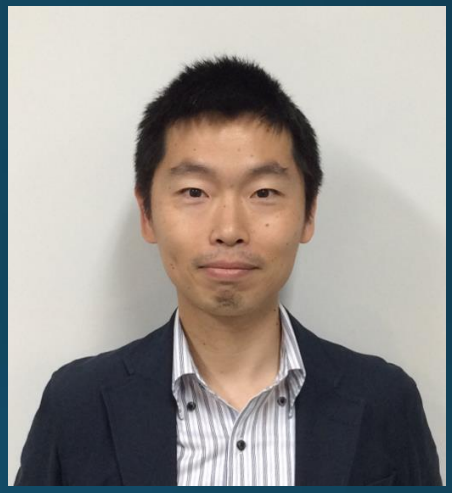
Search for Phase Structure of QCD in Relativistic Heavy-Ion Collisions

Masakiyo Kitazawa
北澤 正清
(Osaka U.)

Exchange program between SJTU and OU
Mini Workshop: Prospect on particle and nuclear physics, and related subjects

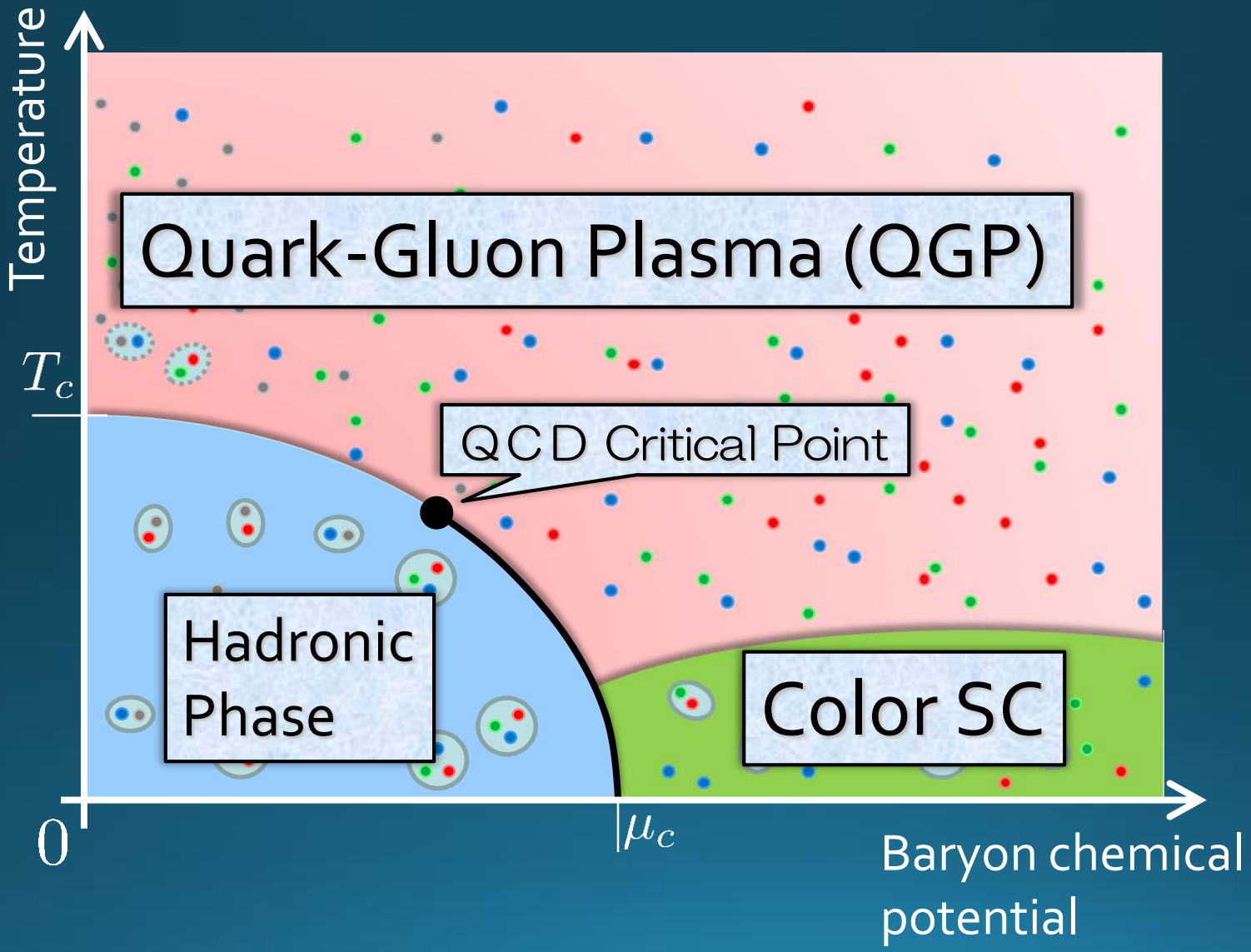
Introducing Myself…

- **Research Interest**
  - **QCD in medium** Today's topics
  - Relativistic heavy-ion collisions
    - Non-Gaussian fluctuations
  - Lattice numerical simulations
    - Gradient flow, energy-momentum tensor
  - Machine learning / Hadron structure
  - Marathon

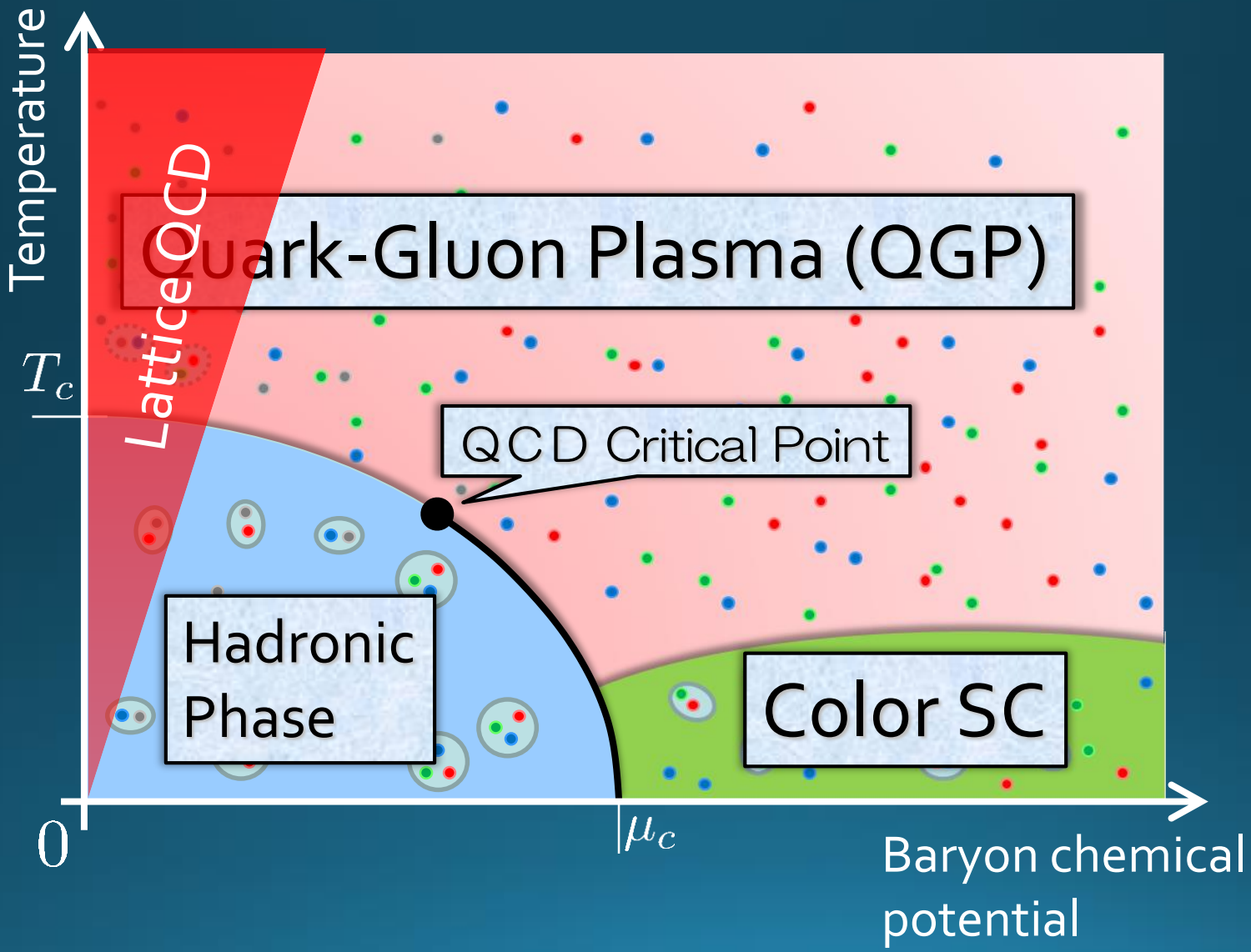


- **Past Affiliations**
  - Tsukuba, Kyoto (Japan)
  - Frankfurt U. (Germany)
  - Brookhaven National Lab. (USA)

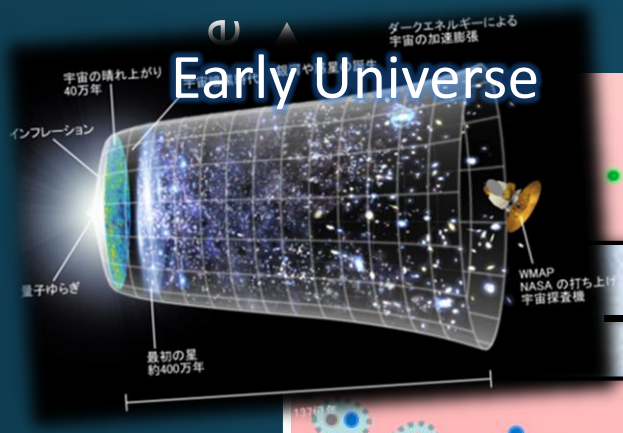
QCD Phase Diagram



QCD Phase Diagram



QCD Phase Diagram



-Gluon Plasma (QGP)

T_c

QCD Critical Point

Hadronic Phase

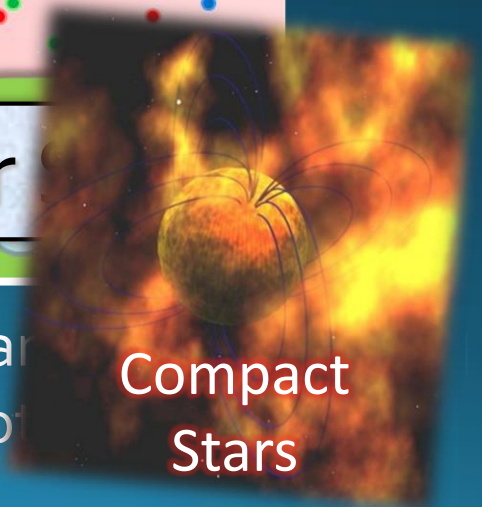
Color

0

μ_c

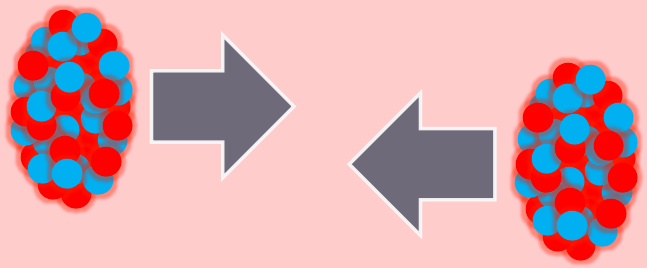
Ba

po



Relativistic Heavy-Ion Collisions

Collide 2 heavy nuclei



Physics

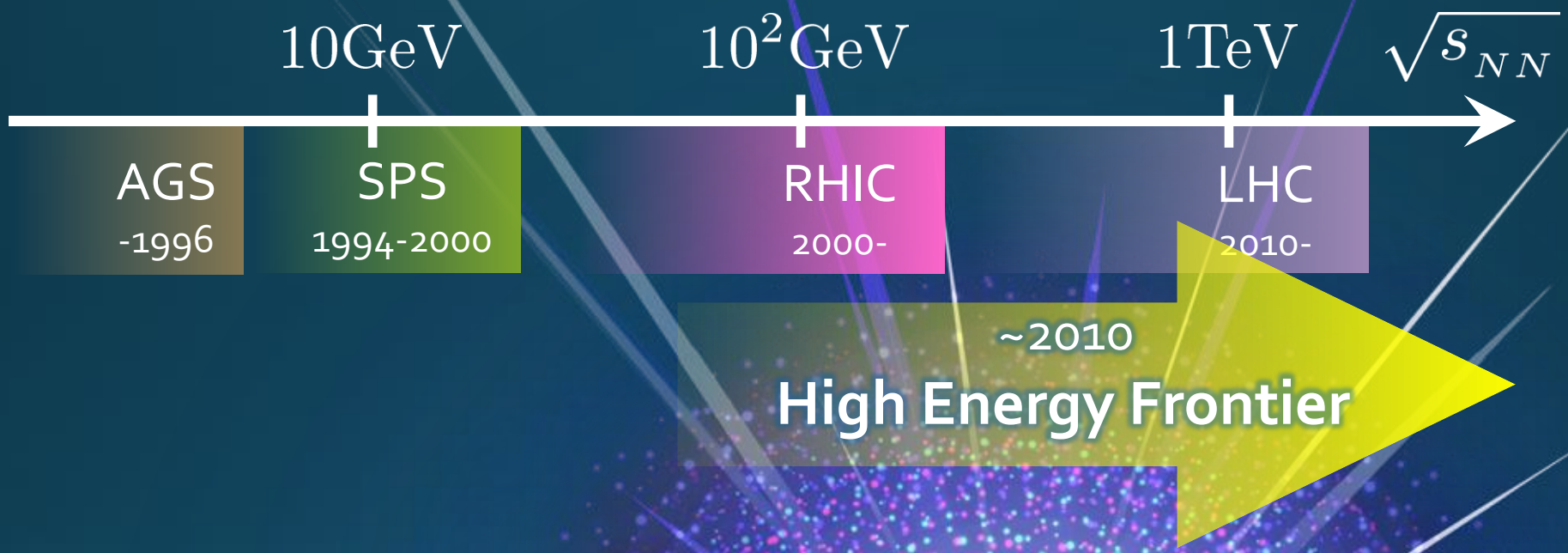
- Hot & dense medium
- Early Universe
- Quark-gluon plasma
- QCD phase structre

RHIC (2000~)
QGP Formation
Strongly coupled QGP

LHC (2010~)
Precision measurement
of the QGP

Picture of fireball by Soushi Nonaka

Brief History of Relativistic HIC



Picture of fireball by Soushi Nonaka

Brief History of Relativistic HIC

AGS
-1996

SPS
1994-2000

RHIC
2000-

LHC
2010-

RHIC-BES
2010-

~2010
High Energy Frontier

NICA
FXT: 2019-

FAIR
2025-

2010~
Lower Energy

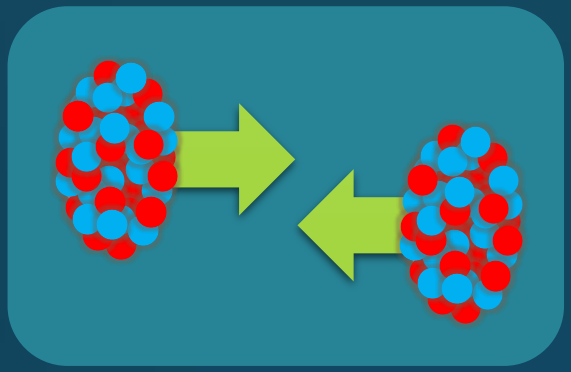
J-PARC-HI
2025-?

Interaction rate

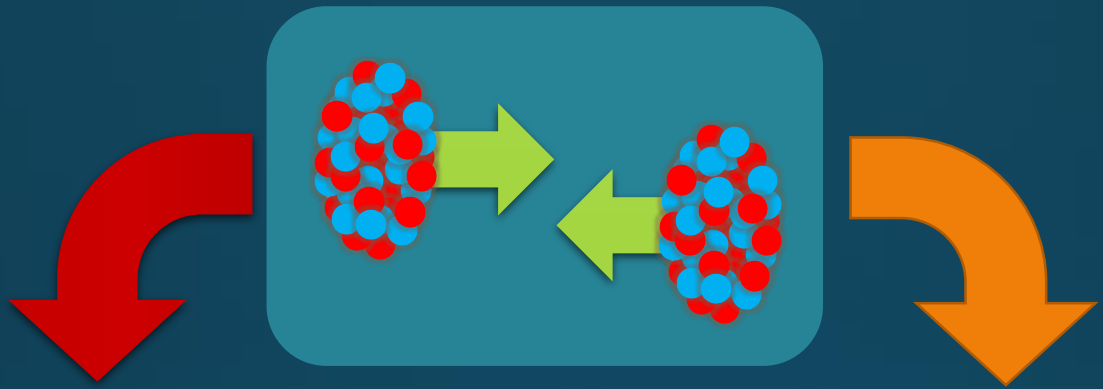
- **FAIR, J-PARC-HI: ~10^7 Hz**
- AGS, SPS: ~10^2 Hz

Picture of fireball by Soushi Nonaka

Beam-Energy Dependence

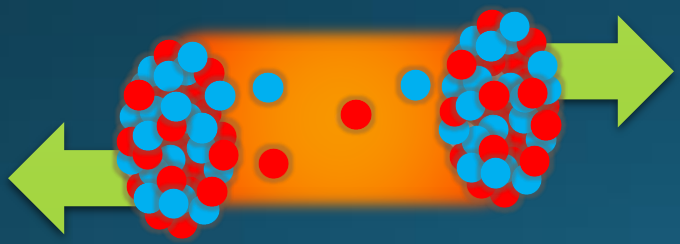


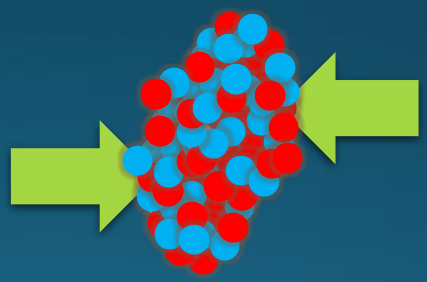
Beam-Energy Dependence



High energy

Low energy





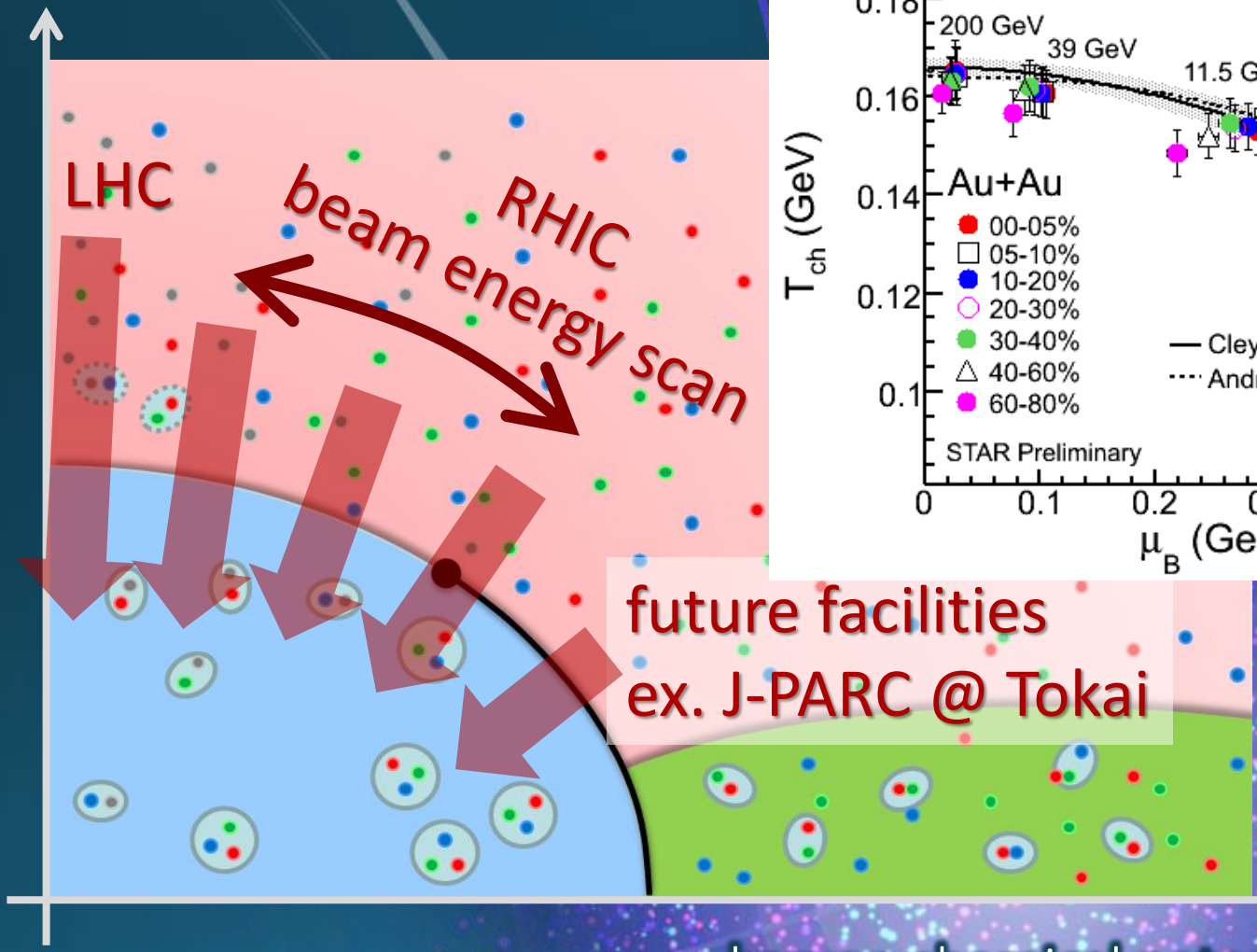
Nuclear transparency

net-baryon #: small

Baryon stopping

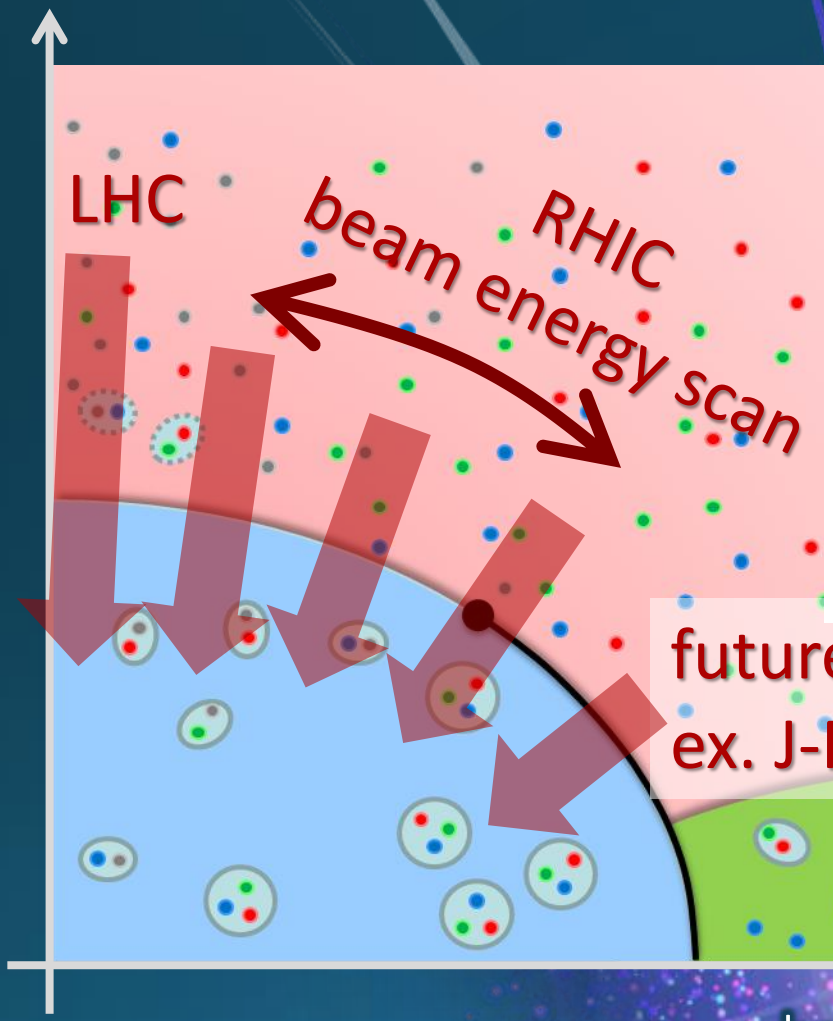
net-baryon #: large

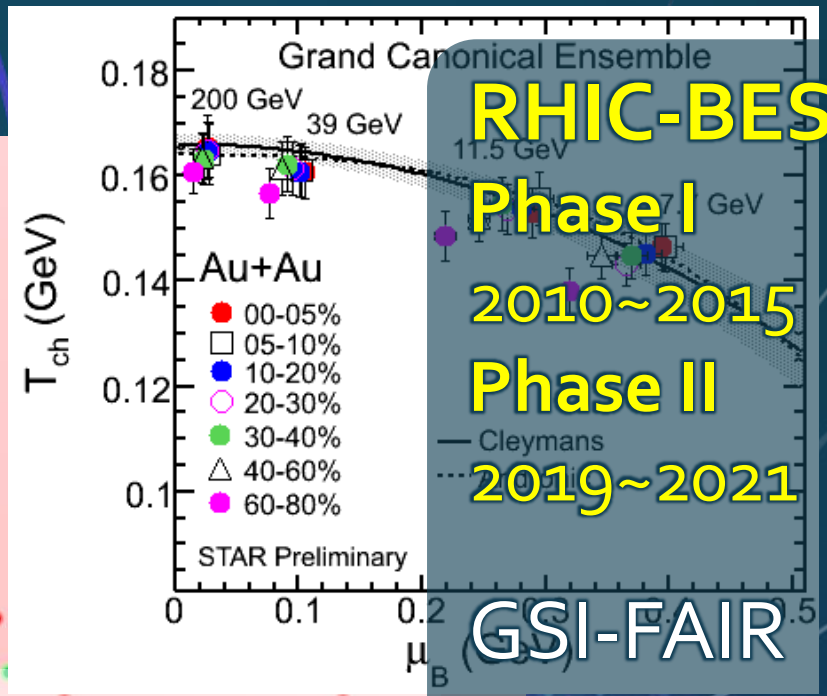
Beam-Energy Scan



Picture of fireball by Soushi Nonaka

Beam-Energy Scan





RHIC-BES

Phase I

2010~2015

Phase II

2019~2021

GSI-FAIR

2025~?

J-PARC-HI

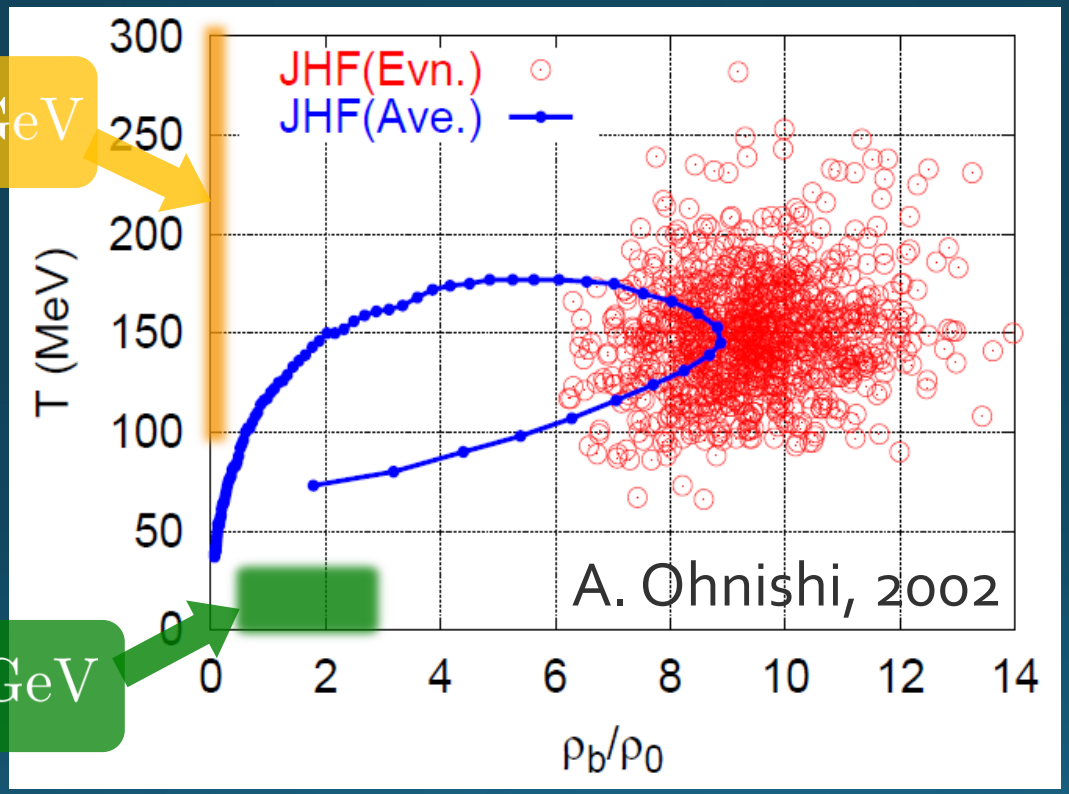
2025~??

Picture of fireball by Soushi Nonaka

Maximum Density

Time evolution in *T*-ρ plane by JAM

$\sqrt{s_{\rm NN}} > 100$ GeV



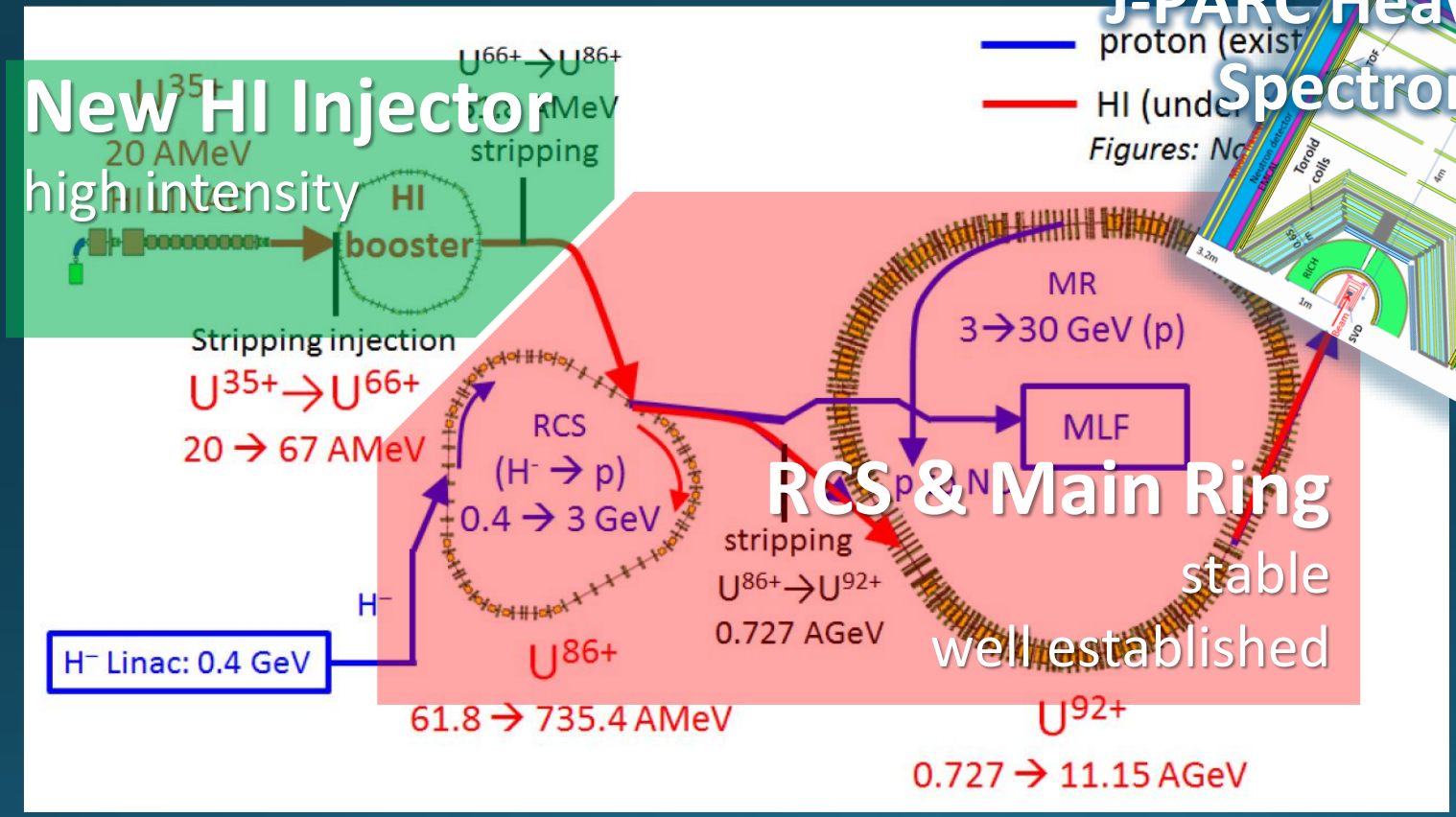
$E/A < 1$ GeV

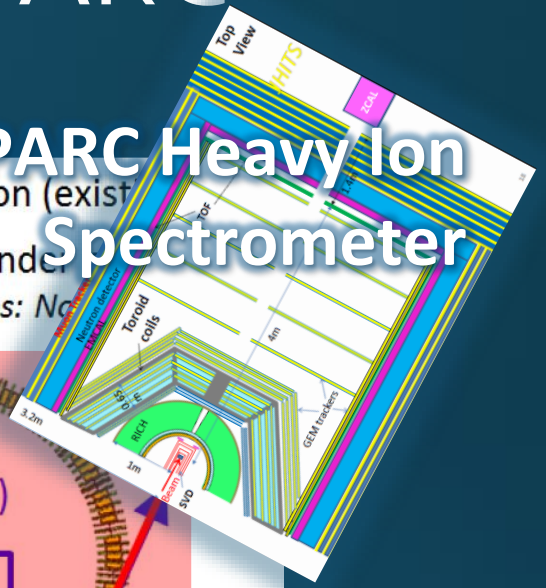
$E/A = 20\mathrm{GeV}$

$\sqrt{s_{NN}} \simeq 6\mathrm{GeV}$

- Maximum density 5~10ρ_0 @ E/A~20GeV
- Large event-by-event fluctuations?

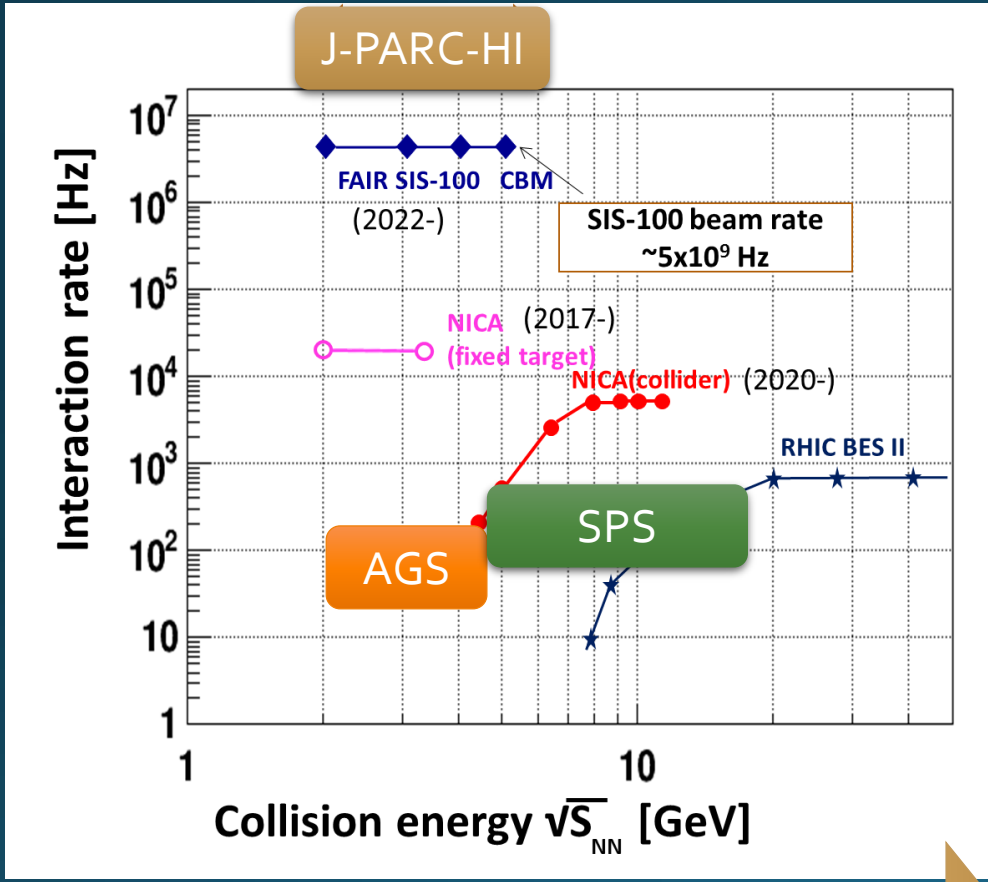
HI Acceleration @ J-PARC





- Use of reliable / high-performance RCS & main ring
- →Reduce cost and time

Collision Rate



J-PARC-HI:

High-luminosity X Fixed target

→World highest rate～10^8Hz

5-order higher than AGS,SPS

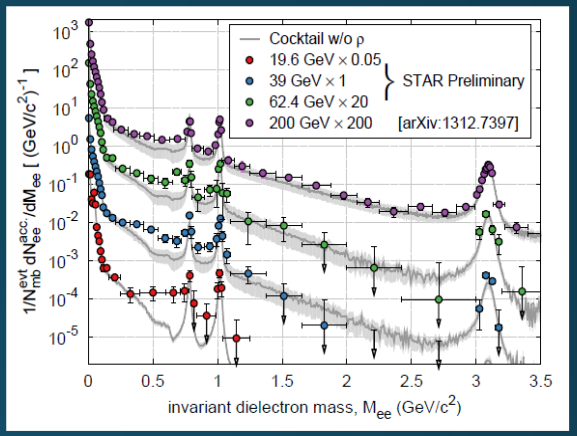
AGS, SPS 1 year = J-PARC-HI 5 min.

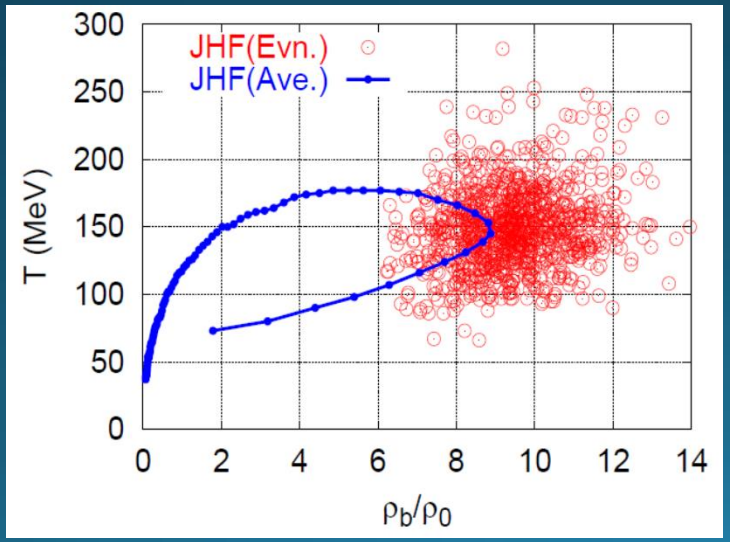
- ☐ High-statistical exp.
- ☐ various event selections
- ☐ higher order correlations
- ☐ search of rare events

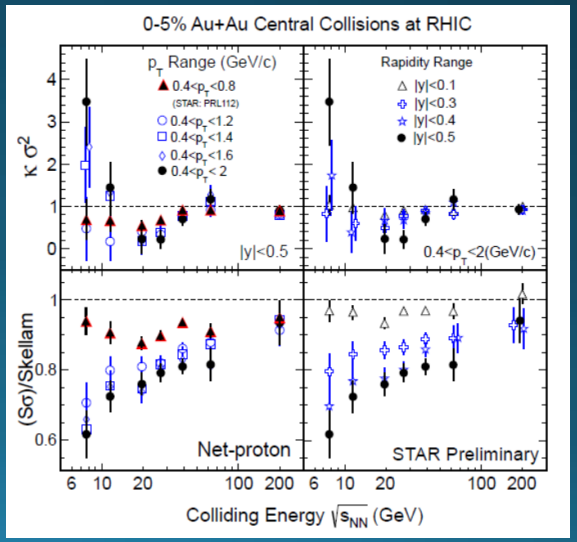
Various Observables

- Flow
- Dilepton / photon
- Fluctuations, higher-order cumulants
- Ξ, Ω, …

- Sophisticated event selections
- Various correlations

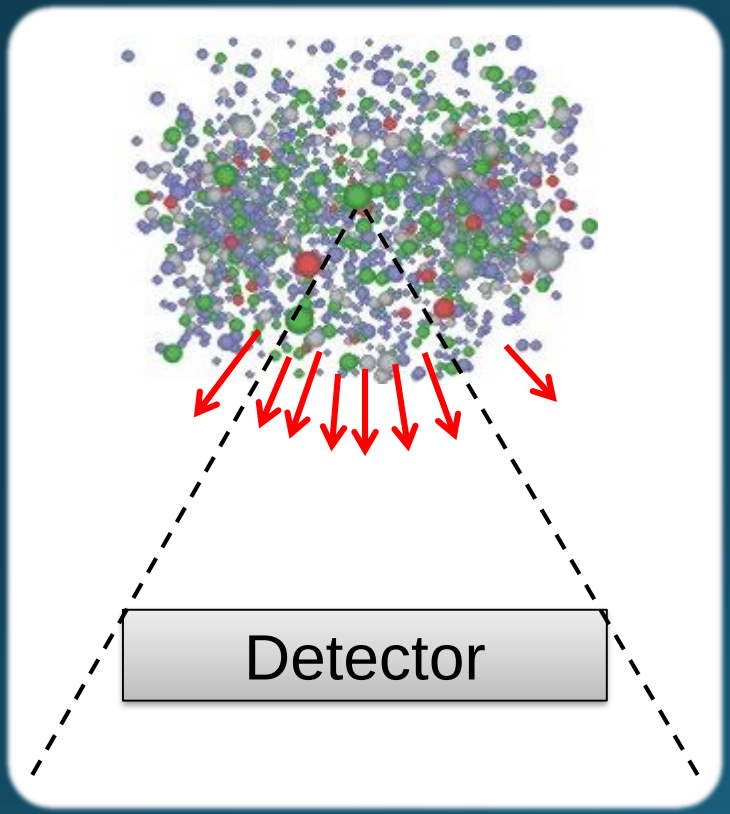




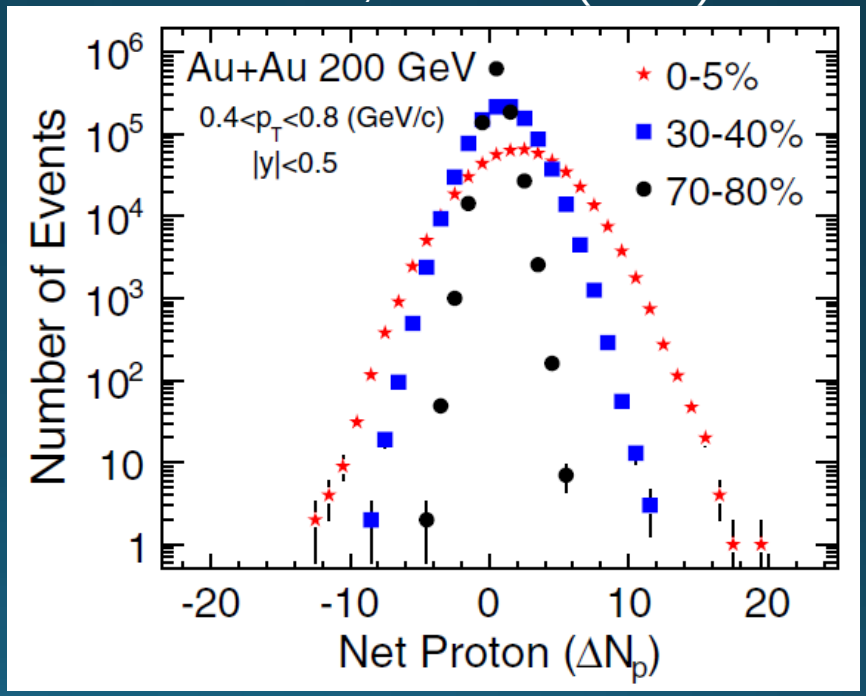


Event-by-Event Fluctuations

Review: Asakawa, MK, PPNP **90** (2016)



STAR, PRL**105** (2010)

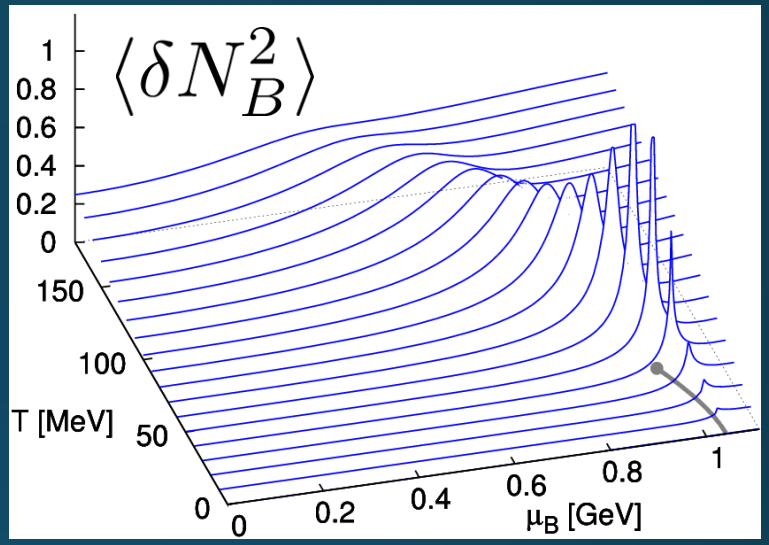


Cumulants

$$\langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c$$

Non-Gaussian Cumulants

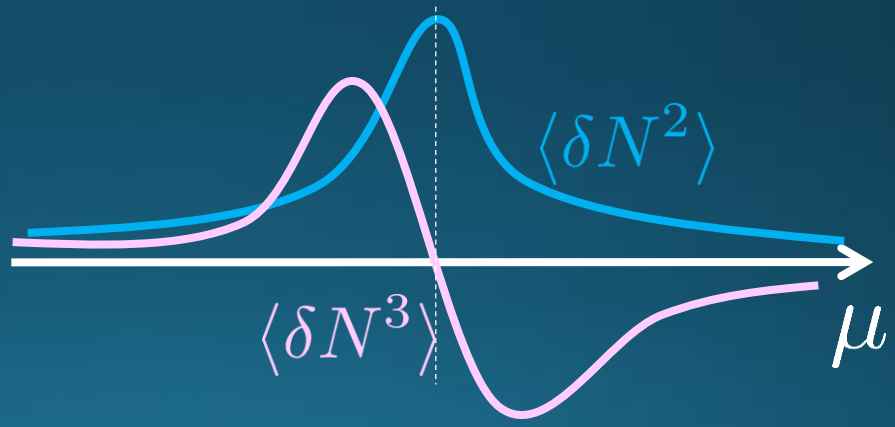
Gaussian fluctuations diverge at the QCD-CP



- Higher order cumulants change sign at the phase boundary

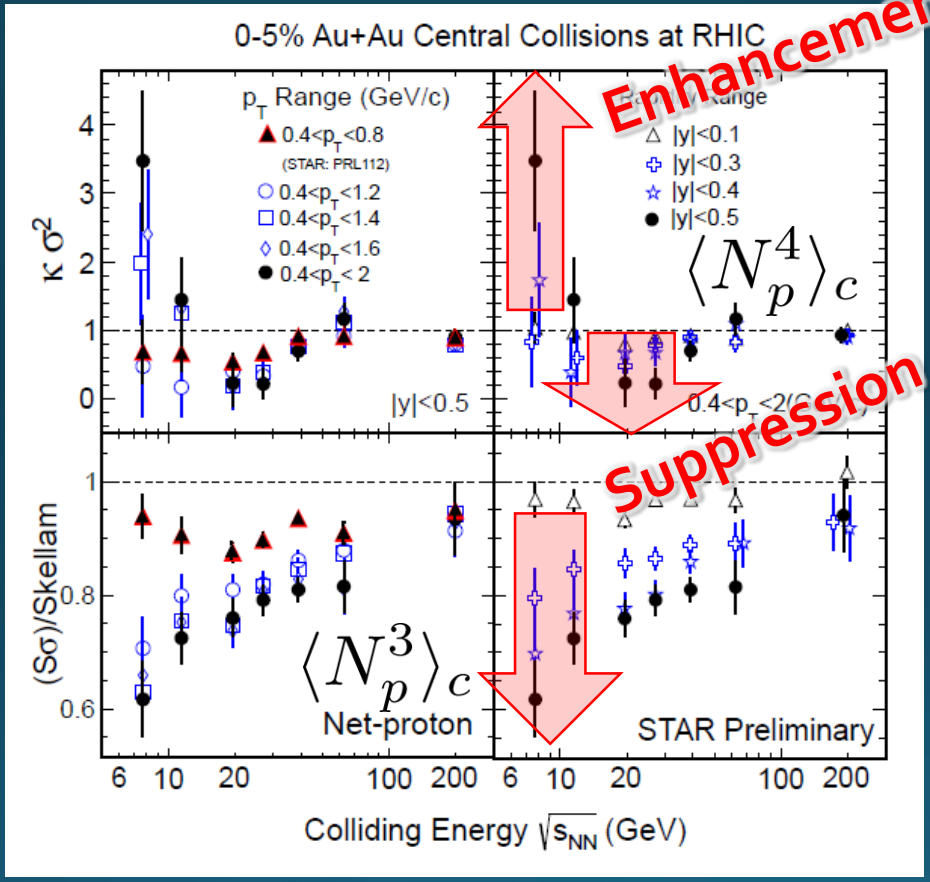
$$\langle \delta N^3 \rangle = T \frac{\partial \langle \delta N^2 \rangle}{\partial \mu}$$

Asakawa, Ejiri, MK, 2009



- Steeper divergence for higher-order cumulants Stephanov, 2009

Experimental Results

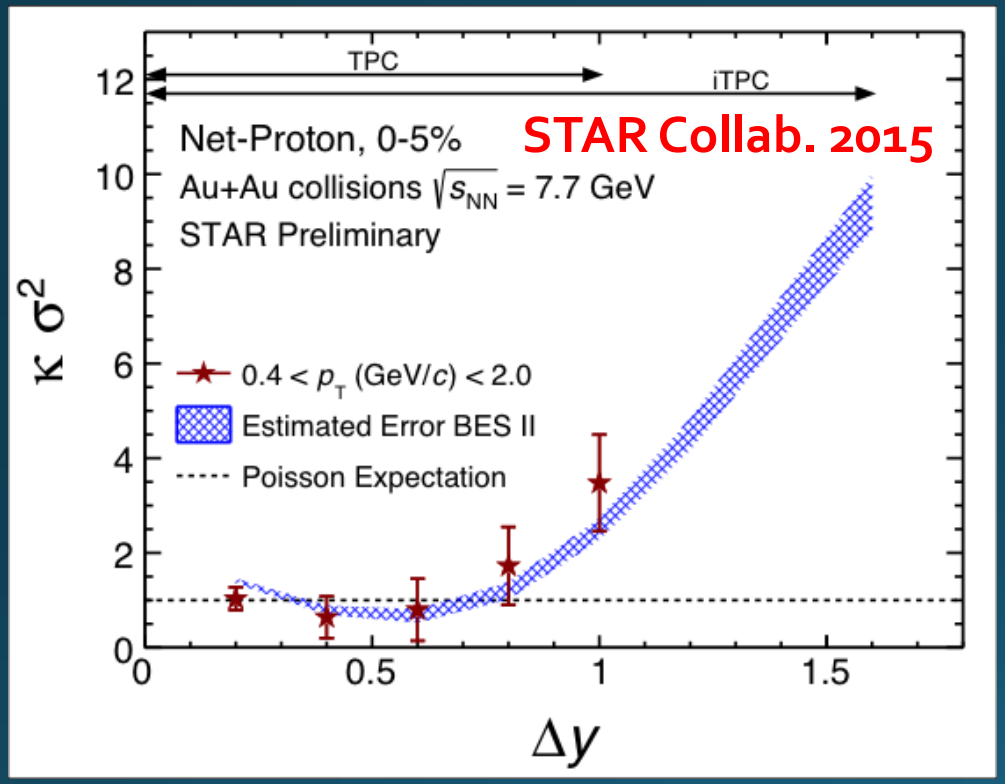


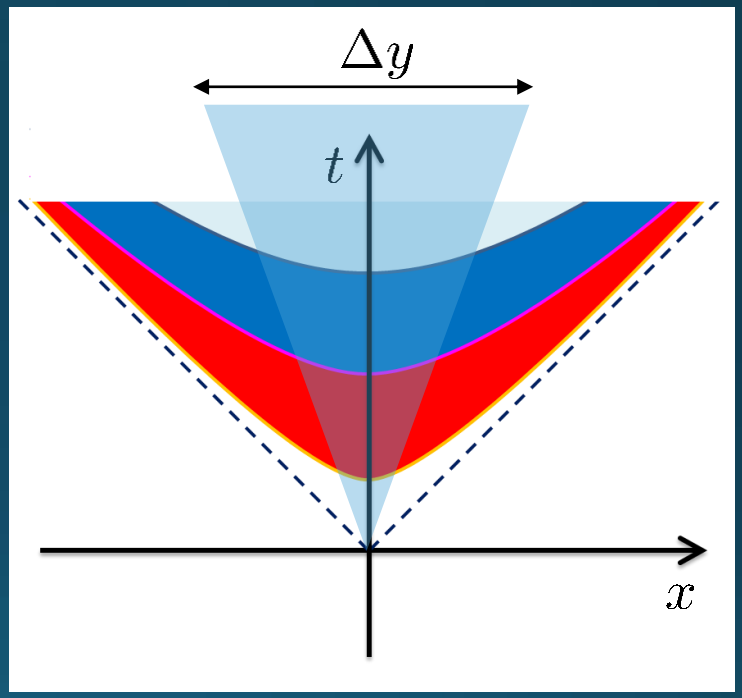
STAR Collab.
2010~

Enhancement & Suppression of non-Gaussian cumulants!

Have we observed QCD critical point?

Rapidity Window Dependence

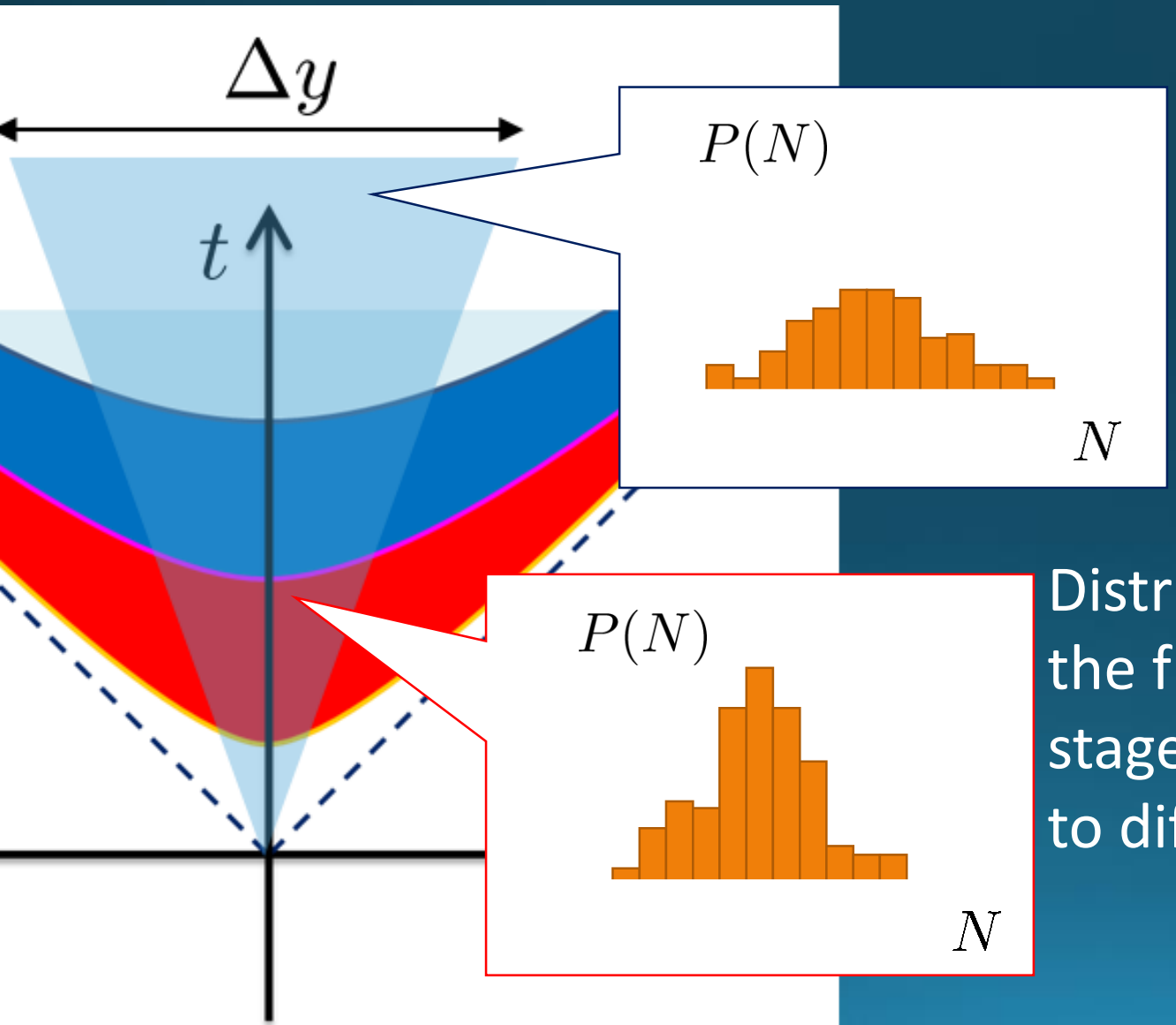




- Non-Gaussian Cumulants have been observed as a function of rapidity window Δy.
- Some results have non-monotonic Δy dependence.

Diffusion of Fluctuations

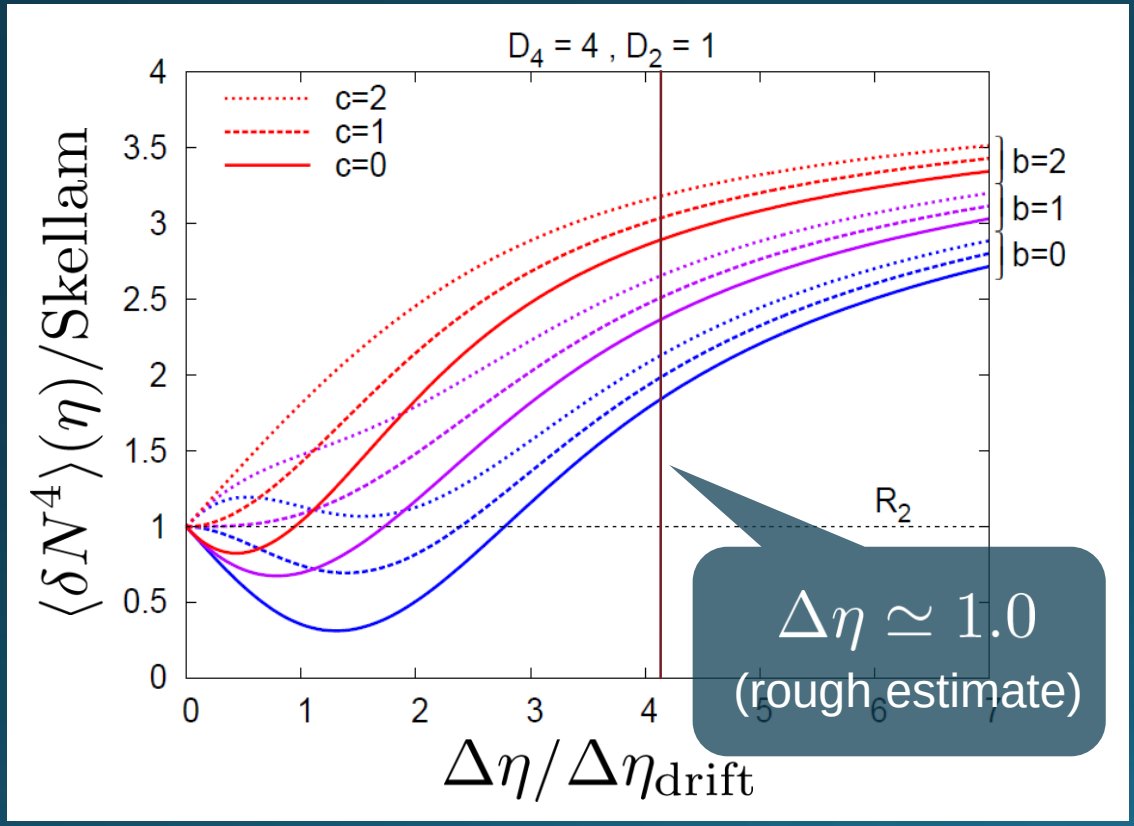
MK, Ohno, Asakawa 2014
MK 2015



Distributions in Δy in the final state and early stage are different due to diffusion.

Rapidity Window dependence
as a Result of Diffusion

MK+ (2014); MK (2015)



Parameters

$$D_4 = \frac{\langle Q^4_{(\mathrm{net})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle} = 4$$

$$D_2 = \frac{\langle Q^2_{(\mathrm{net})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle} = 1$$

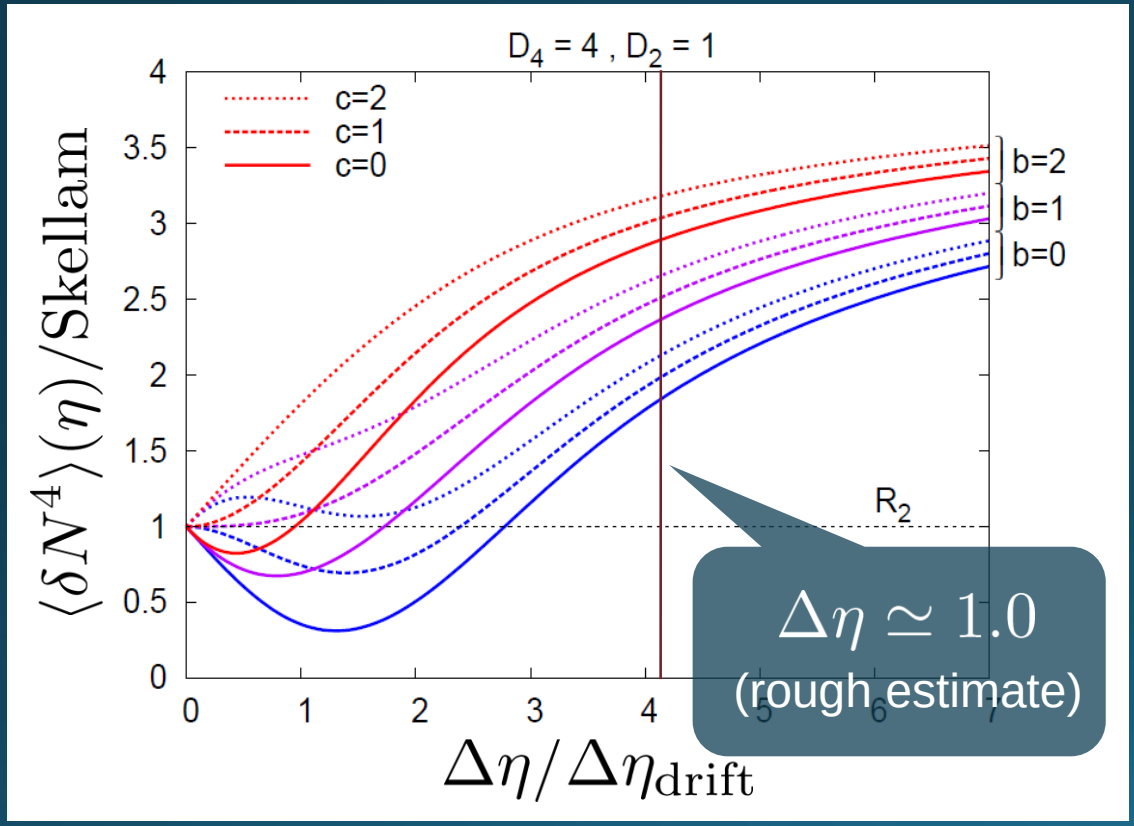
$$b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{net})} \rangle}$$

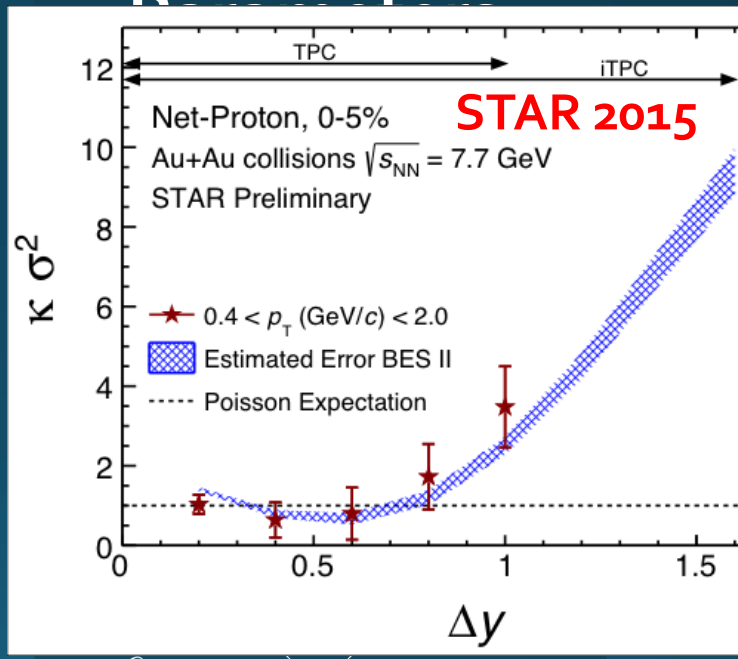
$$c = \frac{\langle Q^2_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

- Higher order cumulants can behave non-monotonically.
- $\Delta\eta$ dependence encodes history of time evolution.

Rapidity Window dependence
as a Result of Diffusion

MK+ (2014); MK (2015)





$$c = \frac{\quad}{\langle Q_{(\mathrm{tot})} \rangle}$$

- Higher order cumulants can behave non-monotonically.
- $\Delta\eta$ dependence encodes history of time evolution.

Summary

- Exploring dense medium in relativistic heavy-ion collisions is one of the hottest topics in this field. Many new experiments will start in the near future!

- Fluctuations are promising observables for the search for the phase structure of QCD. Non-Gaussian fluctuations attract much attention, and active experimental and theoretical studies are ongoing.