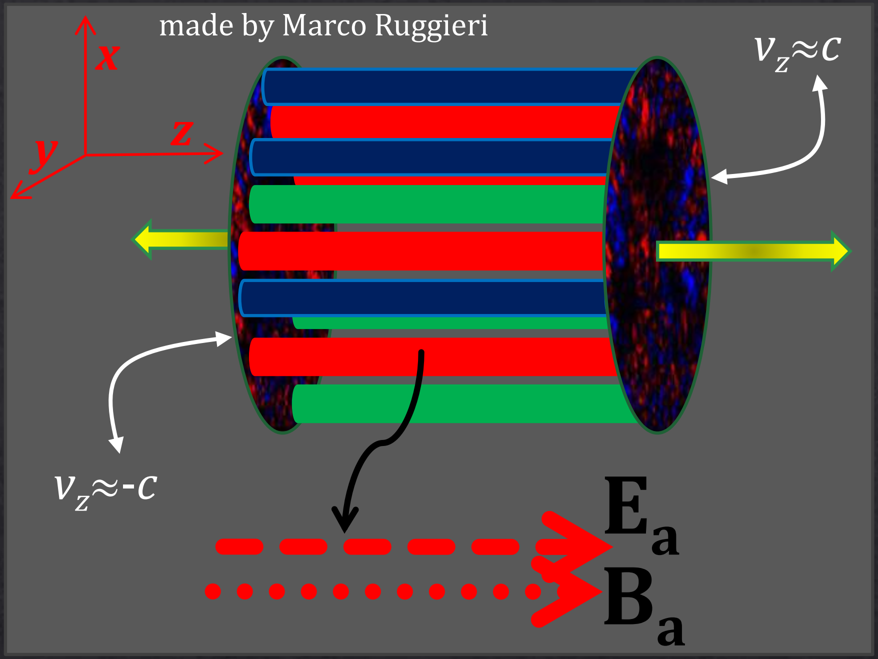
BUT clearly visible in
simulations at fixed
impact parameter…
…experimental challenge!

FROM GLASMA TO QUARK-GLUON PLASMA

SCHWINGER MECHANISM

Vacuum with an electric field is unstable towards pair creation

Euler-Heisenberg (1936)
Schwinger, Phys. Rev. 82, 664 (1951)



Longitudinal chromo-electric fields decay in gluon pairs and quark-antiquark pairs

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

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

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

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

ABELIAN FLUX TUBE MODEL (AFTm)

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

BOLTZMANN TRANSPORT EQUATION

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

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

Field interaction

Source term

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

conductive current

polarization current

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

SELF-CONSISTENTLY SOLUTION OF BOLTZMANN AND MAXWELL EQUATIONS

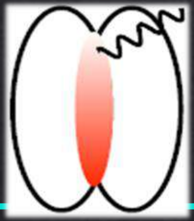
Florkowski and Ryblewski, PRD 88 (2013) 034028
Ruggieri, Puglisi, Oliva, Plumari, Scardina and Greco , PRC 92 (2015) 064904

QGP and hadronic photons

fireball evolution

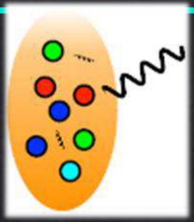
Pre-equilibrium photons

During classical field decay



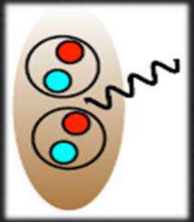
Thermal QGP photons

During thermal QGP evolution



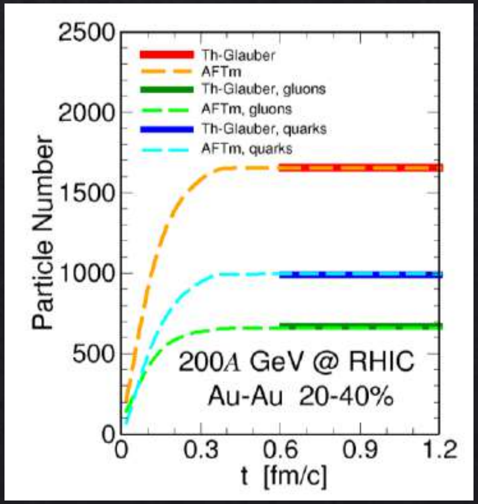
Thermal hadronic photons

During thermal HG evolution

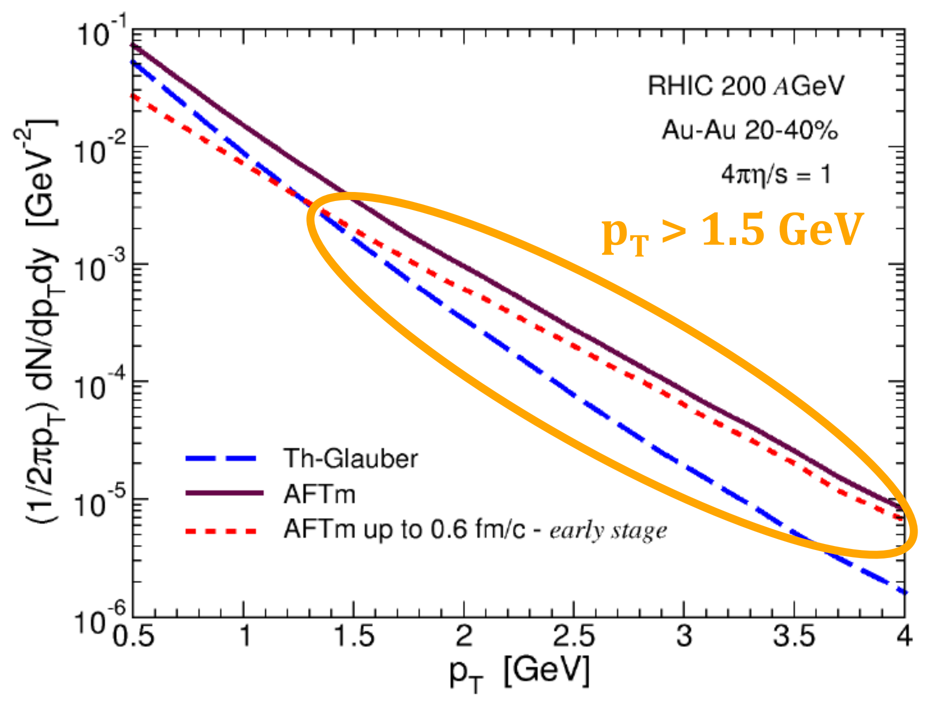


In our fireball we consider the QGP photons produced in the pre-equilibrium stage and after thermalization

NO NET DISTINCTION WITHIN AFTM



Pre-equilibrium photon production



Th-Glauber*:*

$t_0 = 0.6$ fm/c , hydro-like evolution

AFTm

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

AFTm, *early stage:*

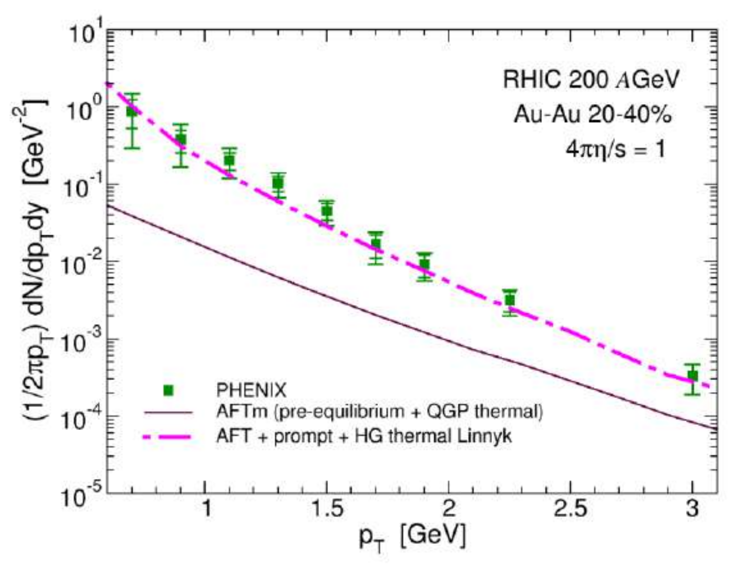
AFTm before thermalization time t = 0.6 fm/c

Photon spectrum from QGP is dominated by the early stage photons for p_T > 1.5 GeV

Contributions added to AFTm:

- Prompt photons from McGill group
  Paquet *et al.* (McGill), PRC 93 (2016) 044906
- Hadronic thermal photons from PHSD
  Linnyk et al. (Frankfurt) PRC 92 (2015) 054914

Exp. data: PHENIX, Phys. Rev. C 91 (2015) 064904

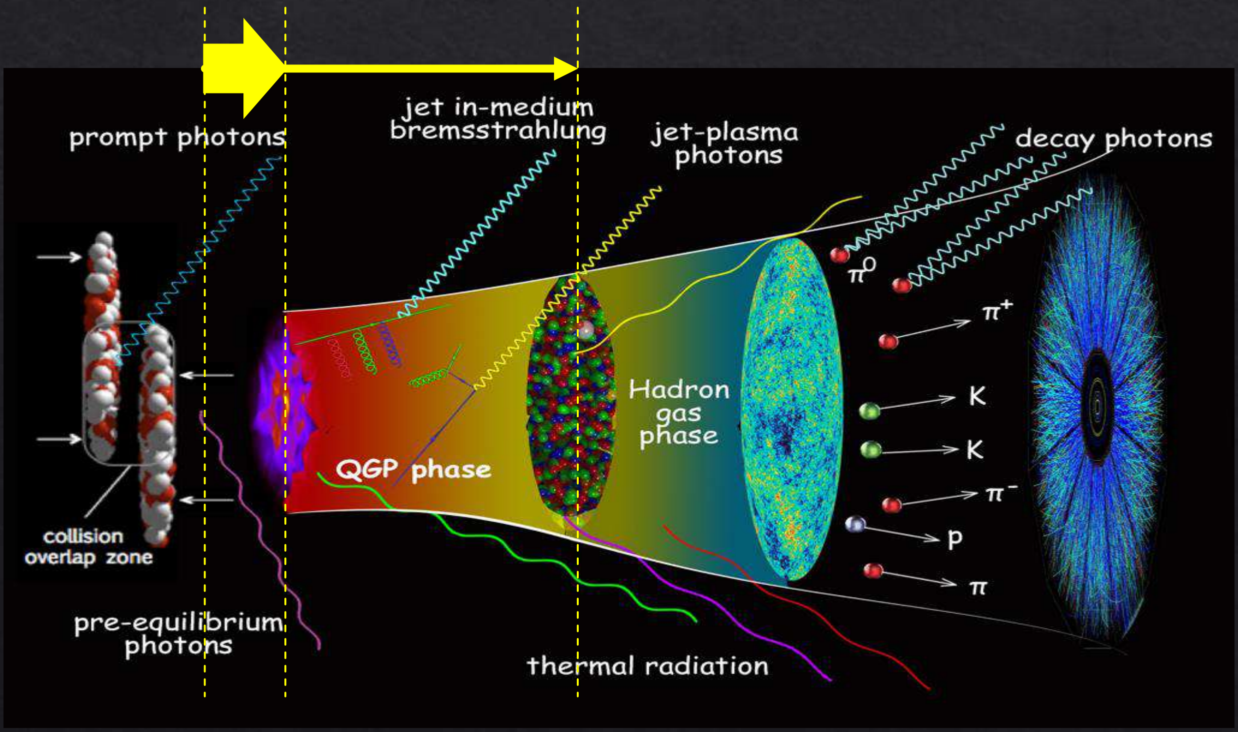


Oliva, Ruggieri, Plumari, Scardina, Peng and Greco, Phys. Rev. C 96, 014914 (2017)

Pre-equilibrium photon production

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