Strong-field physics in heavy-ion collisions

Hidetoshi Taya

(RIKEN)

Plan

Interaction b/w heavy-ion & strong-field communities must be useful !

(1) Heavy-ion coll. can be used as a tool to study strong-field QED

(2) The knowledge of strong-field QED can be used to understand heavy-ion coll.

1. One-page introduction of heavy-ion collisions

2. Creation of strong EM field in heavy-ion coll.

- Different creation mechanisms at high and low energies
- "Non-perturbativeness" of the EM field

  ⇒ Non-perturbative regime can be accessed by low-energy collisions

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in preparation]

3. Open question in HIC, related to strong color physics

- Non-equilibrium dynamics of QGP formation [HT, Ph. D thesis]

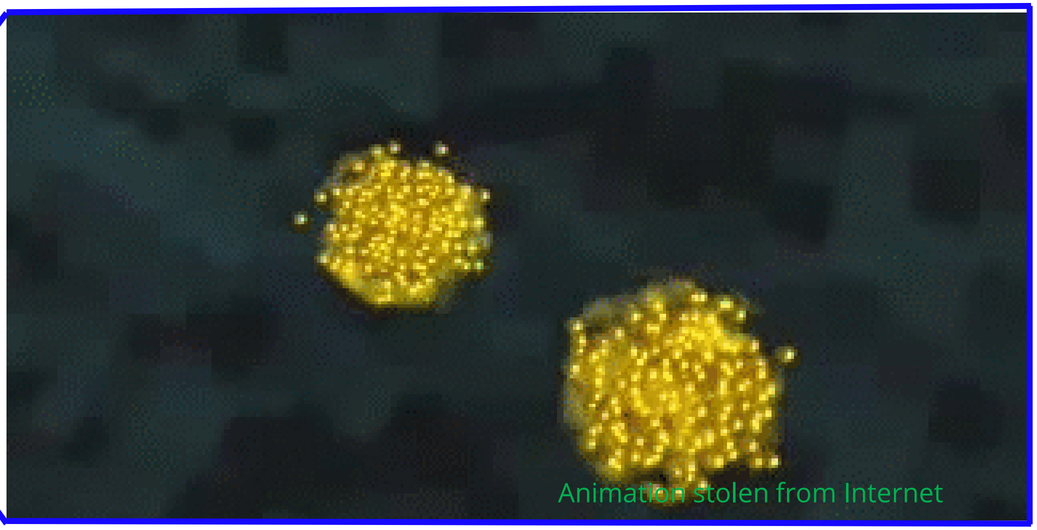
1. **One-page introduction of heavy-ion collisions**

2. Creation of strong EM field in heavy-ion coll.

3. Open question in HIC, related to strong color physics

4. Summary

What is heavy-ion collisions ?



✔ **Accelerator experiments at RHIC @ Brookhaven (2000~) & LHC @ CERN (2010~)**

✔ **The goal: Understand the origin of matter**

(1) Reproduce an extremely high temperature & dense state just after the Big Bang

(2) Understand properties of matter under extreme conditions, i.e., quark-gluon plasma (QGP)

(3) Better understand the fundamental theory of matter, i.e., quantum chromodynamics (QCD)

✔ **Current status:**

Energy regime of $E_{\rm CM} = O(100\ {\rm GeV} - 5\ {\rm TeV})$ per nucleon has been studied experimentally

- Many successful results (e.g., realization of $T = O(10^{12}\ {\rm K})$, QGP found to be perfect liquid , …)
- But still remain various theoretical problems (e.g., non-equilibrium dynamics of QGP formation)
- Future plan: go to higher $O(40\ {\rm TeV})$ (e.g., FCC@CERN) or lower energies $O(1\ {\rm GeV})$ (FAIR@GSI, NICA@JINR, …)

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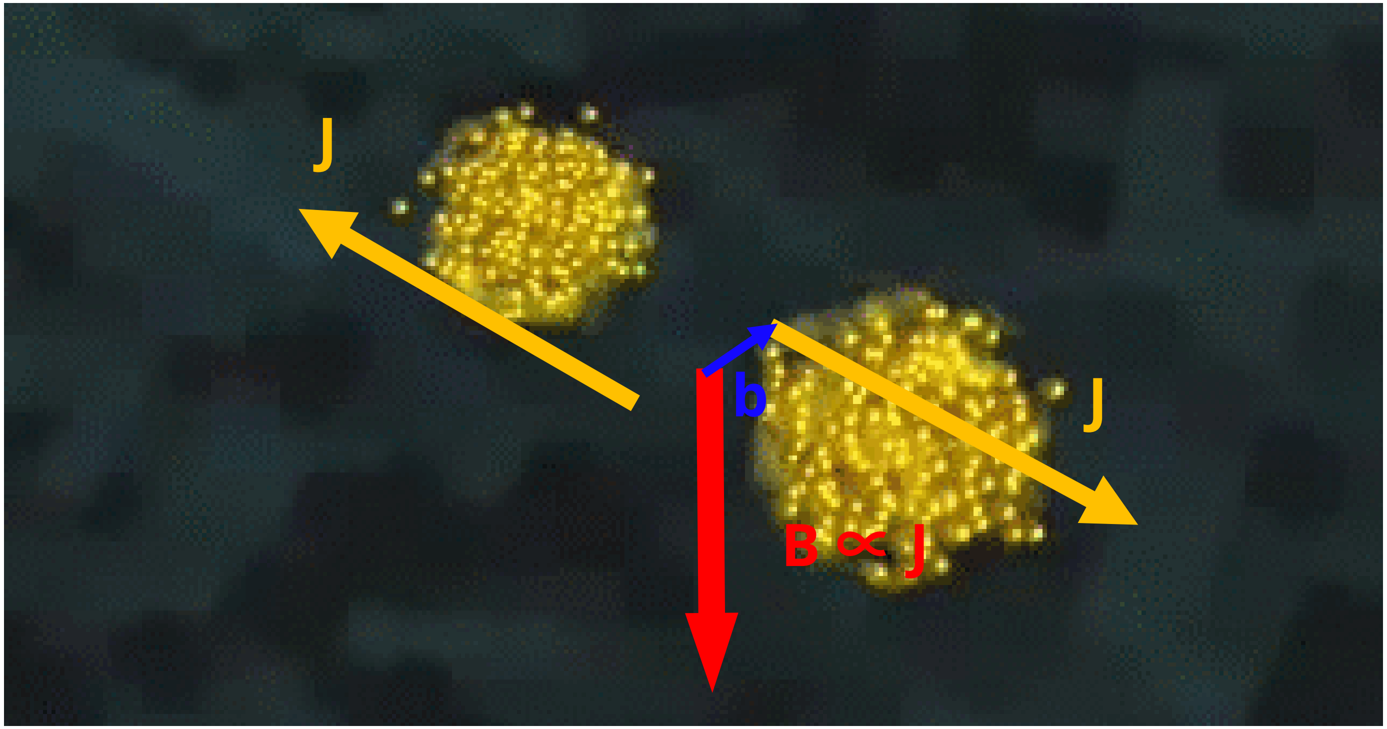
Strong B field in heavy-ion coll. at high energies



✔ **Strong magnetic field is created** (∵ large $Z \sim 80$, large velocity $v \approx c$ or $\gamma \sim 10^{2-3}$ ⇒ large J)

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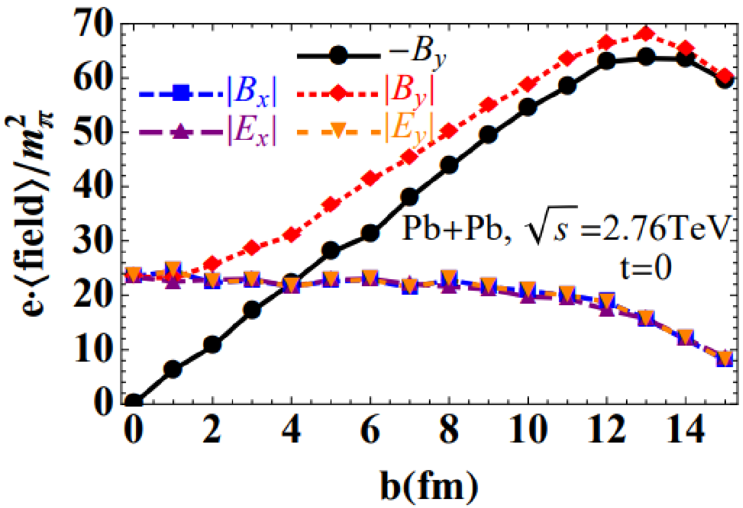
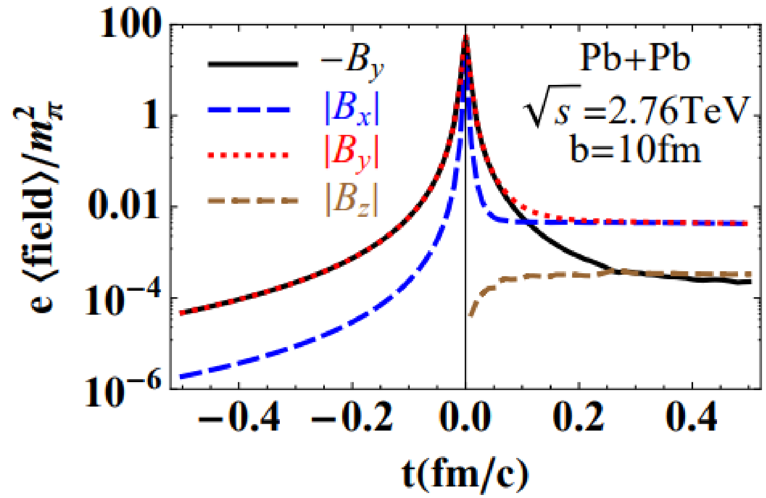




[Deng, Huang (2012)]

See also [Bzdak, Skokov (2012)] [Hattori, Huang (2016)]

✔ **Strong magnetic field is created** (∵ large $Z \sim 80$, large velocity $v \approx c$ or $\gamma \sim 10^{2-3} \Rightarrow$ large J)

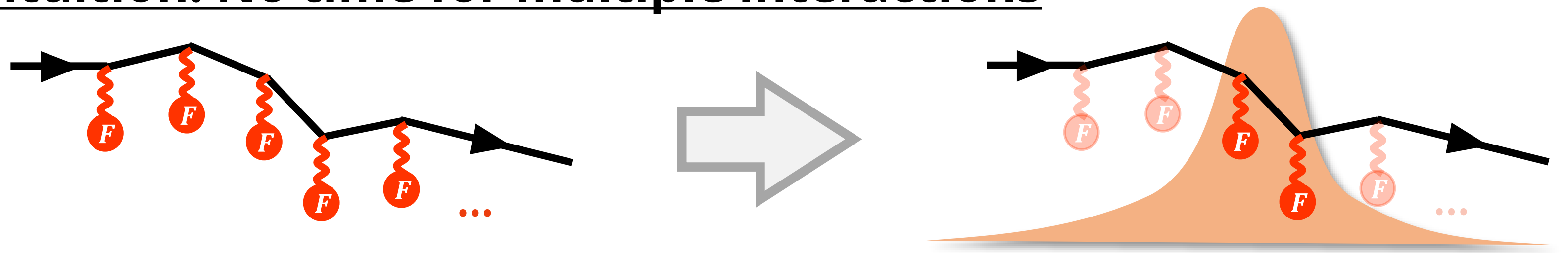
Pro: Super strong $eB = O(1\ \mathrm{GeV}^2) \approx O(10^{42}\ \mathrm{W/cm^2})$ (Strongest in the Universe !)

Cons: Extremely short-lived $\tau \ll 1\ \mathrm{fm}/c = O(10^{-24}\ \mathrm{sec})$

⇒ Affects "non-perturbativeness" of physics

Shorter lifetime ⇒ more perturbative

✔ Intuition: No time for multiple interactions



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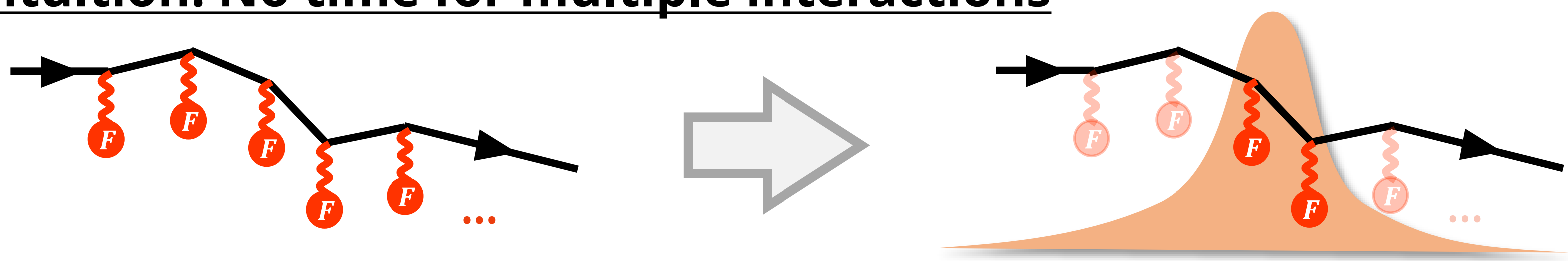


✔ "Phase diagram" of strong-field physics

[HT, Fujiii, Itakura (2014)]
[HT, Fujimori, Misumi, Nitta, Sakai (2021)]

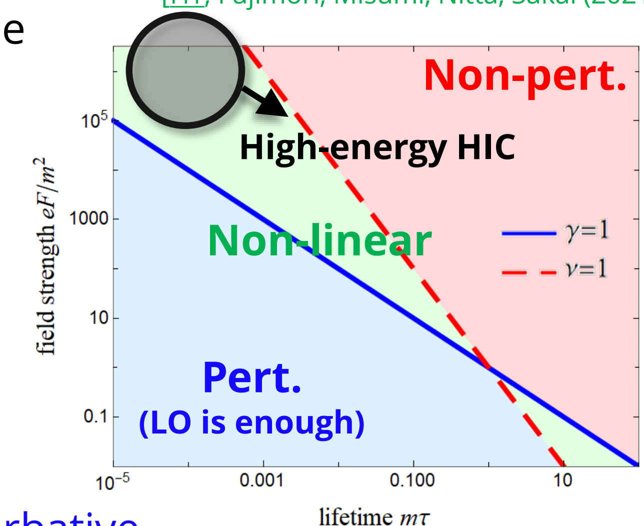
As example: Vacuum particle prod. by E field w/ finite lifetime

- Three dimensionful parameters in the system: eE, τ, m

  ⇒ Two dim.-less parameters determine the physics

$$\gamma = \frac{m}{eE\,\tau} = \frac{\text{(Typical energy)}}{\text{(Work by field)}}$$ ⇒ Characterize the magnitude of work

$$\nu = \frac{eE\,\tau}{1/\tau} = \frac{\text{(Work by field)}}{\text{(Photon energy)}}$$ ⇒ Characterize the number of photons



- $\boldsymbol{\gamma \ll 1, \nu \gg 1}$ ⇒ Non-perturbative, $\boldsymbol{\gamma \gg 1, \nu \ll 1}$ ⇒ perturbative

- High-energy HIC: $eF \sim (1\text{ GeV})^2$, $\tau \sim 0.1\text{ fm}/c \Rightarrow \gamma \sim 10^{-5}, \nu \sim 0.1$ (for QED $m = m_e$)

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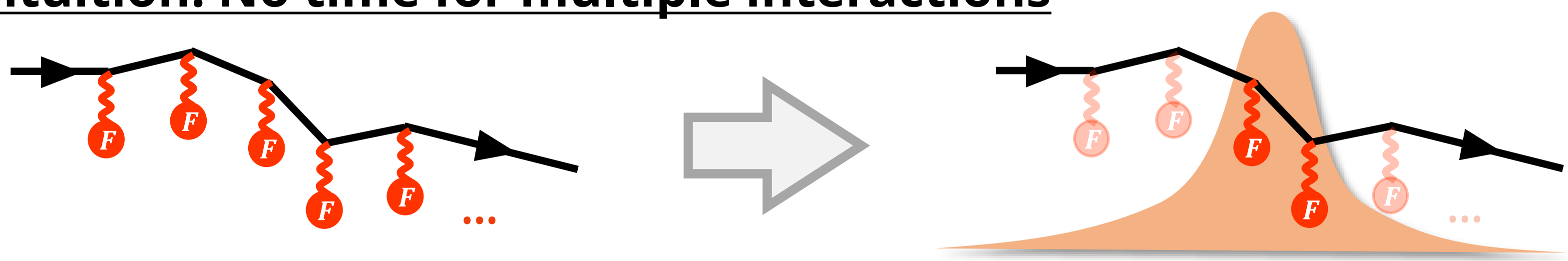

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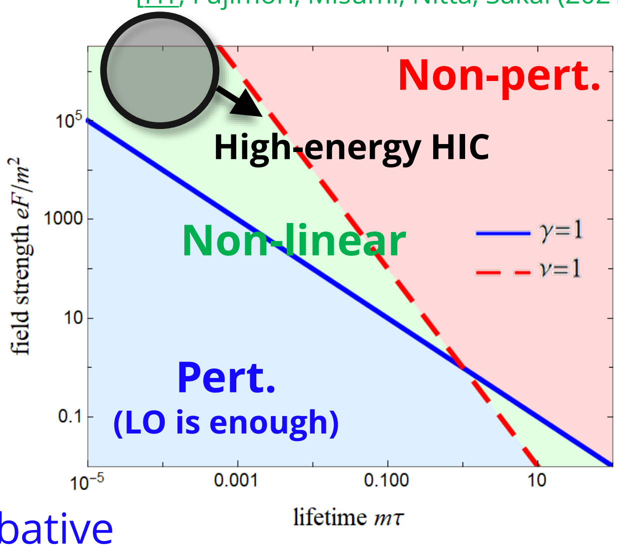

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⇒ High-energy heavy-ion coll. is meaningless for strong-field physics ?

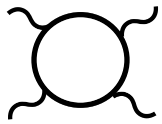
⇒ Not necessarily. Still a good chance to study non-linear effects

Experimental results

✔ Very first observation of high-order QED processes

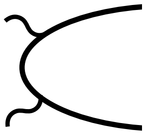
(Prior to any other experiments; e.g., high-power laser)

ex. 1) Light-by-light scattering



[ATLAS (2016)]

ex. 2) Breit-Wheeler process



[STAR (2019)]

But, that's all in HIC. Your input for more interesting observables needed !

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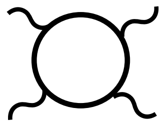

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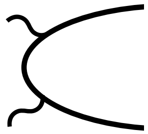

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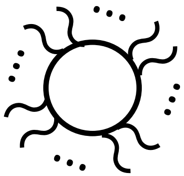
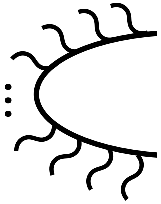
But, that's all in HIC. Your input for more interesting observables needed !

✔ But, what we really want is something non-pert. !



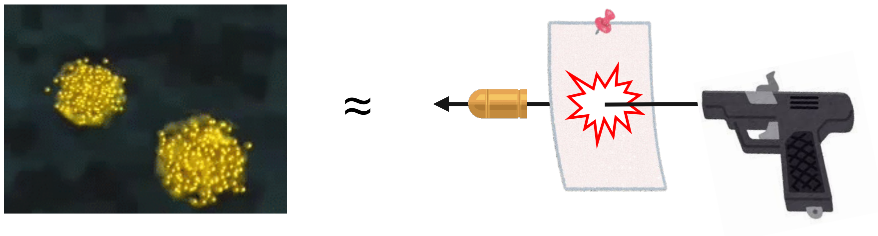


So, heavy-ion is useless ??? ⇒ **can be useful at low energies !**

Strong E field in heavy-ion coll. at low energies

✔ **Different mechanism due to nuclear stopping (Landau picture)**

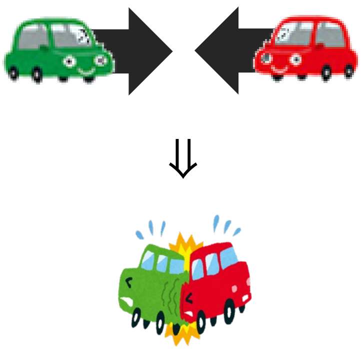
High energy



penetrate with each other

⇒ current ⇒ B

Low energy



merge at the center

⇒ charge ⇒ E

✔ **The E field would be strong and long-lived**

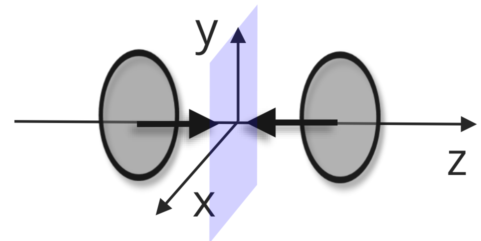
Rough idea: large atomic number $Z_{\rm tot} = Z_1 + Z_2 = O(150) \gtrsim 1/\alpha$

⇒ Strong Coulomb field $eE = \frac{\alpha Z_{\rm tot}}{r^2} \gtrsim m_e^2$ over the Compton wavelength $V \gtrsim m_e^{-3}$

Estimation with hadron trans. model (JAM) (1/2)

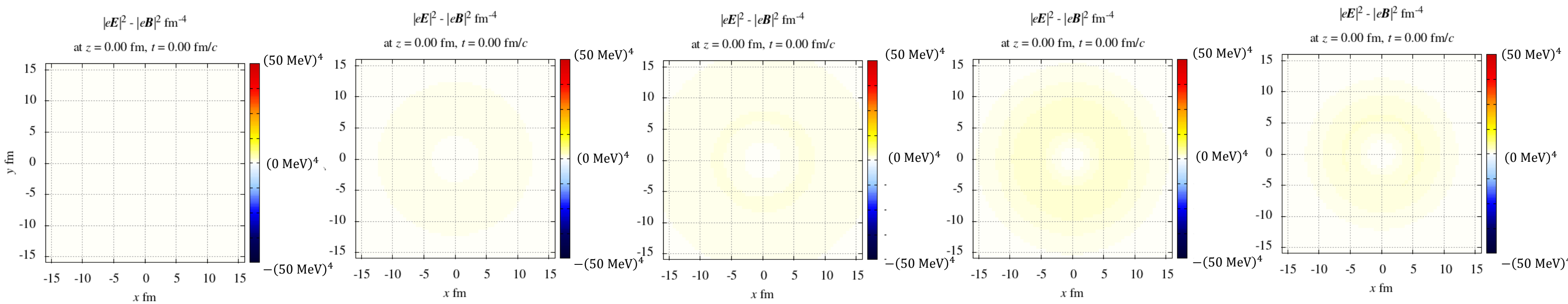
[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ **Time evolution of EM field (central coll. b=0) @ z=0**



- Lorentz inv. $F := E^2 - B^2$ (F>0: Electric, F<0: Magnetic)

E_{CM} = 2.0 GeV 3.0 GeV 4.0 GeV 6.3 GeV 7.7 GeV



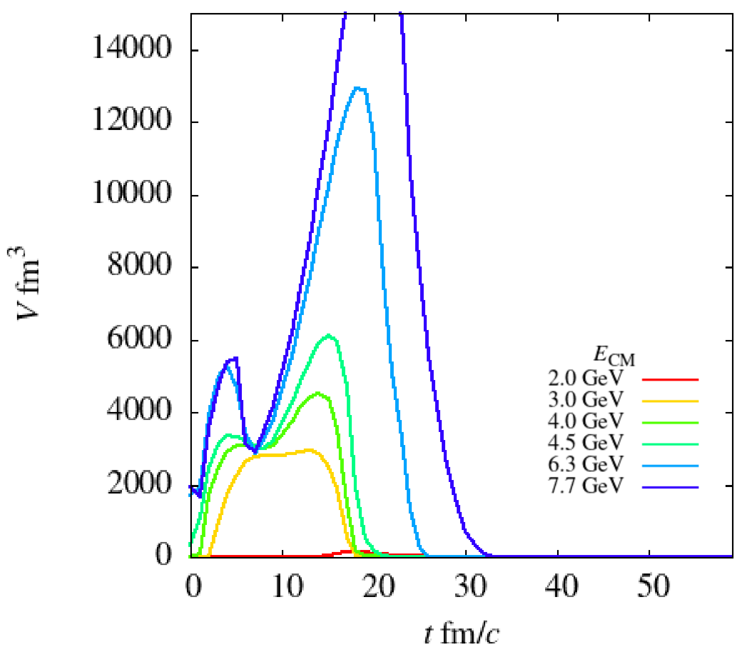
- Field strength can be strong as $e^2 F \sim (eE)^2 = O\big((50\ \mathrm{MeV})^4\big)$

⇒ Very strong for QED ($m_e = 0.511$ MeV)

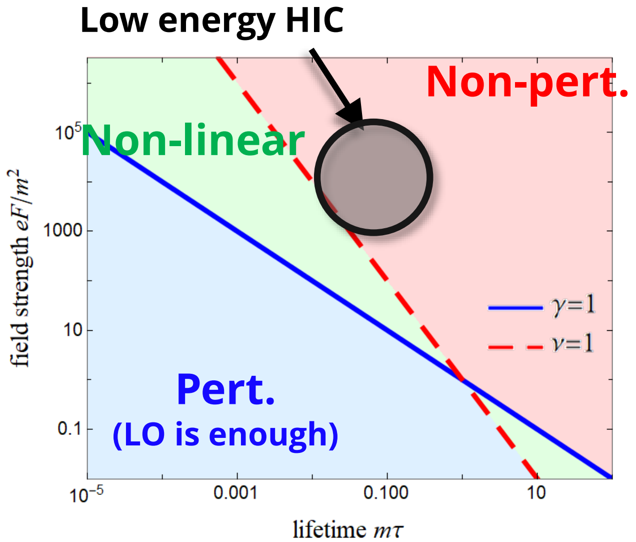
Estimation with hadron trans. model (JAM) (2/2)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ Spacetime volume of EM field



Volume for
$e^2F = |e\boldsymbol{E}|^2 - |e\boldsymbol{B}|^2 > (30\ \mathrm{MeV})^4$



- Strong E field with $e^2F \sim (eE)^2 \sim (30\ \mathrm{MeV})^2$, lifetime $\tau \gtrsim 20\ \mathrm{fm}/c$, volume $V \gtrsim (15\ \mathrm{fm})^3$

  ⇒ Non-perturbative !

  $\because \gamma = \frac{m}{eE\tau}\ \mathrm{or}\ \frac{m}{eEl} = O(0.1),\ \nu = eE\tau^2\ \mathrm{or}\ eEl^2 = O(10)$

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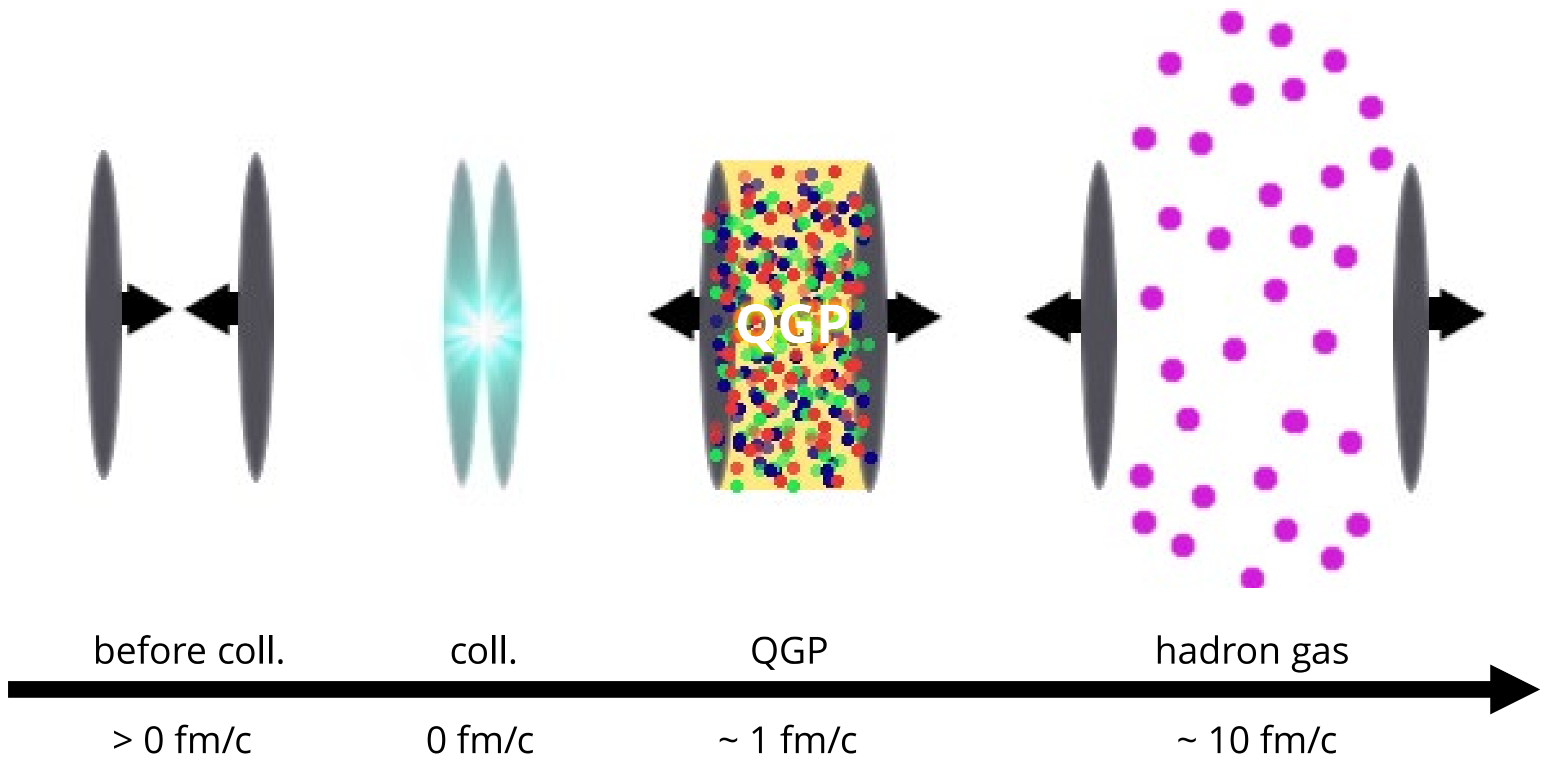
Unsolved problem in HIC: Formation process of QGP



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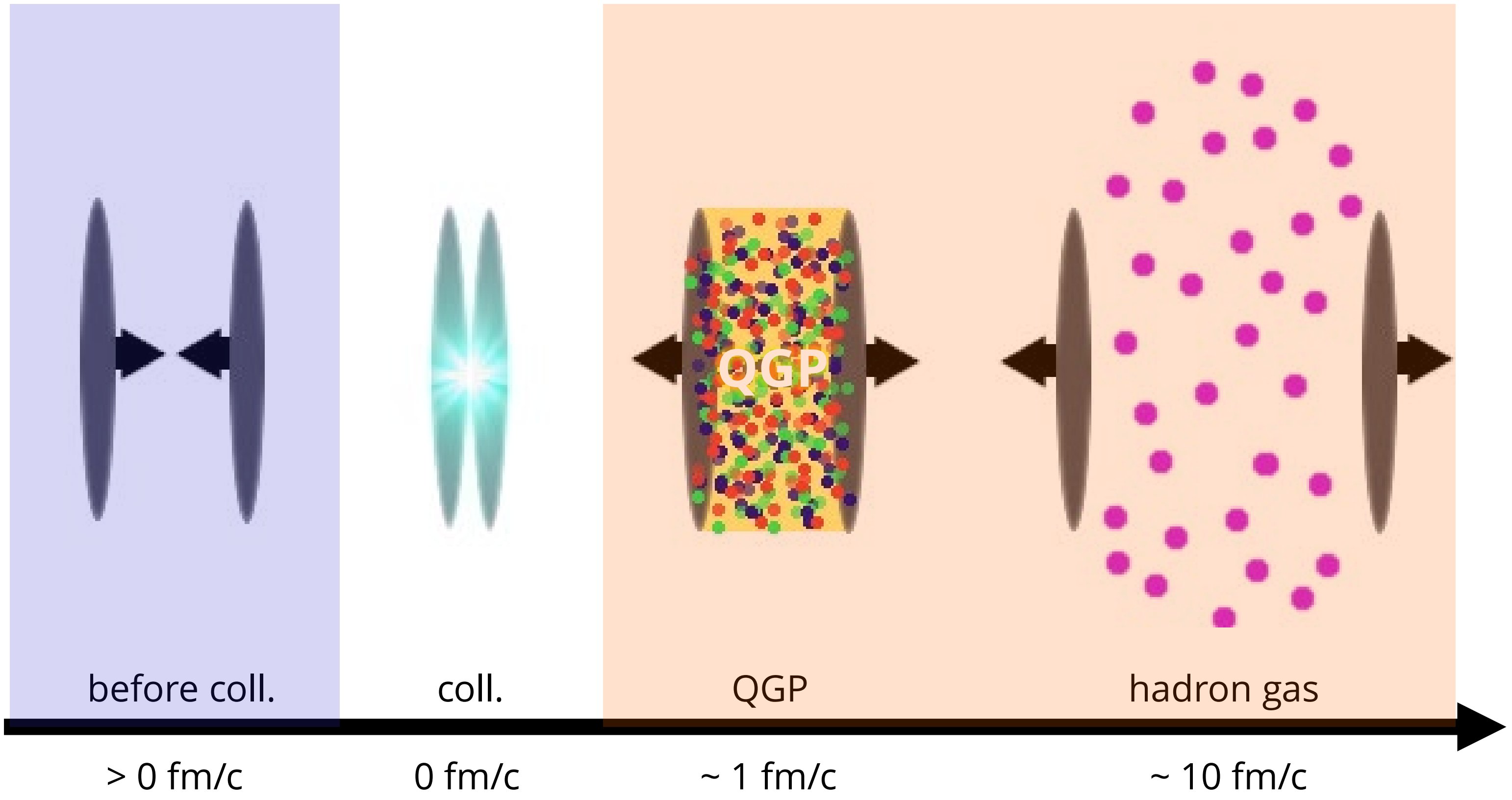

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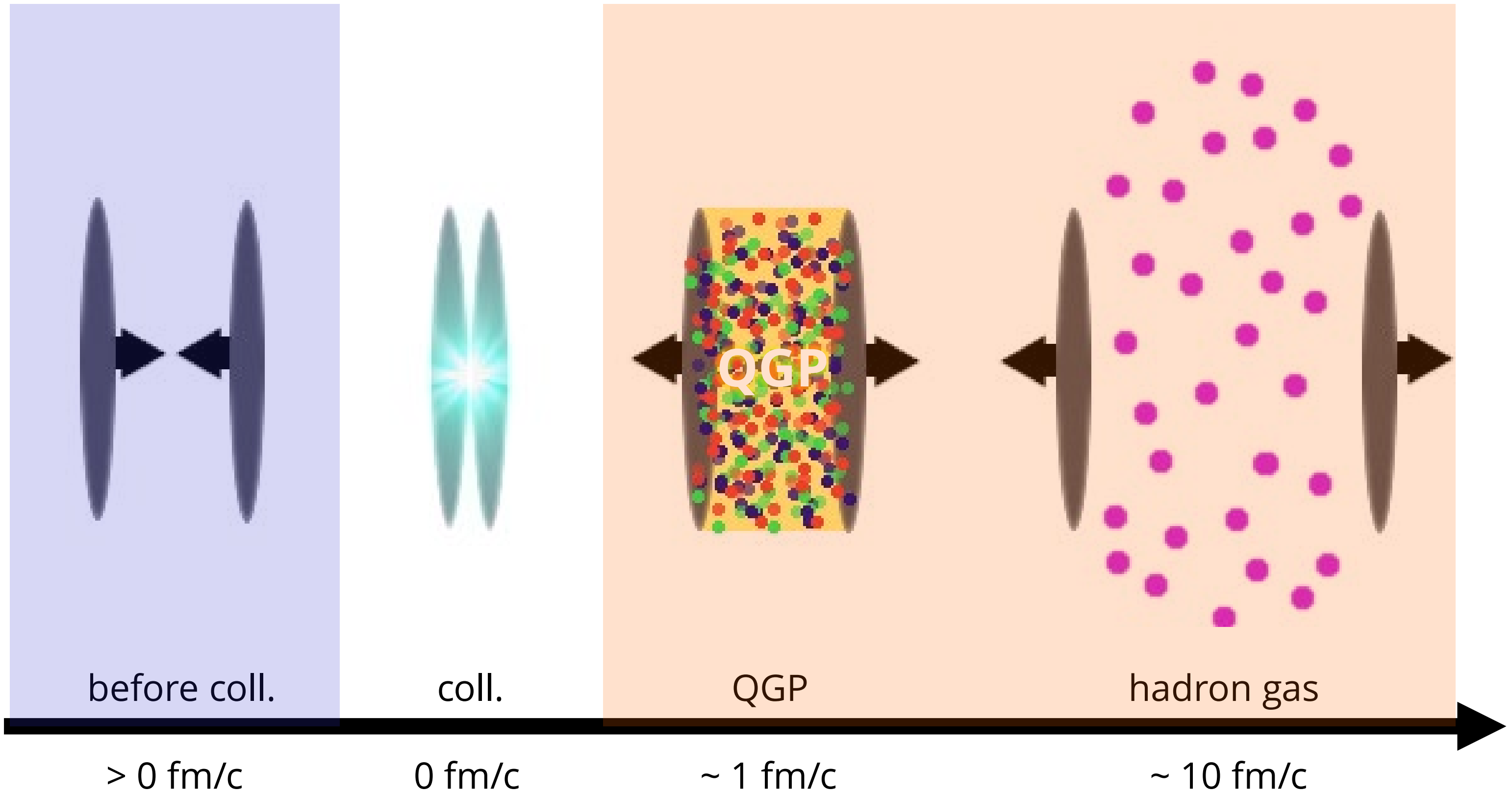
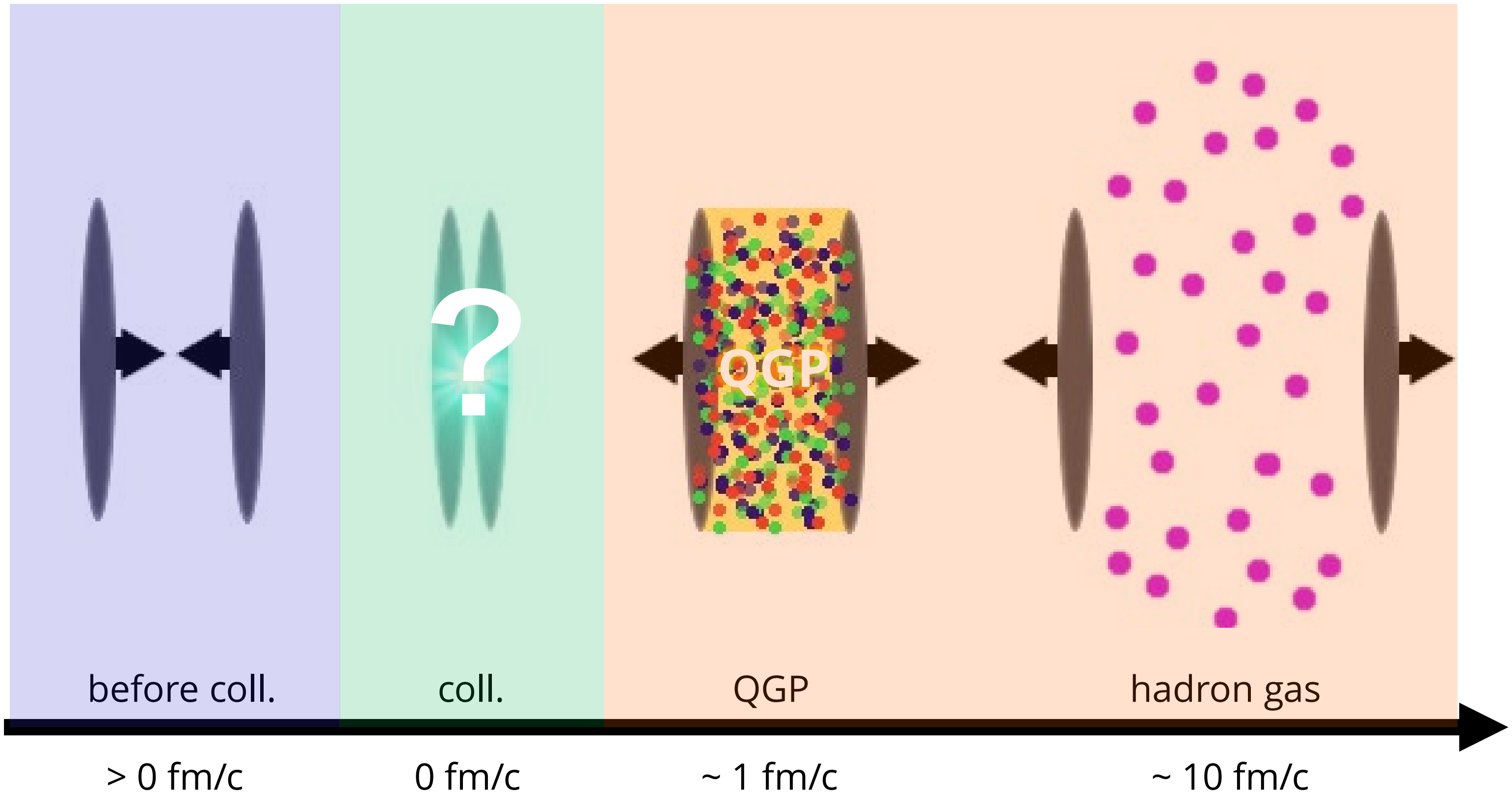


■ ⇒ Exp: Deep inelastic scattering
Theory: pQCD (or color glass condensate)

■ ⇒ Exp: Many observables, e.g., collective flow, thermal photon, ...
Theory: Relativistic hydrodynamics (with tiny viscosity)

Unsolved problem in HIC: Formation process of QGP

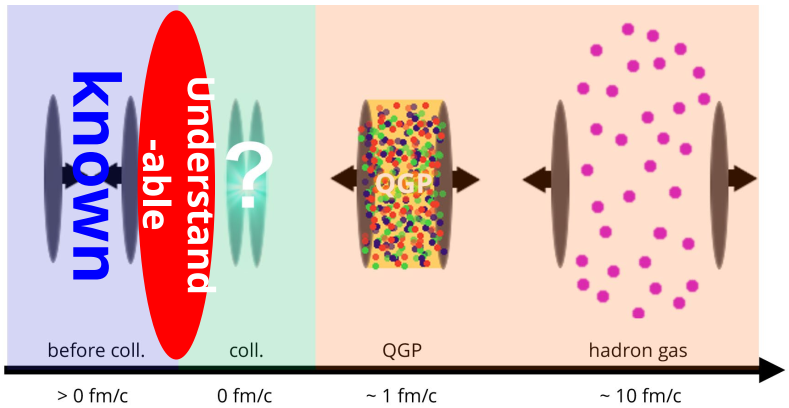


- (blue) ⇒ Exp: Deep inelastic scattering
  Theory: pQCD (or color glass condensate)
- (red) ⇒ Exp: Many observables, e.g., collective flow, thermal photon, ...
  Theory: Relativistic hydrodynamics (with tiny viscosity)
- (green) ⇒ **Understood neither experimentally nor theoretically**

Key: Strong-field physics

✔ **The formation process of QGP**

= How does strong color EM field decay into a hydro. matter ?



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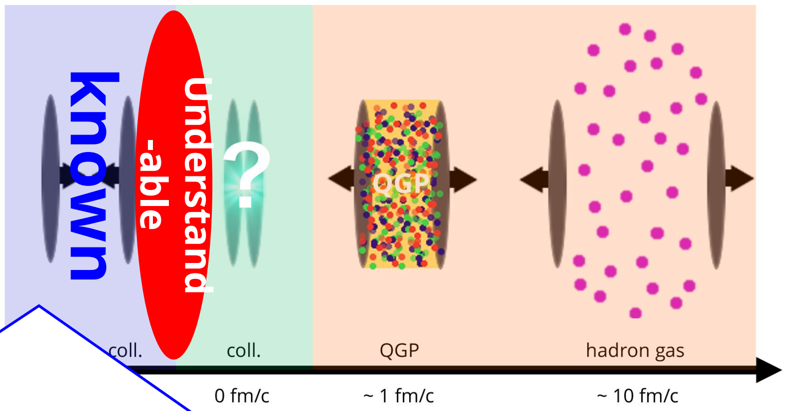

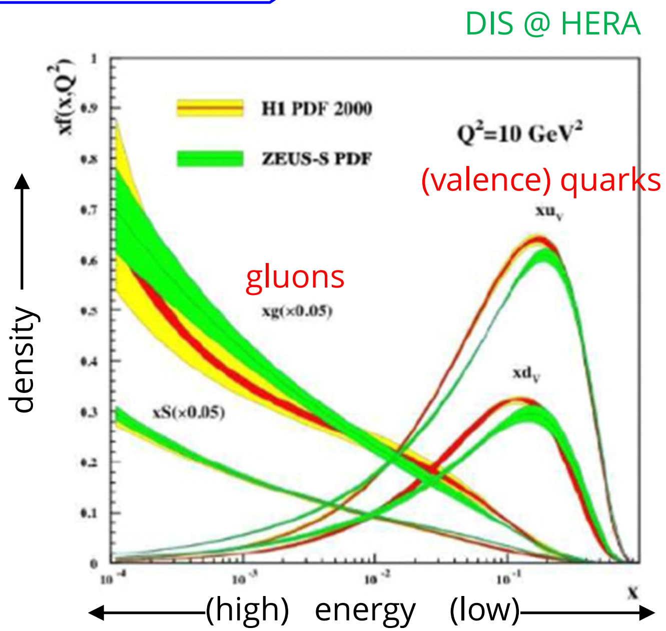

High-energy heavy ions

||

Super dense gluon state

≀≀

"color charged plate"
with huge color charge density
($\sigma \sim Q_s^2 \sim O(1)\mathrm{GeV}^2$)

Key: Strong-field physics

- ✔ **The formation process of QGP**

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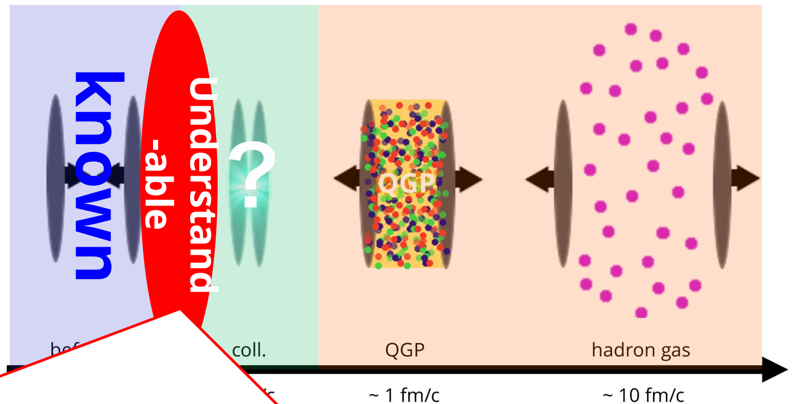
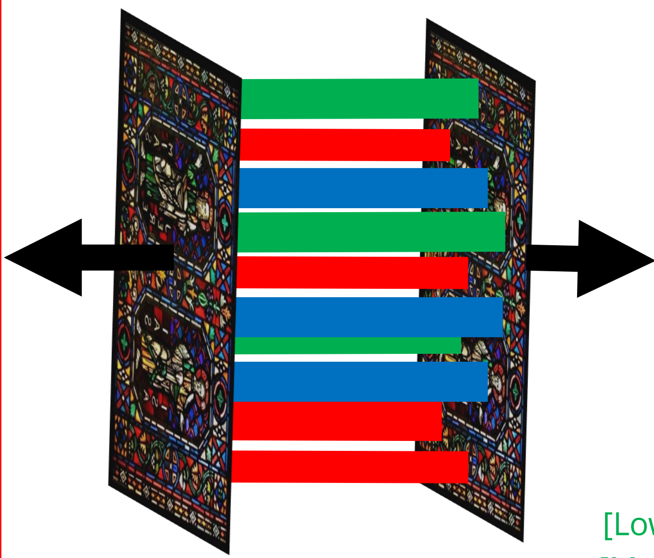




Just after a collision

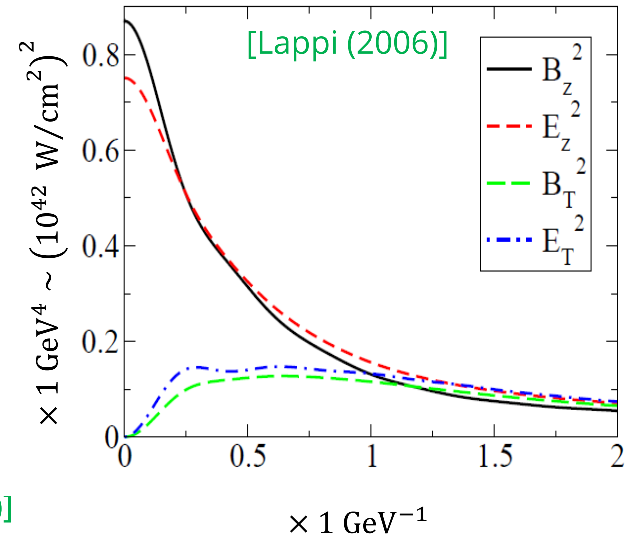
≀

“color capacitor”
(w/ $\sigma \sim Q_s^2 \sim O(1)\mathrm{GeV}^2$)

⇓

Generation of
strong color EM field
($gE, gB = O(1)\ \mathrm{GeV}^2$)

[Low, Nussinov, Casher, Neuberger (1970s)]
[McLerran, Lappi, Kovner, Weigert (2005)]



Application of strong-field QED ideas

✔ **Borrowed ideas from strong-field QED**

Review: [Mrowczynski (2006)]

- Plasma instability (e.g., Weibel) (but not very successful at the moment …)
- Schwinger effect [Kerman, Matsui, Gatoff (1987)] [Tanji (2008)] [HT (2017)]

(✔ **I don't explain today, but …**

New ideas & techniques have been developed in HIC, possibly useful in strong-field QED

- non-equil. attractor, non-equil. universality, hydrodynamization, validity of classical/quantum description, …
- 2PI formalism, classical statistical simulation, chiral kinetic theory, realtime lattice technique, …)

Application of QED theory of Schwinger to HIC/QCD

QED: [Kluger, Eisenberg, Svetitsky, Cooper, Mottola (1990s)]
QCD: [HT, Ph. D thesis (2017)]

✔ Mean-field treatment of the backreaction problem

Maxwell eq. $\partial_\mu F^{\mu\nu} = \bar{\psi}\gamma^\nu\psi$

Dirac eq. $[i\partial - eA - m]\psi = 0$

Split the total EM field A into strong $\bar{A} = \langle A \rangle$
and quantum fluctuation a as $A = \bar{A} + a$

Maxwell eq. for $\bar{A}$ $\partial_\mu \bar{F}^{\mu\nu} = \langle \bar{\psi}\gamma^\nu\psi \rangle$

Maxwell eq. for a $\partial_\mu f^{\mu\nu} = \bar{\psi}\gamma^\nu\psi - \langle \bar{\psi}\gamma^\nu\psi \rangle$

Dirac eq. $[i\partial - e\bar{A} - m]\psi = ea\psi$

annoying…

Mean-field approximation $\mathrm{RHS} \to \langle \mathrm{RHS} \rangle$

Maxwell eq. for $\bar{A}$ $\partial_\mu \bar{F}^{\mu\nu} = \langle \bar{\psi}\gamma^\nu\psi \rangle$

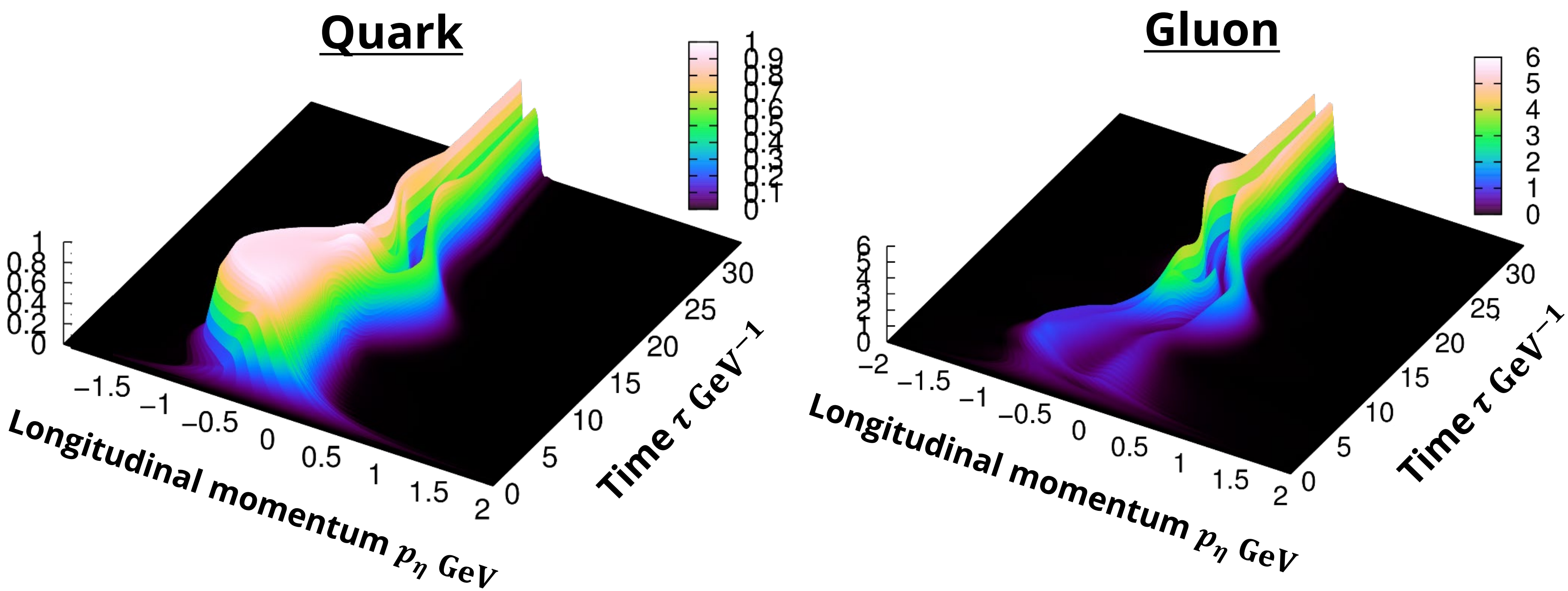
Maxwell eq. for a $\partial_\mu f^{\mu\nu} = 0$

Dirac eq. $[i\partial - e\bar{A} - m]\psi = 0$

Solvable !
(numerically)

Result: Particle distribution

Longtidinal distribution $\dfrac{d^6N}{dx_T^2 d\eta \, dp_T^2 dp_\eta}$ **at** $p_T \sim 0$



- ✔ Plasma oscillation + Pauli blocking & Bose enhancement + Redshift by expansion
- ✔ Particle yield after momentum integration ~ 1000 particles/rapidity

  ⇒ consistent with exp. ⇒
  - Schwinger effect is the mechanism of the particle prod. in HIC
  - QED technique is actually useful
- ✔ But, not the end: mean-field theory does not explain thermalization

  ⇒ need to go beyond mean-field ⇒ needs your inputs !

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(2) The knowledge of strong-field QED can be used to understand heavy-ion coll.

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Different creation mechanisms at high and low energies

⇒ strong B field at high energy, strong E field at low energy

3. Open question in HIC, related to strong color physics

Non-equilibrium dynamics of QGP formation

⇒ Schwinger effect nicely explains
the particle-production process in HIC
but needs more to describe
the thermalization/hydrodynamization process