New proposal: HAD_03

Observing Critical Fluctuations in the Dynamics of Heavy Ion Collisions

Masakiyo Kitazawa
(Osaka U., Osaka / KEK)

with

Marlene Nahrgang
(SUBATECH, Nantes)

TYL/FJPPL, FKPPL workshop, Nara, May. 9, 2018
QCD Phase Diagram

Early Universe

Early Universe Compact Stars

QCD Critical Point

Hadron Phase (confined)

Color SC

Our Universe

\[ \sim 10^{15} \text{g/cm}^3 \]
Beam-Energy Scan Program in Heavy-Ion Collisions

- Quark-Gluon Plasma
- QCD Critical Point
- Hadron Phase (confined)
- Color SC

Our Universe

150MeV

\( T \)

\( \sim 10^{15} g/cm^3 \)

\( \mu \)
Beam-Energy Dependence
Beam-Energy Dependence

High energy

Nuclear transparency
net-baryon #: small

Low energy

Baryon stopping
net-baryon #: large
Baryon Stopping

rapidity dep. of net-proton #

\[ \sqrt{s_{NN}} \approx 4 - 6 \text{GeV} \]

Baryons stop at collision point

\[ \sqrt{s_{NN}} > 10 \text{GeV} \]

Baryons pass through
Heavy-Ion Collisions

J-PARC-HI
2025~?
2-6.2 GeV

FAIR
2023~?

NICA
2020~?

BES-II
2019~?

RHIC-BES
2010~

AGS
-1996

SPS
1994-2000

RHIC
2000~

LHC
2010~

creation of quark-gluon plasma, strongly-interacting QGP

~2010
History of HIC = increasing energy

2010~
Beam-energy scan
Low-energy exp.

10GeV

10^2GeV

1TeV

\sqrt{s_{NN}}
HI Acceleration @ J-PARC

- Use of reliable / high-performance RCS & main ring
- Reduce cost and time
Search for QCD Phase Structure with Fluctuation Observables

Our Universe

Quark-Gluon Plasma

QCD Critical Point

Hadron Phase (confined)

Color SC

$\sim 10^{15} g/cm^3$

$T$

$\mu$

150MeV

high

beam energy

low
Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.

- Phase transition $\rightarrow$ Large fluctuation
- Non-Gaussian fluctuations: good observables of QCD-CP

Stephanov, PRL (2009); Asakawa, Ejiri, MK, PRL (2009)

Review: Asakawa, MK, PPNP90 ('16)
Event-by-Event Fluctuations

Fluctuations can be measured by e-by-e analysis in experiments.

Cumulants

\[ \langle \delta N^2_p \rangle, \langle \delta N^3_p \rangle, \langle \delta N^4_p \rangle_c \]
Enhanement in non-Gaussian cumulants has been observed!

Have we measured critical fluctuations?
Particle-number fluctuations in a phase space continue to change during the time evolution.
Effect of Dynamical Evolution

- **Growth**
  Growth of the critical fluctuation is limited by the critical slowing down.

- **Decay by diffusion**
  Fluctuations developed at CP are modified by the time evolution in later stage before observation.

So far, these problems have not been studied seriously…
Two Groups Working Actively on Dynamics

Masakiyo Kitazawa
(Osaka University/KEK)
- Diffusion in Brownian model
  2014~
- Thermal blurring effects
  2016
- Stochastic diffusion model
  2017

Marlene Nahrgang
(SUBATECH)
- Chiral fluid dynamics: model building
  2011~
- Chiral fluid dynamics: applications
  2014~
- Diffusion of non-Gaussianity
  2018

Osaka
Nantes
Stochastic Diffusion Equation

- **Diffusion equation**
  \[ \partial_\tau n = D \partial_\eta^2 n \]
  - Describe a relaxation of a conserved density \( n \) toward uniform state without fluctuation

- **Stochastic diffusion equation**
  \[ \partial_\tau n = D \partial_\eta^2 n + \partial_\eta \xi(\eta, \tau) \]
  \[ \langle \xi(\eta_1)\xi(\eta_2) \rangle \sim \chi \delta(\eta_1 - \eta_2) \]
  - Describe a relaxation toward fluctuating uniform state
  - Only Gaussian fluctuations

Review: Asakawa, MK, PPNP 90 (2016)

Sakaida, MK, et al. PRD95, 064905 (2017)
Solve the time evolution **analytically** for Gaussian fluctuations.

Non-monotonic \( \Delta y \) dep. as a signal of QCD-CP.
Extension to Non-Gaussianity

\[ \partial_{\tau} n = D \partial_{\eta}^2 n + \partial_{\eta} \xi(\eta, \tau) \]

Include non-linear effects

\[ \partial_{\tau} n = D \partial_{\eta}^2 \frac{\delta F(n)}{\delta n} + \partial_{\eta} \xi(\eta, \tau) \]

\[ F(n) = n^2 + an^3 + bn^4 + cn^6 \]

Solve the time evolution stochastically including non-Gaussian fluctuations

Many Things To Do

Gaussian Analytic

Stochastic diffusion model

Non-Gaussian Stochastic

Japanese flag

French flag
Many Things To Do

Comparison
Deeper understanding on dynamics of fluctuations
Many Things To Do

Stochastic diffusion model

Comparison
Deeper understanding on dynamics of fluctuations

Gaussian Analytic
analytic result for non-Gaussian

Non-Gaussian Stochastic
coupling to chiral condensate in chiral-fluid model

Diffusion on Brownian particle model

Parameter dependence

Non-Gaussian Stochastic parameter dependence

Analytic analytic result for non-Gaussian
Many Things To Do

Comparison
Deeper understanding on dynamics of fluctuations

Stochastic diffusion model

- Gaussian Analytic
- analytic result for non-Gaussian
- Diffusion on Brownian particle model

- Non-Gaussian Stochastic
- parameter dependence
- Coupling to chiral condensate in chiral-fluid model

Dynamical evolution in realistic space-time evolution
Many Things To Do

- Gaussian Analytic
- Analytic result for non-Gaussian
- Stochastic diffusion model
- Coupling to chiral condensate in chiral-fluid model
- Non-Gaussian Stochastic
- Parameter dependence

Comparison
Deeper understanding on dynamics of fluctuations

Dynamical evolution in realistic space-time evolution

- Realistic description of fluctuation dynamics
- New methodology to search for phases of QCD
Summary

- **Beam-energy scan**: world-wide exciting topics!
- **Fluctuations**: important observables for the search for QCD phase structure

- Proper description of dynamics of fluctuations is necessary, but has not been studied well.
- **Osaka-Nantes bilateral collaboration will play a crucial role in resolving these problems!!**

### Osaka Group
- Masakiyo Kitazawa
- Yukinao Akamatsu

### Nantes Group
- Marlene Nahrgang
- Iurii Karpenko
- Marcus Bluhm

and young students…