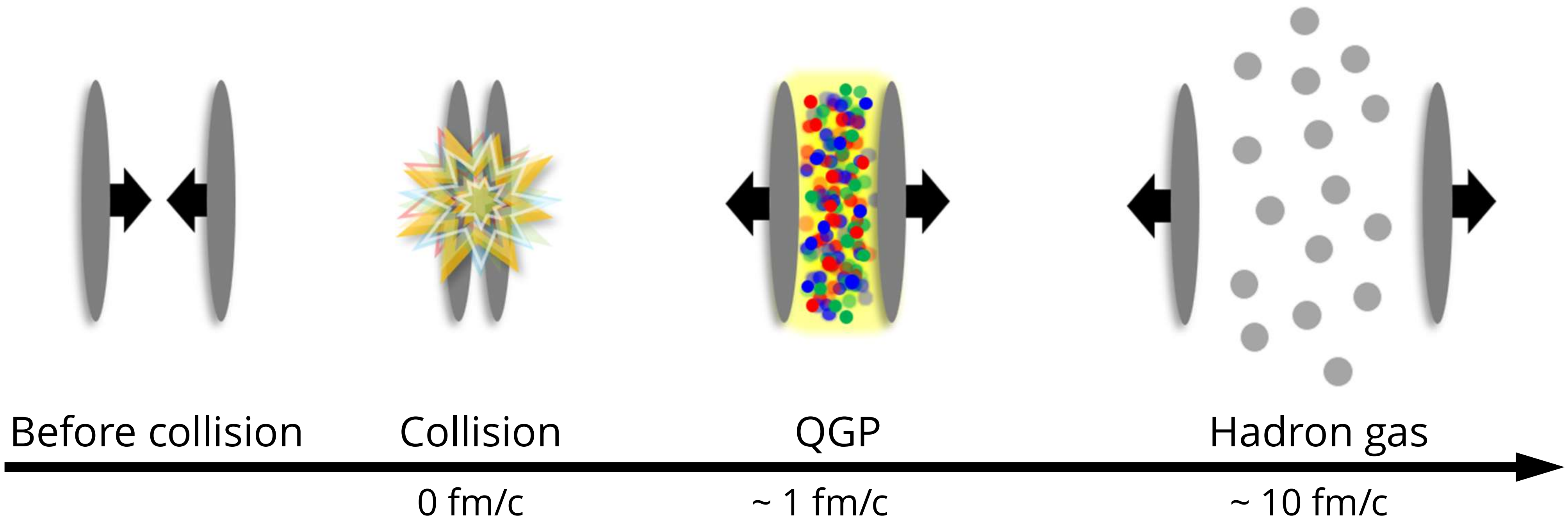
Initial state and early-time dynamics

Hidetoshi Taya

Keio University

Sep. 7th @ Initial Stages 2025

What I'm going to talk …



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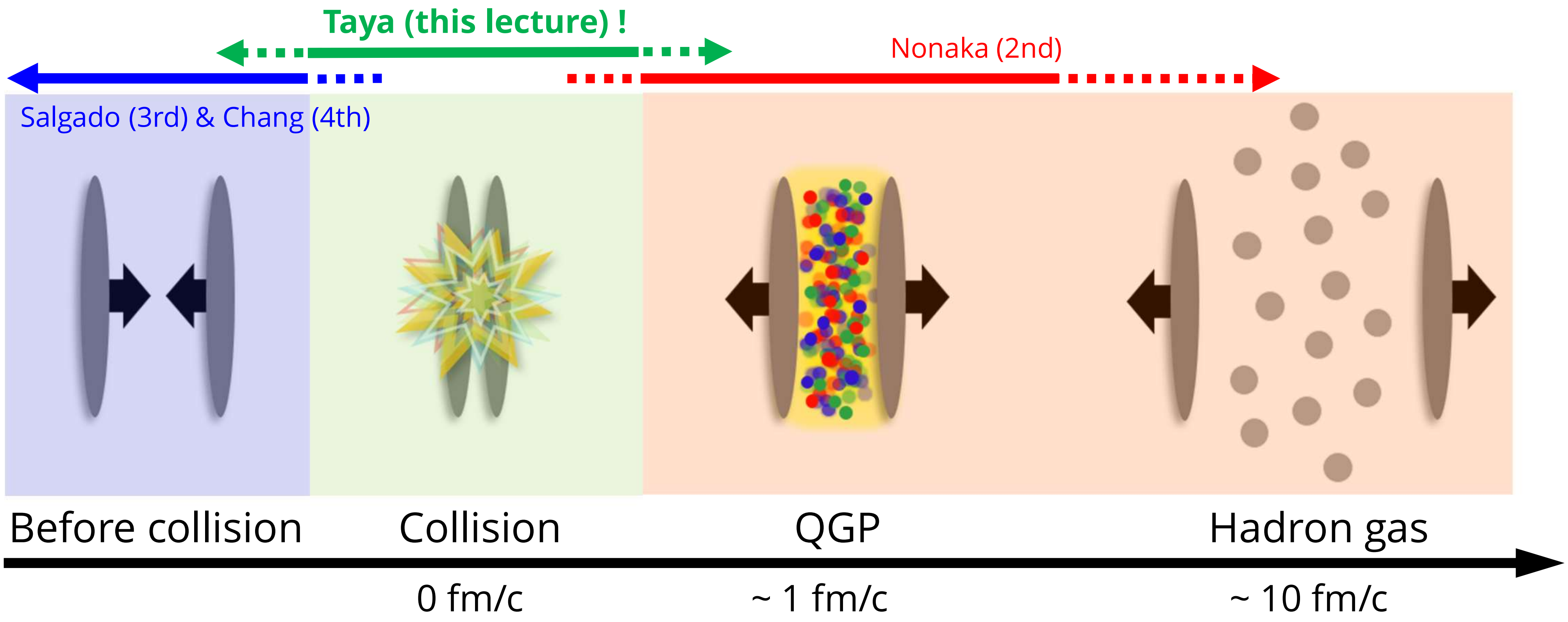

Early-time dynamics of HIC contains rich & important physics

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

origin of the QGP in HIC

- strong EM field
- strong vorticity

provide opportunity to study "new physics"

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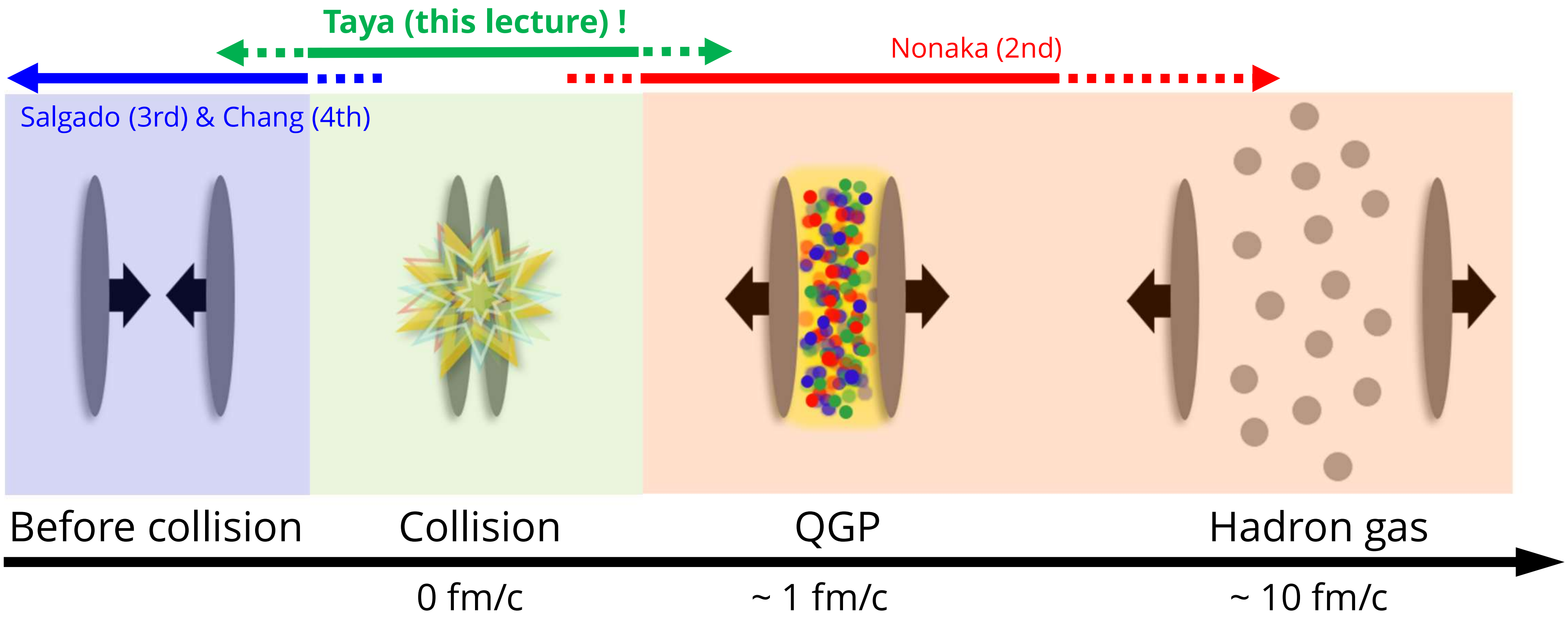

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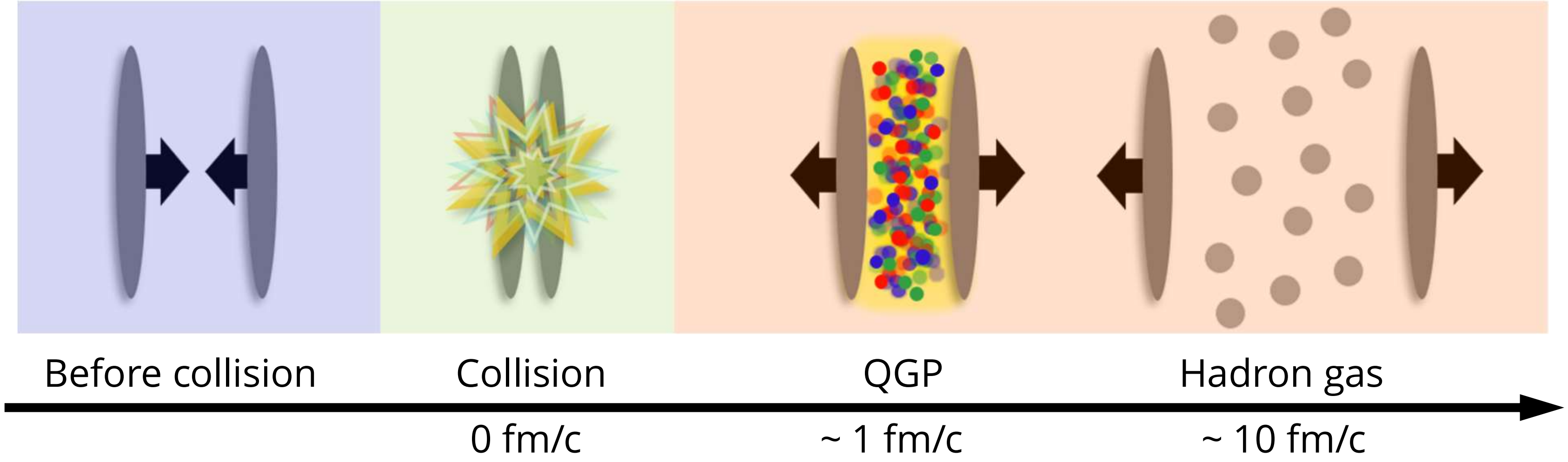

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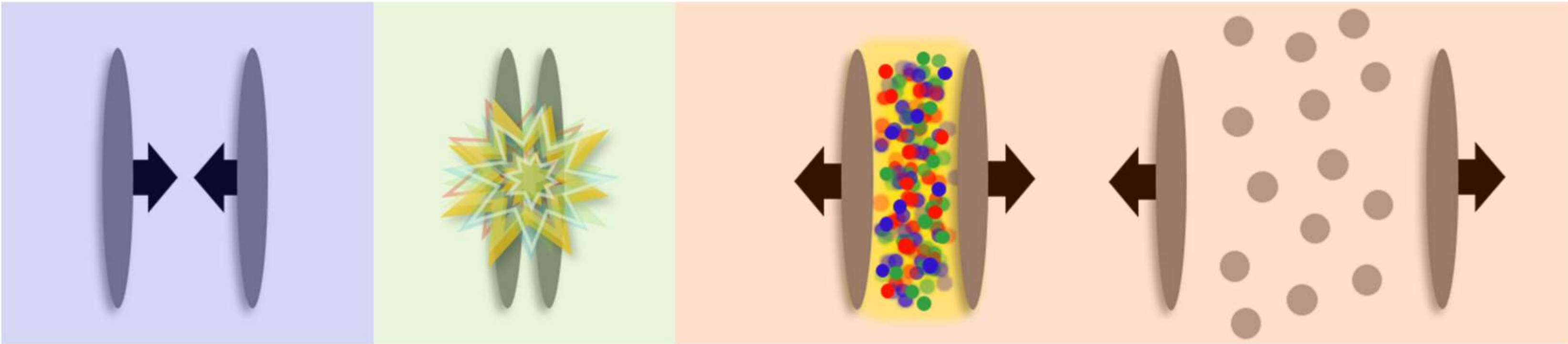

Before collision	Collision	QGP	Hadron gas
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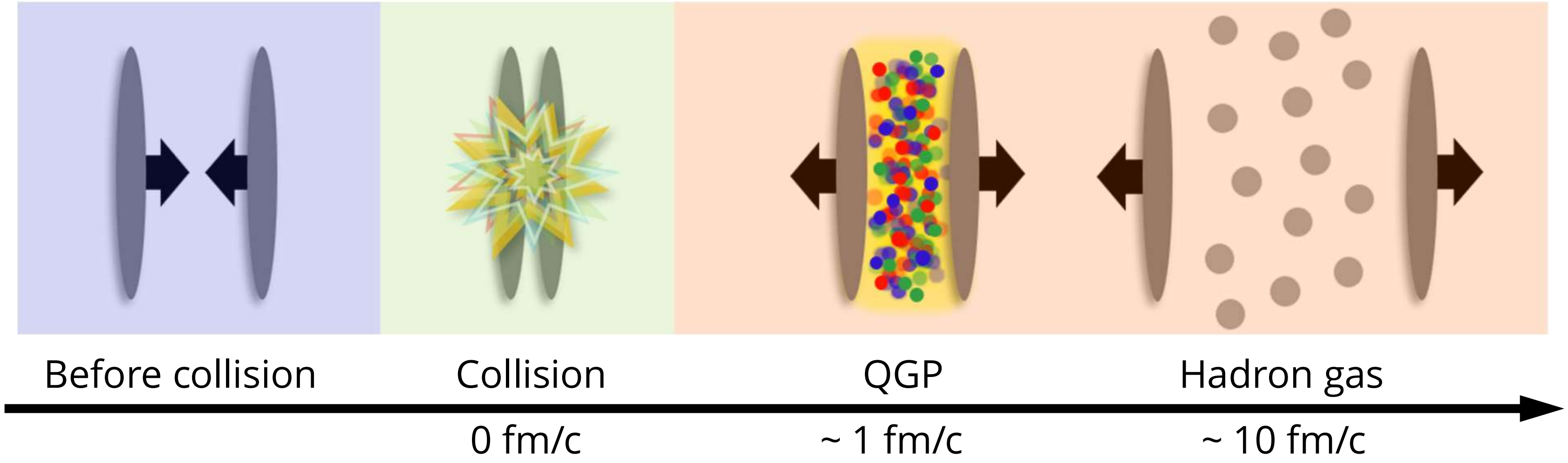

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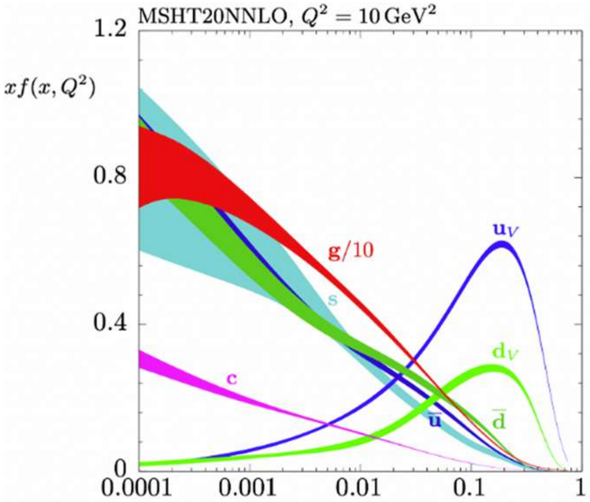
+ Global fit of many obs: Jets, Drell-Yan, ...

(will be explored further in EIC)



Bjorken x (~ 1/energy)

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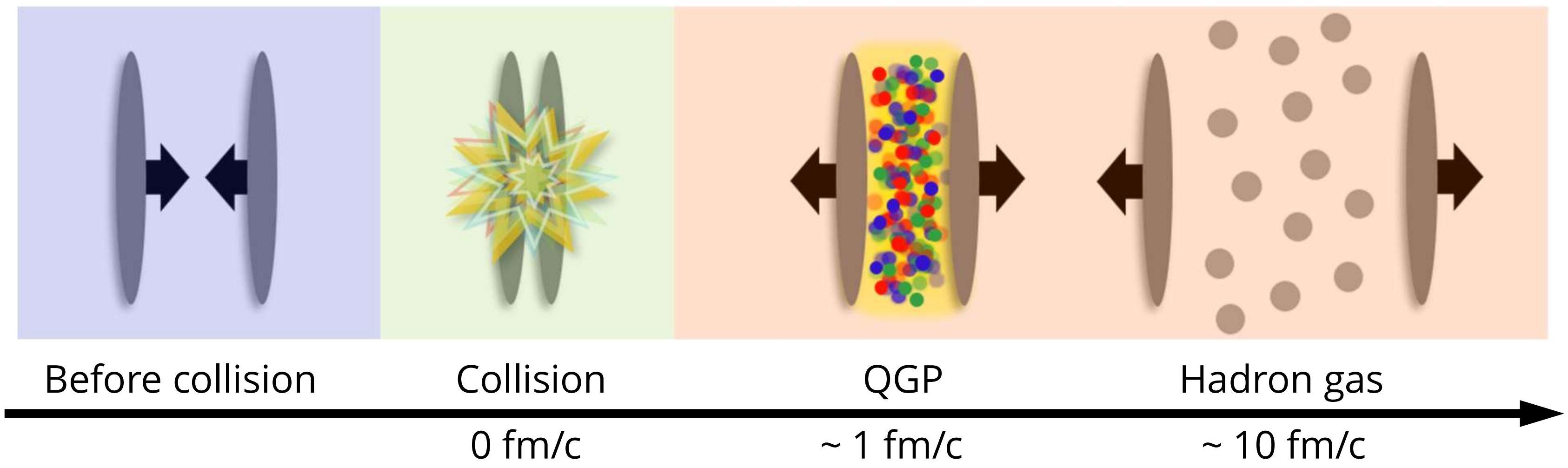

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- **Theory: perturbative QCD**

  cf. Color Glass Condensate
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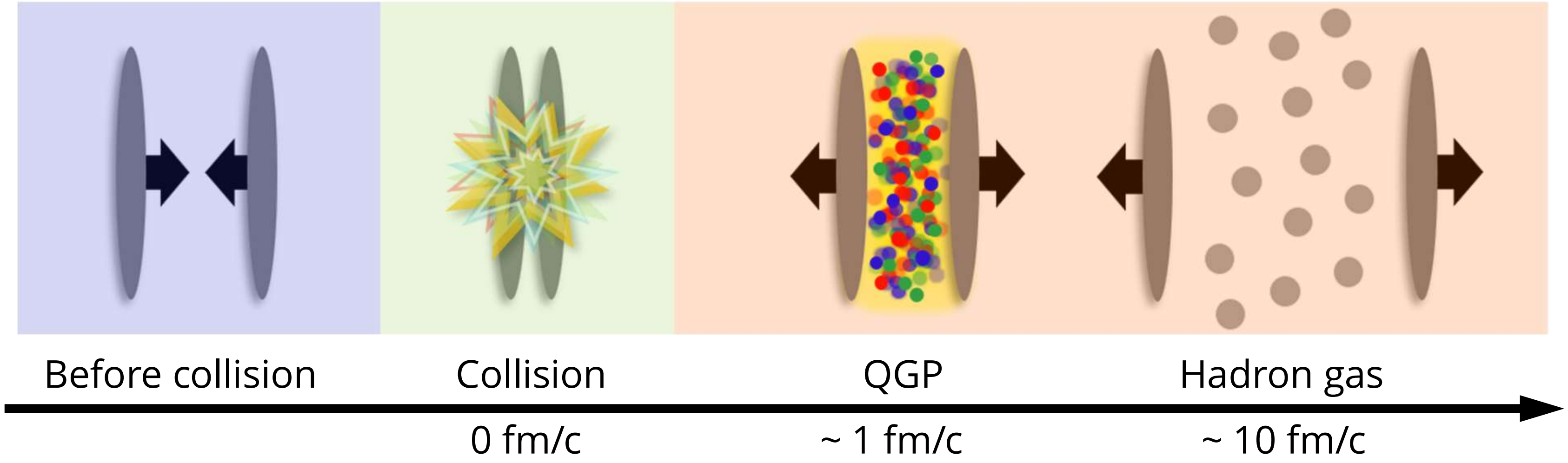

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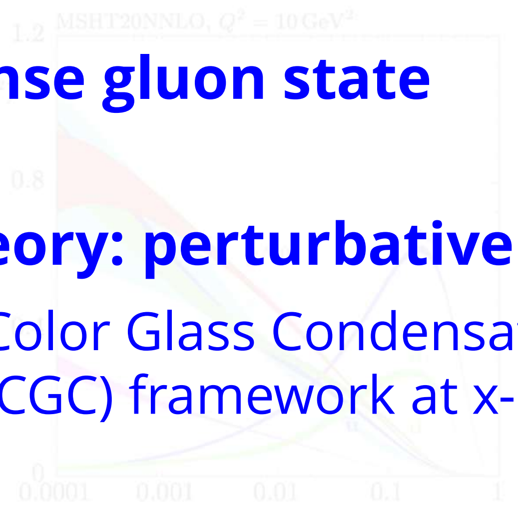

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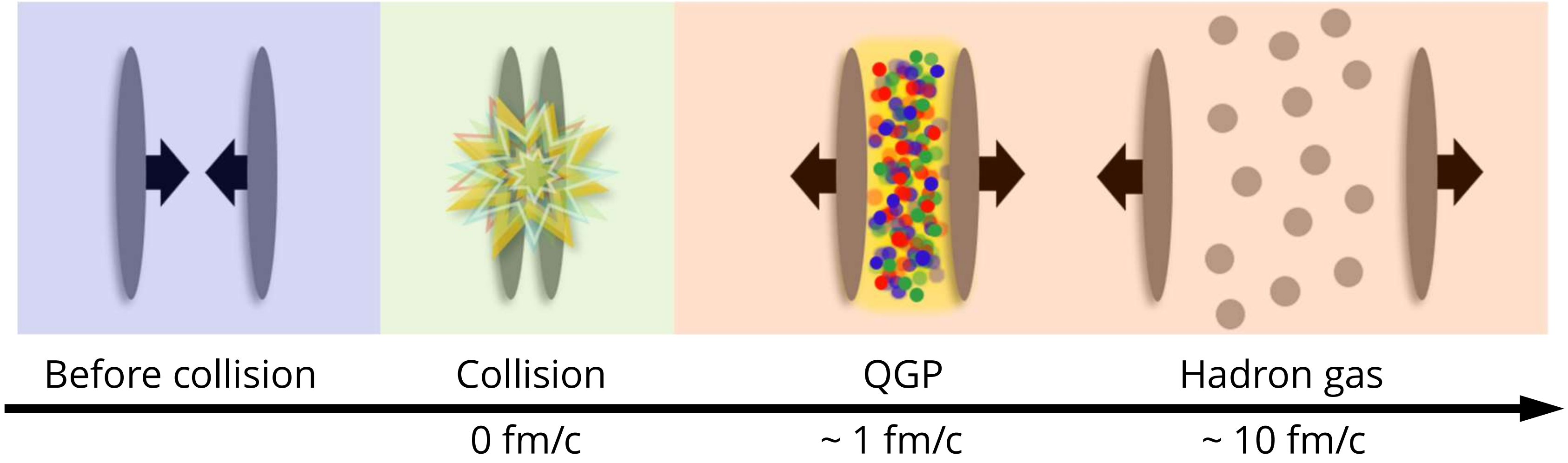

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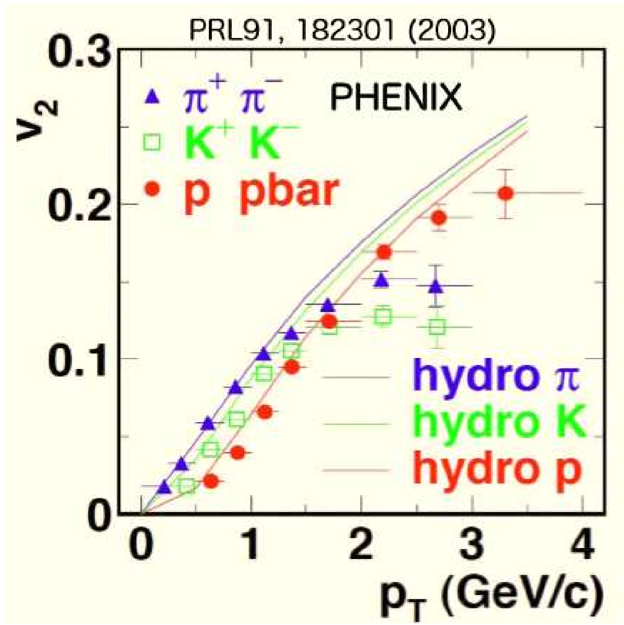

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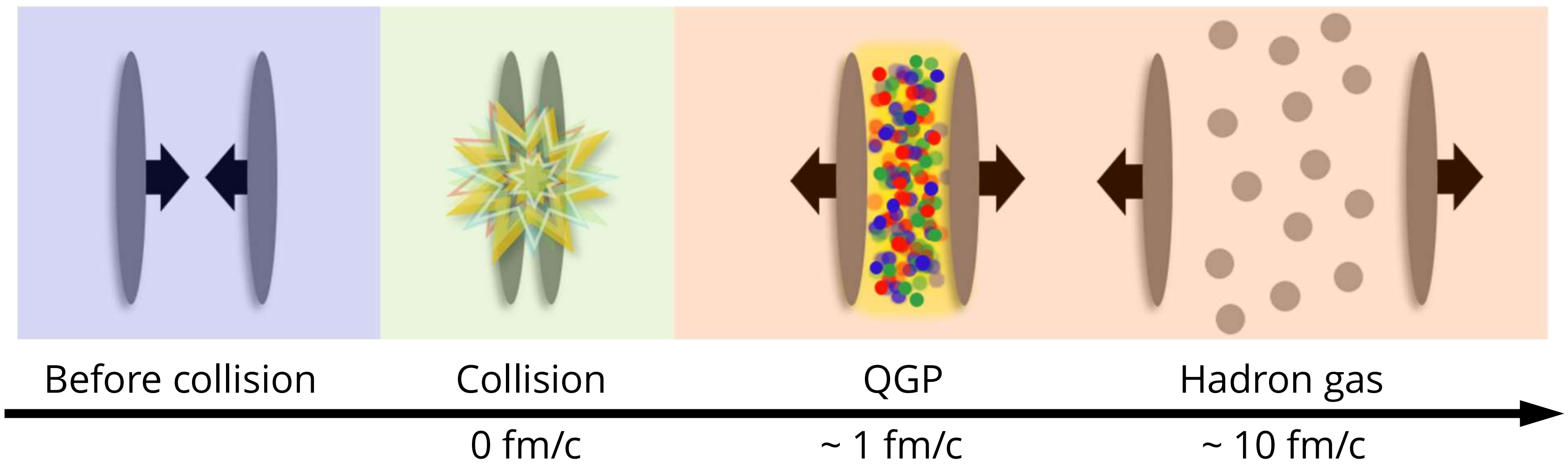

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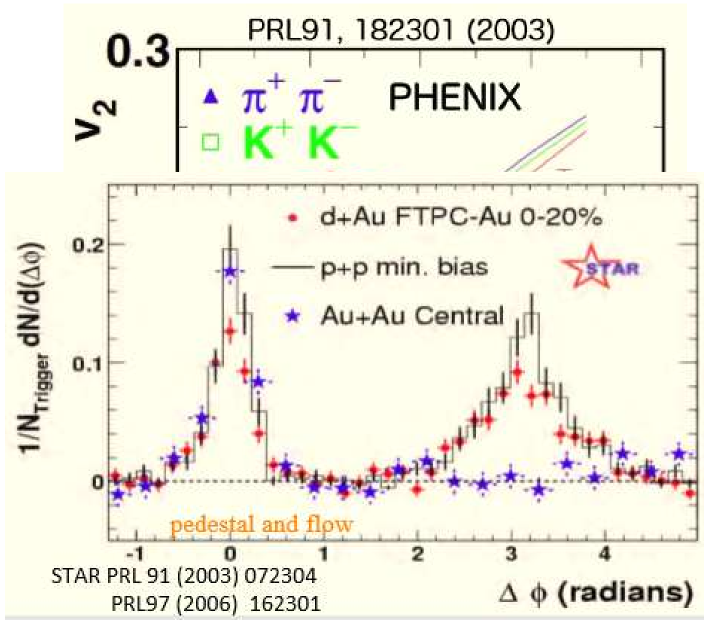

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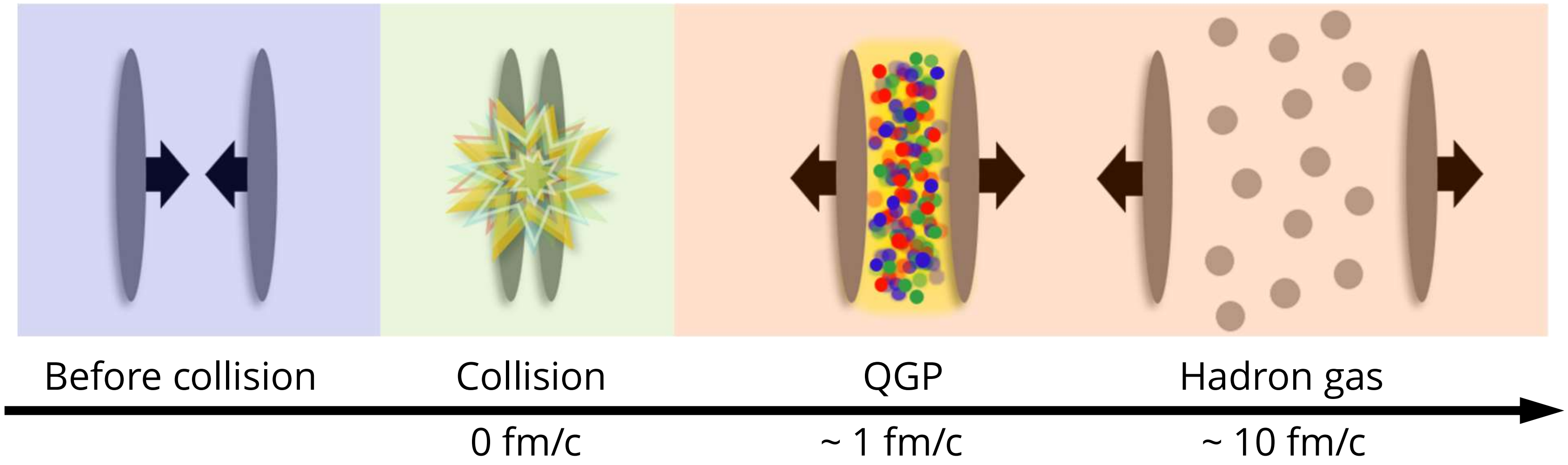

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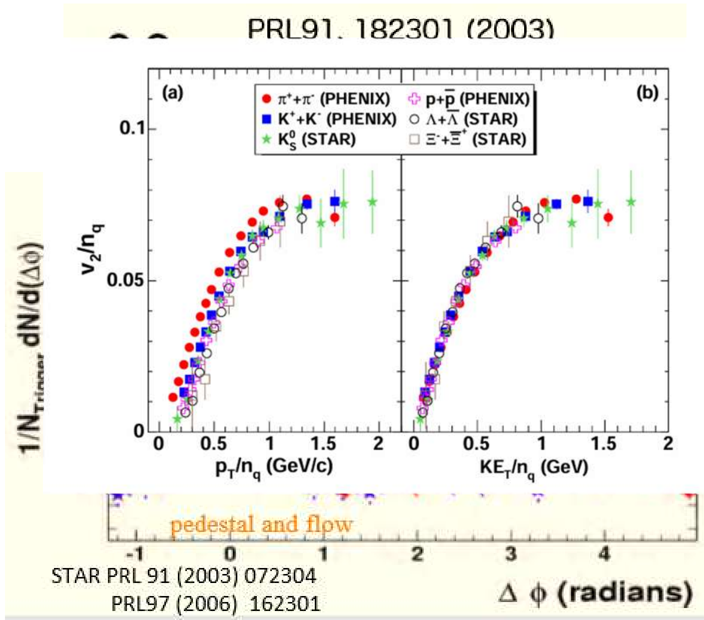

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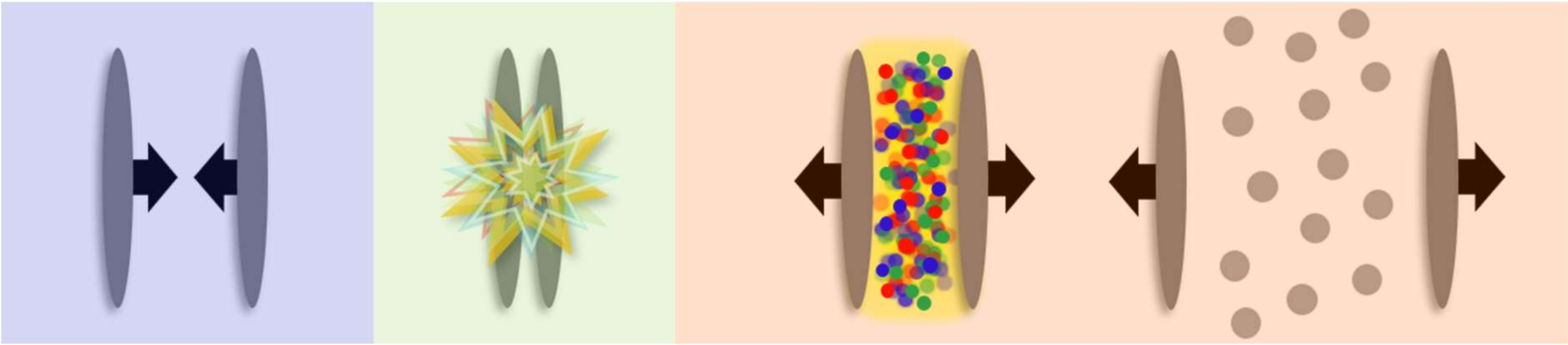

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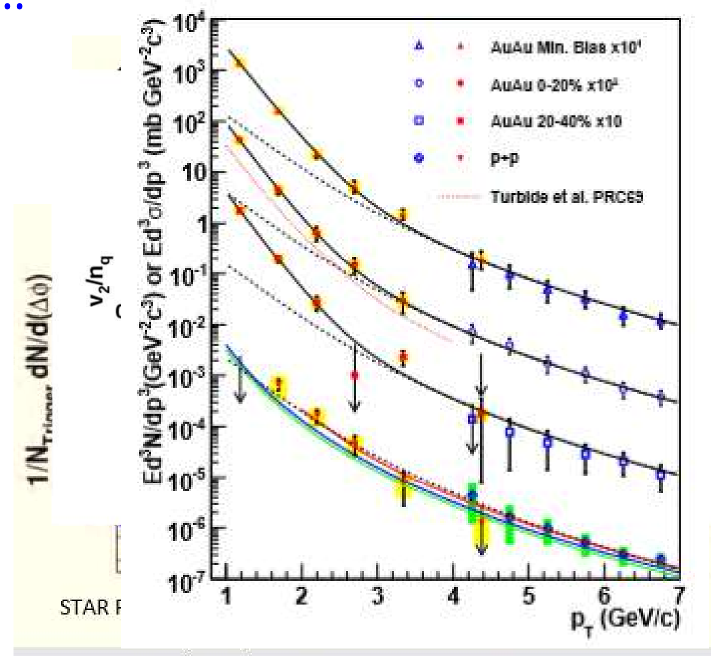

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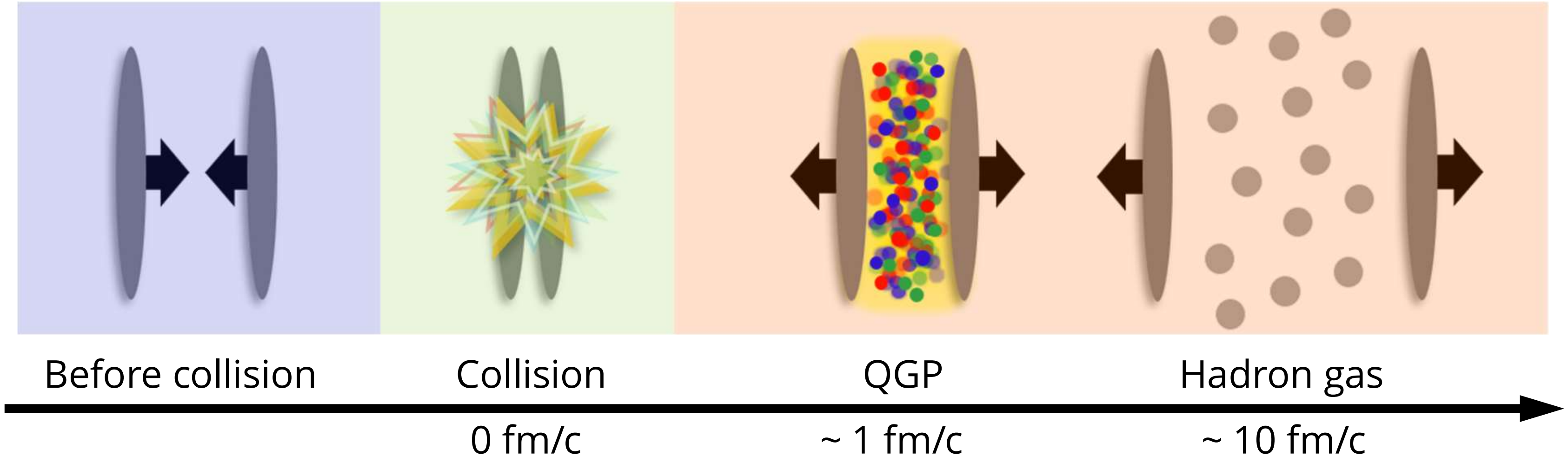

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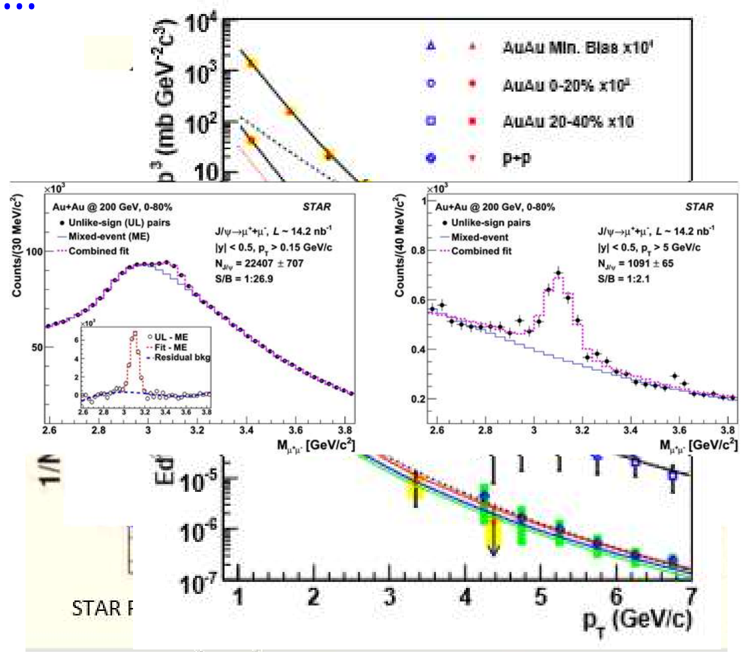

- elliptic flow
- jet quenching
- quark # scaling
- thermal photon
- J/ψ suppression
- ...

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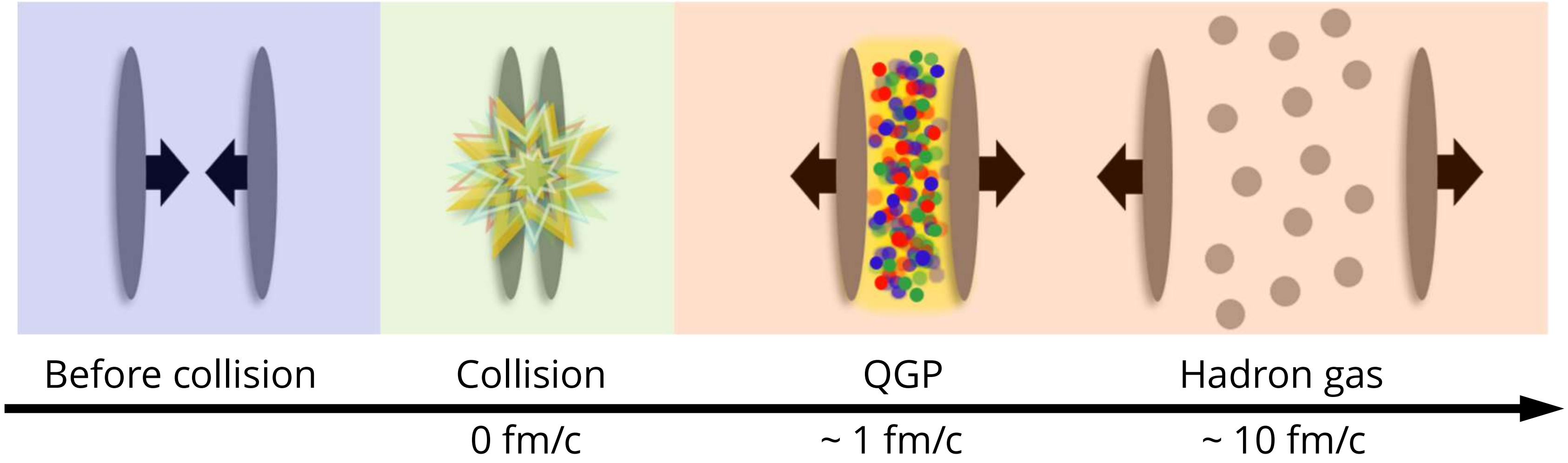

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- **QGP created**

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

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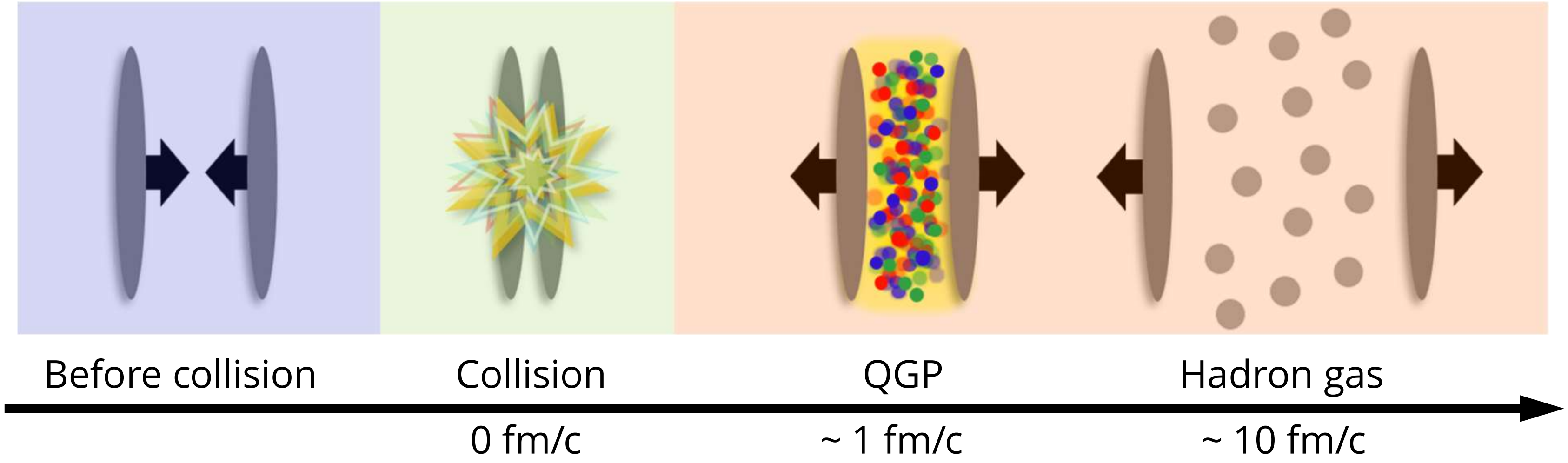

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■ : No established understanding

- 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) ?

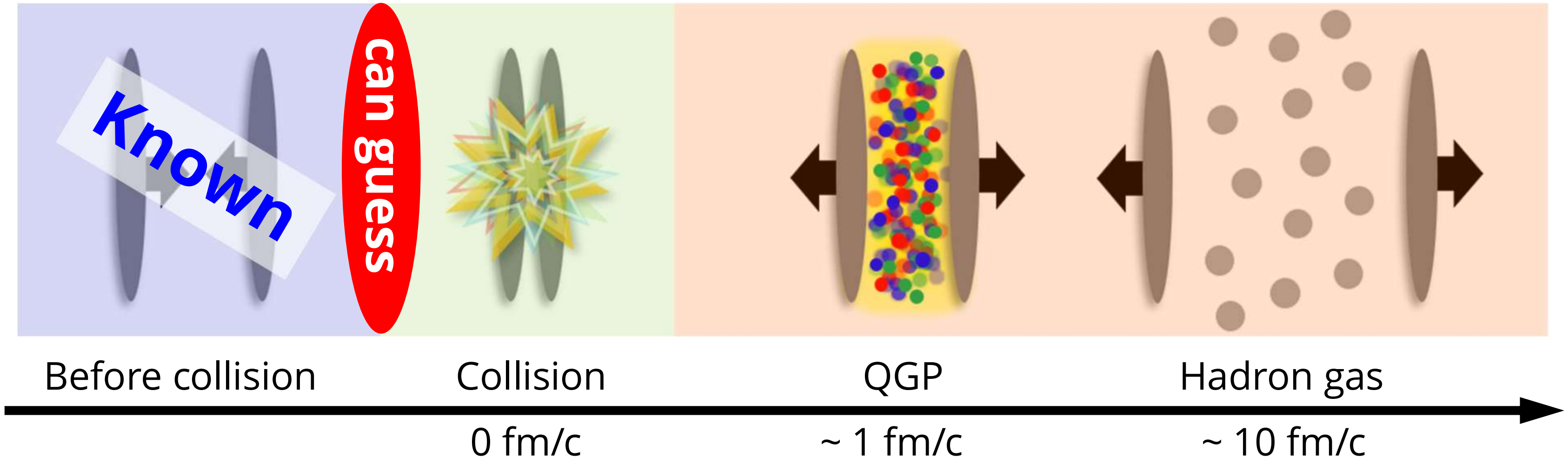
  - Thermalization ("hydrodynamization"):
  how thermalize to form the liquid-like QGP? how can it be fast ~ 1fm/c?

  - 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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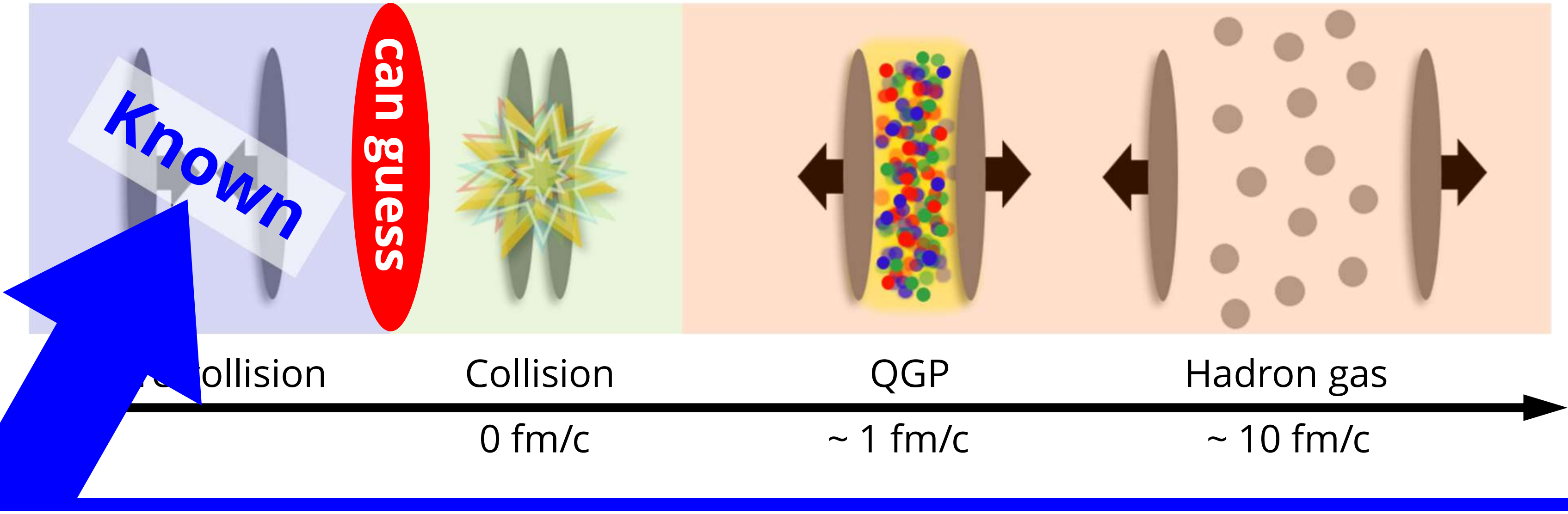
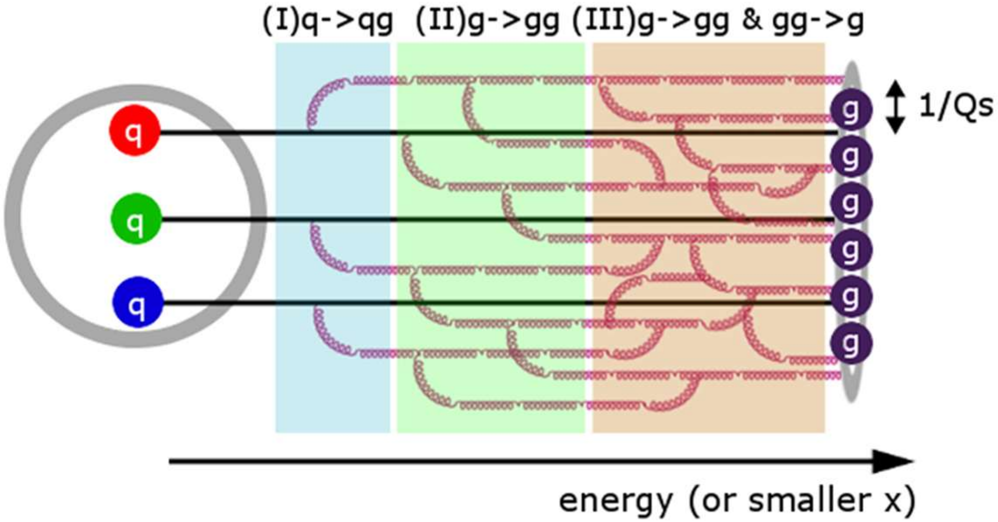


High-energy nucleus = a dense gluon state ≈ a "color capacitor plate"

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

↖ saturation scale



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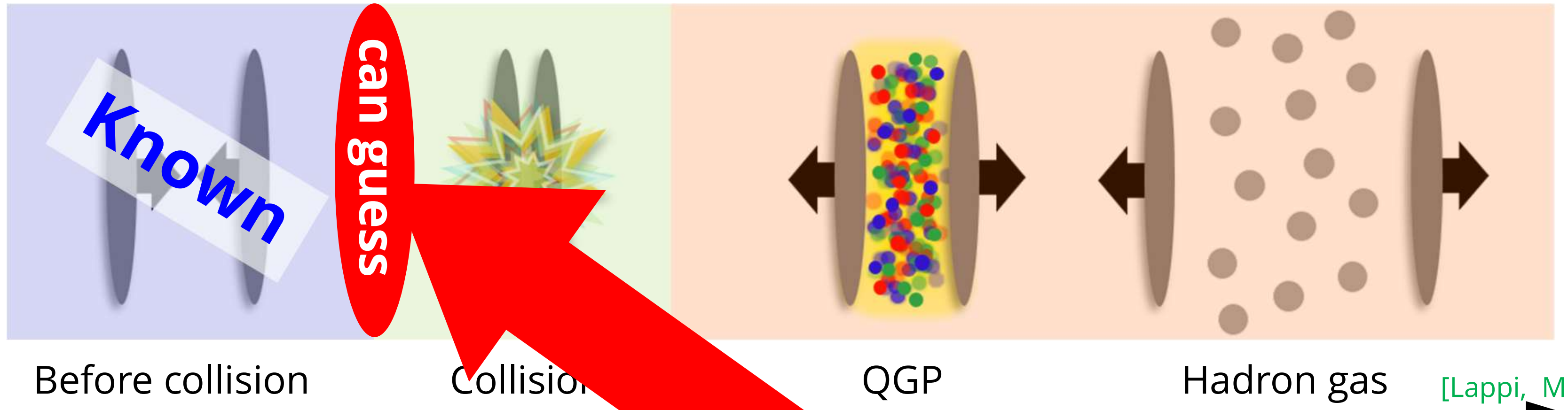
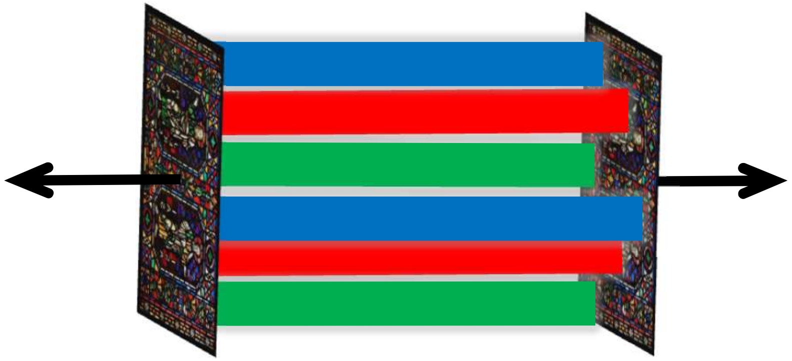


[Lappi, McLerran (2006)]

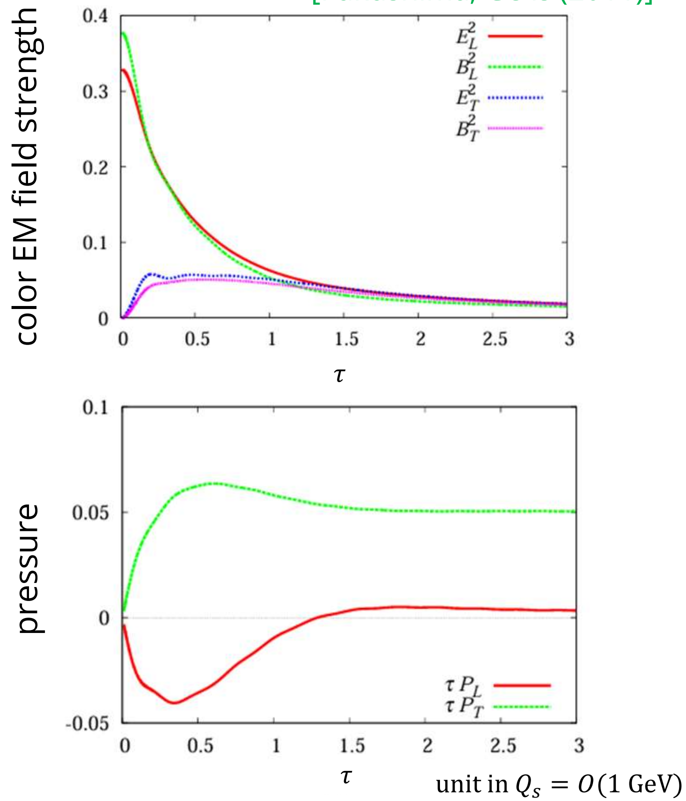
Formation of a "colored capacitor" ⇒ Strong color field (:= glasma)



⇒

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) Topological $\boldsymbol{E}\cdot\boldsymbol{B} \neq 0$ ($\because$ div $\boldsymbol{B} \neq 0$ in QCD)

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

(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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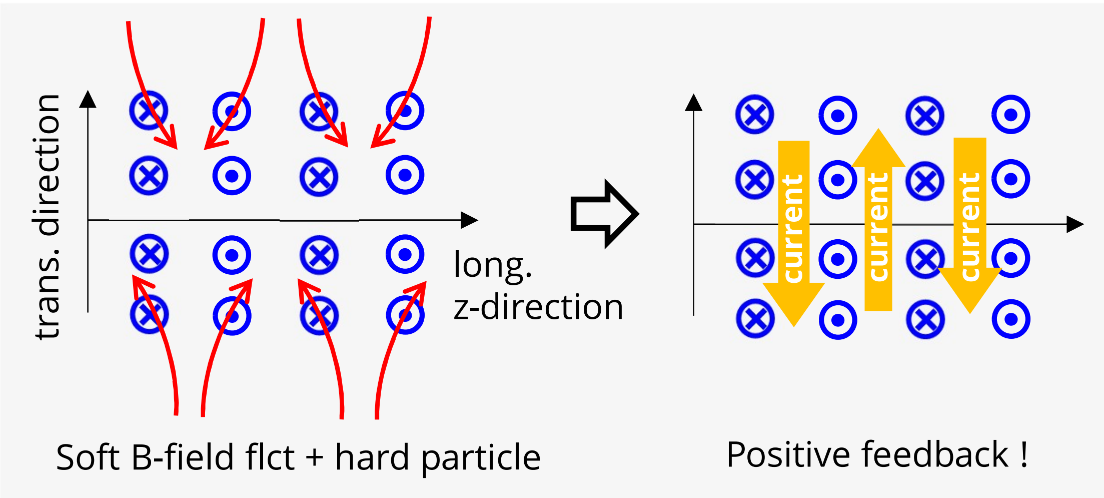
- **Microscopically, two mechanisms:**

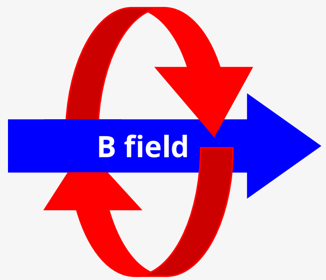
Weibel instability

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, $p_z < \sqrt{gB}$

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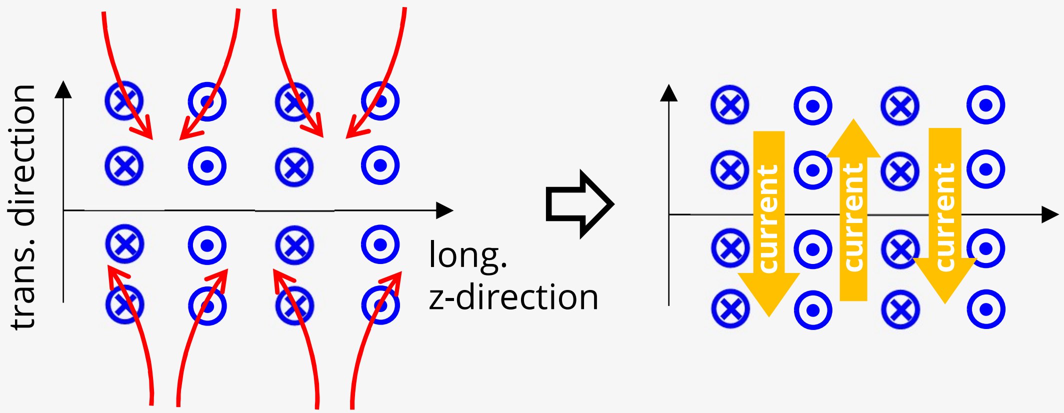

Soft B-field flct + hard particle   Positive feedback !

[Fujii, Itakura, Iwasaki (2008)]

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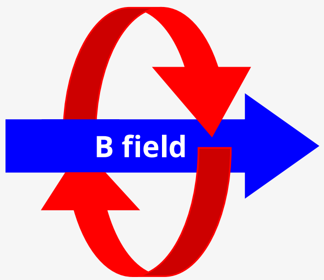

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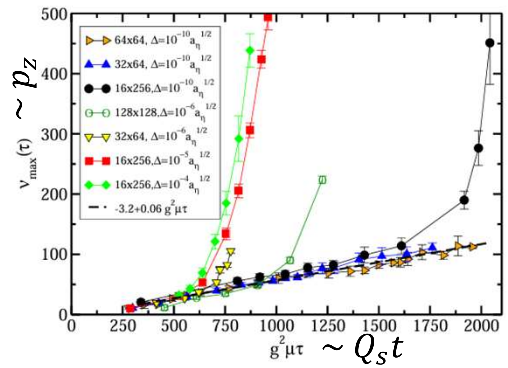
- **Can be studied numerically** [Romatschke, Venugopalan (2006)]

  ⇒ 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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Glasma is unstable ⇒ decays & isotropitizes spontaneously

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

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

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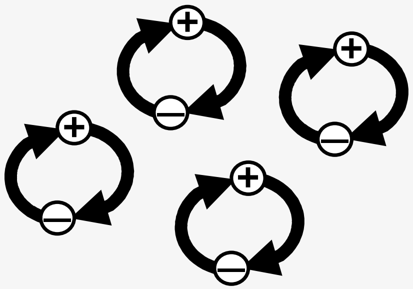
Our vacuum = full of quantum fluct.



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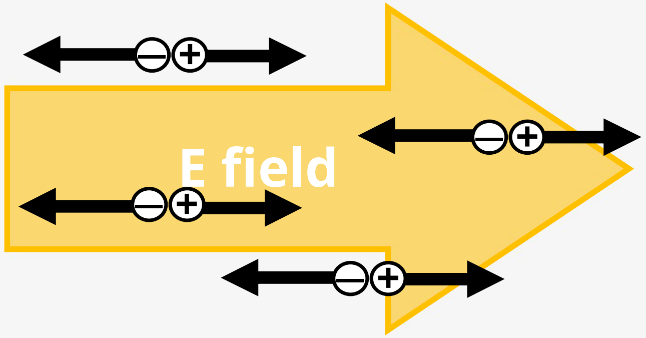

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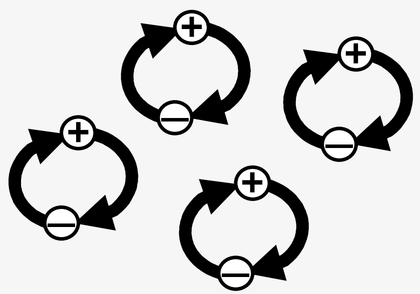

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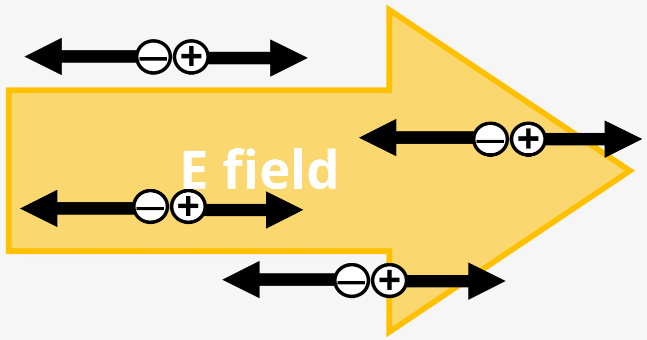

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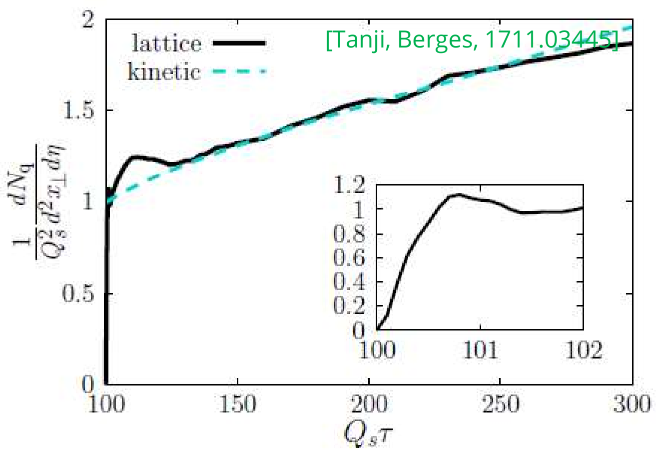
- **Can be studied numerically**

⇒ Very fast & huge quark production

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

⇒ would be important for chemical eq.



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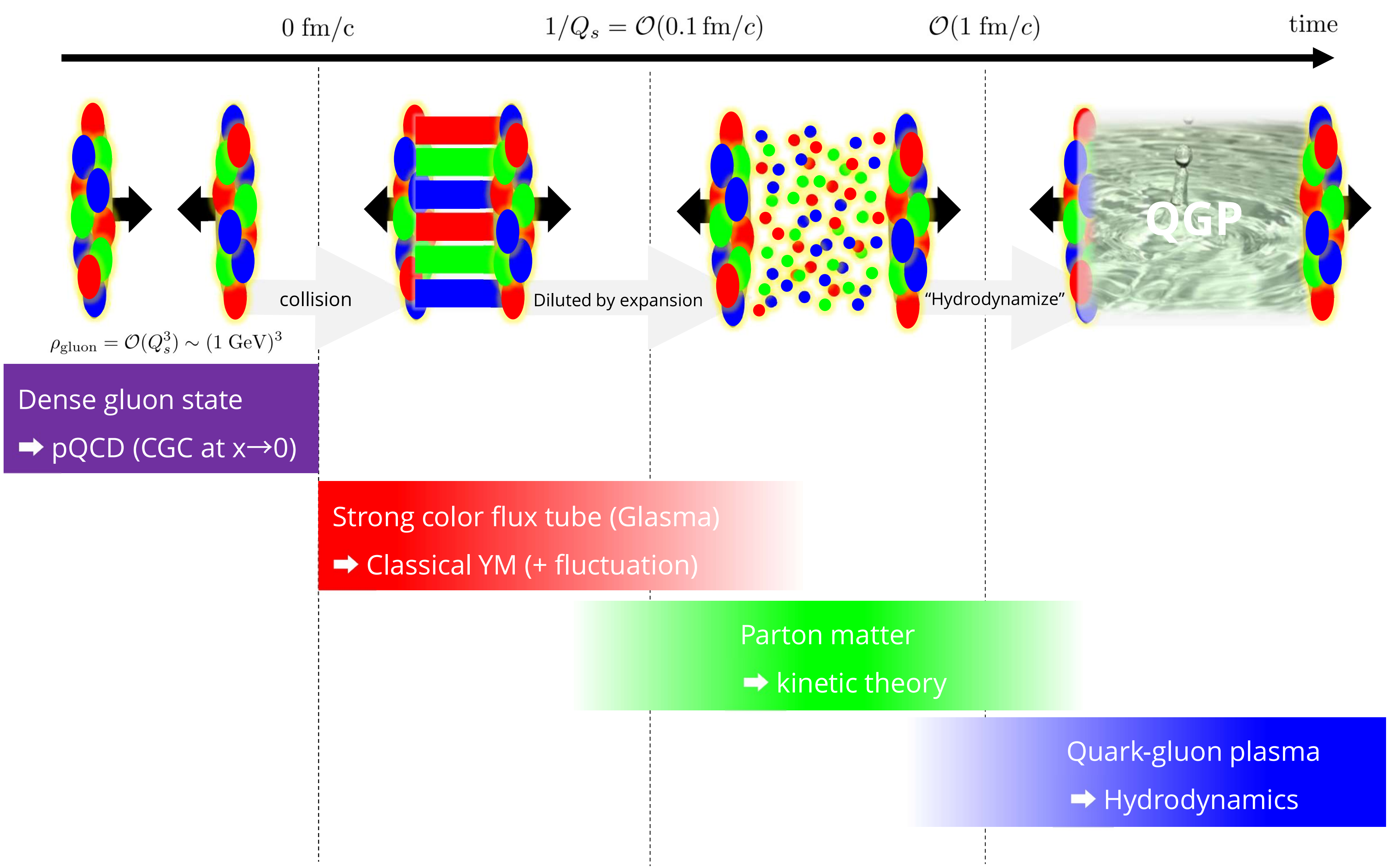

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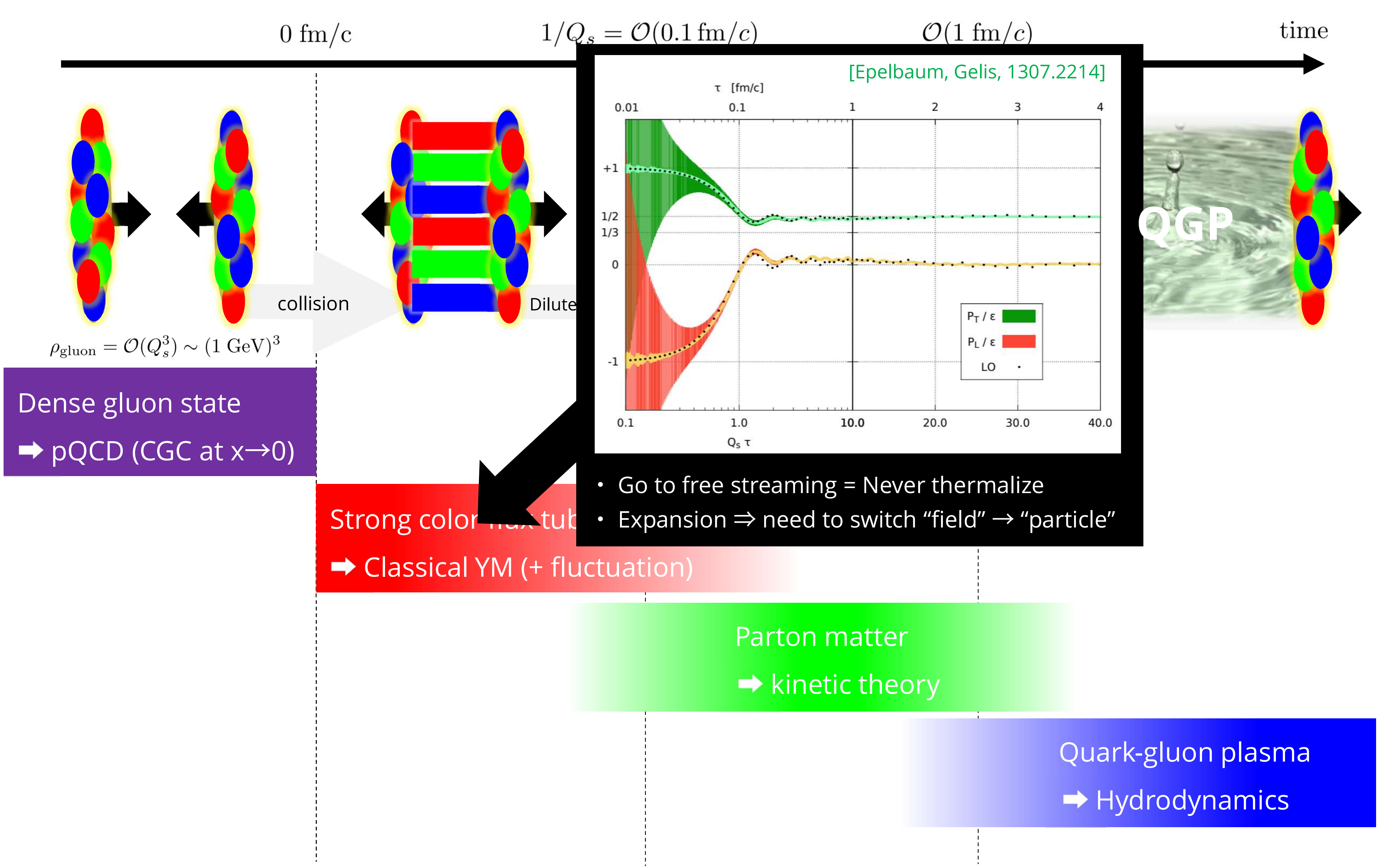
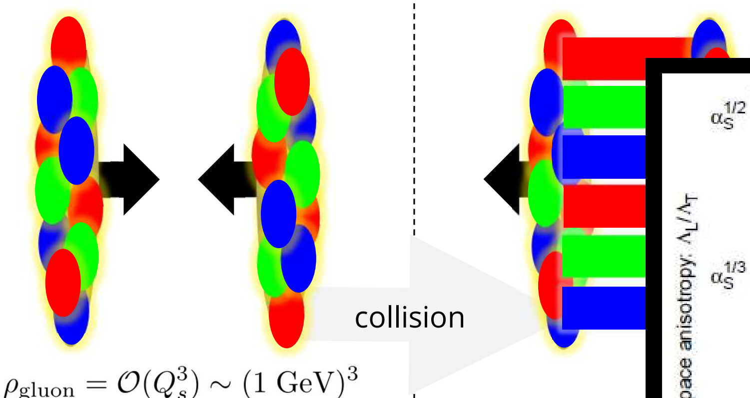


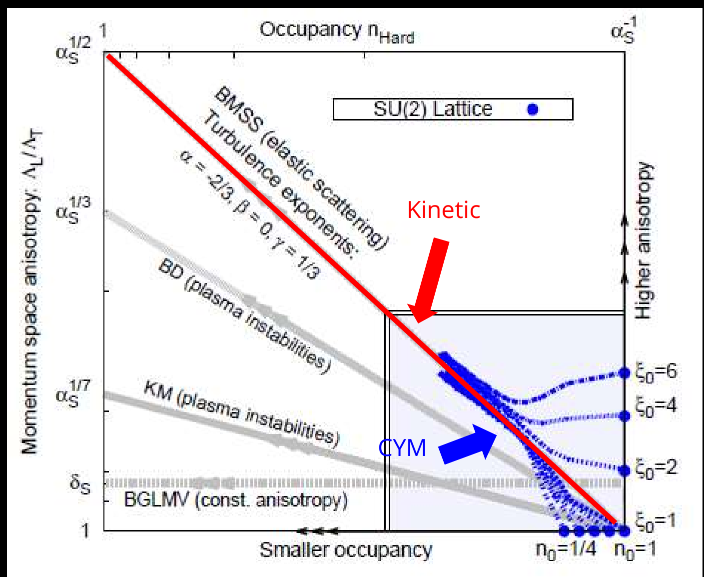
Weak-coupling scenario: particle + hydrodynamization

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



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

Dense gluon state
➡ pQCD (CGC at x→0)



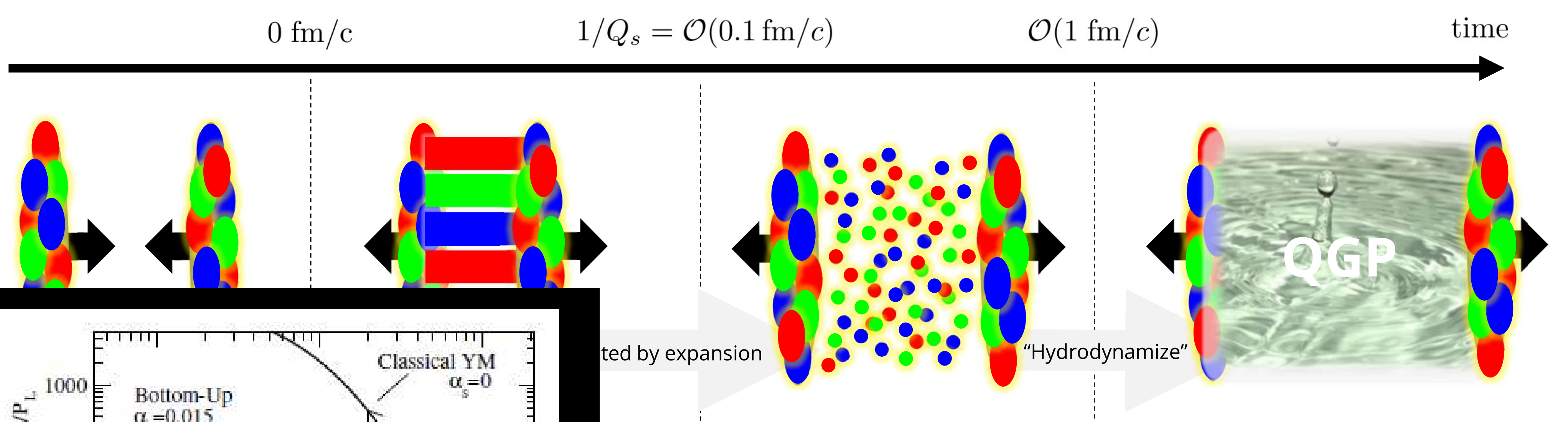
- CYM and kinetics are smoothly connected with each other
  - overlap at $1/g^2 \gg f \gg 1$
    [Mueller, Son, hep-ph/0212198]
    [Jeon, hep-ph/0412121]
  - consistent with bottom-up scenario
    [Baier, Mueller, Schiff, Son, hep-ph/0009237]
  - non-thermal attractor
    [Berges, Boguslavski, Schlichting,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

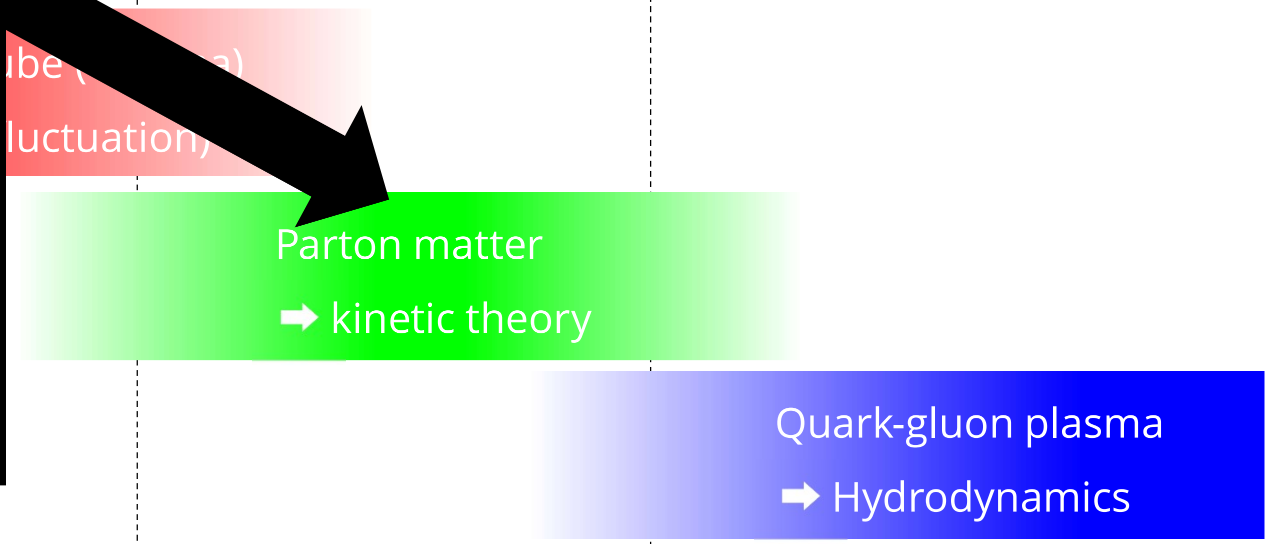
Strong color flux tube (Glasma)
➡ Classical YM (+ fluctuatio...

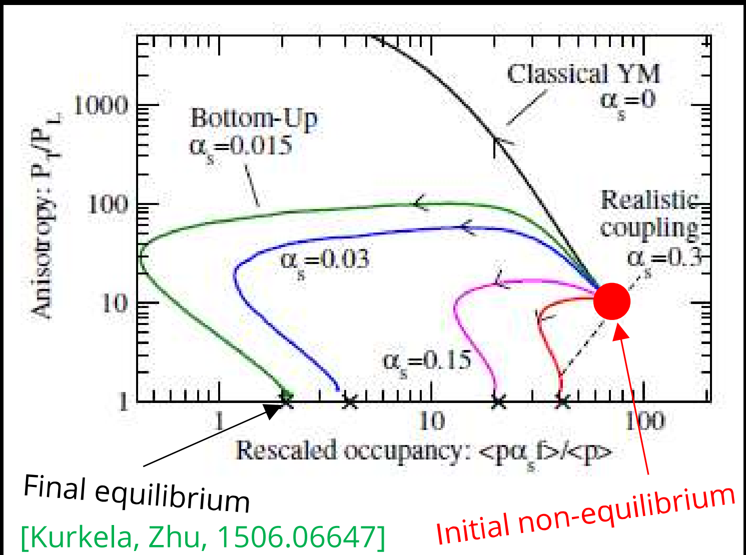
Parton matter
➡ kinetic theory

Quark-gluon plasma
➡ Hydrodynamics

Weak-coupling scenario: particle + hydrodynamization

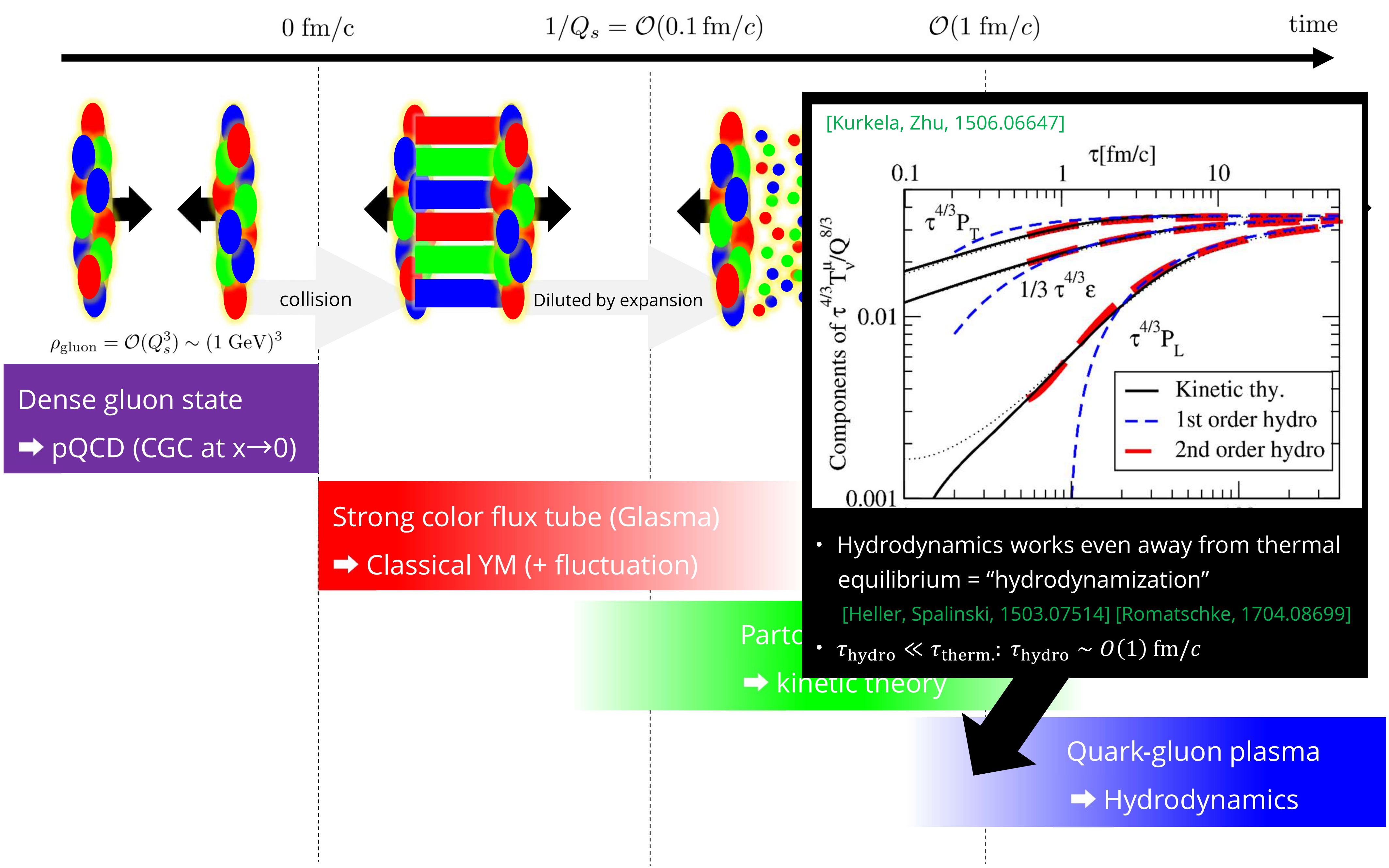




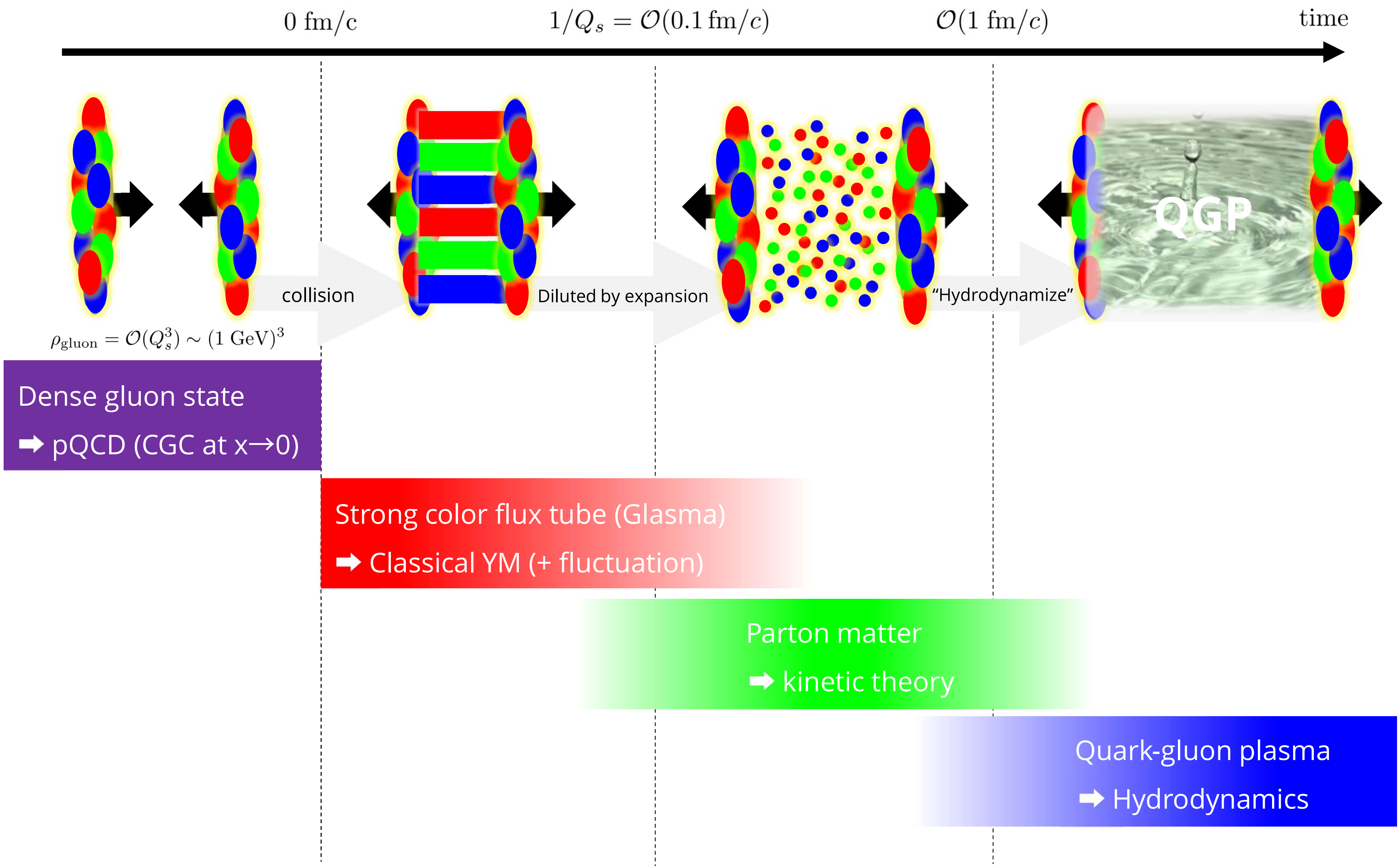


- Kinetic theory of QCD (AMY) [Arnold, Moore, Yaffe, hep-ph/0209353] does describe isotropization & thermalization
- BUT, the time scale is too slow $\tau \sim 10\ \mathrm{fm}/c$

Weak-coupling scenario: particle + hydrodynamization



Weak-coupling scenario: particle + hydrodynamization



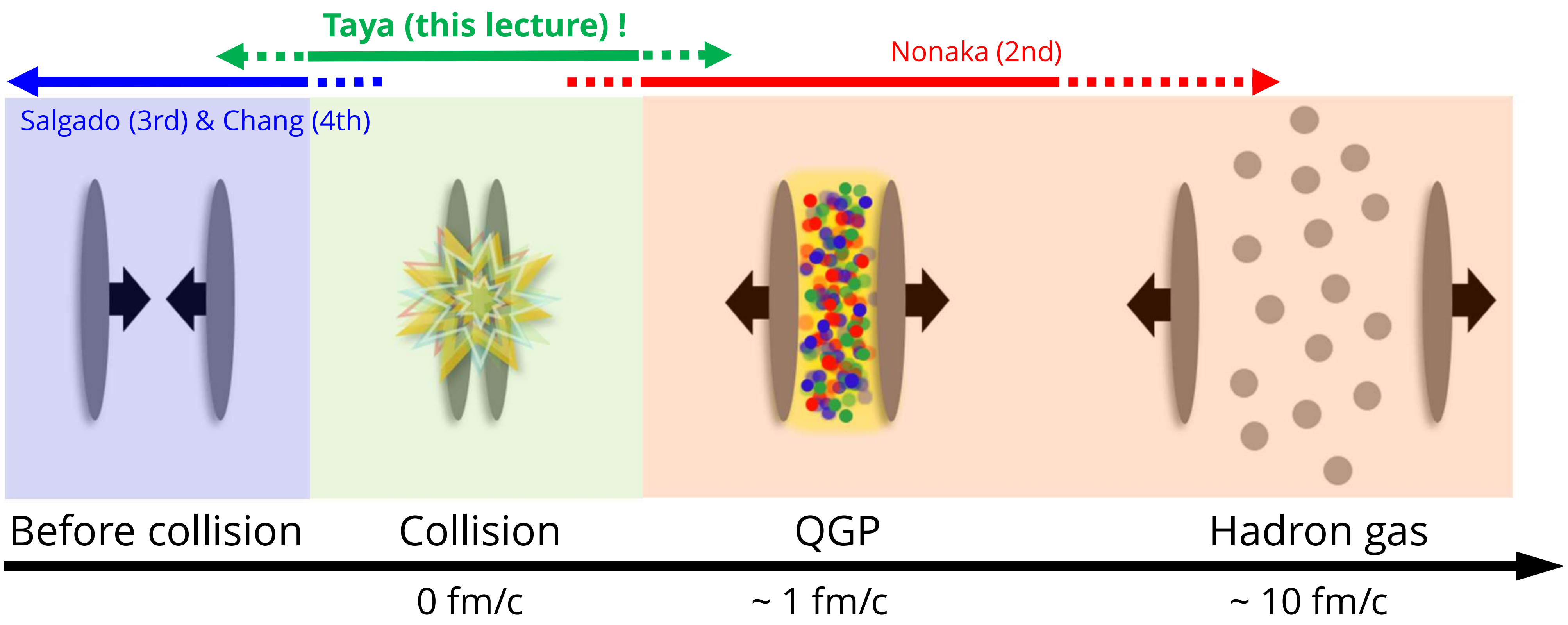
Short summary so far

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, Nielesen-Olesen instability, Schwinger effect)
- Nice development in the weak-coupling scenario
- Hydrodynamization: applicability of hydro ≠ 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

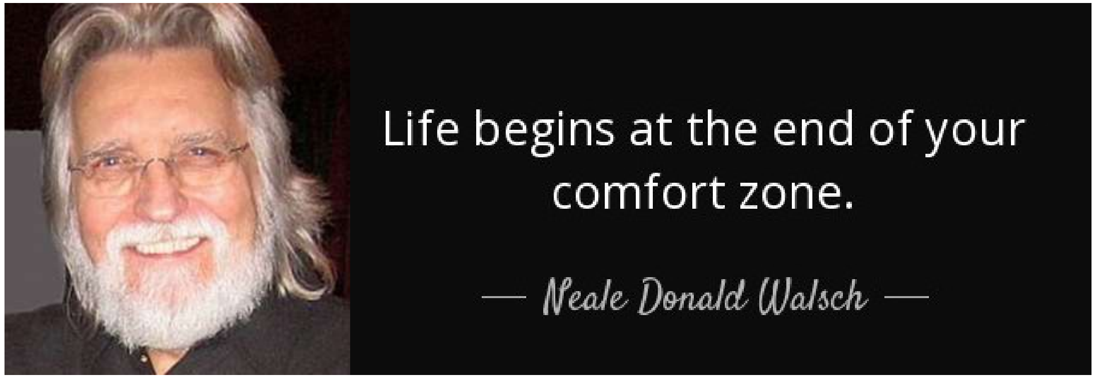
- strong EM field
- strong vorticity

} provide opportunity to study "new physics"

- ...

Why strong field interesting ?

A general lesson from life:



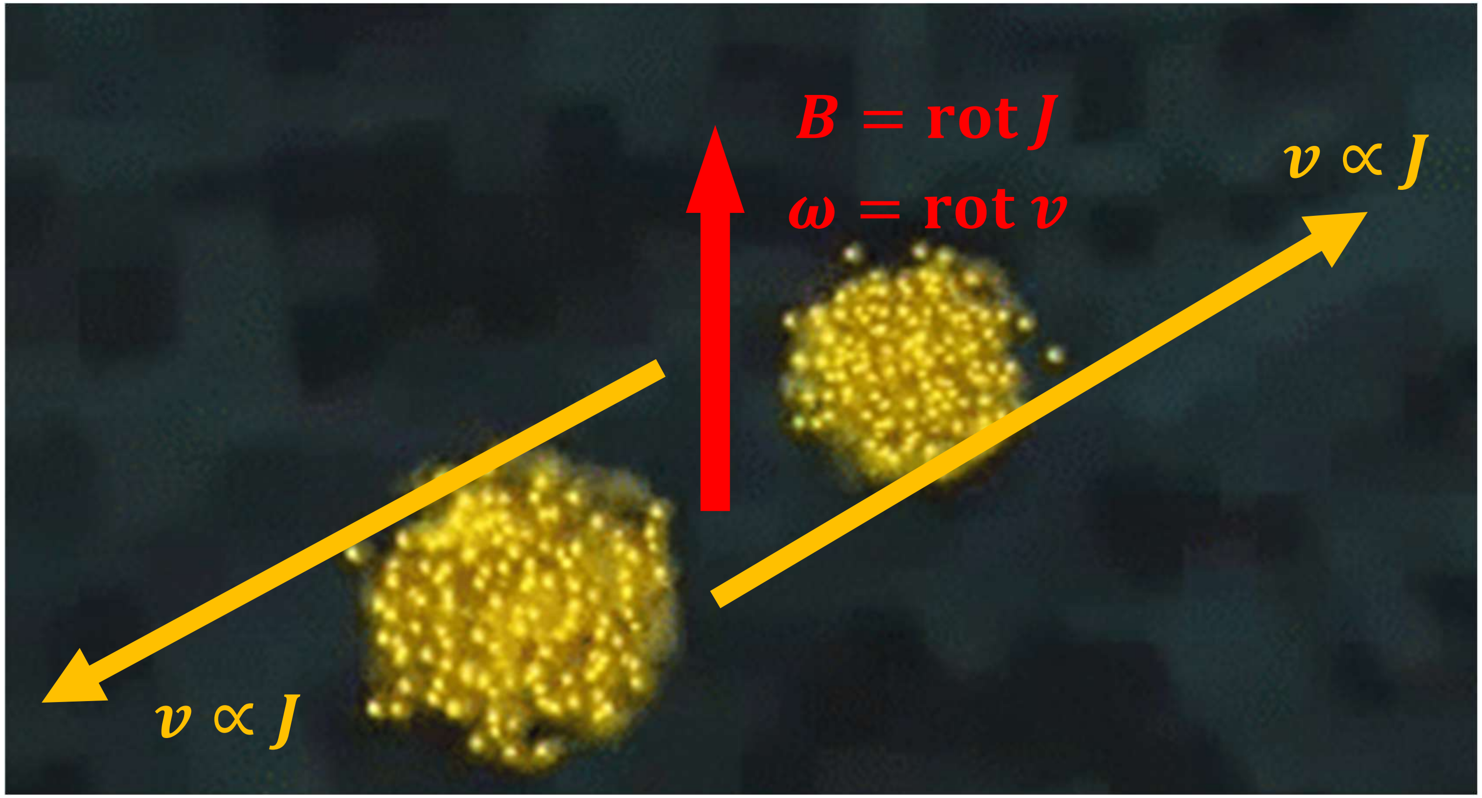
⇒ Translate to physics:

Must go to **dis**comfort 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 ⇒ large "rotating" velocity/current ⇒ strong vorticity/magnetic field

We should then ask:

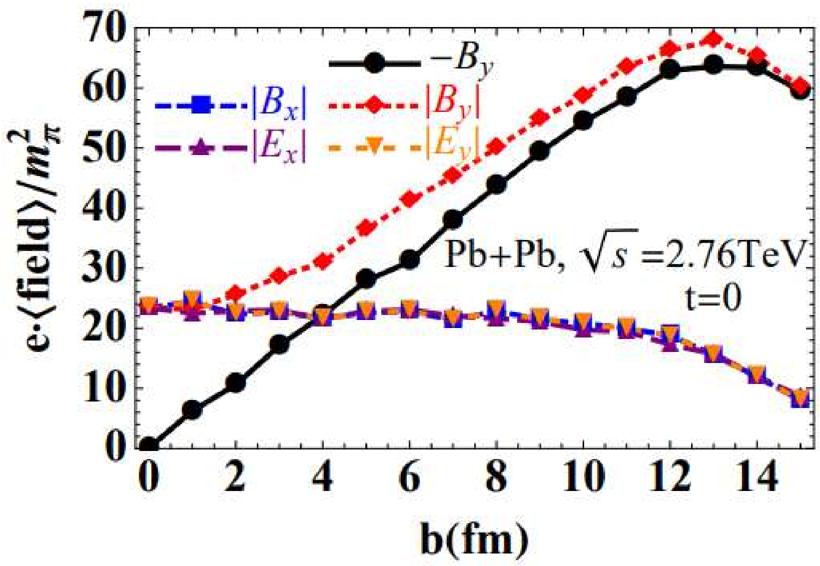
(1) How strong are they <u>quantitatively</u>?

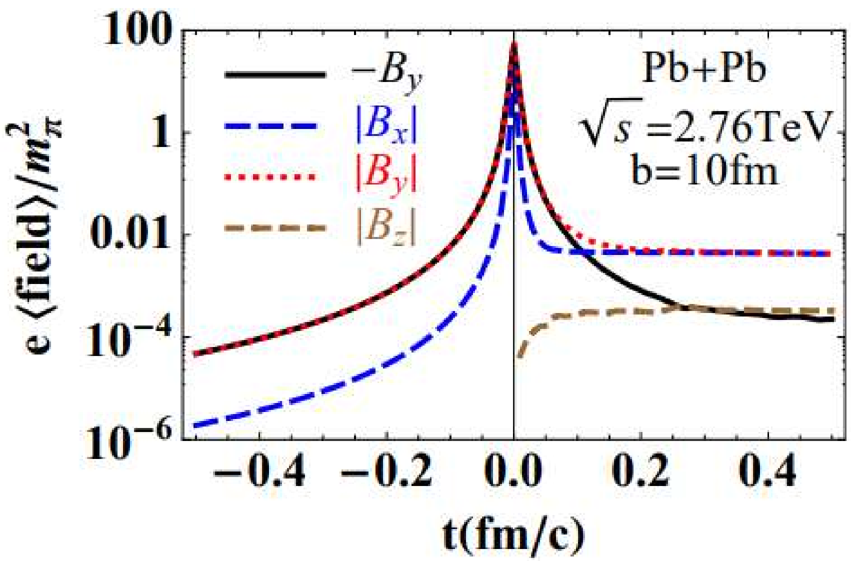
(2) What can happen?

EM field: How strong ?

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

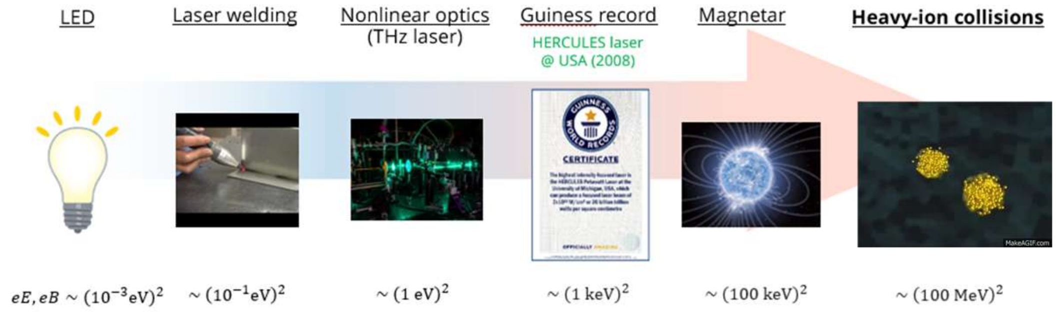
[Deng, Huang (2012)] (see also [Bzdak, Skokov (2012)] [Hattori, Huang (2016)])





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

$\Rightarrow$ Strongest in the Universe!

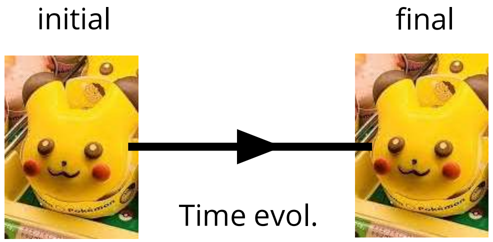


Cons: Extremely short-lived $\tau \ll 0.1\ \mathrm{fm}/c$

- 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)

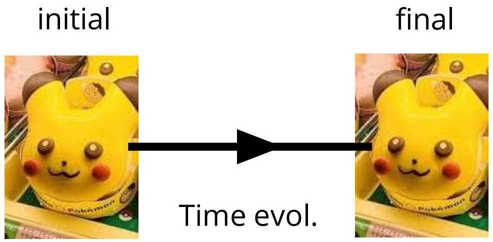
Theoretical essence: Non-perturbative dress of the propagator



Vacuum

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

Theoretical essence: Non-perturbative dress of the propagator



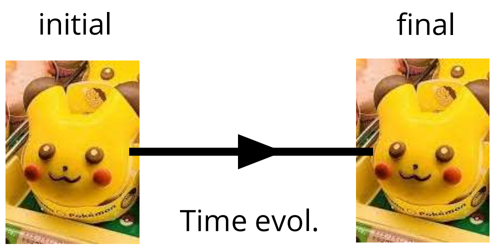
Vacuum

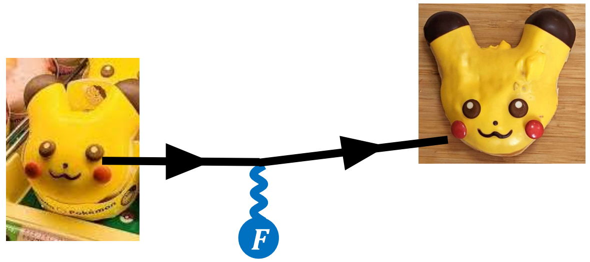
Weak field ($eF/m^2 \ll 1$)

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

$\Rightarrow$ well understood
both theoretically
& experimentally

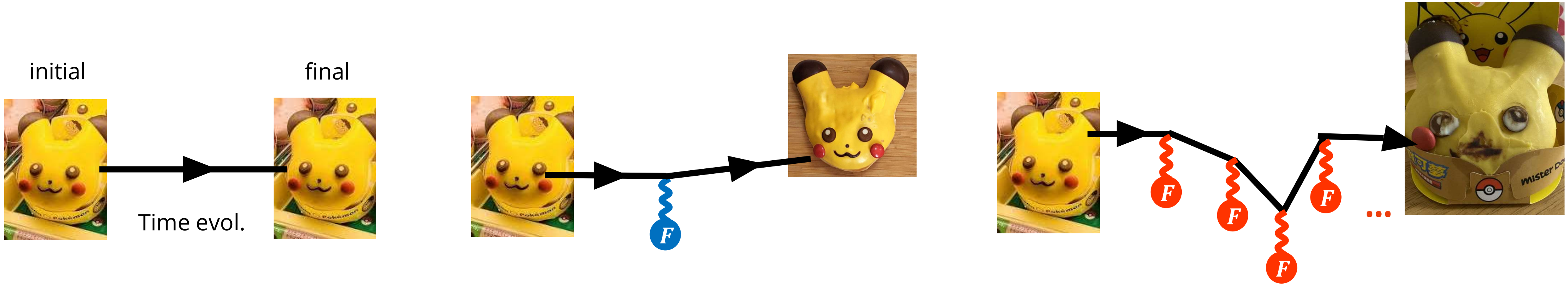
e.g., Electron anomalous magnetic moment

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

[Aoyama, Kinoshta, Nio (2017)]

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

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

[Aoyama, Kinoshta, Nio (2017)]

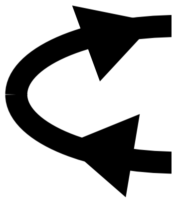
EM field: What can happen ? (2/2)

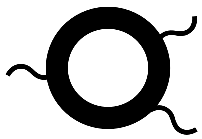
Lots theoretical predictions !

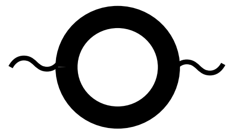
- Examples

<u>Novel QED processes</u> Review: [Fedotov, Ilderton, Karbstein, King, Seipt, <u>HT</u>, Torgrimsson, 2203.00019]

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







<u>Also affect QCD/hadron physics</u> Review: [Hattori, Itakura, Ozaki, 2305.03865]

ex 1) Hadron properties

$\Rightarrow$ mass, form factor, decay rate, …

ex 2) QCD phase diagram

$\Rightarrow$ novel phase, (inverse) magnetic catalysis, …

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

$\Rightarrow$ 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 $\Rightarrow$ exp. search is an active topic
  (i.e., this conference !)

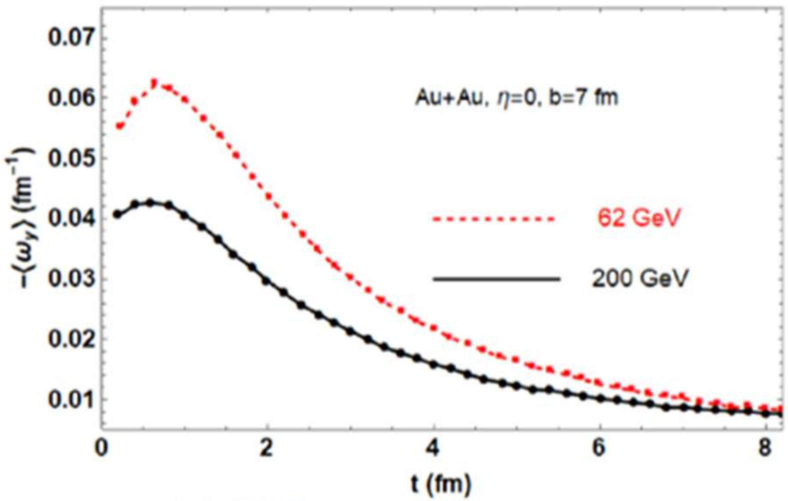
Vorticity: How strong ?

Again, can be estimated by event generators

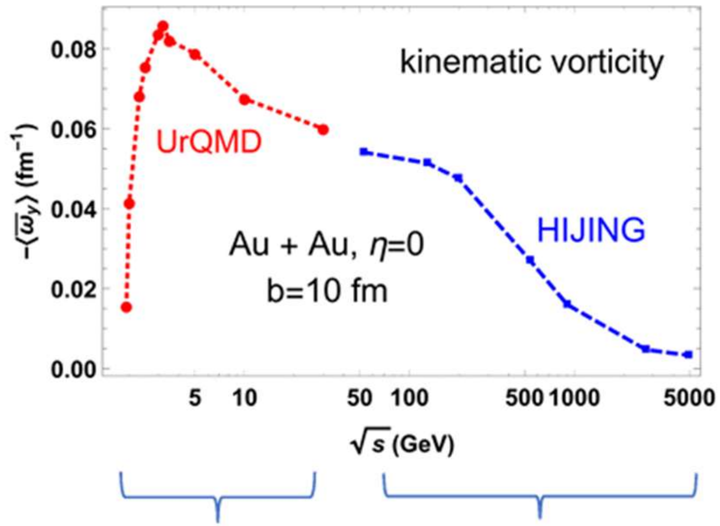
Time dependence

Courtesy of X.-G. Huang

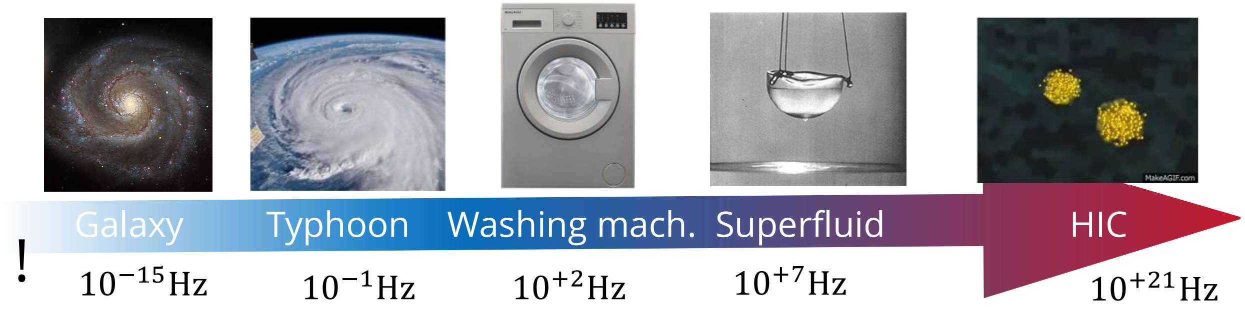
Energy dependence



AMPT (Jiang-Lin-Liao PRC2016)



Deng-XGH-Ma-Zhang PRC2020 Deng-XGH PRC2016



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

$\Rightarrow$ Fastest in the Universe !

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 $\frac{\omega}{T} \sim 1\%$

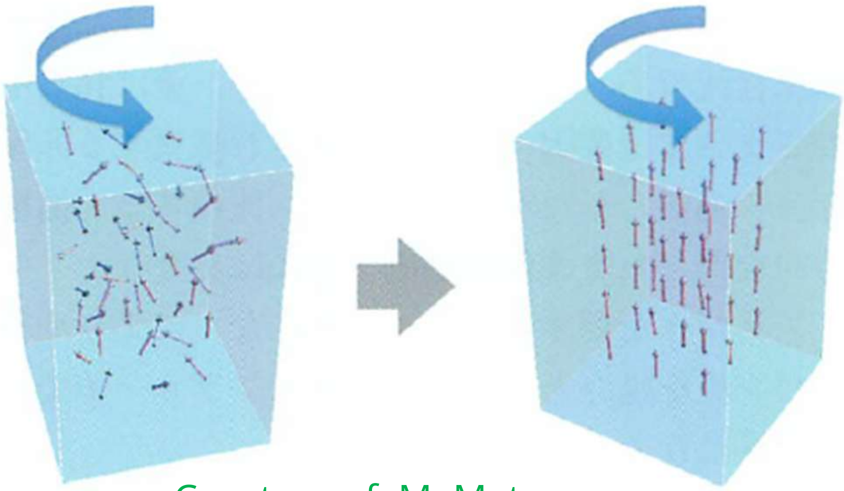
Vorticity: What can happen ? (1/2)

Spin & chirality physics have been discussed in the community

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

$E \to E - \boldsymbol{\omega} \cdot \boldsymbol{s}$: A vorticity analog of the magnetic Zeeman effect $\delta E \propto q\boldsymbol{B} \cdot \boldsymbol{s}$

$\Rightarrow$ Spin alignment along $\boldsymbol{\omega}$ (analog of the Barnett effect for magnetization)



Courtesy of M. Matsuo

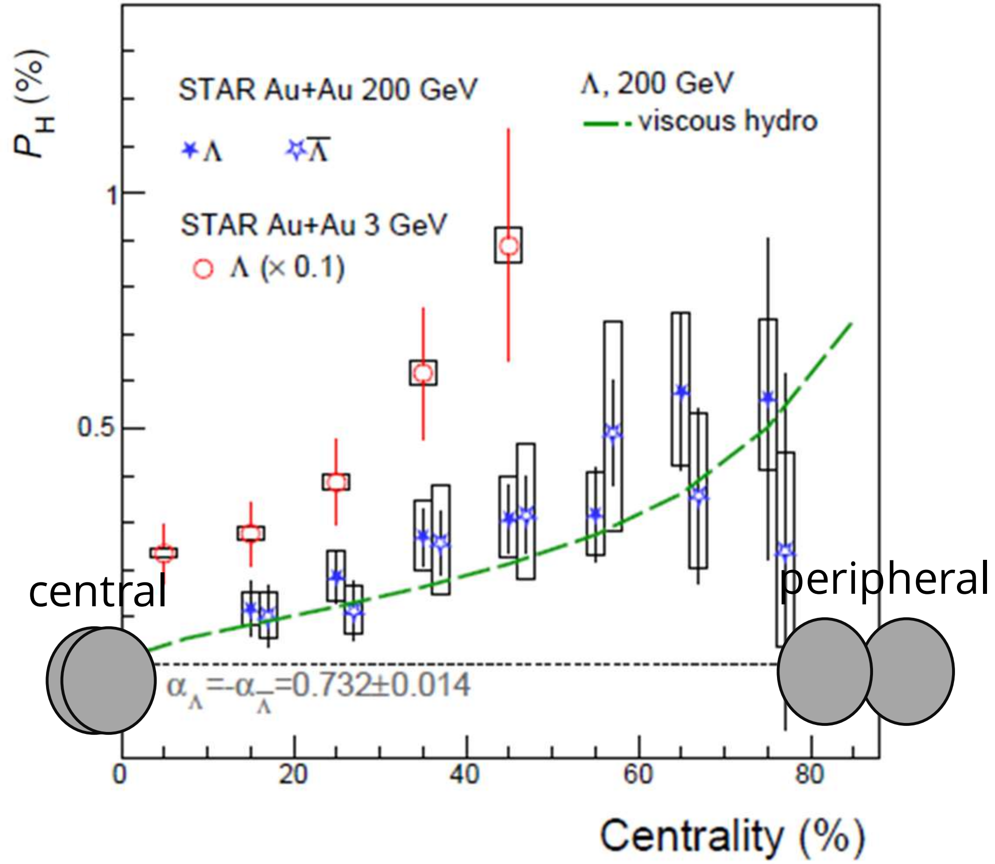
ex 2) Anomalous transport

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

Vorticity: What can happen ? (2/2)

Exp. observation of spin polarization

[STAR (2017)]
(Recent review [Niida, Voloshin (2024)])



- As expected, O(1%) = ω/T signals are seen and is consistent w/ theory
- Current trend: study the local structure of the spin pol. (e.g., azimuthal dist.)

  ⇒ sometimes appear in tension w/ theory (more on this conference !)

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:

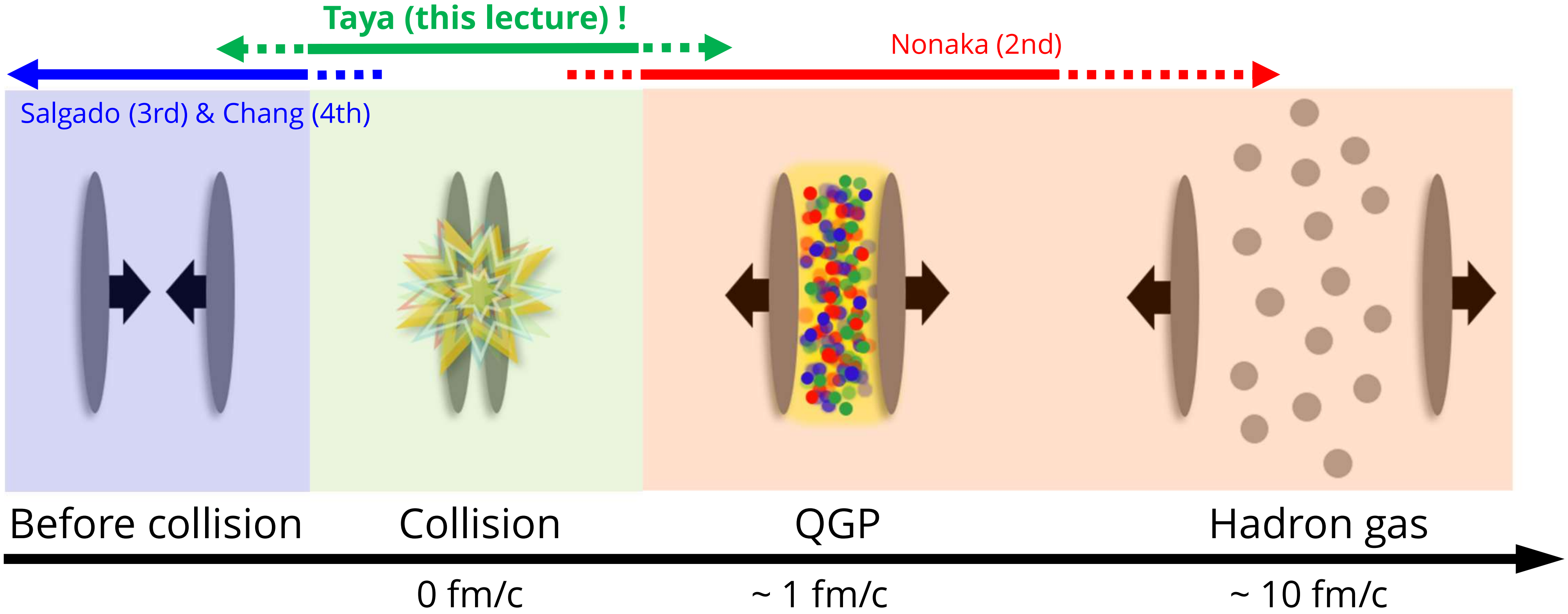
  EM field is strong $eB \gg \Lambda_{\mathrm{QCD}}^2$ but is short-lived $\tau \ll 0.1\ \mathrm{fm}/c$ (if no conductivity)

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

- Many phenomena proposed and are actively searched in experiments

  e.g., spin polarization of Λ hyperons

Summary



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- strong color field (glasma)

origin of the QGP in HIC

- strong EM field
- strong vorticity

provide opportunity to study “new physics”

- …