Pioneering session in KPS meeting, Changwon, Korea, Oct. 25, 2018

QCD Phase Diagram and Future Heavy-Ion Programs

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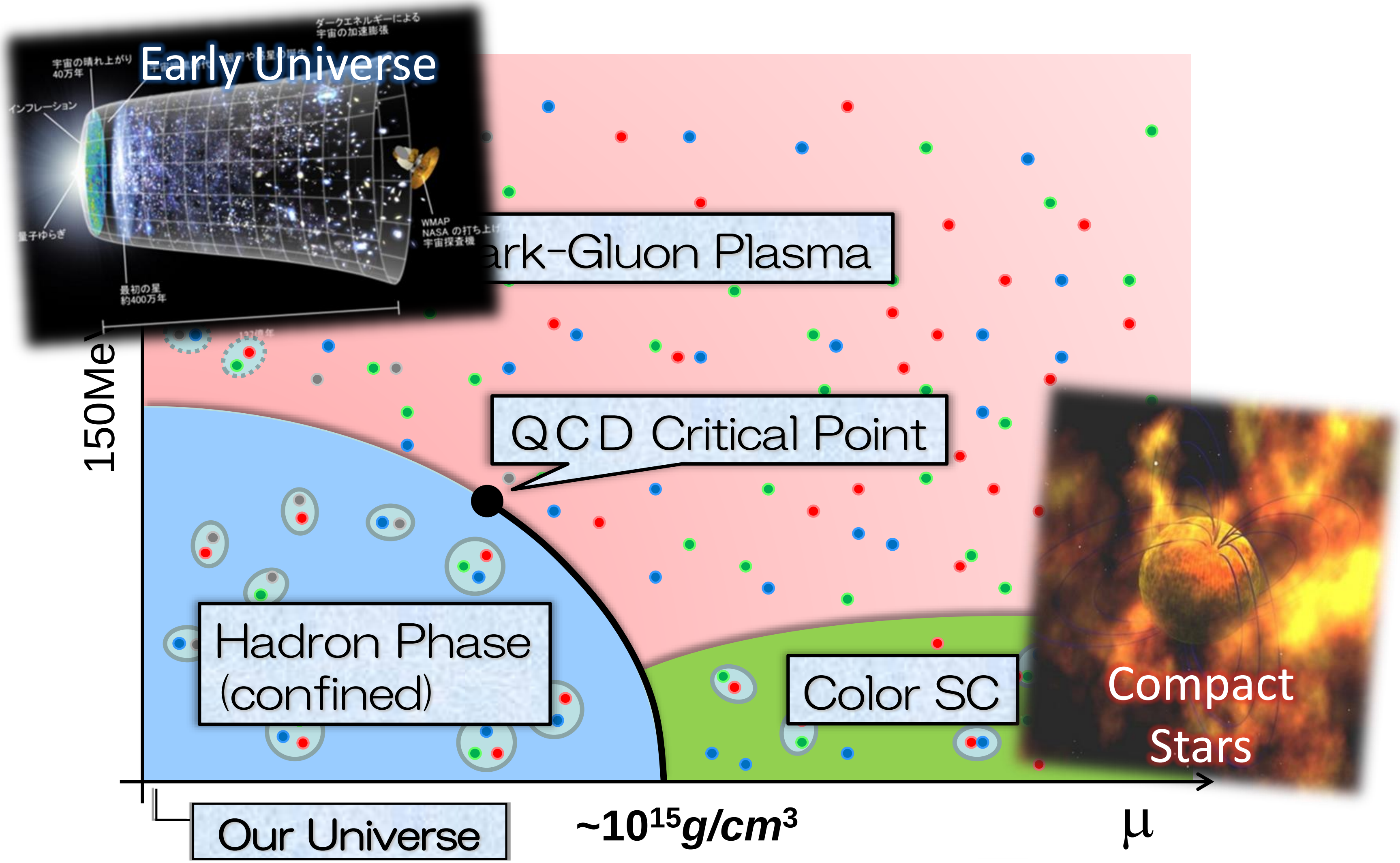
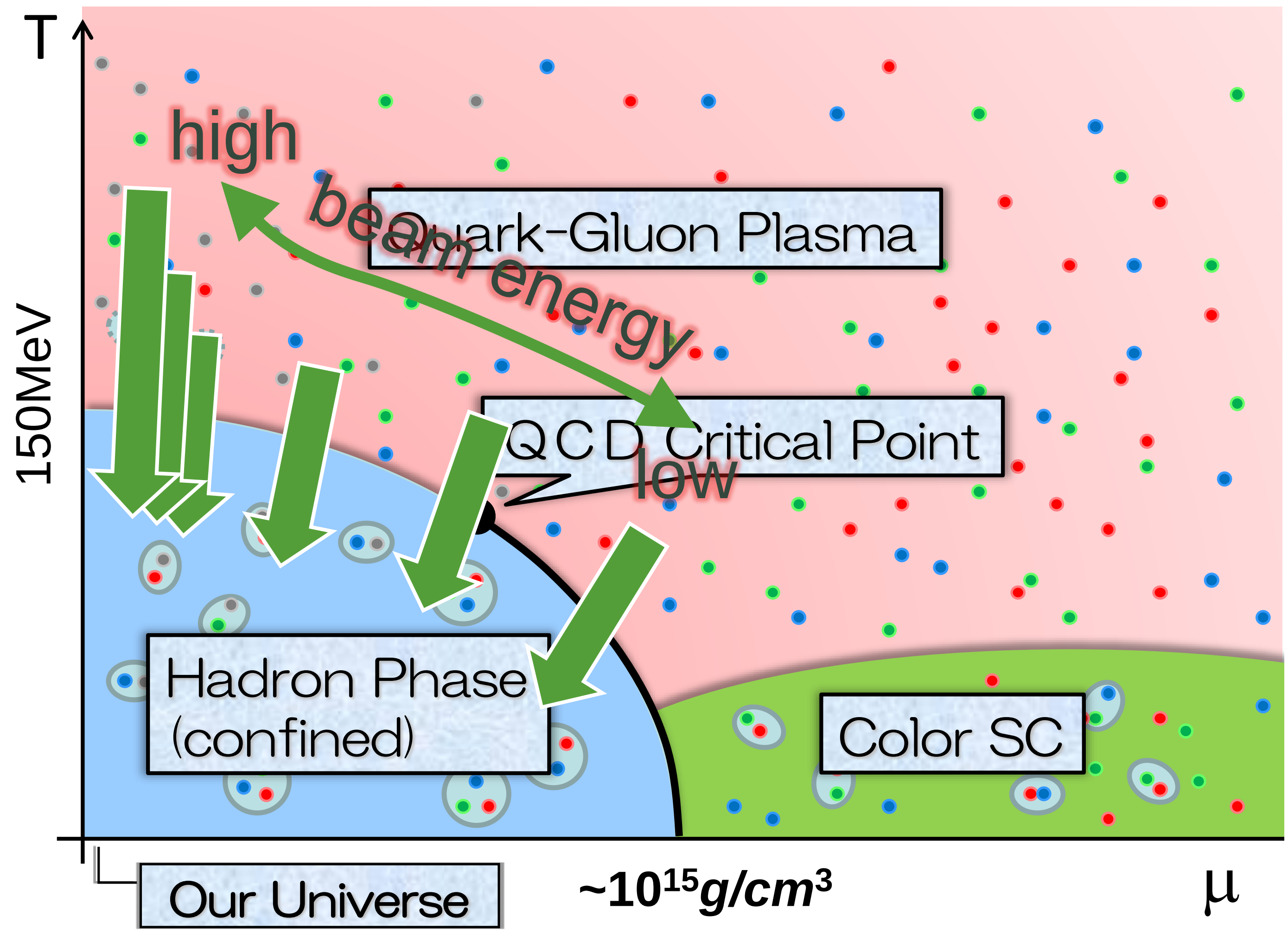
(Osaka U.)

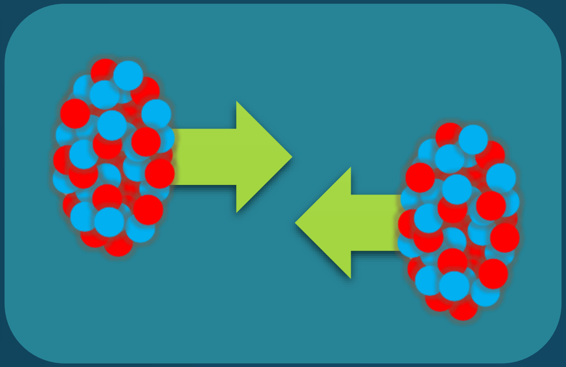
QCD Phase Diagram



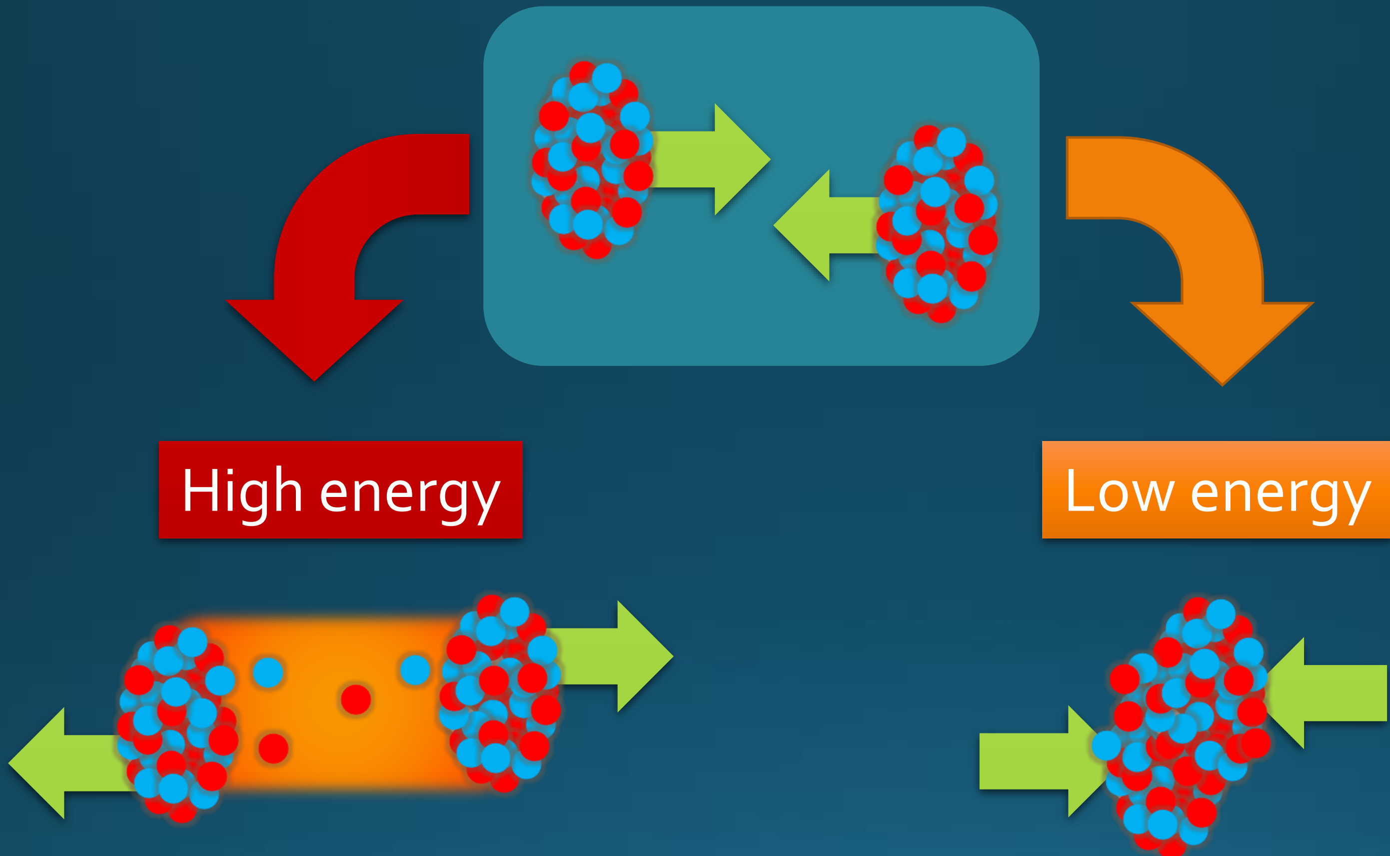
Beam-Energy Scan Program in Heavy-Ion Collisions



Beam-Energy Dependence



Beam-Energy Dependence



Nuclear transparency

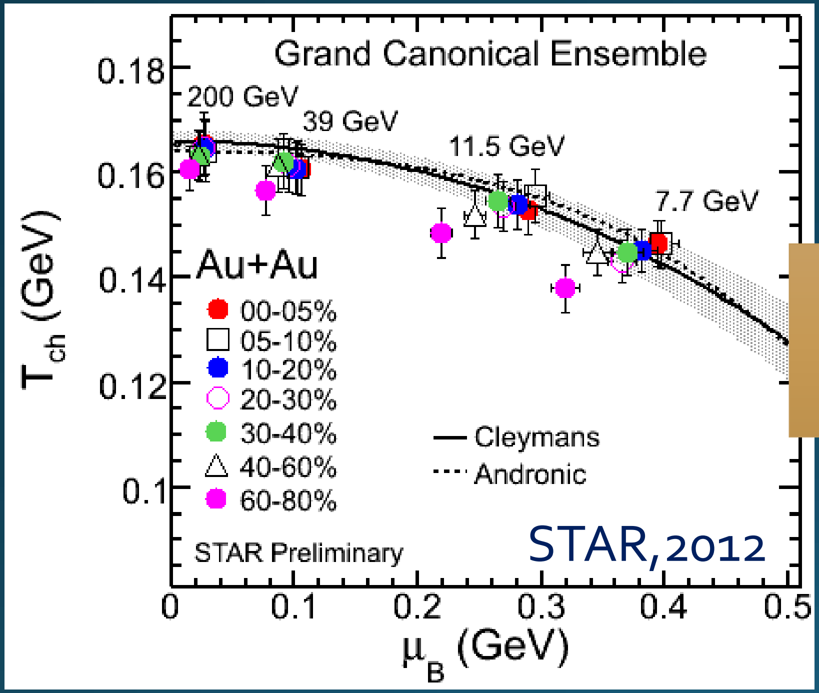
net-baryon #: small

Baryon stopping

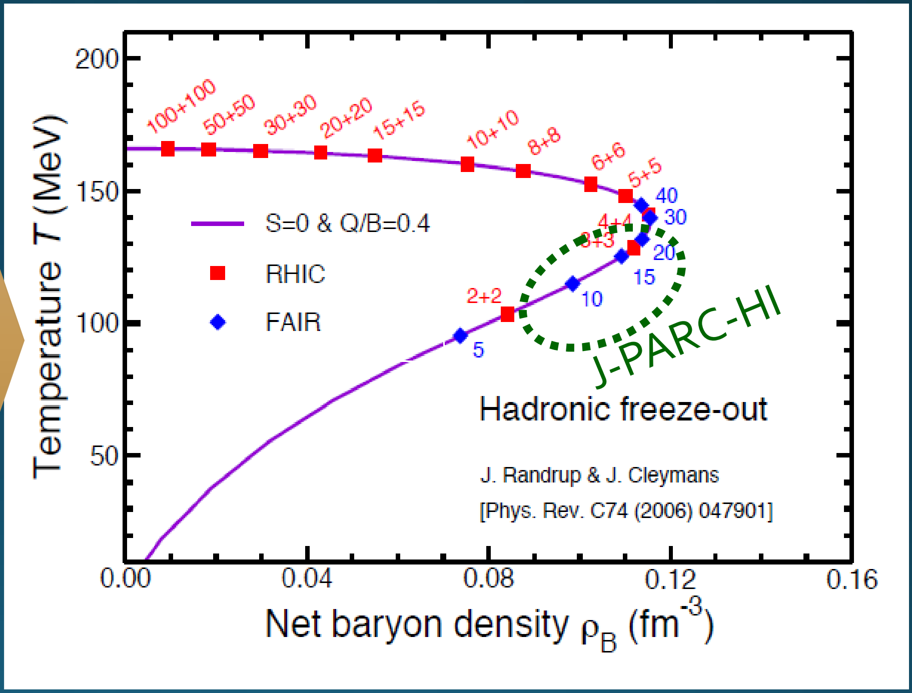
net-baryon #: large

Beam-Energy Scan

T, μ from particle yield



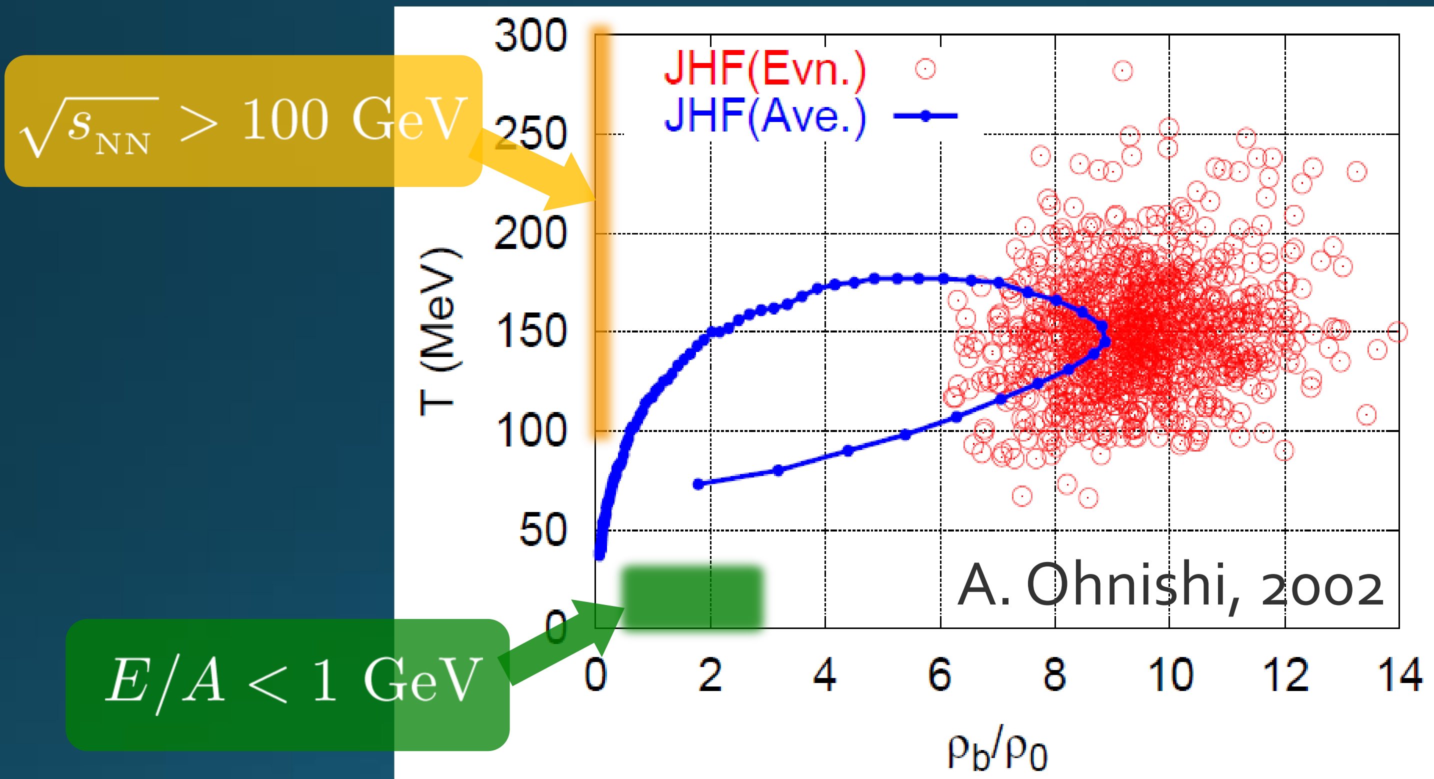
Translation to baryon density



J-PARC energy = highest baryon density

Maximum Density

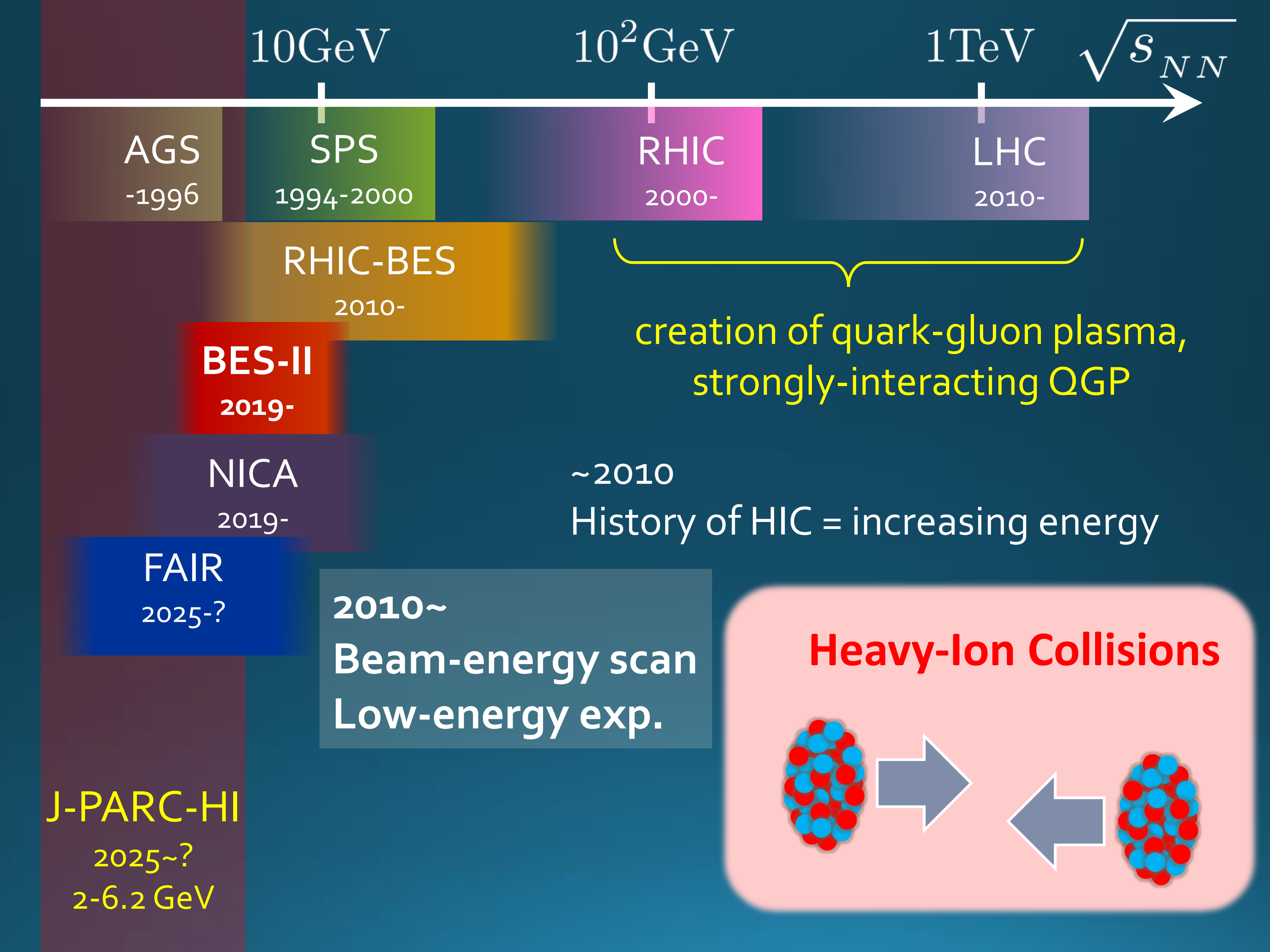
Time evolution in T-ρ plane by JAM



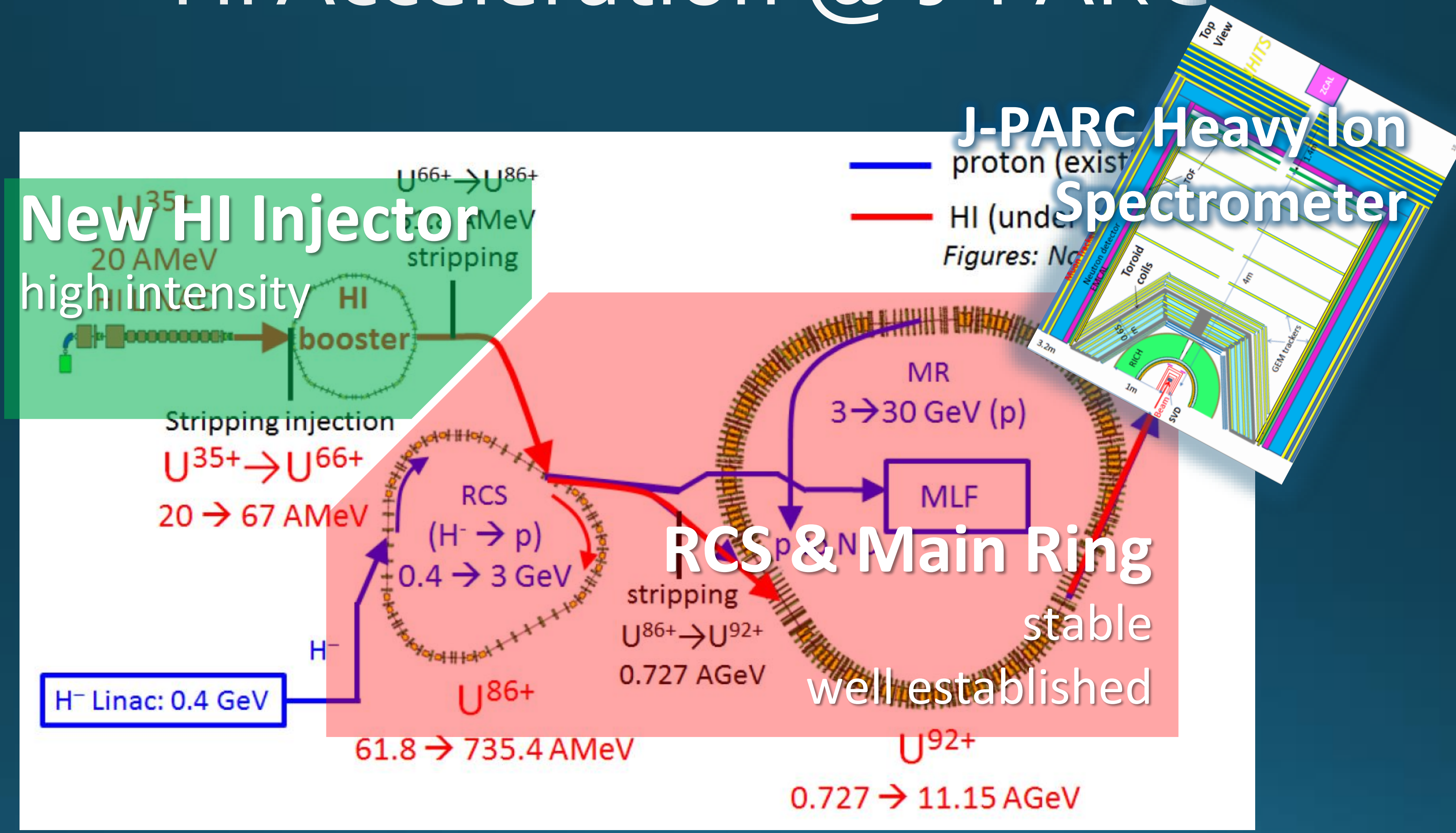
$$E/A = 20\text{GeV}$$

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

- ☐ Maximum density 5~10ρ_0 @ J-PARC energy
- ☐ Large event-by-event fluctuations?

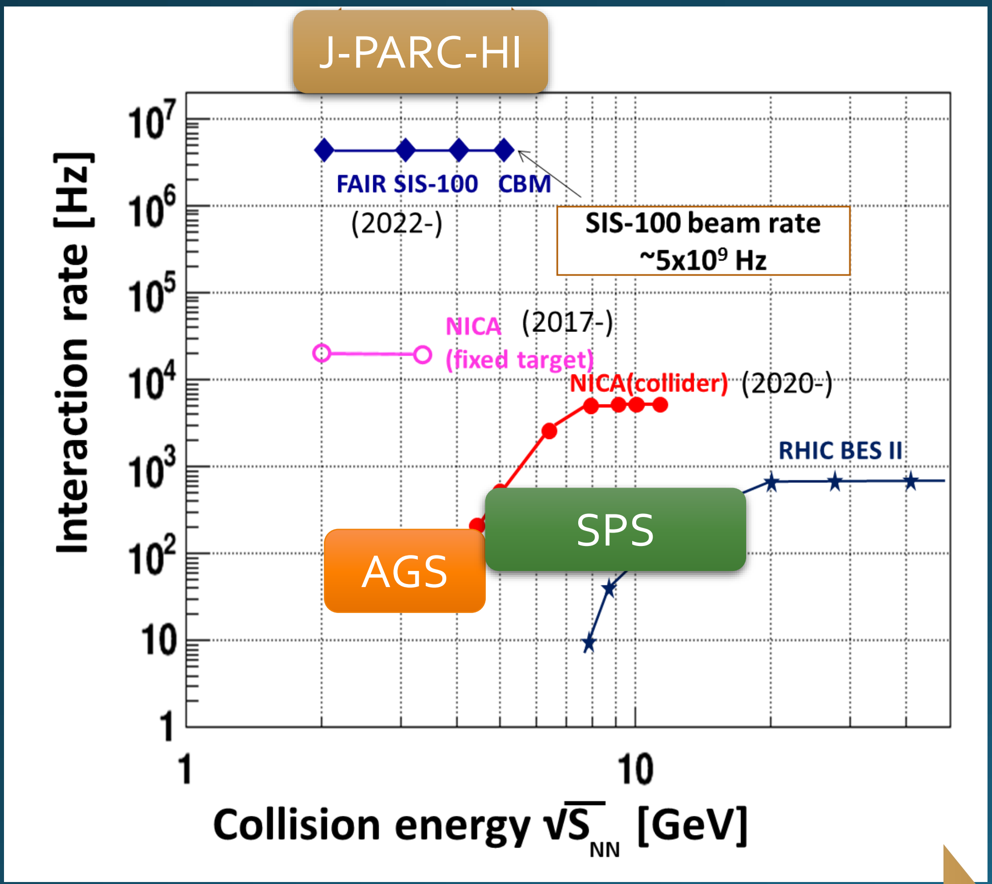

10GeV
10^2GeV
1TeV
$\sqrt{s_{NN}}$
AGS
-1996
SPS
1994-2000
RHIC
2000-
LHC
2010-
RHIC-BES
2010-
creation of quark-gluon plasma,
strongly-interacting QGP
BES-II
2019-
NICA
2019-
~2010
History of HIC = increasing energy
FAIR
2025-?
2010~
Beam-energy scan
Low-energy exp.
Heavy-Ion Collisions
J-PARC-HI
2025~?
2-6.2 GeV

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

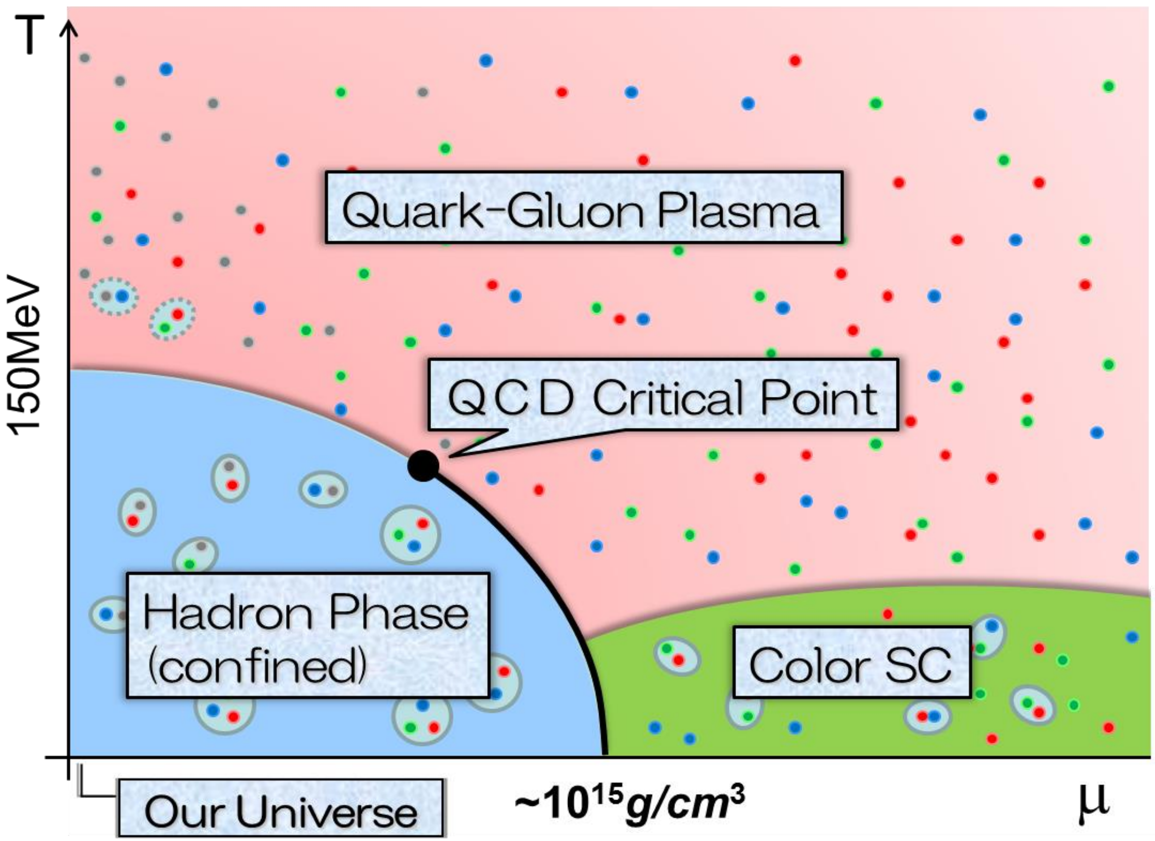
→World highest rate～10^8Hz

5-order higher than AGS,SPS

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

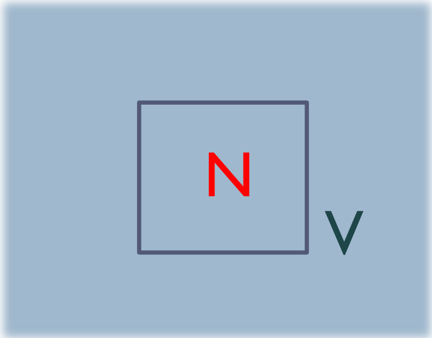
- ☐ High-statistical exp.
- ☐ various event selections
- ☐ higher order correlations
- ☐ search of rare events

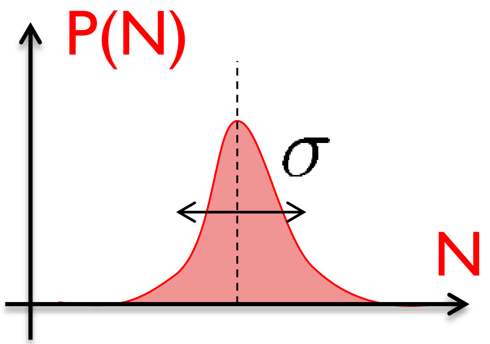
Searh for QCD Phase Structure with Fluctuation Observables



Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.





- Phase transition → Large fluctuation
- **Non-Gaussian fluctuations**: good observables of QCD-CP

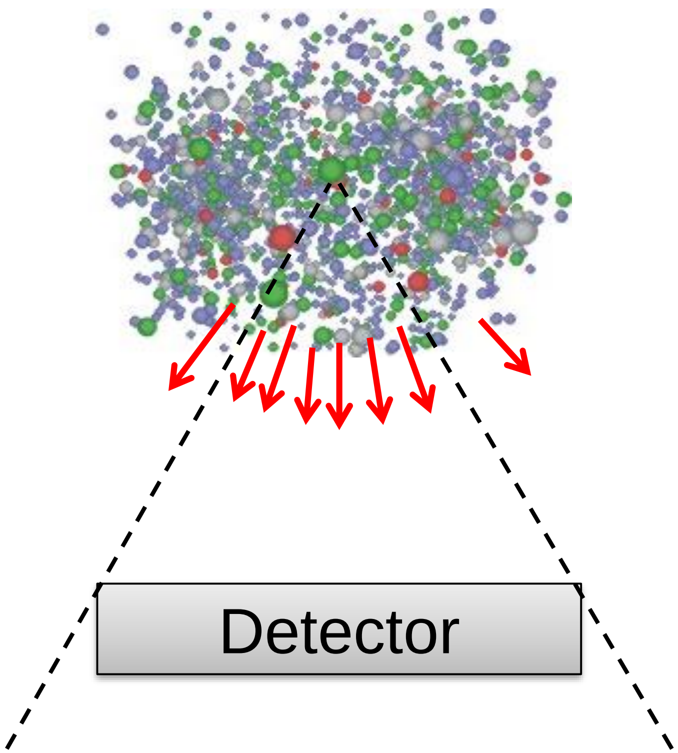
Stephanov, PRL (2009); Asakawa, Ejiri, MK, PRL (2009)

Review: Asakawa, MK, PPNP**90** ('16)

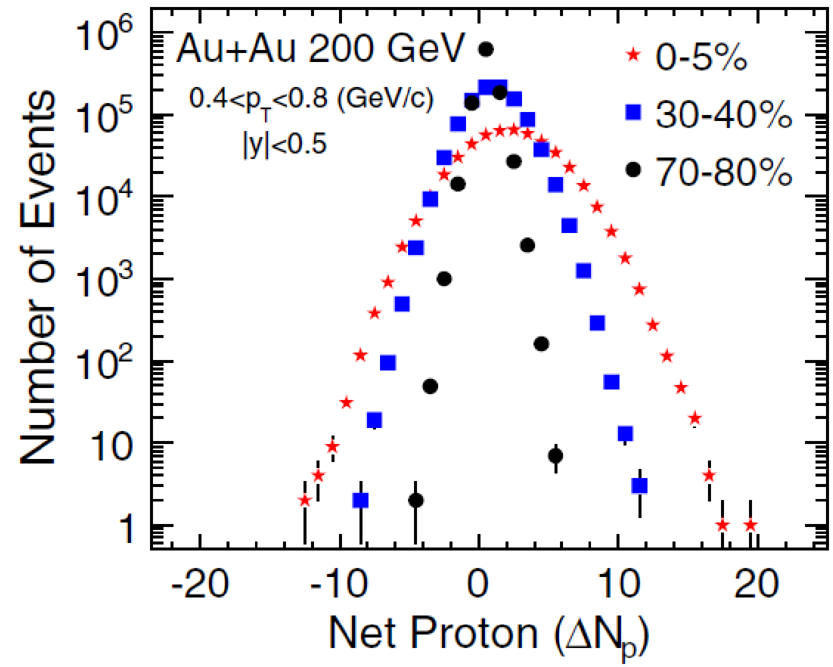
Event-by-Event Fluctuations

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

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



STAR, PRL**105** (2010)

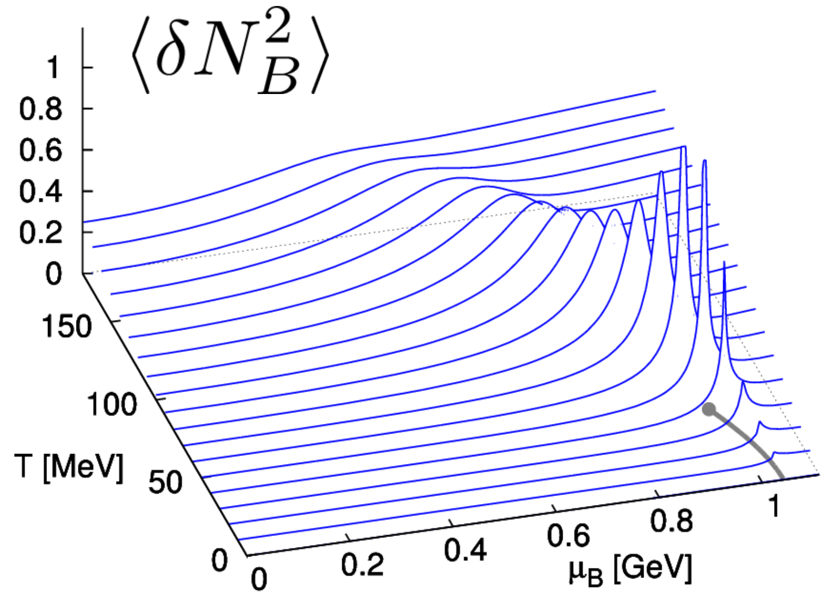


Cumulants

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

Fluctuation and QCD Critical Point

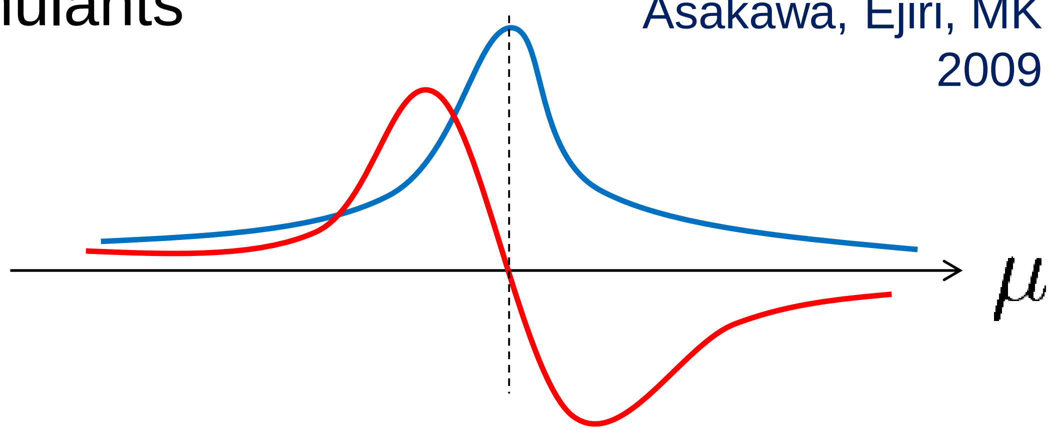
Fluctuations diverge at the QCD critical point



Asakawa, Ejiri, MK 2009

- Geometric interpretation to signs of higher order cumulants

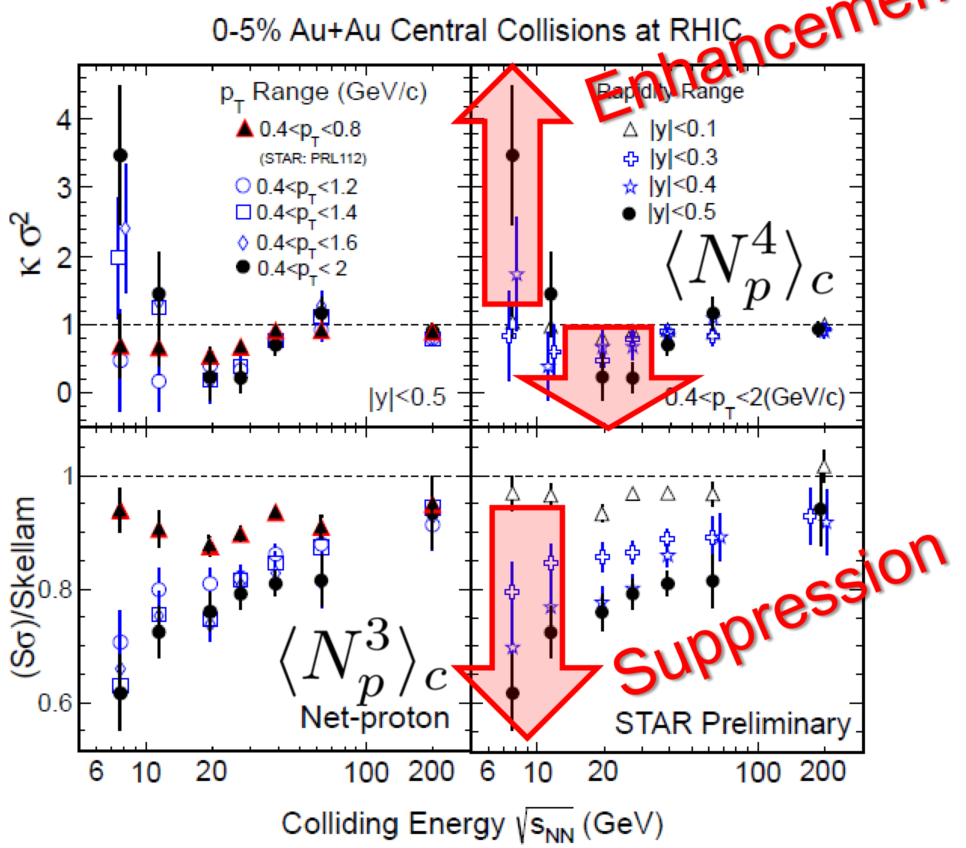
$$\langle \delta N^3 \rangle = T \frac{\partial \langle \delta N^2 \rangle}{\partial \mu}$$



- More severe divergence for higher-order cumulants

Stephanov, 2009

Higher-Order Cumulants



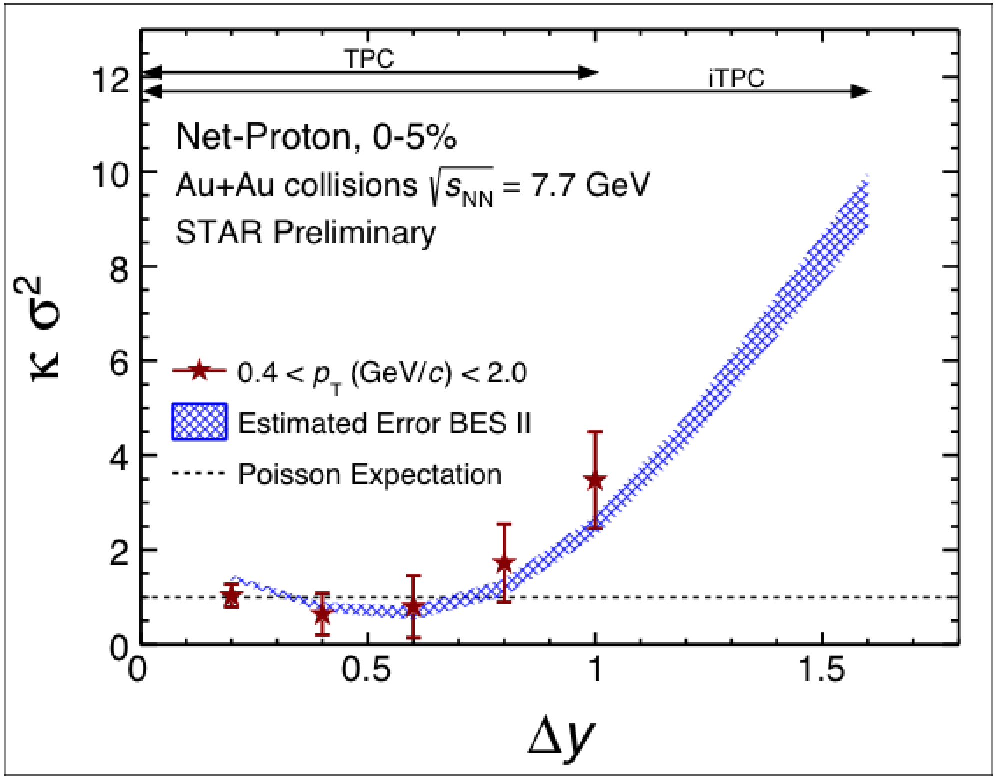
STAR Collab.
2010~

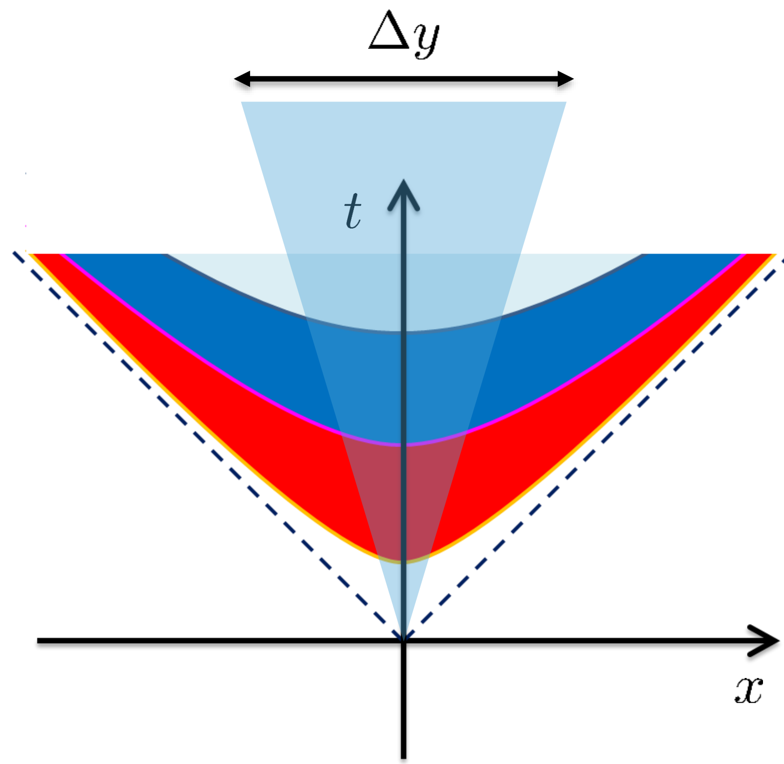
Enhancement & Suppression of non-Gaussian cumulants has been observed!

Have we measured critical fluctuations?

Rapdity-Window Dep. of Non-Gaussianity

STAR Collab. 2015

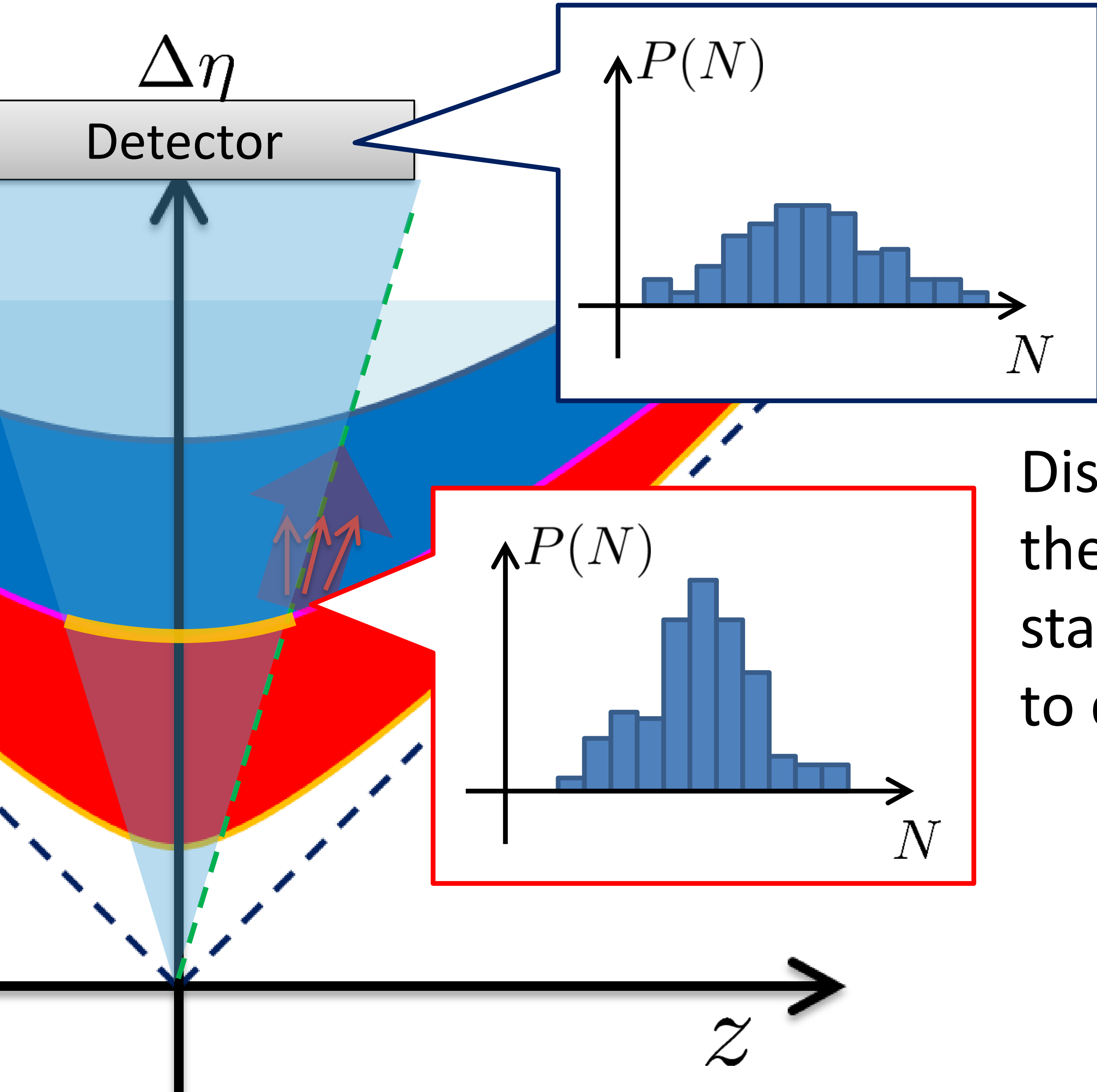




- ☐ Non-Gaussian Cumulants have been observed as a function of rapidity window Δη.
- ☐ Some results have non-monotonic Δη dependence.

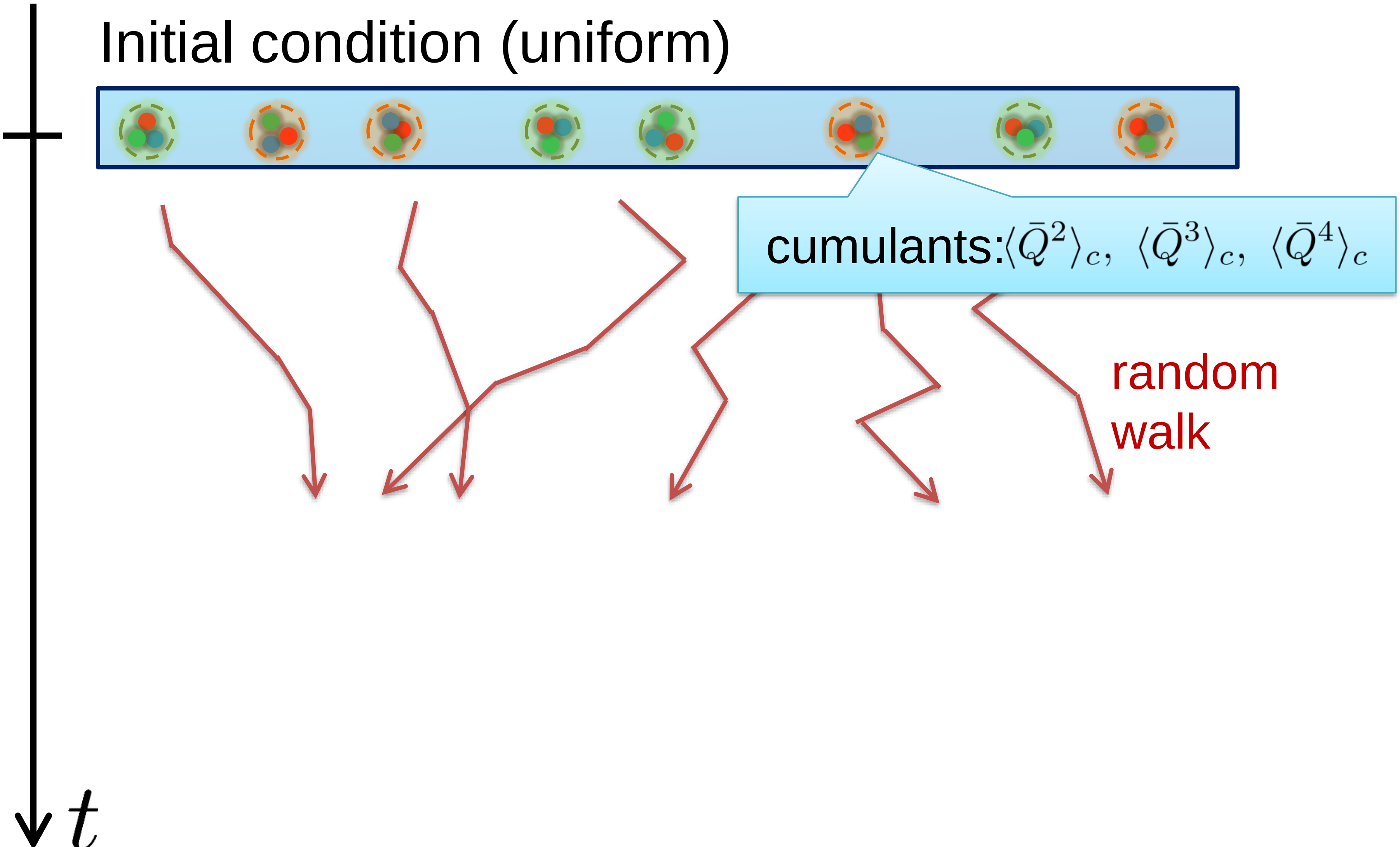
Diffusion of Fluctuations

Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000
Shuryak, Stephanov, 2001



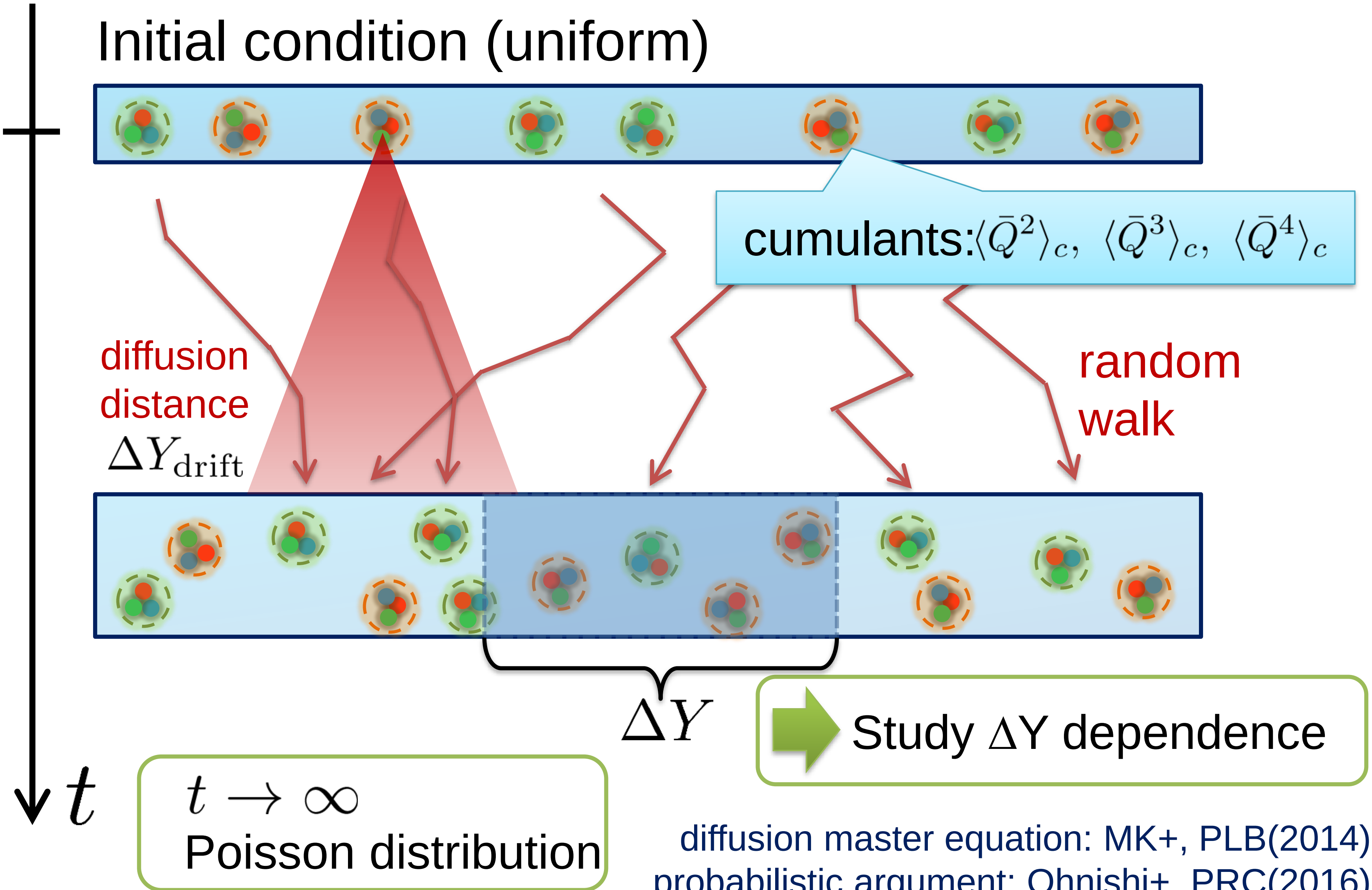
Distributions in Δη at the final state and early stage are different due to diffusion.

Non-Interacting Brownian Particle System



diffusion master equation: MK+, PLB(2014)
probabilistic argument: Ohnishi+, PRC(2016)

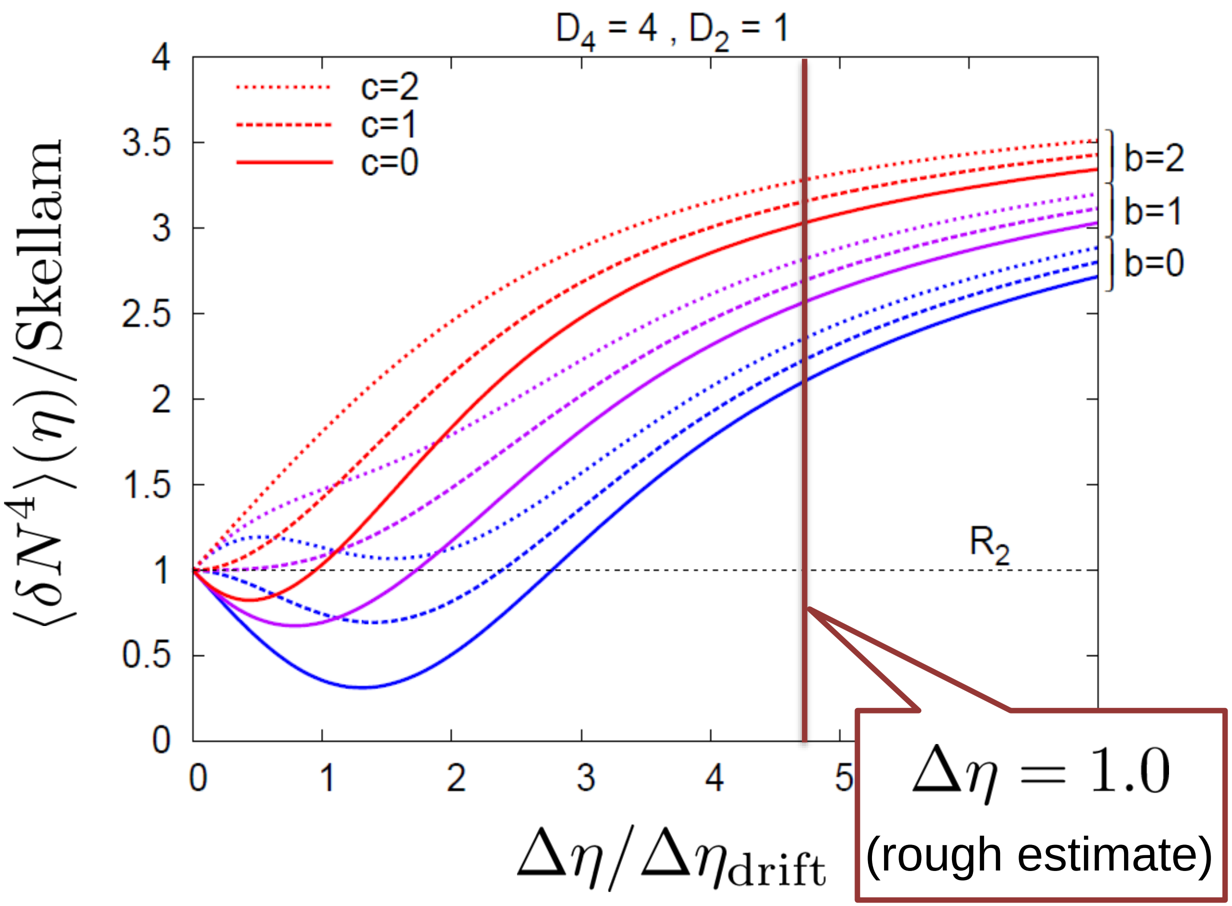
Non-Interacting Brownian Particle System



diffusion master equation: MK+, PLB(2014)
probabilistic argument: Ohnishi+, PRC(2016)

4^{th} order : w/ Critical Fluctuation

MK+ (2014)
MK (2015)



Initial Condition

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

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

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

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

- Higher order cumulants can behave non-monotonically.

Rapidity Window Dep.

4^{th}-order cumulant

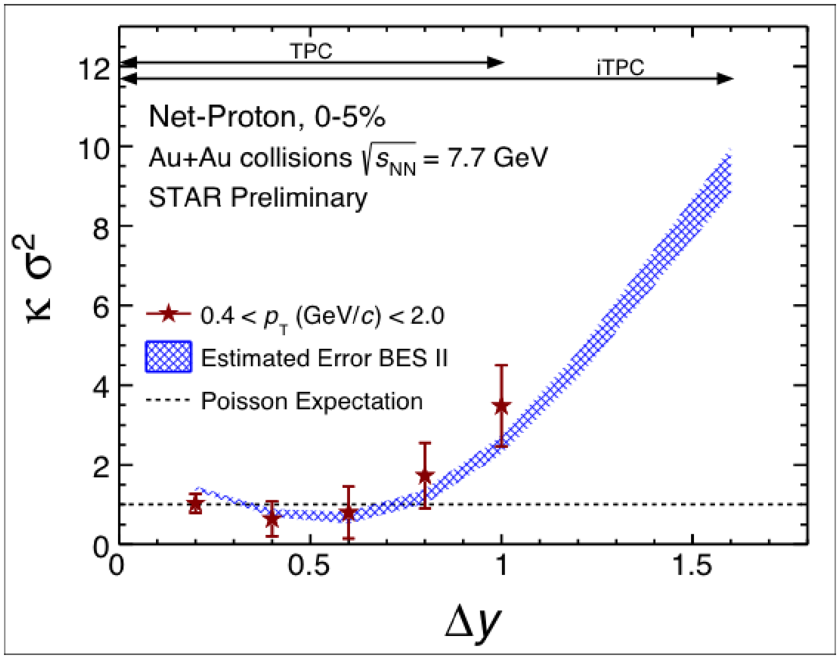
MK+, 2014
MK, 2015

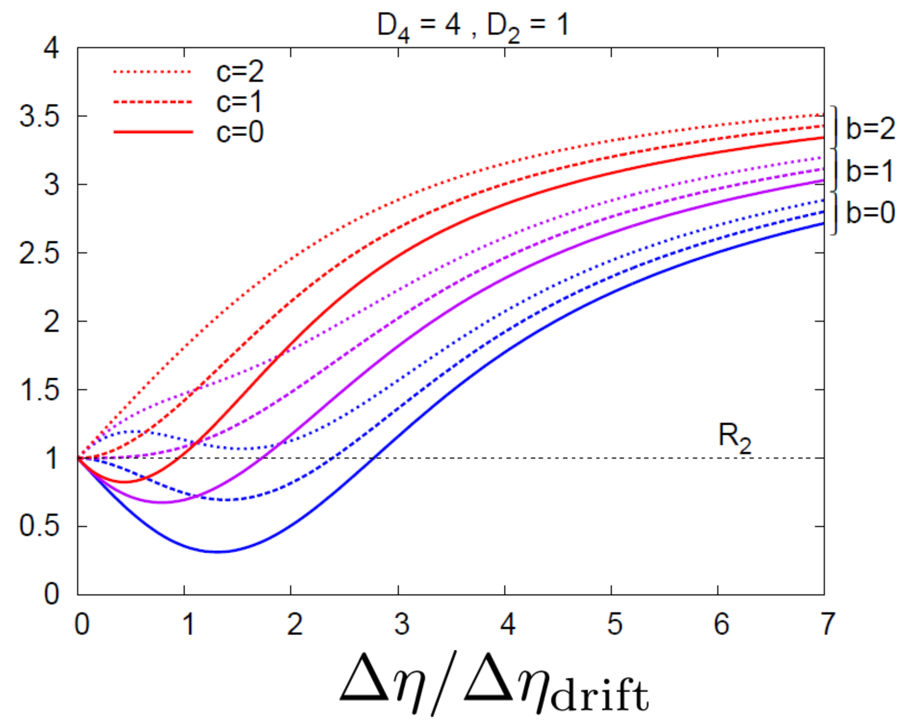
Initial Conditions

$$D_4 = \frac{\langle Q^4_{(\mathrm{net})}\rangle_c}{\langle Q_{(\mathrm{tot})}\rangle} \qquad b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})}\rangle_c}{\langle Q_{(\mathrm{net})}\rangle}$$

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

STAR Collab.

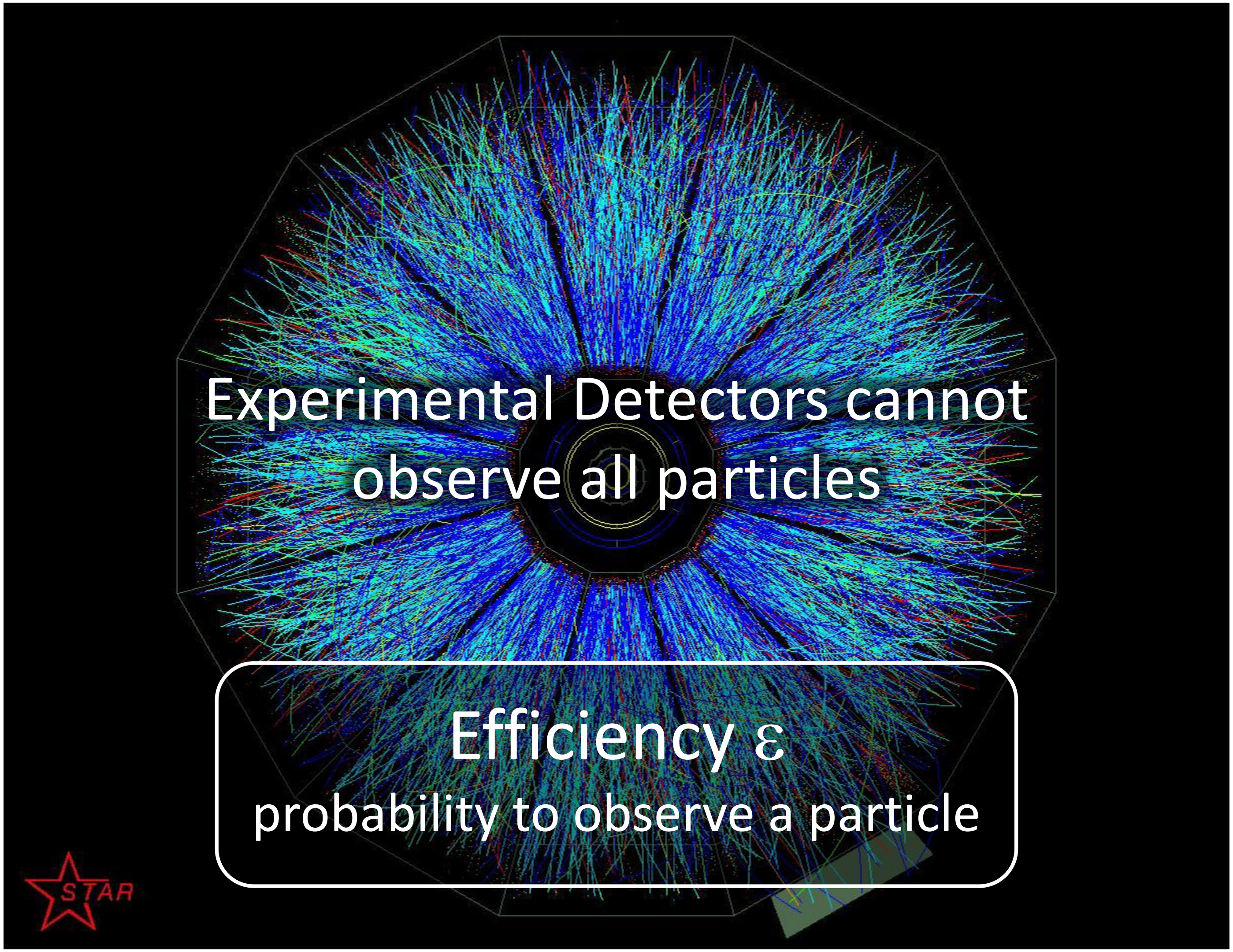




- ☐ Different initial conditions give rise to different characteristic Δη dependence. → Study initial condition
- ☐ Non-monotonic behaviors can appear in Δη dependence.

Finite volume effects: Sakaida+, PRC90 (2015)

Efficiency Correction



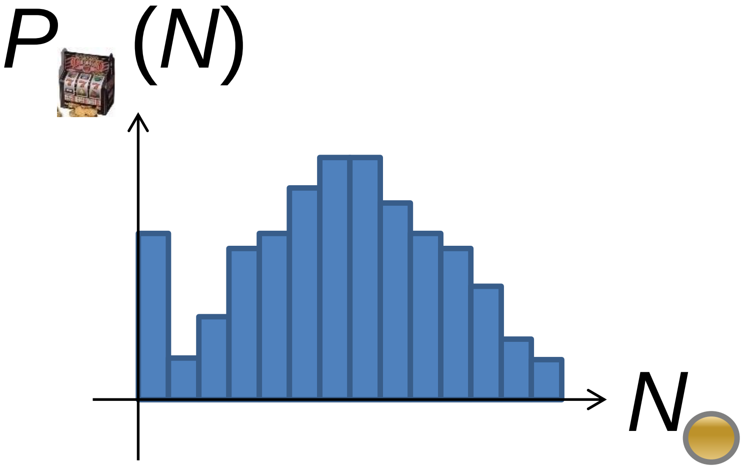
Experimental Detectors cannot observe all particles

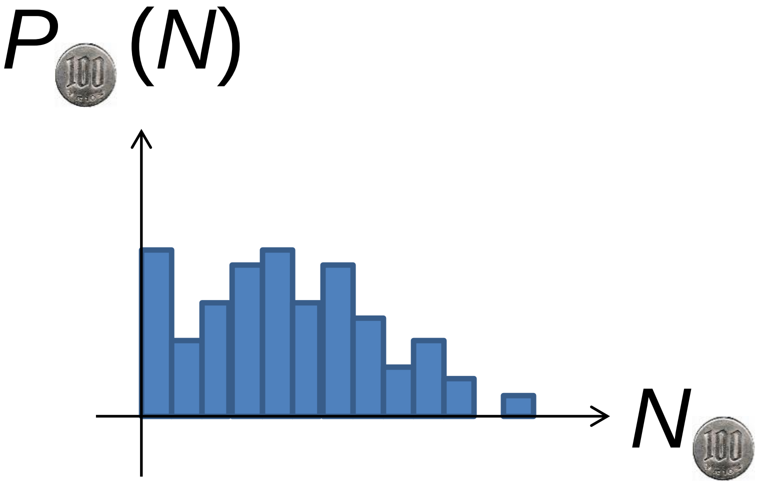
Efficiency ε

probability to observe a particle

Efficiency correction is indispensable in experimental analyses!

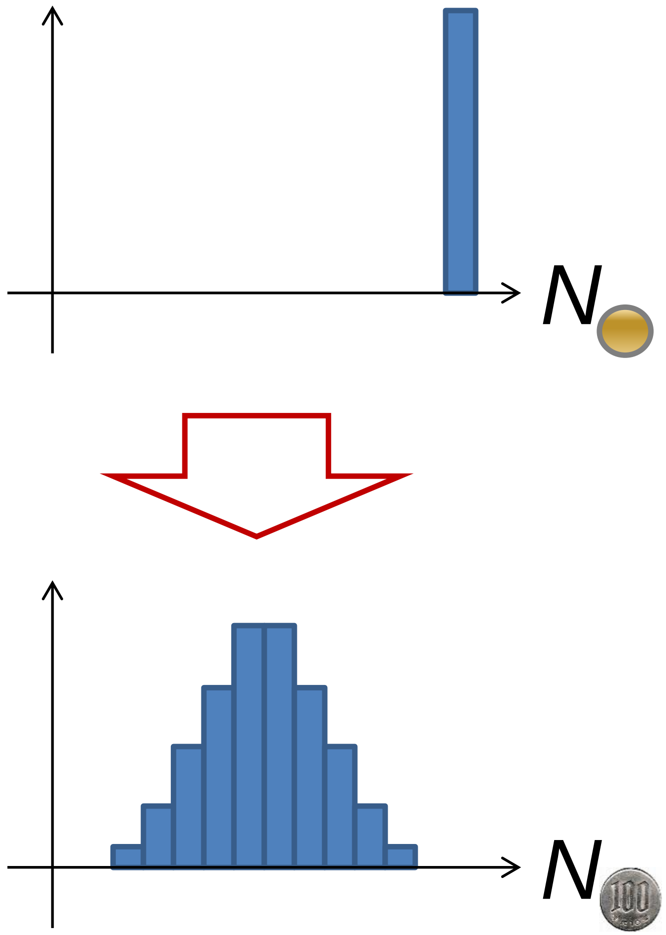
Slot Machine Analogy



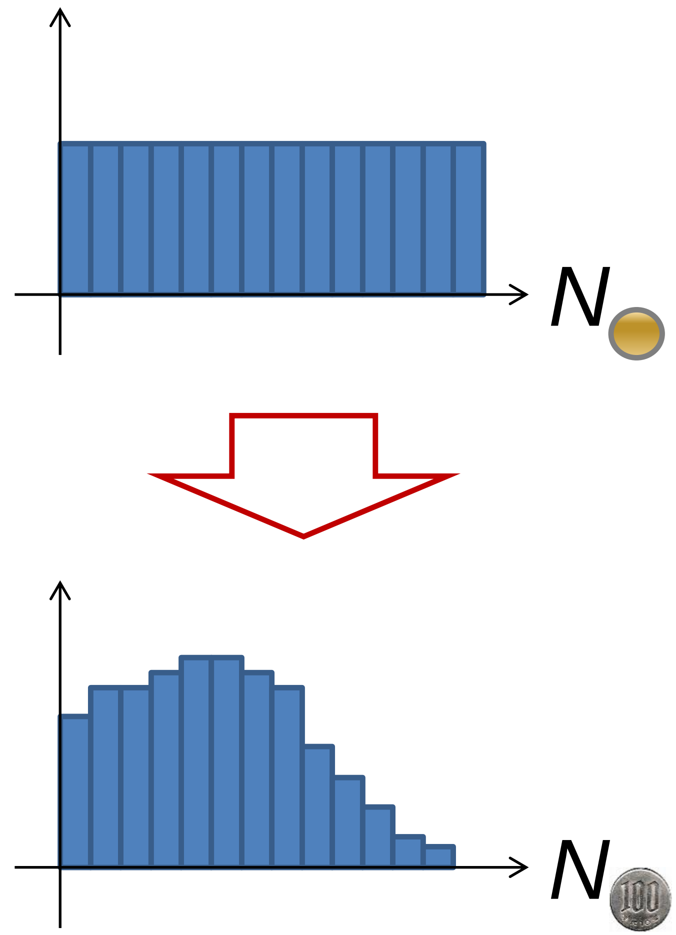


Slot Machine Analogy

Fixed # of coins



Constant probabilities



The Binomial Model

MK, Asakawa, 2012; 2012
Bzdak, Koch, 2012

When efficiency for individual particles are **independent**

$$P_{\rm obs}(n) = \sum_N B_p(n;N) P(N)$$

dist. func. of **observed** particle #

binmial dist. func.

dist. func. of **original** particle #

The cumulants connected with each other

$$\langle n^m \rangle_{\rm c} \Longleftrightarrow \langle N^m \rangle_{\rm c}$$

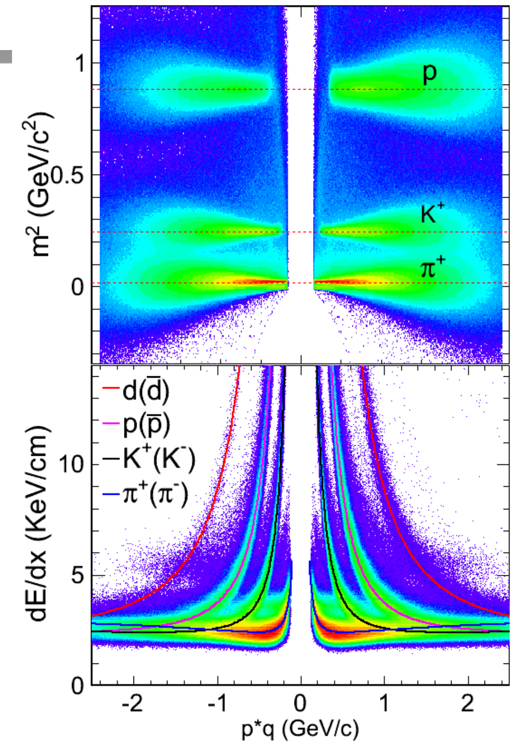
Caveat: Effects of nonvanishing correlations: Holtzman+ 2016

Multi-efficiency Bin Problem

- efficiency for proton ≠ anti-proton
- efficiency has p_T dependence

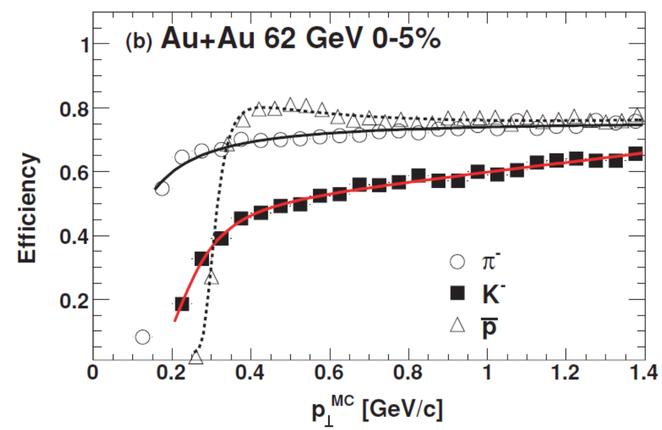
STAR, net proton

$$\begin{cases} p_T < 0.8\text{GeV} & \text{TPC } \varepsilon\sim 80\% \\ p_T > 0.8\text{GeV} & \text{TPC+TOF } \varepsilon\sim 50\% \end{cases}$$



- Multi-variable efficiency correction

A method was proposed, but too large numerical costs



Luo, 2014
Bzdak, Koch, 2015

Efficient Formulas for Efficiency Correction

☐ Cumulant expansion method MK,2016

$$
\begin{aligned}
\langle Q\rangle_c =& \langle\!\langle q_{(1)}\rangle\!\rangle_c, \\
\langle Q^2\rangle_c =& \langle\!\langle q_{(1)}^2\rangle\!\rangle_c - \langle\!\langle q_{(2)}\rangle\!\rangle_c, \\
\langle Q^3\rangle_c =& \langle\!\langle q_{(1)}^3\rangle\!\rangle_c - 3\langle\!\langle q_{(2)}q_{(1)}\rangle\!\rangle_c + \langle\!\langle 3q_{(2,1|2)} - q_{(3)}\rangle\!\rangle_c, \\
\langle Q^4\rangle_c =& \langle\!\langle q_{(1)}^4\rangle\!\rangle_c - 6\langle\!\langle q_{(2)}q_{(1)}^2\rangle\!\rangle_c + 12\langle\!\langle q_{(2,1|2)}q_{(1)}\rangle\!\rangle_c \\
& + 6\langle\!\langle q_{(1,1|2)}q_{(2)}\rangle\!\rangle_c - 4\langle\!\langle q_{(3)}q_{(1)}\rangle\!\rangle_c - 3\langle\!\langle q_{(2)}^2\rangle\!\rangle_c \\
& + \langle\!\langle -18q_{(2,1,1|2,2)} + 6q_{(2,1,1|3)} + 4q_{(3,1|2)} \\
& + 3q_{(2,2|2)} - q_{(4)}\rangle\!\rangle_c,
\end{aligned}
$$

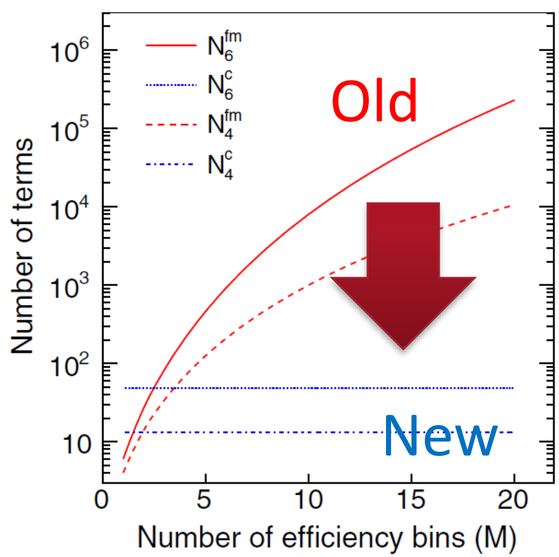
Number of terms is drastically reduced!

Substantial reduction of numerical cost

☐ Factorial cumulant method Nonaka, MK, Esumi, 2017

Systematic procedure with the use of factorial cumulants

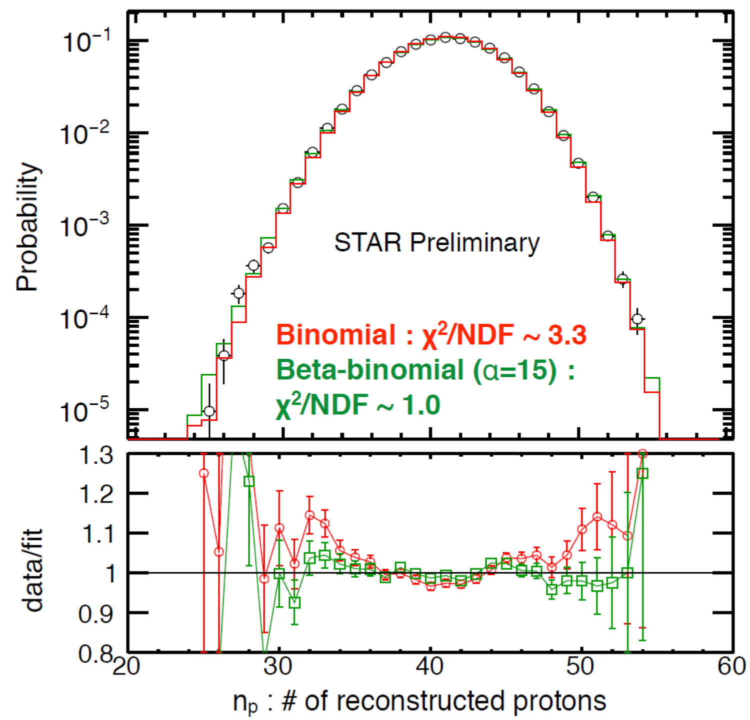
Numerical Cost



Violation of Binomial Model

Typical detectors have clear deviation from the binomial response.

Estimates of systematic uncertainty arising from this deviation are needed!



☐ General procedure for efficiency correction

Nonaka, MK, Esumi, 2018

$$P_{\rm obs}(\vec{n}) = \sum_{N} R(\vec{n};\vec{N}) P_{\rm true}(\vec{N})$$

- Efficiency correction for **any** response matrix R(n,N)
- We must understand the property of the detector

Summary

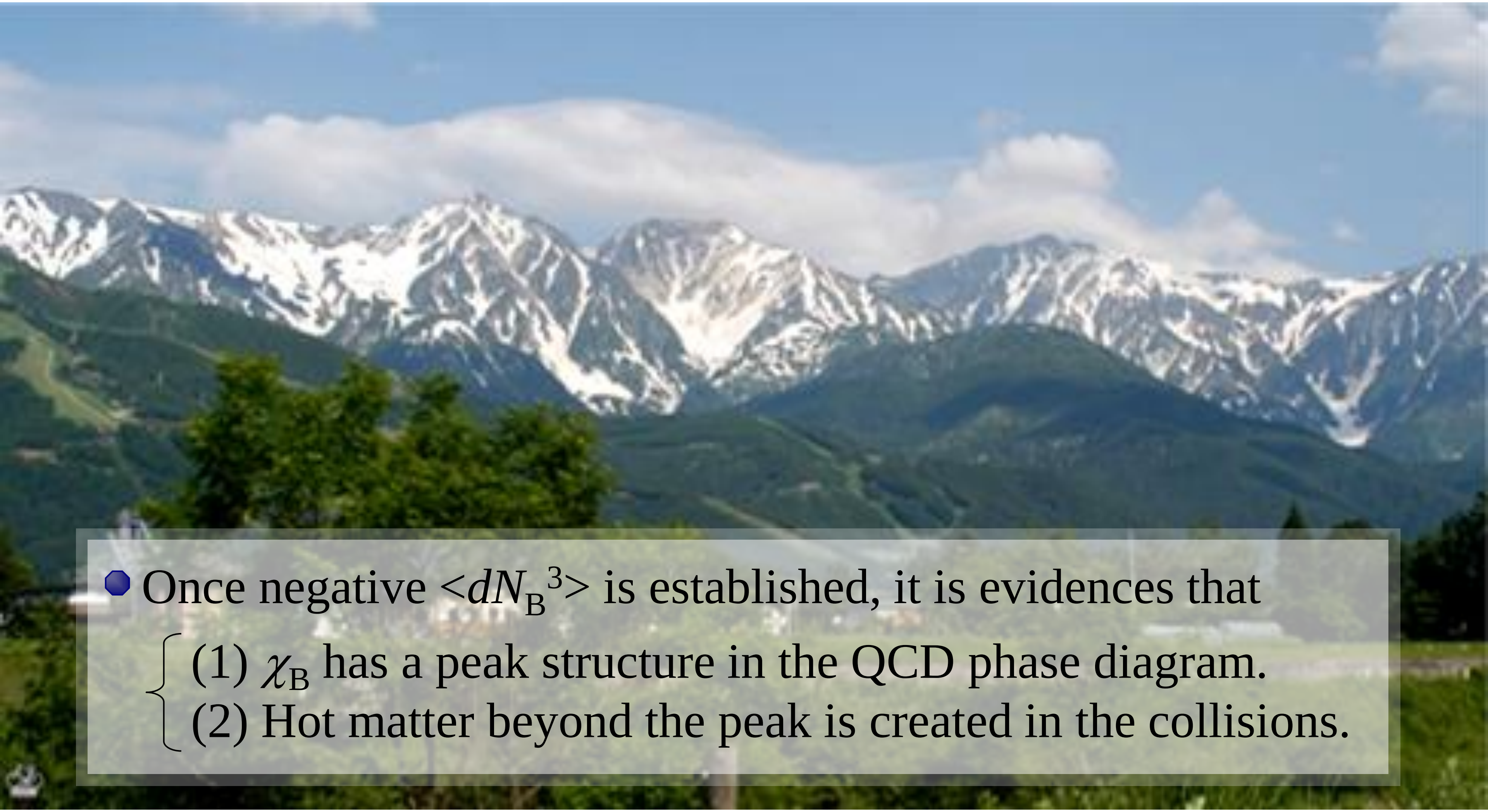
- Exploring dense medium in relativistic heavy-ion collisions is one of the hottest topics in this field. Many facilities including J-PARC-HI will start future experiments soon!

- Fluctuations are promising observables for the search for the phase structure of QCD. However, further detailed studies are needed.

- High-intensity beam at J-PARC-HI will play a crucial role for the search for the QCD phase diagram in the future.

Impact of Negative Third Moments

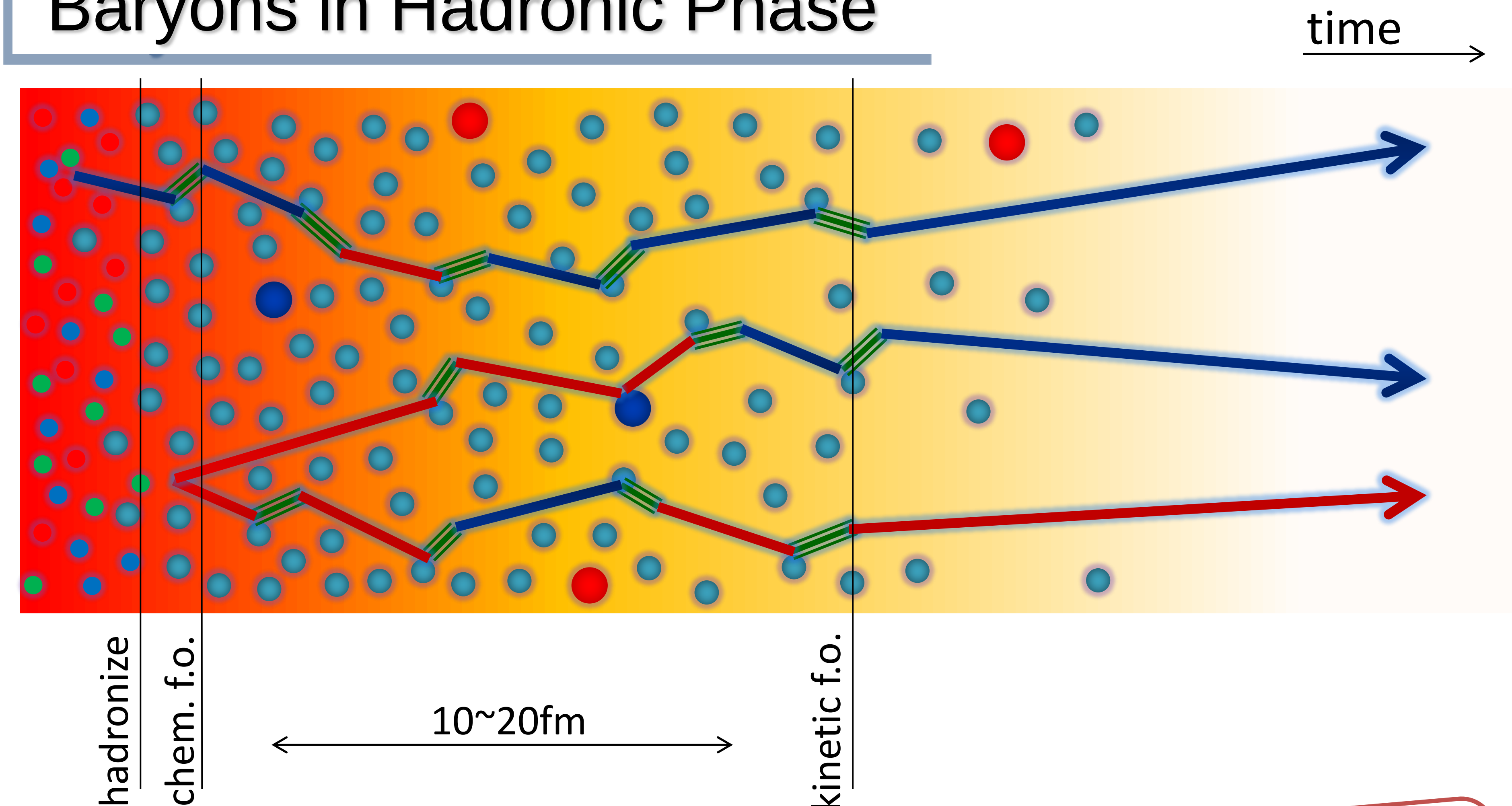
Asakawa, Ejiri, MK, 2009

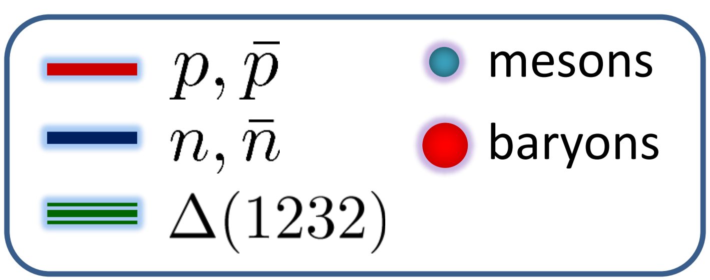


- Once negative $<dN_B^3>$ is established, it is evidences that
  - (1) χ_B has a peak structure in the QCD phase diagram.
  - (2) Hot matter beyond the peak is created in the collisions.

- •**No** dependence on any specific models.
  •Just the sign! **No** normalization (such as by N_{ch}).

Baryons in Hadronic Phase





Baryons behave like
Brownian pollens in water