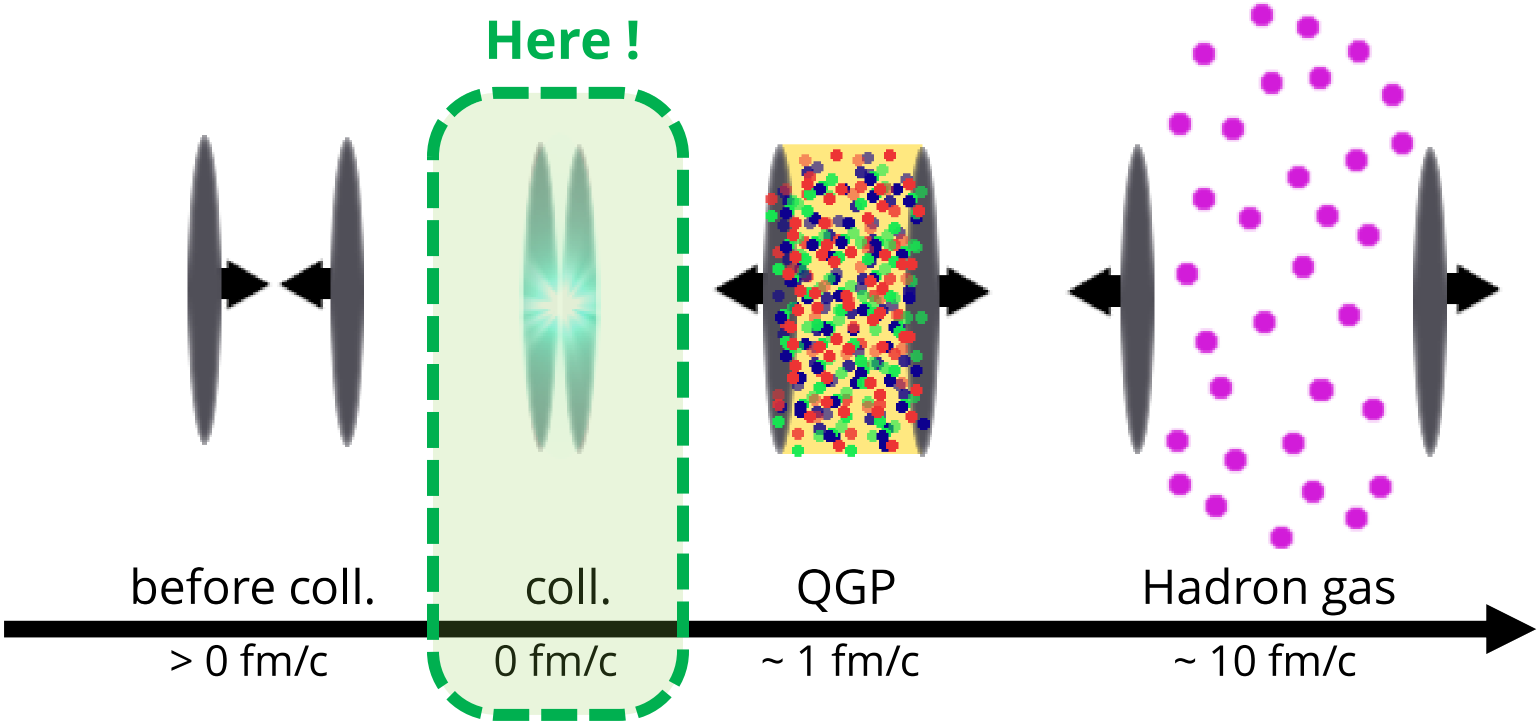
Initial state and Early time dynamics

Hidetoshi Taya

Keio University

Contents



Rich & important physics in the early-time dynamics of HIC

- gluon saturation (color glass condensate)
- strong color field (glasma)
- strong EM field
- ...

} origin of the QGP in HIC (gluon saturation, strong color field)

} provide opportunity to study "new physics" (strong EM field)

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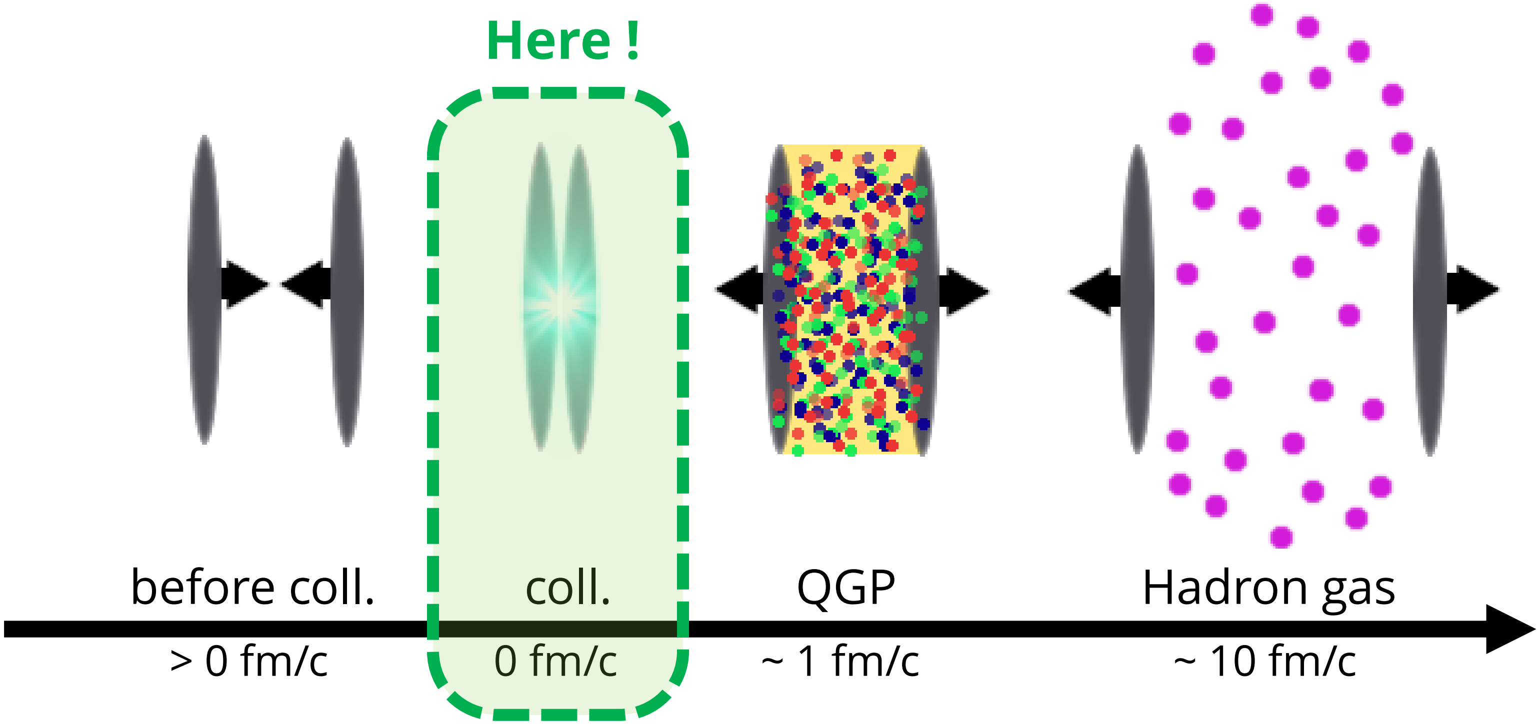

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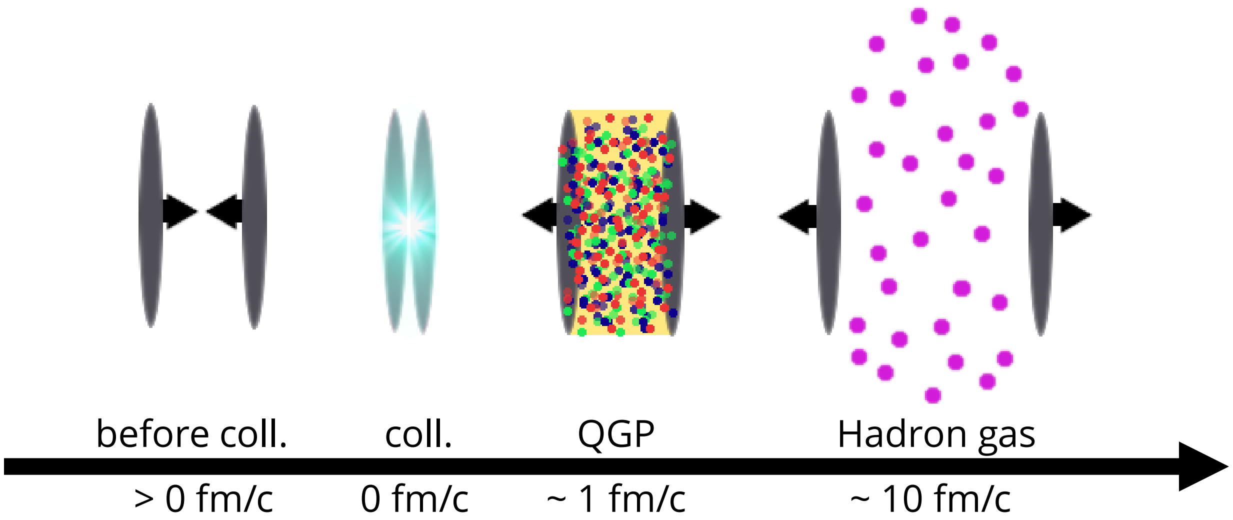

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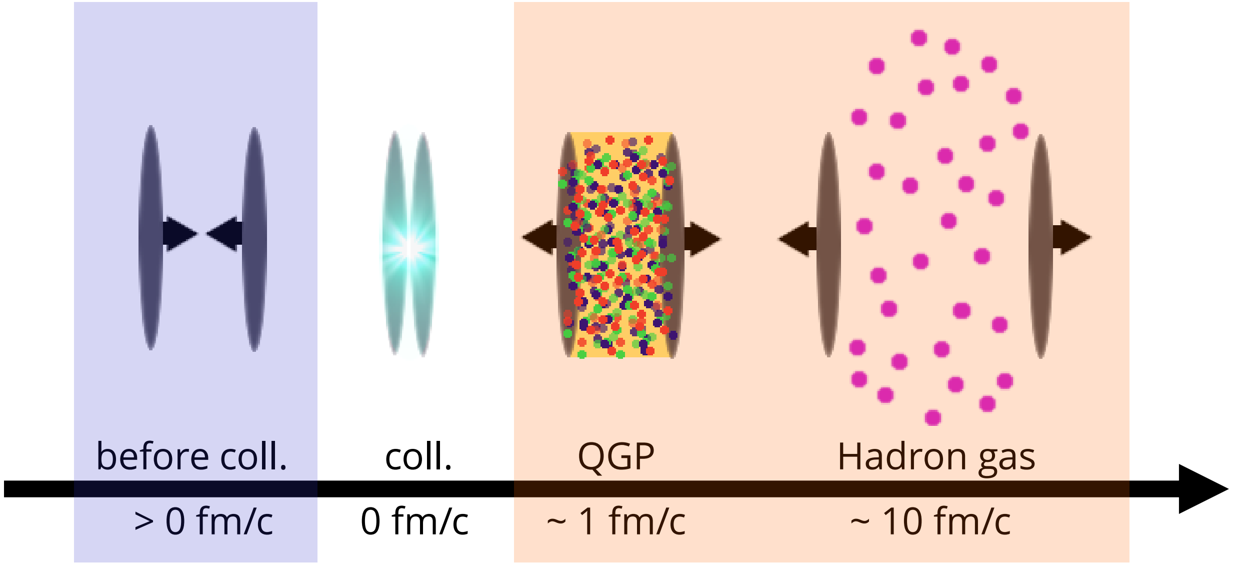

✔ ■ & ■ : well understood

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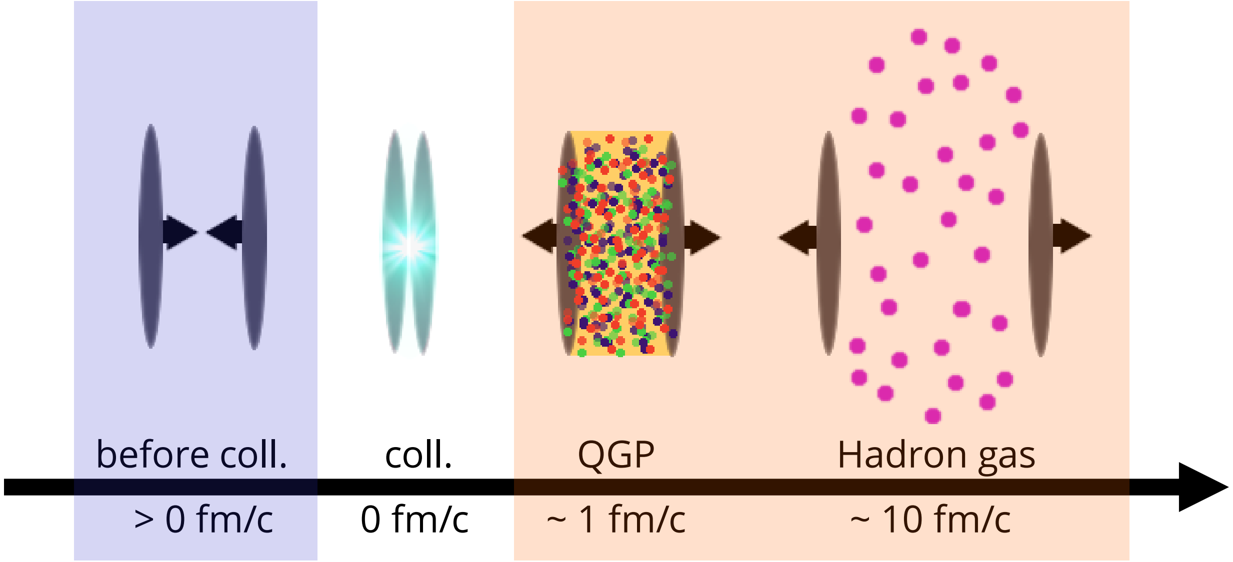

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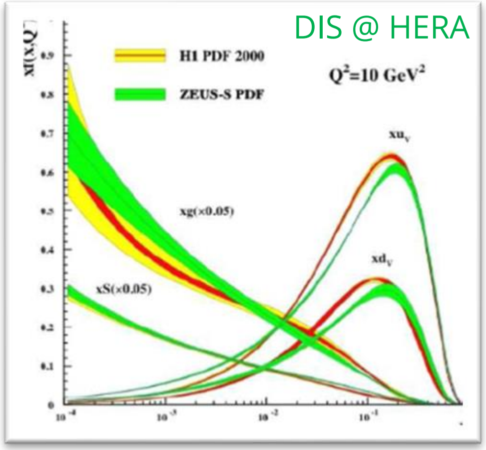

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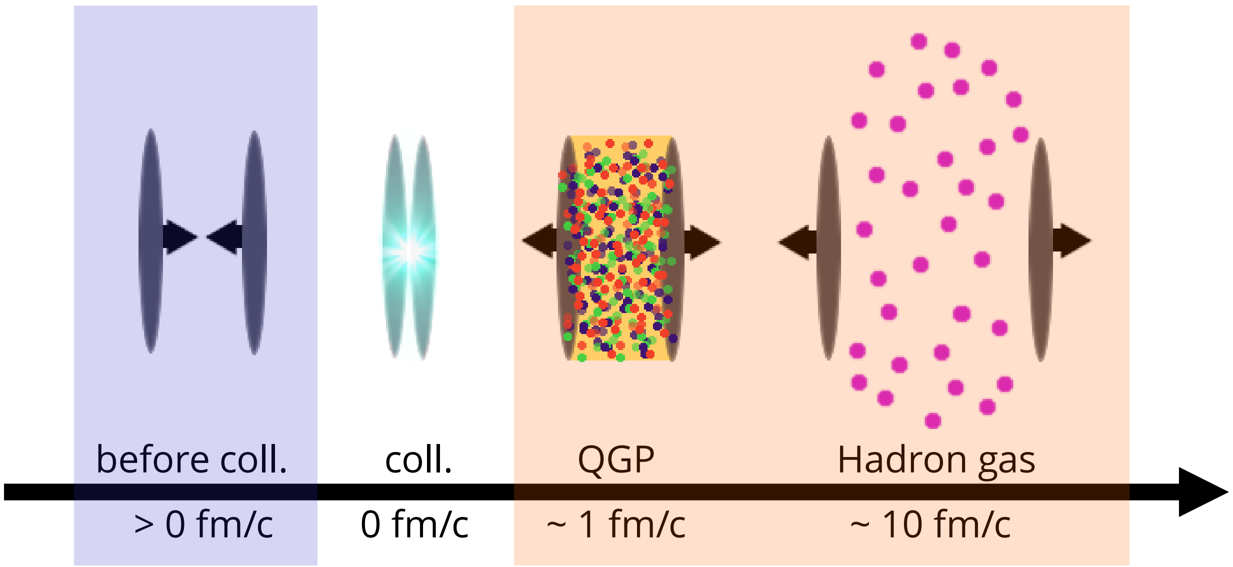

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- **Dense gluons**
  (color glass condensate ?)
- **Theory: pQCD**

(* will be studied further with EIC)

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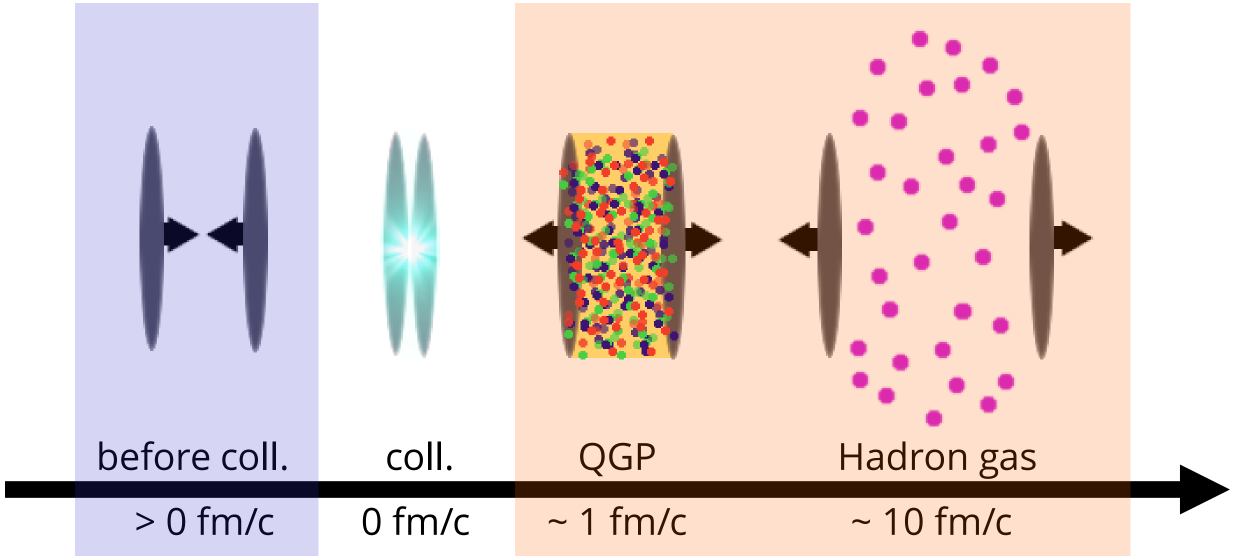

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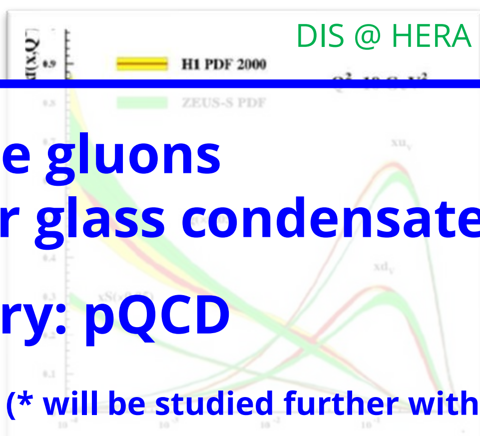

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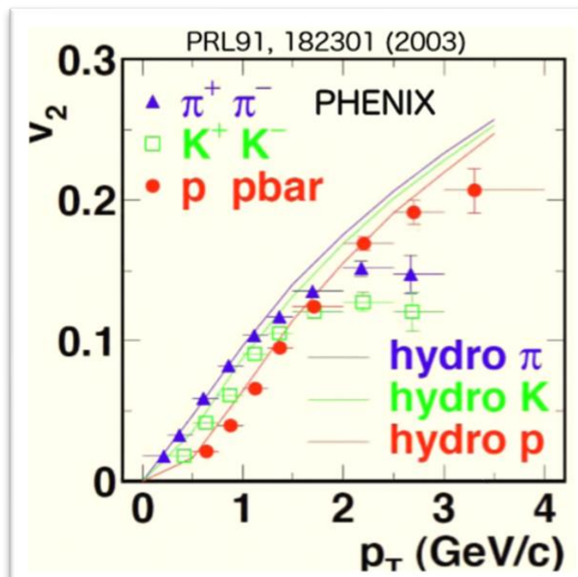

- elliptic flow

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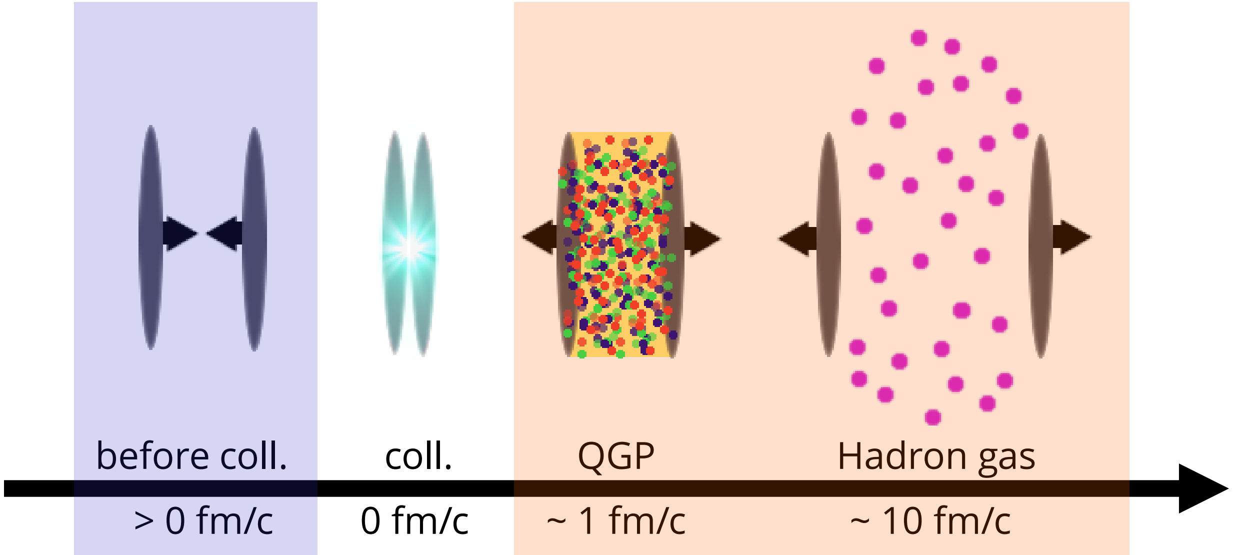

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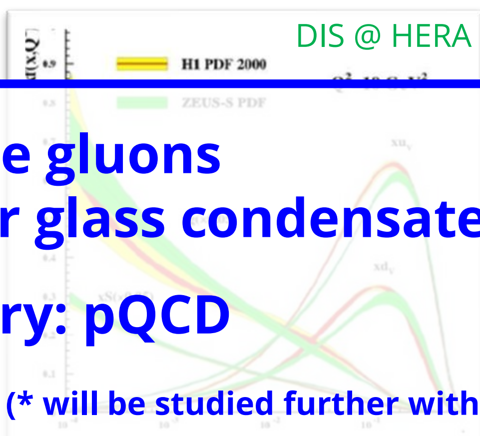

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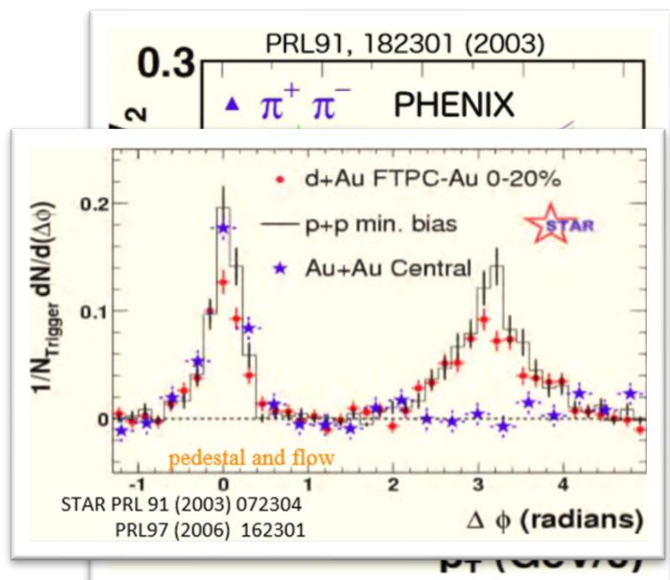

- elliptic flow
- jet quenching

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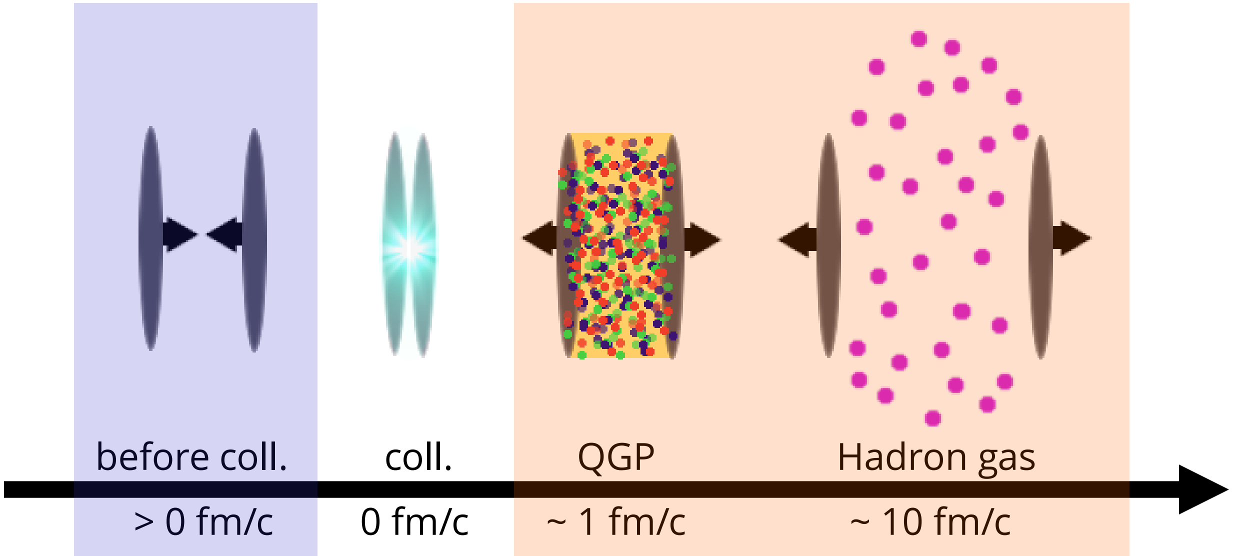

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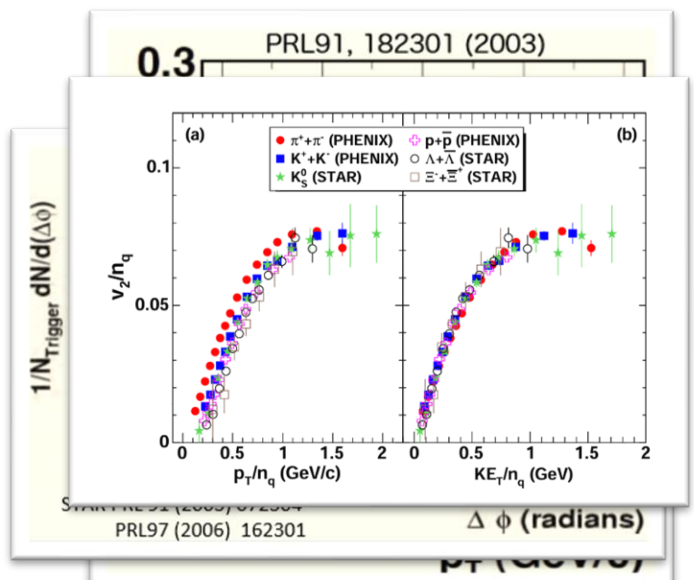

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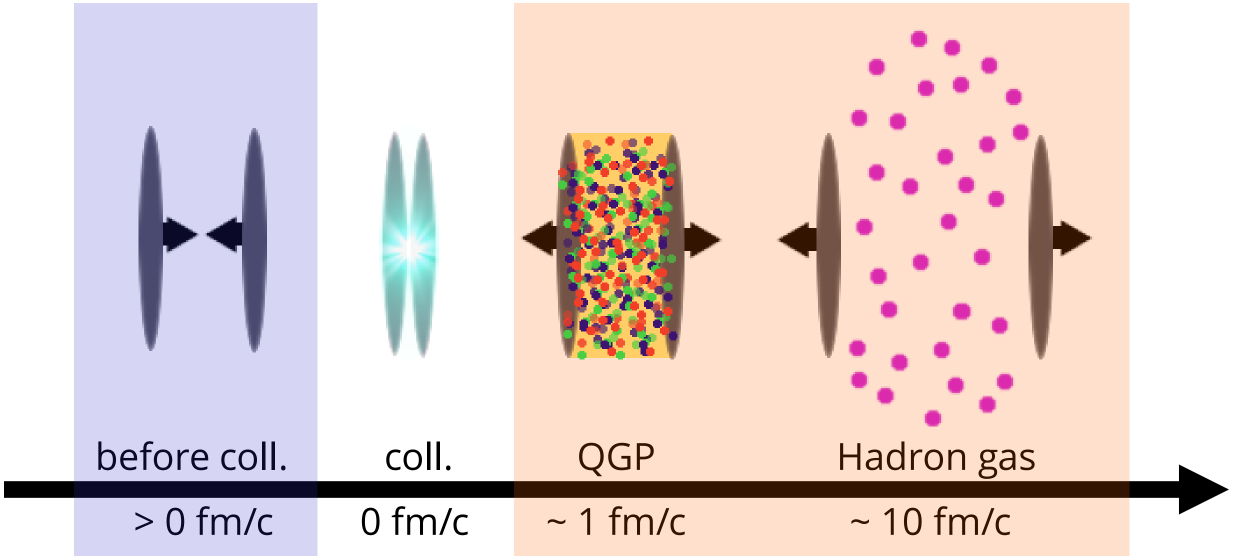

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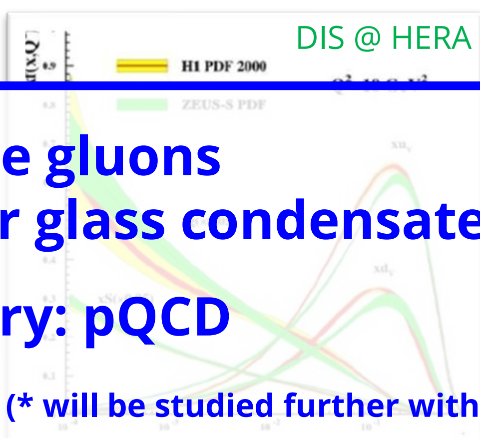

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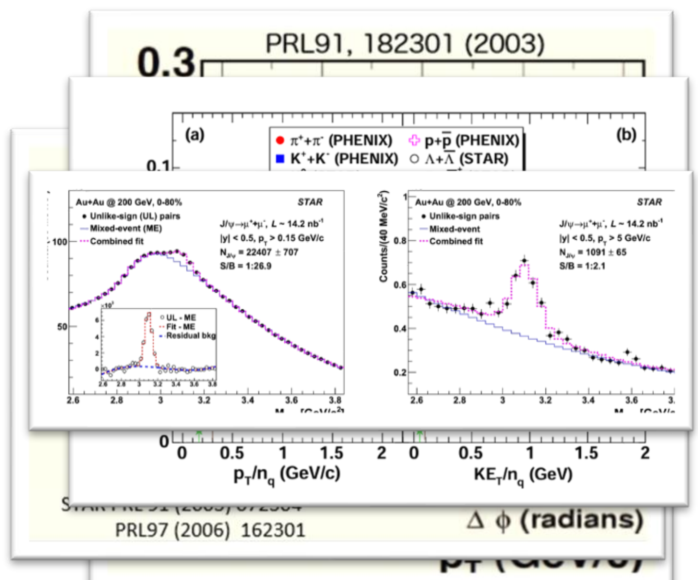

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- quark # scaling
- J/ψ suppression

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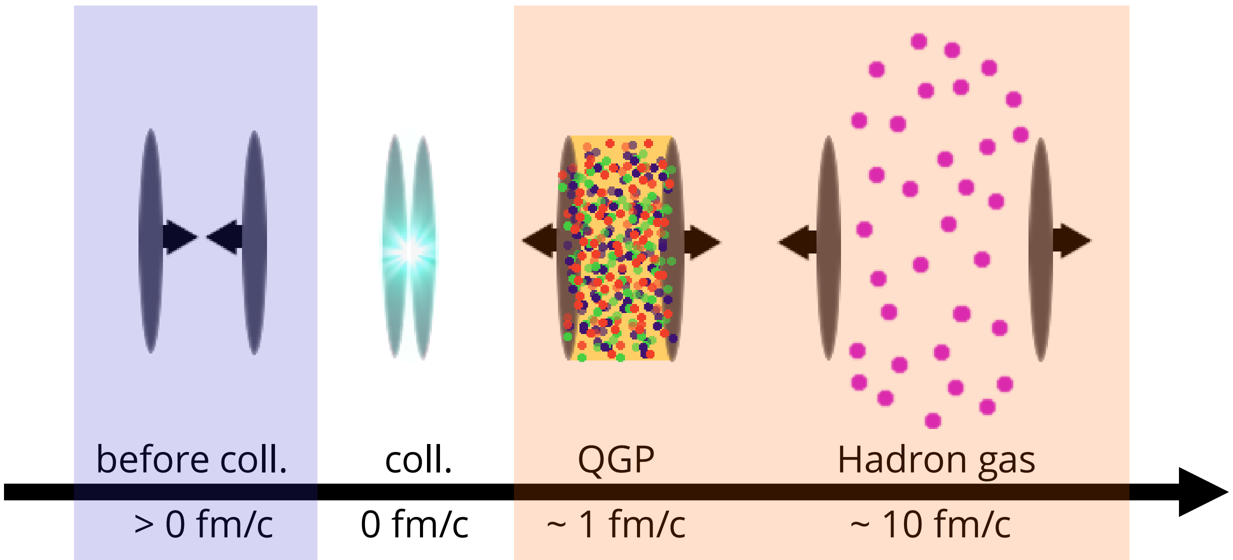

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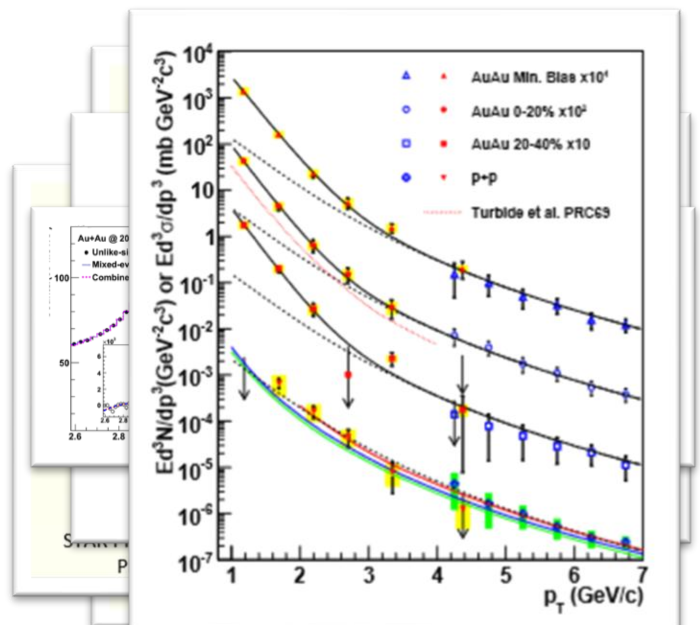

- elliptic flow
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- quark # scaling
- J/ψ suppression
- thermal photon
- …

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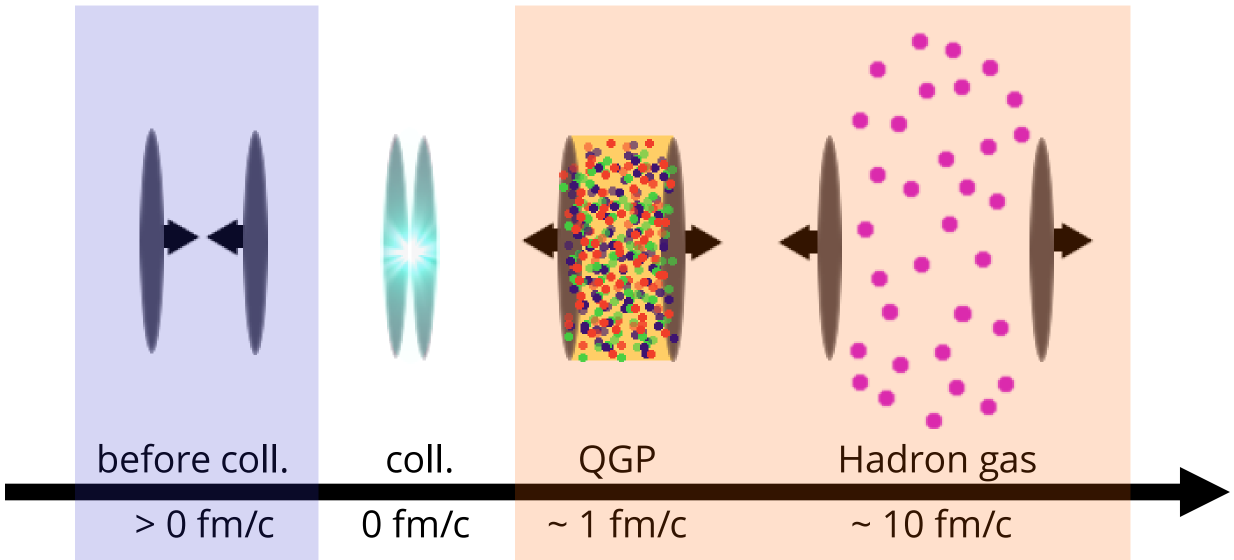


✔ ■ & ■ : well understood

DIS @ HERA

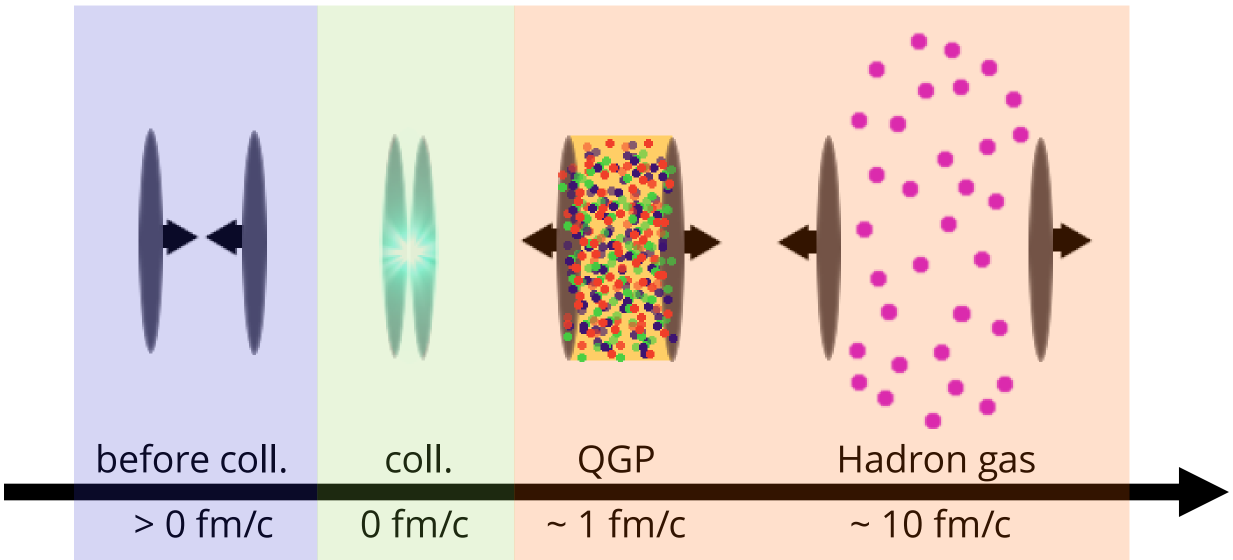
- **Dense gluons (color glass condensate ?)**
- **Theory: pQCD**

(* will be studied further with EIC)

- **QGP created**
  (=: matter composed of deconfined quark & gluons)
- **QGP is a (nearly) perfect liquid**
- **Theory: Hydrodynamics (+ hadron transport)**

- elliptic flow
- jet quenching
- quark # scaling
- J/ψ suppression
- thermal photon
- …

QGP formation dynamics = a big missing link in HIC

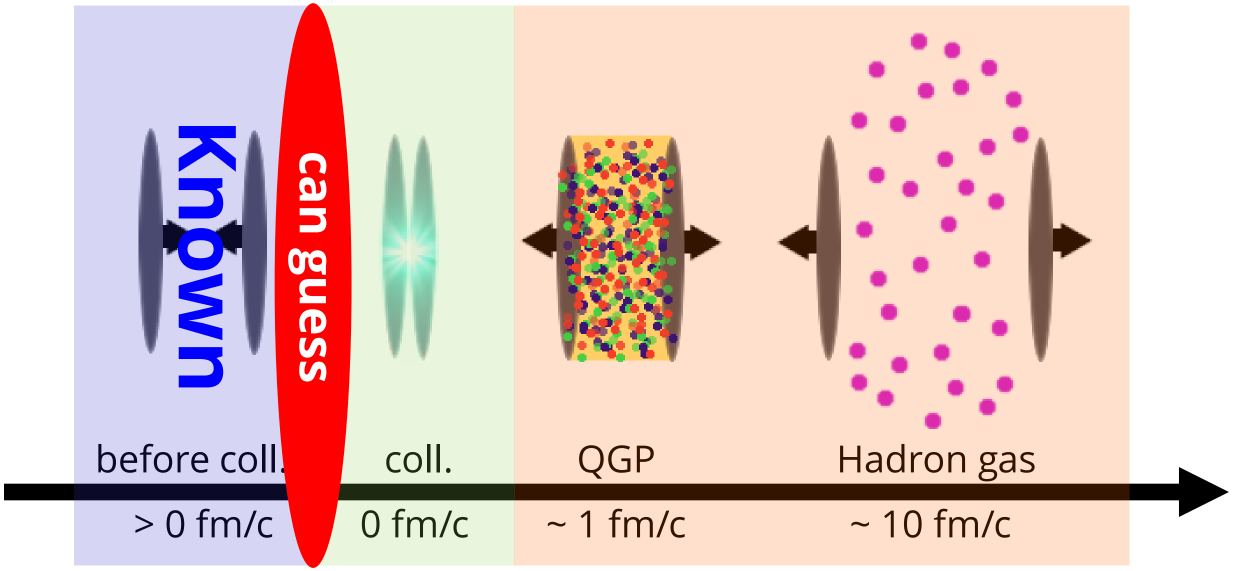


✔ ■ & ■ : **well understood**

✔ ■ : **No established physics picture nor theory**

- Many open questions, e.g.,
  - How are the huge number of quarks & gluons produced dN/dy=O(1000) ?
  - How do they thermalize/hydrodynamize to form the liquid-like QGP ?
  - How to explain the "early thermalization" O(1fm/c), indicated by exp data ?
  - How to make a more realistic initial condition for hydro ?
  - How to probe the early time experimentally ?
- But had a lot of progress in the last decade !

Strong color field (glasma) is the key



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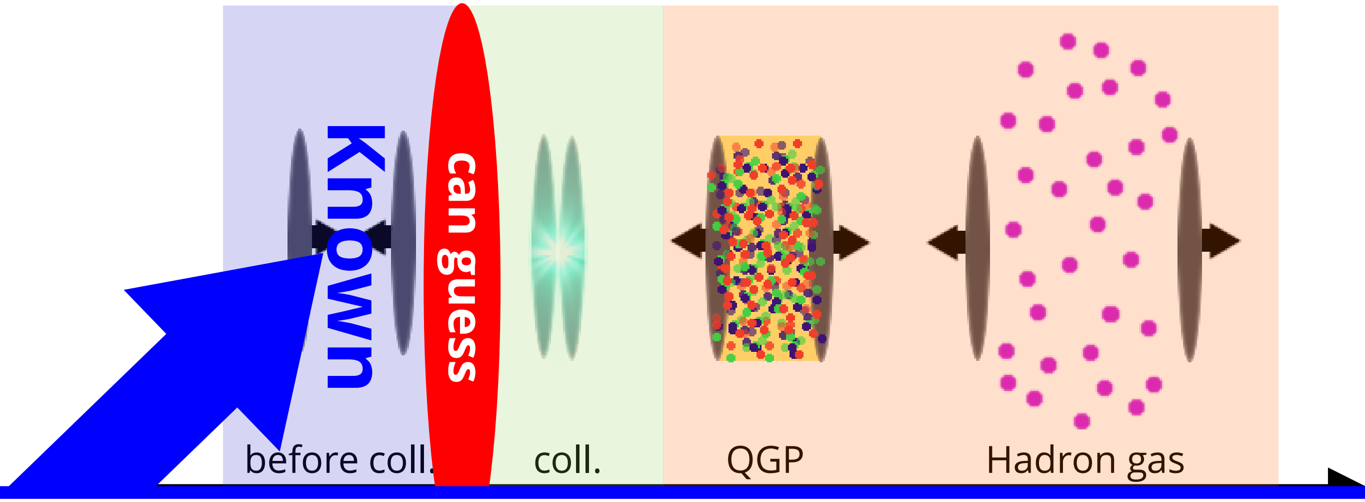
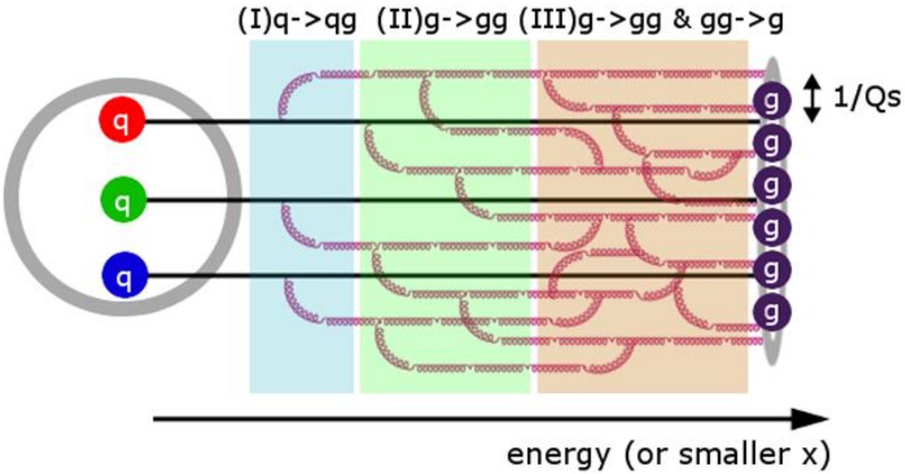


High-energy nucleus = a dense gluon state ≈ a "color capacitor plate"

- **Non-linearity of gluon**



- **Large color charge density**

$$\sigma \sim Q_s^2 = O(1\ \mathrm{GeV}^2)$$

since the saturation condtion is

$$\underbrace{\underbrace{\frac{\alpha_S}{Q_s^2}}_{\text{cross sect. per a gluon}} \times \underbrace{xG_A}_{\text{gluon dist. func.}}}_{\text{total size of the gluons}} \sim \underbrace{R_A^2}_{\text{size of the nucleus}} \Rightarrow Q_s = O(1\ \mathrm{GeV}\ \ )$$

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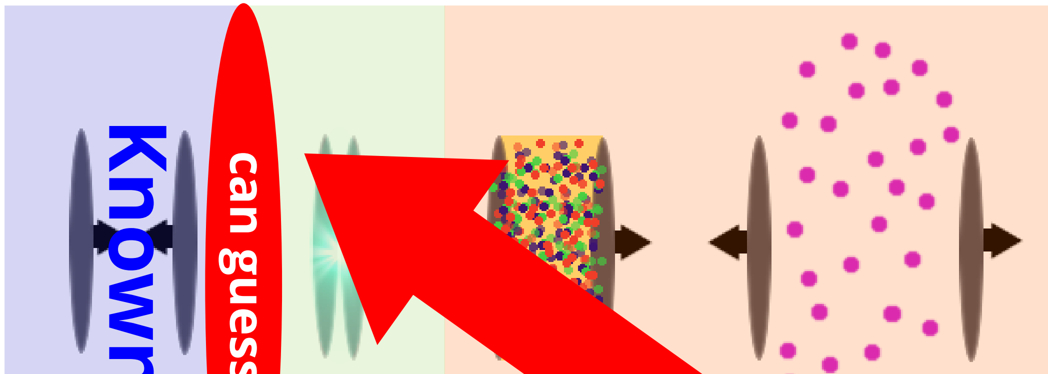


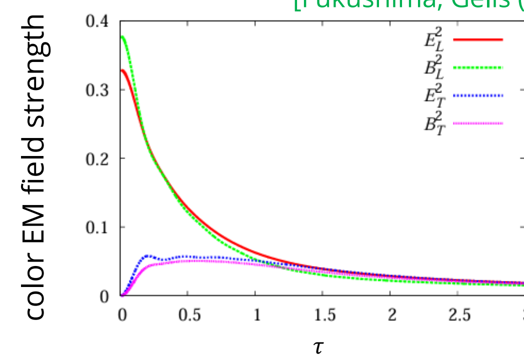
[Lappi, McLerran (2006)]

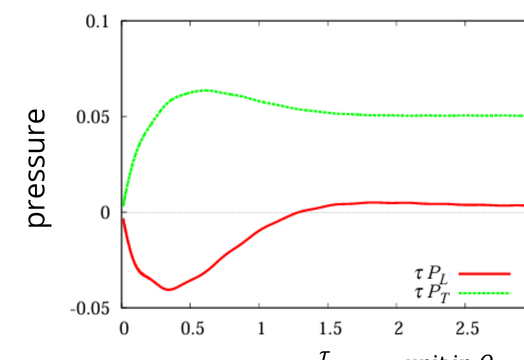
Formation of a "colored capacitor" ⇒ Strong color field (= glasma)

⇒

Solve classical Yang-Mills eq.

[Fukushima, Gelis (2011)]





unit in $Q_s = O(1\ \mathrm{GeV})$

Key features of glasma:

(1) Longitudinal color fields

(2) Very strong: $g\boldsymbol{E}, g\boldsymbol{B} \propto \sigma^2 \propto Q_s^2 = O(1\ \mathrm{GeV}^2)$

(3) Very anisotropic and never isotropitized

(4) Topological $\boldsymbol{E} \cdot \boldsymbol{B} \neq 0$

How glasma turns into QGP ?

Many scenarios:

Reviews: [Fukushima 1603.02340] [Schlichting, Teaney 1908.02113] [Berges et al. 2005.12299] [Gelis 2102.07604] …

may roughly be categorized into 3 scenarios

- Strong-field scenario: instabilities of glasma
- Weak-coupling (particle-picture) scenario:
  kinetic description (bottom-up picture) + "hydrodynamization"
- Strong-coupling scenario: AdS/CFT

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Glasma is unstable ⇒ decays & isotropitizes spontaneously

both magnetic B- and electric E-fields can induce instabilities

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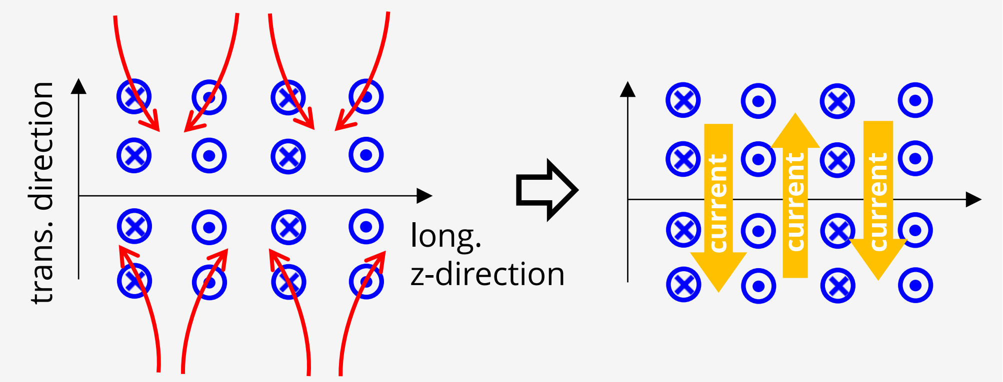
- **Microscopically, two mechanisms:**

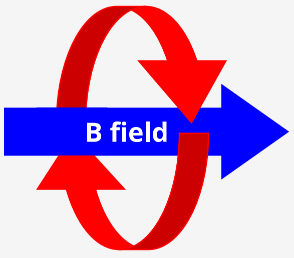
Weibel instability

Review: [Mrowczynski, Schenke, Strickland (2017)]



[Fujii, Itakura, Iwasaki (2008)]

Nielesen-Olesen instability



⇒ Landau quantization

$E = \sqrt{p_z^2 + p_T^2}$

$\to \sqrt{p_z^2 + (2n+1)gB - 2gBs}$

quantized trans. motion

Zeeman splitting

⇒ tachionic for LLL n=0, s=1, $p_z < \sqrt{gB}$

$E_{n=0,\,s=1} \sim \sqrt{-gB}$ ⇒ long. flct. grow as $e^{iEt} \sim e^{\sqrt{gB}t}$

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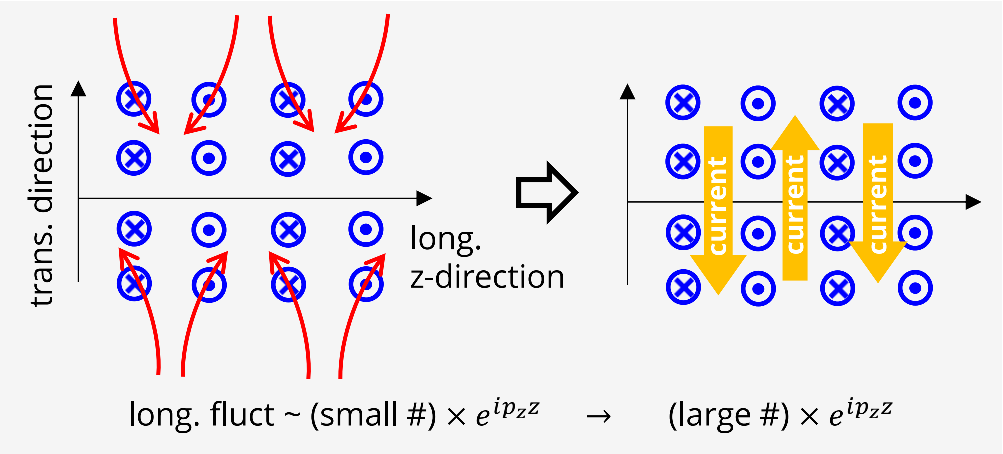

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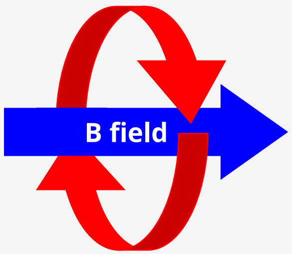

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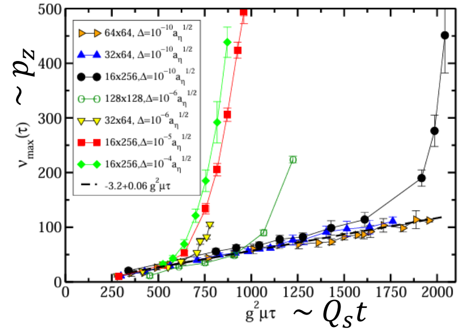
- **Can be studied numerically** [Romatschke, Venugopalan (2006)]

  ⇒ It exists, but so slow ($\sim 100/Q_s > 20$ fm$/c$)

  ⇒ could play some role
  but would not be the essence (within the current understanding)



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- **Especially important for particle (quark) production**

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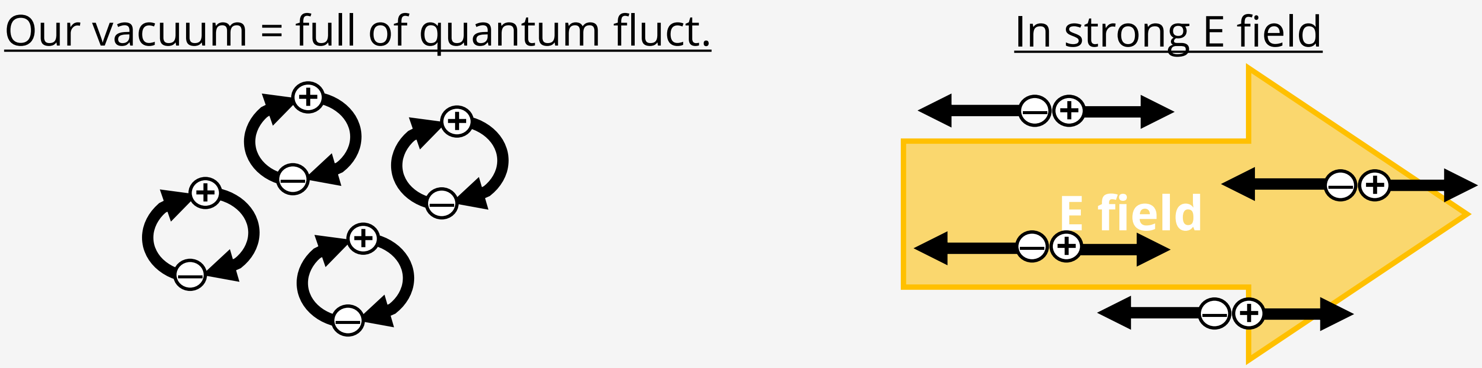
- **Mechanism: the Schwinger effect** [Gelis, Kajantie, Lappi, hep-th/049508 & 0508229] [Gelfand, Hebenstreit, Berges, 1601.03576] [HT, 1609.06189] [Tanji, Berges, 1711.03445]



E field supplies energy to tear the loop apart ⇒ pair particle production !

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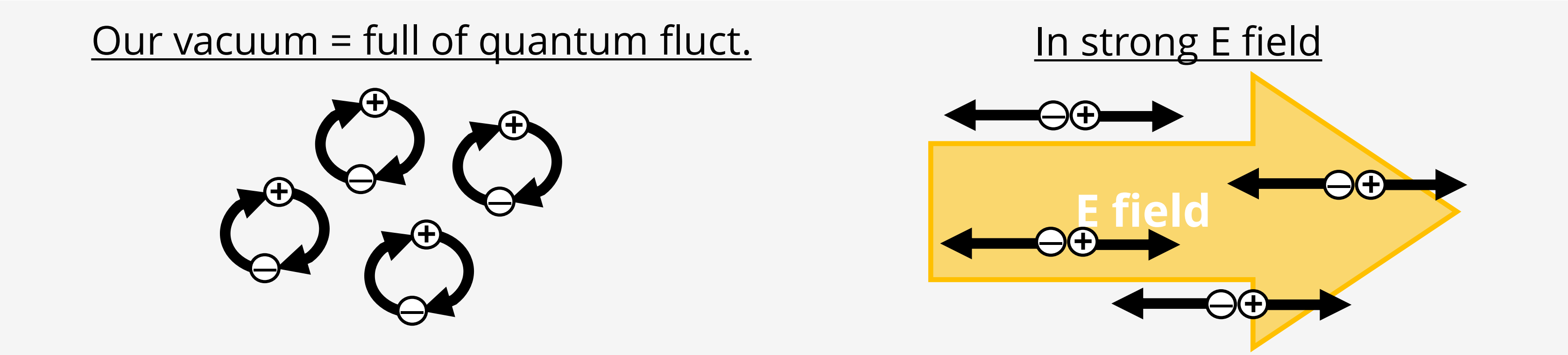


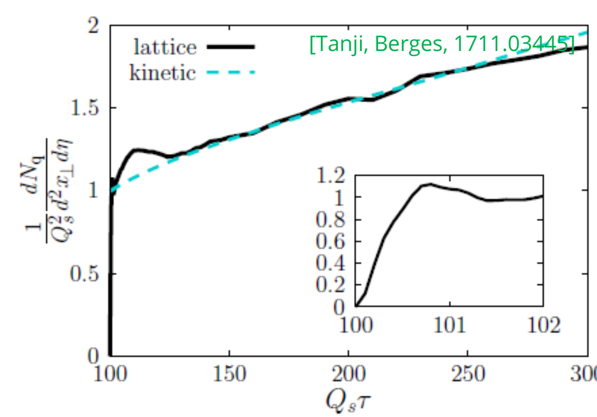
E field supplies energy to tear the loop apart ⇒ pair particle production !

- **Can be studied numerically**

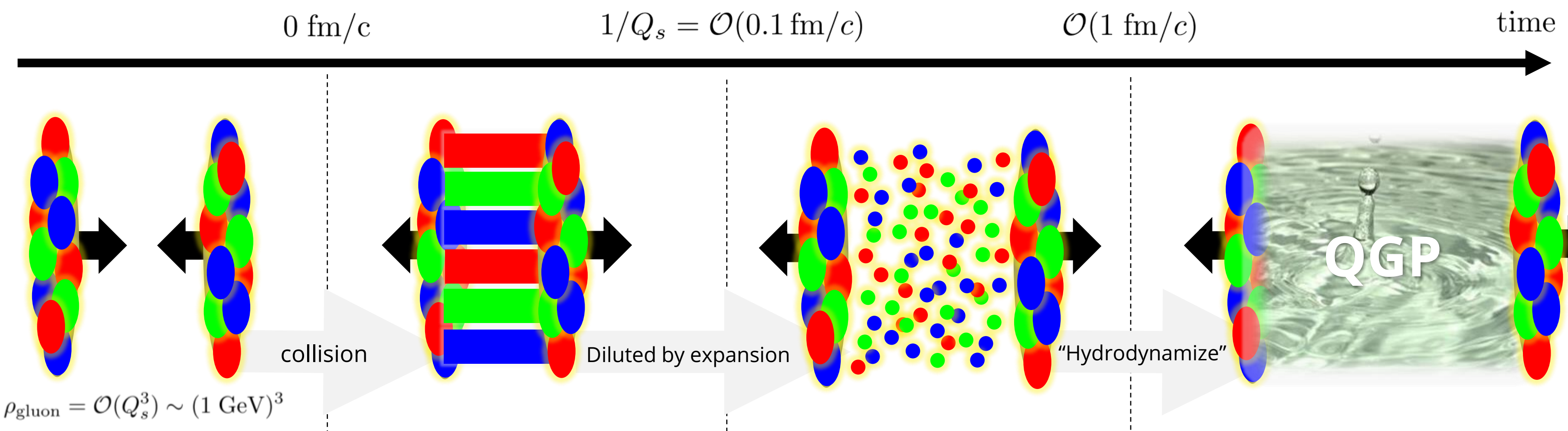
⇒ Very fast & huge quark production

$\because \tau \sim \frac{m}{gE} \sim \frac{m}{Q_s^2} \ll Q_s^{-1} \sim 0.1\ \mathrm{fm}/c$

⇒ important for chemical equilibration and also for μ5



Weak-coupling scenario: particle + hydrodynamization



Gluon saturation
➡ pQCD (CGC)

Strong color flux tube (Glasma)
➡ Classical YM (+ fluctuation)

Parton matter
➡ kinetic theory

Quark-gluon plasma
➡ Hydrodynamics

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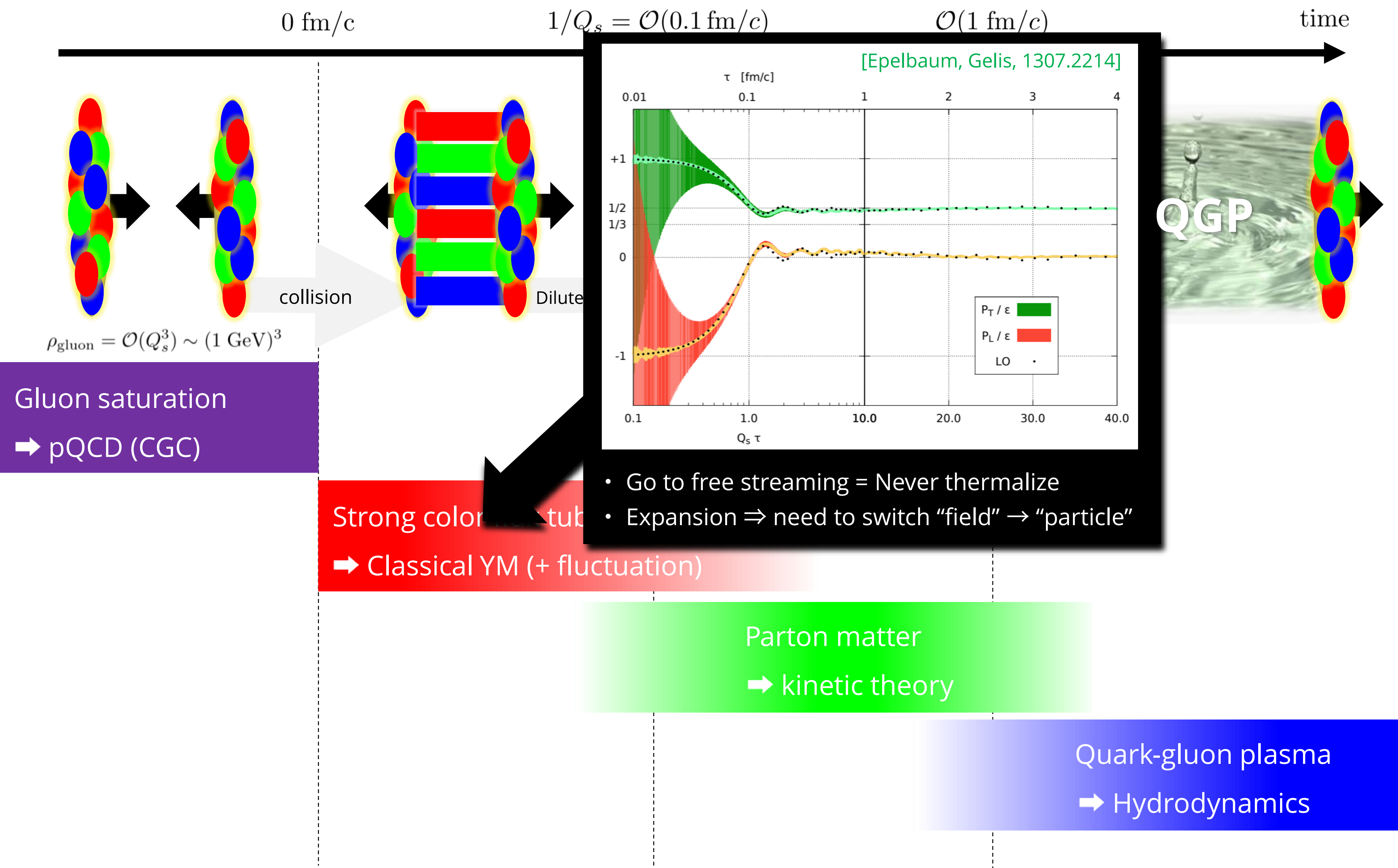
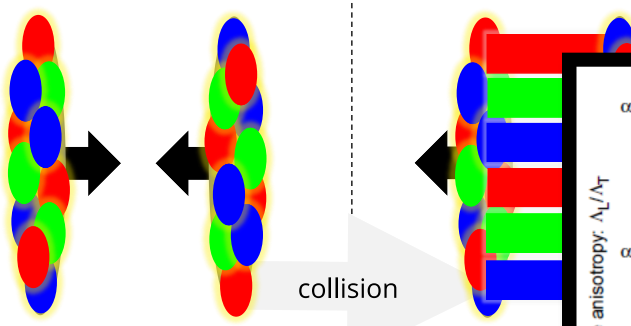


Weak-coupling scenario: particle + hydrodynamization

0 fm/c — $1/Q_s = \mathcal{O}(0.1\,\mathrm{fm}/c)$ — $\mathcal{O}(1\,\mathrm{fm}/c)$ — time



$\rho_{\mathrm{gluon}} = \mathcal{O}(Q_s^3) \sim (1\,\mathrm{GeV})^3$

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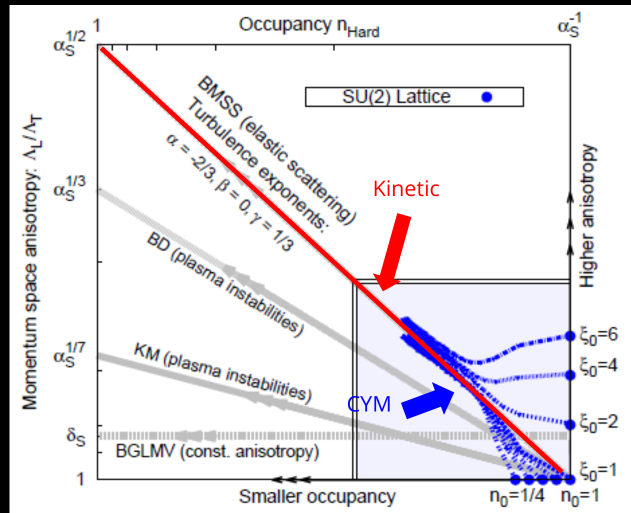
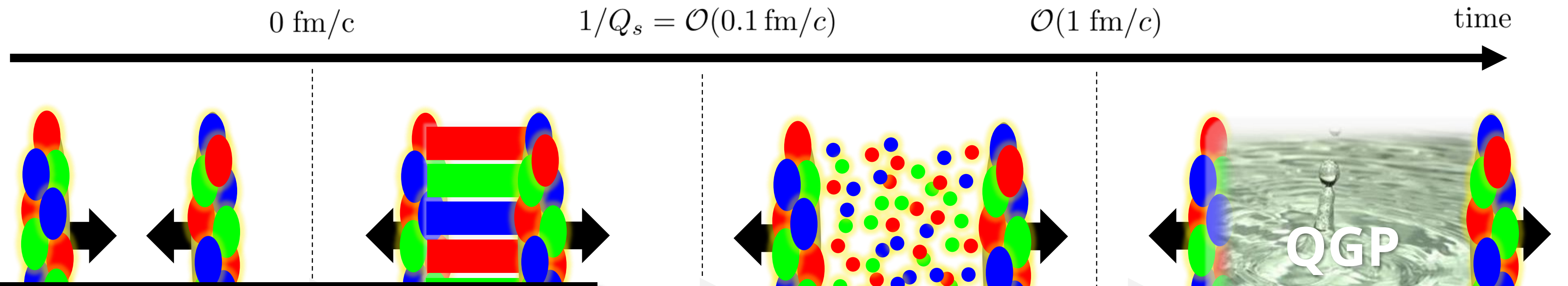
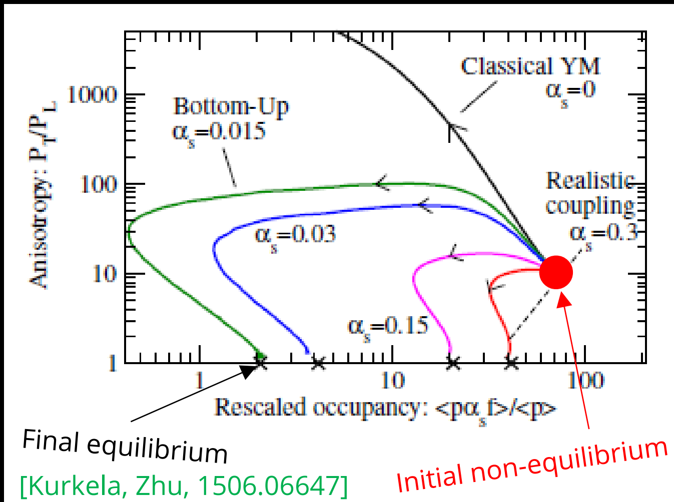


- CYM and kinetics are smoothly connected with each other
  - overlap at $1/g^2 \gg f \gg 1$
    [Mueller, Son, hep-ph/0212198]
    [Jeon, hep-ph/0412121]
  - consistent with bottom-up scenario
    [Baier, Mueller, Schiff, Son, hep-ph/0009237]
  - non-thermal attractor
    [Berges, Boguslavski, Schlichting, Venugopalan, 1303.5650]

Weak-coupling scenario: particle + hydrodynamization





- Kinetic theory of QCD (AMY) [Arnold, Moore, Yaffe, hep-ph/0209353] does describe isotropization & thermalization
- BUT, the time scale is too slow $\tau \sim 10\ \mathrm{fm}/c$

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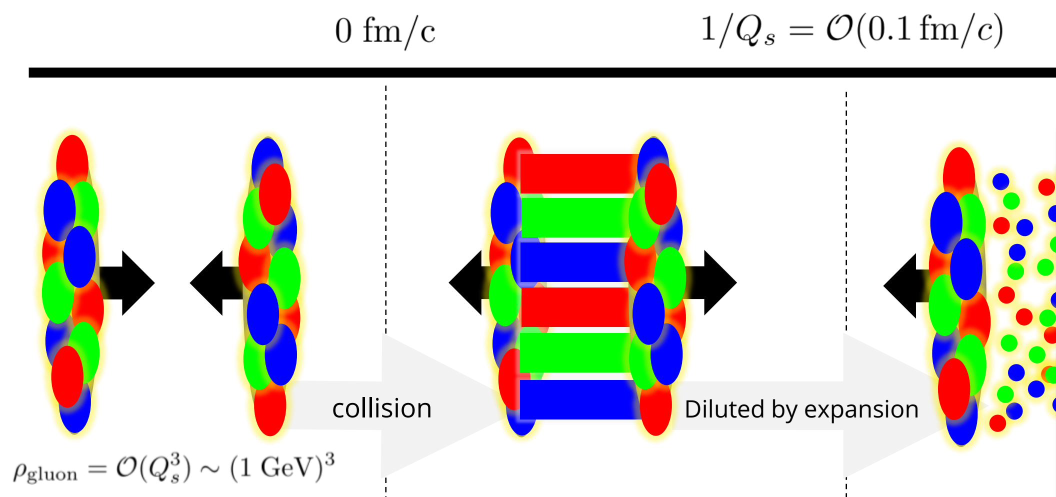

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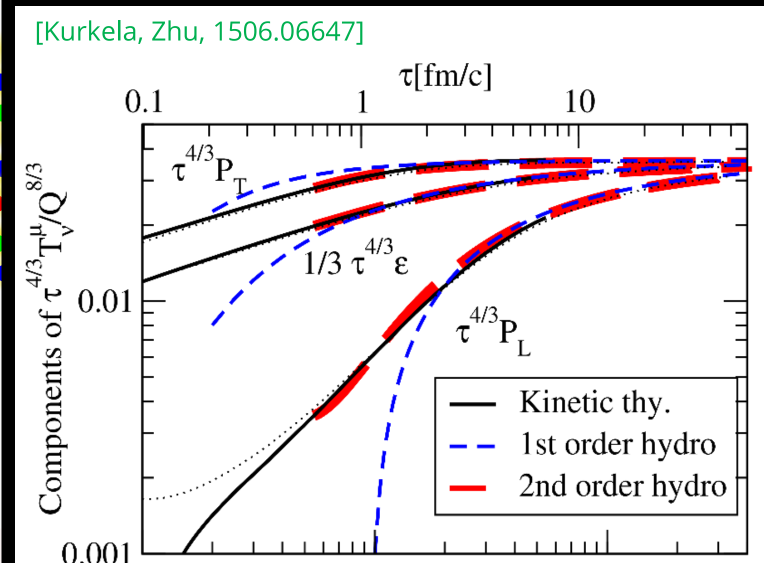
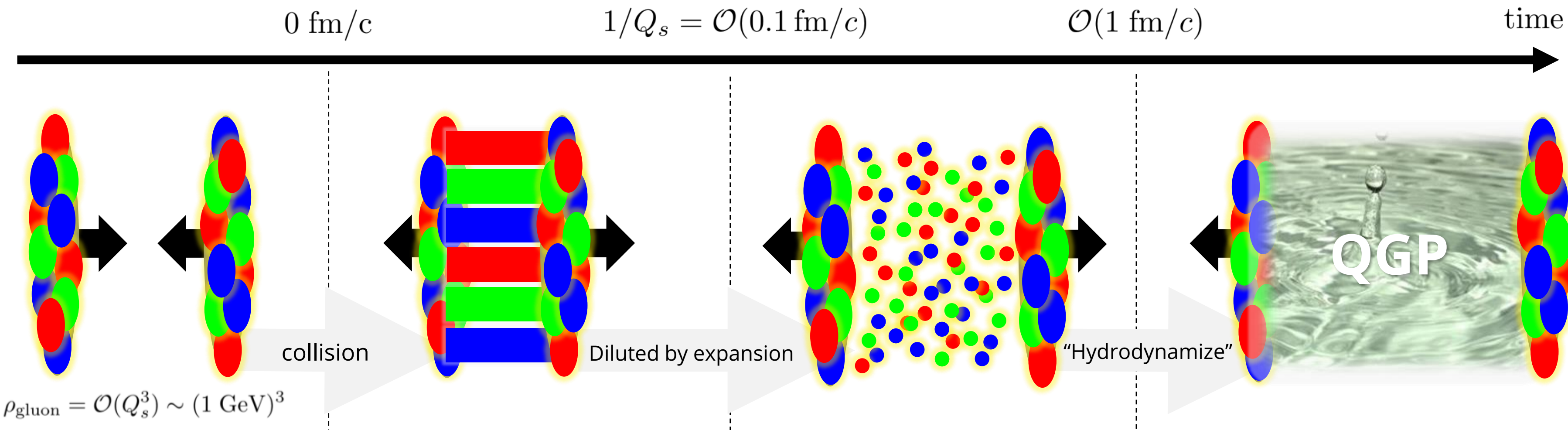


- Hydrodynamics works even away from thermal equilibrium = "hydrodynamization"
  [Heller, Spalinski, 1503.07514] [Romatschke, 1704.08699]
- $\tau_{\mathrm{hydro}} \ll \tau_{\mathrm{therm.}}$: $\tau_{\mathrm{hydro}} \sim O(1)\ \mathrm{fm}/c$

Weak-coupling scenario: particle + hydrodynamization



Gluon saturation
➡ pQCD (CGC)

Strong color flux tube (Glasma)
➡ Classical YM (+ fluctuation)

Parton matter
➡ kinetic theory

Quark-gluon plasma
➡ Hydrodynamics

Short summary: QGP formation

✔ **Still incomplete but had a lot of progress in the last decade**

- How are the huge number of quarks & gluons produced dN/dy=O(1000) ?
- How do they thermalize/hydrodynamize to form the liquid-like QGP ?
- How to explain the "early thermalization" O(1fm/c), indicated by exp data ?

} This lecture

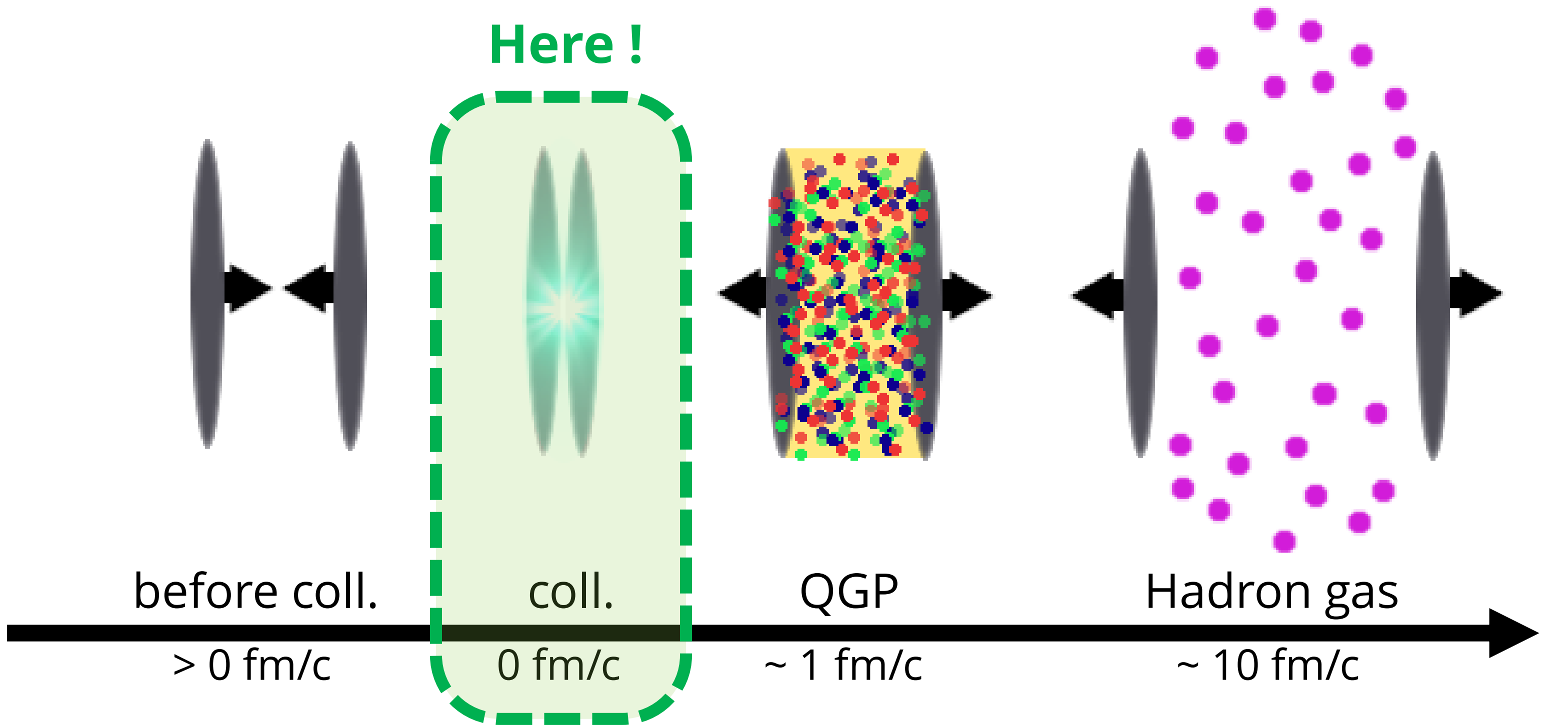
- How to make a more realistic initial condition for hydro ?
- How to probe the early time experimentally ?

} This conference ! (KΦMPOST, … dilepton, photon, quarkonia, …)

✔ **Key ideas**

- The very first stage is described by glasma
- Glasma is unstable
- Nice development in the weak-coupling scenario
- Hydrodynamization: applicability of hydro ≠ local thermal equilibrium

Contents



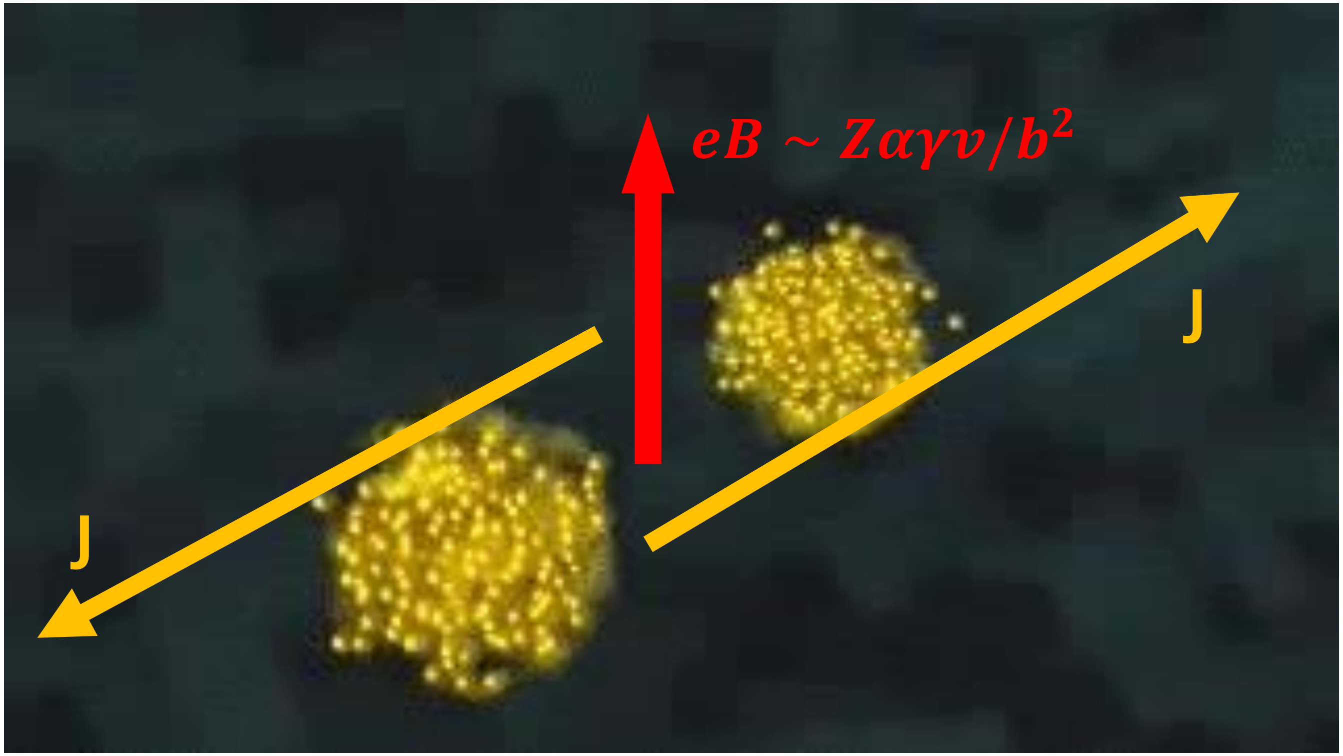
Rich & important physics in the early-time dynamics of HIC

- gluon saturation (color glass condensate)
- strong color field (glasma)

} origin of the QGP in HIC

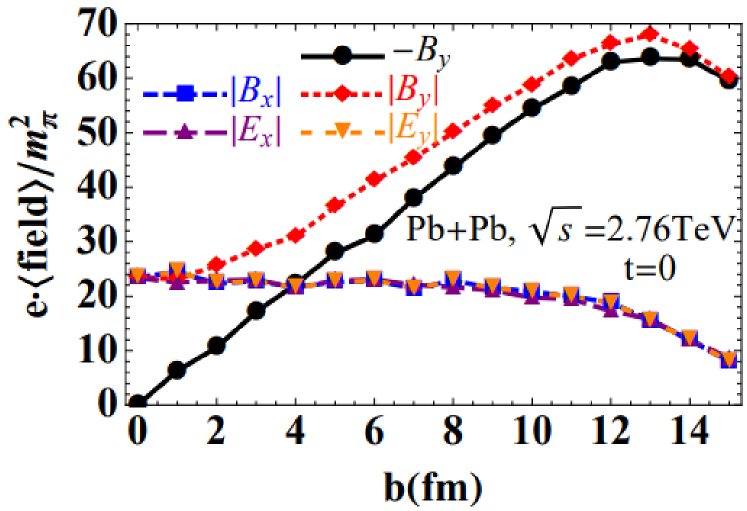
- strong EM field } provide opportunity to study "new physics"
- ...

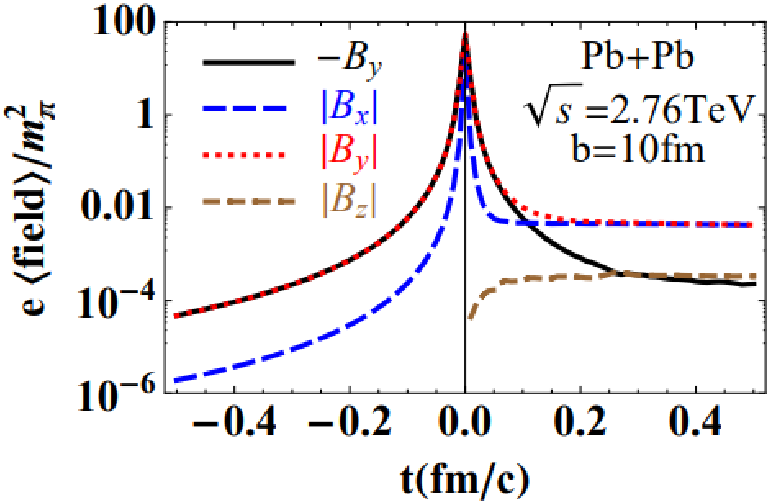
How strong EM field produced ?



Energetic ⇒ Large current ⇒ Strong magnetic field

How strong EM field produced ?





[Deng, Huang (2012)]

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

Energetic ⇒ Large current ⇒ Strong magnetic field

Pros: Very strong $eB \gg \Lambda_{\rm QCD}^2$

Cons: Extremely short-lived $\tau \ll 0.1\ \mathrm{fm}/c$

HIC is the strongest !

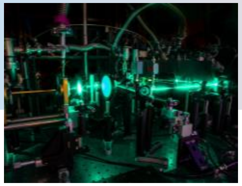
LED

$eE, eB \sim (10^{-3}\mathrm{eV})^2$

Laser welding

$\sim (10^{-1}\mathrm{eV})^2$

Nonlinear optics
(THz laser)



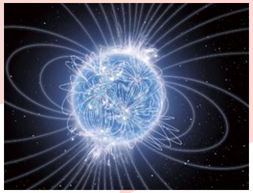
$\sim (1\ \mathrm{eV})^2$

Guiness record

HERCULES laser
@ USA (2008)

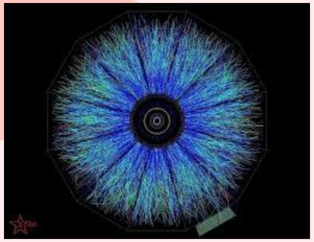
$\sim (1\ \mathrm{keV})^2$

Magnetar



$\sim (100\ \mathrm{keV})^2$

Heavy-ion collisions



$\sim (100\ \mathrm{MeV})^2$

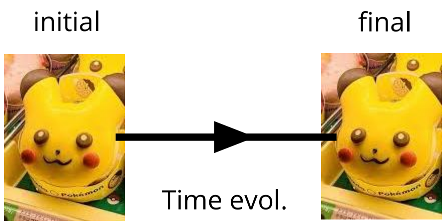
⇒ A unique environment to study “strong-field physics”

Why strong-field physics interesting ?

Stronger ⇒ More non-linearity (or non-perturbativity) **⇒ New physics**

Why strong-field physics interesting ?

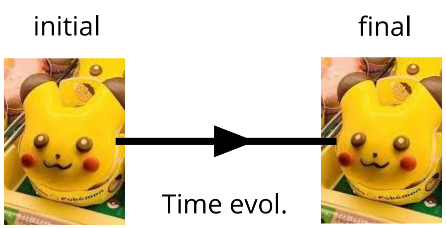
Stronger ⇒ More non-linearity (or non-perturbativity) ⇒ New physics



Vacuum

Why strong-field physics interesting ?

Stronger ⇒ More non-linearity (or non-perturbativity) ⇒ New physics



Vacuum

Weak field ($eF/m^2 \ll 1$)

Strong field ($eF/m^2 \gg 1$)

Why strong-field physics interesting ?

Stronger ⇒ More non-linearity (or non-perturbativity) ⇒ New physics

Vacuum | **Weak field ($eF/m^2 \ll 1$)** | **Strong field ($eF/m^2 \gg 1$)**

Perturbative

⇒ well understood
both theoretically
& experimentally

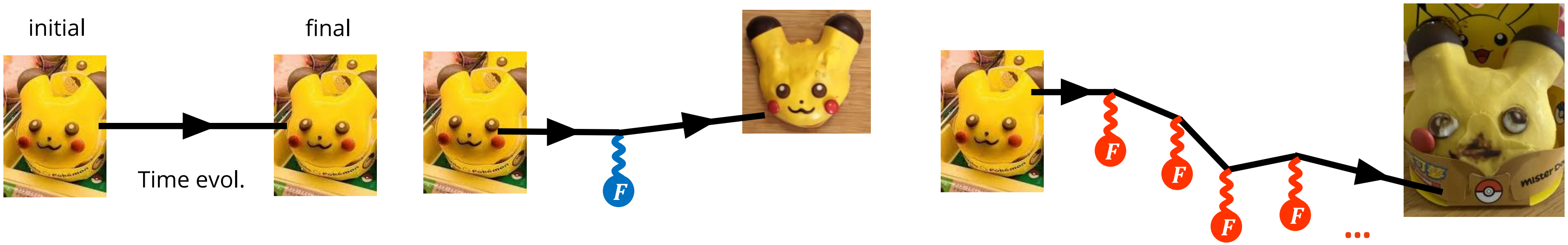
e.g., Electron anomalous magnetic moment

$$\alpha^{-1}(\text{theor.}) = 137.03599914\ldots$$
$$\alpha^{-1}(\text{exp.}) = 137.03599899\ldots$$

[Aoyama, Kinoshta, Nio (2017)]

Why strong-field physics interesting ?

Stronger ⇒ More non-linearity (or non-perturbativity) **⇒ New physics**



Vacuum **Weak field ($eF/m^2 \ll 1$)** **Strong field ($eF/m^2 \gg 1$)**

Perturbative

⇒ well understood
both theoretically
& experimentally

Non-linear/perturbative

⇒ beyond the pert. paradigm
⇒ "new physics"

e.g., Electron anomalous magnetic moment

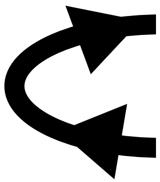
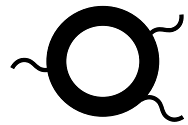
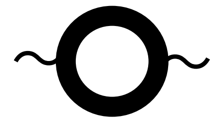
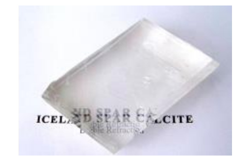
$$\alpha^{-1}(\text{theor.}) = 137.03599914\ldots$$
$$\alpha^{-1}(\text{exp.}) = 137.03599899\ldots$$

[Aoyama, Kinoshta, Nio (2017)]

Examples of strong-field physics

✔ **Novel QED processes** Review: [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson, 2203.00019]

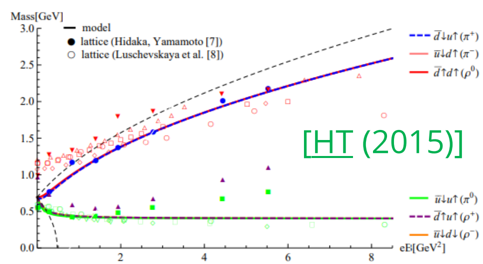
ex 1) Schwinger effect ex 2) Photon splitting ex 3) vacuum birefringence

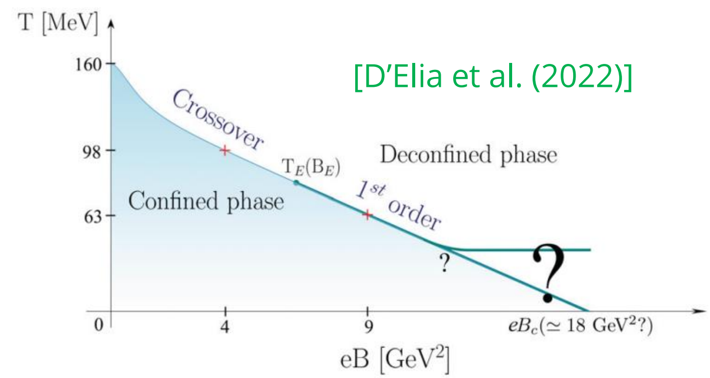
✔ **Can also affect QCD/hadron physics**

ex 1) hadron properties:

mass, form factor,
decay rate, …



[HT (2015)]



[D'Elia et al. (2022)]

ex 2) QCD phase diagram

novel phase, (inverse) magnetic catalysis, …

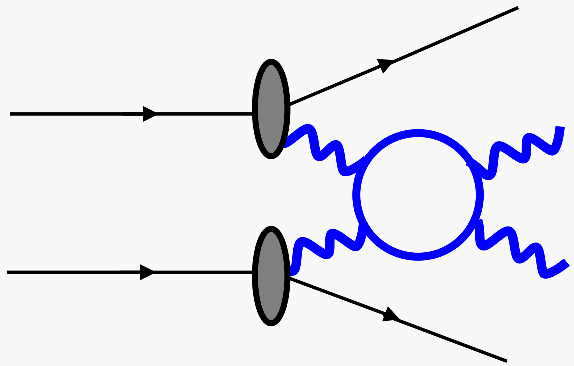
ex 3) Anomalous transport

chiral magnetic effect (CME), chiral magnetic wave (CMW), …

Lots of thy. predictions but none of them have been observed exp.
⇒ HIC can be a game changer

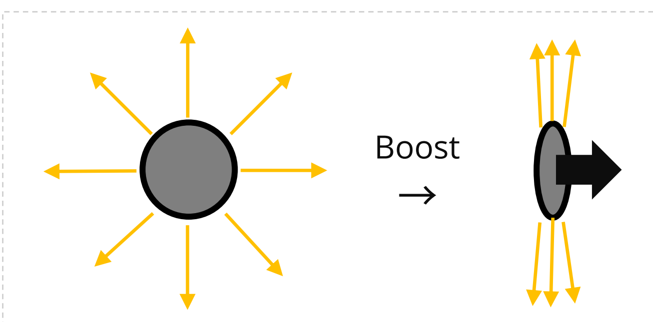
Discoveries of QED strong-field phenomena in HIC

Light-by-light scattering [ATLAS (2017)] **(linear) Breit-Wheeler process** [STAR (2021)]



- Nonlinear process ⇒ strong suppression α ⇒ never observed previously
- HIC has strong field ⇒ large photon density, compensating the suppression by α
- Theory: Equivalent photon approximation [Li, Zhou, Zhou (2019)]

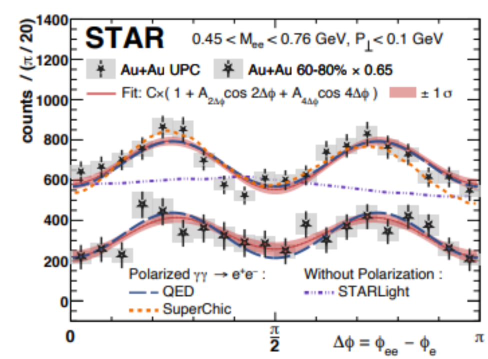
Idea: Highly boosted Coulomb field ≈ collection of real photons



⇗ $\sigma_{\text{total}} = f_{\text{photon}} \times \sigma_{\text{elementary process}}$

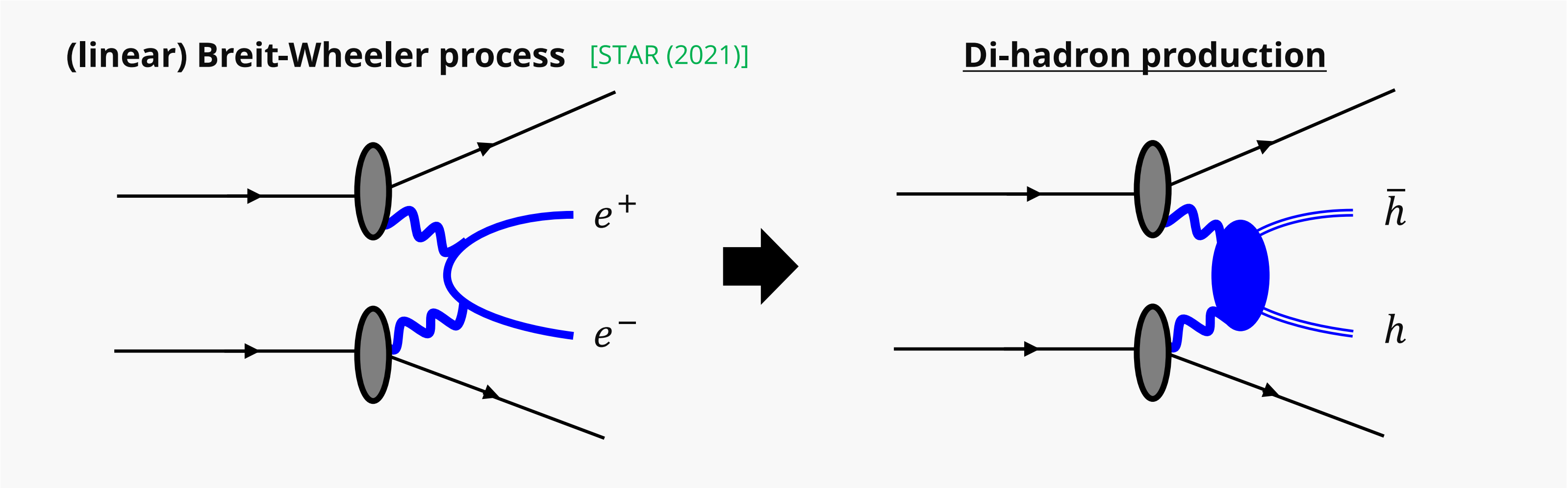
⇓

can reproduce exp. data



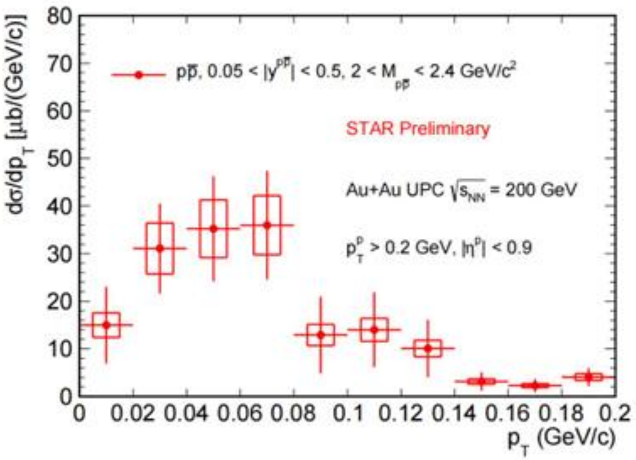
Strong-field physics of QCD/hadron ?

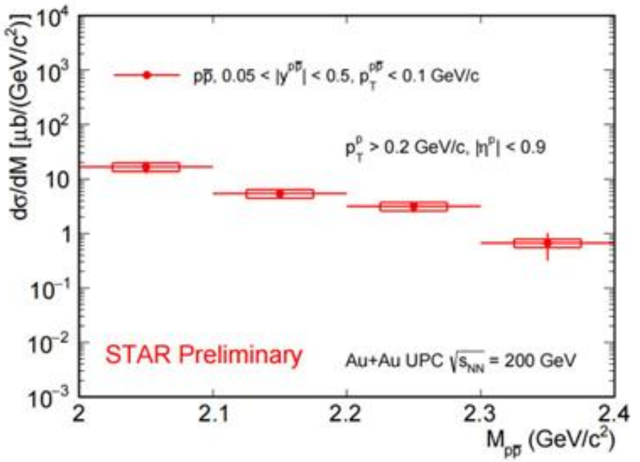
✔ **Di-hadron production should also be possible**



[Zhang, Zhang, Shao (2024)] [Hu, Lin, Pu, Wang (2024)]

Recent exp. for proton (theory has also been developed only very recently):



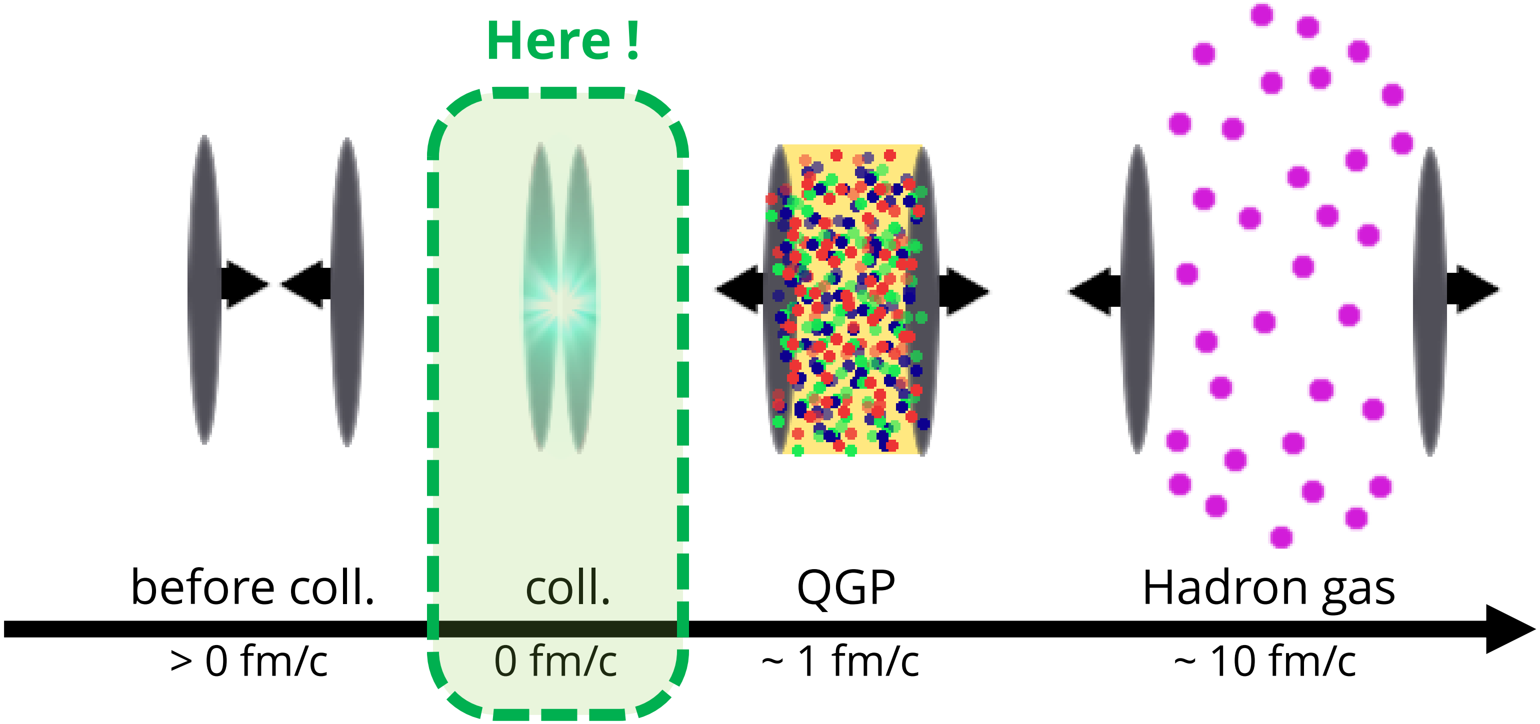


Short summary: Strong EM field

✔ **HIC creates the strongest EM fields in the Universe**

- In peripheral HIC, $eB \gg \Lambda_{\mathrm{QCD}}^2$ is created, although short-lived $\tau \ll 0.1\ \mathrm{fm}/c$
- A unique opportunity to study strong-field physics
- First observations of nonlinear QED phenomena: L-by-L scattering & (linear) BW process

Summary



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