

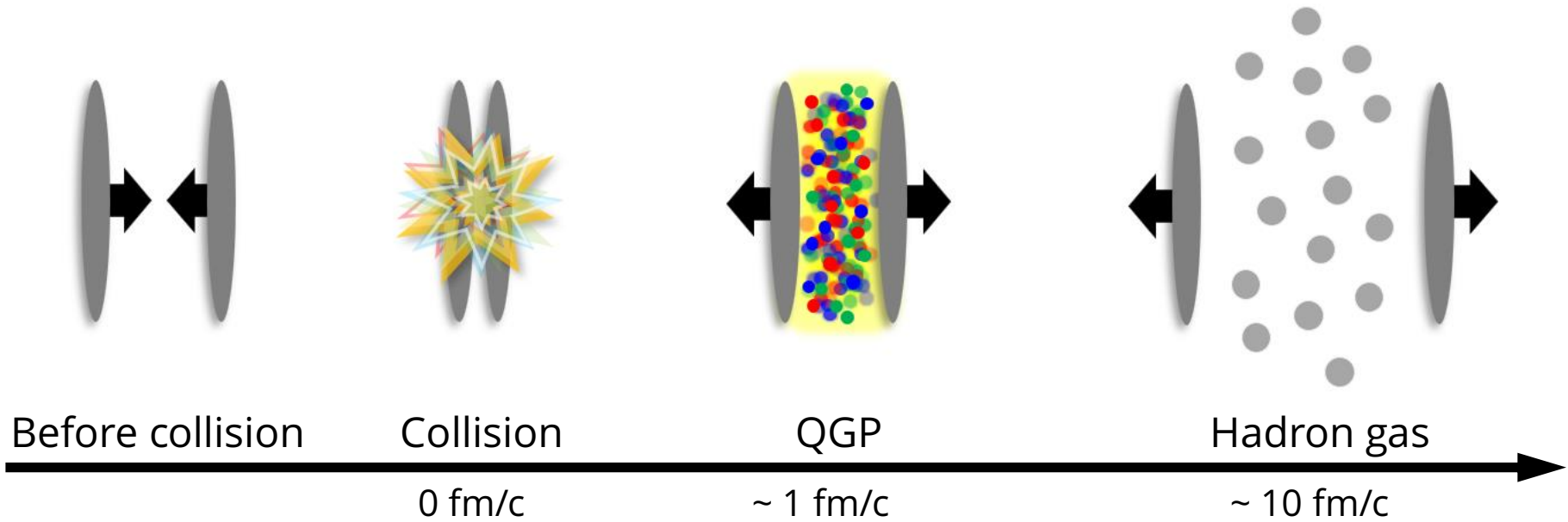
Initial state and early-time dynamics

Hidetoshi Taya

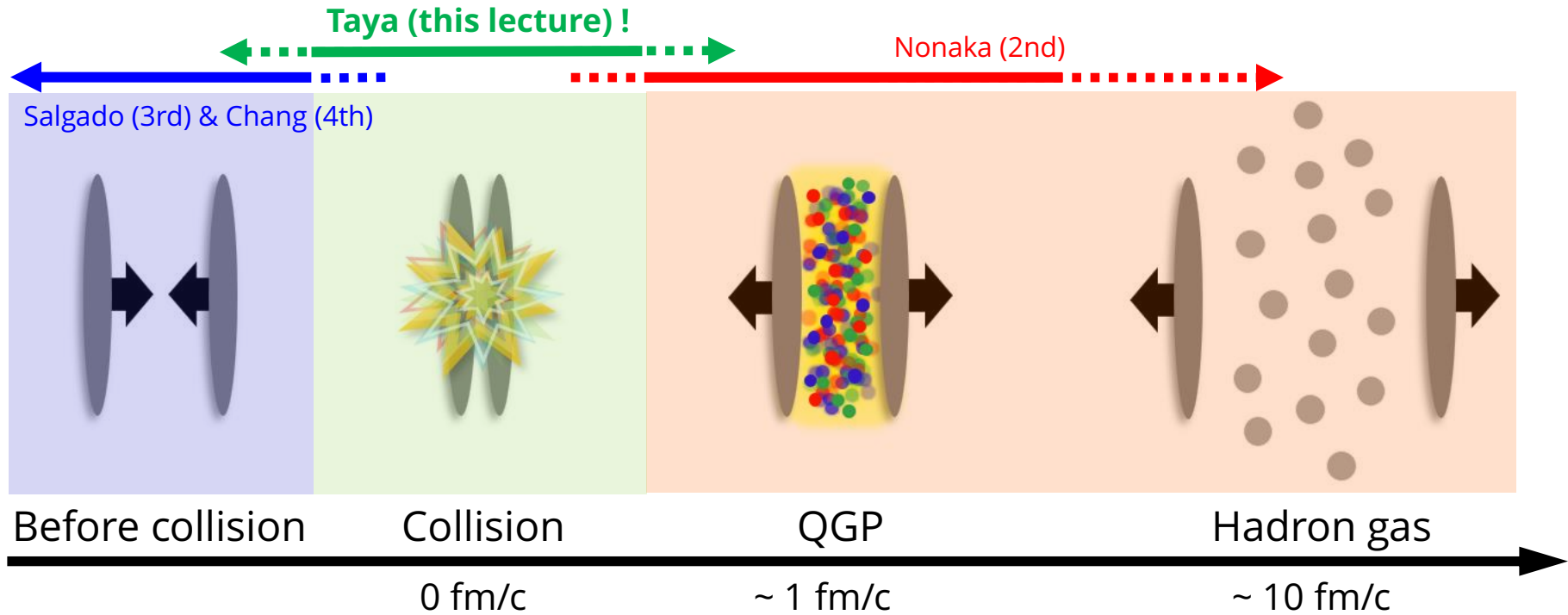
Keio University

Sep. 7th @ Initial Stages 2025

What I'm going to talk ...



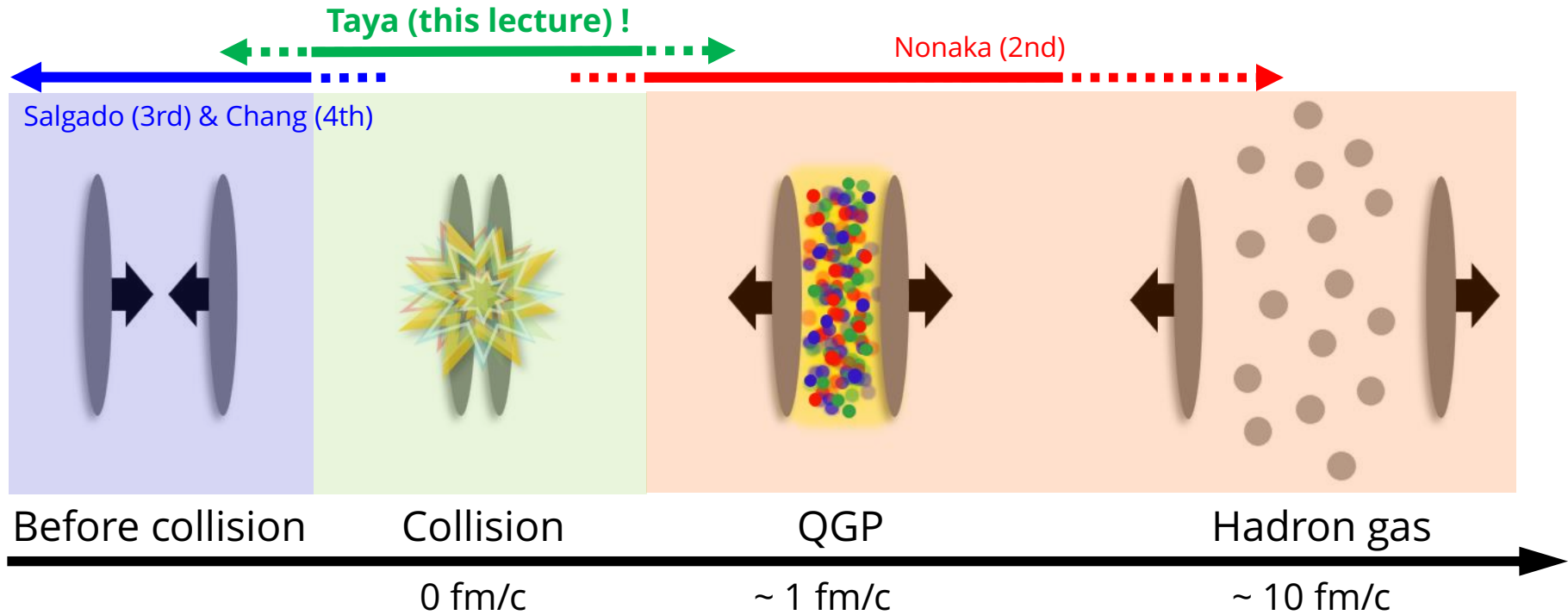
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Early-time dynamics of HIC contains rich & important physics

- gluon saturation (color glass condensate)
 - strong color field (glasma)
 - strong EM field
 - strong vorticity
 - ...
- } origin of the QGP in HIC
- } provide opportunity to study “new physics”

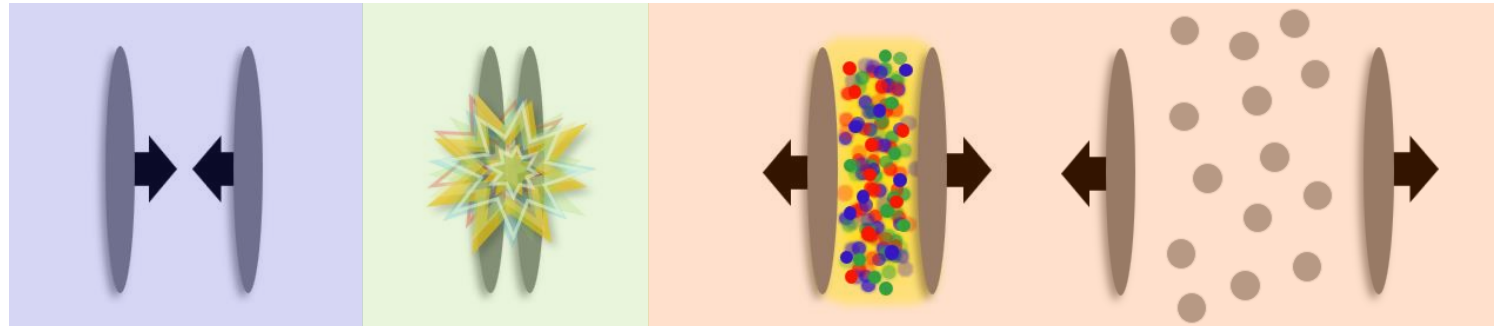
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What is the issue of ■ ? \Rightarrow A big missing link in HIC



Before collision

Collision

QGP

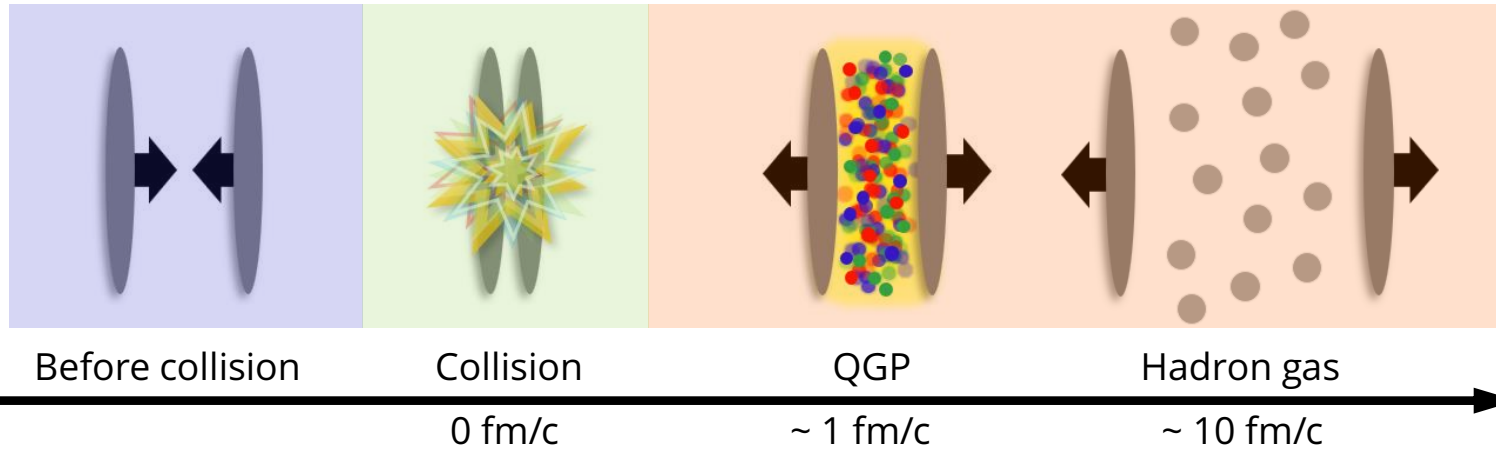
Hadron gas

0 fm/c

~ 1 fm/c

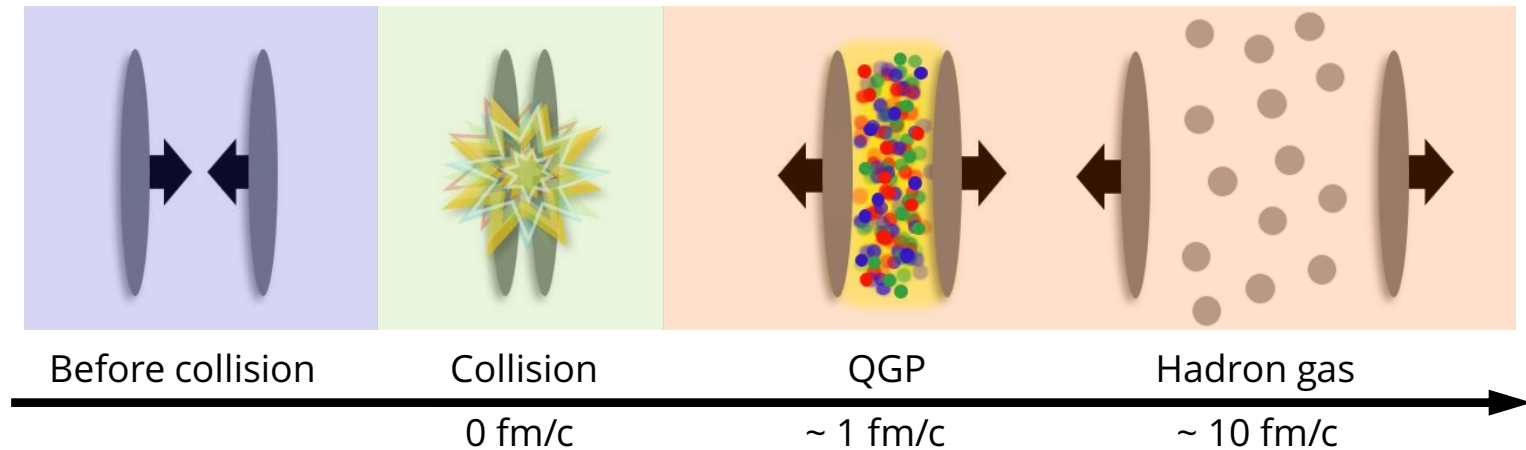
~ 10 fm/c

What is the issue of ■ ? ⇒ A big missing link in HIC



■ & ■ : Relatively well understood ⇒ "standard model"

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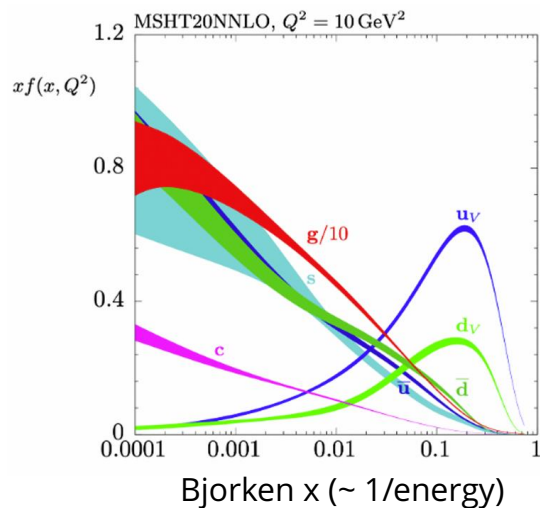


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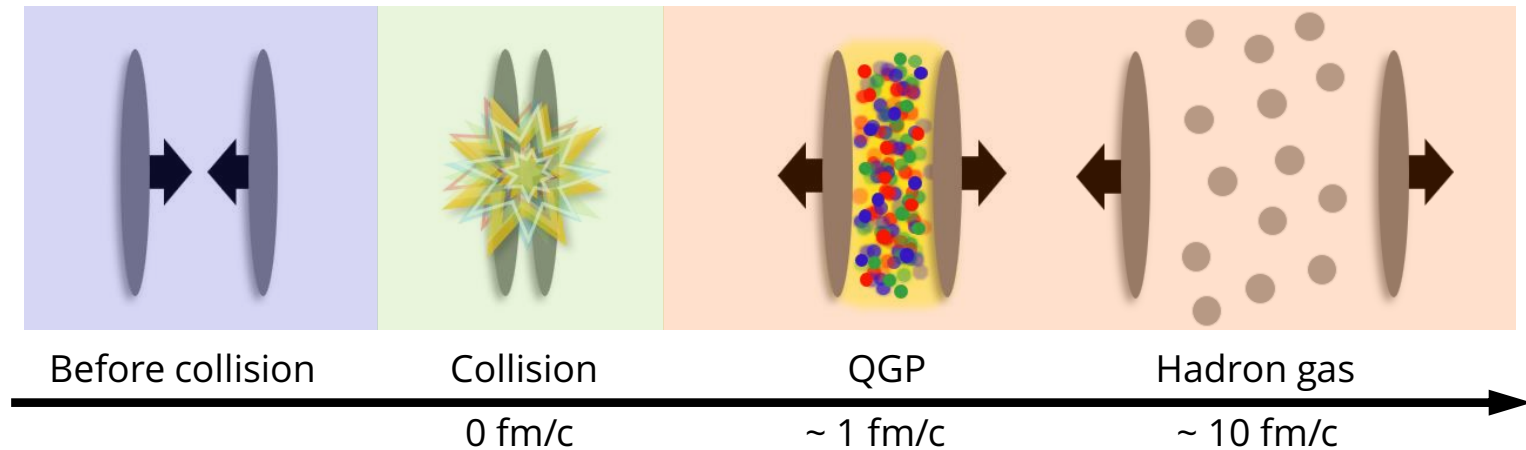
Exp: Deep-inelastic scattering (DIS)

+ Global fit of many obs: Jets, Drell-Yan, ...

(will be explored further in EIC)



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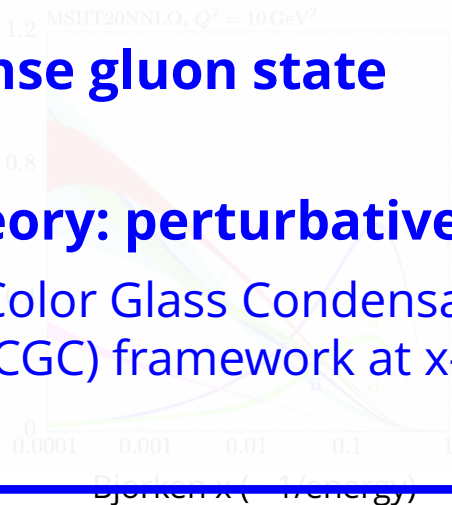


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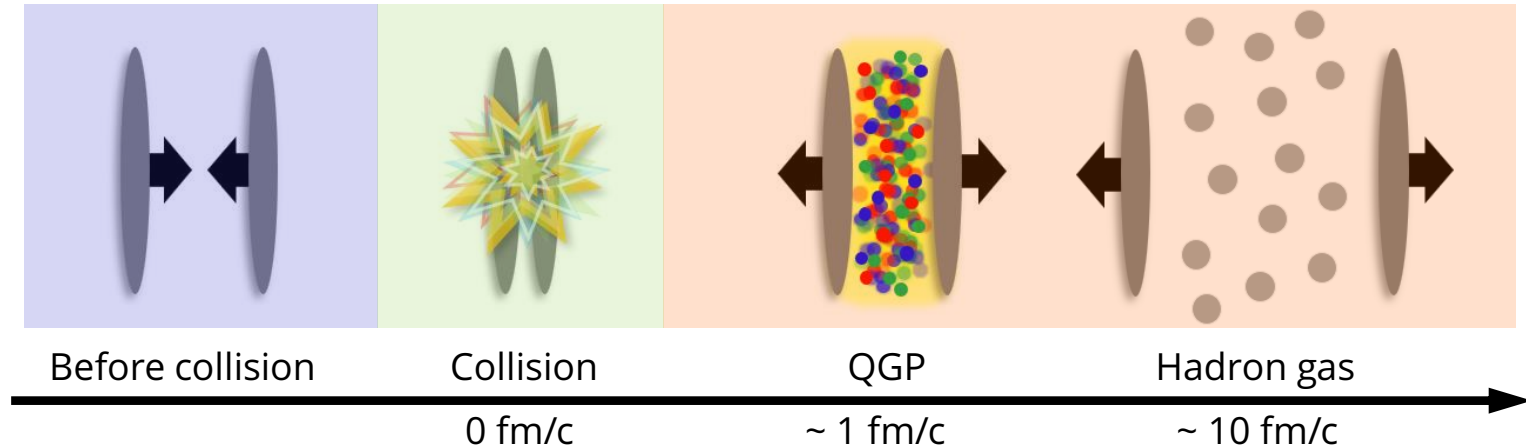
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- **Theory: perturbative QCD**
cf. Color Glass Condensate (CGC) framework at $x \rightarrow 0$



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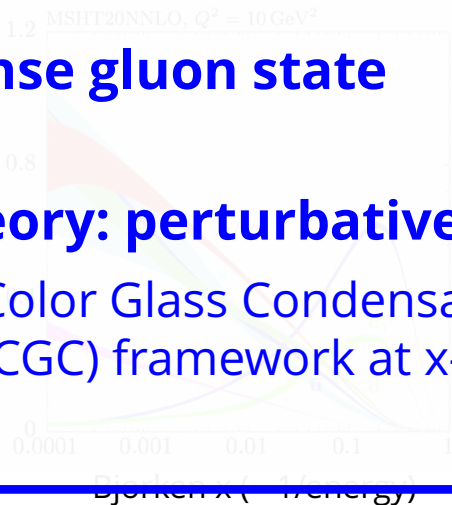
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Exp: Lots of data from A+A

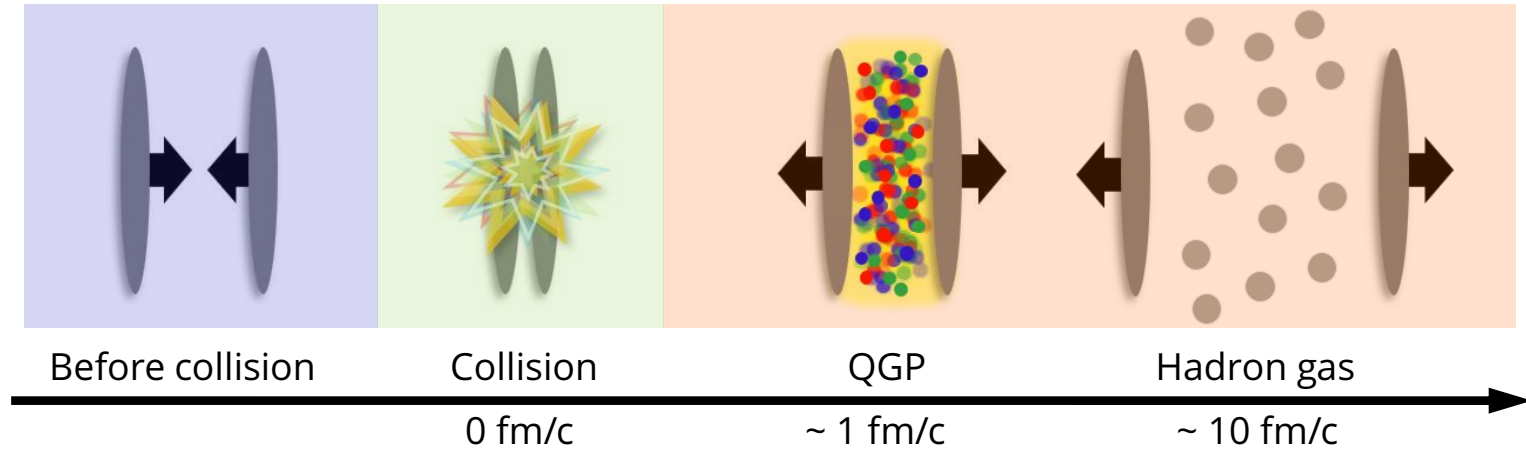
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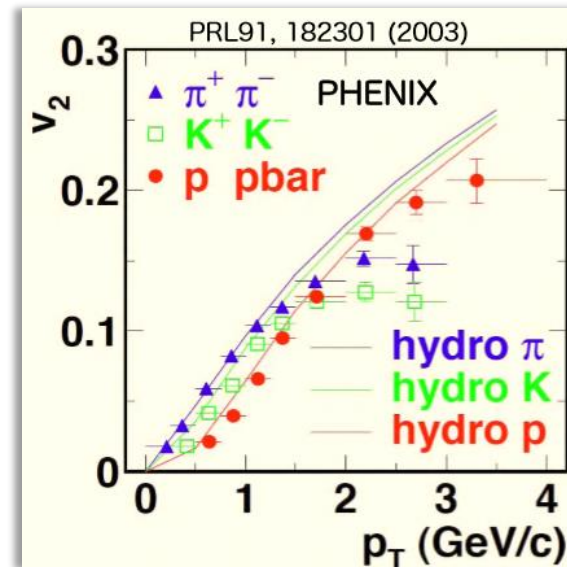
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• elliptic flow

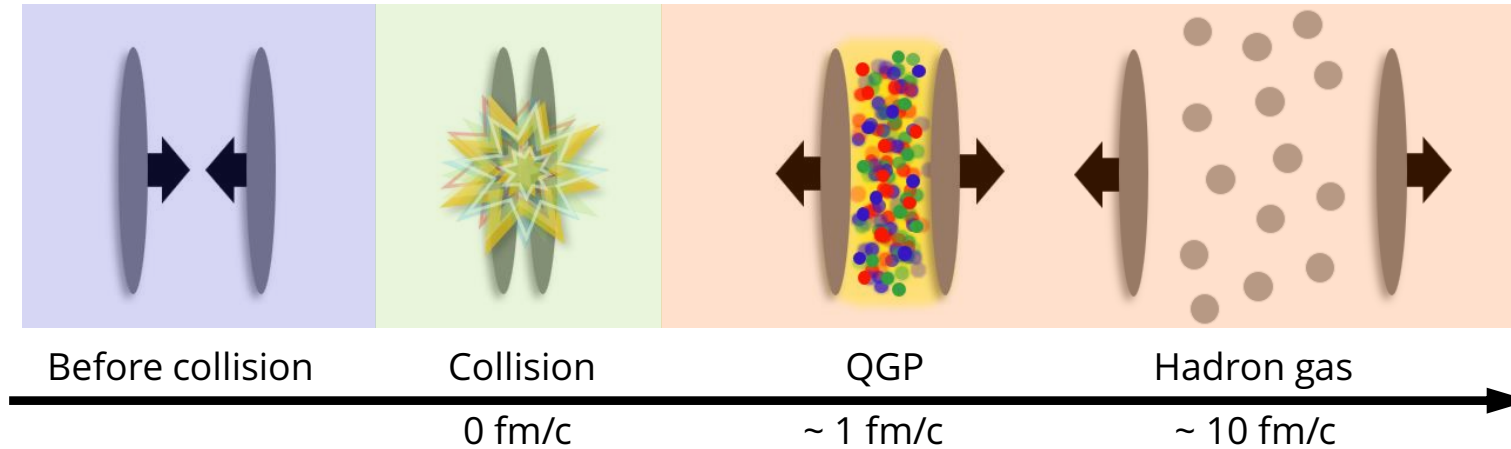
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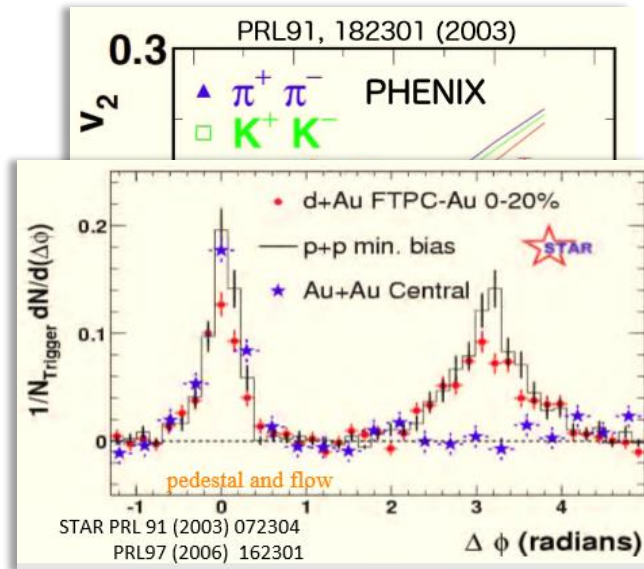
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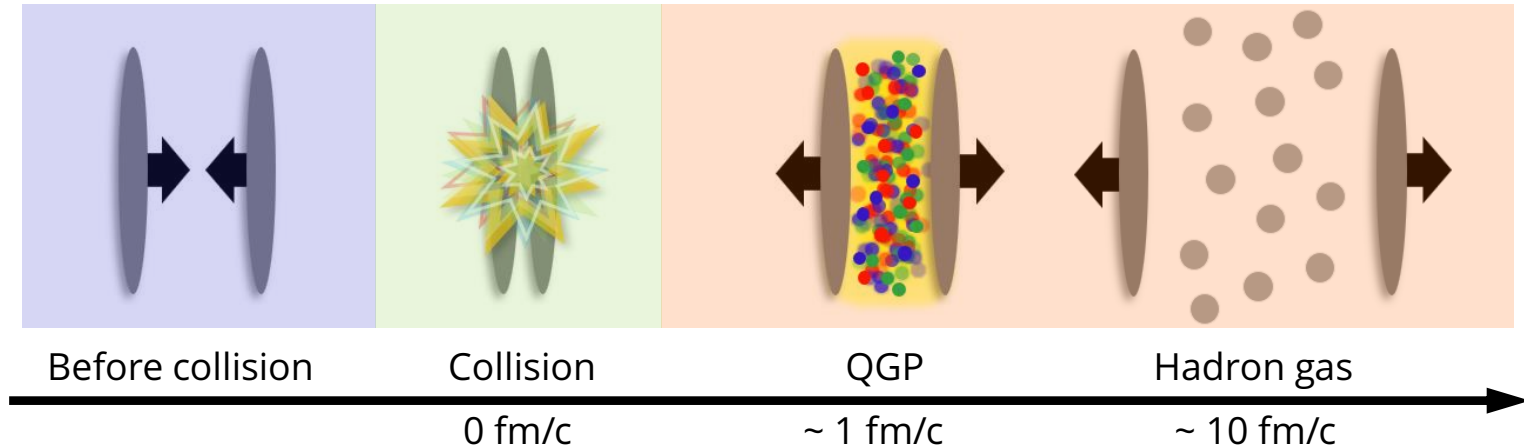
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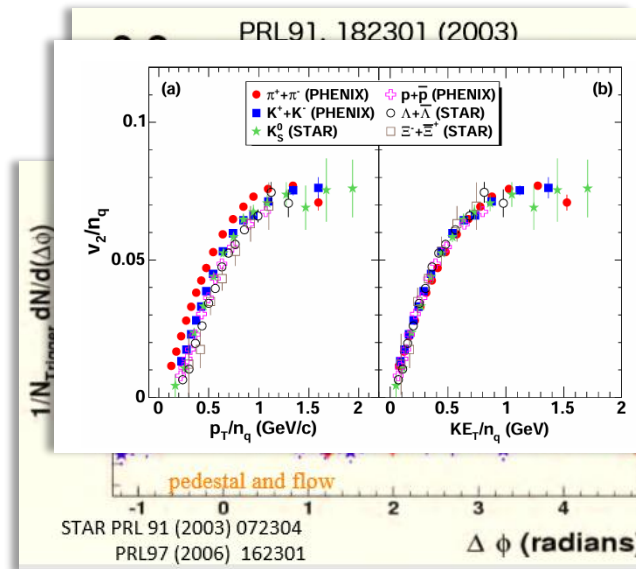
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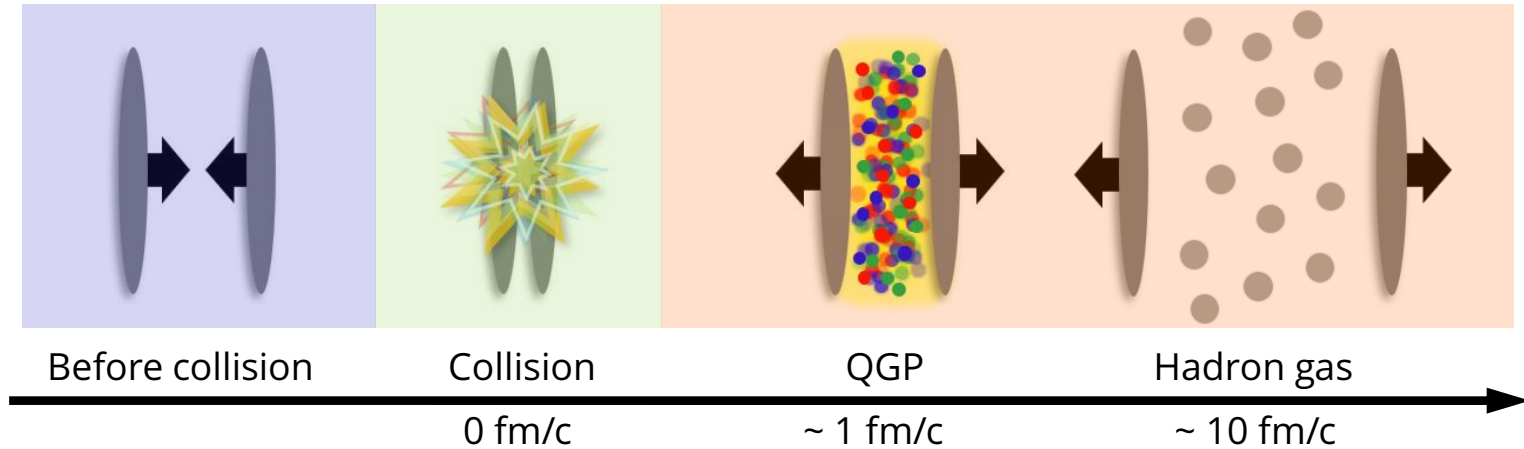
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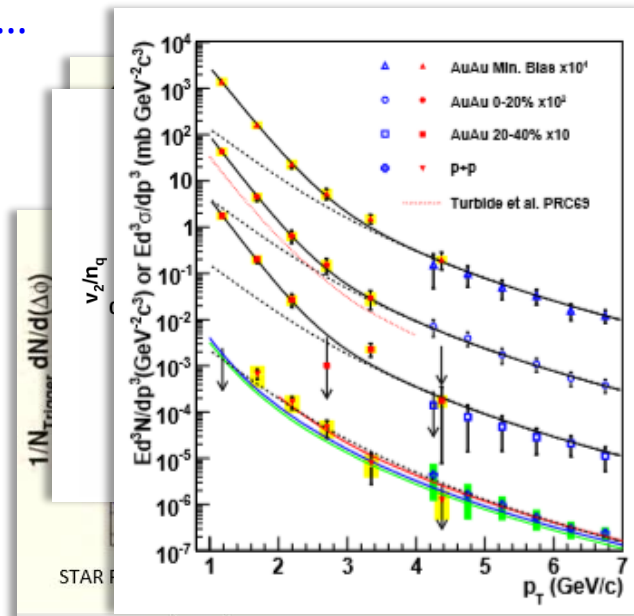


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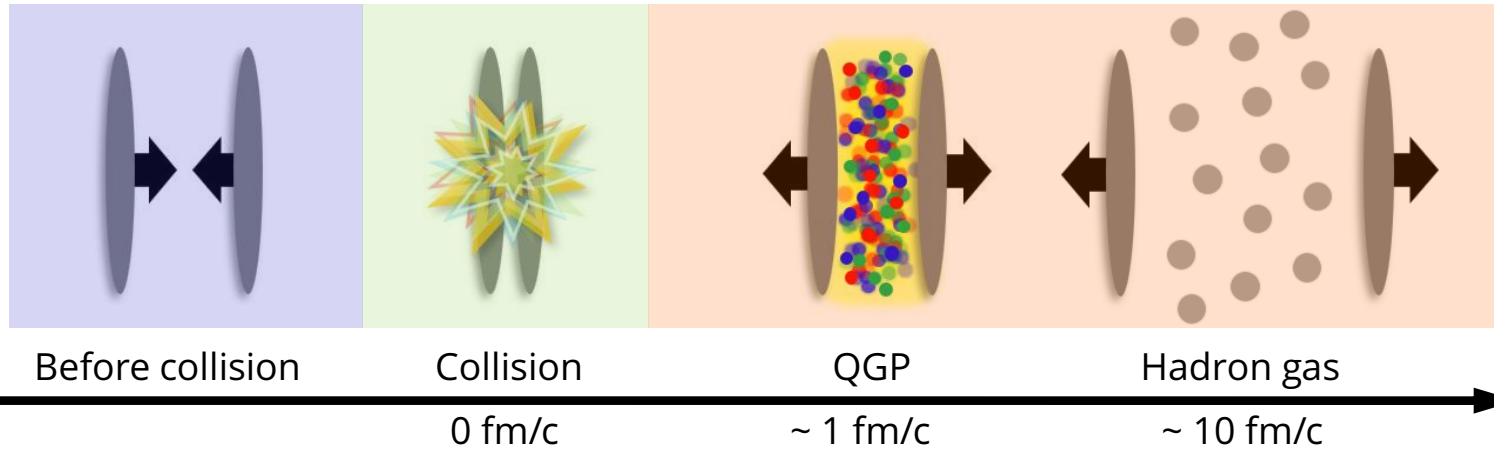
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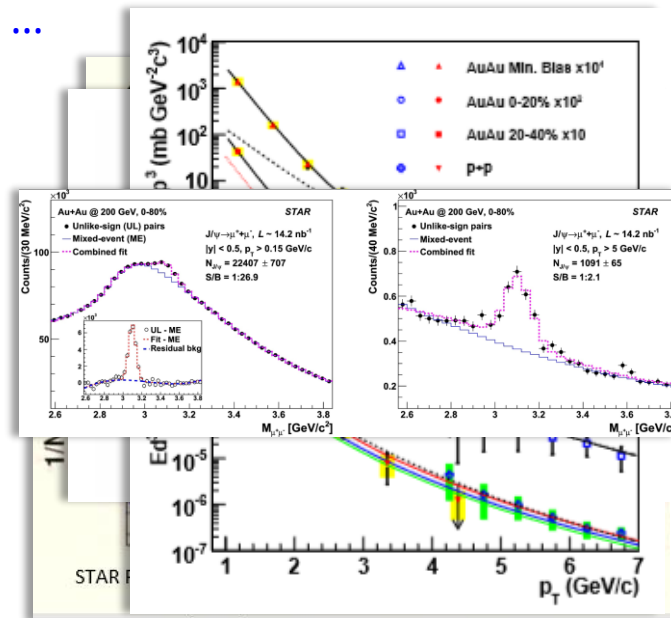
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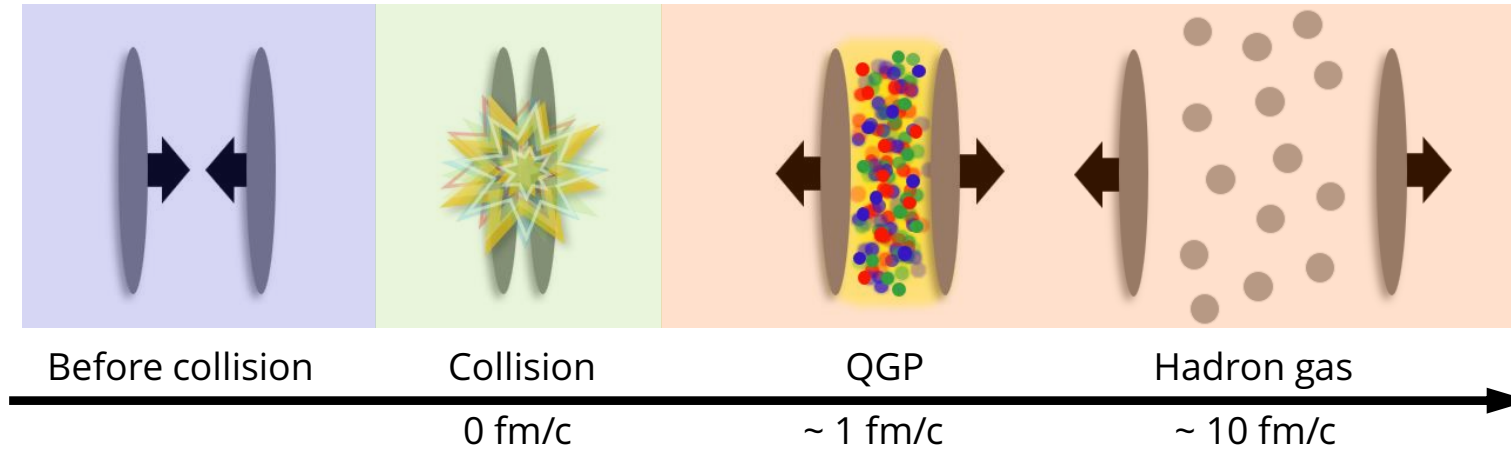
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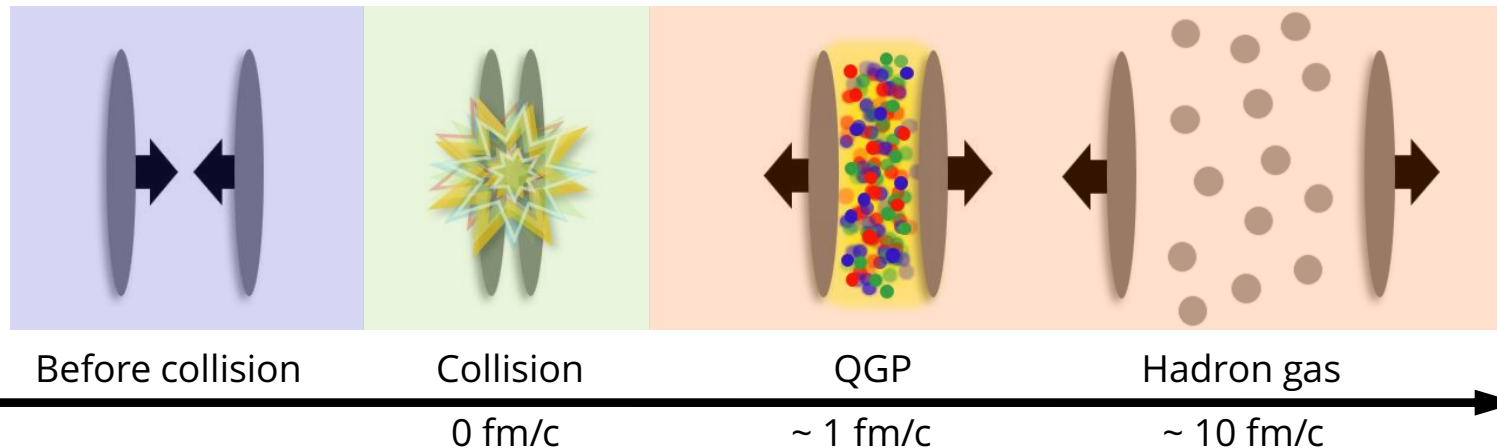


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- **QGP created**
(= matter composed of deconfined quark & gluons)
- **QGP is a (nearly) perfect liquid**
- **Theory: Hydrodynamics (+ hadron transport)**

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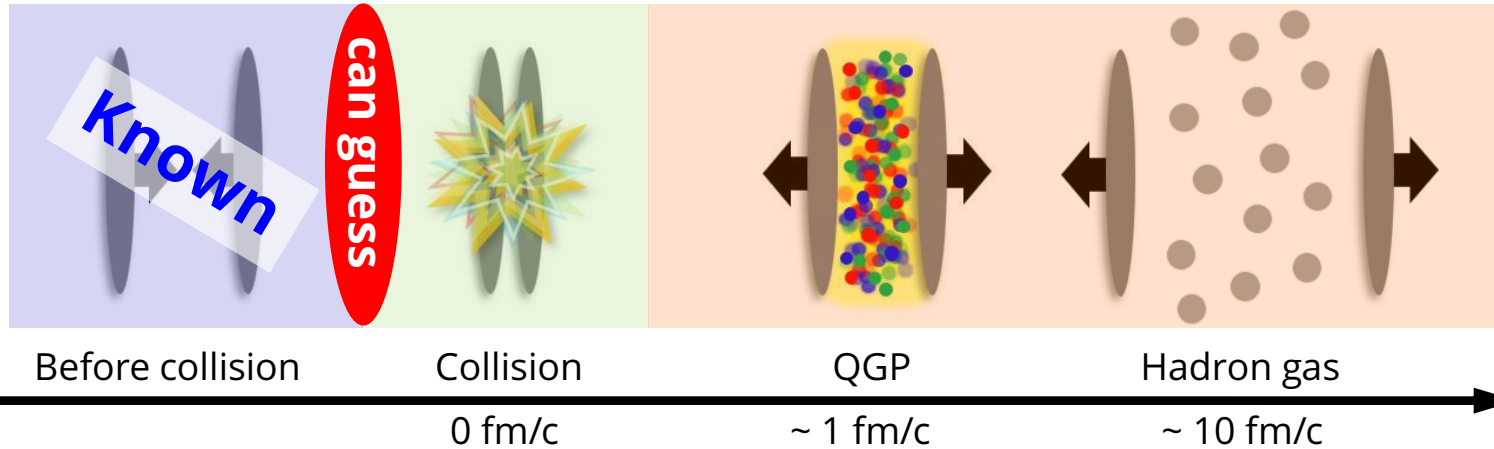


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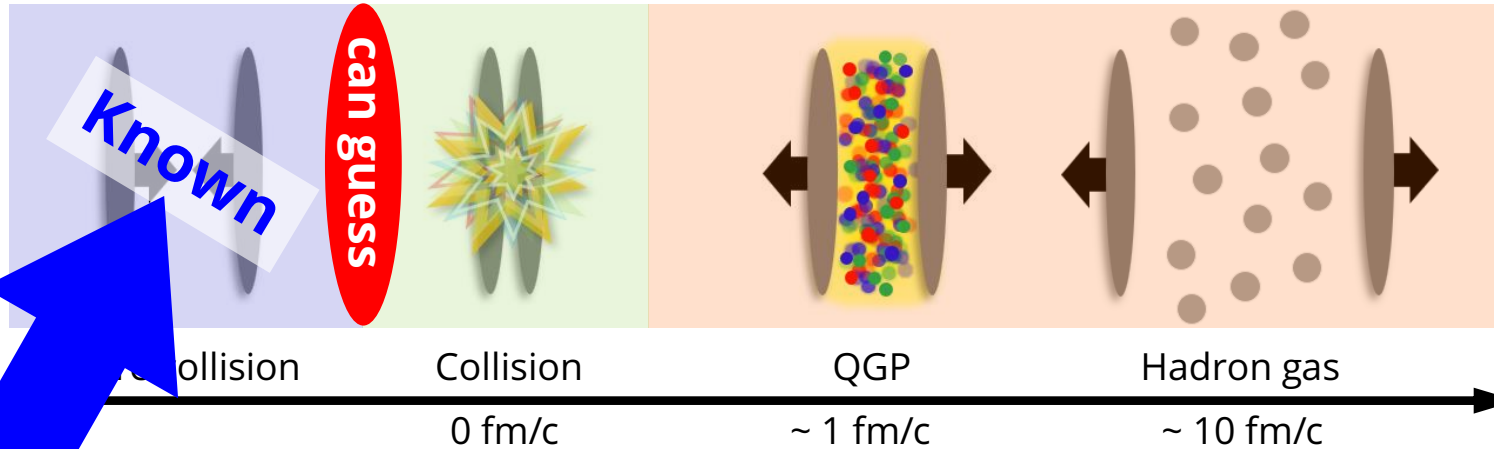
■ : No established understanding

- A longstanding issue from 1980s [Bjorken (1983)]
- Many open questions; e.g.,
 - **Particle production:**
how the huge # of quarks & gluons produced $dN/dy=O(1000)$?
 - **Thermalization (“hydrodynamization”):**
how thermalize to form the liquid-like QGP? how can it be fast $\sim 1\text{ fm/c}$?
 - **Input for hydro:** a must for better modeling and extraction of QGP properties
 - **Experimental probes**
- Had significant progress in the last decade !

Key: Strong color field (glasma)



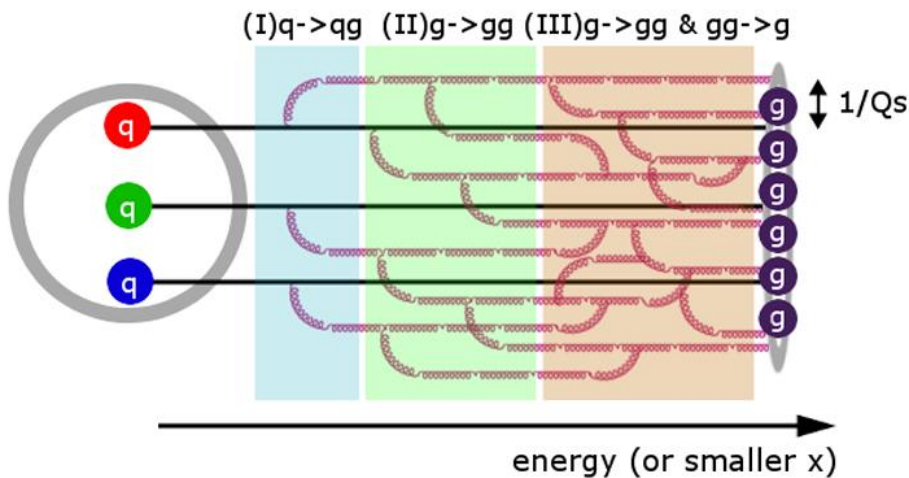
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High-energy nucleus = a dense gluon state \approx a “color capacitor plate”

Non-linearity of gluon \Rightarrow huge gluon density of order $\sigma \propto Q_s^2 = O(1 \text{ GeV}^2)$

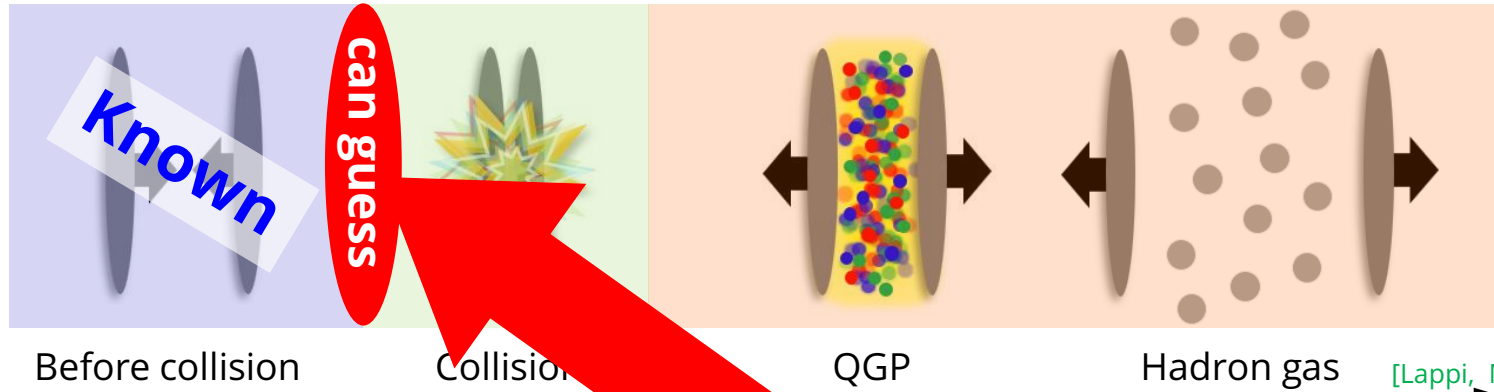
\nwarrow saturation scale



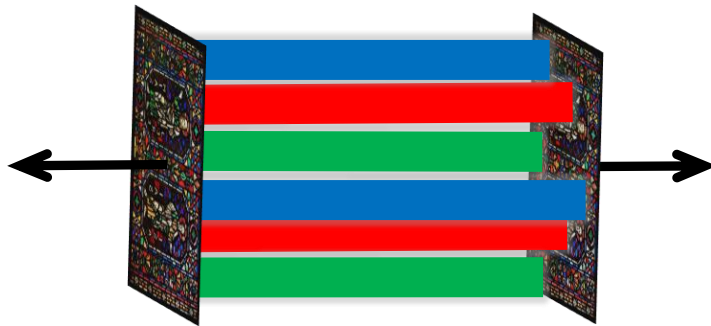
\approx



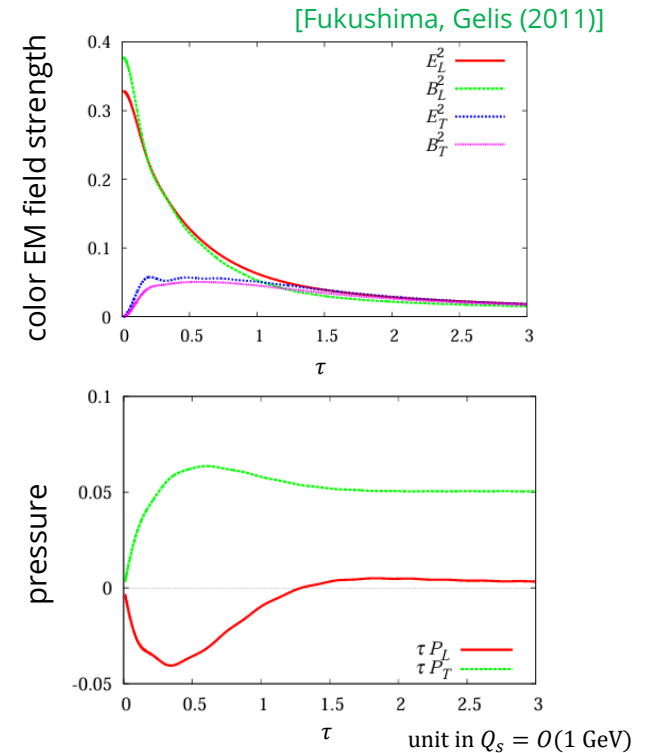
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Formation of a "colored capacitor" \Rightarrow Strong color field (:= glasma)



\Rightarrow
Solve classical
Yang-Mills eq.



Key features of glasma:

- (1) Longitudinal color fields
- (2) Topological $\mathbf{E} \cdot \mathbf{B} \neq 0$ ($\because \text{div } \mathbf{B} \neq 0$ in QCD)
- (3) Very strong: $g\mathbf{E}, g\mathbf{B} \propto \sigma \propto Q_s^2 = O(1 \text{ GeV}^2)$
- (4) Very anisotropic and never isotropitized

How QGP created = how glasma decays into QGP

Various 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 \Rightarrow decays & isotropitizes spontaneously
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\Rightarrow B-field instabilities enhance the long. fluct. to relax the anisotropy

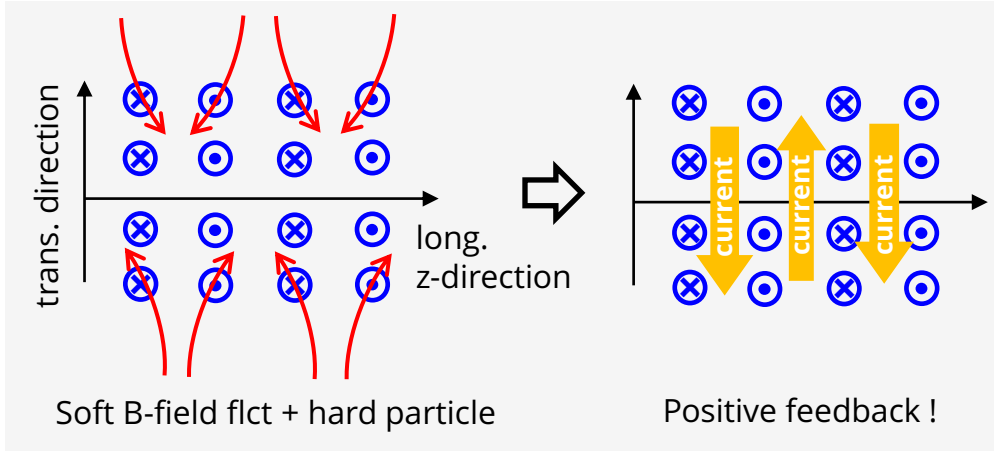
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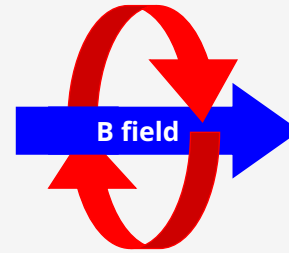
Weibel instability

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



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Nielesen-Olesen instability



Landau quantization

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

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

quantized trans. motion

Zeeman splitting

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

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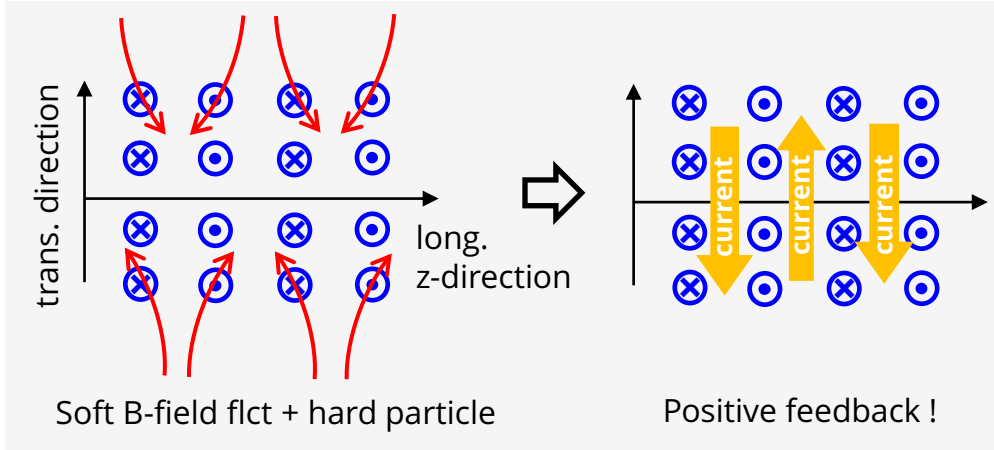
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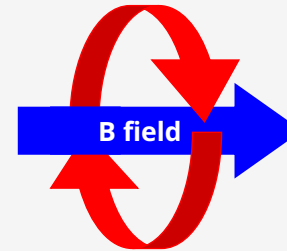
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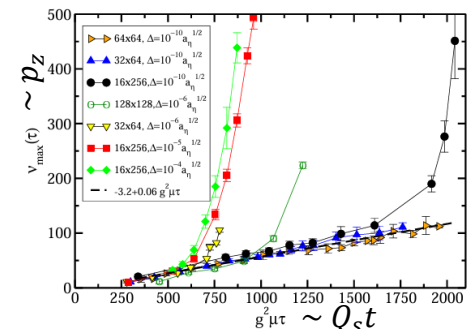
↑ quantized trans. motion ↑ Zeeman splitting

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

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

\Rightarrow It exists, but so slow ($\sim 100/Q_s > 20 \text{ fm}/c$)

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



Strong-field scenario: glasma instabilities (2/2)

Glasma is unstable \Rightarrow decays & isotropitizes spontaneously
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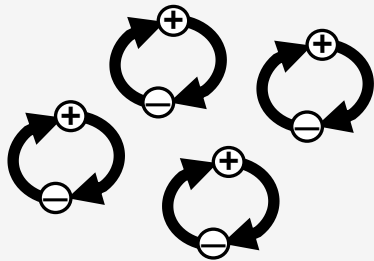
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- **Mechanism: the Schwinger effect**

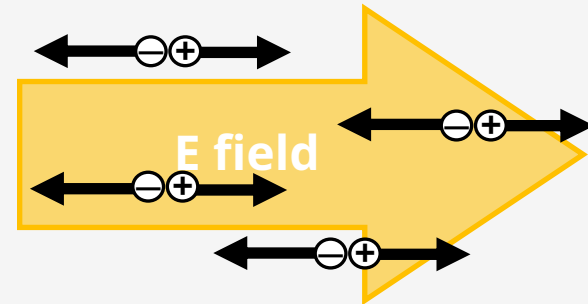
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Our vacuum = full of quantum fluct.



In strong E field



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

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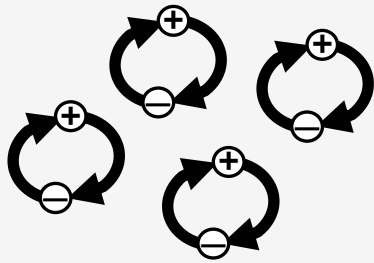
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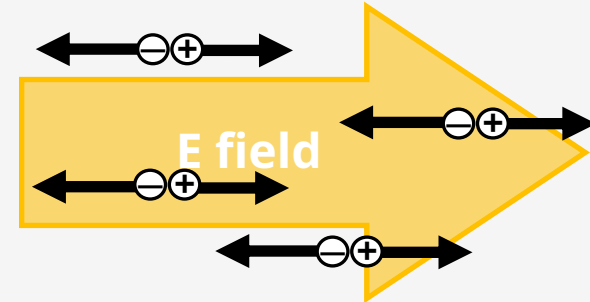
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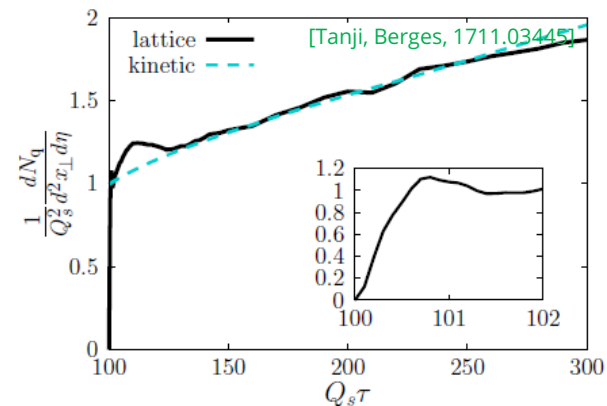
E field supplies energy to tear the loop apart \Rightarrow pair particle production !

• **Can be studied numerically**

\Rightarrow Very fast & huge quark production

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

\Rightarrow would be important for chemical eq.



How QGP created = how glasma decays into QGP

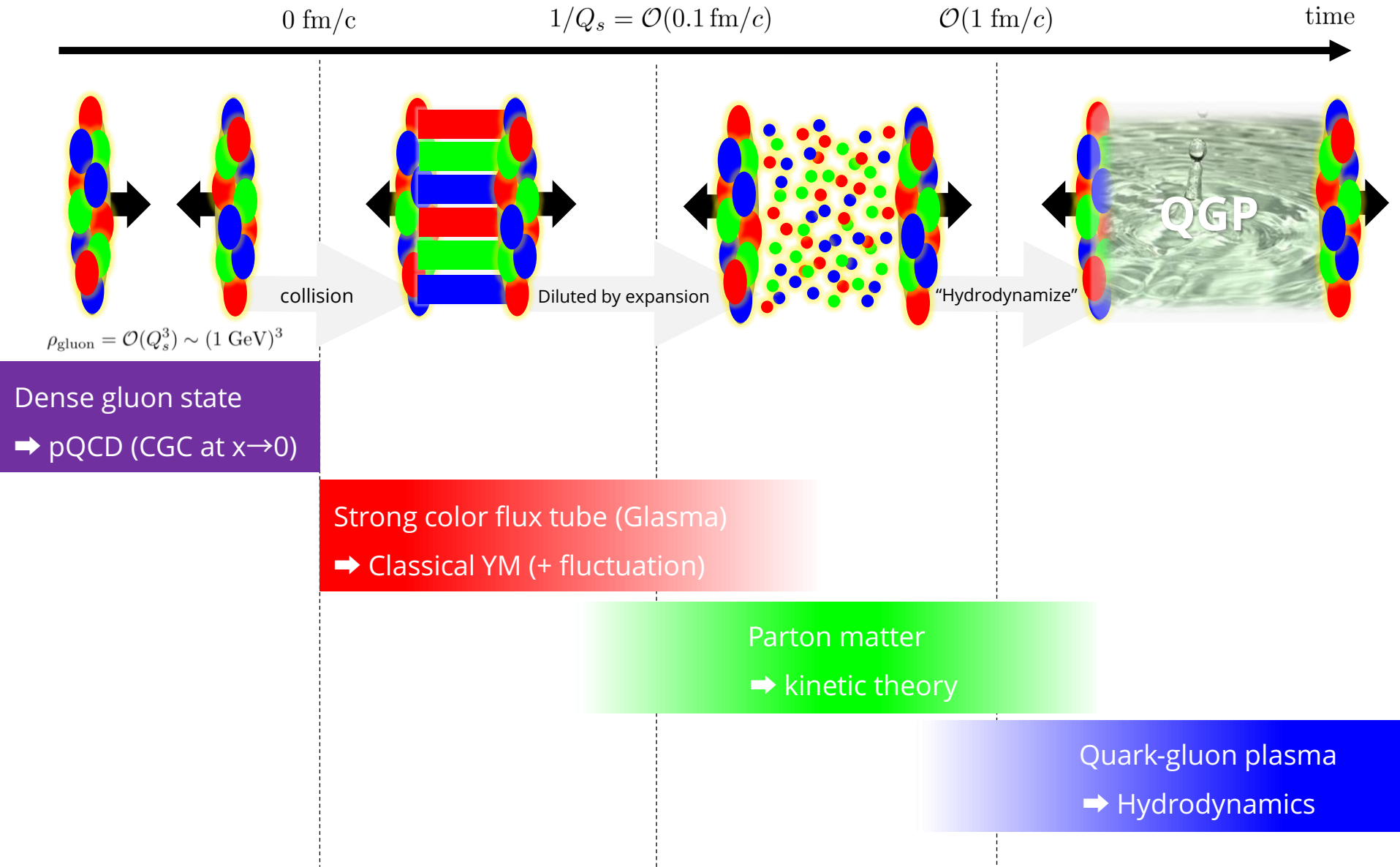
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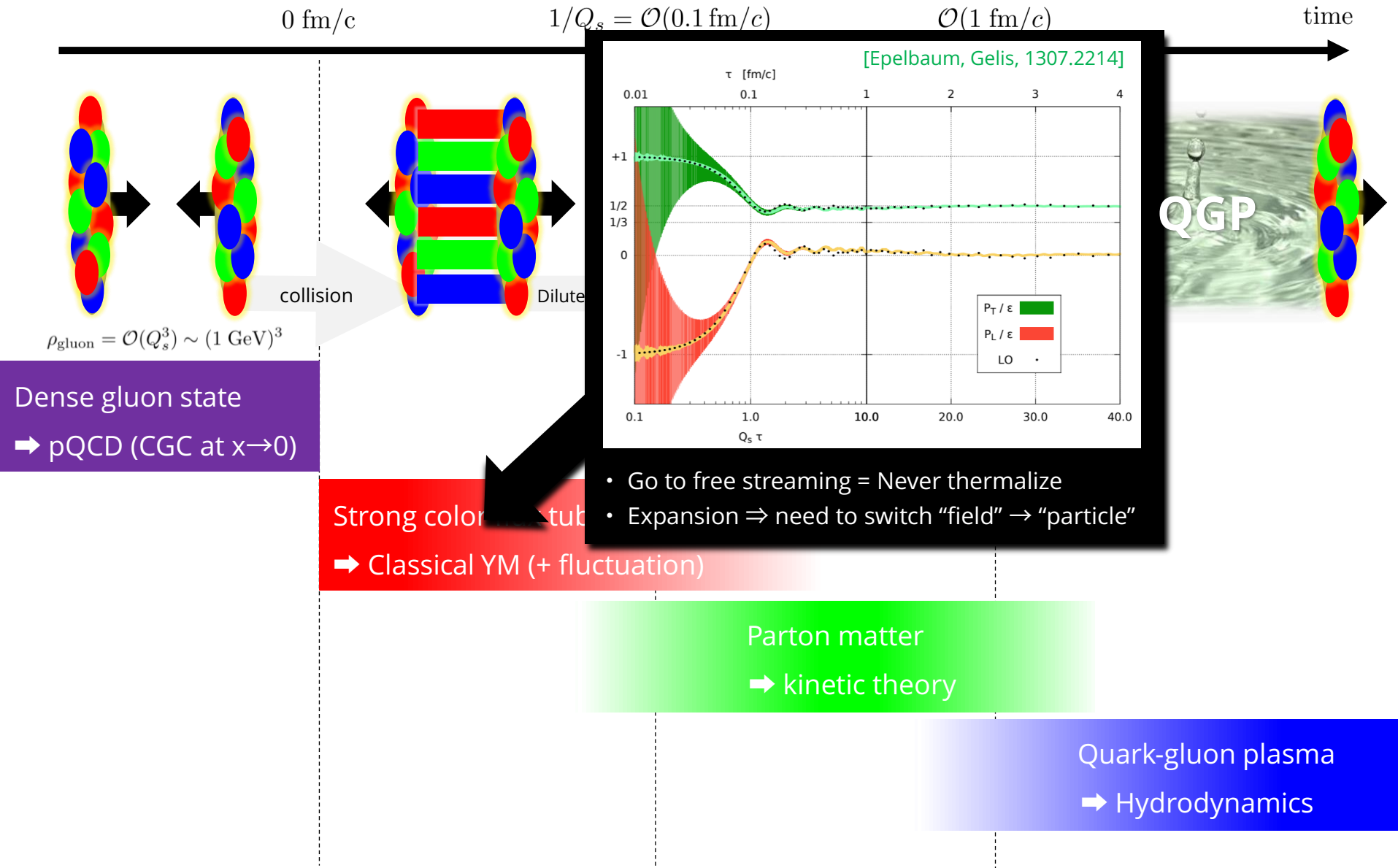
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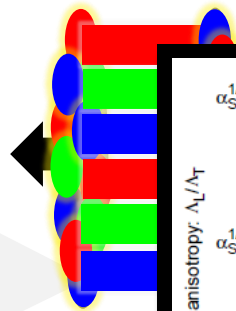
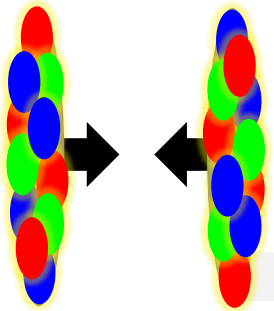
Weak-coupling scenario: particle + hydrodynamization

0 fm/c

$1/Q_s = \mathcal{O}(0.1 \text{ fm}/c)$

$\mathcal{O}(1 \text{ fm}/c)$

time



collision

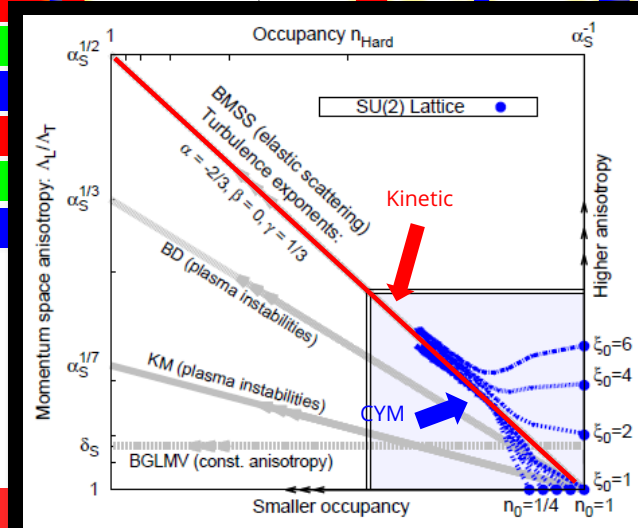
$$\rho_{\text{gluon}} = \mathcal{O}(Q_s^3) \sim (1 \text{ GeV})^3$$

Dense gluon state

→ pQCD (CGC at $x \rightarrow 0$)

Strong color magnetic fields

→ Classical YM (+ fluctuations)



- 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]

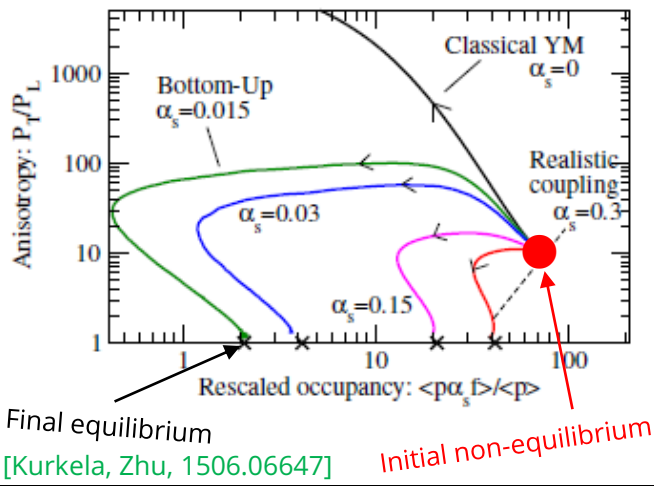
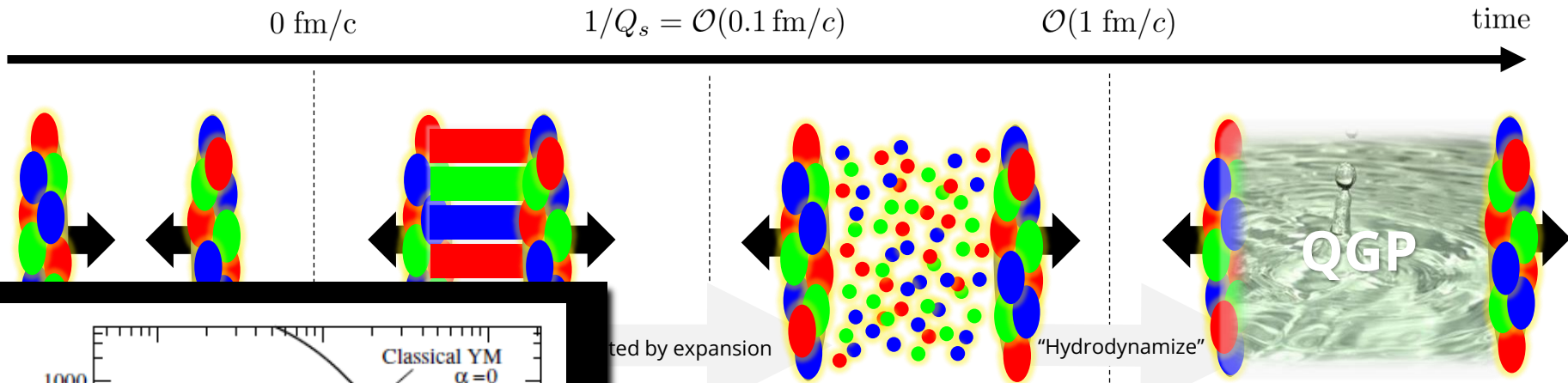
Parton matter

→ kinetic theory

Quark-gluon plasma

→ Hydrodynamics

Weak-coupling scenario: particle + hydrodynamization



driven by expansion

"Hydrodynamize"

be
uctuation,

Parton matter
→ kinetic theory

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

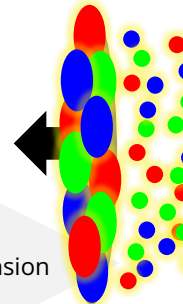
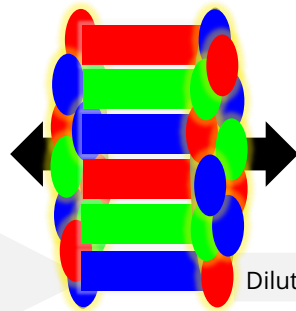
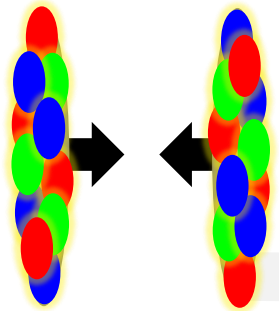
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time



collision

Diluted by expansion

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

Dense gluon state

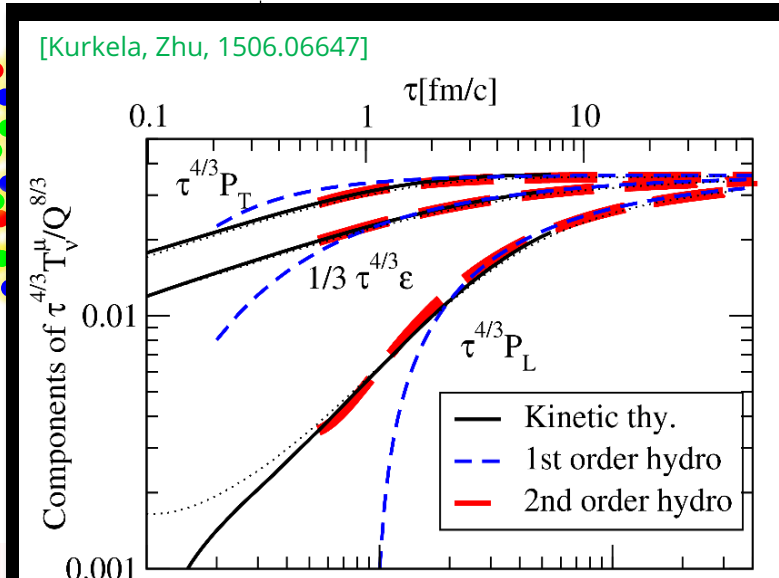
→ pQCD (CGC at $x \rightarrow 0$)

Strong color flux tube (Glasma)

→ Classical YM (+ fluctuation)

Partons

→ kinetic theory



- Hydrodynamics works even away from thermal equilibrium = "hydrodynamization"

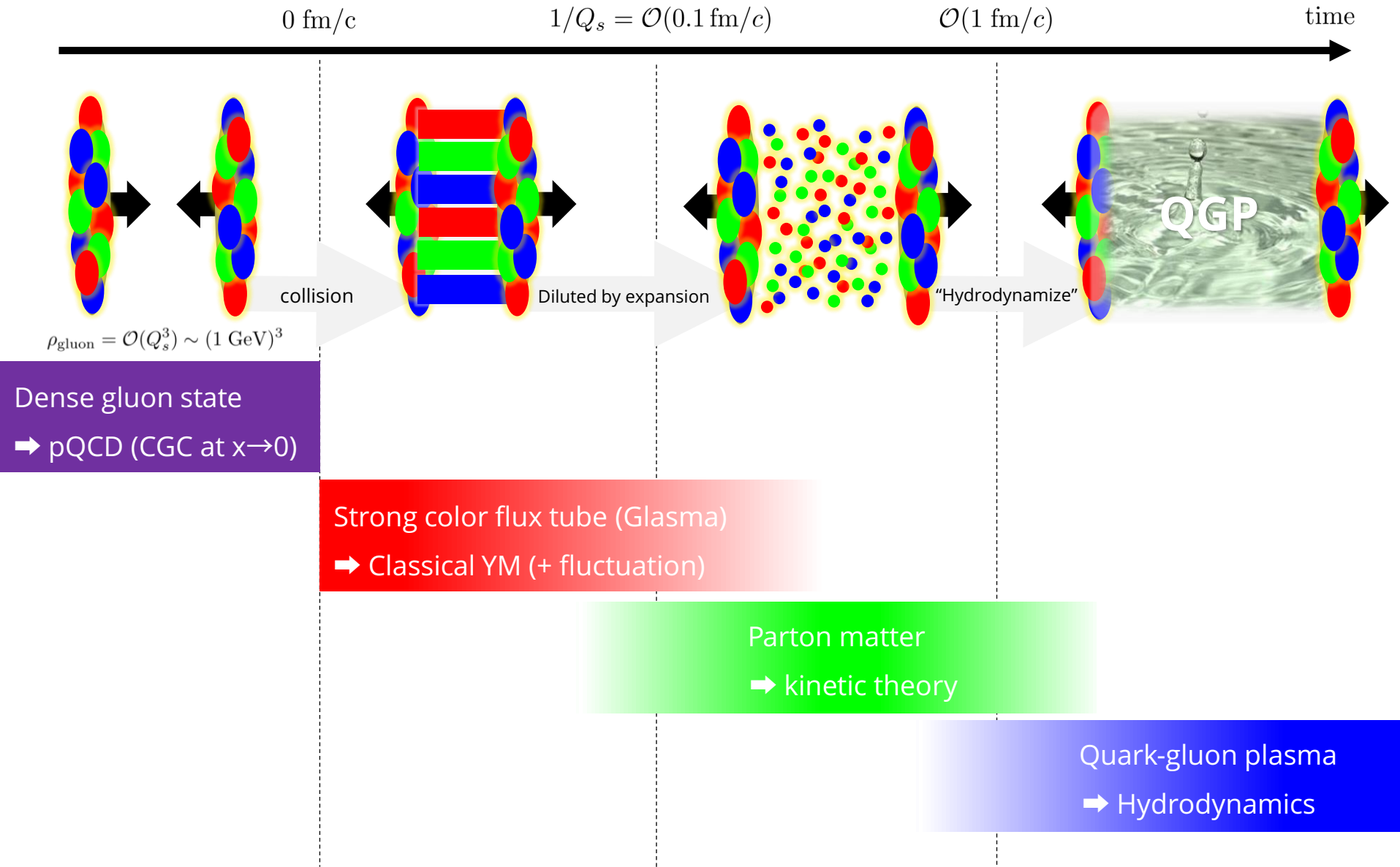
[Heller, Spalinski, 1503.07514] [Romatschke, 1704.08699]

- $\tau_{\text{hydro}} \ll \tau_{\text{therm.}}$: $\tau_{\text{hydro}} \sim \mathcal{O}(1) \text{ fm}/c$

Quark-gluon plasma

→ Hydrodynamics

Weak-coupling scenario: particle + hydrodynamization



Short summary so far

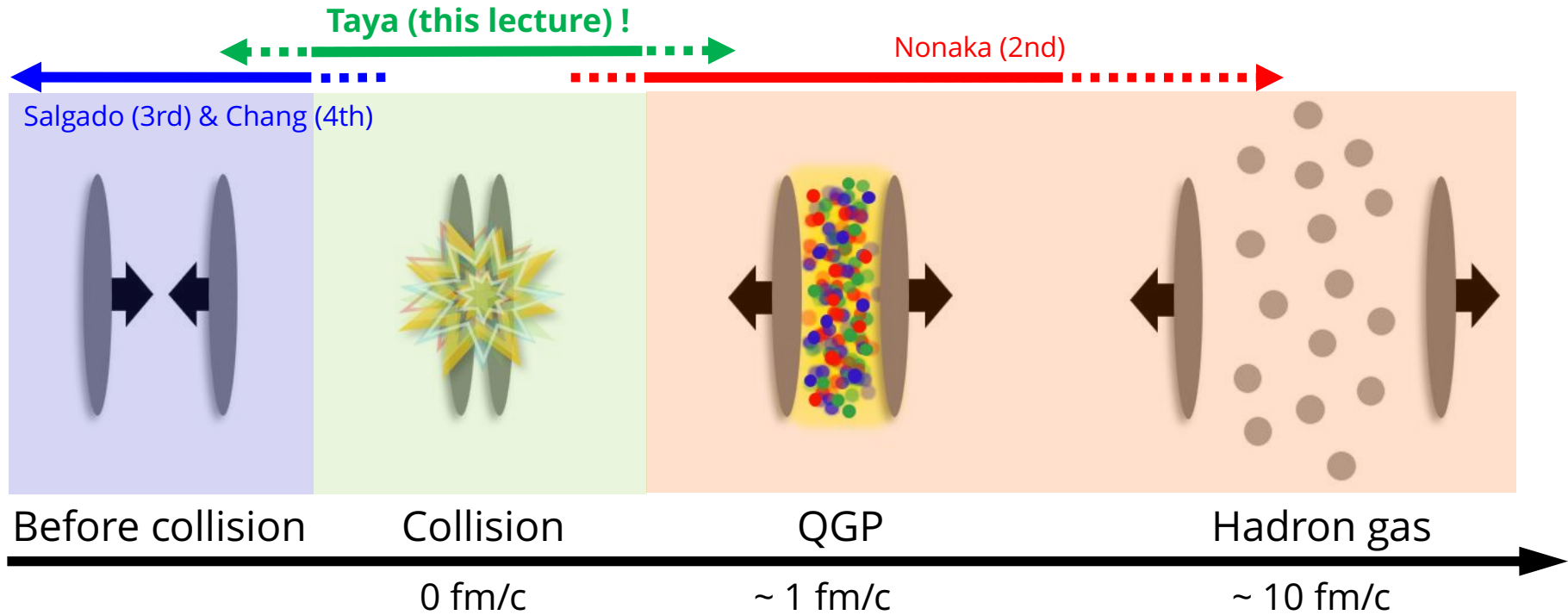
QGP formation in early-time dynamics of HIC

= a longstanding issue in HIC but had/having lots of progress

Key ideas explained

- The very first stage is described by glasma
- Glasma is unstable (Weibel instability, Nieves-Olesen instability, Schwinger effect)
- Nice development in the weak-coupling scenario
- Hydrodynamization: applicability of hydro \neq local thermal equilibrium

What I'm going to talk ...



Early-time dynamics of HIC contains rich & important physics

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

} origin of the QGP in HIC

- strong EM field
- strong vorticity

} provide opportunity to study "new physics"

• ...

Why strong field interesting ?

A general lesson from life:



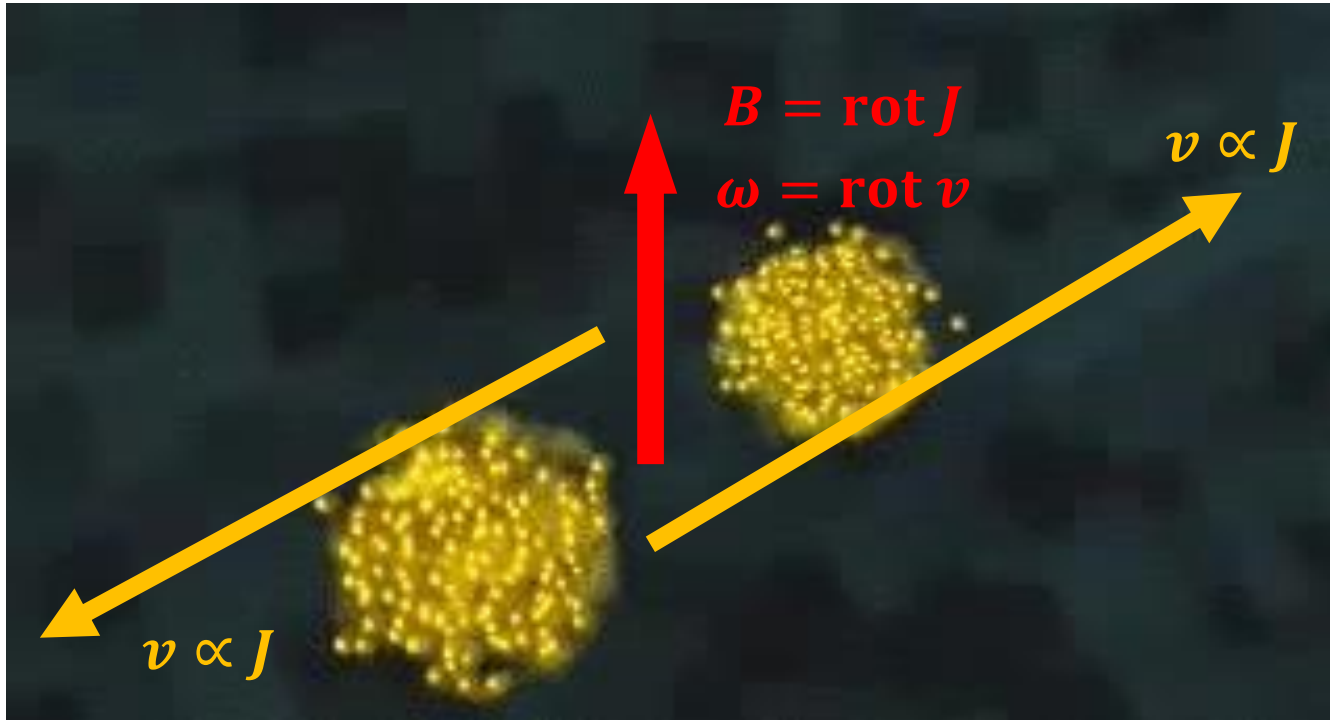
⇒ Translate to physics:

Must go to **discomfort** zone
(= **extreme conditions**) to
discover something new !

HIC is the best way to go there. Because it creates:

- **Hottest matter** ⇒ QGP: the origin of our Universe and matter
RHIC, LHC
- **Densest matter** ⇒ QCD at finite density: fate of our Universe and matter
FAIR, NICA, HIAF, J-PARC-HI, ...
- **Strongest EM and vorticity fields** ⇒ ???

How strong EM & vorticity field produced ?



Idea is simple

Energetic \Rightarrow large “rotating” velocity/current \Rightarrow strong vorticity/magnetic field

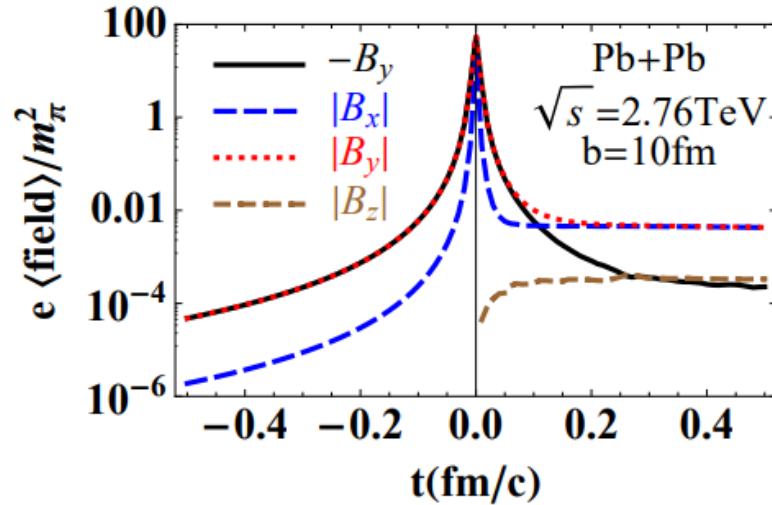
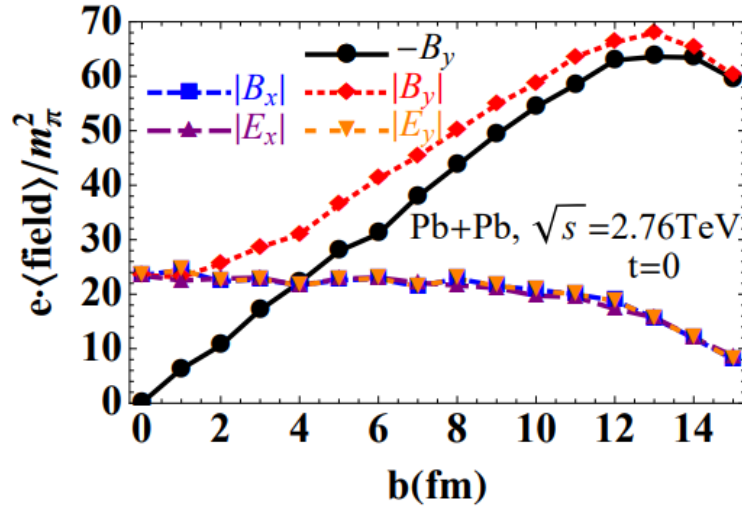
We should then ask:

- (1) How strong are they quantitatively?
- (2) What can happen?

EM field: How strong ?

Estimates by event generators (e.g., HIJING, UrQMD, JAM, ...)

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



Pros: Very strong $eB \gg \Lambda_{\text{QCD}}^2$
 \Rightarrow Strongest in the Universe!

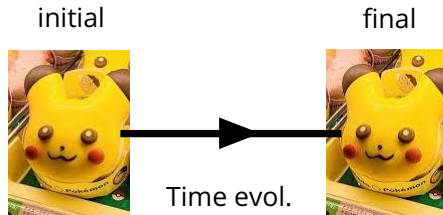
Cons: Extremely short-lived $\tau \ll 0.1 \text{ fm}/c$

- very bad news, as it would reduce the signals significantly
- BUT, could be prolonged by finite conductivity (Faraday induction)



EM field: What can happen ? (1/2)

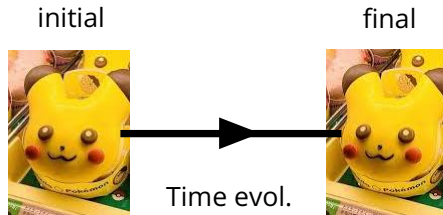
Theoretical essence: Non-perturbative dress of the propagator



Vacuum

EM field: What can happen ? (1/2)

Theoretical essence: Non-perturbative dress of the propagator



Vacuum

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

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

EM field: What can happen ? (1/2)

Theoretical essence: Non-perturbative dress of the propagator



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

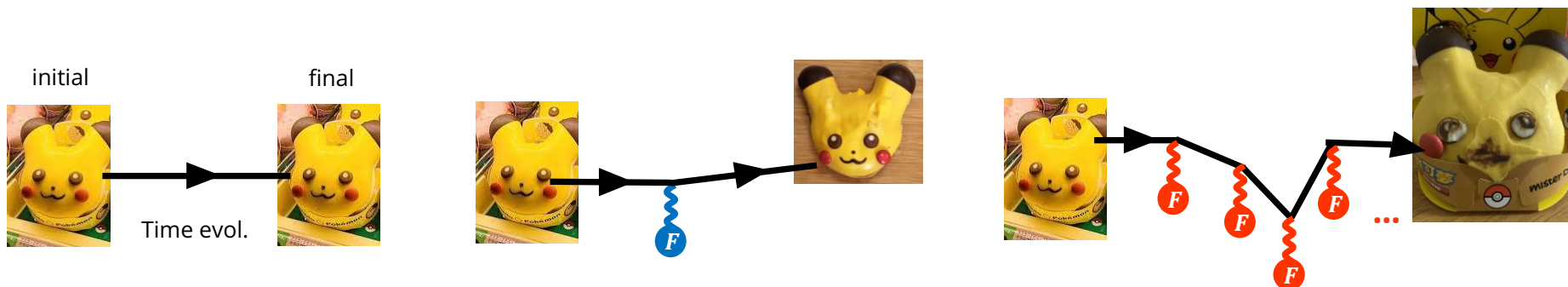
$$\alpha^{-1}(\text{theor.}) = 137.03599914 \dots$$

$$\alpha^{-1}(\text{exp.}) = 137.03599899 \dots$$

[Aoyama, Kinoshita, Nio (2017)]

EM field: What can happen ? (1/2)

Theoretical essence: Non-perturbative dress of the propagator



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

$$\alpha^{-1}(\text{theor.}) = 137.03599914 \dots$$

$$\alpha^{-1}(\text{exp.}) = 137.03599899 \dots$$

[Aoyama, Kinoshita, Nio (2017)]

EM field: What can happen ? (2/2)

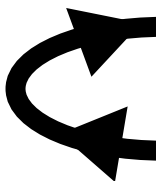
Lots theoretical predictions !

- Examples

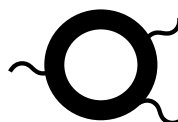
Novel QED processes

Review: [Fedotov, Ilderton, Karbstein, King, Seipt, [HT](#), Torgrimsson, 2203.00019]

ex 1) Schwinger effect



ex 2) Photon splitting



ex 3) vacuum birefringence



Also affect QCD/hadron physics

Review: [Hattori, Itakura, Ozaki, 2305.03865]

ex 1) Hadron properties

⇒ mass, form factor, decay rate, ...

ex 2) QCD phase diagram

⇒ novel phase, (inverse) magnetic catalysis, ...

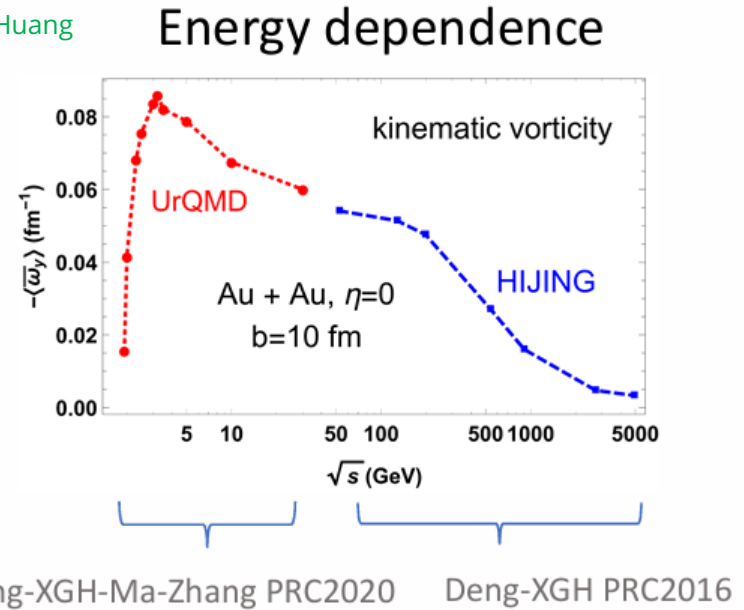
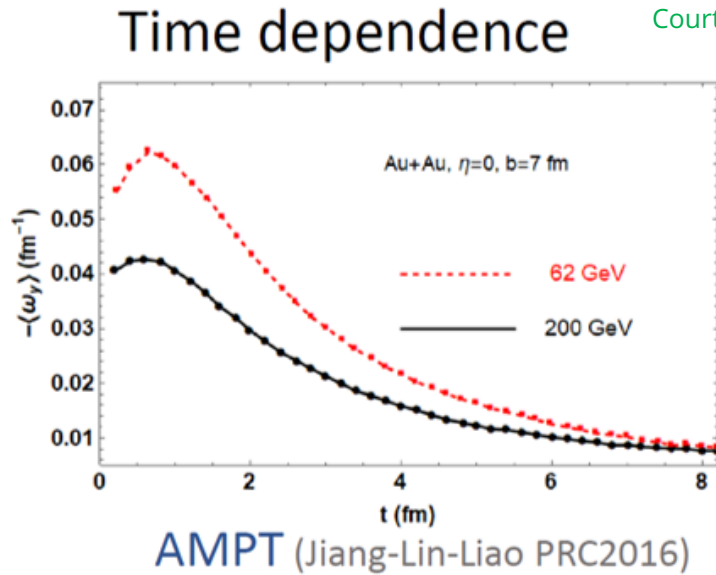
ex 3) Anomalous transport (or non-equilibrium processes in general)

⇒ chiral magnetic effect (CME) = current driven by B field under chirality imbalance
chiral magnetic wave, chiral plasma instability, ...

- Too many, so, don't explain them in detail
- Just remember: **most of them are unobserved** ⇒ **exp. search is an active topic** (i.e., this conference !)

Vorticity: How strong ?

Again, can be estimated by event generators



Pros: $\omega \sim 10^{21}$ Hz

⇒ Fastest in the Universe !



Galaxy

10^{-15} Hz



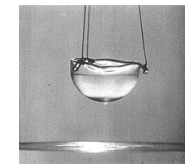
Typhoon

10^{-1} Hz



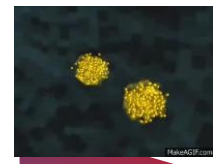
Washing mach.

10^{+2} Hz



Superfluid

10^{+7} Hz



HIC

10^{+21} Hz

Cons: “weak” in the unit of eV: $\omega = O(10 \text{ MeV})$

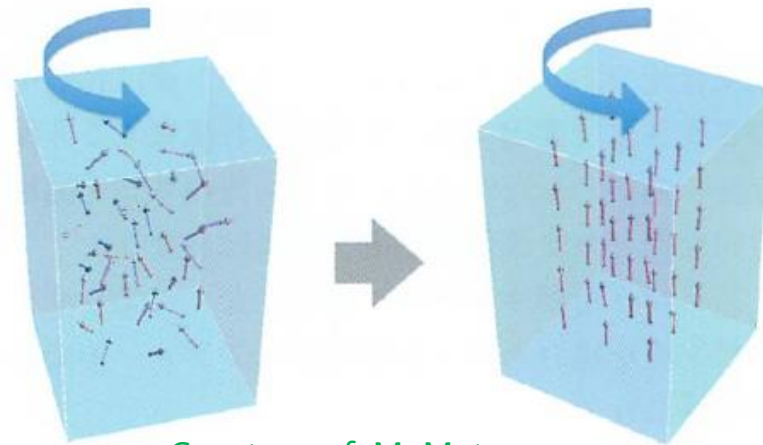
BUT, is relatively long-lived $O(5 \text{ fm}/c) \Rightarrow$ may leave signals of order $\frac{\omega}{T} \sim 1\%$

Vorticity: What can happen ? (1/2)

Spin & chirality physics have been discussed in the community

ex 1) Spin polarization via spin-vorticity coupling [Liang, Wang (2004)]

$E \rightarrow E - \boldsymbol{\omega} \cdot \mathbf{s}$: A vorticity analog of the magnetic Zeeman effect $\delta E \propto q\mathbf{B} \cdot \mathbf{s}$
 \Rightarrow Spin alignment along $\boldsymbol{\omega}$ (analog of the Barnett effect for magnetization)



Courtesy of M. Matsuo

ex 2) Anomalous transport

chiral vortical effect (CVE): $\mathbf{J} \propto \boldsymbol{\omega} \Leftarrow$ A vorticity analog of CME $\mathbf{J} \propto \mathbf{B}$

Short summary of the last part

HIC creates the strongest EM and vorticity fields ever

= can be used as a unique tool to study “new physics”

Key ideas explained

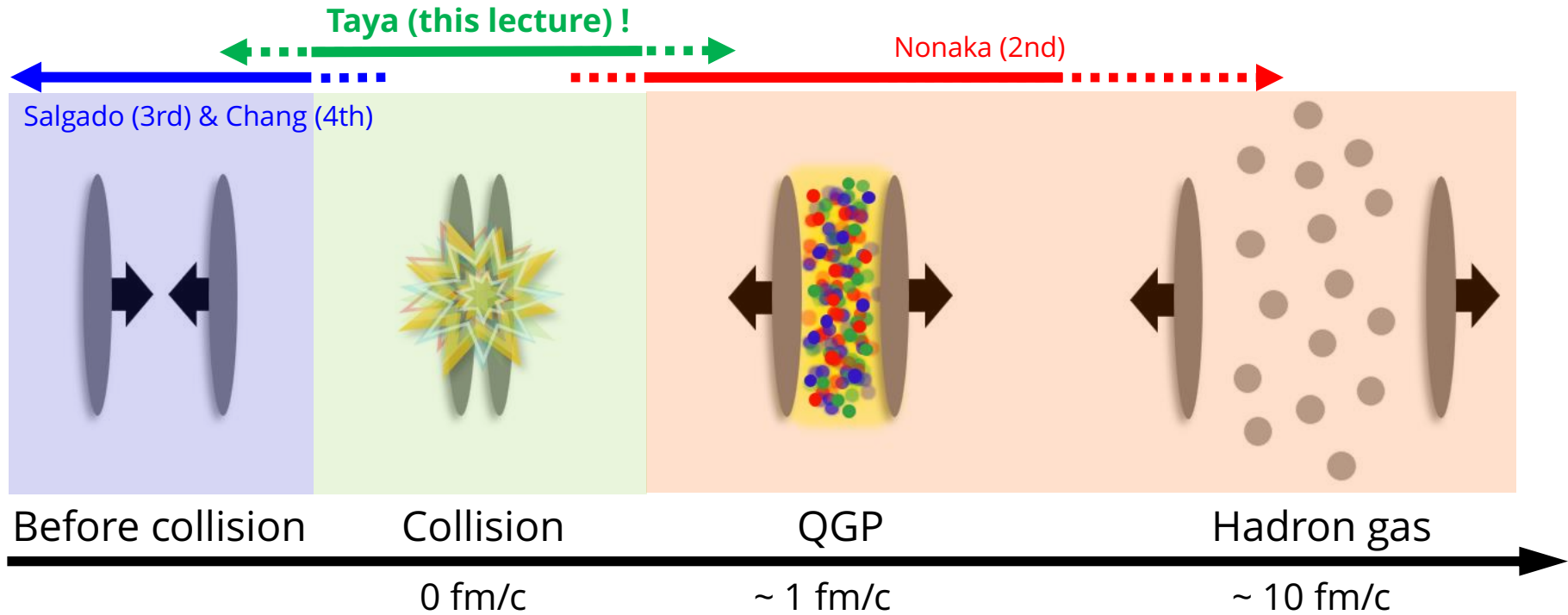
- Pros and cons:

EM field is strong $eB \gg \Lambda_{\text{QCD}}^2$ but is short-lived $\tau \ll 0.1 \text{ fm}/c$ (if no conductivity)

Vorticity is not so strong $\omega \sim 10 \text{ MeV}$ but is long-lived $\tau \sim 5 \text{ fm}/c$

- Many phenomena proposed and are actively searched in experiments
e.g., spin polarization of Λ hyperons

Summary



Early-time dynamics of HIC contains rich & important physics

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

} origin of the QGP in HIC

} provide opportunity to study “new physics”