J-PARC Heavy-Ion Program and Search of the QCD Critical Point

Masakiyo Kitazawa

(Osaka U.)

CSQCD-VI, JINR, Dubna, Russia, Sep. 27, 2017

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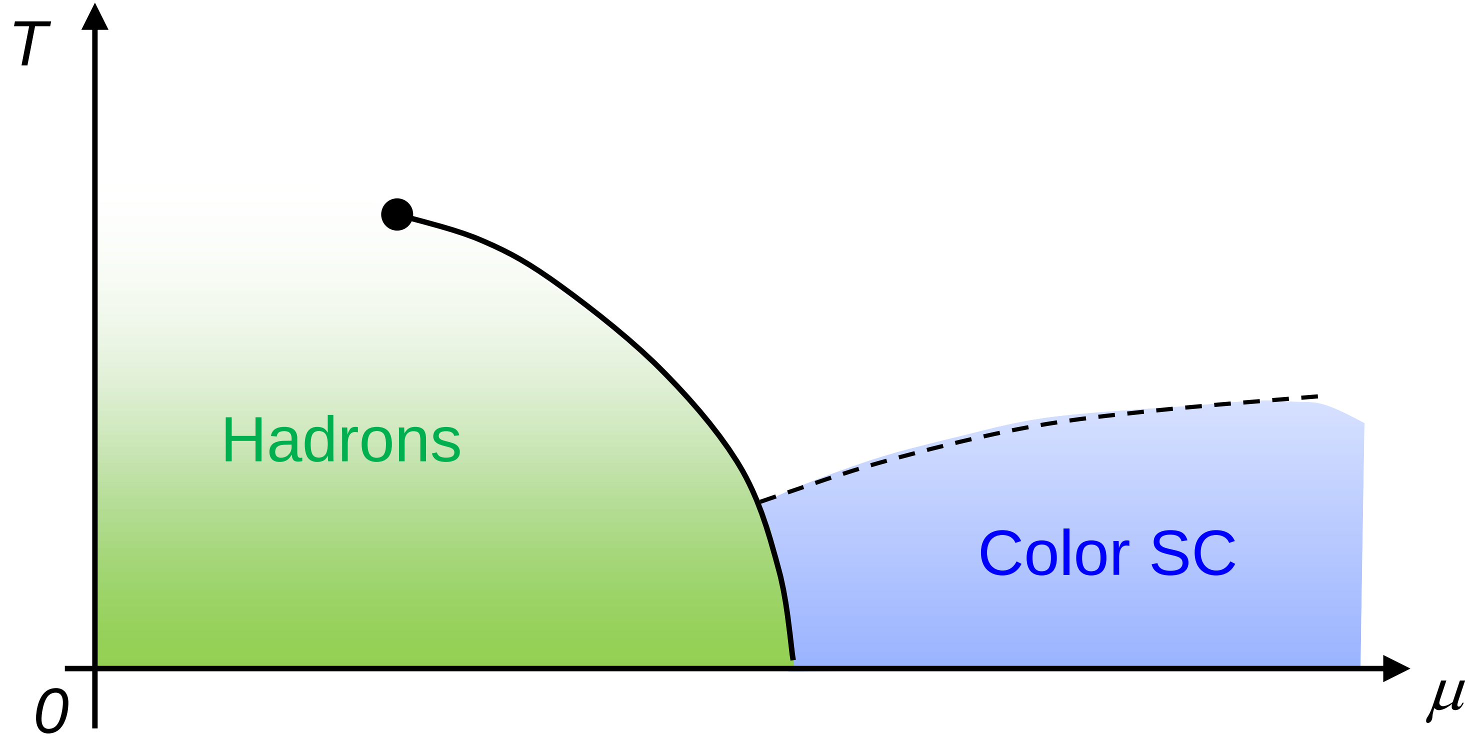
Two topics covered in this talk

① J-PARC Heavy-Ion Program

② Exp. Search for QCD-CP with fluctuations

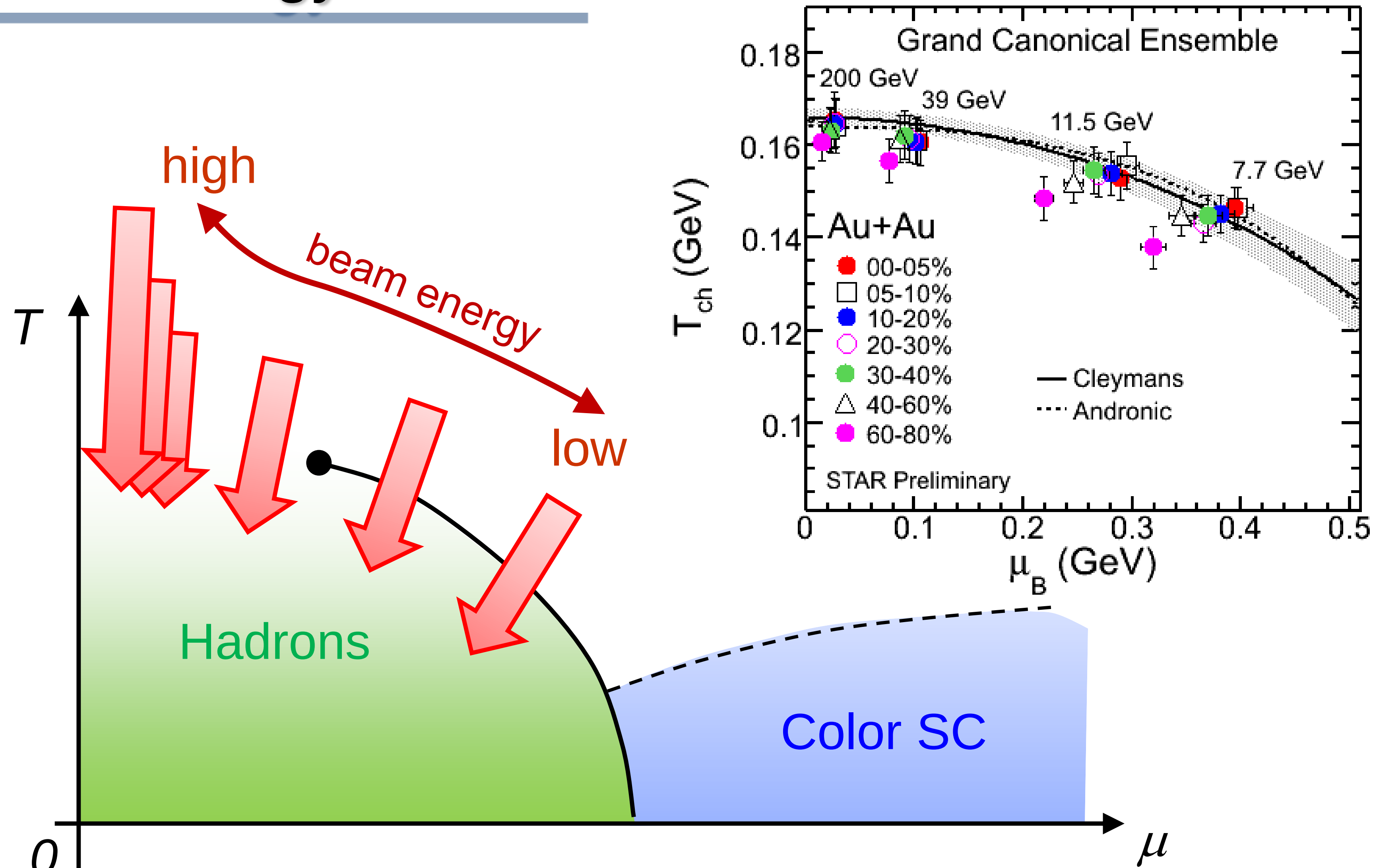
CSQCD-VI, JINR, Dubna, Russia, Sep. 27, 2017

Beam-Energy Scan



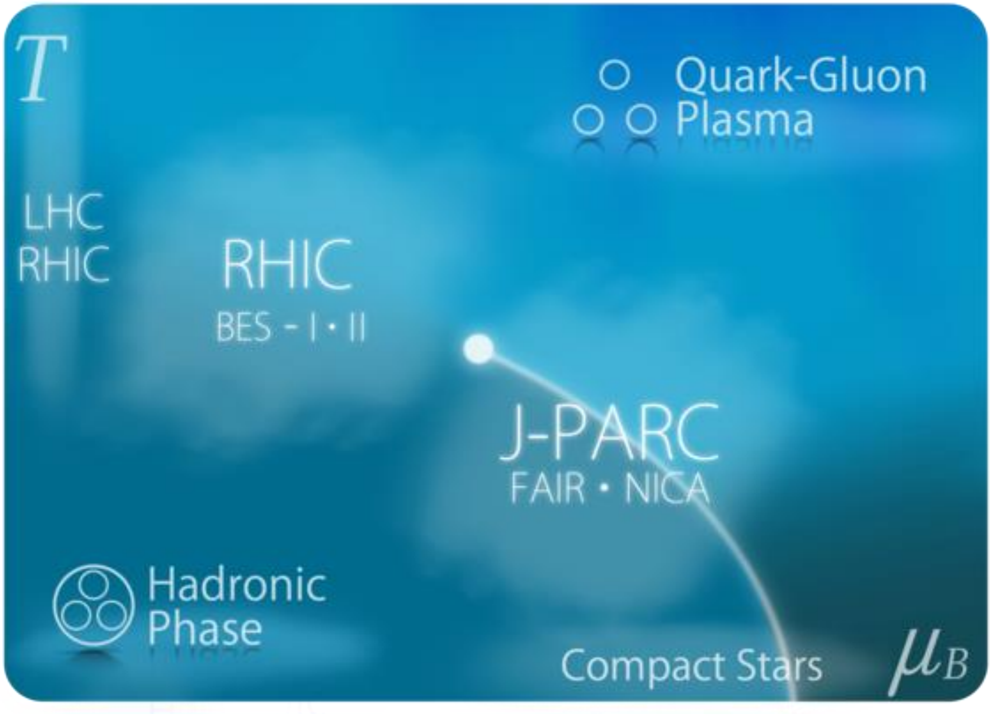
Beam-Energy Scan

STAR 2012



Search for QCD phase structure / critical point

J-PARC Heavy-Ion Program (J-PARC-HI)



J-PARC

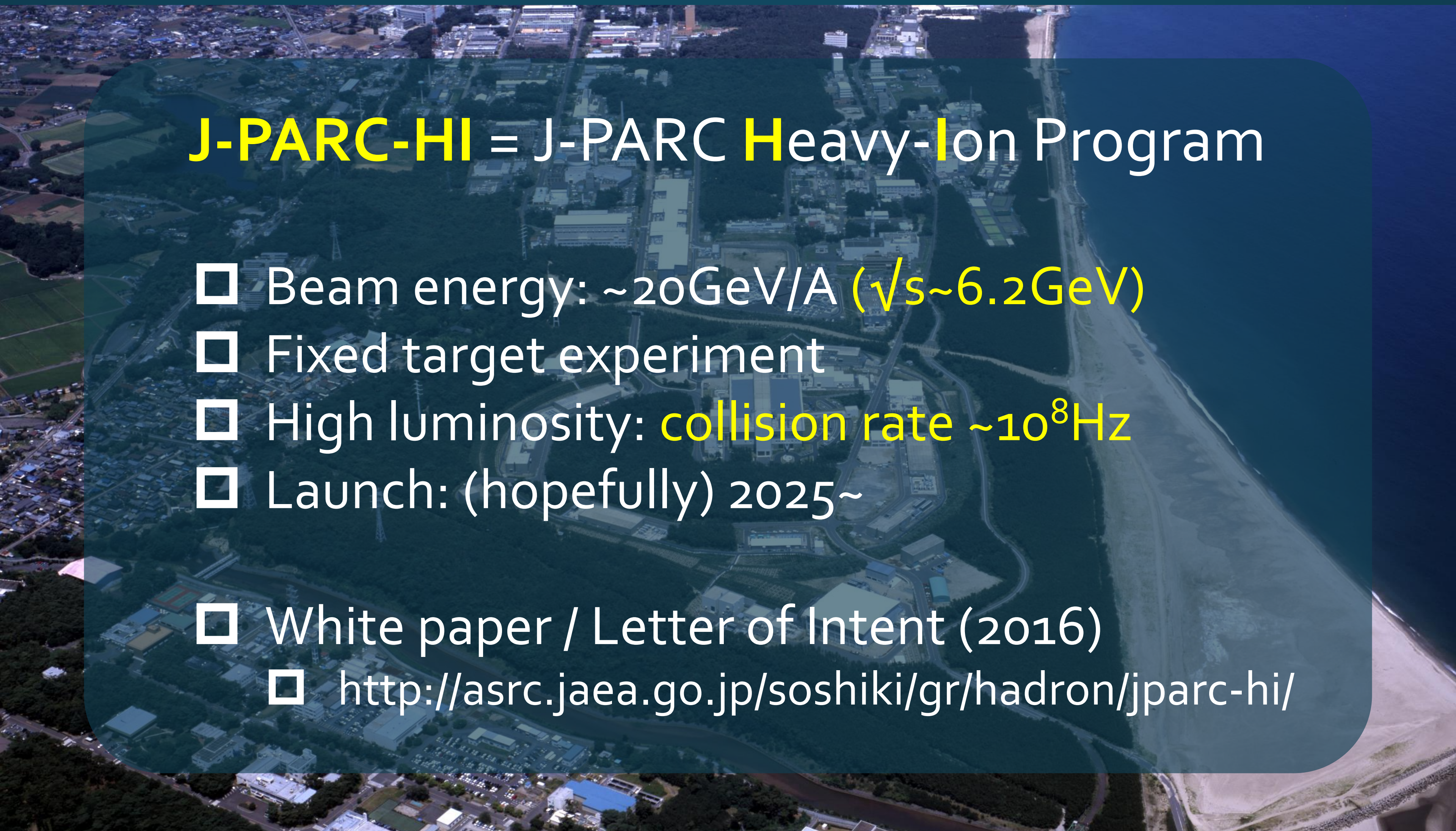
Japan Proton Accelerator Research Complex

High-power Proton Beam

- T2K(Tokai-to-Kaminoka)
- Hadron physics
- etc…

J-PARC

Japan Proton Accelerator Research Complex

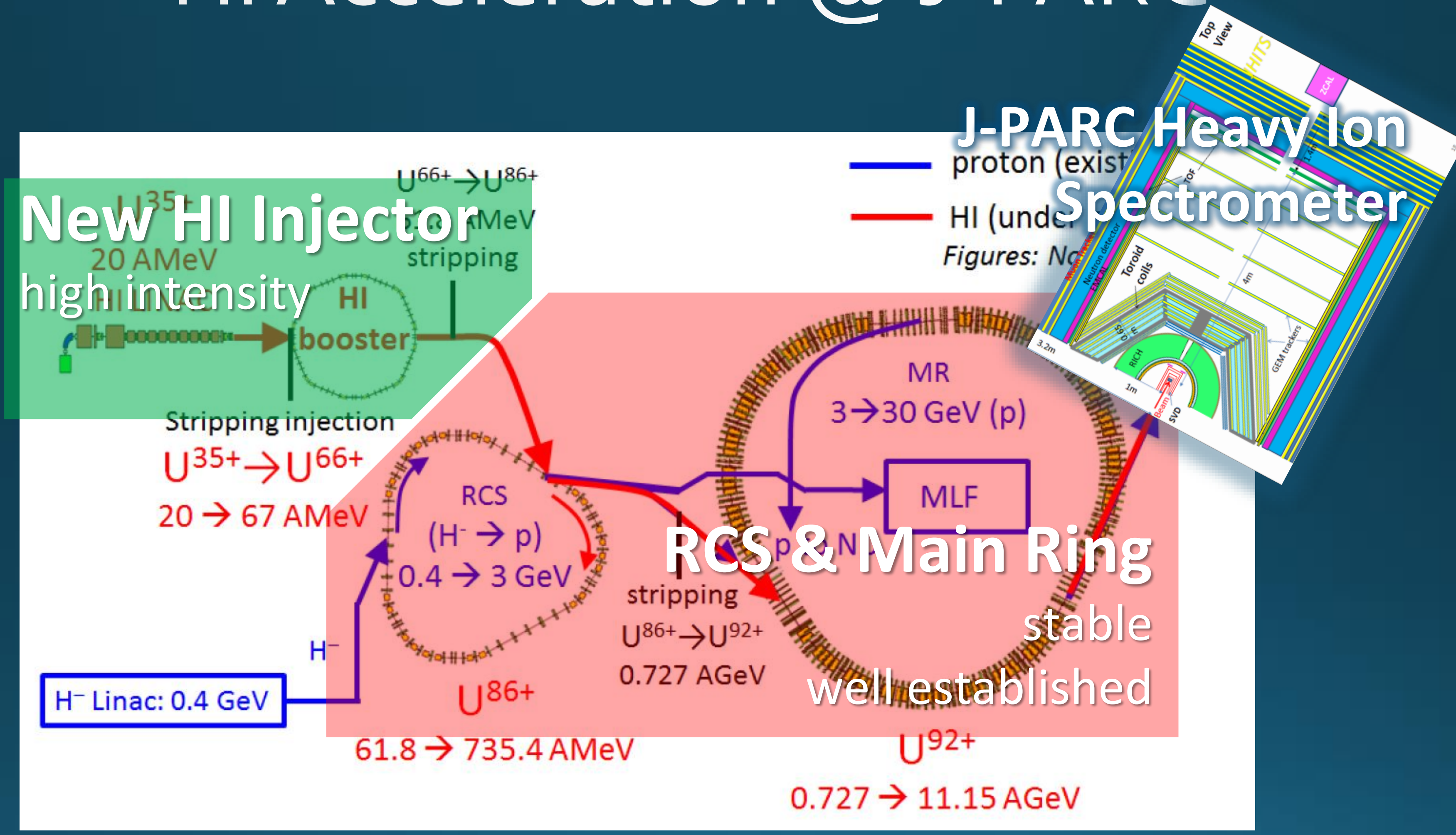


J-PARC-HI = J-PARC **H**eavy-**I**on Program

- Beam energy: ~20GeV/A ($\sqrt{s}$~6.2GeV)
- Fixed target experiment
- High luminosity: collision rate ~10^8Hz
- Launch: (hopefully) 2025~

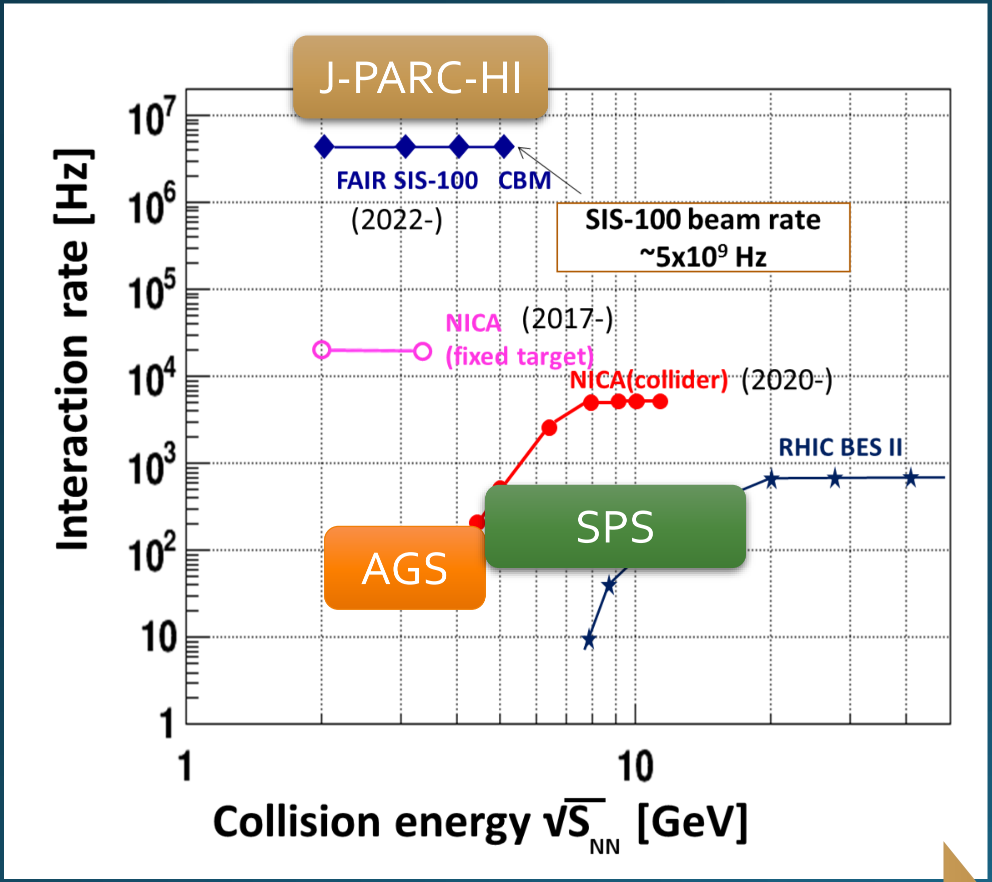
- White paper / Letter of Intent (2016)
  - http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

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

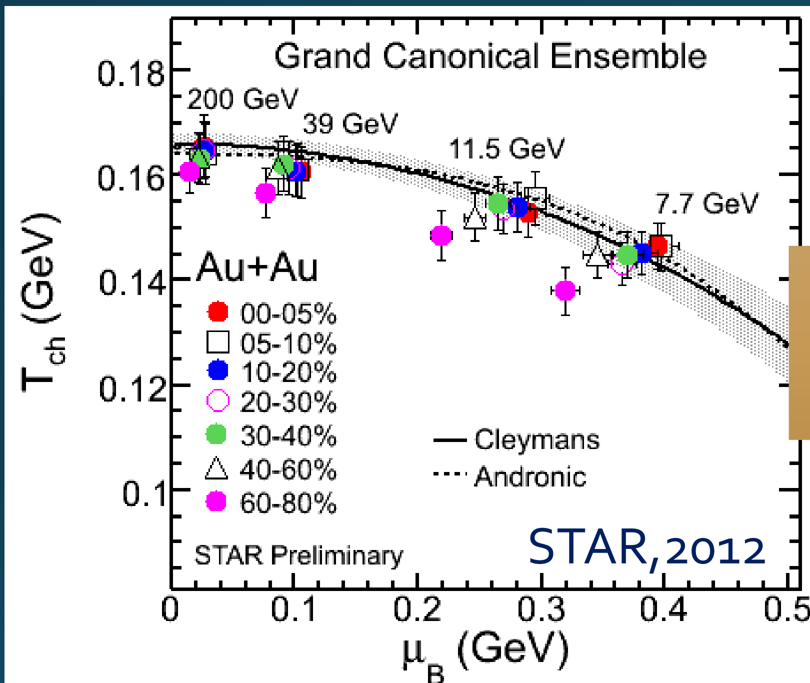
5-order higher than AGS,SPS

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

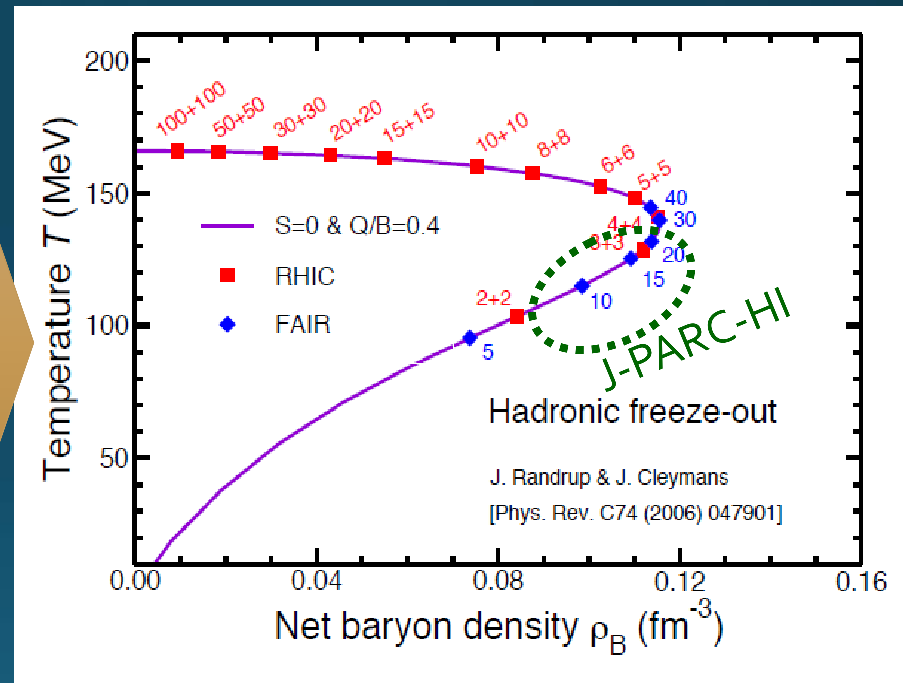
- ☐ High-statistical exp.
- ☐ various event selections
- ☐ higher order correlations
- ☐ search of rare events

Beam-Energy Scan

T, μ from particle yield



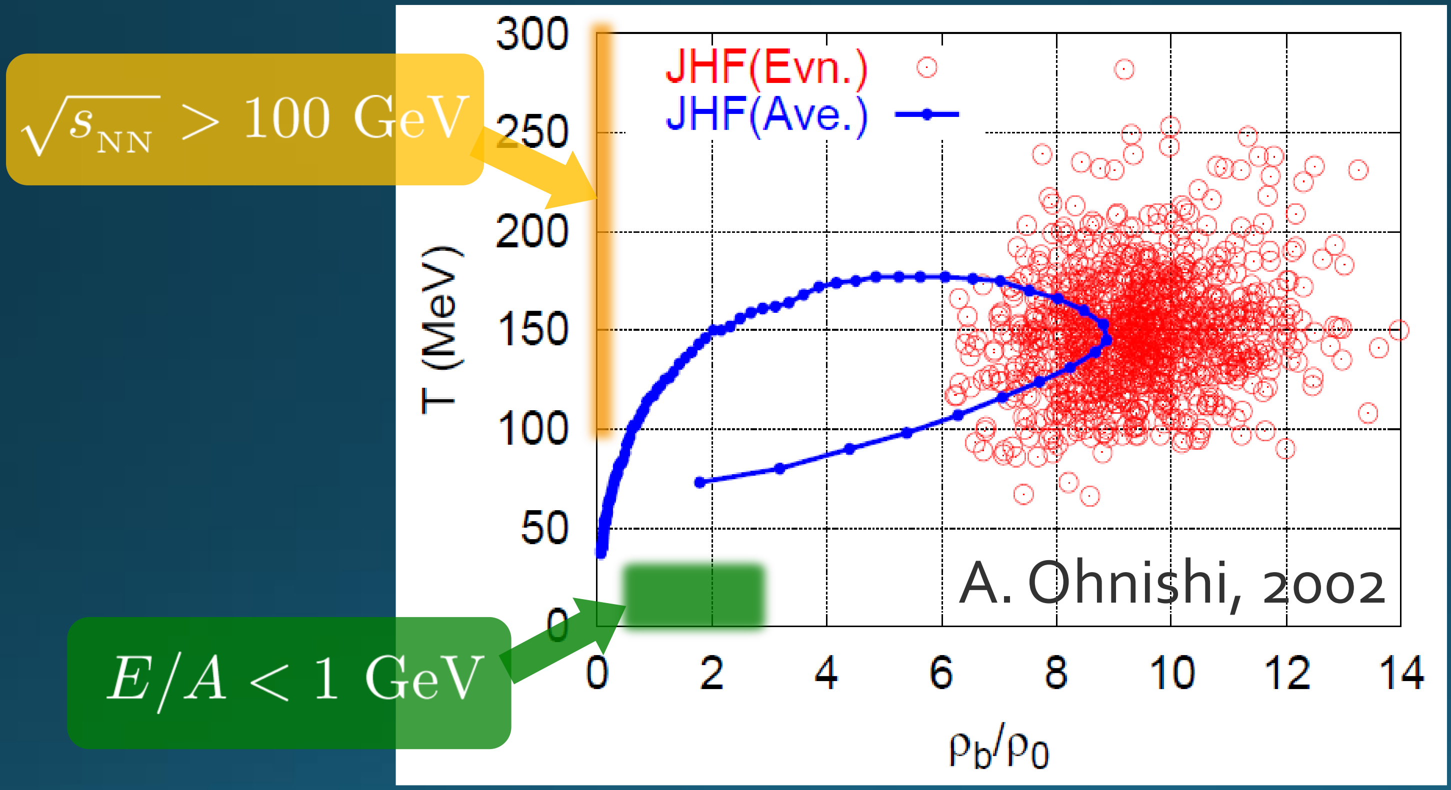
Translation to baryon density



J-PARC energy = highest baryon density

Maximum Density

Time evolution in *T*-ρ plane by JAM

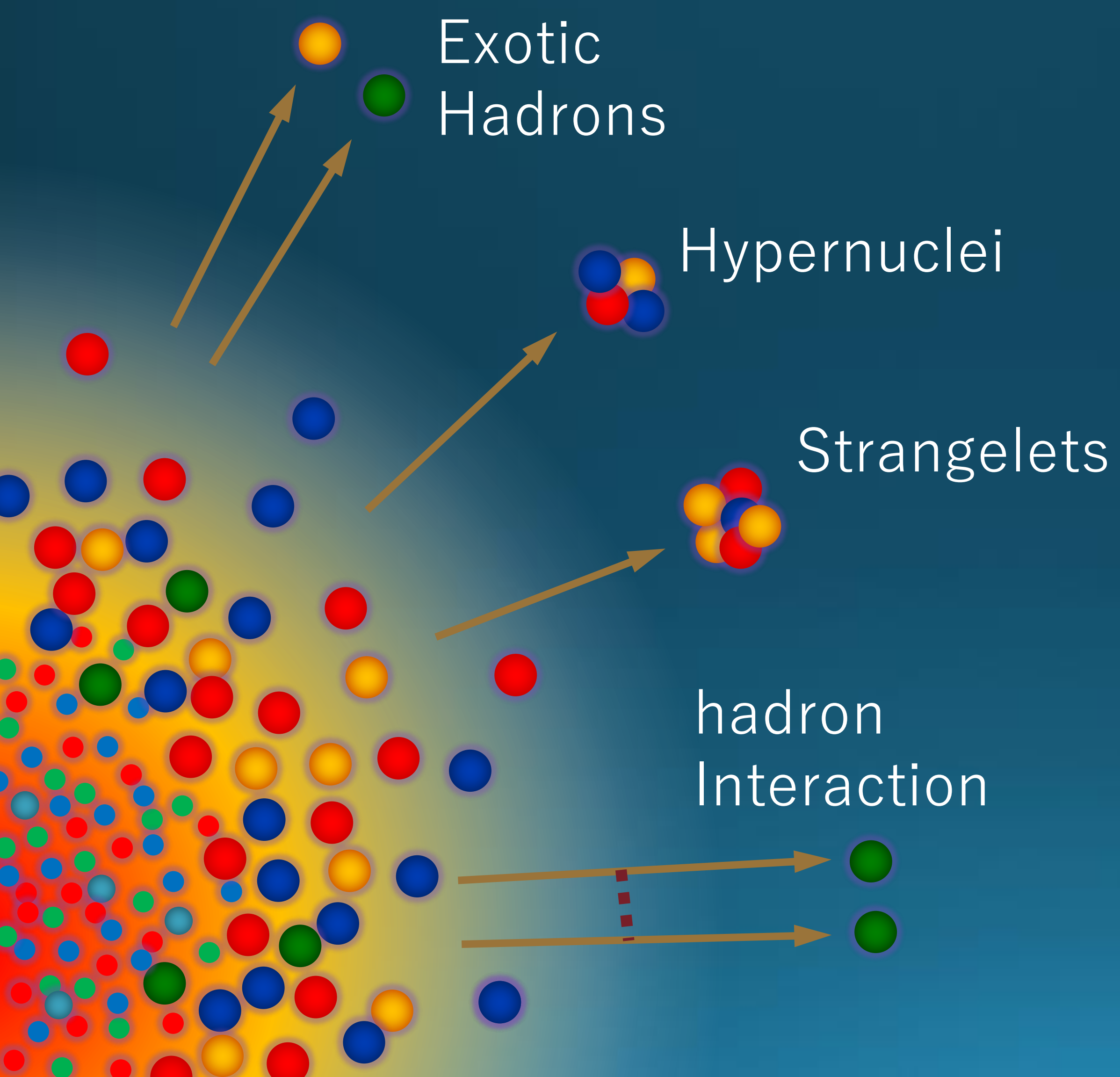


$E/A = 20\text{GeV}$

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

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

Search of Rare Events



- High density
- High luminosity
- High strange yield

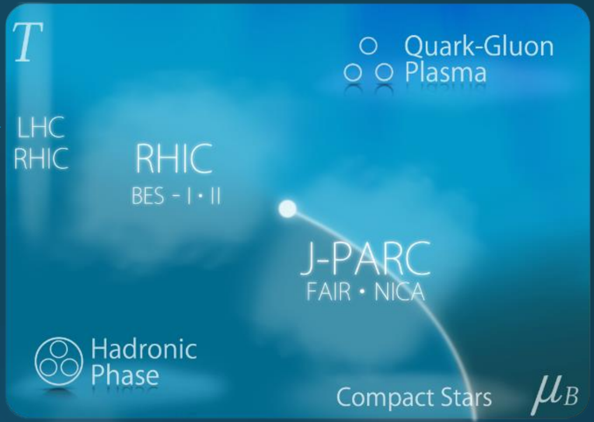
Rare-event Factory

- creation
- properties
- interaction

Future Plan

Recent activities:

June 2016 White Paper uploaded
July 2016 Submission of LOI
Aug. 2016 International Workshop
Sep. 2016 Symposium @ JPS meeting

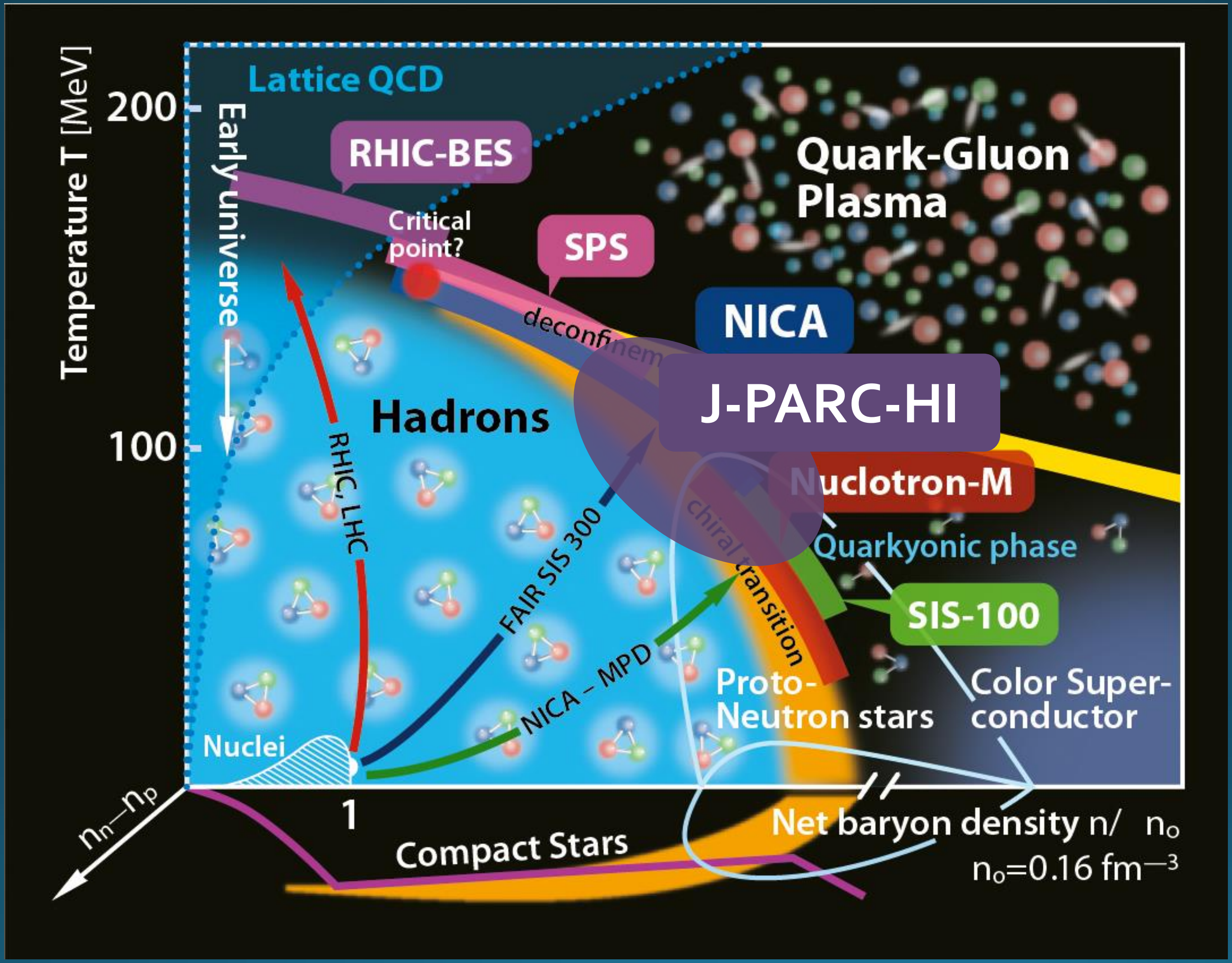


Visit J-PARC-HI Web Page
http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

Future plan:

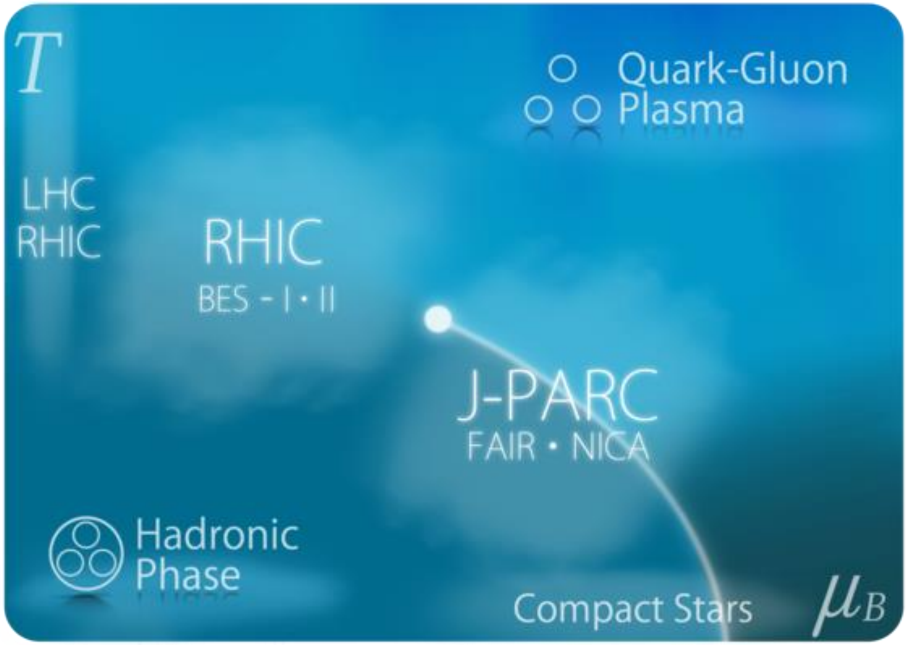
2020 **Funding request to MEXT**
2021 **Earliest approval of funding**
2021-2022 Construction of HI Injector
2021-2023 Construction of HI injection system in RCS
2023-2024 Construction of HI spectrometer
2025 First collision

To Summarize this part…



One more experimental facility!

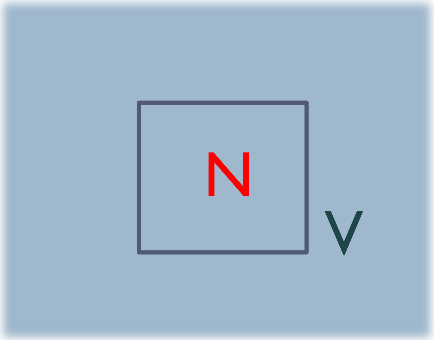
Search for QCD Critical Point with Fluctuations

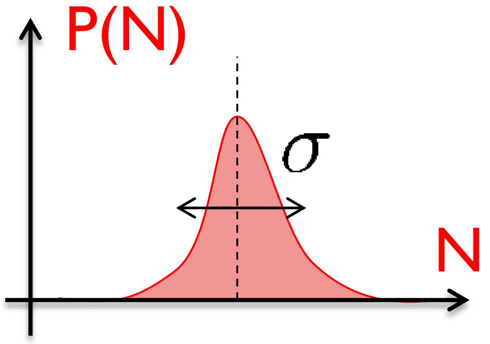


Sakaida, Asakawa, Fujii, MK, Phys. Rev. C95, 064509 (2017)
Asakawa, MK, Prog. Part. Nucl. Phys. 90, 299 (2016)
Ohnishi, MK, Asakawa, Phys. Rev. C94, 044905 (2016)
MK, Nucl. Phys. A942, 65 (2015)
MK, Asakawa, Ohno, Phys. Lett. B728, 386 (2014)

Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.





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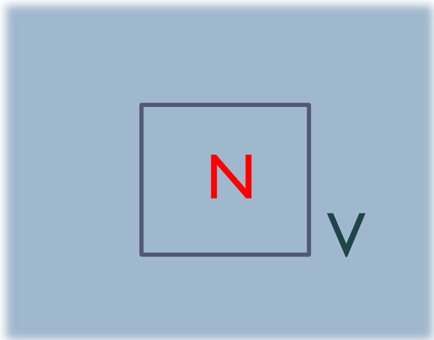
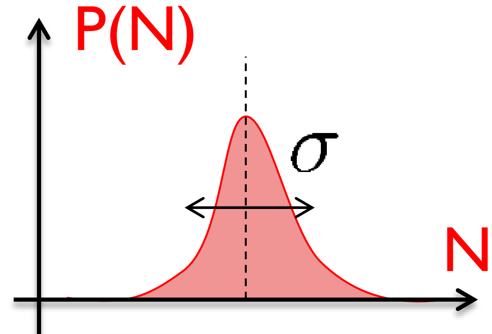




$$\delta N = N - \langle N \rangle$$

- Variance: $\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$
- Skewness: $S = \frac{\langle \delta N^3 \rangle}{\sigma^3}$
- Kurtosis: $\kappa = \frac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$

Non-Gaussianity

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

A Coin Game

① Bet 25 Euro

② You get head coins of

A. 50 x 1 Euro

B. 25 x 2 Euro

Same expectation value.

A Coin Game

① Bet 25 Euro
② You get head coins of

A. 50 x 1 Euro

B. 25 x 2 Euro

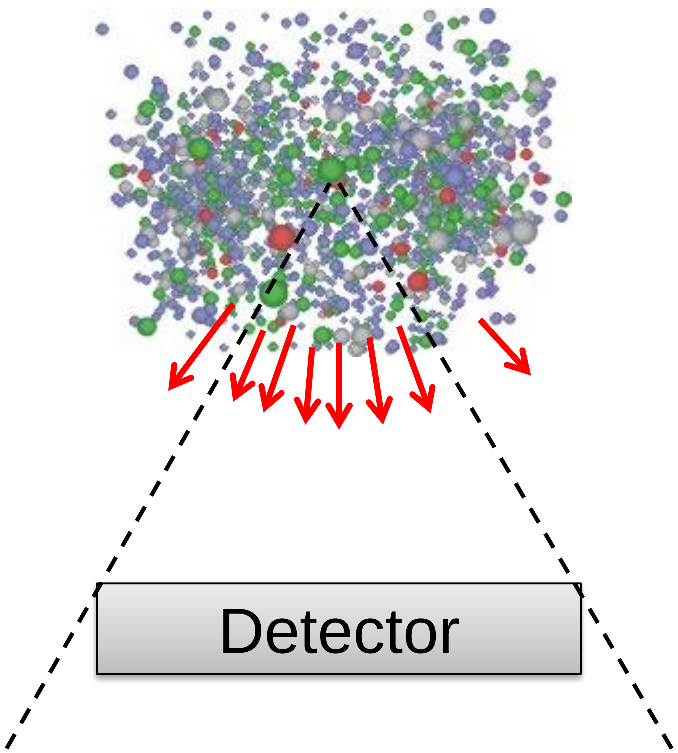
C. 1 x 50 Euro

Same expectation value.
But, different fluctuation.

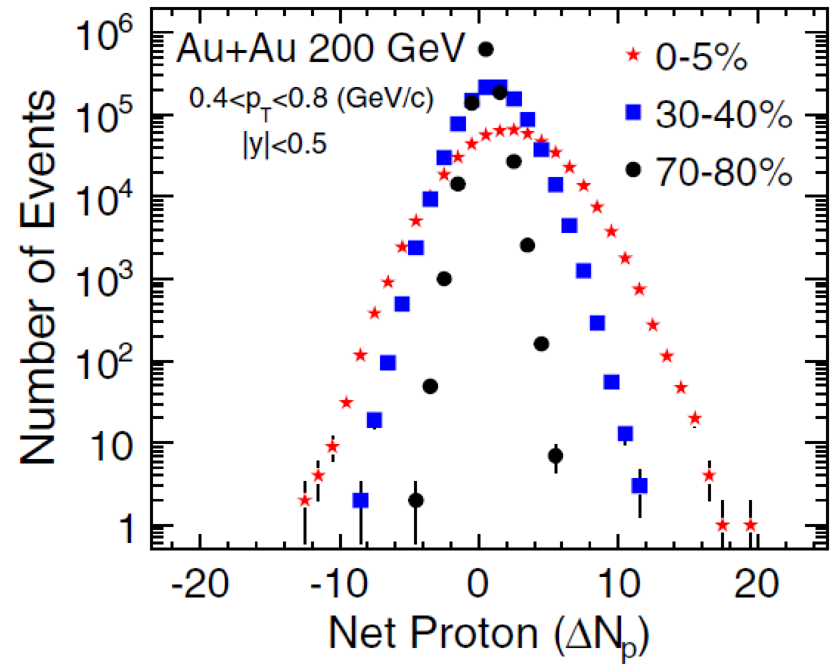
Event-by-Event Fluctuations

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

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



STAR, PRL**105** (2010)

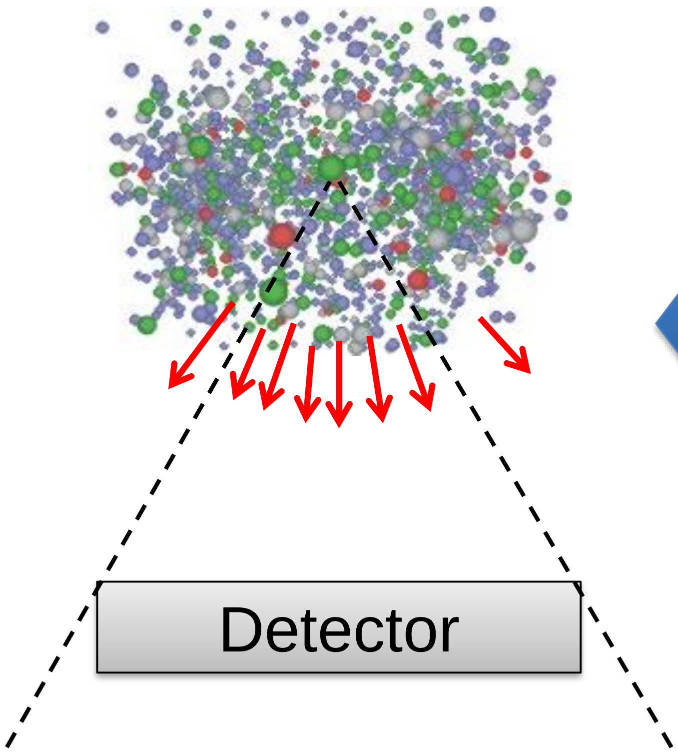


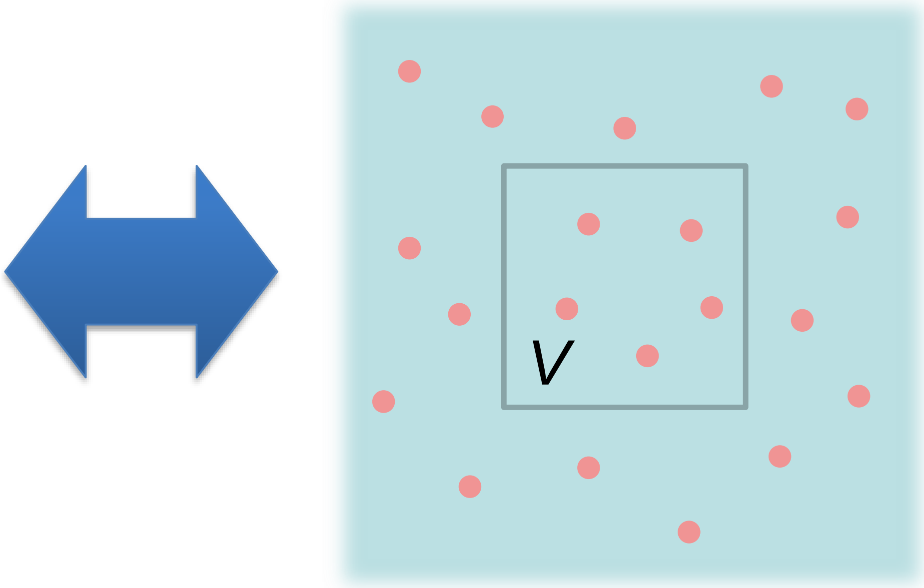
Cumulants

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

Event-by-Event Analysis @ HIC

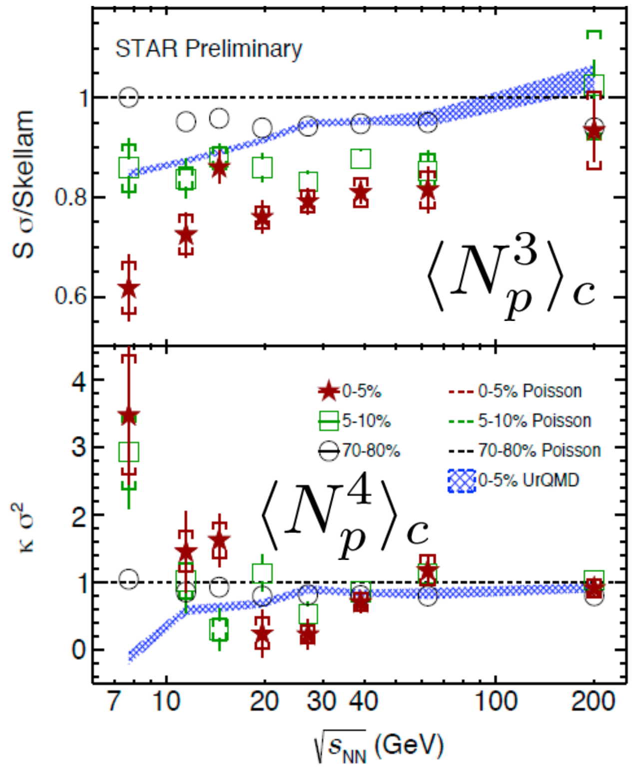
Fluctuations can be measured by e-by-e analysis in experiments.

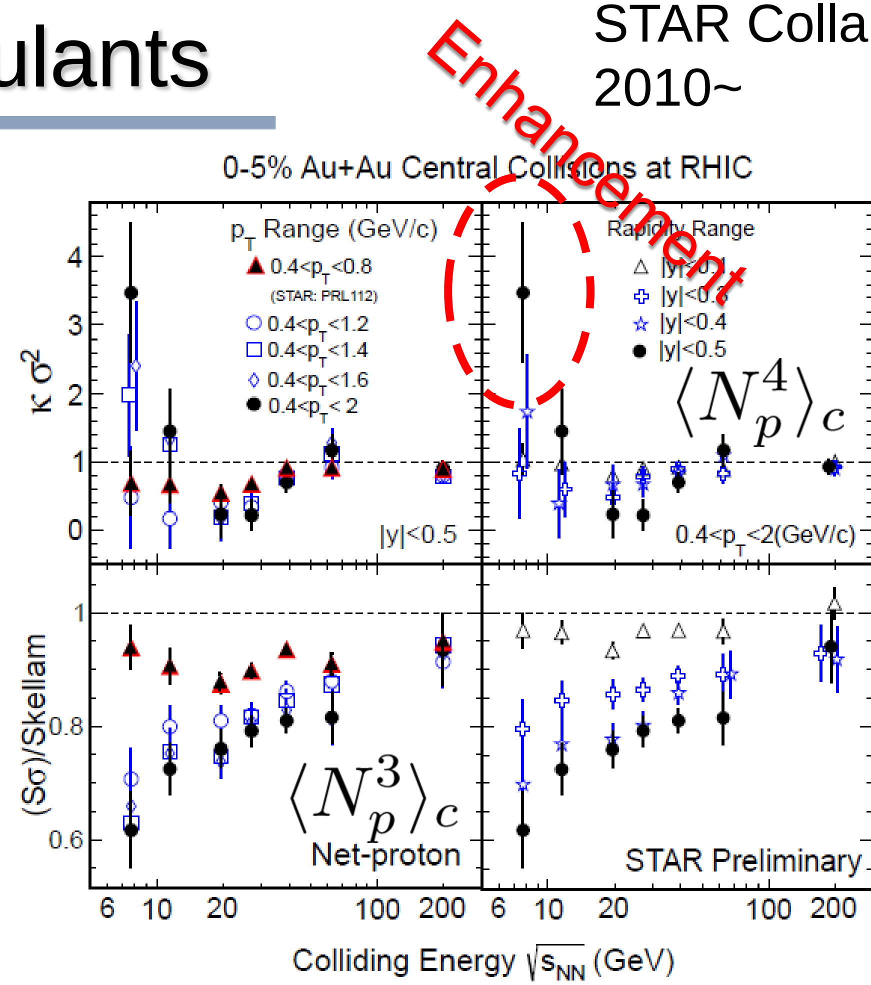




Higher-Order Cumulants

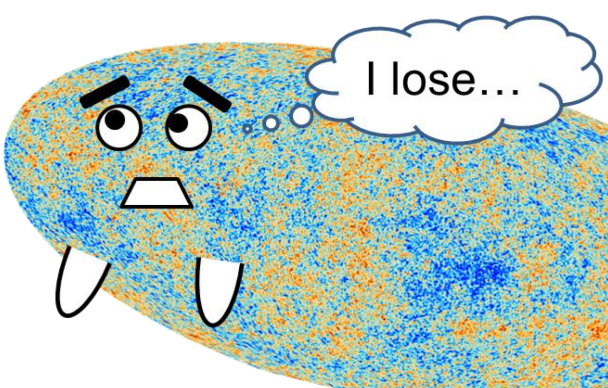
STAR Collab.
2010~





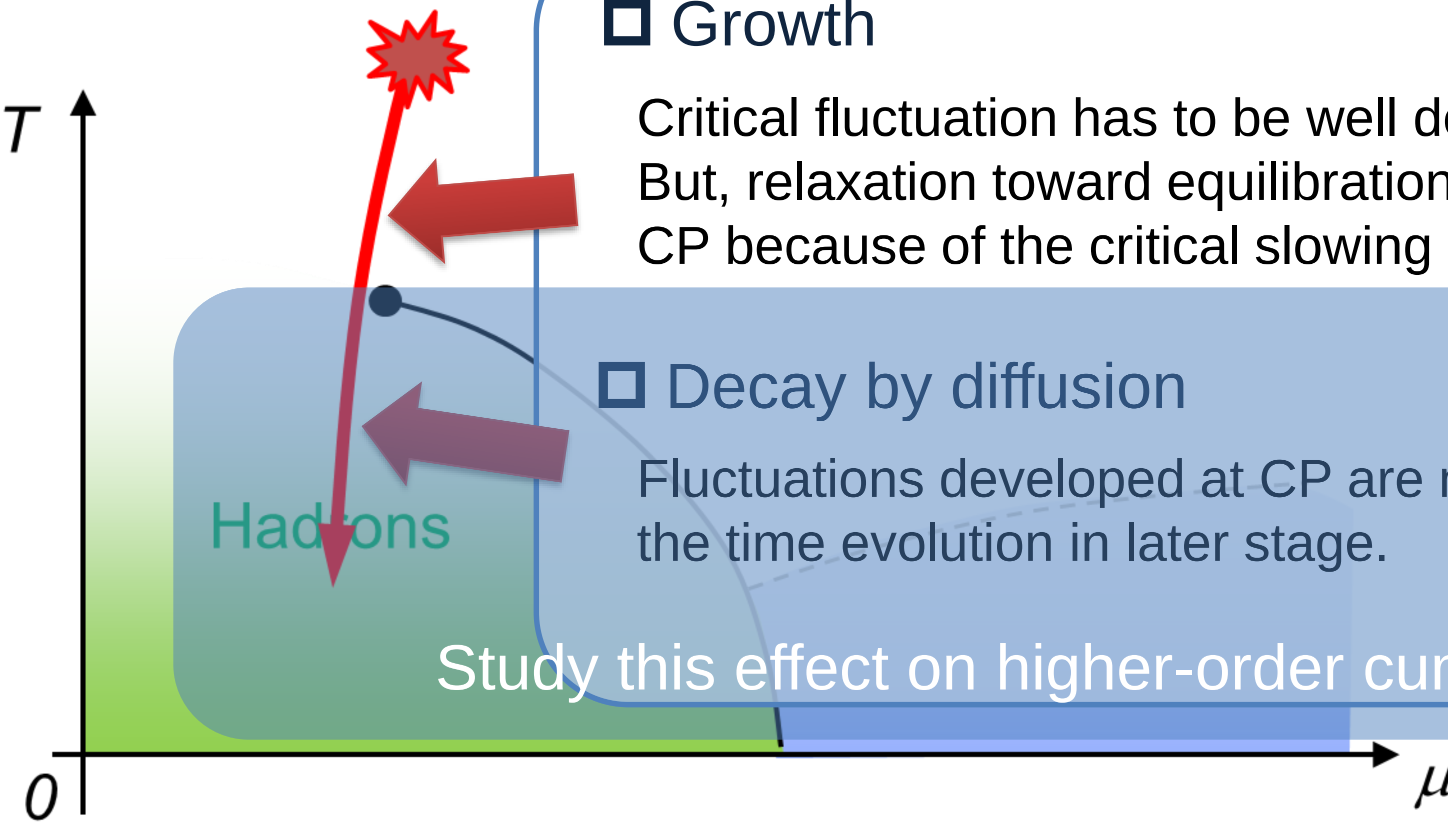
Non-zero **non**-Gaussian cumulants
have been established!

Have we measured critical fluctuations?



Remarks on Critical Fluctuation

Experiments cannot observe critical fluctuation in equilibrium directly.



☐ Growth

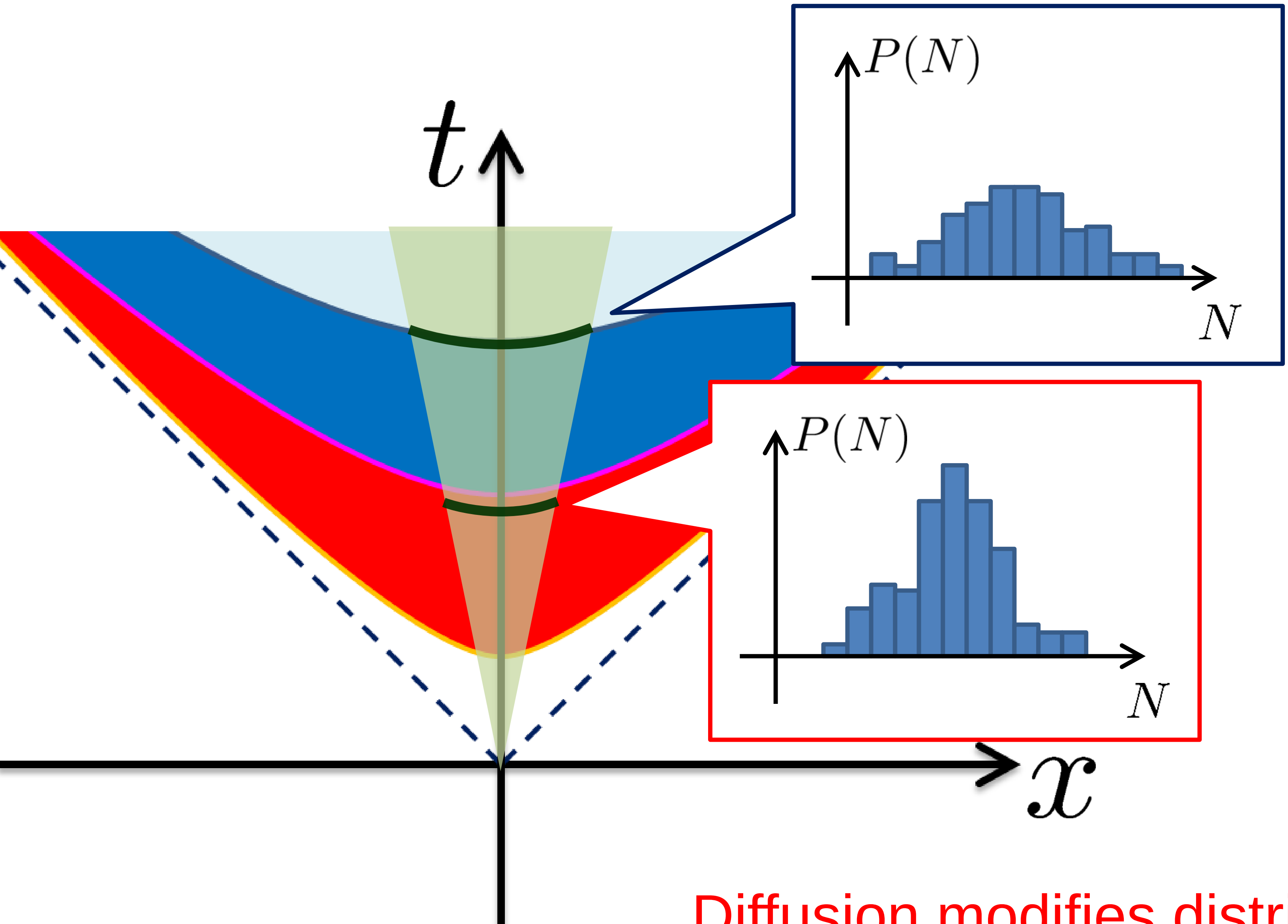
Critical fluctuation has to be well developed.
But, relaxation toward equilibration is slow around CP because of the critical slowing down.

☐ Decay by diffusion

Fluctuations developed at CP are modified by the time evolution in later stage.

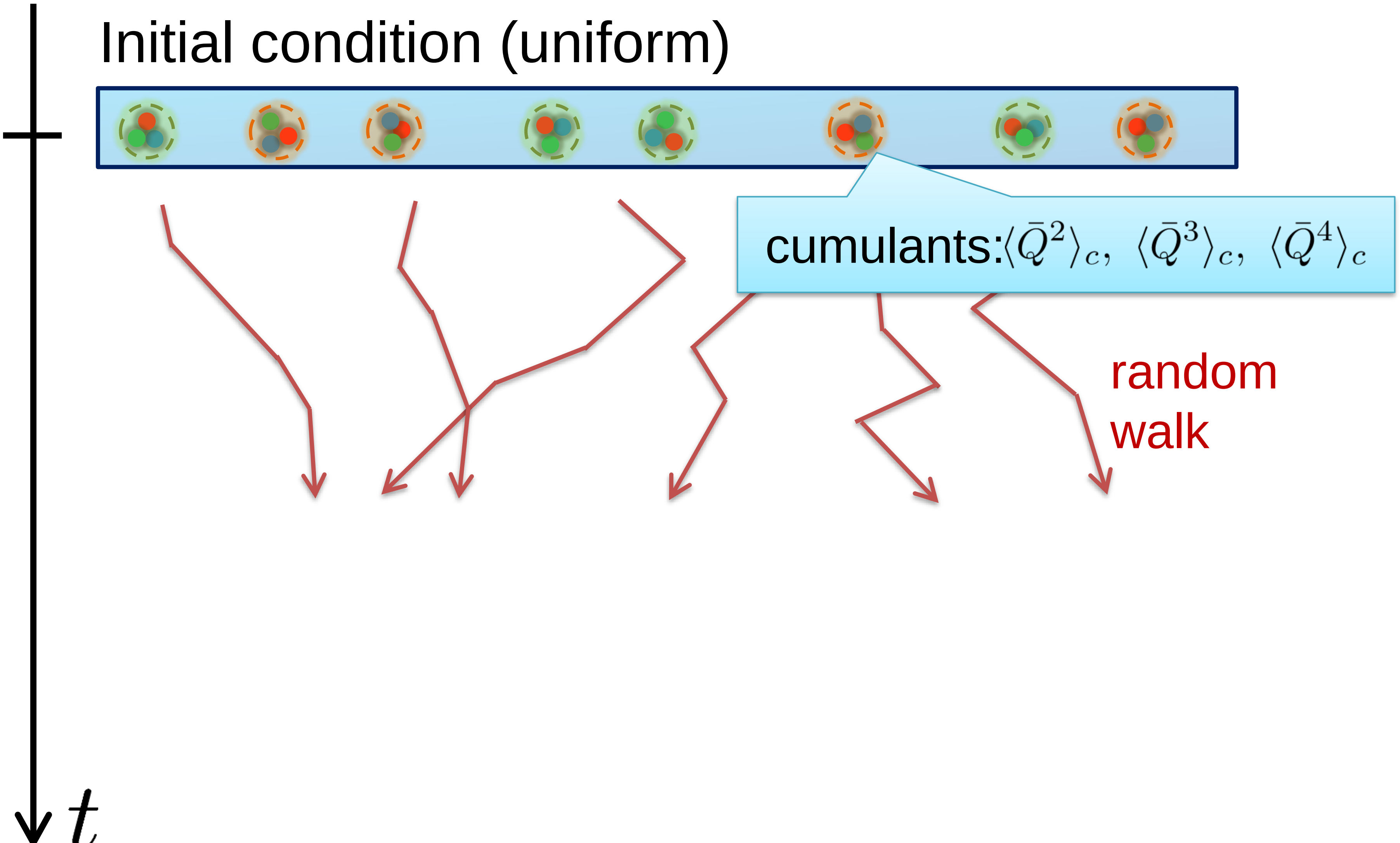
Study this effect on higher-order cumulants

Time Evolution of Fluctuations



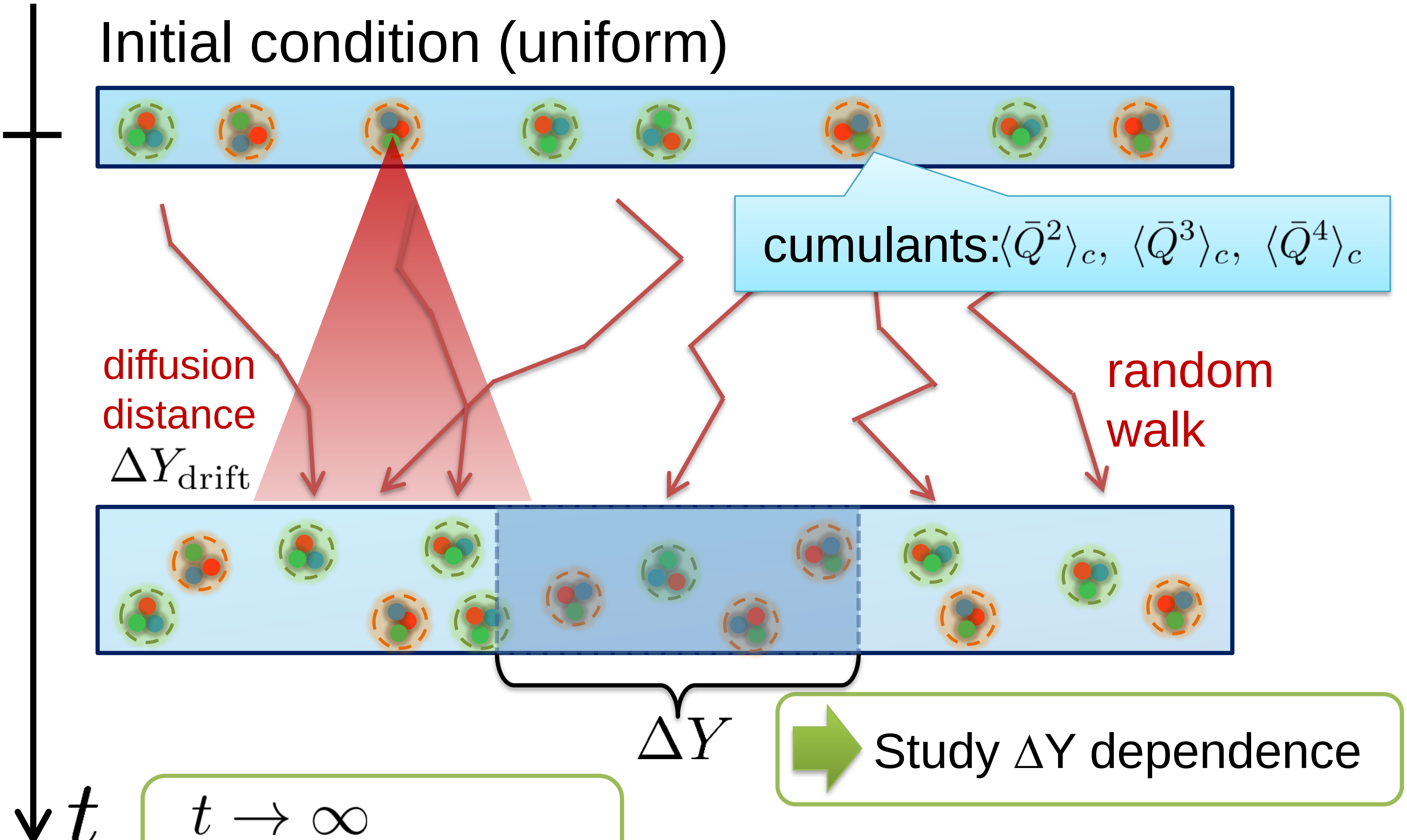
Diffusion modifies distribution

Non-Interacting Brownian Particle System



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

Non-Interacting Brownian Particle System

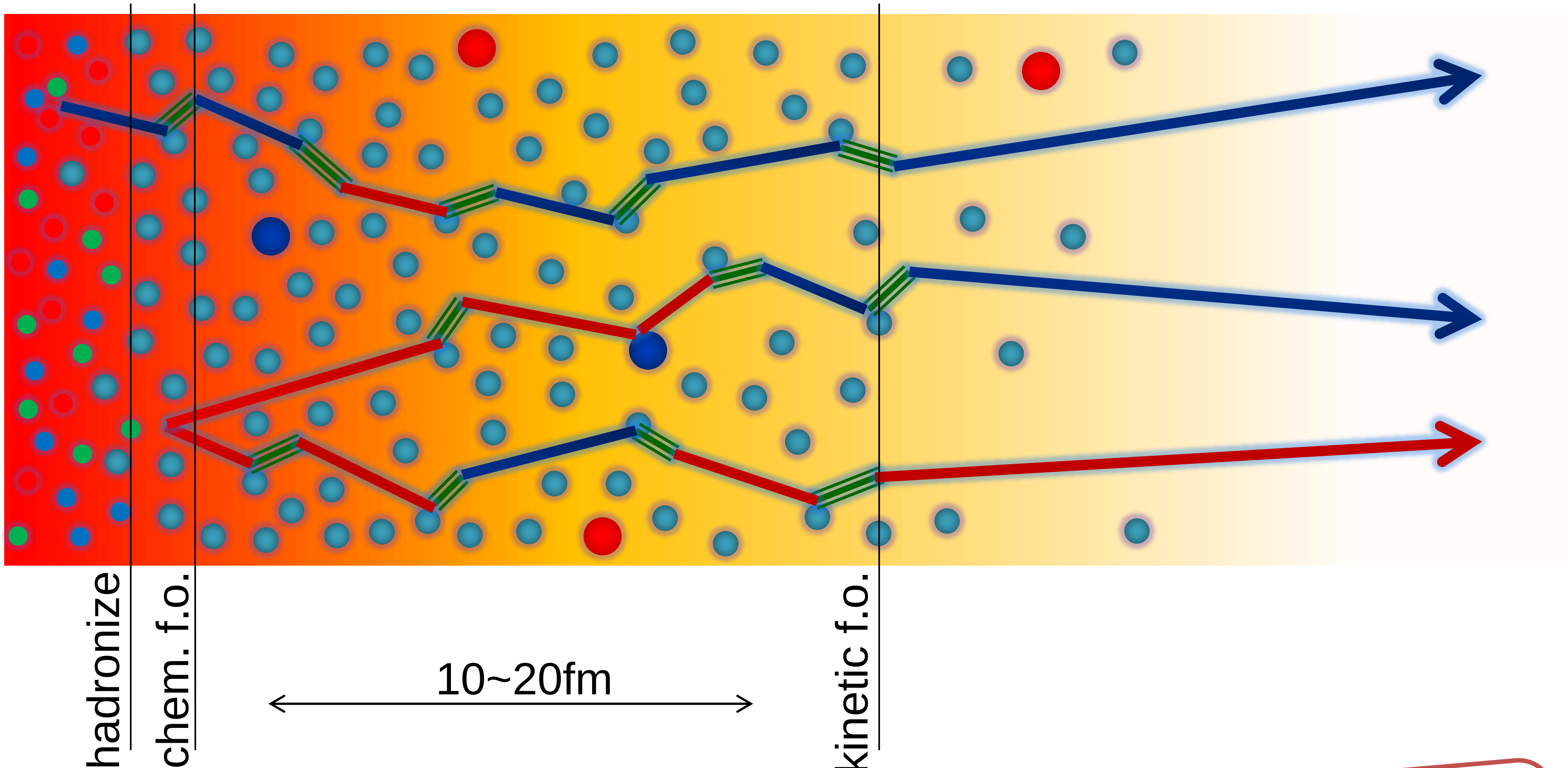


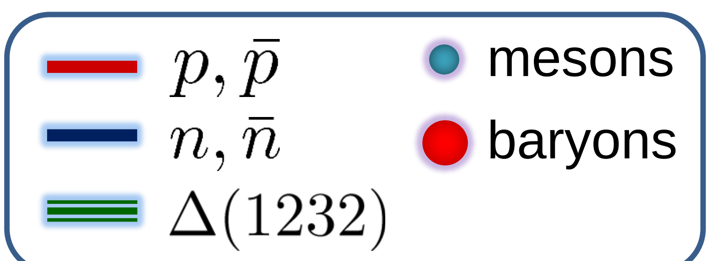
$t \to \infty$
Poisson distribution

Study ΔY dependence

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

Baryons in Hadronic Phase

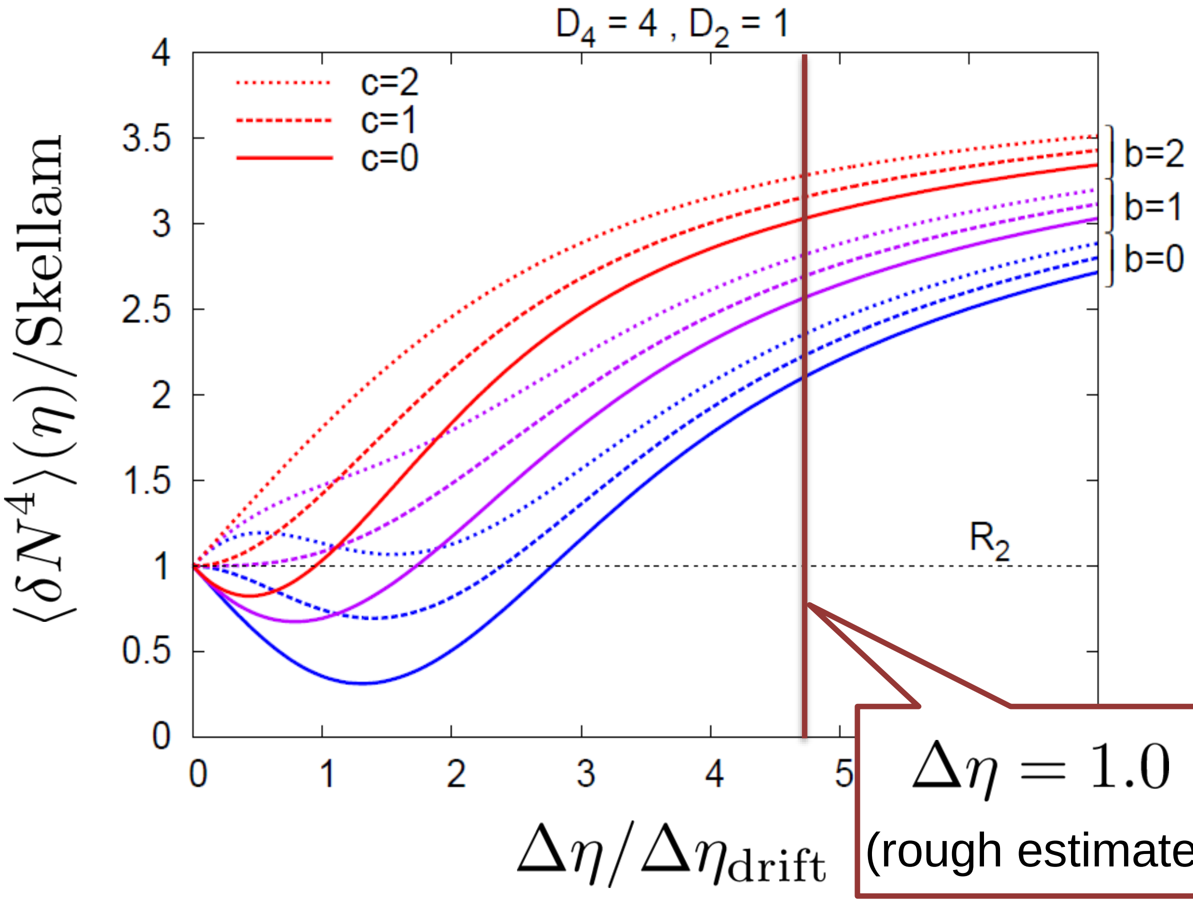




Baryons behave like Brownian pollens in water

4^{th} order : w/ Critical Fluctuation

MK+ (2014)
MK (2015)



$\Delta\eta = 1.0$
(rough estimate)

Initial Condition

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

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

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

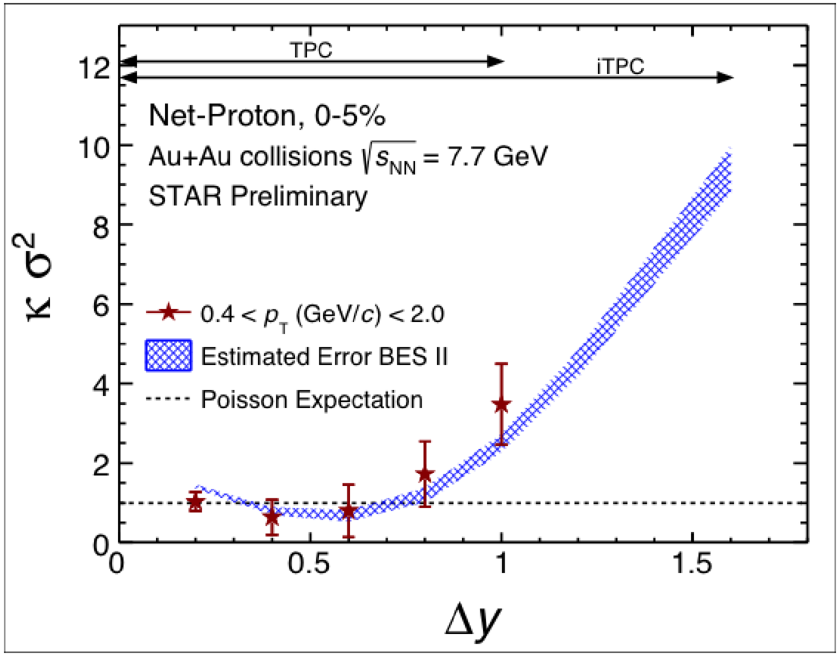
$$D_2 = \frac{\langle Q^2_{(\mathrm{net})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle} = 1$$

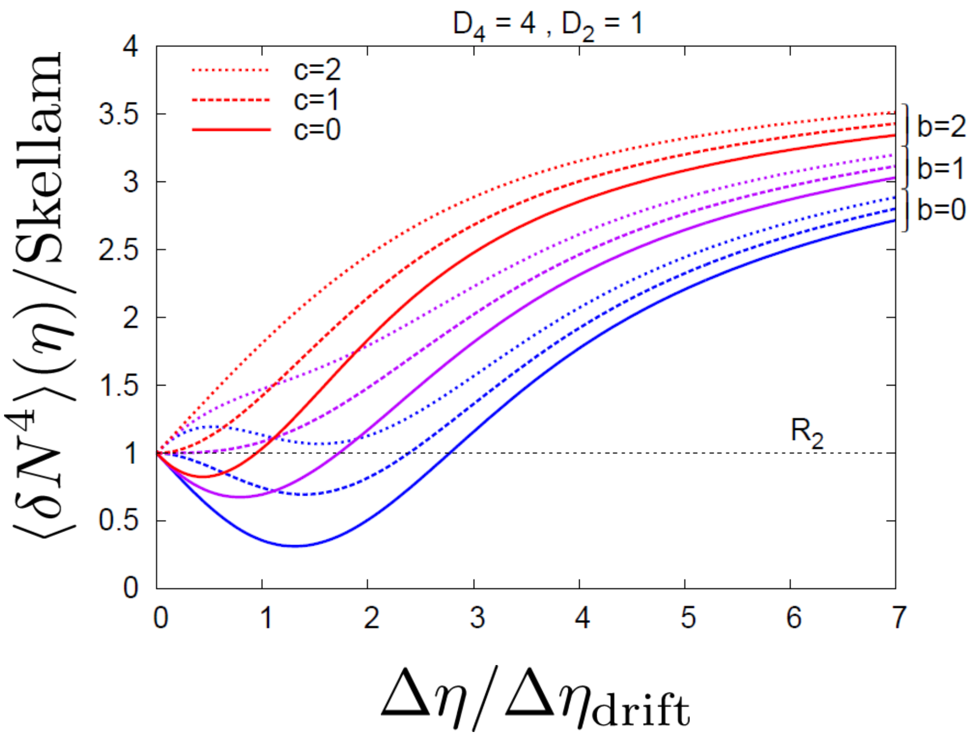
- Higher order cumulants can behave non-monotonically.

Δη Dependence @ STAR

MK+ (2014)
MK (2015)

X. Luo, CPOD2014



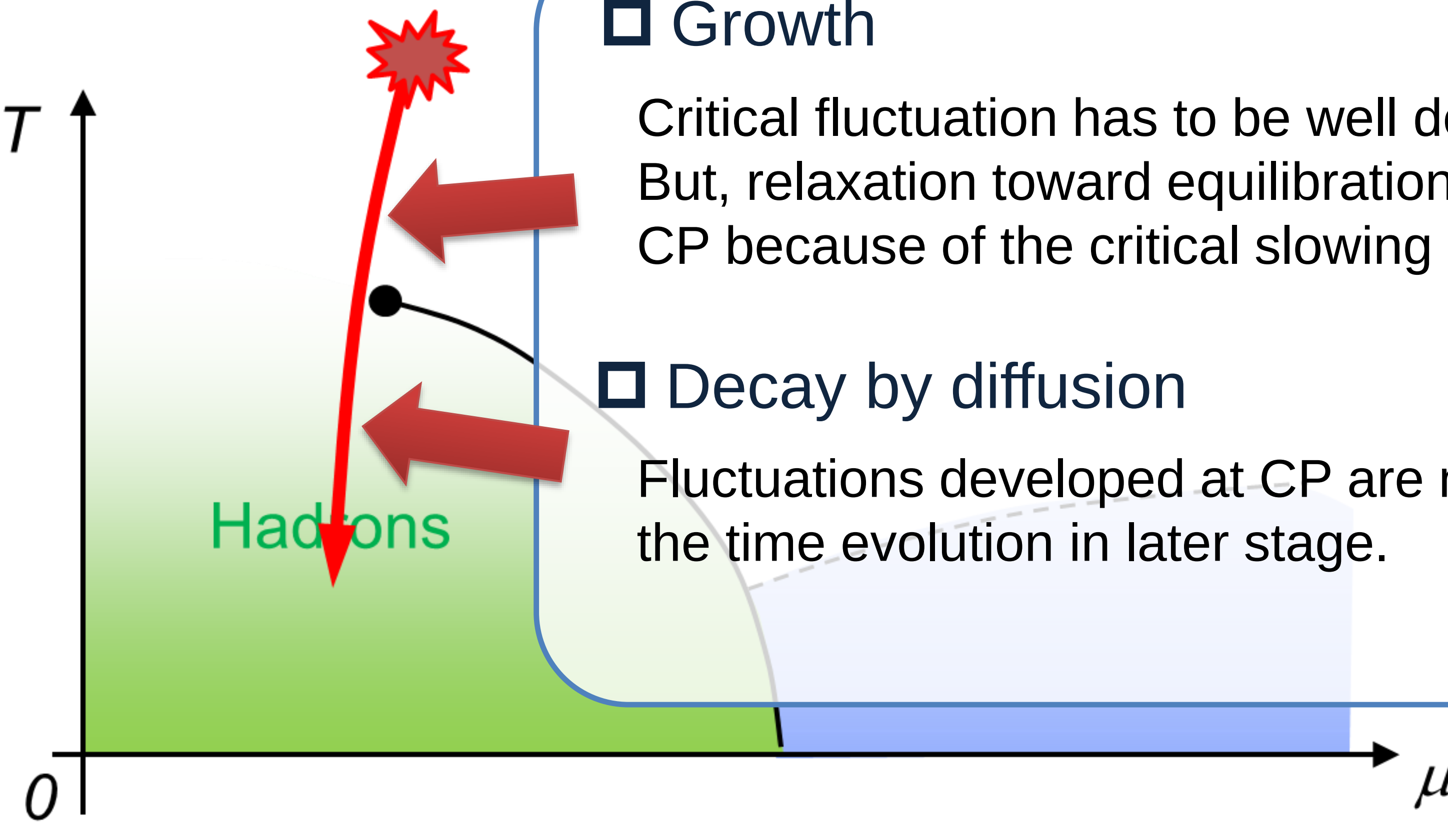


- Non monotonic behavior of cumulants.
- Approach initial value as Δy→large

finite volume effect: Sakaida+, PRC064911(2014)
More sophisticated analysis with **factorial cumulants**, MK, Luo (2017)

Remarks on Critical Fluctuation 1

Experiments cannot observe critical fluctuation in equilibrium directly.



- **Growth**

  Critical fluctuation has to be well developed. But, relaxation toward equilibration is slow around CP because of the critical slowing down.

- **Decay by diffusion**

  Fluctuations developed at CP are modified by the time evolution in later stage.

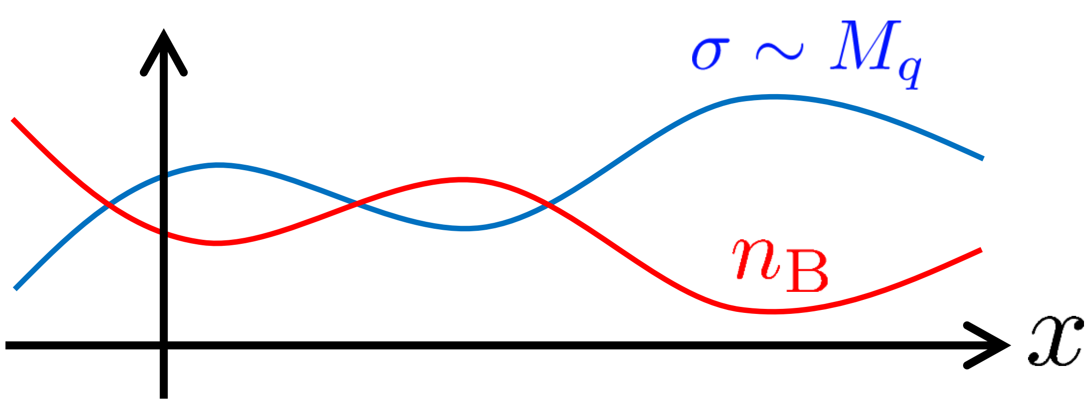
Remarks on Critical Fluctuation 2

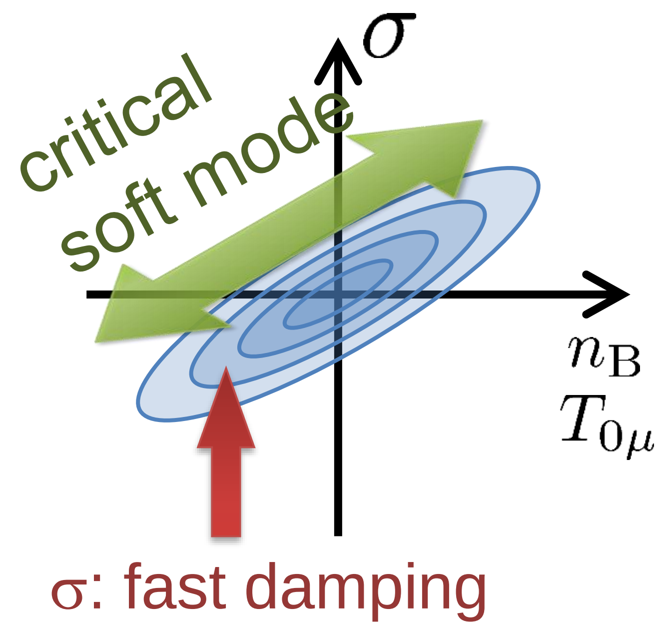
Critical fluctuation is a conserved mode!

Fujii 2003; Fujii, Ohtani, 2004; Son, Stephanov, 2004

Fluctuations of σ and n_B are coupled around the CP!

$$\delta\sigma \simeq \delta n_B$$



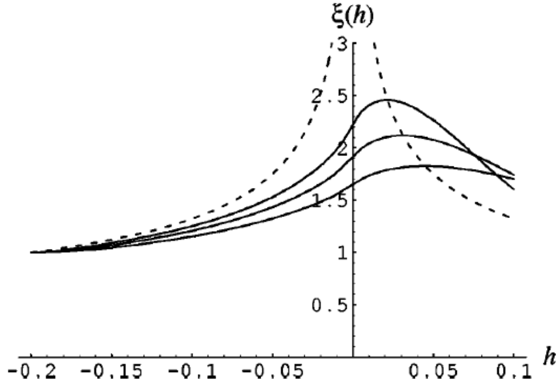


$$F(\sigma, n) = A\sigma^2 + B\sigma n + Cn^2 + \cdots$$

Dynamical Evolution of Critical Fluctuations

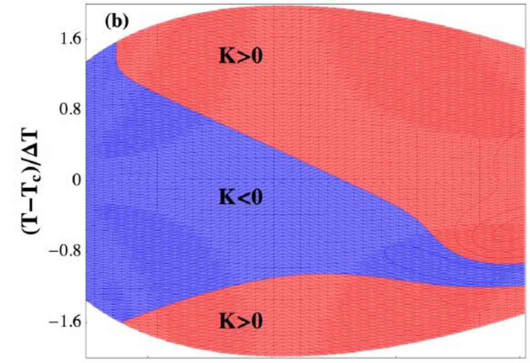
- Evolution of correlation length

Berdnikov, Rajagopal (2000)
Asakawa, Nonaka (2002)



- Higher orders (spatially uniform “σ” mode)

Mukherjee, Venugopalan, Yin (2015)



- Dynamical evolution in chiral fluid model

Nahrgang, Herold, … (2014~)

- Correlation functions

Kapusta, Torres-Rincon (2012)

Aim of This Study

- Describe **conserved nature** of critical fluctuation.
- We want to study **experimental observables**.
  - focus on a **conserved charge** **(baryon number)**
  - study evolution of **conserved-charge** fluctuation
- Concentrate on **2nd order** fluctuation. (not higher)
- We study
  - **rapidity window denepdence** of the cumulant
  - 2-particle **correlation function**

Our Main Conclusion

Non-monotonicity in 2nd-order cumulants or correlation func.	=	Signal of QCD-CP

Stochastic Diffusion Equation (SDE)

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
- χ: susceptibility (fluctuation in equil.)

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

Soft Mode of QCD Critical Point

Fujii 2003; Fujii, Ohtani, 2004; Son, Stephanov, 2004

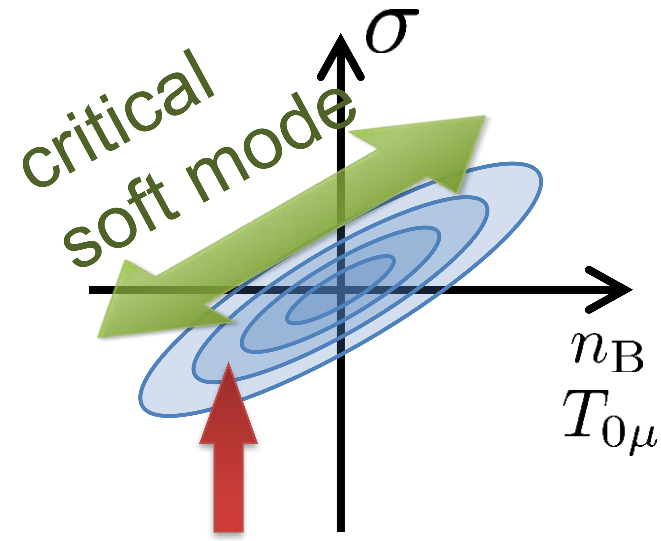
- Effective potential

$$F(\sigma, n) = A\sigma^2 + B\sigma n + Cn^2 + \cdots$$

- Time dependent Ginzburg-Landau

$$\begin{pmatrix} \dot{\sigma} \\ \dot{n} \end{pmatrix} = \begin{pmatrix} \Gamma_{\sigma\sigma} & \Gamma_{\sigma n} \\ \Gamma_{n\sigma} & \Gamma_{nn} \end{pmatrix} \begin{pmatrix} \sigma \\ n \end{pmatrix}$$

$\sim k^2$



For slow and long wavelength,

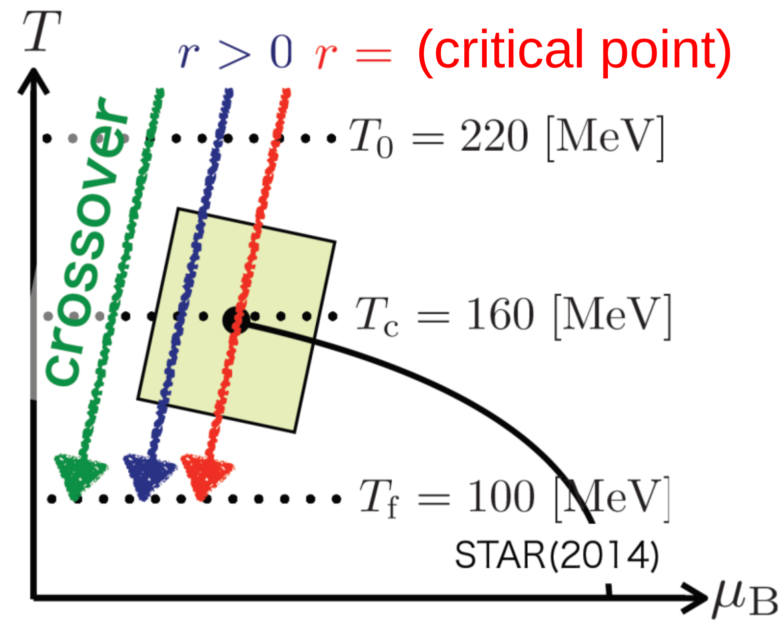
SDE $\quad \partial_\tau n = D(\tau)\partial_\eta^2 n + \partial_\eta \xi$

singularities in $D(\tau)$ and $\chi(\tau)$

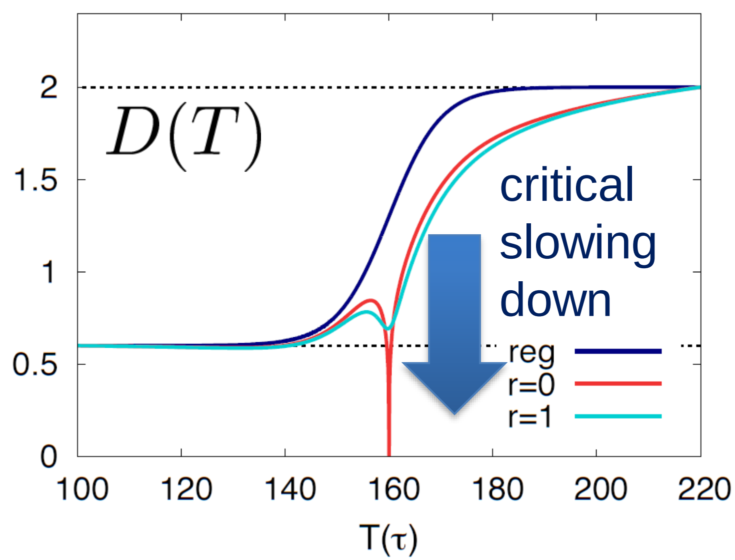
Parametrizing D(τ) and χ(τ)

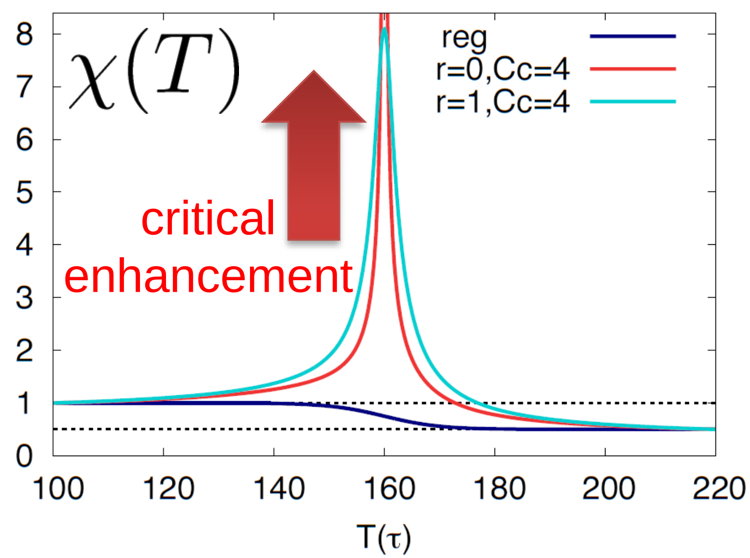
Sakaida+, 2017

- Critical behavior
  - 3D Ising (r,H)
  - model H



- Temperature dep.

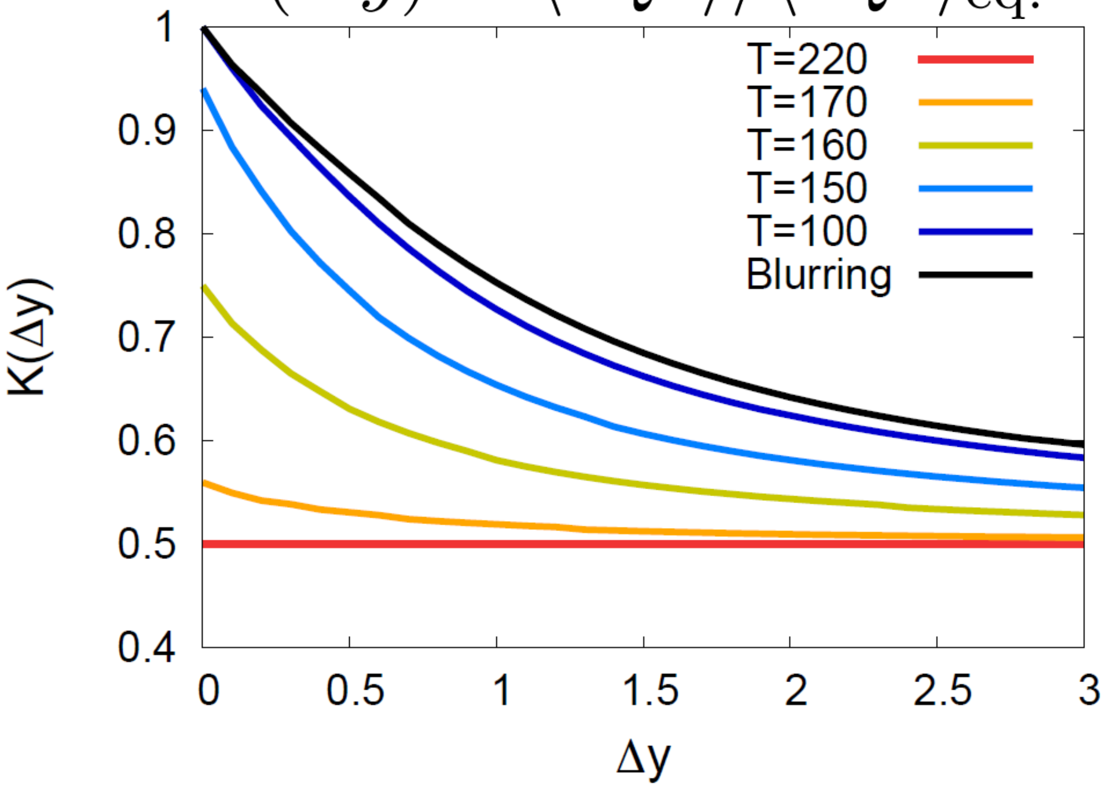


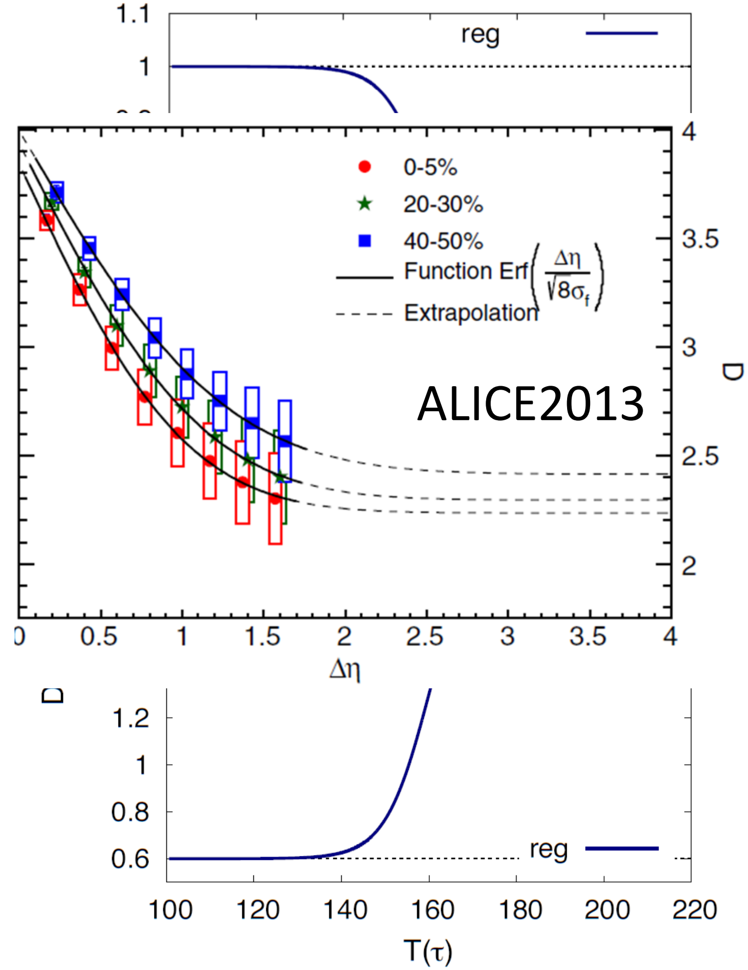


Crossover / Cumulant

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\text{eq.}}$$





□ monotonically decresing

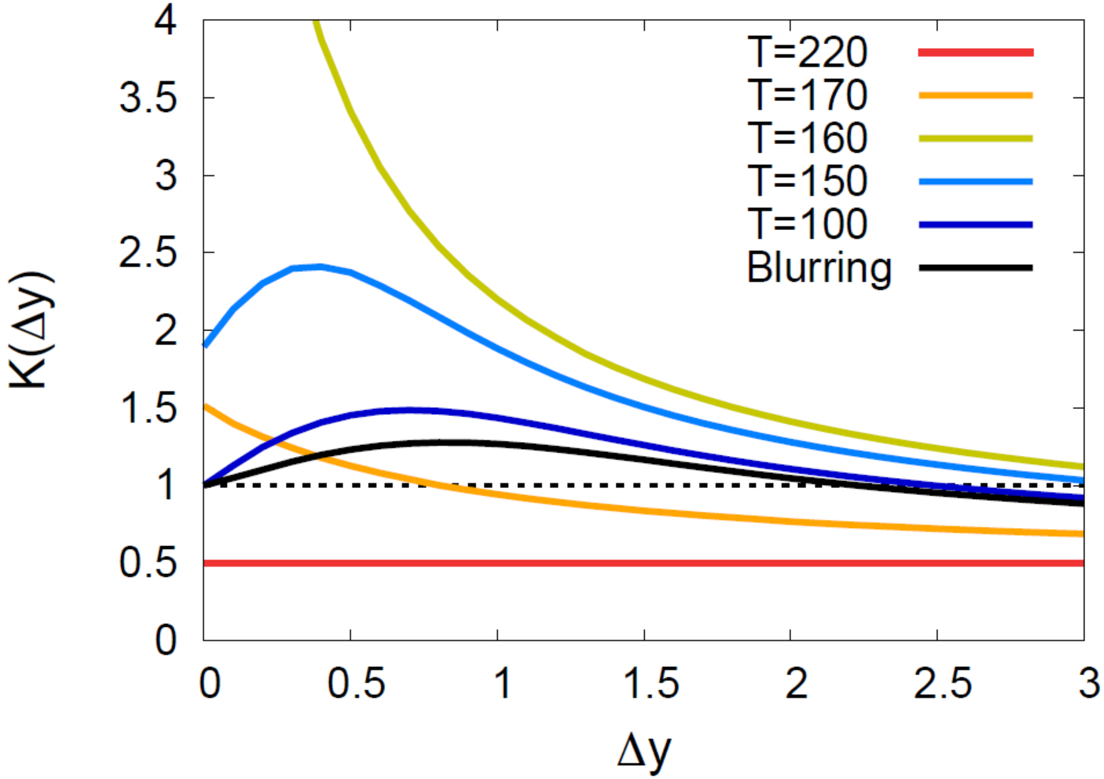
Analytic result

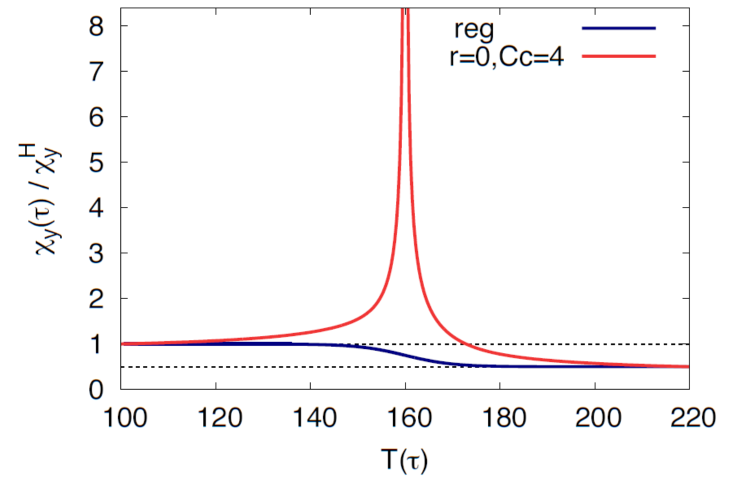
$\chi(\tau)$ monotonically increasing → $K(\Delta y)$ monotonically decreasing

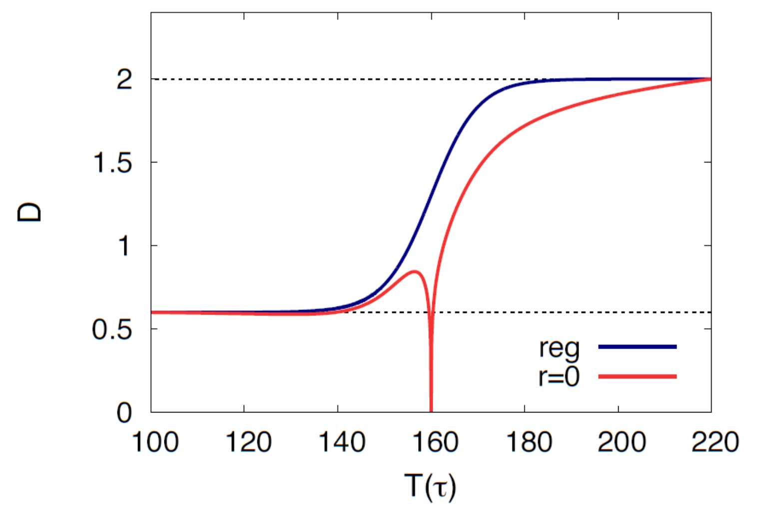
Critical Point / Cumulant

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\mathrm{eq.}}$$







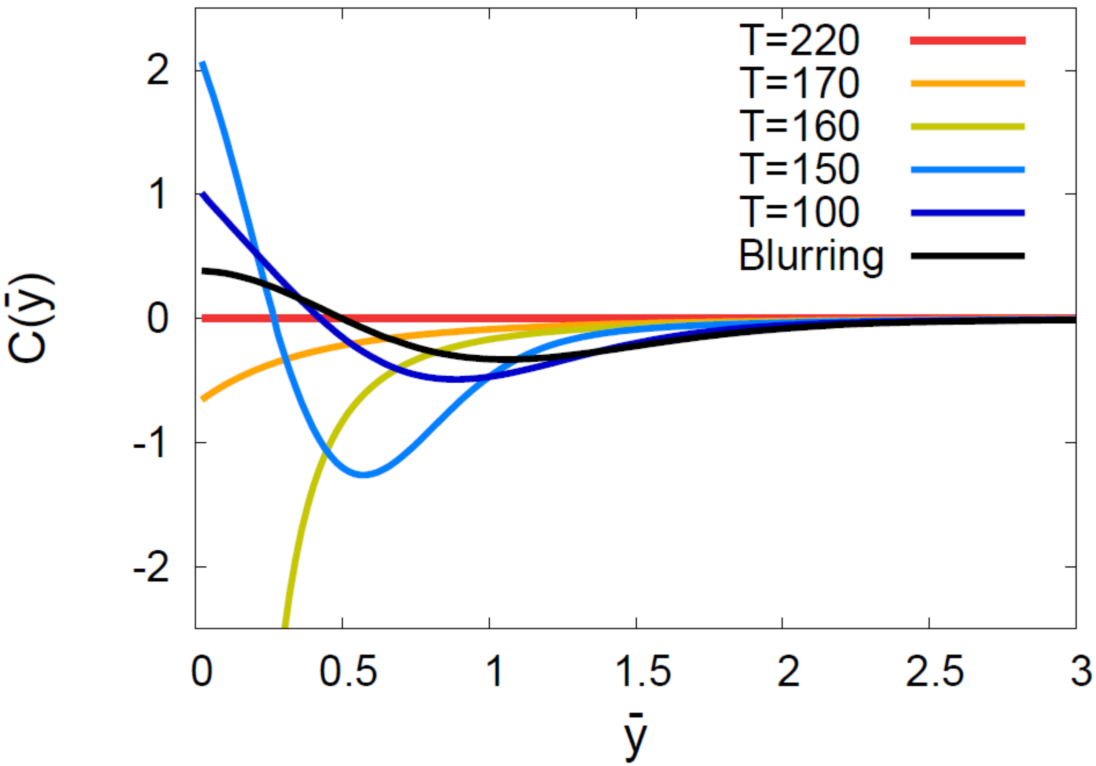
- non-monotonic Δy dep.

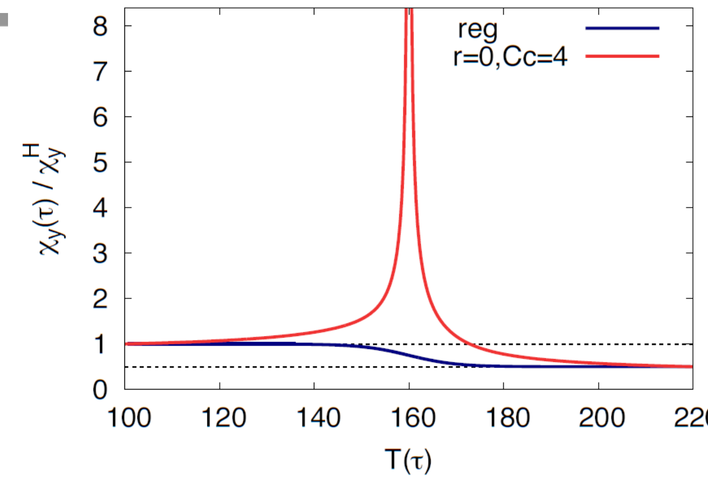
Analytic result: $K(\Delta y)$ non-monotonic ⇒ $\chi(\tau)$ non-monotonic

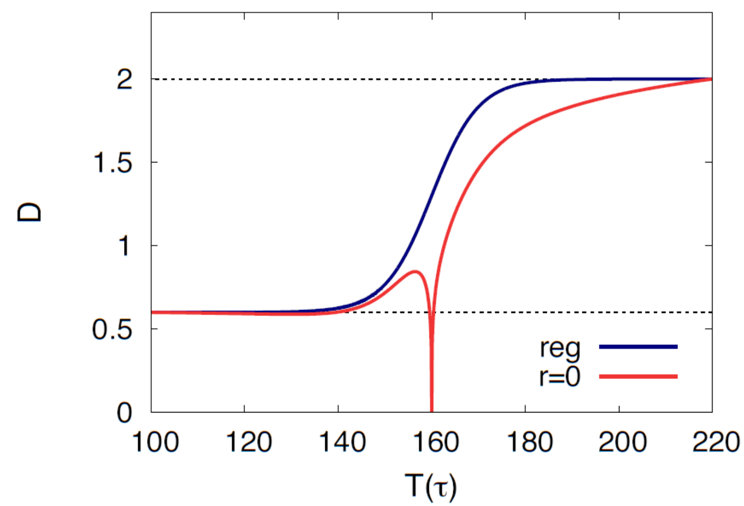
Criticap Point / Correlation Func.

Sakaida+, 2017

$$C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\mathrm{hadron}}$$







- non-monotonic Δy dep.

Analytic result

$C(\Delta y)$ non-monotonic → $\chi(\tau)$ non-monotonic

Cumulants and Correlation Function

$$Q = \int_V dx\, n(x)$$

total charge

charge density

$$\langle \delta Q^2 \rangle = \int_V dx dy \langle \delta n(x) \delta n(y) \rangle$$

2^{nd} order cumulant (fluctuation)

correlation function

1-to-1 correspondence

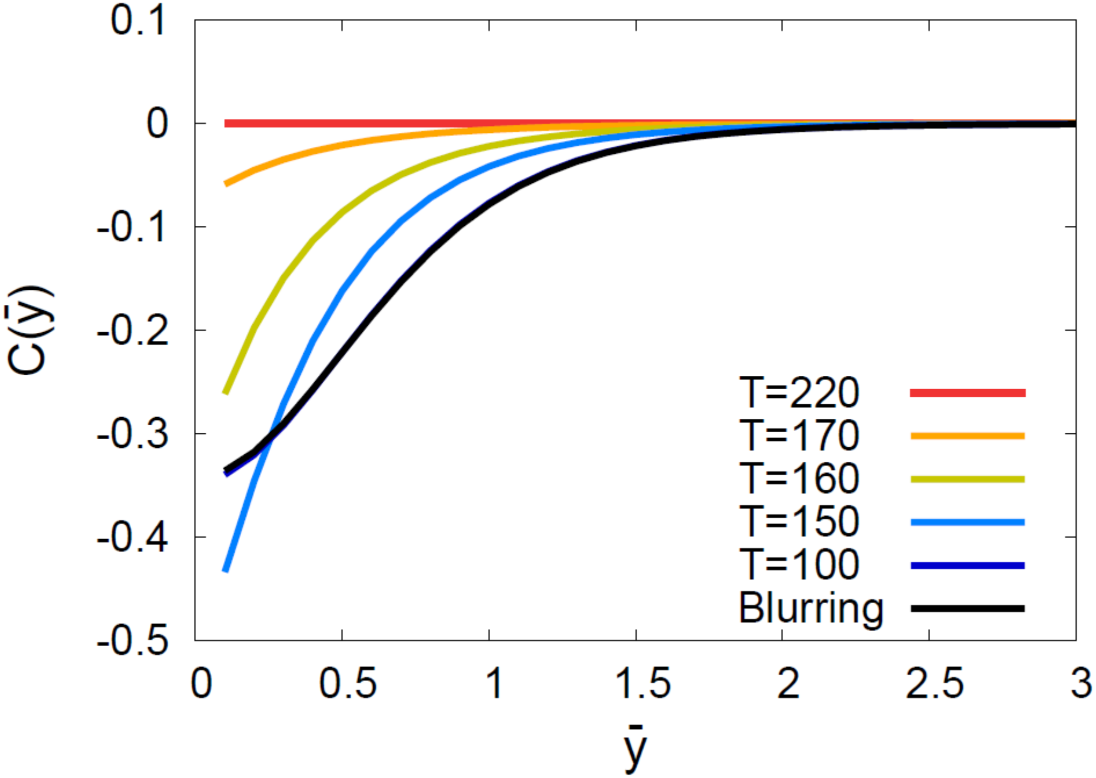
1-dim case

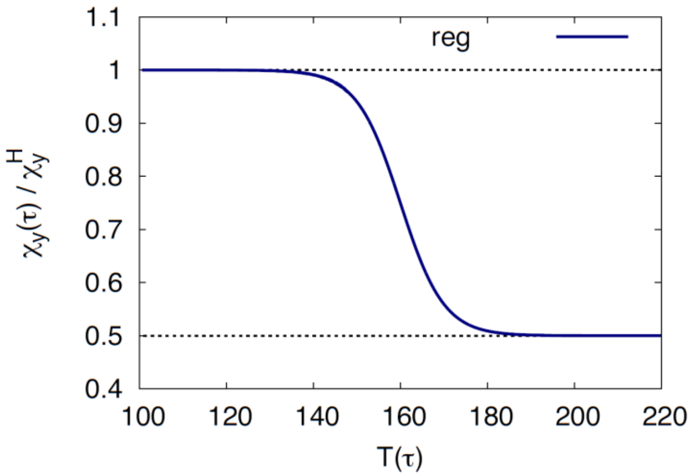
$$\langle \delta Q^2 \rangle_{\Delta y} = \int_{\Delta y} dy (\Delta y - |y|) \langle \delta n(y) \delta n(0) \rangle$$

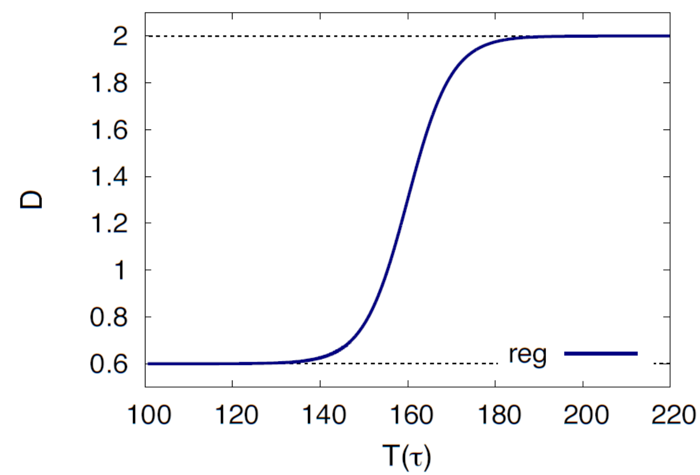
Crossover / Correlation Func.

Sakaida+, 2017

$$C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\text{hadron}}$$







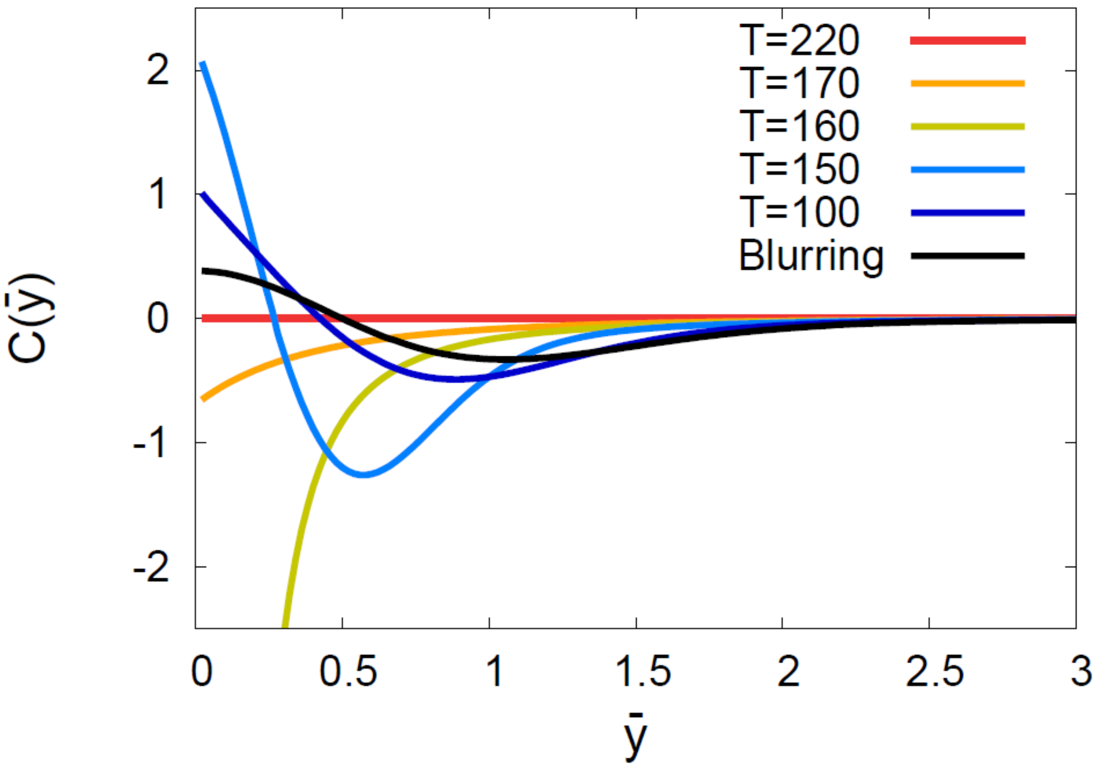
- monotonically decresing

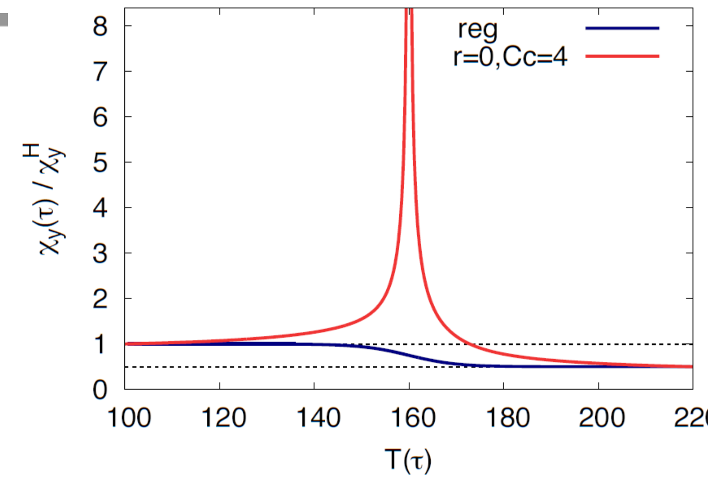
Analytic result: $\chi(\tau)$ monotonically increasing → $C(\bar{y})$ monotonically decreasing

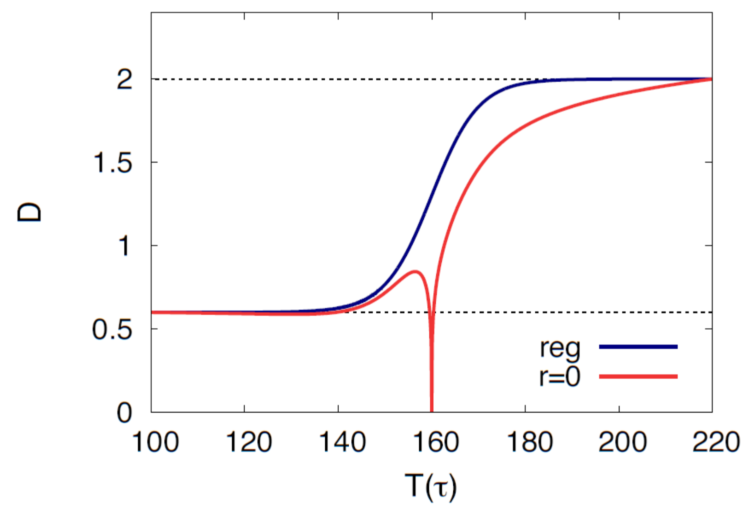
Criticap Point / Correlation Func.

Sakaida+, 2017

$$C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\text{hadron}}$$







- non-monotonic Δy dep.

Analytic result: $C(\Delta y)$ non-monotonic ⇒ $\chi(\tau)$ non-monotonic

Summary

- Fluctuations observed in HIC are not in equilibrium.
- Non-equil. property can be understood from Δy dependence of cumulants.

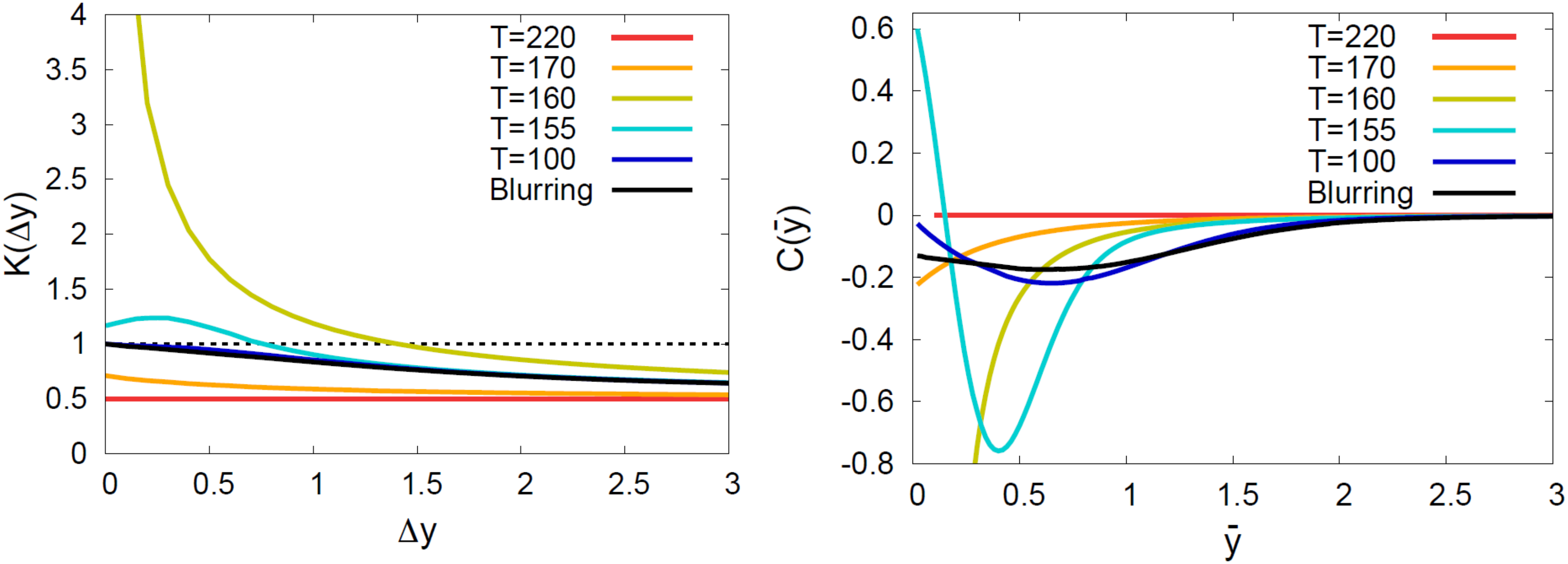
- A simple diffusion model leads to non-monotonic Δy dependence of **higher order** cumulant.
- Non-monotnic Δy dependence of **2nd order** cumulant is a signal of QCD critical point.

- **Detailed understanding on fluctuations can be established from the study of Δy dependences of various cumulants!**

Weaker Critical Enhancement

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\text{eq.}} \quad C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\text{hadron}}$$



- Non-monotonicity in K(Δy) disappears.
- But C(y) is still non-monotonic.

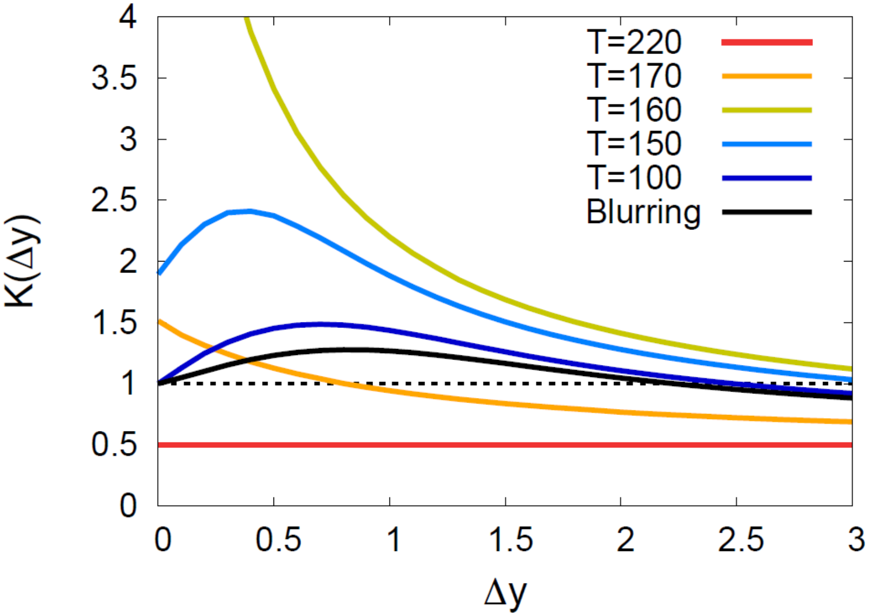
Analytic result: $K(\Delta y),\ C(\bar{y})$ monotonic ⇒ no information on $\chi(\tau)$

- C(y) is better to see non-monotonicity.

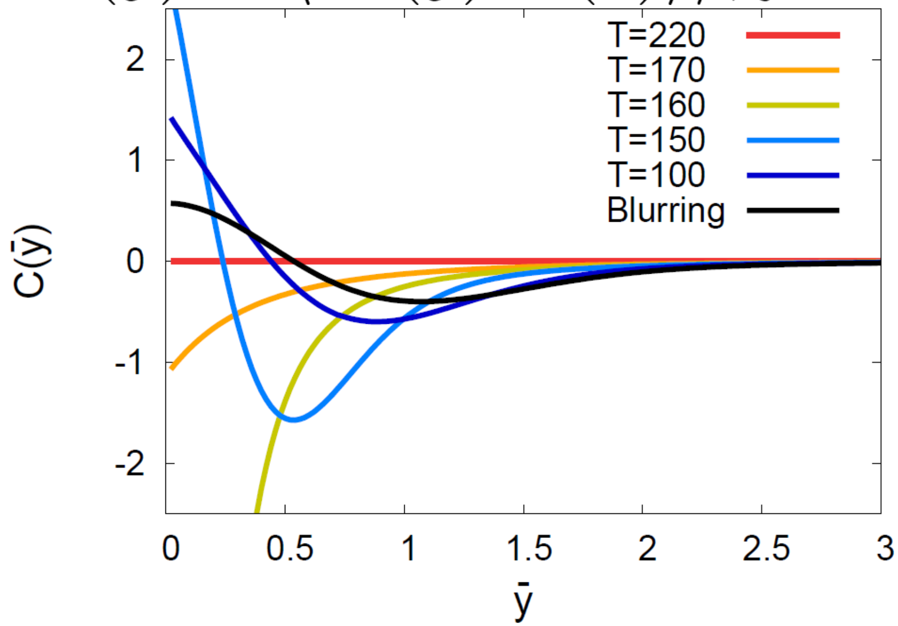
Away from the CP

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\mathrm{eq.}}$$



$$C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\mathrm{hadron}}$$

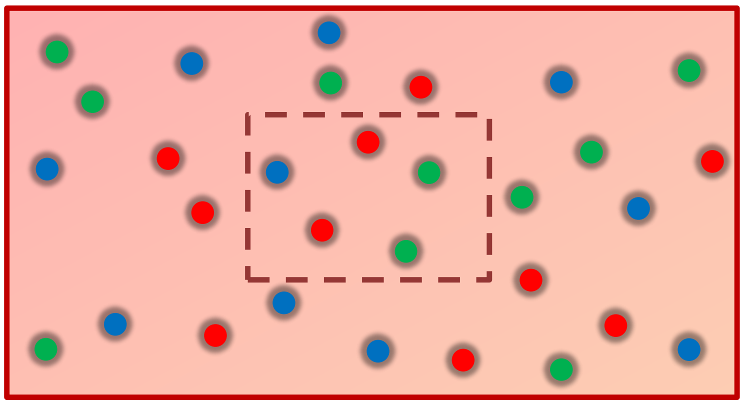


- Signal of the critical enhancement can be clearer on a path away from the CP.

Away from the CP → Weaker critical slowing down

Fluctuations and Elemental Charge

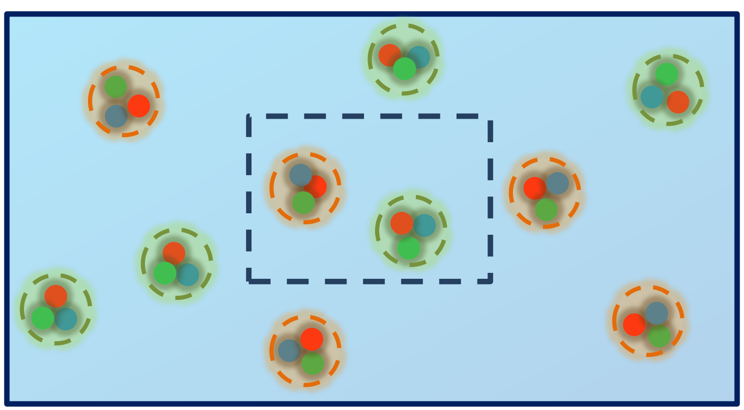
Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000
Ejiri, Karsch, Redlich, 2005

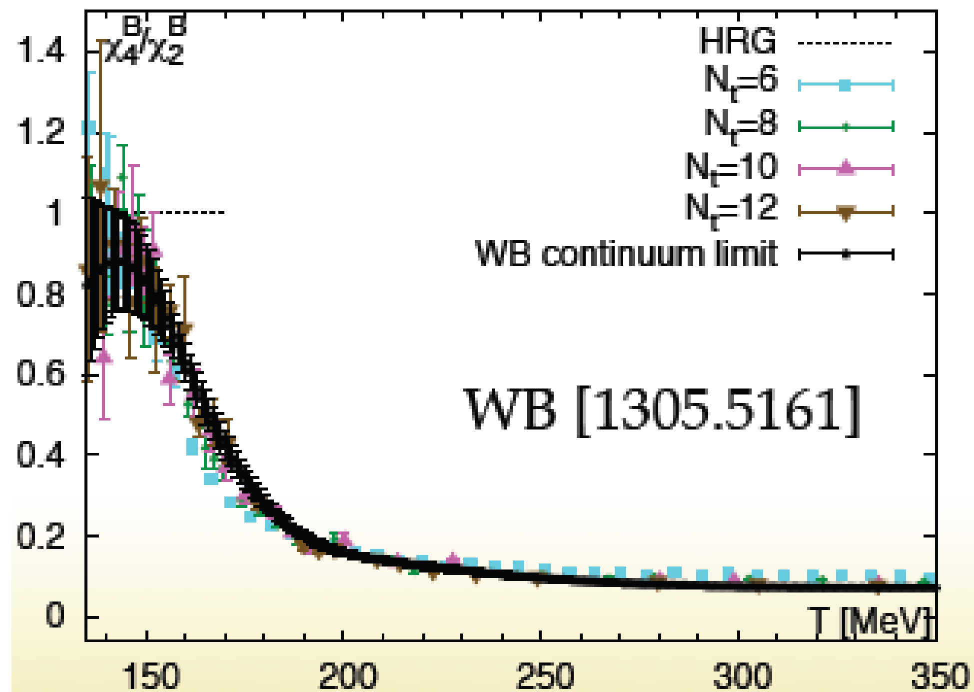


$$\langle \delta N_q^n \rangle_c = \langle N_q \rangle$$

$$\Rightarrow \langle \delta N_B^n \rangle_c = \frac{1}{3^{n-1}} \langle N_B \rangle$$

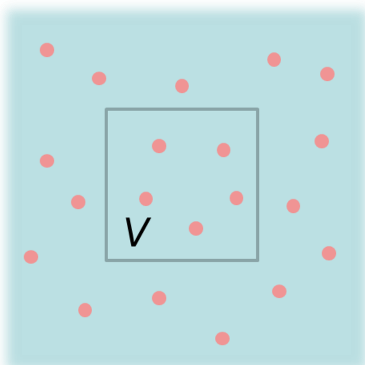
$$3N_B = N_q$$





Fluctuations: Theory vs Experiment

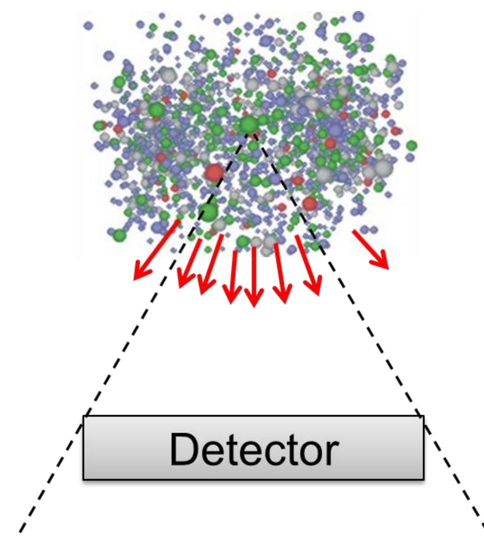
Theoretical analyses
based on statistical mechanics



lattice, critical point,
effective models, …

Fluctuation in
a spatial volume

Experiments



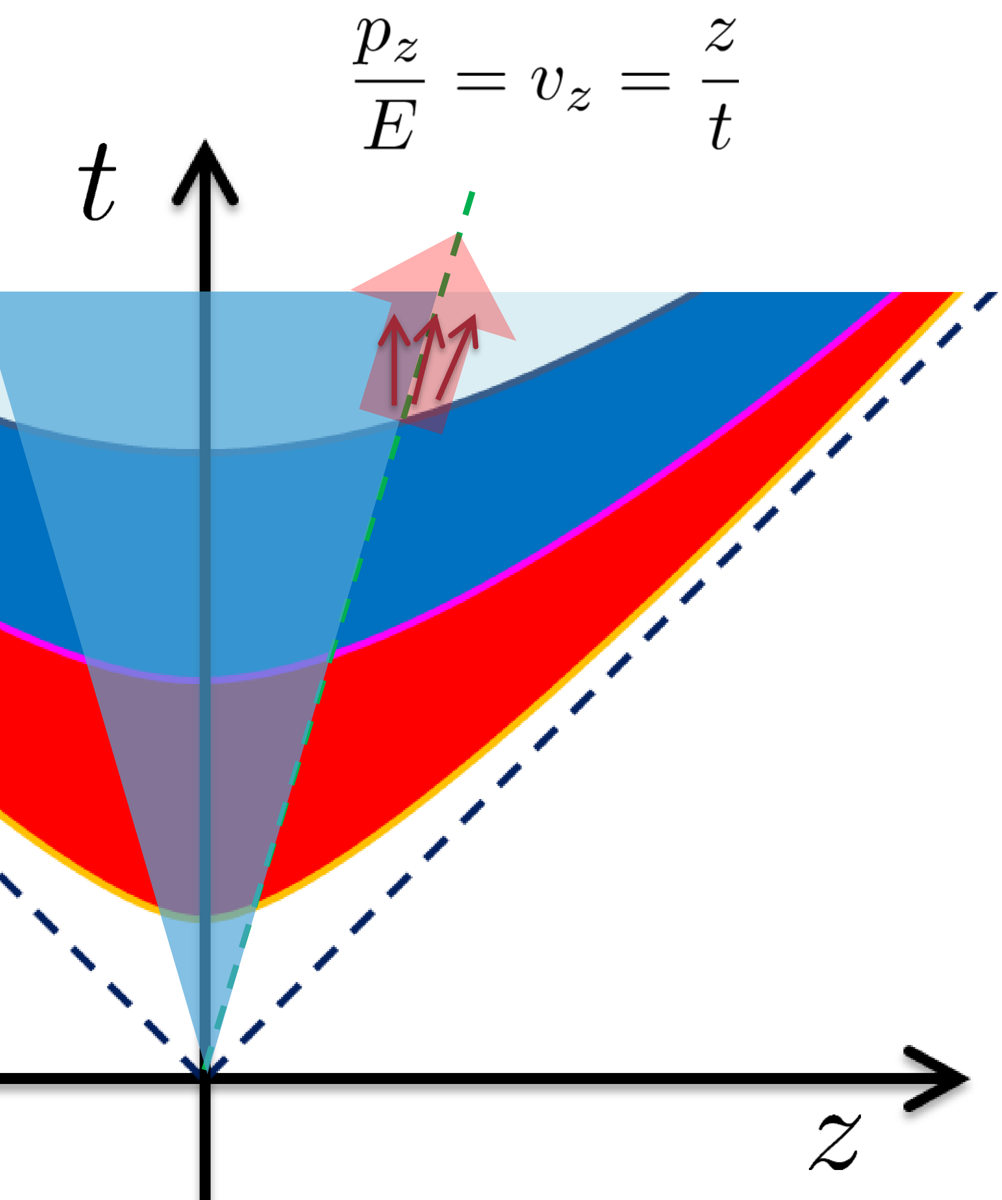
Fluctuations in
a momentum space

discrepancy in phase spaces

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

Thermal Blurring

Ohnishi, MK, Asakawa,
PRC94, 044905 (2016)



Under Bjorken picture,

coordinate-space rapidity *Y*

||

momentum-space rapidity *y*
of medium

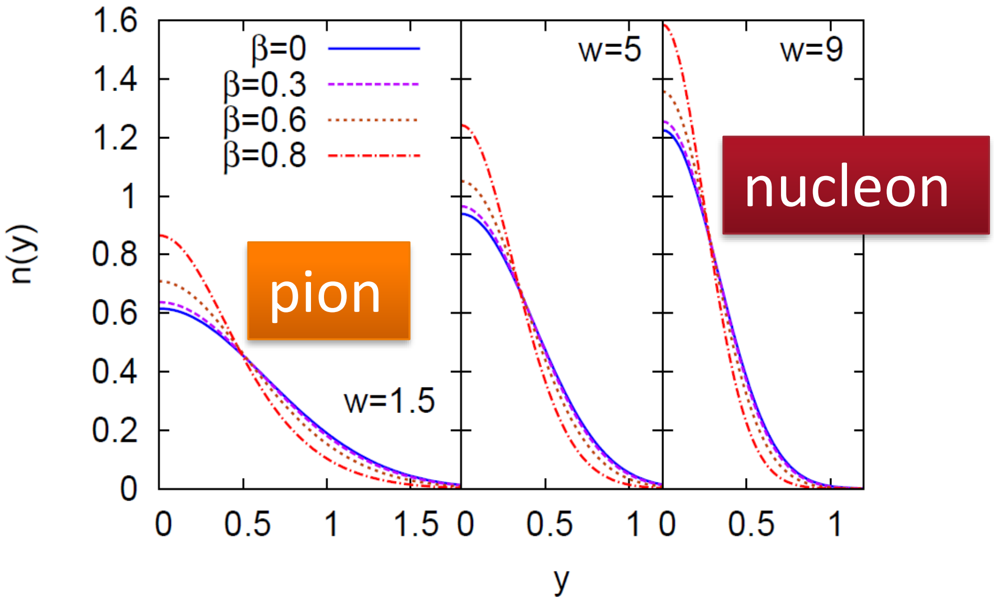
|≀

momentum-space rapidity *y*
of individual particles

$$\Delta y \simeq \Delta Y$$

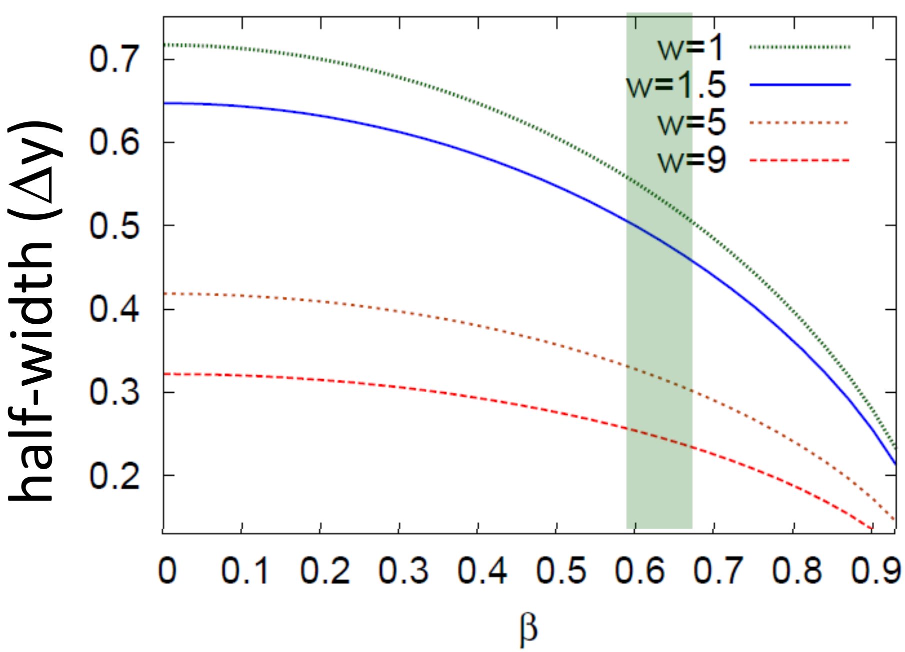
Thermal distribution in y space

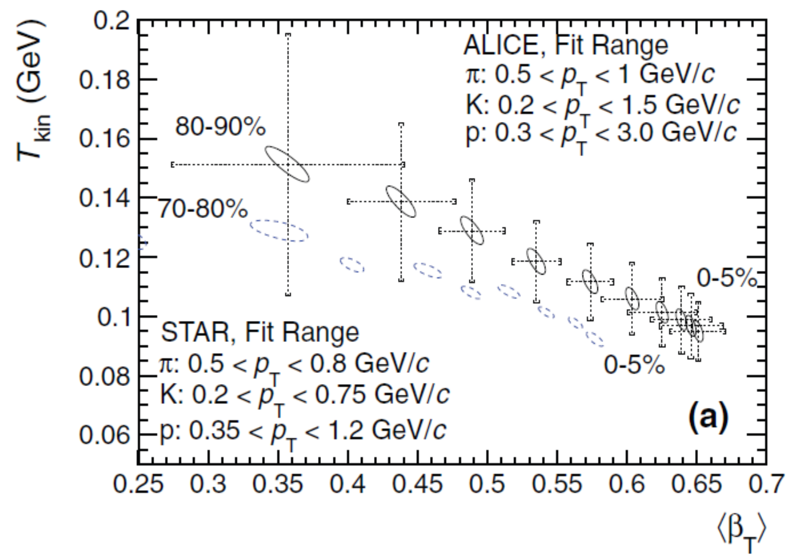
Ohnishi, MK, Asakawa, PRC94, 044905 (2016)



$$w = \frac{m}{T}$$

- pions $w \simeq 1.5$
- nucleons $w \simeq 9$



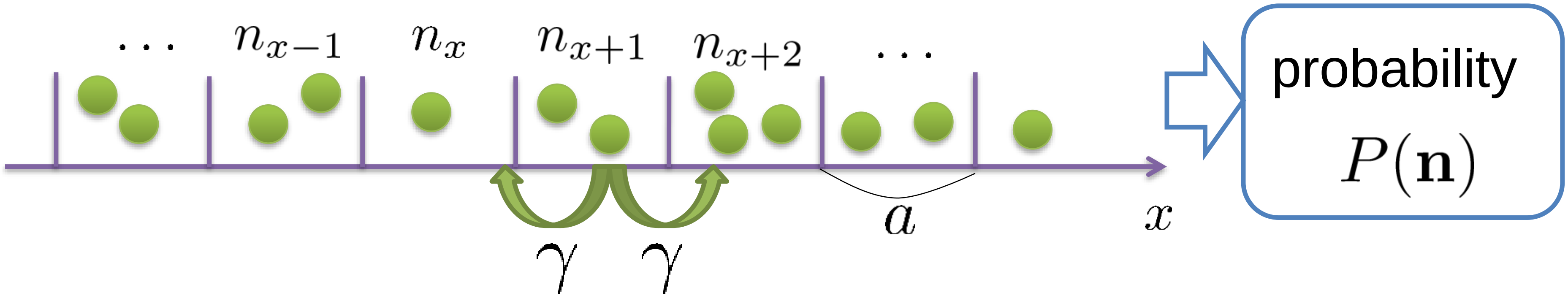


- blast wave
- flat freezeout surface

Diffusion Master Equation

MK, Asakawa, Ono, 2014
MK, 2015

Divide spatial coordinate into discrete cells



Diffusion Master Equation

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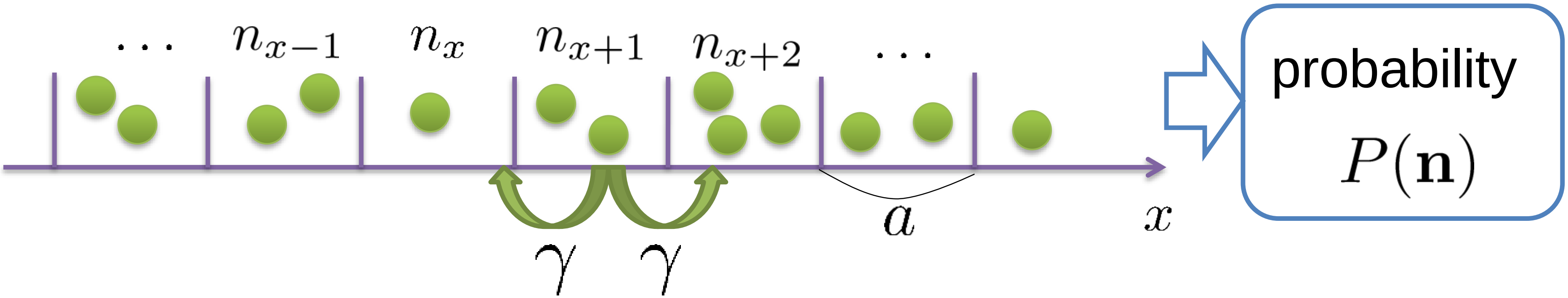
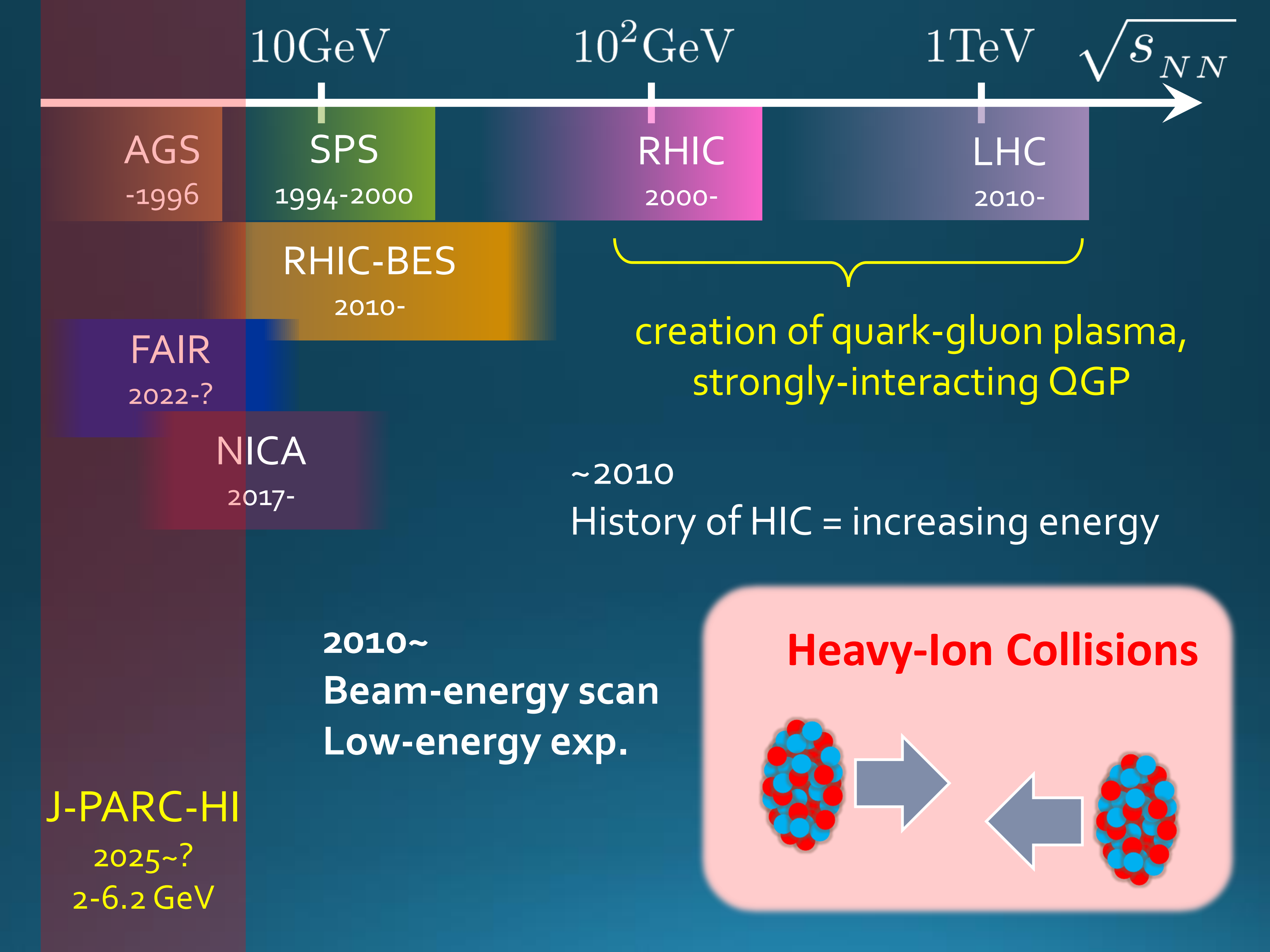


Master Equation for *P*(*n*)

$$\frac{\partial}{\partial t}P(\mathbf{n}) = \gamma \sum_x [(n_x + 1)\{P(\mathbf{n}+\mathbf{e}_x-\mathbf{e}_{x+1}) + P(\mathbf{n}+\mathbf{e}_x-\mathbf{e}_{x-1})\} - 2n_x P(\mathbf{n})]$$

Solve the DME **exactly**, and take *a*→0 limit

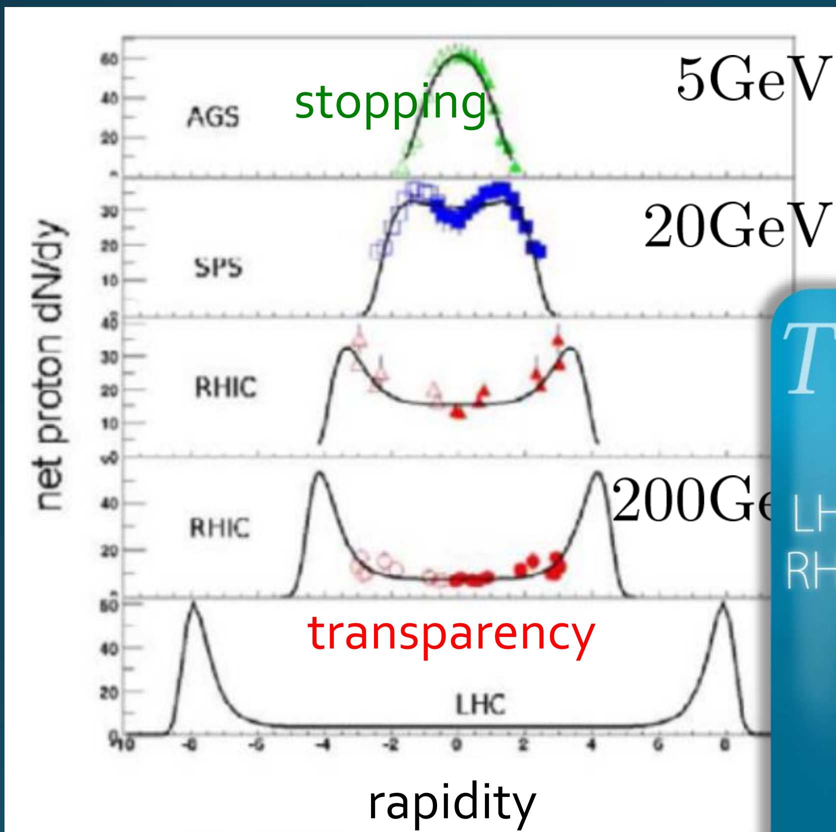
No approx., ex. van Kampen’s system size expansion



10GeV
10^2GeV
1TeV
$\sqrt{s_{NN}}$
AGS
-1996
SPS
1994-2000
RHIC
2000-
LHC
2010-
RHIC-BES
2010-
FAIR
2022-?
NICA
2017-
J-PARC-HI
2025~?
2-6.2 GeV
creation of quark-gluon plasma,
strongly-interacting QGP
~2010
History of HIC = increasing energy
2010~
Beam-energy scan
Low-energy exp.
Heavy-Ion Collisions

Baryon Stopping

rapidity dep. of net-proton #



$\sqrt{s_{NN}} \simeq 4 - 6\text{GeV}$

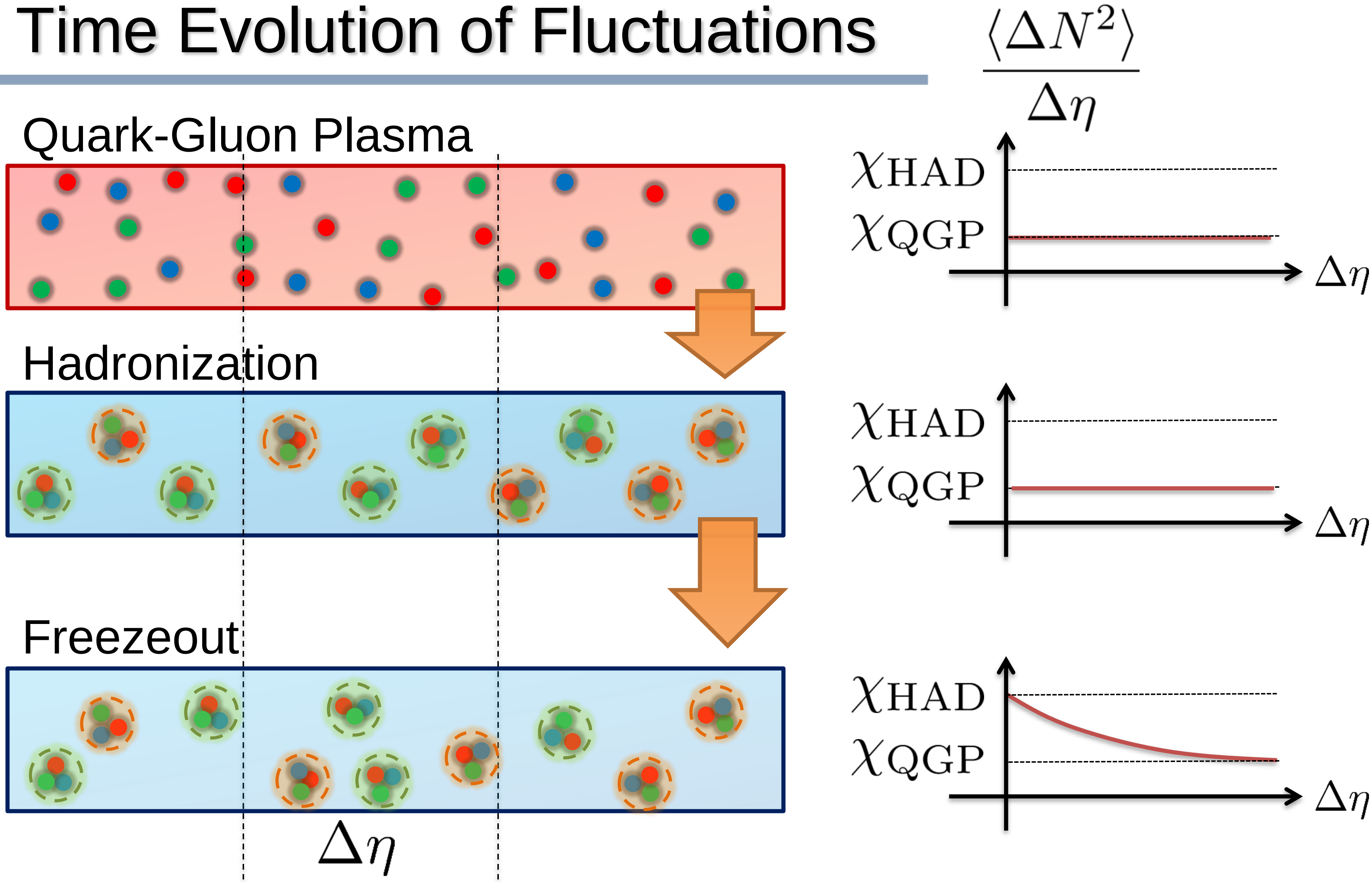
Baryons stop at collision point

$\sqrt{s_{NN}} > 10\text{GeV}$

Baryons pass through

phase diagram from
J-PARC White Paper

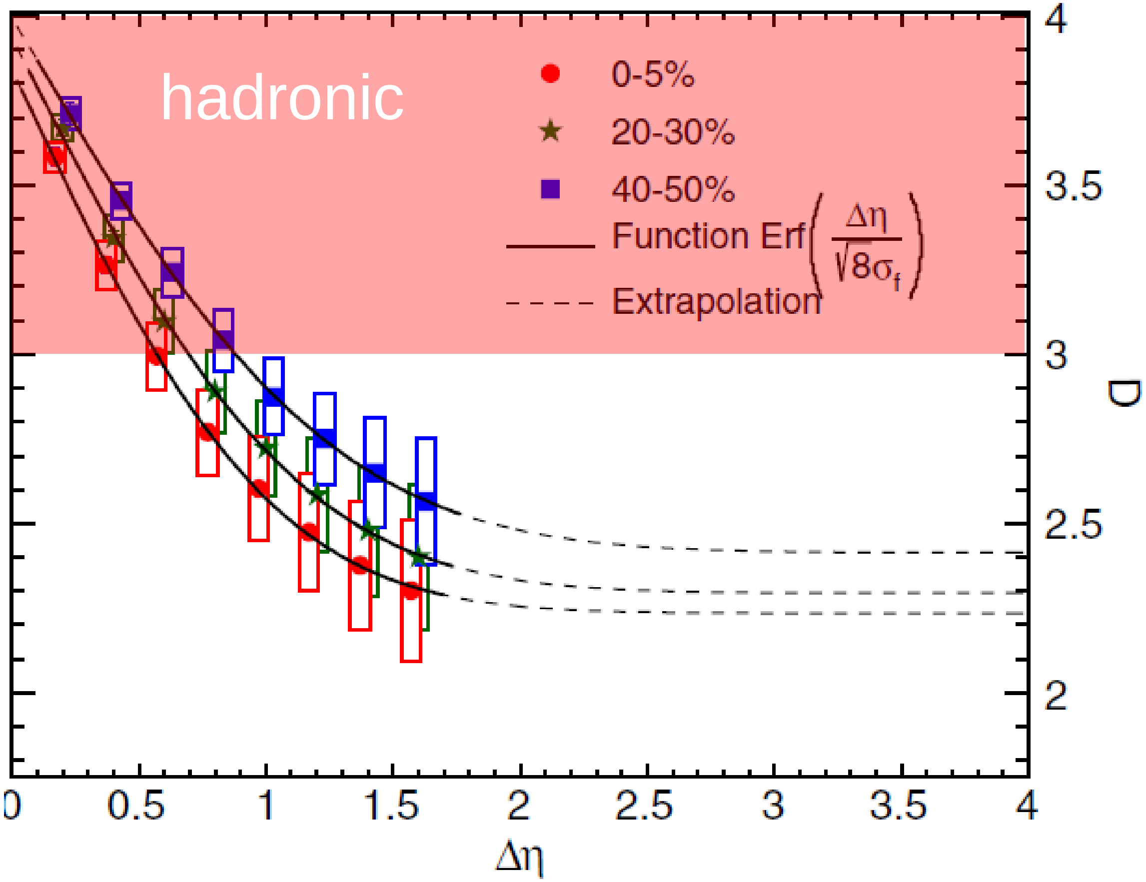
Time Evolution of Fluctuations



Variation of a conserved charge is achieved only through diffusion. ⇒ The larger $\Delta\eta$, the slower diffusion

Δη Dependence @ ALICE

ALICE
PRL 2013

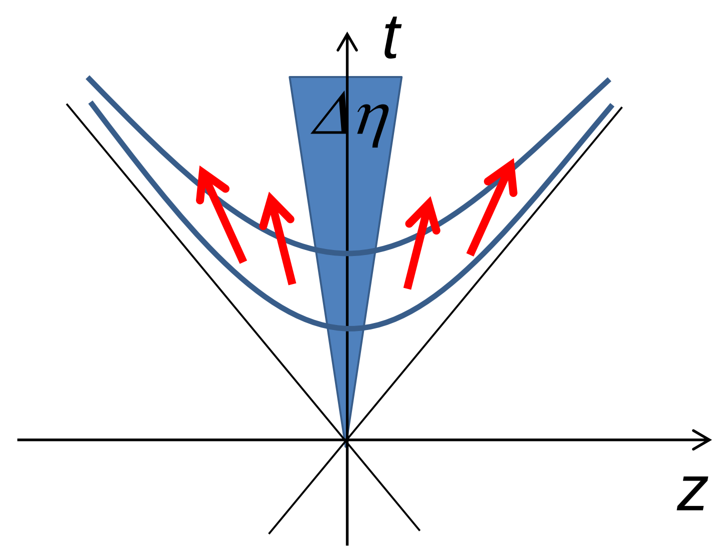


rapidity window

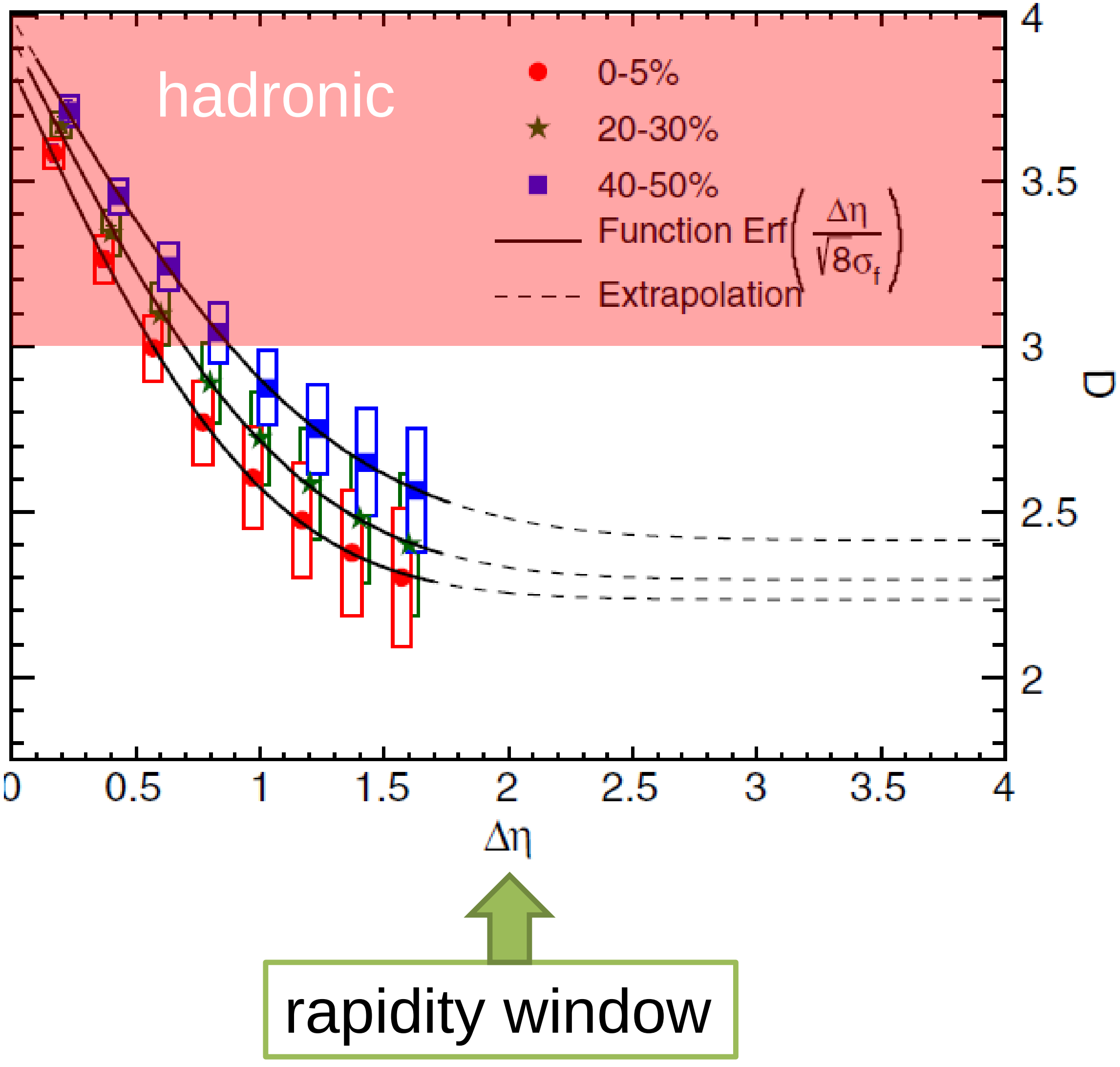
D-measure

$$D = 4\frac{\langle \delta N_Q^2 \rangle}{\langle N_Q^+ + N_Q^- \rangle}$$

- *D* ~ 3-4 Hadronic
- *D* ~ 1-1.5 Quark



Δη Dependence @ ALICE



$$D \sim \frac{\langle \delta N_Q \rangle^2}{\Delta\eta}$$

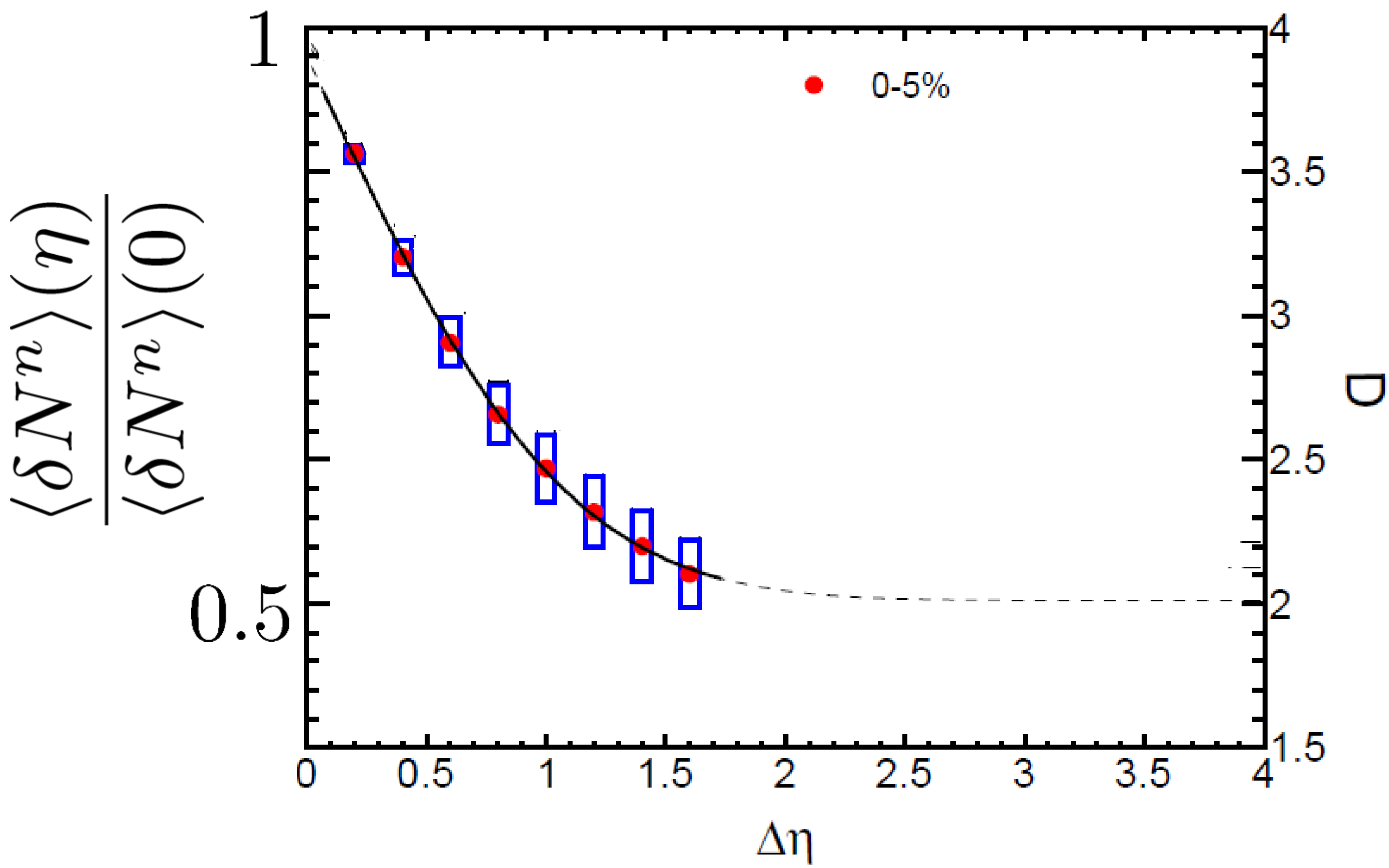
has to be a constant in equil. medium

Fluctuation of N_Q at ALICE is not the equilibrated one.

$\langle \delta N_Q^4 \rangle$ @ LHC ?

How does $\langle \delta N_Q^4 \rangle_c$ behave as a function of $\Delta\eta$?

suppression or enhancement



$<\delta N_Q{}^4>$ @ LHC ?

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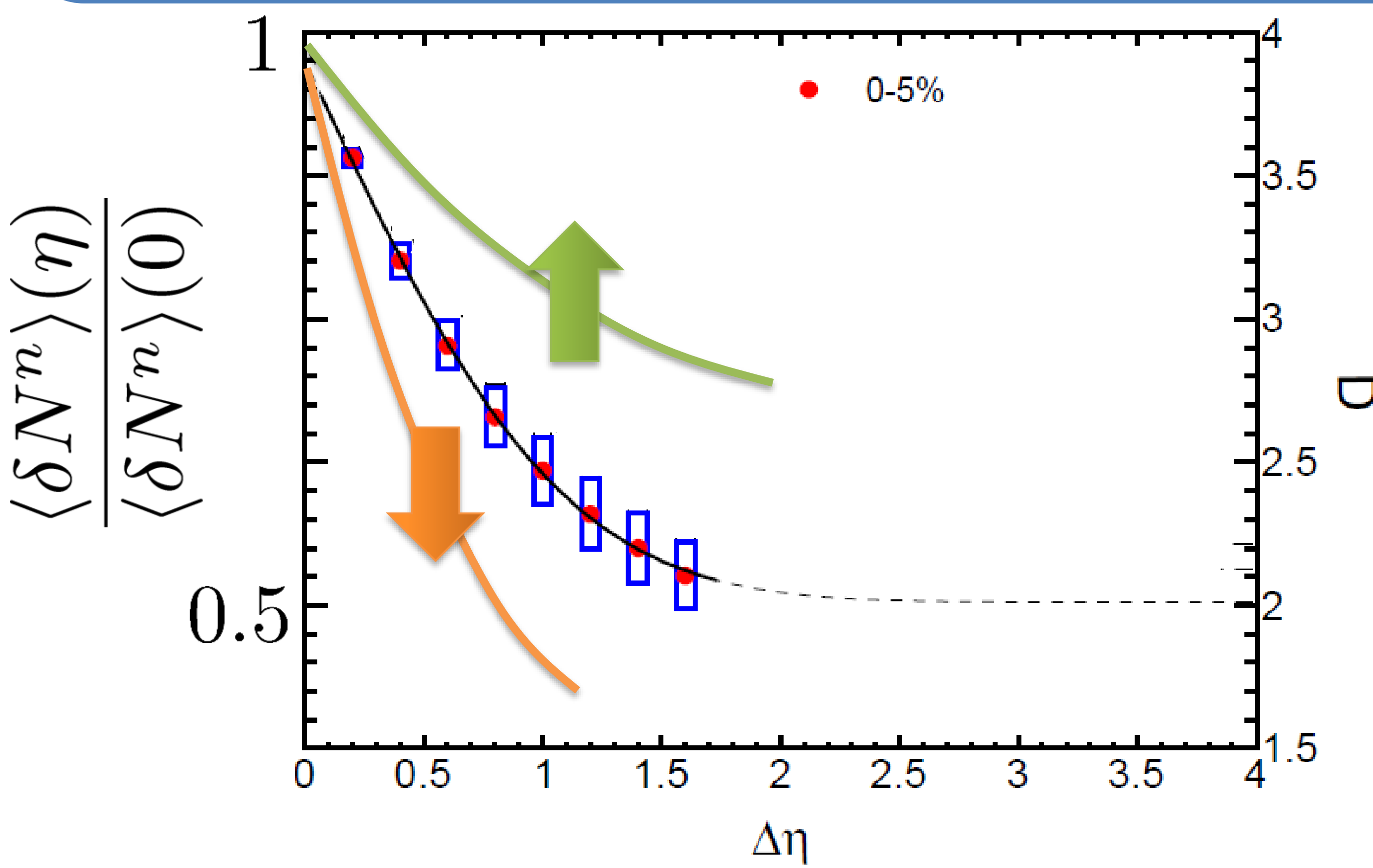

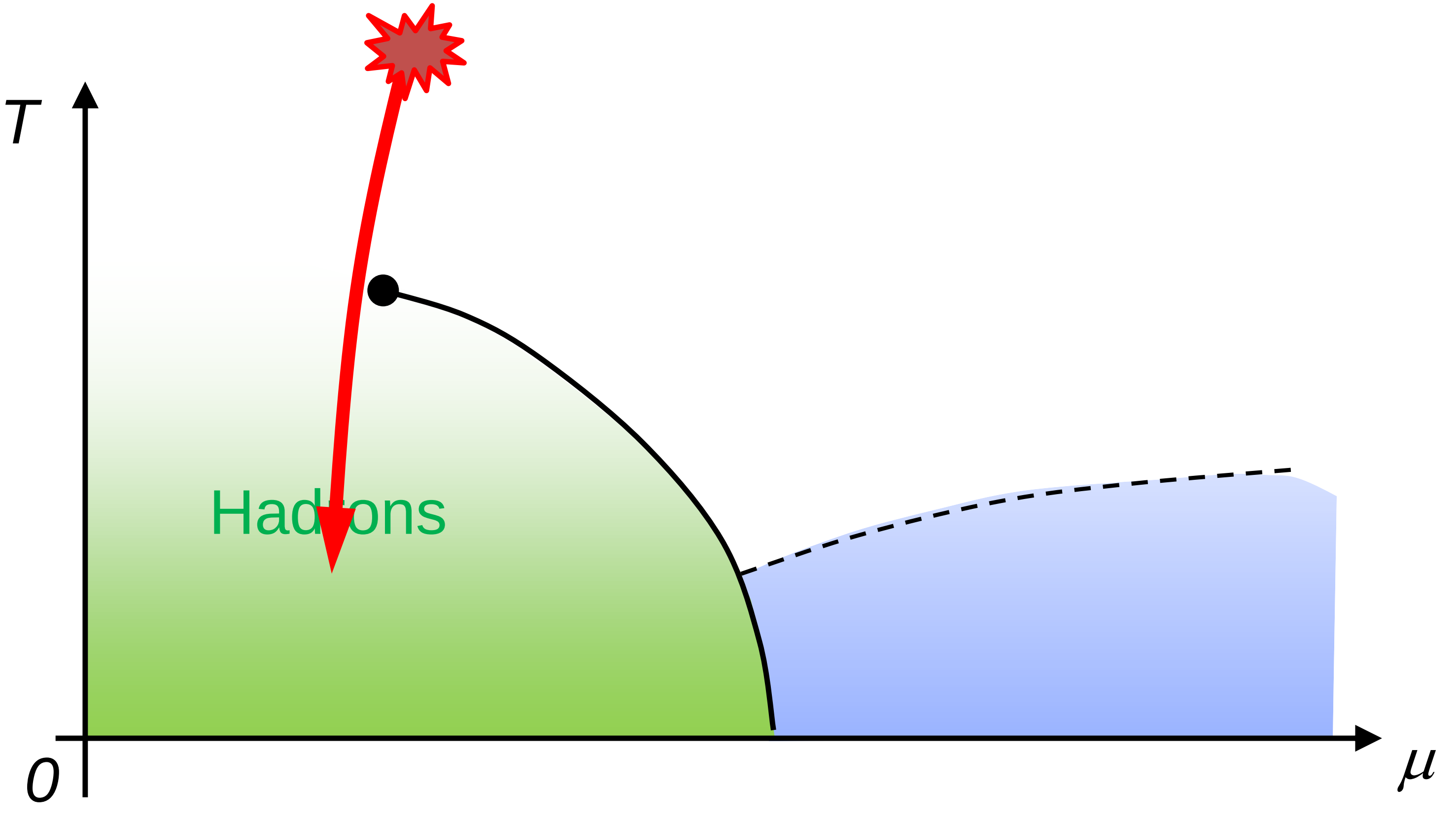

T
Hadrons
0
μ