Initial state
and
thermal equilibrium

(Theory)

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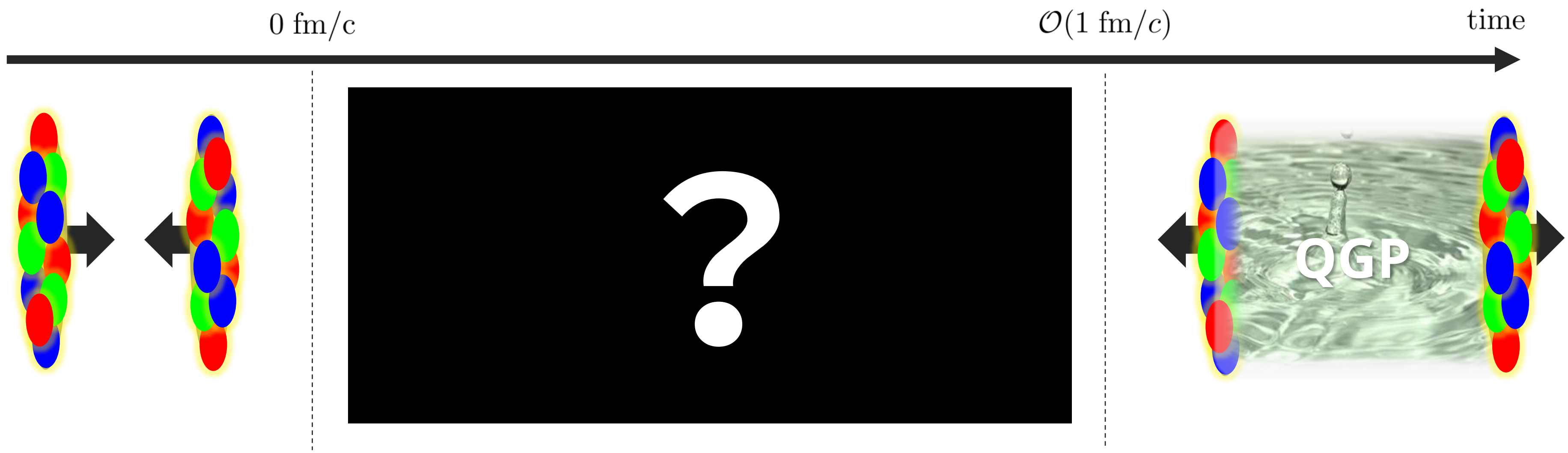
(RIKEN iTHEMS)

ATHIC2023

What I am going to talk



This talk: Review of what is happening in ? (focus on the past 10-year developments)

Short summary: No longer a black box, thanks to

- Significant progress around 2015
  $\Leftarrow$ a weak coupling scenario & hydrodynamization
- Sophistication after ~2015 $\Leftarrow$
  - ~2015's idea is becoming more robust
  - gradually making connection to exp.
  - making rich interactions to other fields

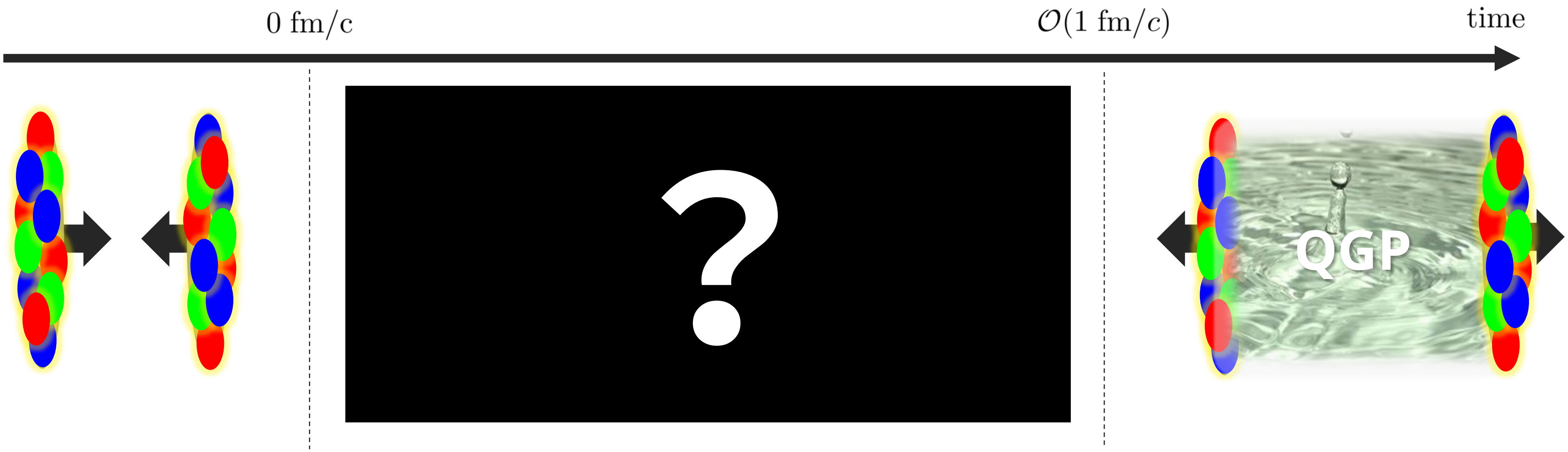
Caveats:
- Don't talk about CGC; please see Talk by Fujii, Wed. 15:05~ Plenary by Xing, Thu. 10:00~
- This is a review talk, i.e., don't talk about my own works

I. Progress ~2015

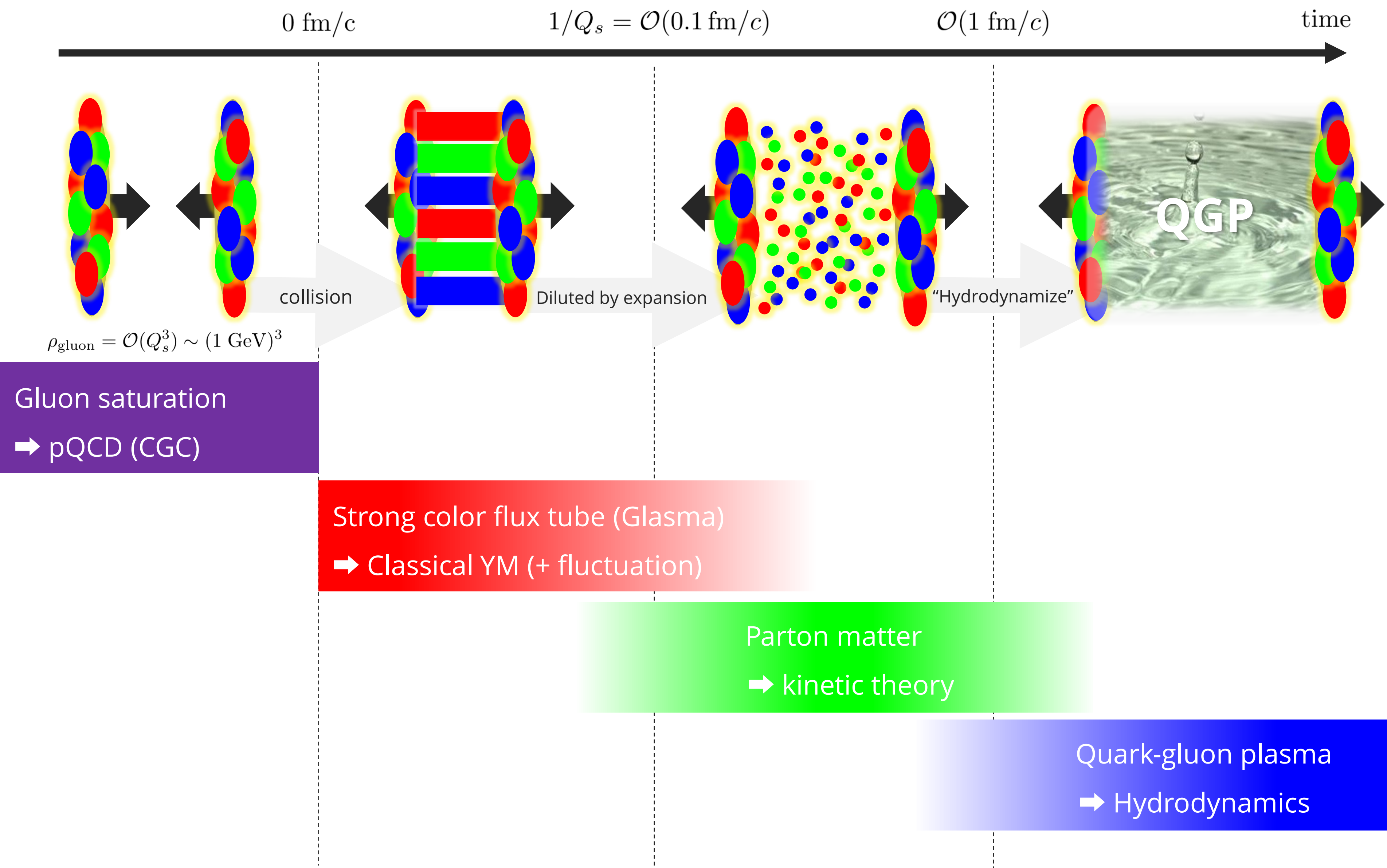
II. Progress after 2015

III. Summary

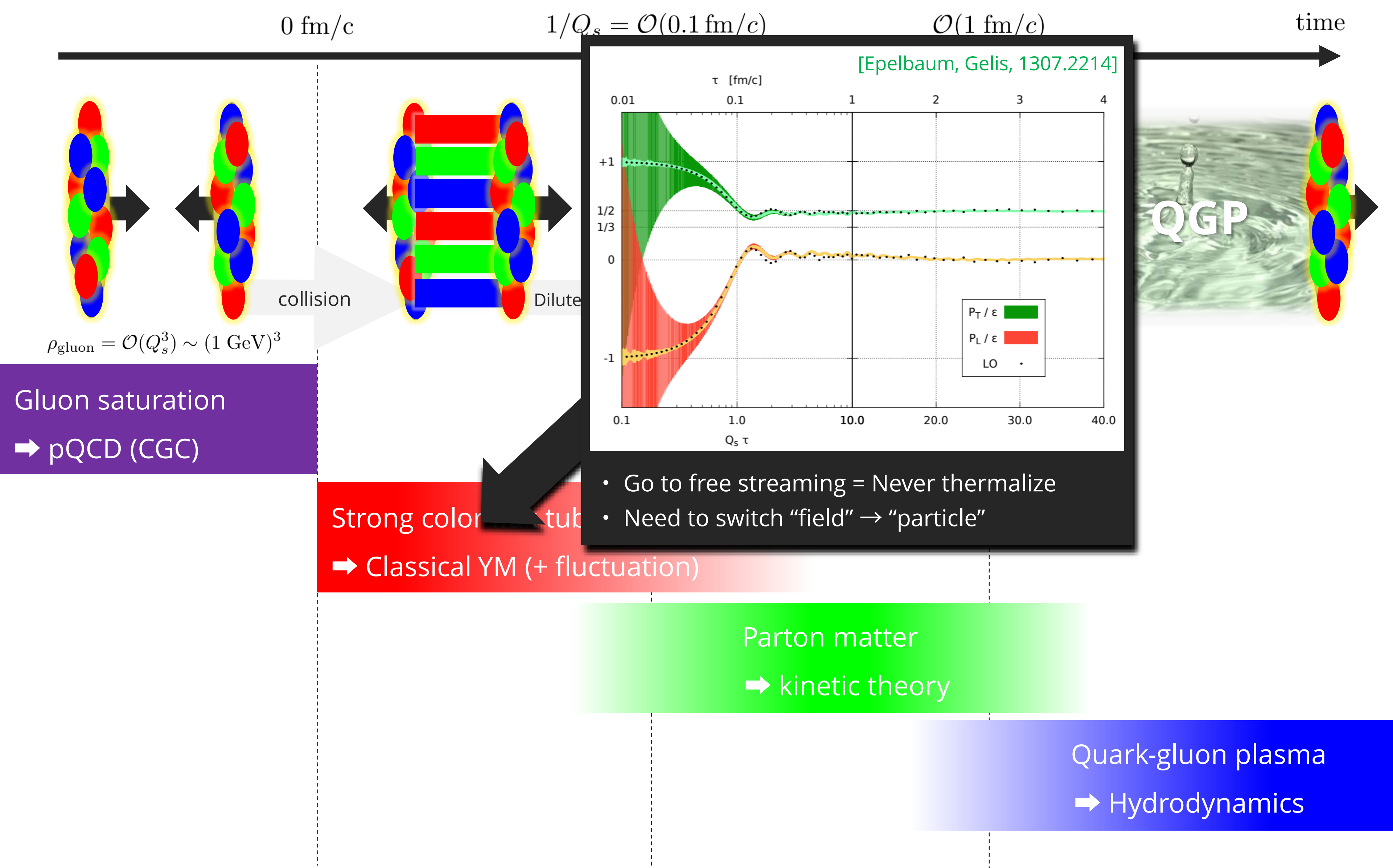
Progress ~2015: weak coupling scenario & hydrodynamization



Progress ~2015: weak coupling scenario & hydrodynamization

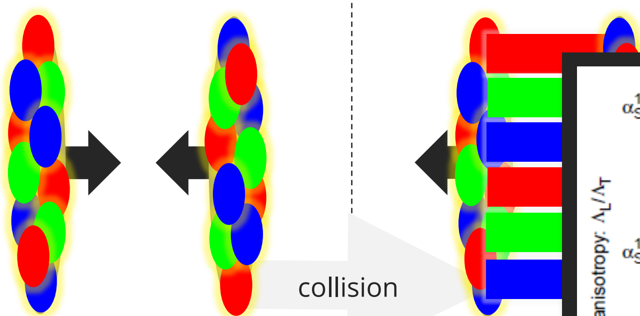


Progress ~2015: weak coupling scenario & hydrodynamization



Progress ~2015: weak coupling scenario & hydrodynamization

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



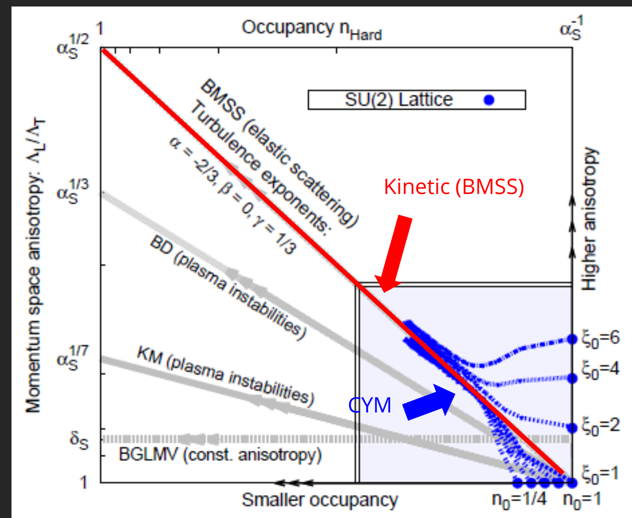
$\rho_{\mathrm{gluon}} = \mathcal{O}(Q_s^3) \sim (1\ \mathrm{GeV})^3$

Gluon saturation
➡ pQCD (CGC)

Strong colo… flux tube (Glas…
➡ Classical YM (+ fluctuatio…

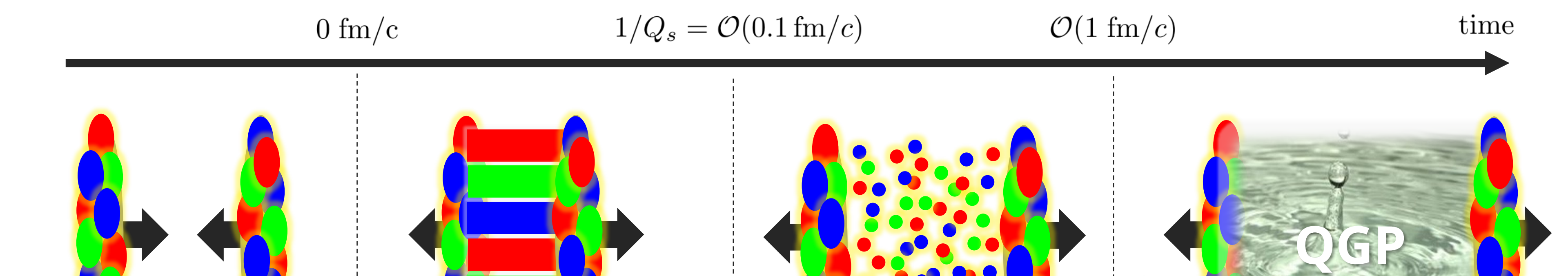
Parton matter
➡ kinetic theory

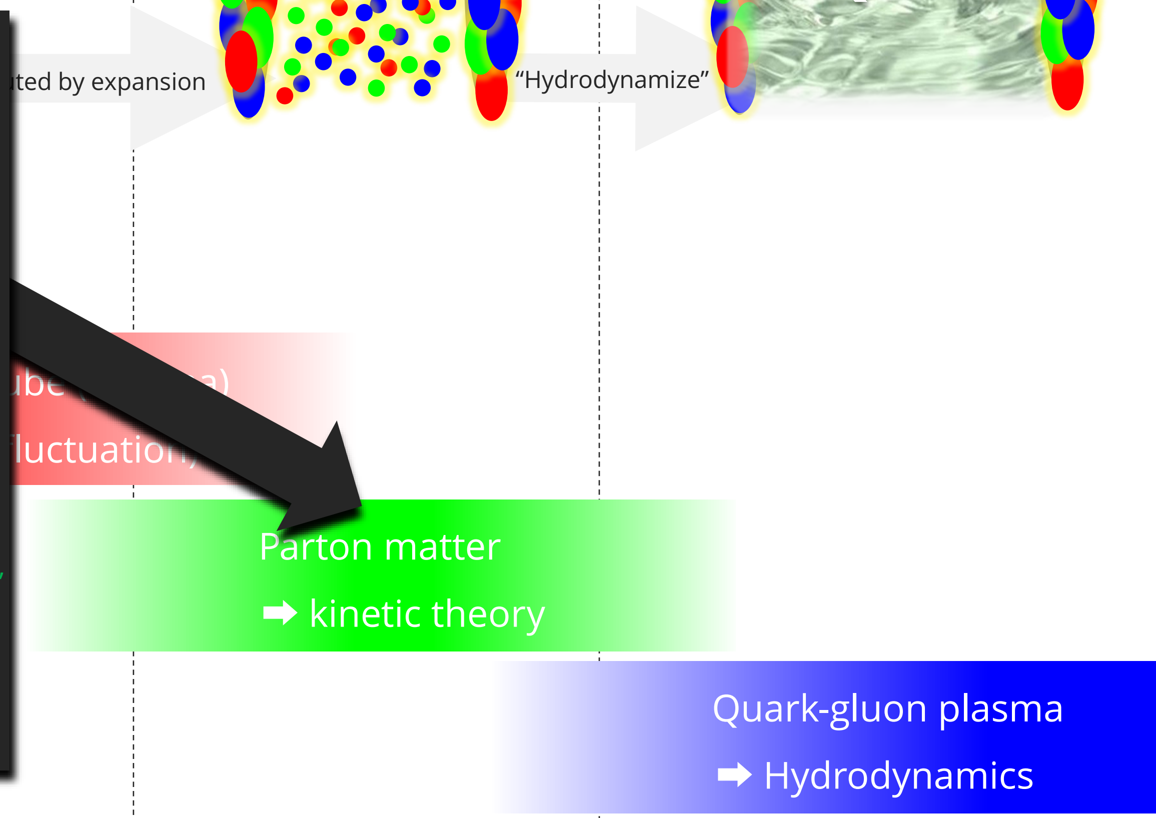
Quark-gluon plasma
➡ Hydrodynamics

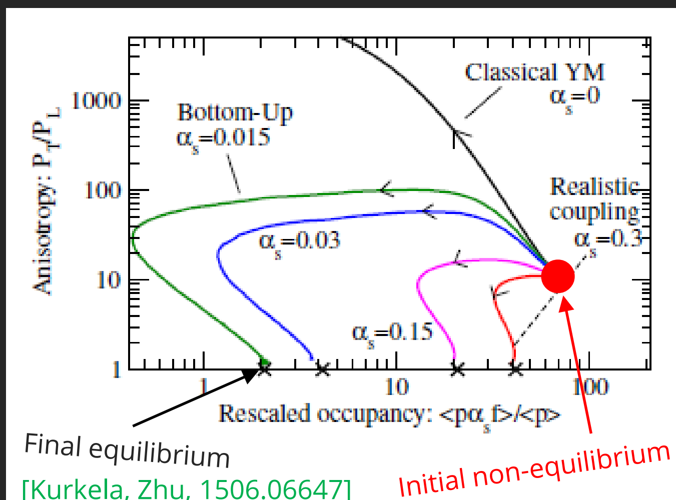


- CYM and kinetics are smoothly connected with each other
  - overlap at $1/g^2 \gg f \gg 1$
    [Mueller, Son, hep-ph/0212198]
    [Jeon, hep-ph/0412121]
  - consistent with bottom-up scenario
    [Baier, Mueller, Schiff, Son, hep-ph/0009237]
  - non-thermal attractor
    [Berges, Boguslavski, Schlichting,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

Progress ~2015: weak coupling scenario & hydrodynamization

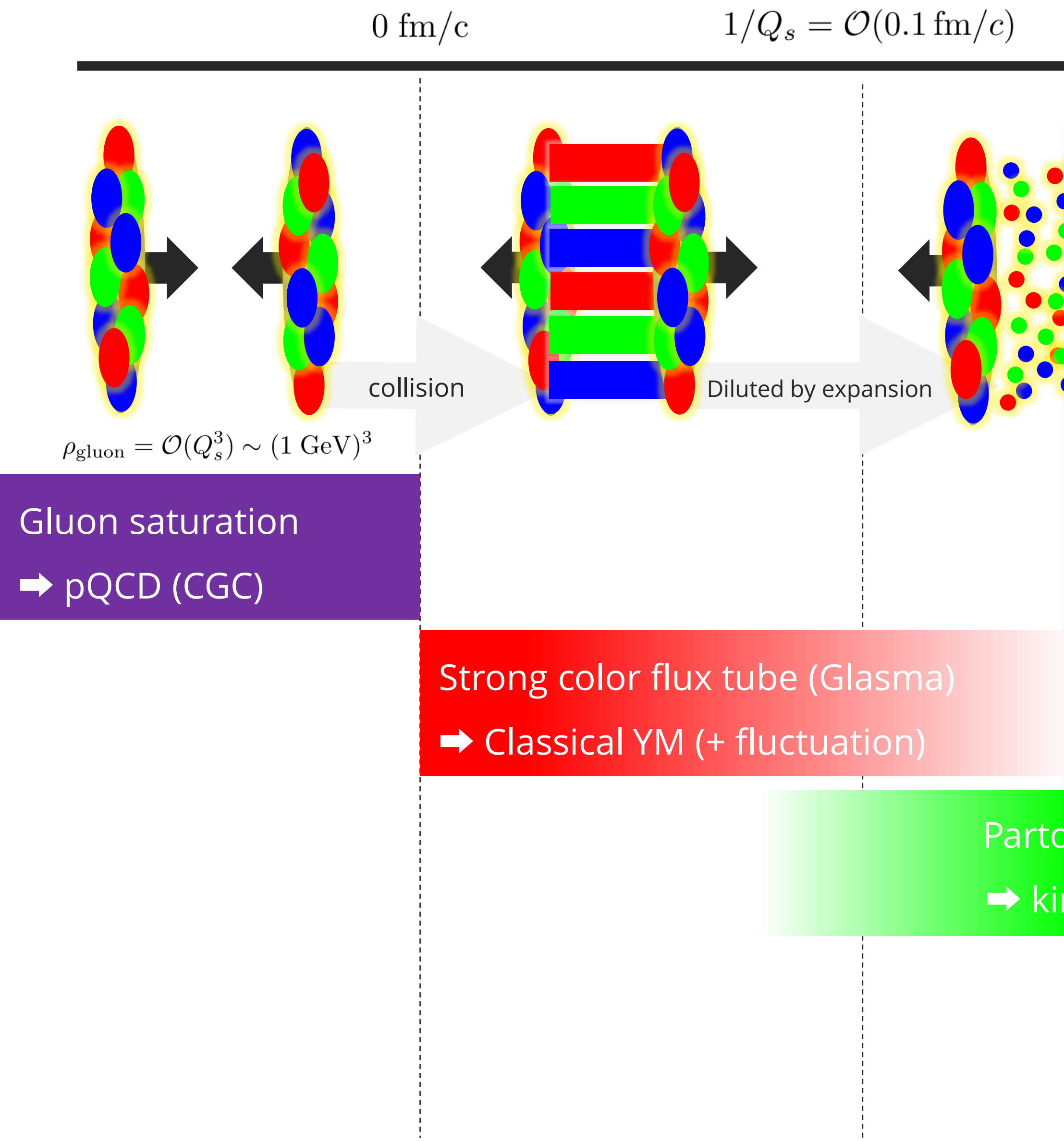


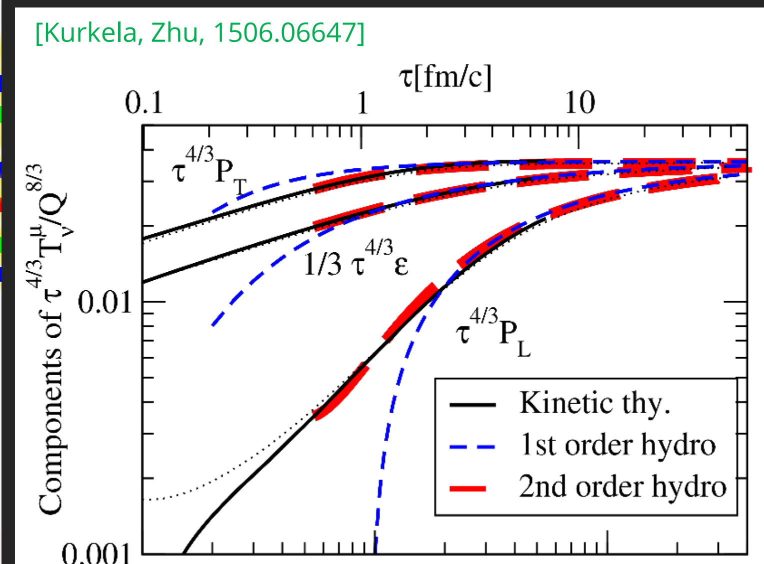




- Kinetic theory of QCD (AMY) [Arnold, Moore, Yaffe, hep-ph/0209353] does describe isotropization & thermalization
- BUT, the time scale is too slow $\tau \sim 10\ \mathrm{fm}/c$

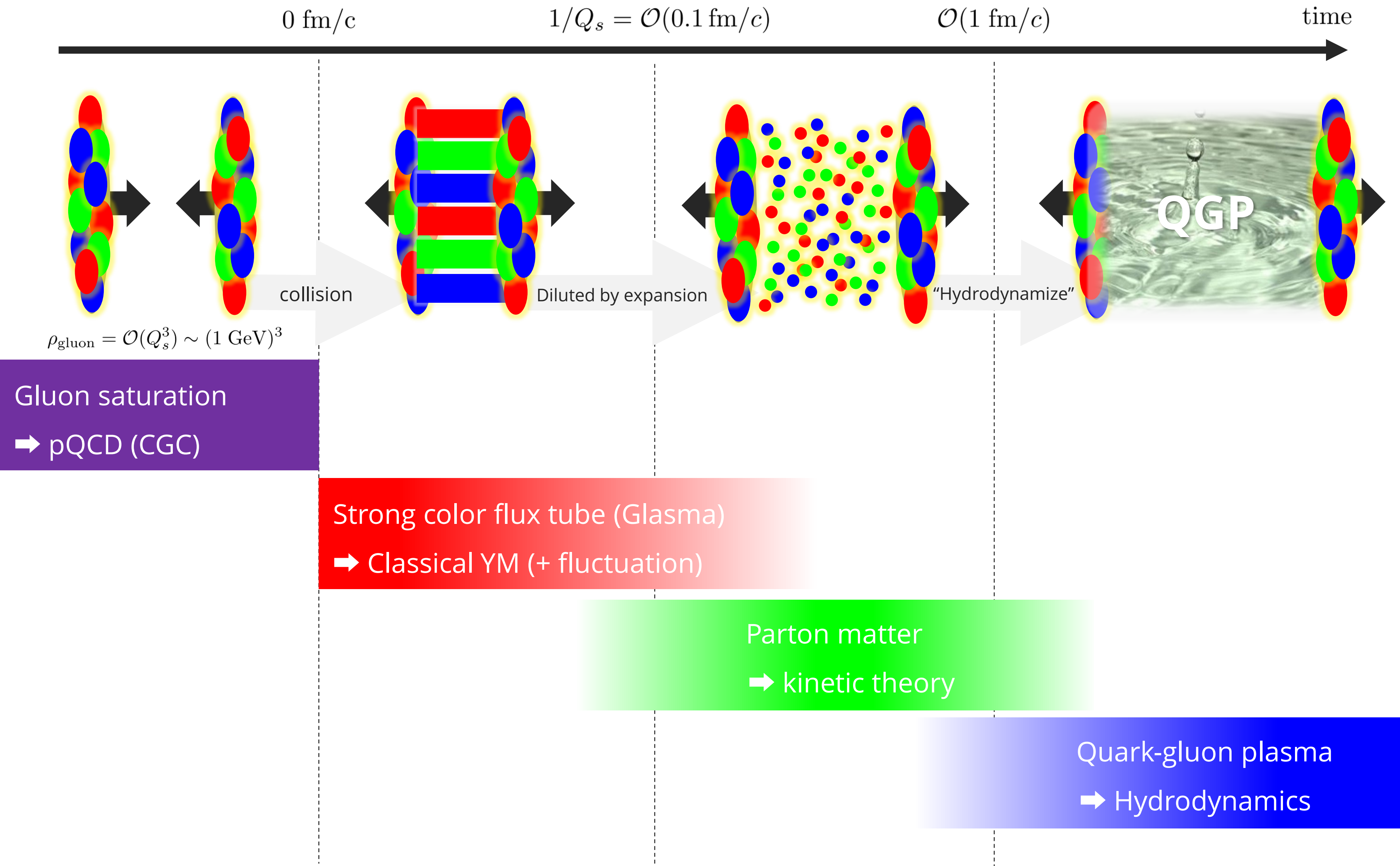
Progress ~2015: weak coupling scenario & hydrodynamization





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

Progress ~2015: weak coupling scenario & hydrodynamization



I. Progress ~2015

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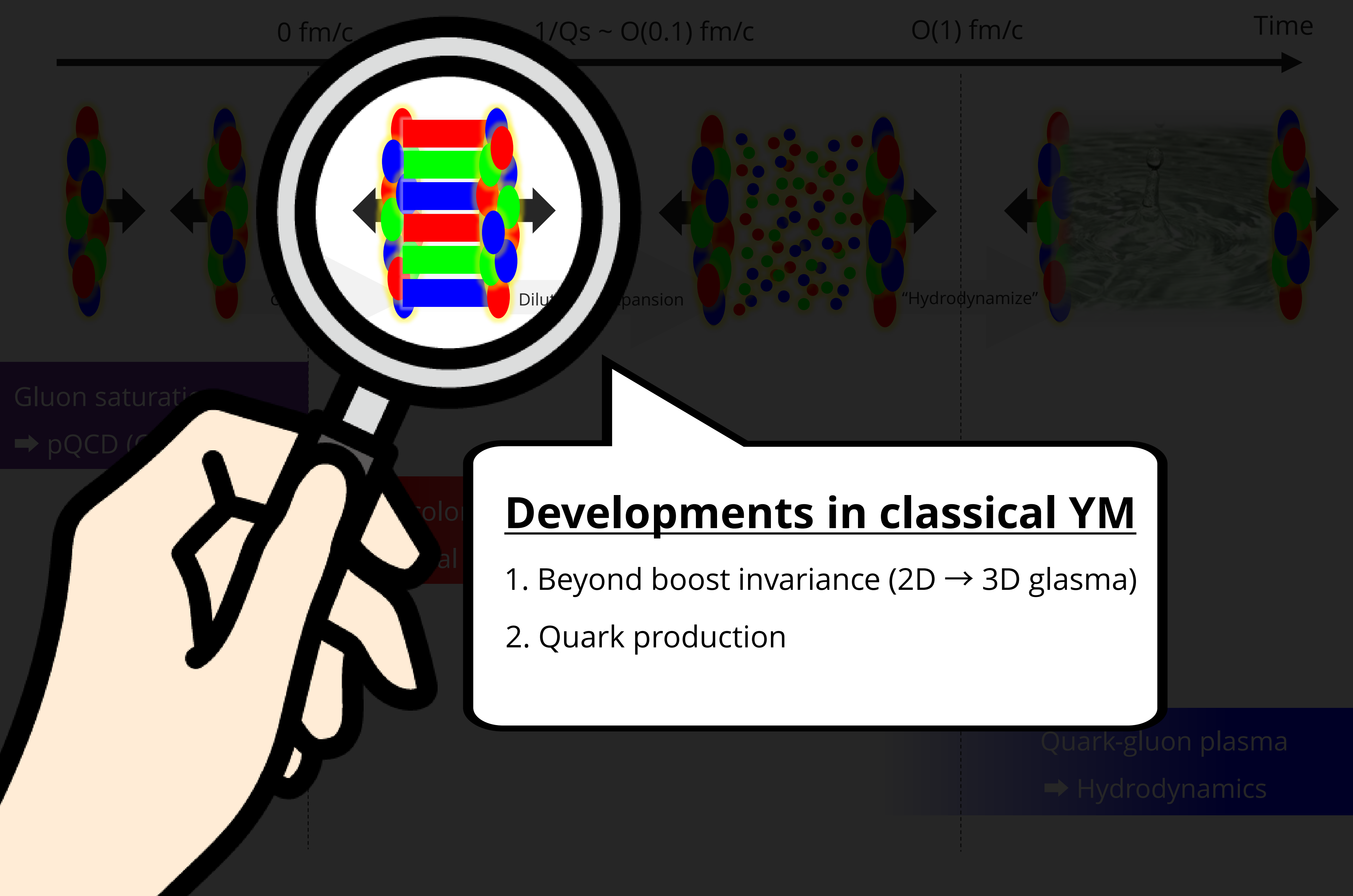
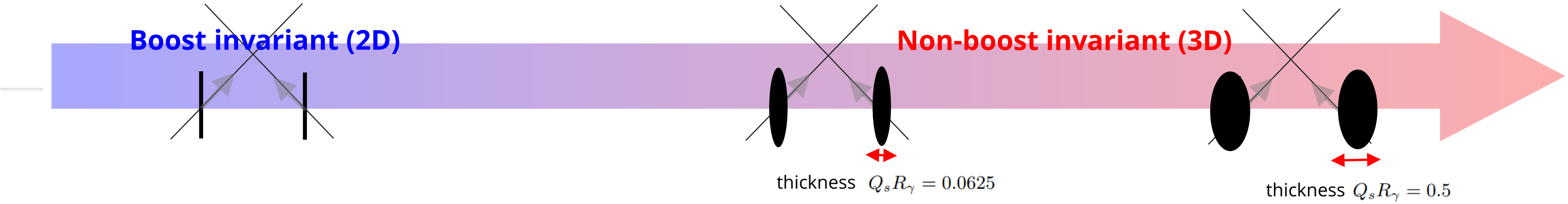
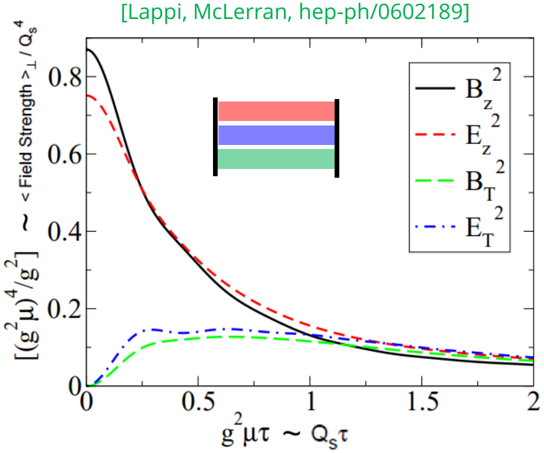

0 fm/c
1/Qs ~ O(0.1) fm/c
O(1) fm/c
Time
“Hydrodynamize”
Quark-gluon plasma
➡ Hydrodynamics
Developments in classical YM
1. Beyond boost invariance (2D → 3D glasma)
2. Quark production

1. Beyond boost invariance (2D → 3D glasma)

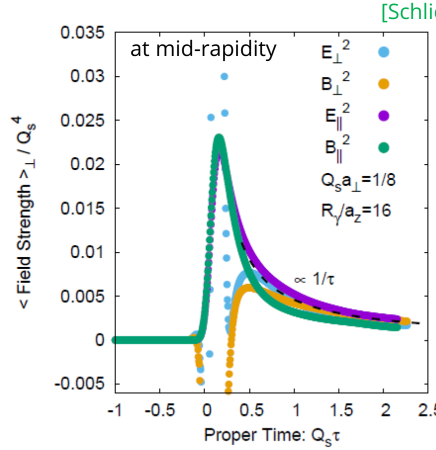
Idea: Solve classical Yang-Mills eq. $D_\mu F^{\mu\nu} = J^\nu$ with finite-thickness source $J^\mu \not\propto \delta(x^\pm)$

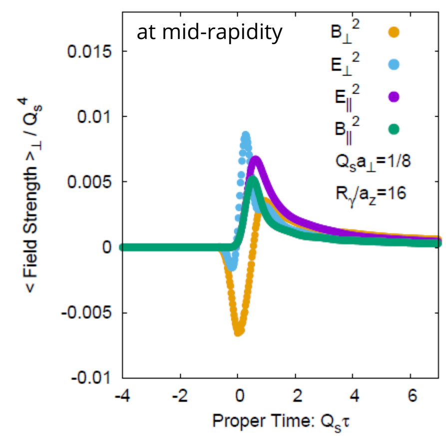


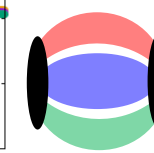
[Lappi, McLerran, hep-ph/0602189]



[Schlichting, Singh, 2010.11172]







- Early times: purely longitudinal
- Late times: free streaming

- Two ways to introduce thickness:
  - JIMWLK [Schenke, Schlichting, 1605.07158] [McDonald, Jeon, Gale, 2001.08636 (proceeding)]
  - Gaussian smearing [Ipp, Muller, 1703.00017] [Schlichting, Singh, 2010.11172]

Talk by Matsuda, Mon. 13:50~

- Early times: Not purely longitudinal
- Late times: free streaming

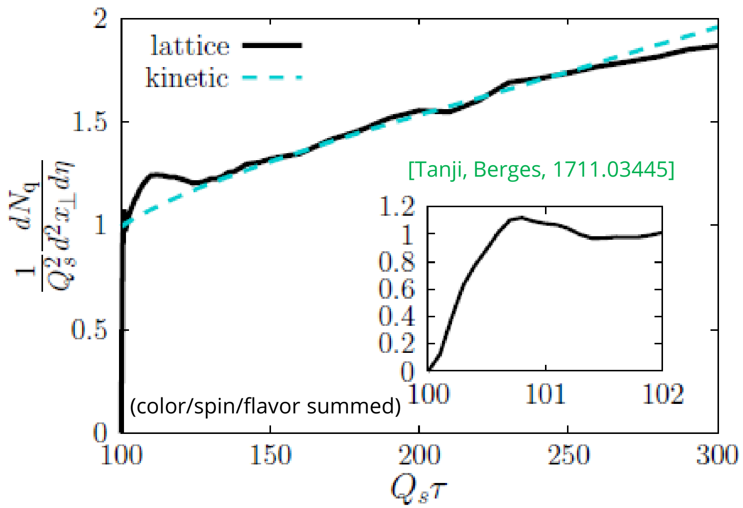
Lessons:
- Non-boost invariance does affect the physics at early times
- Theorists have started to make a better modelling for longitudinal observables

  cf. reproduces longitudinal dependencies of multiplicity and flow [McDonald, Jeon, Gale, 2001.08636 (proceeding)]

2. Quark production

Idea: Solve Dirac eq. in the presence of glasma field $0 = [i\partial\!\!\!/ - gA\!\!\!/ - m]\psi$

Quark production under 2D SU(2) glasma



- Quark production is very fast: [Gelis, Kajantie, Lappi, hep-th/049508 & 0508229] [Gelfand, Hebenstreit, Berges, 1601.03576][HT, 1609.06189] [Tanji, Berges, 1711.03445]

  $Q_s^2 S_\perp = \mathcal{O}(1000) \Rightarrow \mathcal{O}(1000)$ quarks (per rapidity) are produced within $\tau \lesssim 1/Q_s = \mathcal{O}(0.1\,\mathrm{fm}/c)$

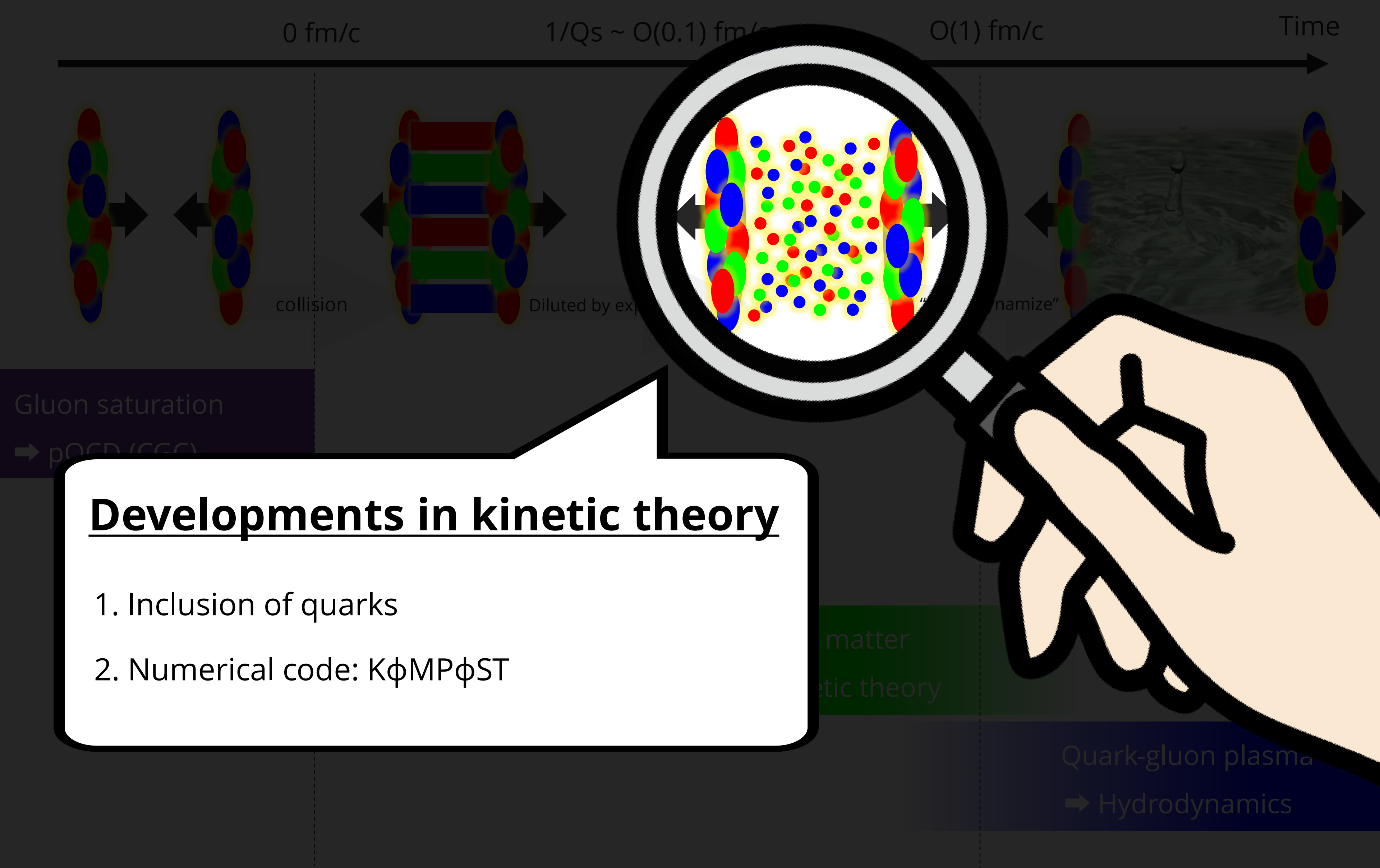
- Q: Why so fast ?

  A: Schwinger effect $\Rightarrow$ occurs when energy supply by the field $W = gE \times \tau \sim Q_s^2 \tau$ exceeds the mass gap $W \gtrsim m$

  $\Rightarrow \tau = m/Q_s^2 \ll 1/Q_s$

Lessons:
- Fast & abundant quark production
- Can leave experimental imprints, e.g., charged flow in asymmetric collisions

Exp: [STAR, 1608.04100]
Thr. [Hirono, Hongo, Hirano, 1211.1114] [V. Voronyuk et al., 1410.1402]



Developments in kinetic theory

1. Inclusion of quarks
2. Numerical code: KϕMPϕST

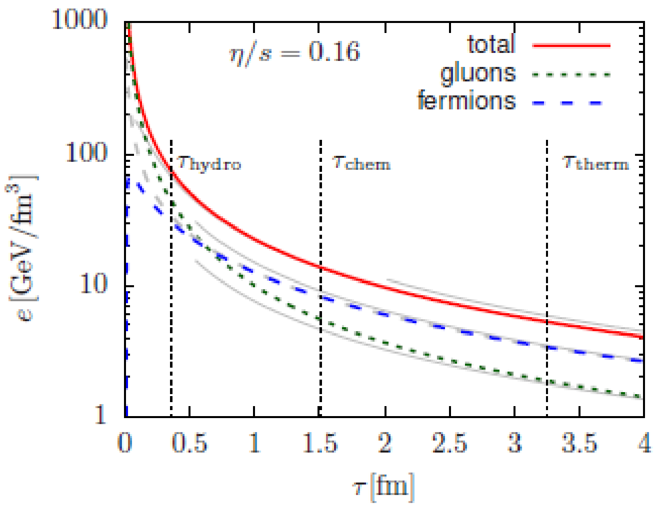
1. Inclusion of quarks

Idea: Add quark D.o.G. to relativistic kinetic eq. $p^\mu \partial_\mu f = \mathcal{C}$

- 2 nice developments

(1) Quark chemical equilibration

[Kurkela, Mazeliauskas, 1811.03040 & 1811.03068]

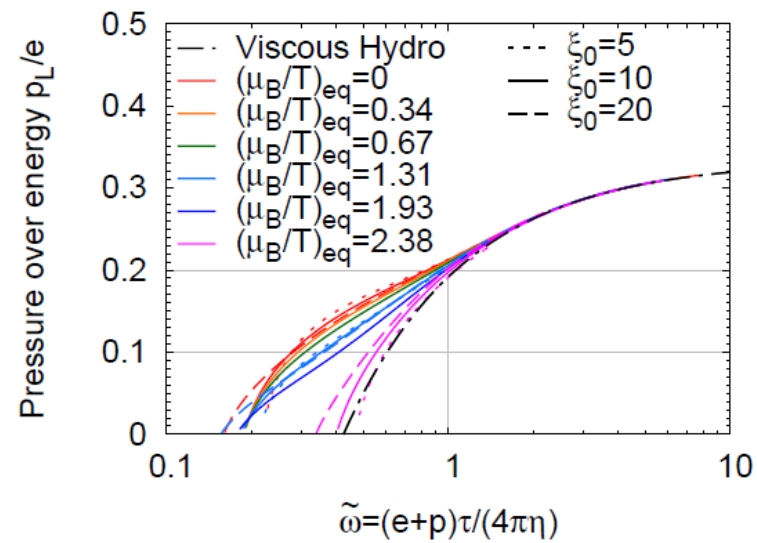


- Hierarchy of time scales $\tau_{\rm hydro} < \tau_{\rm chem} < \tau_{\rm therm}$
- Consistent with the two-stage equilibration picture: Gluons equilibrate first and then quarks [Shuryak, PRL (1992)]

Poster by Abdi, Tue. 18:00~

(2) Impacts on isotropization/hydrodynamization

[Du, Schlichting, 2012.09068 & 2012.09079]



- Quark D.o.G lower the longitudinal pressure
  ⇒ Slower isotropization
- Finite μ significantly affects the effective constitutive relation

Lessons:
- Theorists are now able to discuss the initial quark dynamics in the kinetic phase
  ⇒ Will provide an input for, e.g., photon production at early times
- Quark D.o.G can affect the early-time behaviors

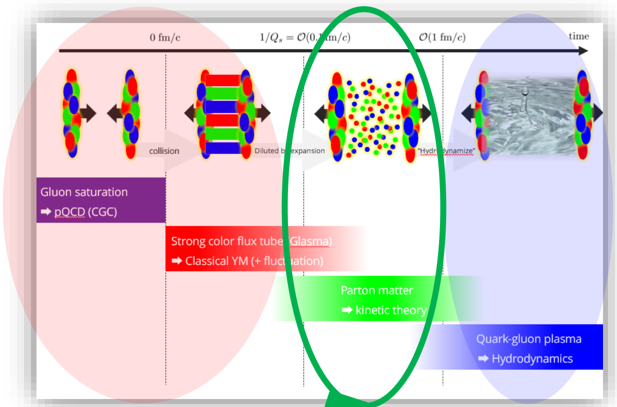
(• No glasma contr. in both. Including both of glasma & kinetic contr. is interesting.)

2. Numerical code: KϕMPϕST (1/2)

Idea: New hydro input accounting for the pre-equilibrium kinetic phase

Initial-state models: Glauber, MC-KLN, IP-Glasma, …

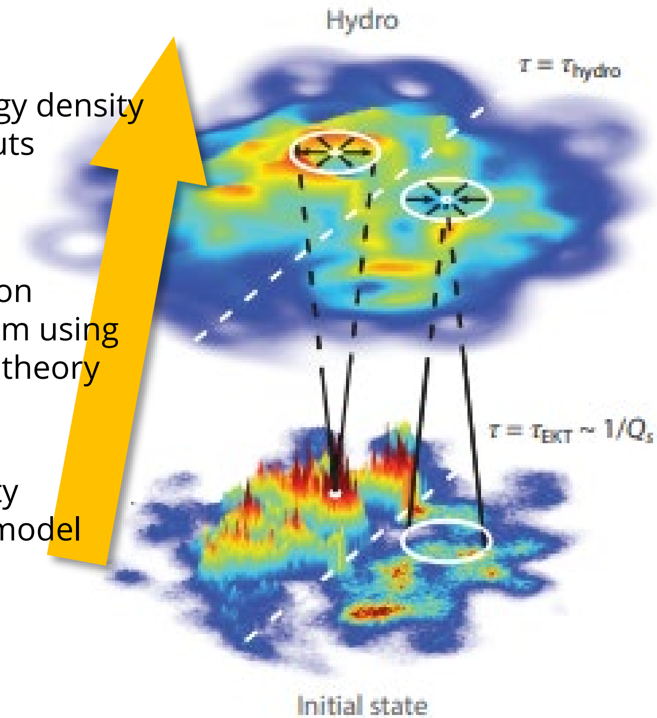
Hydro models: MUSIC, VISUNU, …



STEP 3: Use the energy density as hydro inputs

STEP 2: KϕMPϕST evolution = evolve the system using linear response theory

STEP 1: Get initial energy density with some initial-state model



[Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, 1805.00961 & 1805.01604]

- Model of pre-equilibrium kinetic dynamics: KϕMPϕST

  Basic assumptions: linear response, conformality, (extrapolation of) weak coupling

- Initially energy density only, recently extended to include conserved (U(1), strangeness, baryon) charges (ICCING)

[Carzon, Martinez, Noronha-Hostler, Plaschke, Schlichting, Sievert, 2301.04572]

Lesson: Now we have a numerical code to include the pre-equilibrium dynamics !

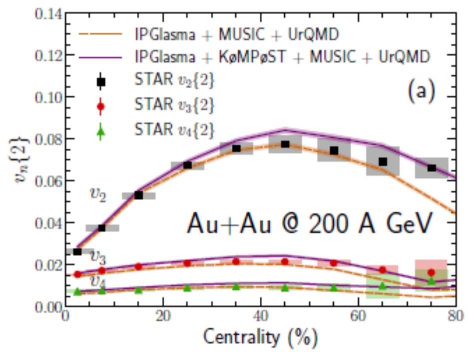
2. Numerical code: KϕMPϕST (2/2)

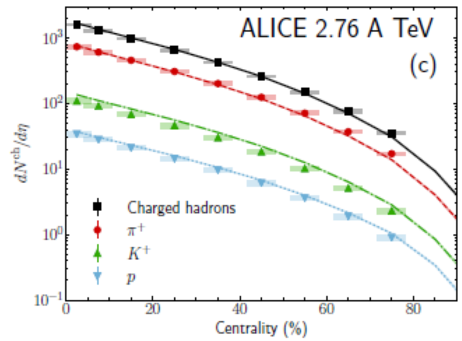
Idea: Use KϕMPϕST as an actual hydro input, and test how it works (or not)

- Can reproduce some observables like flow and multiplicity well

[Gale, Paquet, Schenke, Shen, 2106.11216]
= IP glasma + KϕMPϕst + MUSIC + UrQMD

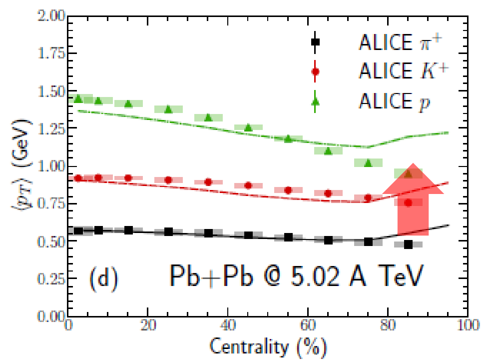
[Nunes da Silva, Chinellato, Hippert, Serenone, Takahashi, Denicol, Luzum, Noronha, 2211.10561]
= Trento + KϕMPϕst + MUSIC + UrQMD

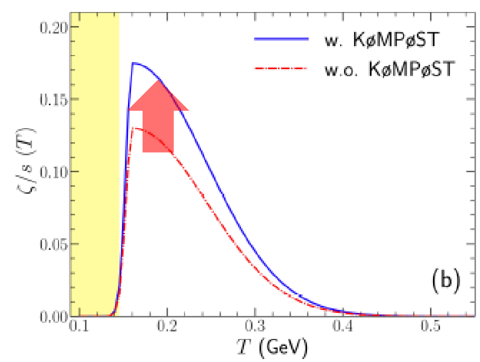




- Significant changes in some observables due to conformality

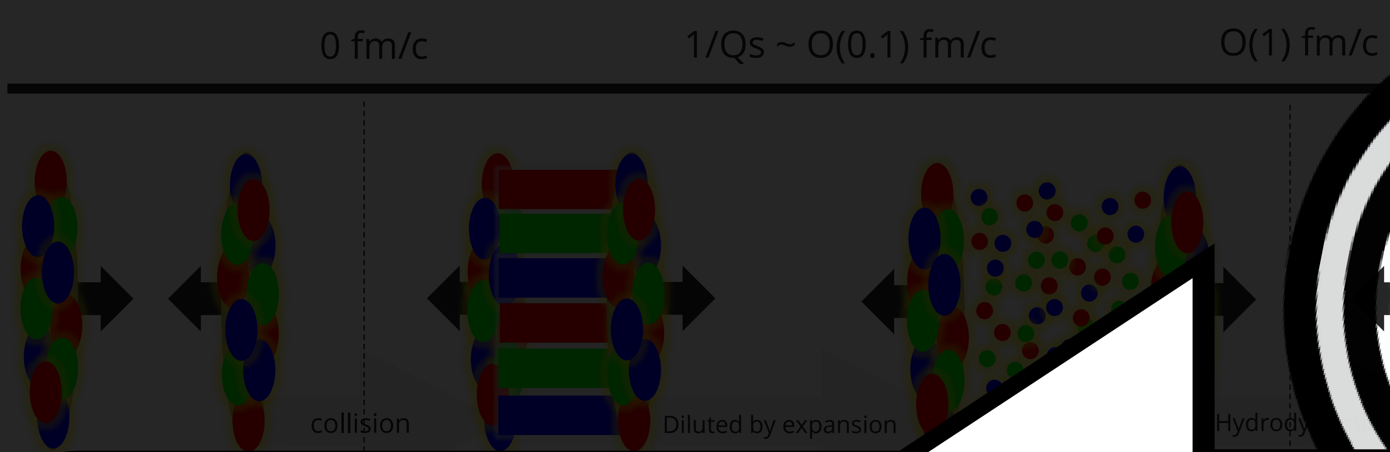
  ⇒ No bulk stress in KϕMPϕST phase ⇒ More radial flow & less entropy production





Lessons:

- Conformality seems a problem ⇒ Needs further sophistication
- Even so, clearly demonstrating that the pre-equilib. dynamics does affect when extracting the QGP properties



Developments in hydrodynamization/attractor

1. Weak vs strong coupling
2. Two origins of attractor: early/late time attractors
3. Attractors beyond $T_{\mu\nu}$
4. Lower symmetries (e.g. non-conformal case)
5. Implications to QCD-phase-diagram study in HIC

1. Weak vs strong couplings

Idea: Compare with the strong-coupling result of AdS/CFT

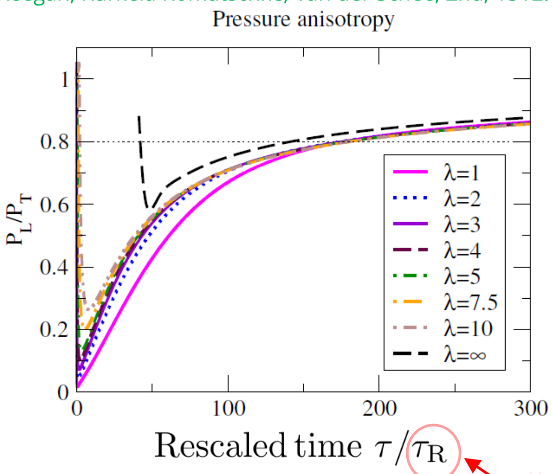
- Actual QCD coupling is not so small $\alpha = \dfrac{g^2}{4\pi} \sim 0.3 \; (\lambda = g^2 N_c \sim 10)$

- Q: Are there any differences ?

  A: Basically consistent with the weak-coupling result after rescaling of time (though there do exist diffs.)
  (I will mention later)

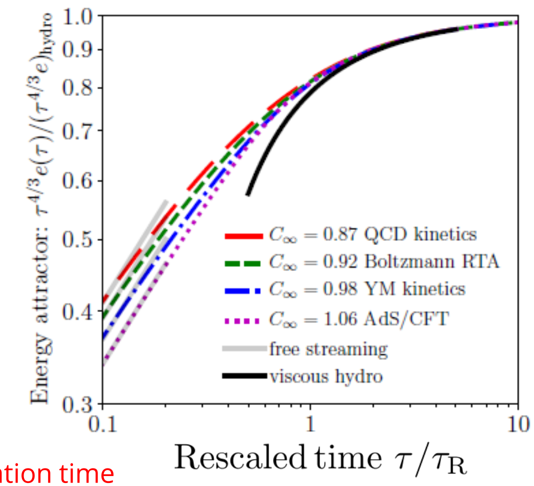
Bjorken expansion with conformal symmetry

[Keegan, Kurkela Romatschke, van der Schee, Zhu, 1512.05347]



(effective) relaxation time

[Giacalone, Mazeliauskas, Schlichting, 1908.02866]



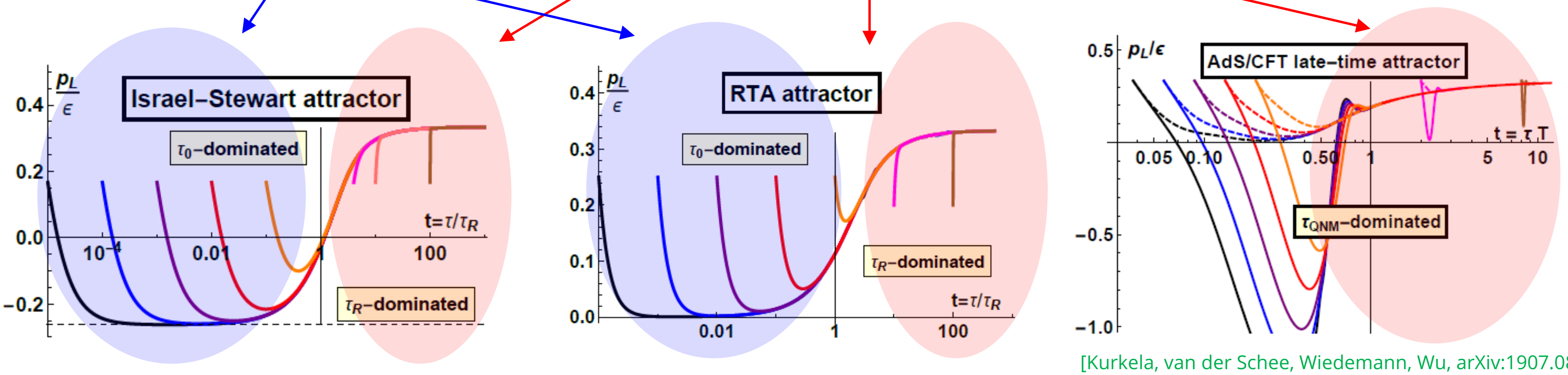
Lessons:
- Hydrodynamization seems universal, independent of coupling strength & micro. theories
  ⇒ imply the weak-coupling scenario is still valid at intermediate couplings
- Rescaling of time may enable us to study hydro attractor in a universal manner
  (• At least when the symmetry is high enough. May be OK in HIC ...)

2. Two origins of attractor: early/late time attractors

Idea: Carefully check the “speed” of attraction to discriminate the origin of attractors

Power-law “slow” early-time attractor

Exponentially-fast late-time attractor



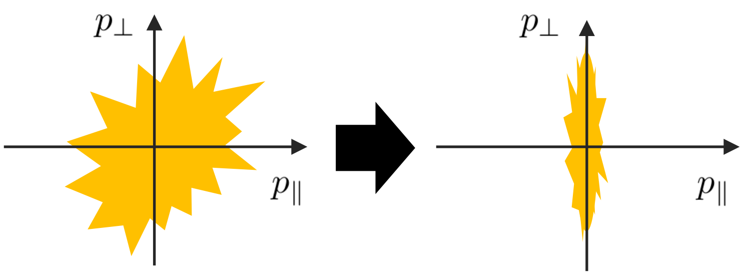
[Kurkela, van der Schee, Wiedemann, Wu, arXiv:1907.08101]

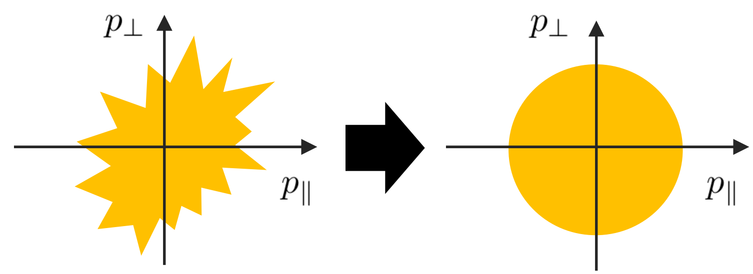
- Origin of attractor = How to forget initial information

[Blaizot, Yan, 1712.03856] [Brewer, Ke, Yan, Yin, 2212.00820]
[Heller, Jefferson, Spalinski, Svensson, 2003.07368]

- Two ways to forget:

Expansion (effective at early-times) vs Collisions (effective at late-times)





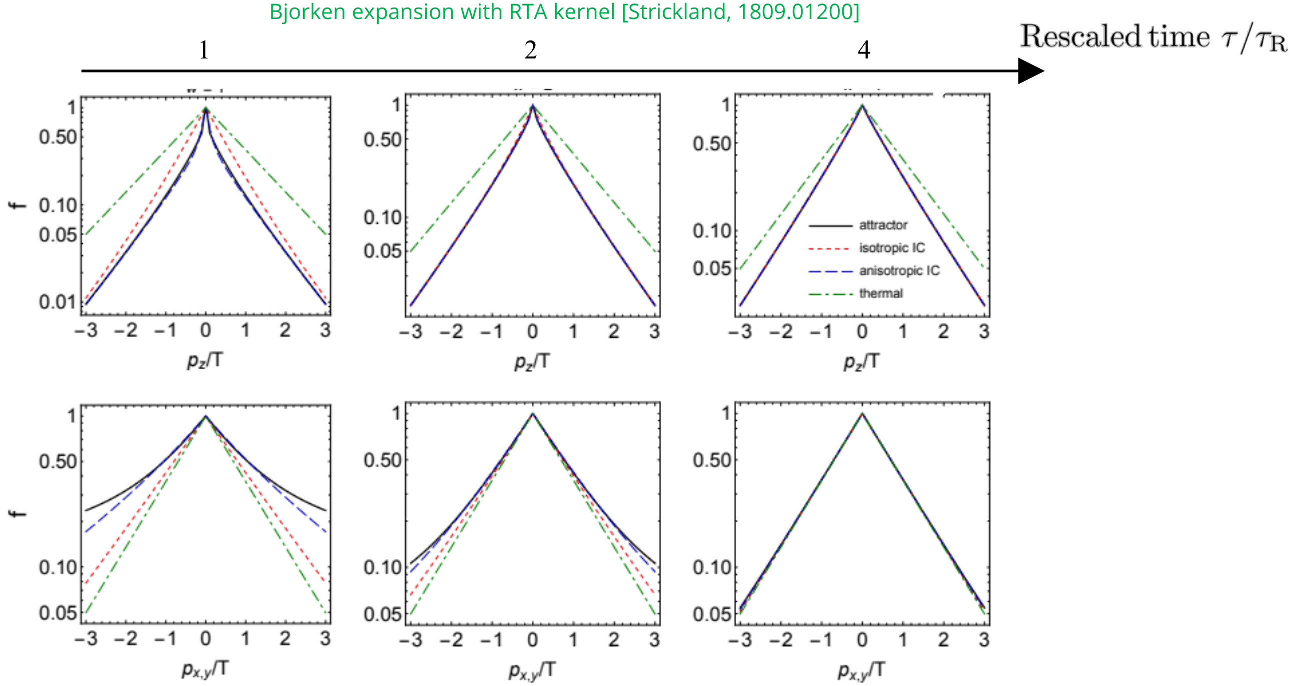
- Which is dominant depends on microscopic theory. cf. Collision effect win in the strong-coupling limit

Lesson: There are in general two origins of the hydrodynamic attractor in HIC

3. Attractors beyond $T_{\mu\nu}$

Idea: Check attractor behaviors of distribution function and higher moments with kinetics

Bjorken expansion with RTA kernel [Strickland, 1809.01200]



- Attractor for distribution function exists ⇒ Faster convergence for lower momentum (pT)
  ⇒ Momentum dependence of hydro behavior

Talk by Monnai, Mon. 13:50~

- Similar attractor behaviors for higher moments
  cf. recent study with AMY kinetics [Almaalol, Kurkela, Strickland, 2004.05195]

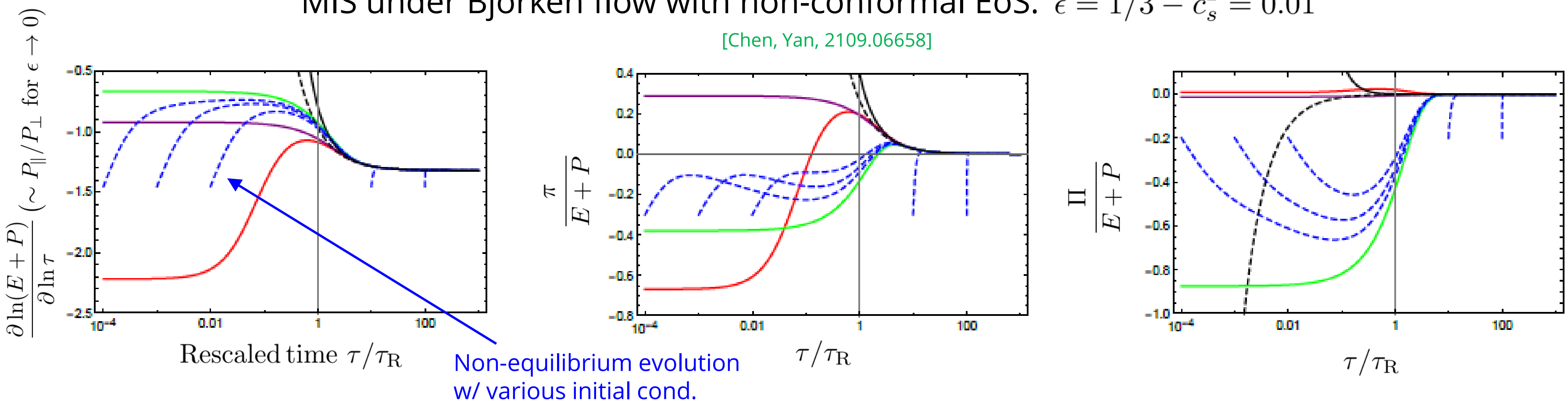
Lesson: Attractor does exist beyond $T_{\mu\nu}$,
though the time-scale depends on momentum scale or the order of moments

4. Lower symmetries (non-conformal case)

Idea: Break the conformality by, e.g., finite mass, non-conformal EoS

MIS under Bjorken flow with non-conformal EoS: $\epsilon = 1/3 - c_s^2 = 0.01$

[Chen, Yan, 2109.06658]



- Attractor does exist for non-conformal case as well [Chattopadhyay, Jaiswal, Du, Heinz, Pal, 2107.05500 & 2107.10248] [Alalawi, Strickland, Pal, 2210.00658]

- Details of attraction can change, e.g., disappearance of early-time attractor in shear π

  early attractor ≈ free streaming of total $P_\parallel = P + \Pi - \pi$

  ⇒ $P_\parallel$ has an early-time attractor, but π and Π do not necessarily to have separately
  (in the conformal limit, π has an early-attractor, as $\Pi = 0$ and thus behaves essentially the same as $P_\parallel$)

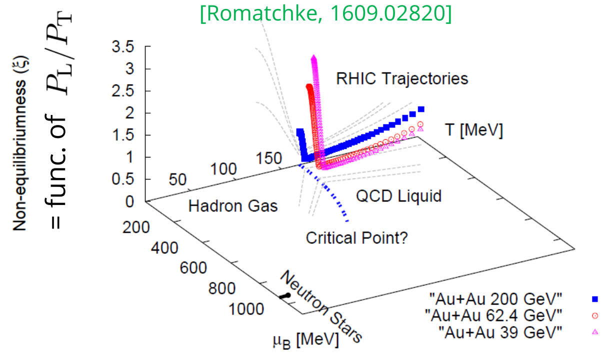
Lessons:
- Hydrodynamization does occur with lower symmetries,
  cf. for other symmetry consideration, see, e.g., with transverse profile: [1907.08101. 2020.135901, 2102.11785]
  other flows: Gubser [1711.01745, 1804.04771, 1911.06406, 2020.135481]
  Hubble [2104.12534]
- The degree of symmetry can affect hydrodynamization ⇒ Needs further study

5. Implications to QCD-phase-diagram study in HIC

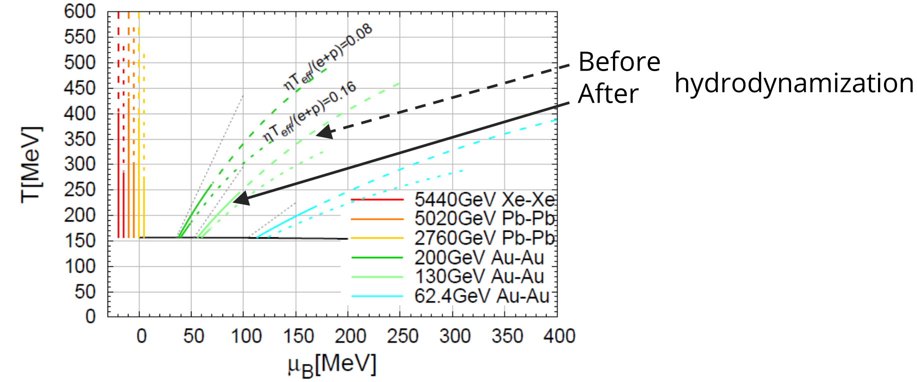
Idea: That hydrodynamics is applicable does NOT mean equilibrium

- Only out-of-equilibrium QCD phase diagram can be explored in HIC

[Romatchke, 1609.02820]



[Du, Schlichting, 2012.09068 & 2012.09079]



⇒ Isotropization (and thus thermalization) never achieved in HIC

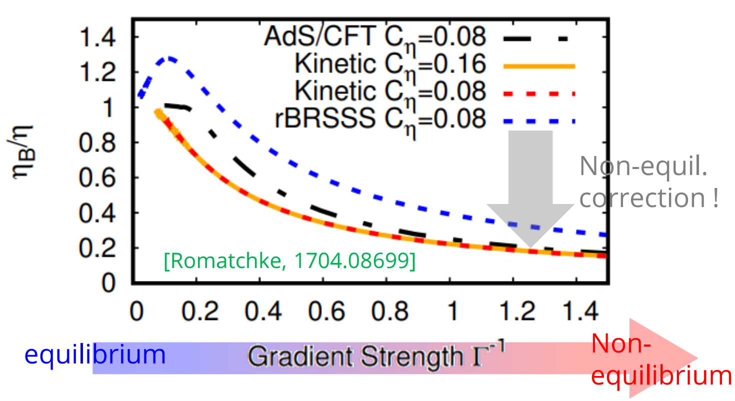
⇒ low energy collisions may not even hydrodynamize

- Non-equilibrium effects can modify matter properties

example) "Non-equilibrium" correction to viscosity

⇐ determined by matching hydro attractor to viscous hydro

Borel-Resummed Viscosity



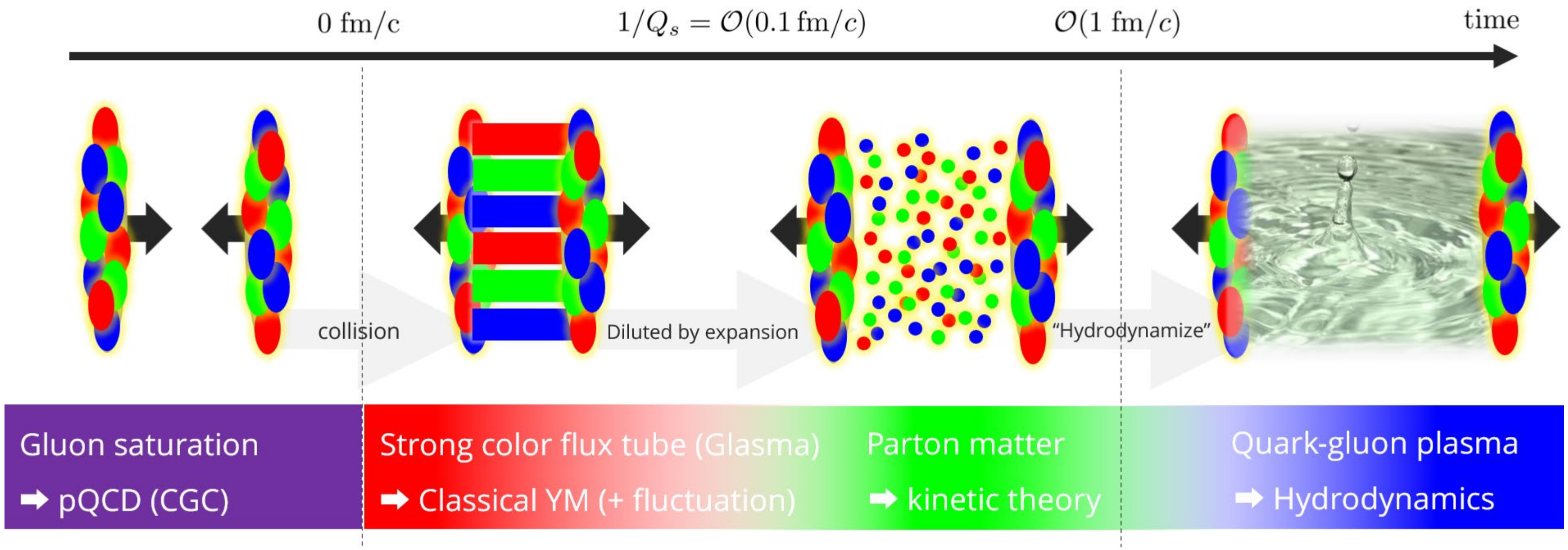
Lessons:
- Open question: need to think what we are really measuring in HIC
- In any case, interesting opportunity to study non-equilibrium QCD

I. Progress ~2015

II. Progress after 2015

III. Summary

Summary: Our understanding as of 2023



Significant progress over the past 10 years ⇒ No longer a black box

- Establishment of the weak coupling picture & proposal of hydrodynamization ~2015
- Many progresses after 2015
  - Classical YM: 3D glasma simulation, quark production, ...
  - Kinetic theory: inclusion of quarks, KϕMPϕST, ...
  - Hydrodynamization: weak vs strong coup., early/late-time attractors, attractors beyond $T_{\mu\nu}$, non-conformal case, implication to QCD-phase-diagram study in HIC, ...
- Have rich connection to others: In HIC ⇒ corr./fluc. observables, intense fields, small system, ...

  Plenary by Sakai, Tue. 10:00~ | **Plenary by Yang, Tue. 11:40~** | **Plenary by Kanakubo, Wed. 10:00~**

  Other area ⇒ cold atom, early Universe, intense lasers, ...

  See reviews: [Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299]
  [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson, 2203.00019]
- But still lots of open questions ⇒ Needs your insights !