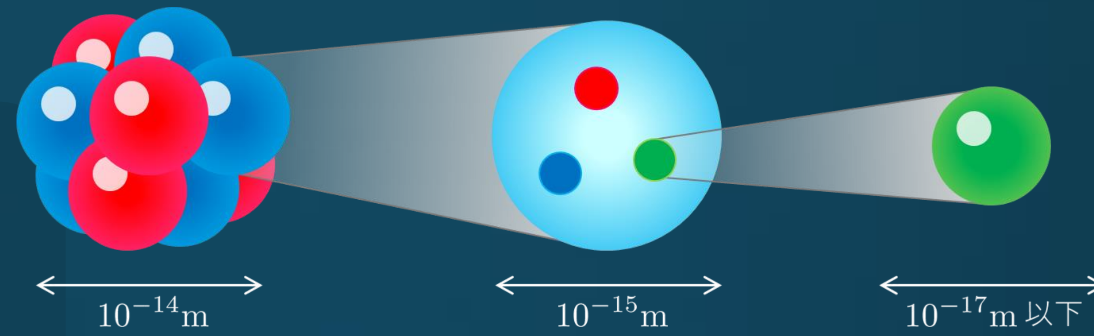
京都大学・原子核ハドロン研究室セミナー　2018年10月3日

北沢正清
(阪大理)

超高密度領域における QCDの相構造と その実験的探索

目次
1. J-PARC-HIとその物理の外観
2. ゆらぎを使って探るQCD相構造

原子核物理の展開

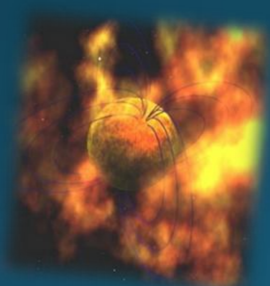


研究対象

- 核構造・核反応
- ハイパー核
- ハドロン
- QCDの相転移現象
- 媒質中のハドロン

歴史的発見

- ストレンジ自由度の発見
- 多様なハドロンの発見
- QCDの成立
- 中性子星・超新星爆発
- 格子QCDの発展



$$\mathcal{L} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}F_{\mu\nu,a}F_a^{\mu\nu}$$

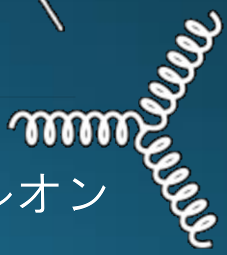
量子色力学
Quantum ChromoDynamics (QCD)

$$\mathcal{L} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}F_{\mu\nu,a}F_a^{\mu\nu}$$

登場人物

- クォーク：物質場、カラー電荷
- グルオン：クォーク間の力を媒介

- 1970年代、物質の基礎理論として確立
- だが、難解すぎて誰にも解けない



QCDの諸性質の理解には、実験的情報が不可欠

J-PARC-HI

J-PARC = Japan Proton Accelerator Research Complex

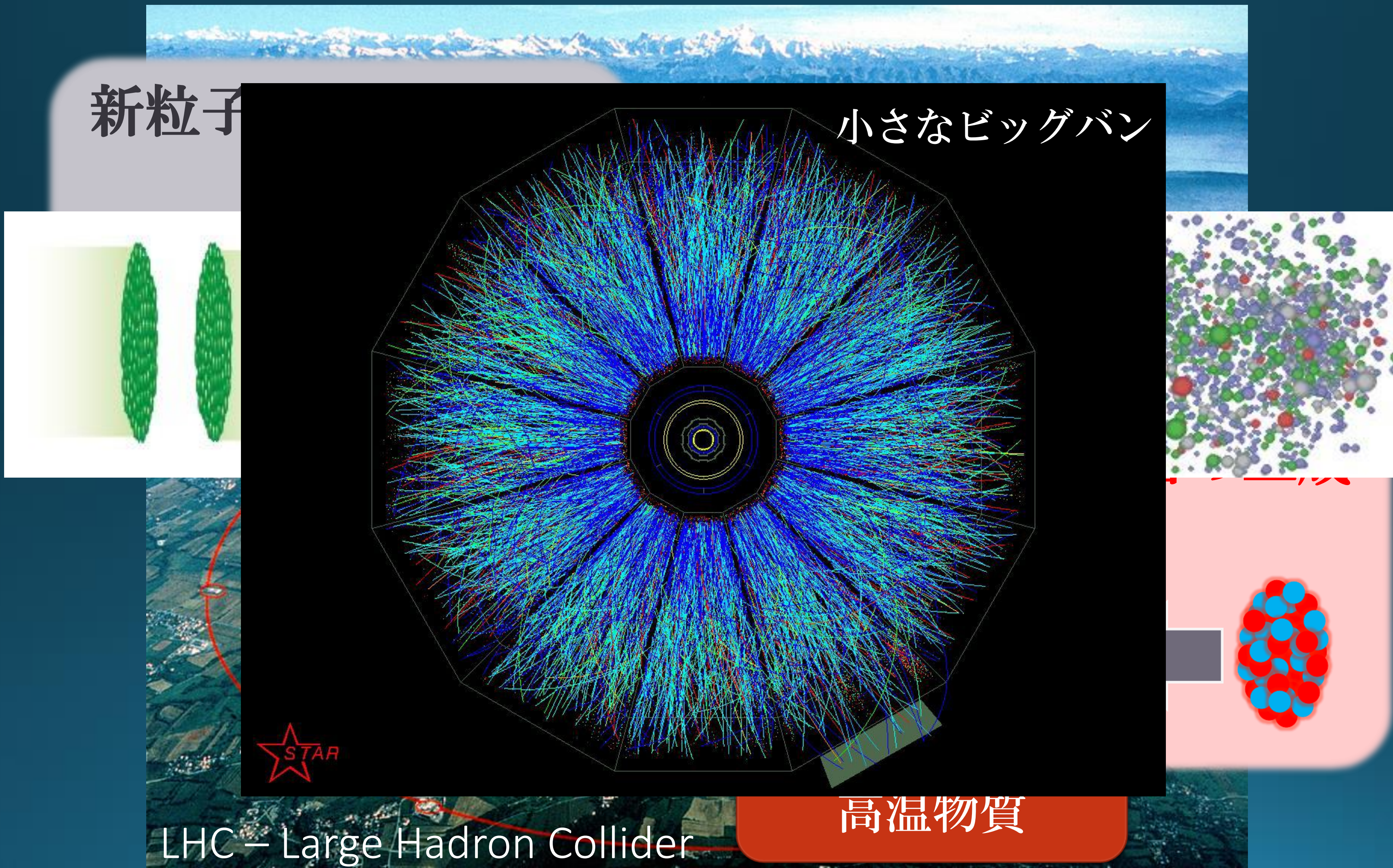
J-PARC-HI = J-PARC **H**eavy-**I**on Program

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

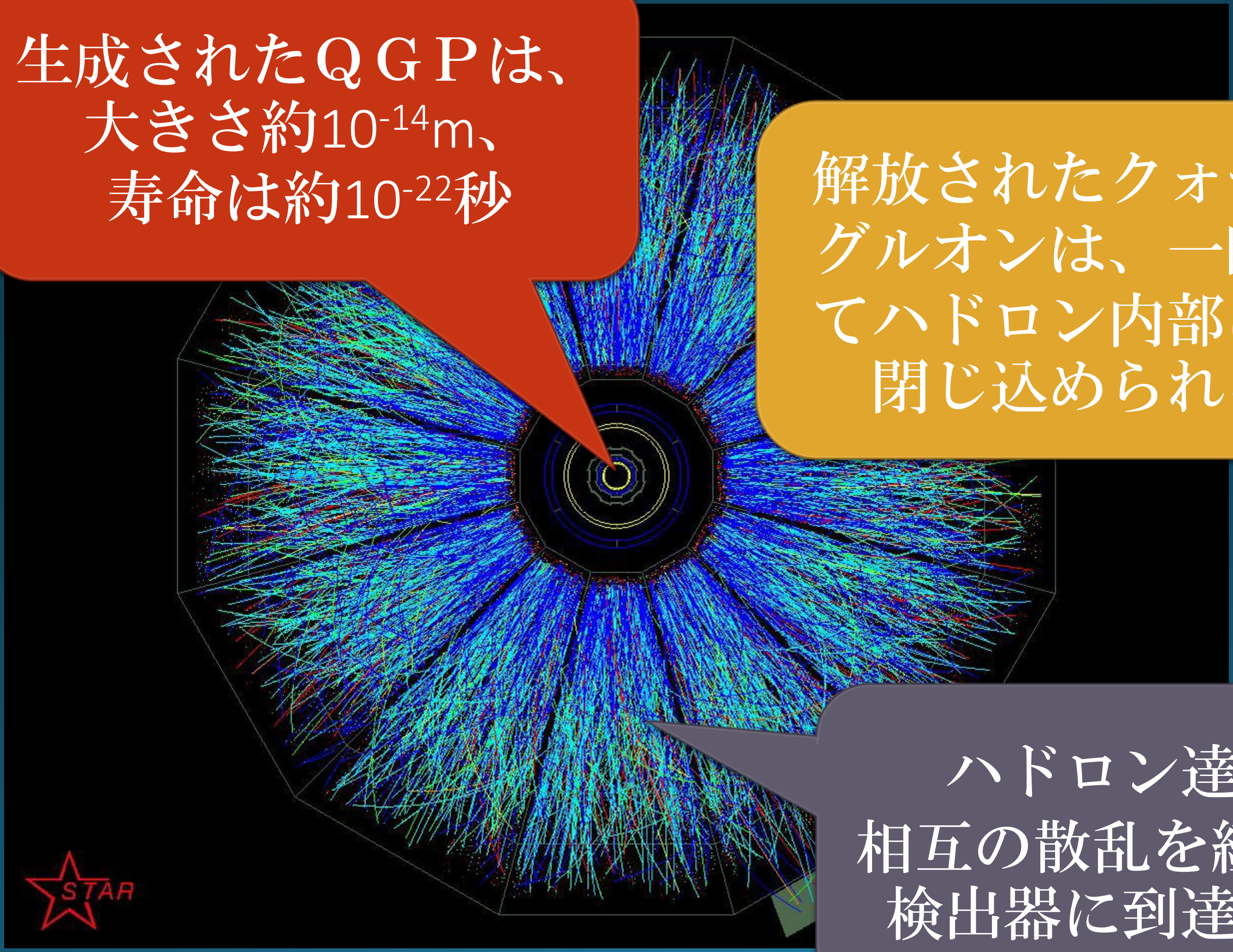
- White paper / Letter of Intent (2016)
  - http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

相対論的重イオン衝突実験

相対論的重イオン衝突実験



ＱＧＰの生成と観測

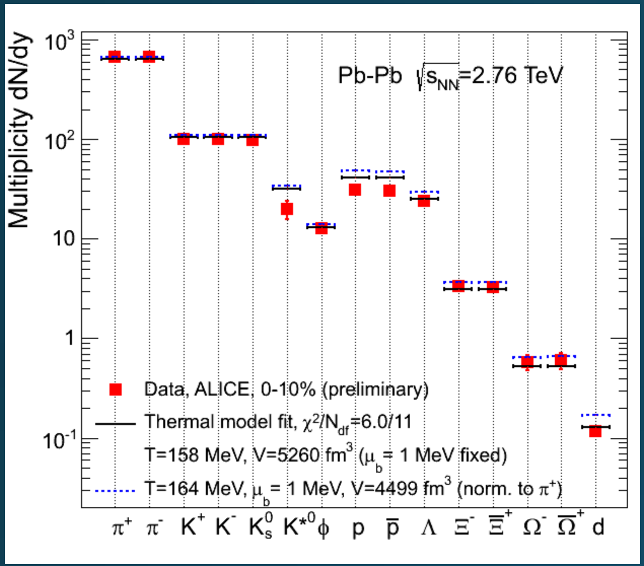


生成されたＱＧＰは、
大きさ約10^{-14}m、
寿命は約10^{-22}秒

解放されたクォークと
グルオンは、一瞬にし
てハドロン内部に再び
閉じ込められる。

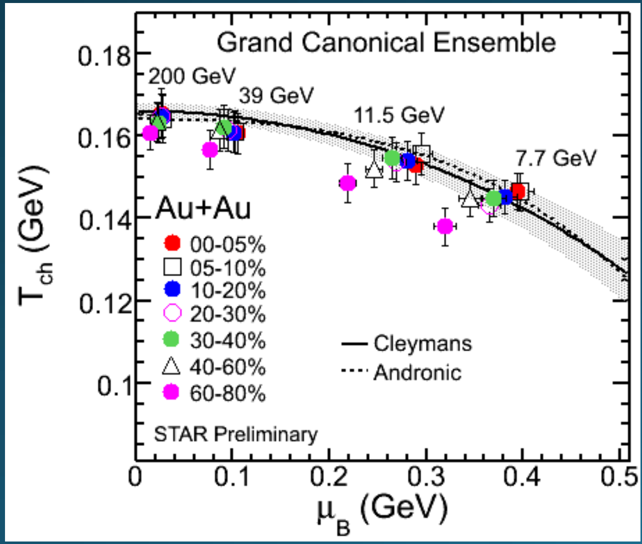
ハドロン達は、
相互の散乱を経ながら
検出器に到達する。

熱平衡化の証拠



各種ハドロンの粒子数は、
温度 *T*、化学ポテンシャルμの
熱平衡値で再現可能

(化学)平衡状態の実現を示唆



実験的に決定した *T*, μは、
衝突エネルギーに応じて
相図上を移動する

$10\,\mathrm{GeV}$ $10^2\,\mathrm{GeV}$ $1\,\mathrm{TeV}$ $\sqrt{s_{NN}}$

AGS
-1996

SPS
1994-2000

RHIC
2000-

LHC
2010-

RHIC-BES
2010-

FAIR
2022-?

NICA
2025-?

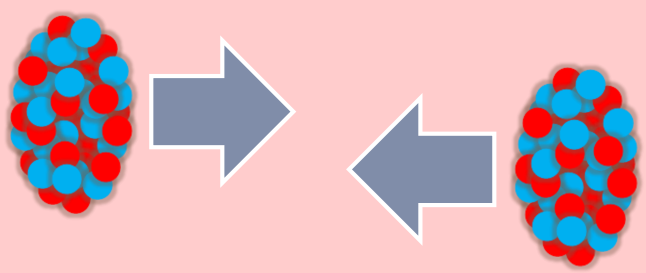
J-PARC-HI
2025~?
2-6.2 GeV

creation of quark-gluon plasma,
strongly-interacting QGP

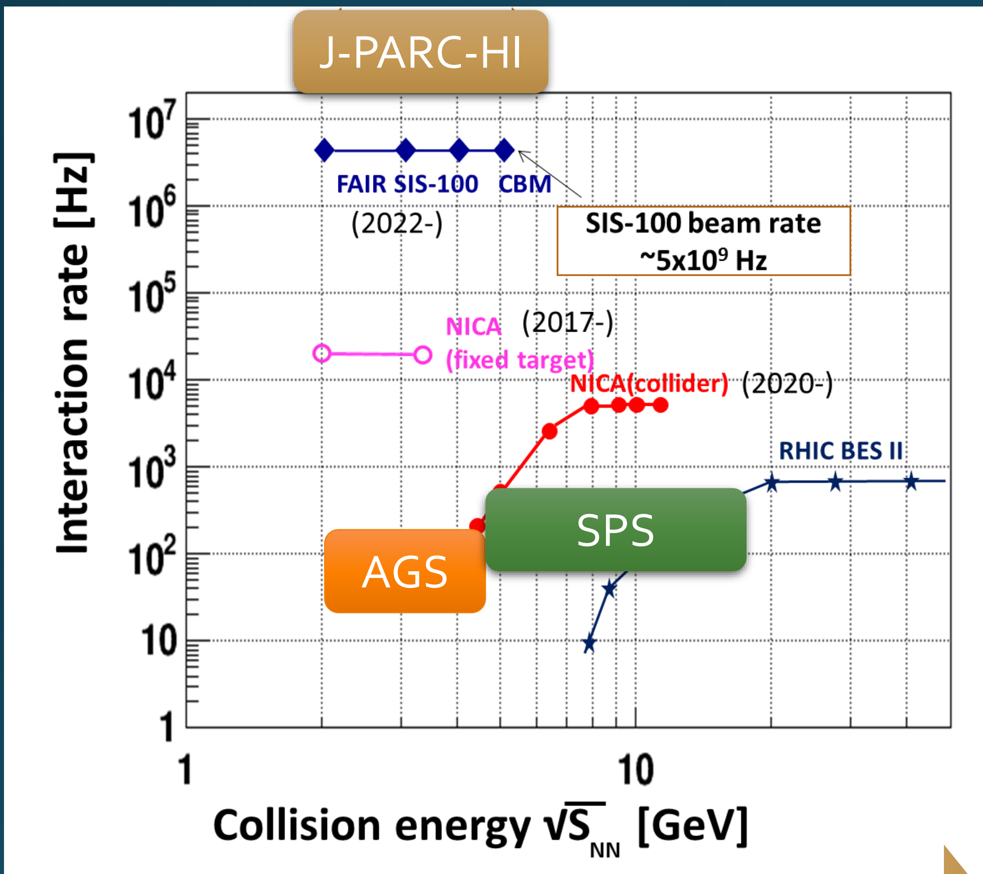
~2010
History of HIC = increasing energy

2010~
Beam-energy scan
Low-energy exp.

Heavy-Ion Collisions



Collision Rate



J-PARC-HI:

High-luminosity X Fixed target

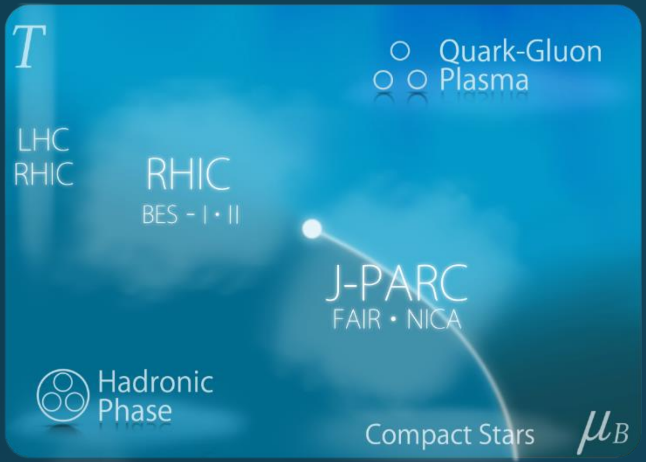
→World highest rate～10^8Hz

5-order higher than AGS,SPS

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

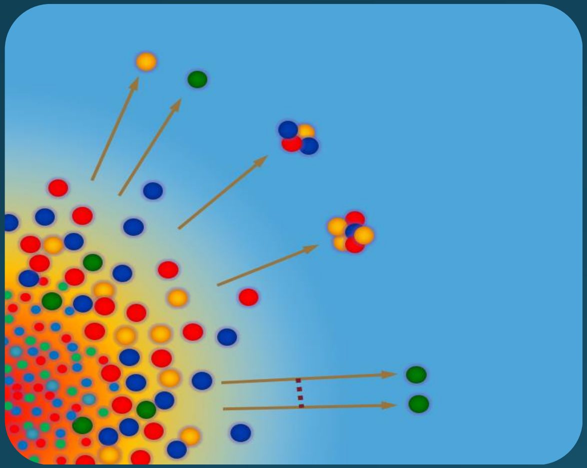
- High-statistical exp.
- various event selections
- higher order correlations
- search of rare events

2 Main Goals of J-PARC-HI



Exploring Dense Medium

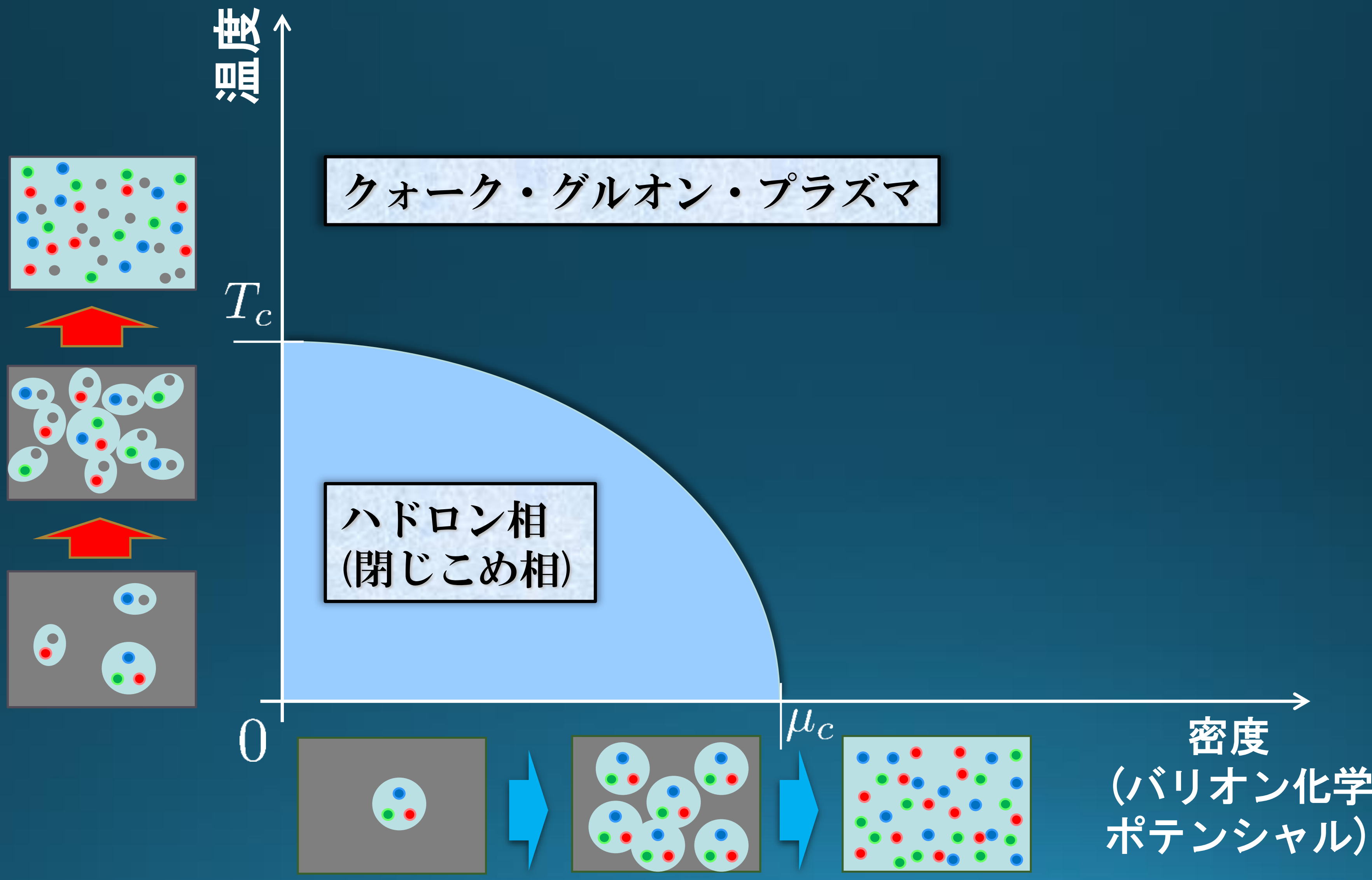
- QCD phase diagram
- 1st order phase transition
- equation of state



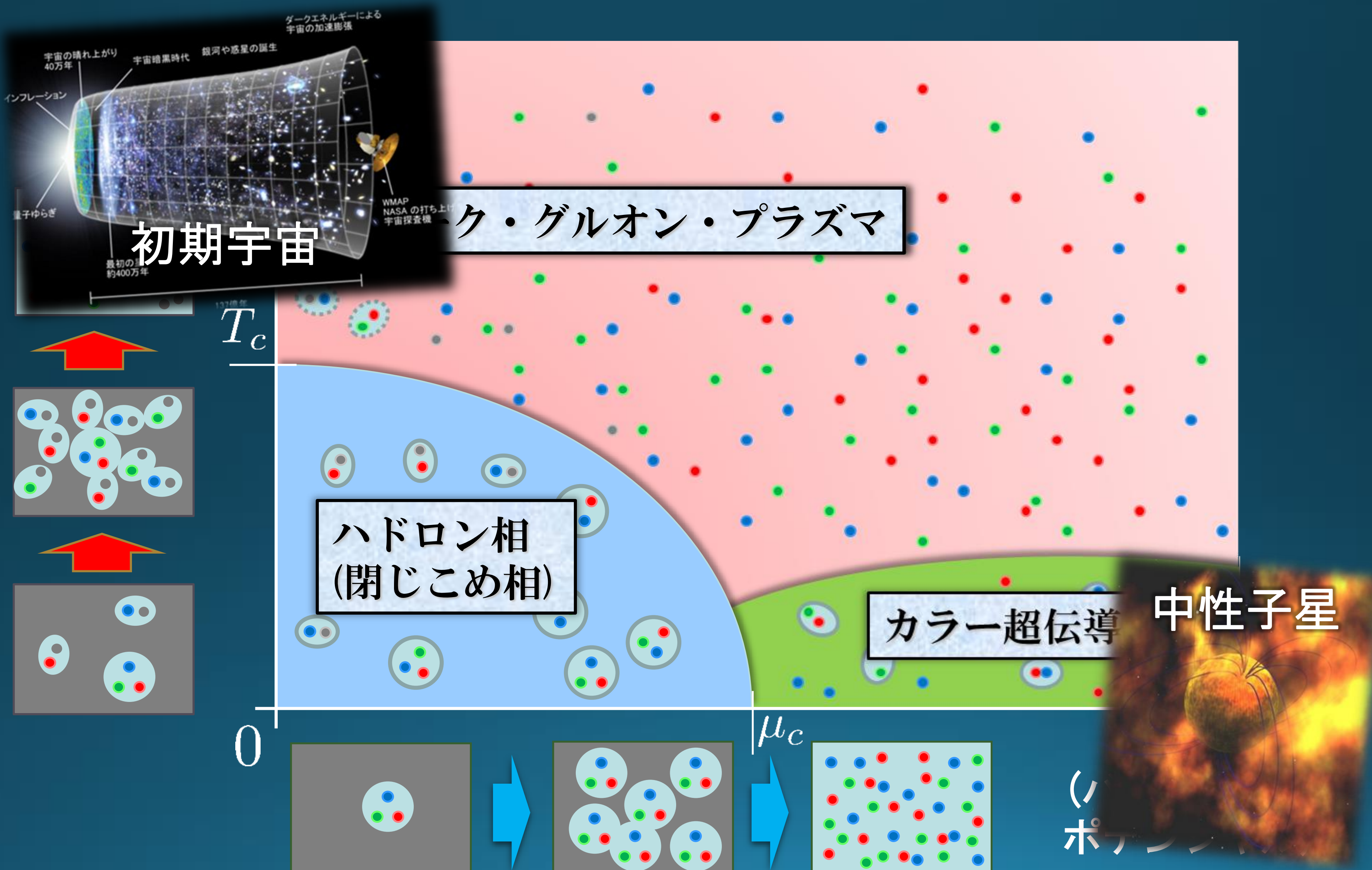
Rare-event Factory

- hyper nuclei
- exotic hadrons
- hadron interaction

素粒子階層の相転移



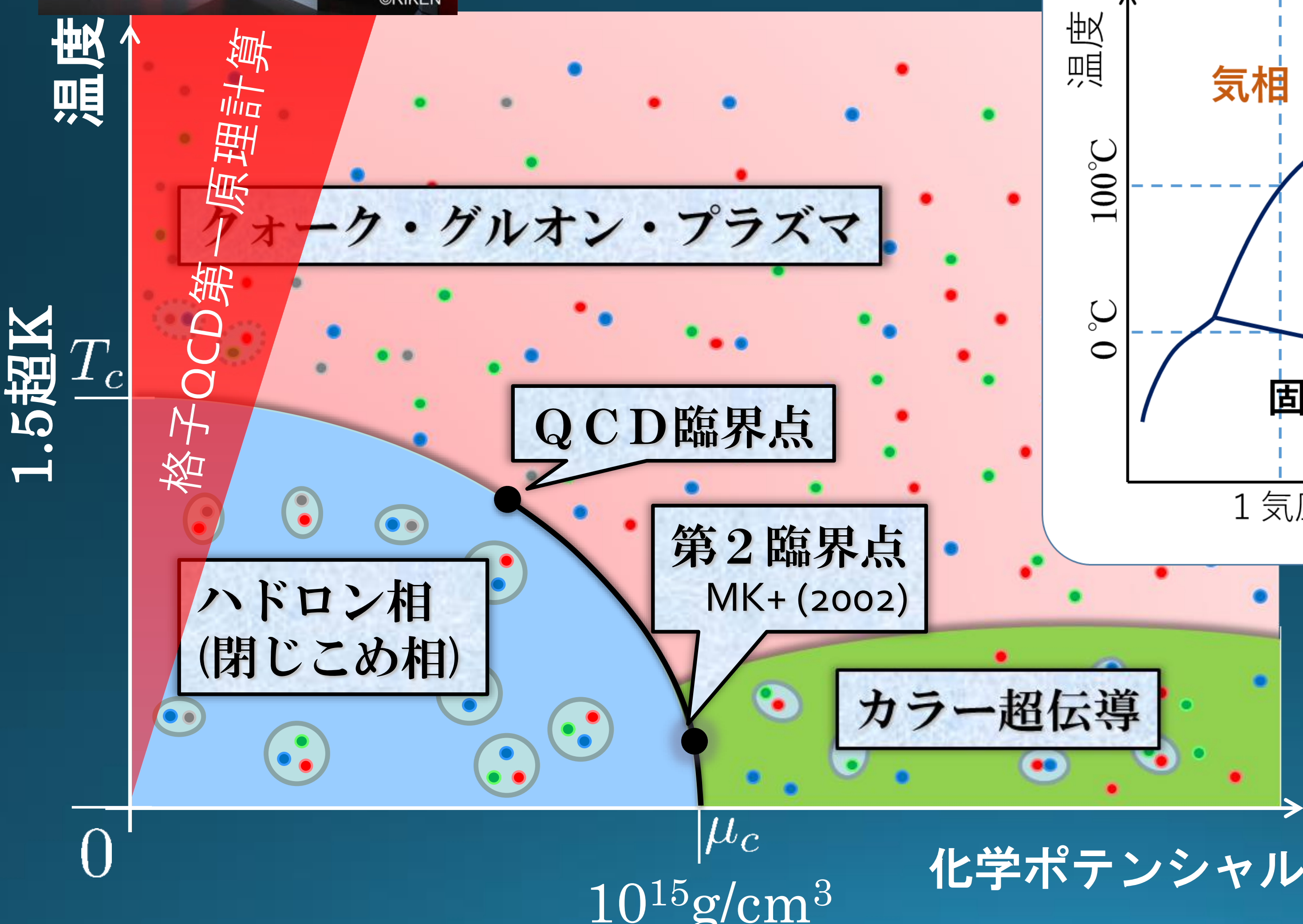
素粒子階層の相転移



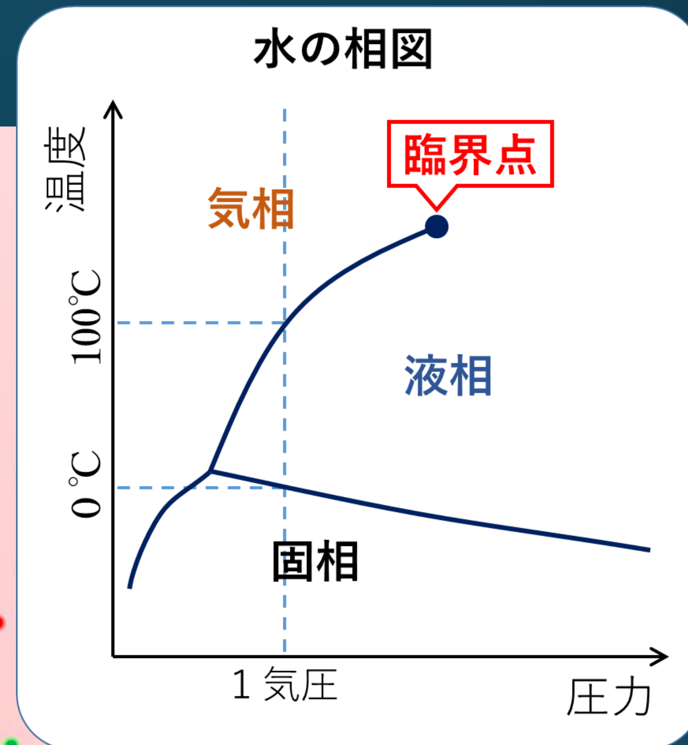
ダークエネルギーによる
宇宙の加速膨張
宇宙の晴れ上がり
40万年
宇宙暗黒時代
銀河や惑星の誕生
インフレーション
WMAP
初期宇宙
ーク・グルオン・プラズマ
T_c
ハドロン相
(閉じこめ相)
カラー超伝導
中性子星
0
μ_c

相転移の次数

京
K computer
©RIKEN

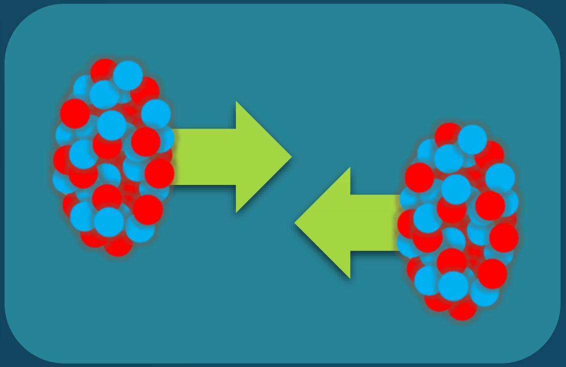


温度
1.5超K
T_c
0
μ_c
10^{15}g/cm^3
化学ポテンシャル
格子QCD第一原理計算
クォーク・グルオン・プラズマ
QCD臨界点
第2臨界点
MK+ (2002)
ハドロン相
(閉じこめ相)
カラー超伝導

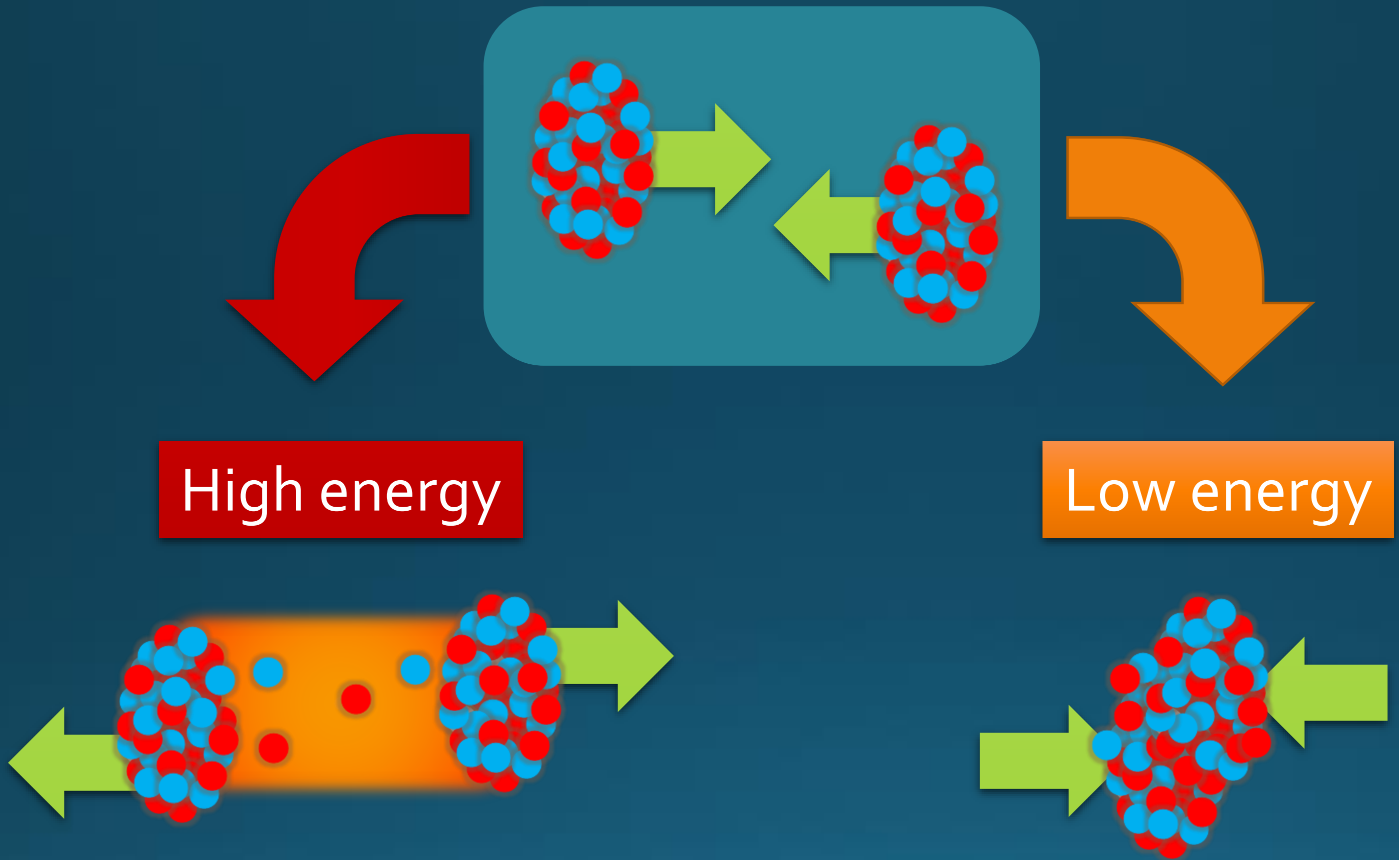


水の相図
温度
100℃
0℃
気相
臨界点
液相
固相
1気圧
圧力

Baryon Stopping



Baryon Stopping



Nuclear transparency

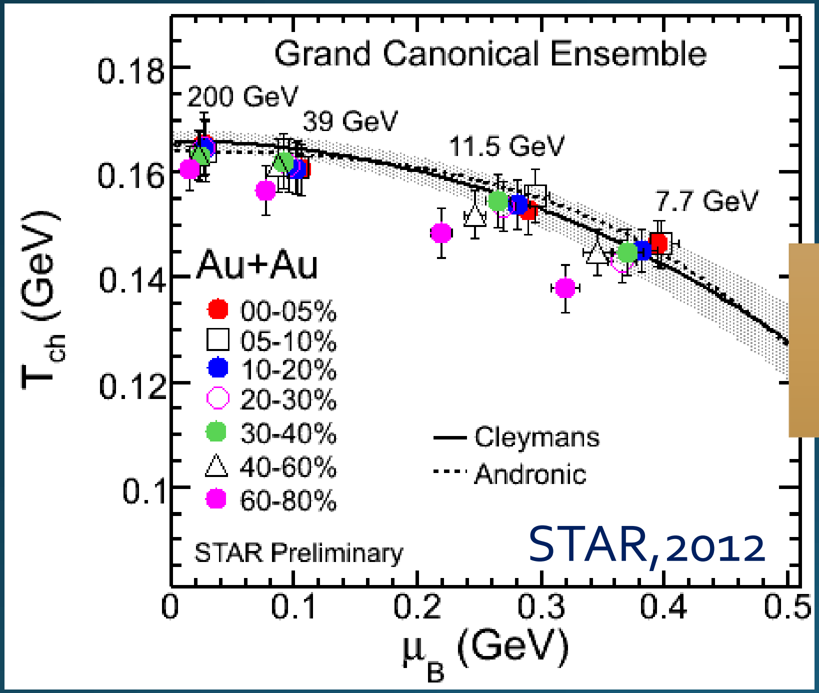
net-baryon #: small

Baryon stopping

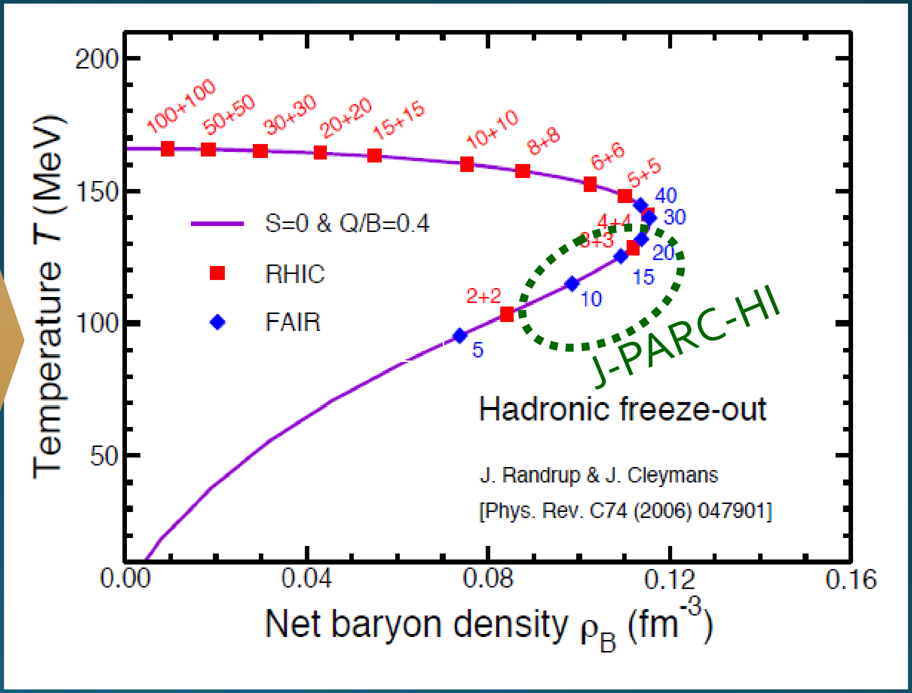
net-baryon #: large

Beam-Energy Scan

T, μ from particle yield



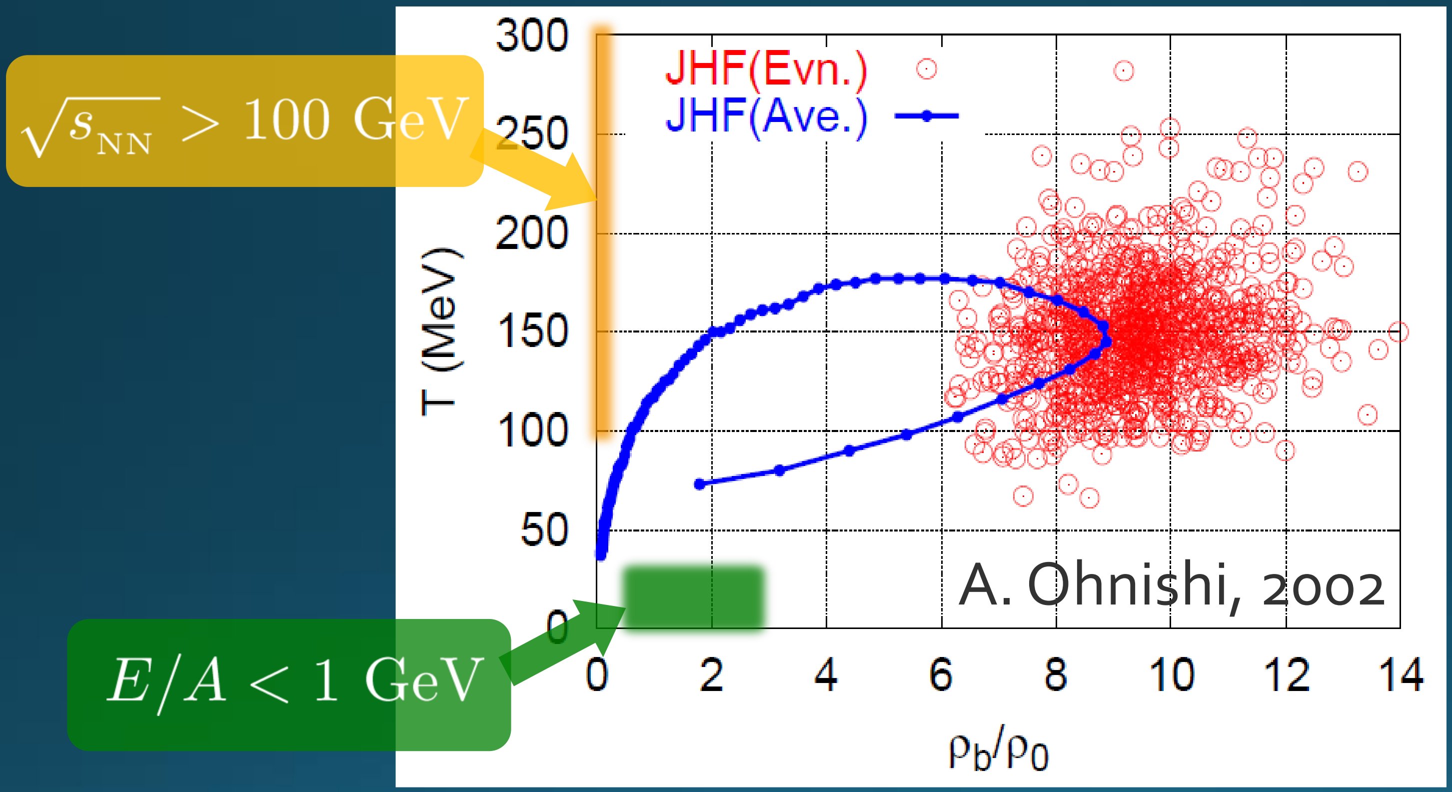
Translation to baryon density



J-PARC energy = highest baryon density

Maximum Density

Time evolution in T-ρ plane by JAM

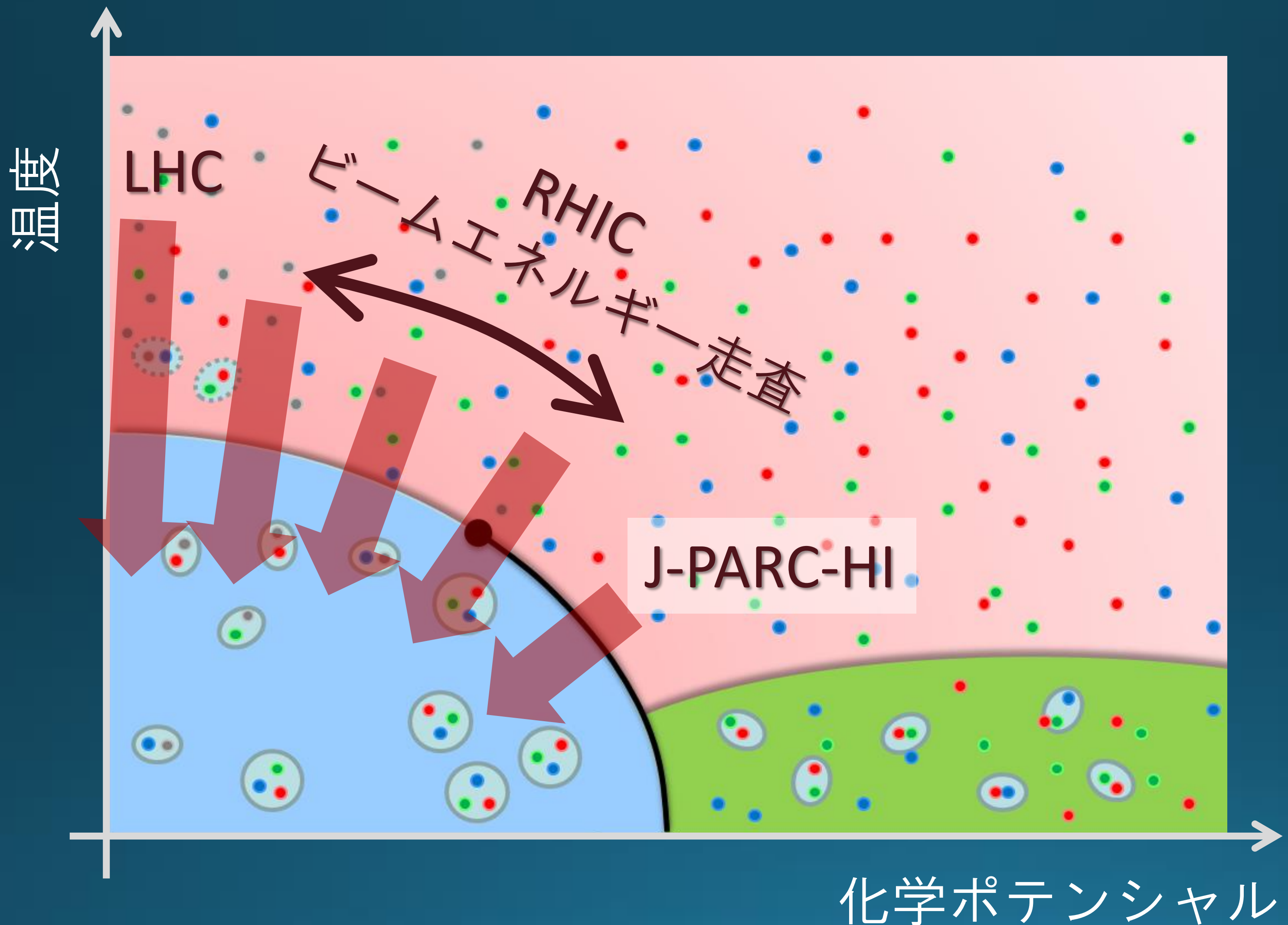


$E/A = 20\text{GeV}$

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

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

ビームエネルギー走査



LHC
2010~

RHIC-BES
Phase I
2010~2014
Phase II
2019~

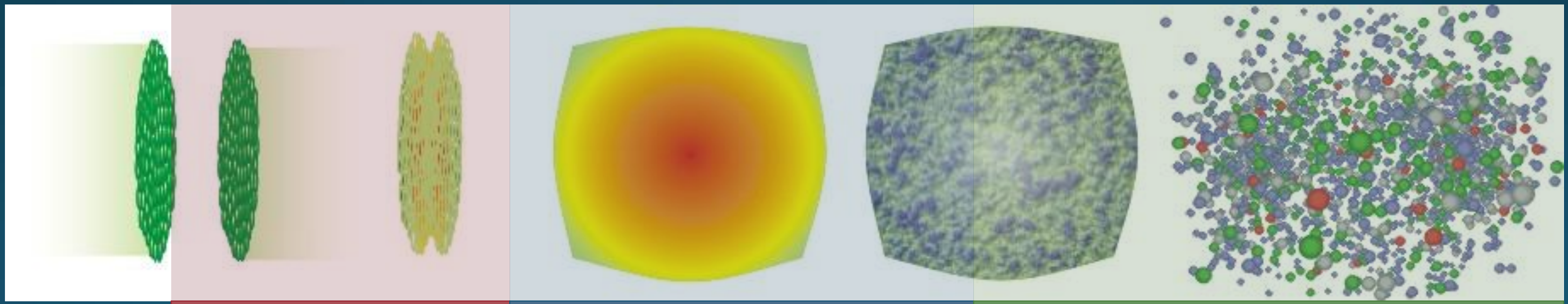
J-PARC
2025~ ⁇

ＱＣＤの相構造は、実験的に探索可能！

Theoretical Challenges

RHIC / LHC

- ☐ creation of QGP
- ☐ hydro. models
- ☐ early thermalization
- ☐ (boost invariance)



RHIC/LHC: Thermalization | Hydrodynamics | Cascade

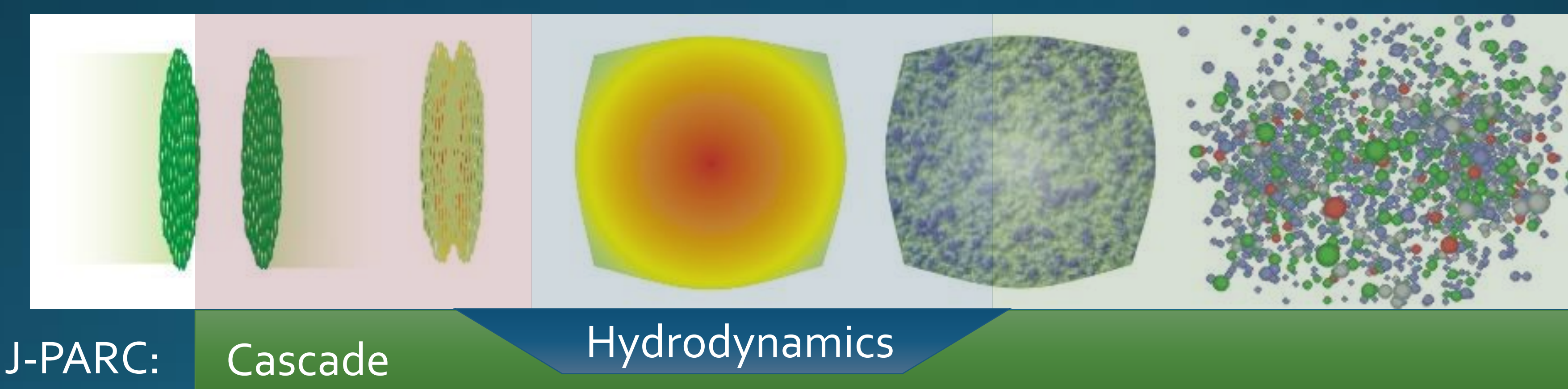
Theoretical Challenges

RHIC / LHC

- ☐ creation of QGP
- ☐ hydro. models
- ☐ early thermalization
- ☐ (boost invariance)

Low-E Collisions

- ☐ Initial condition?
- ☐ Thresholod of QGP formation
- ☐ "Integrated" approach
  - Hydro x Cascade

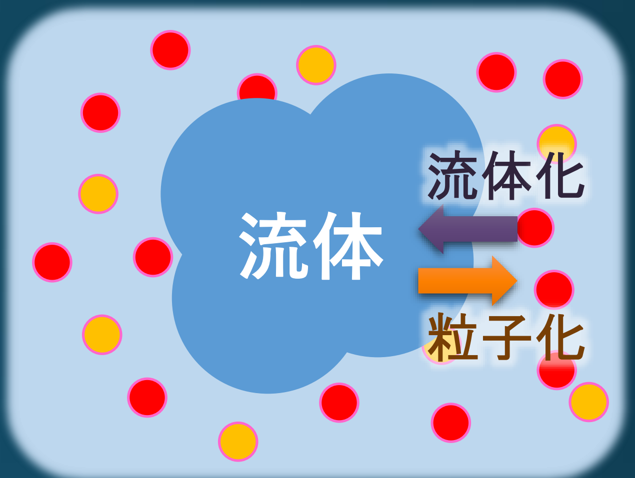


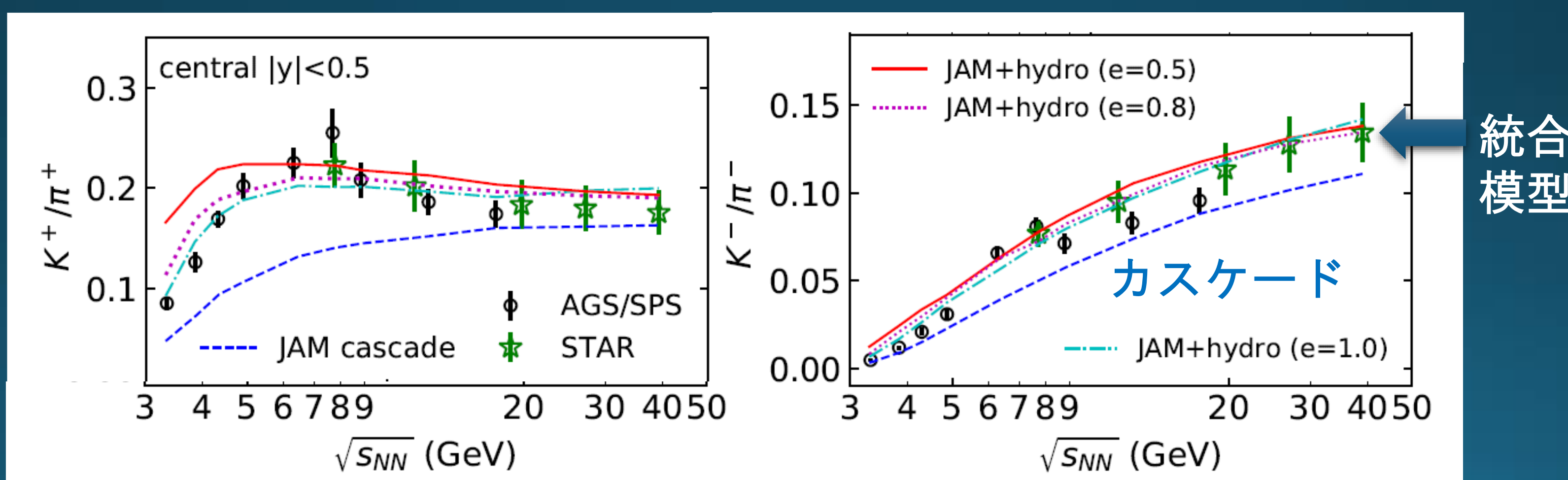
流体・カスケード統合模型

Akamatsu, ..., **Nara**, et al. PRC98 (2018)

流体とハドロンの同時時間発展

- 高密度のハドロン→流体化
- 冷却した流体→ハドロン化



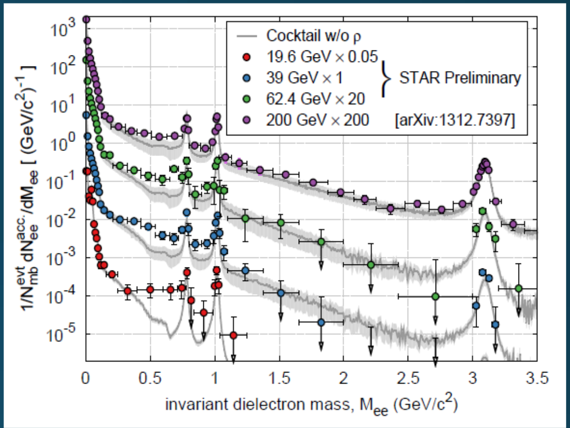


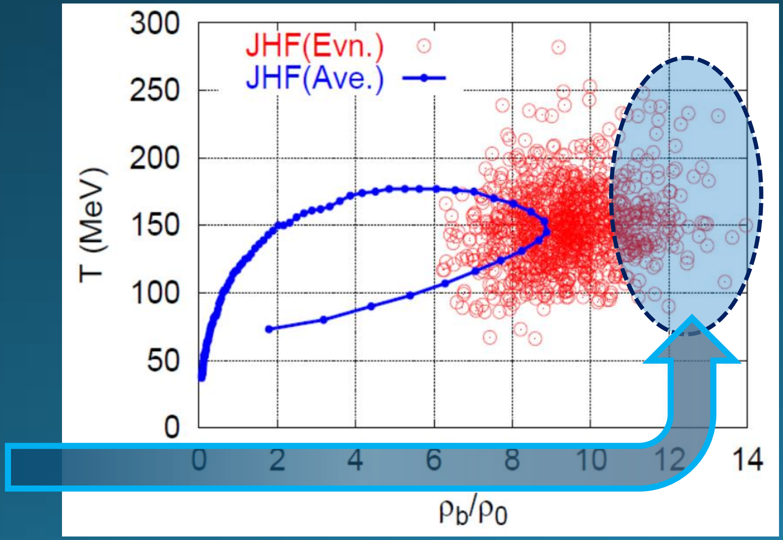
カスケード模型では記述不可能だったデータをよく再現

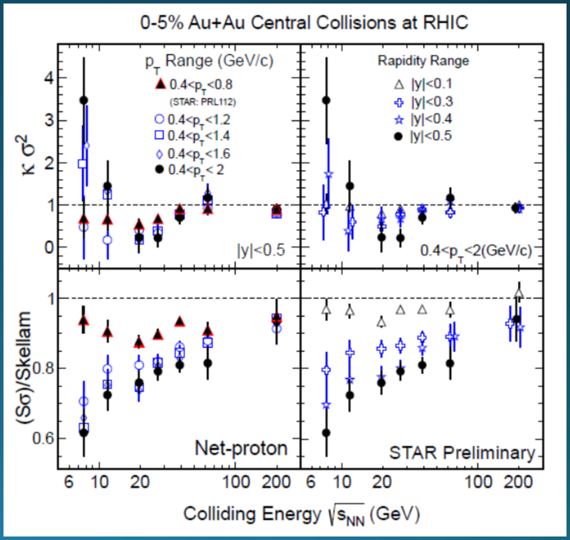
Various Observables

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

- Sophisticated event selections
- Various correlations





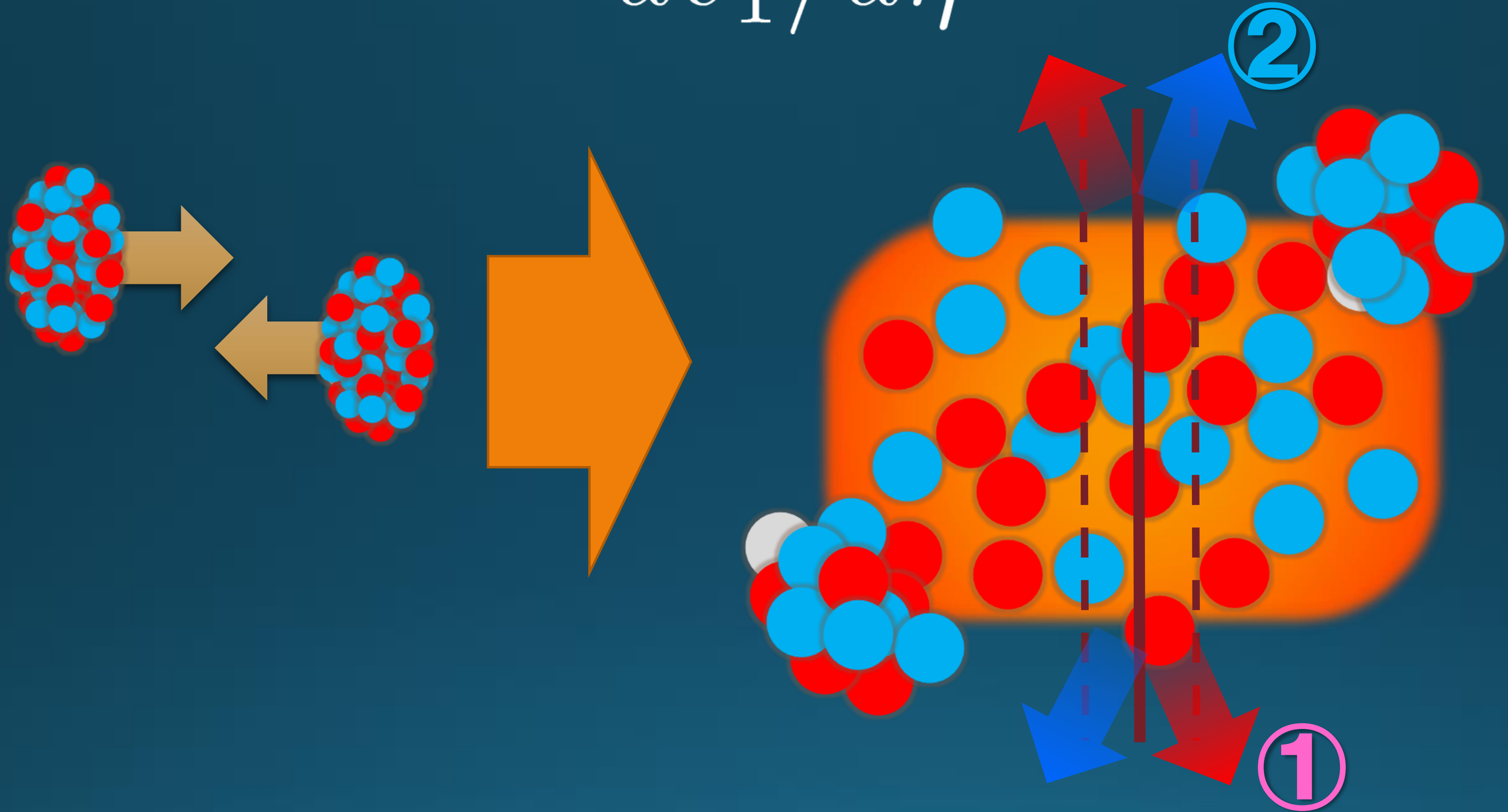


Can we select these events??

MK, Sakaguchi, Sako, Nara, Ohnishi, …

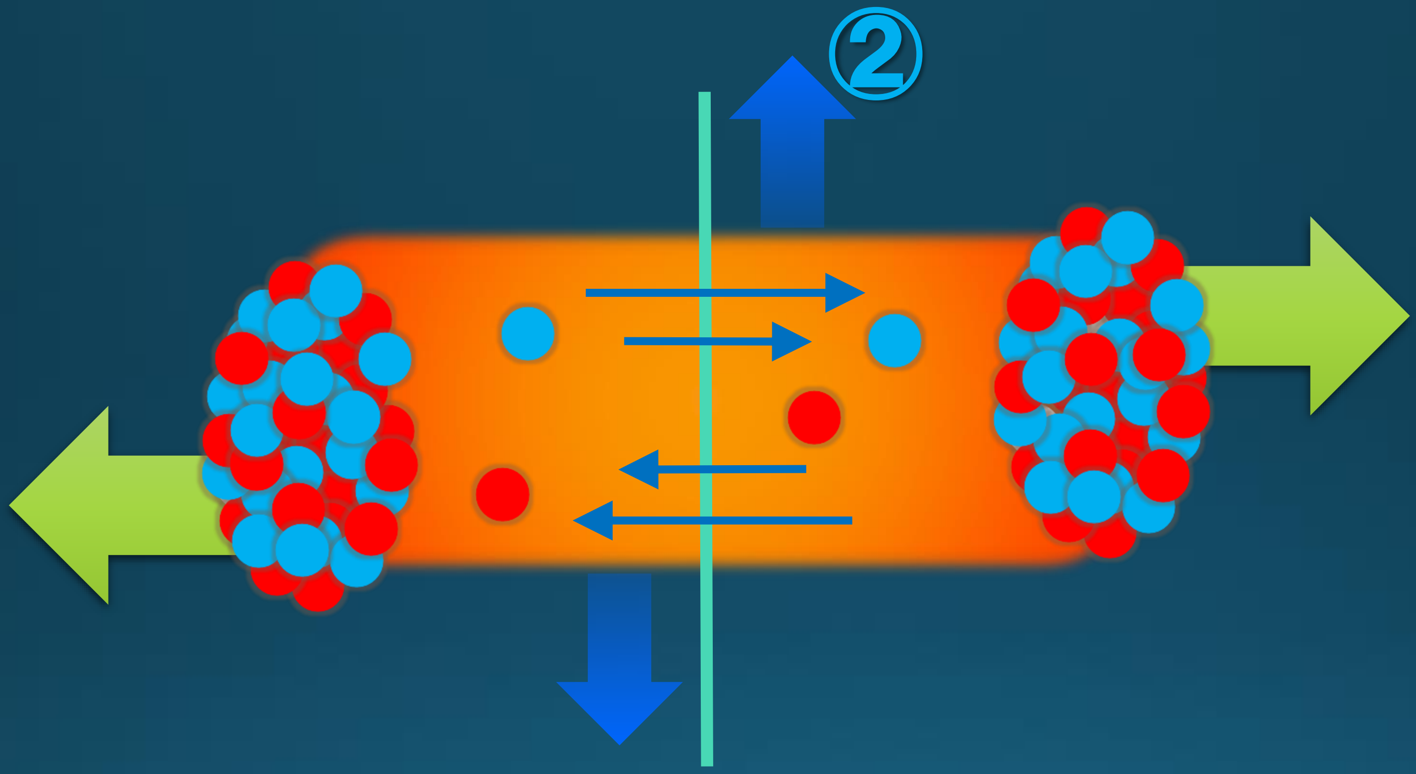
Radial Flow

$$dv_1/d\eta$$

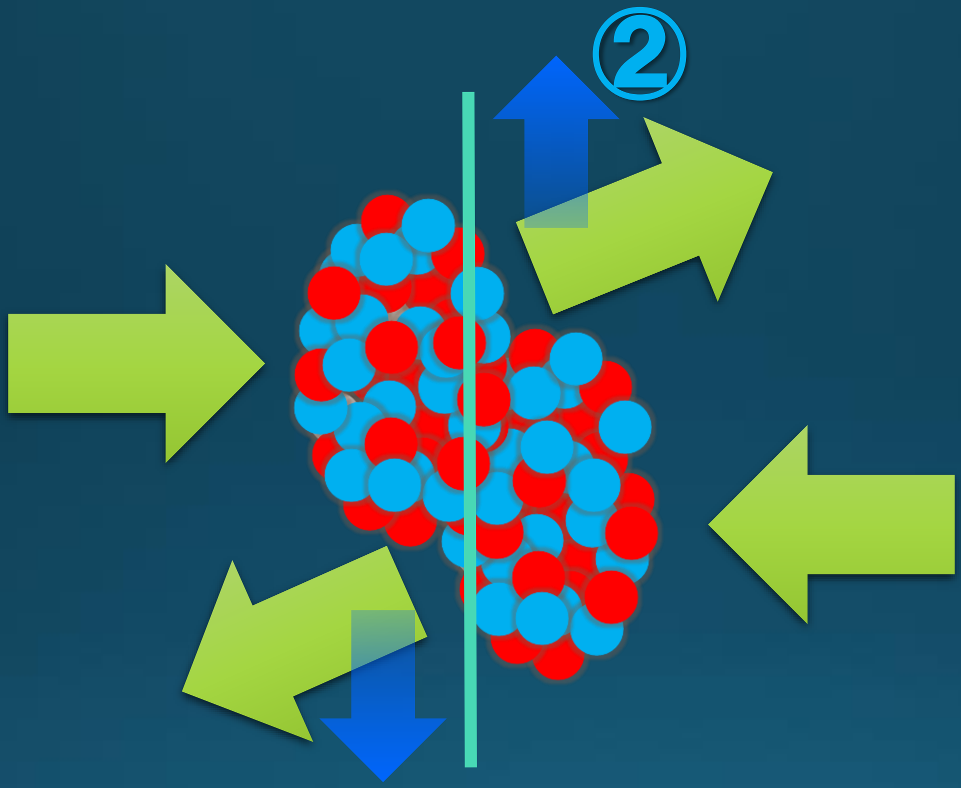


□物質の平均速度は、右上がり？右下がり？

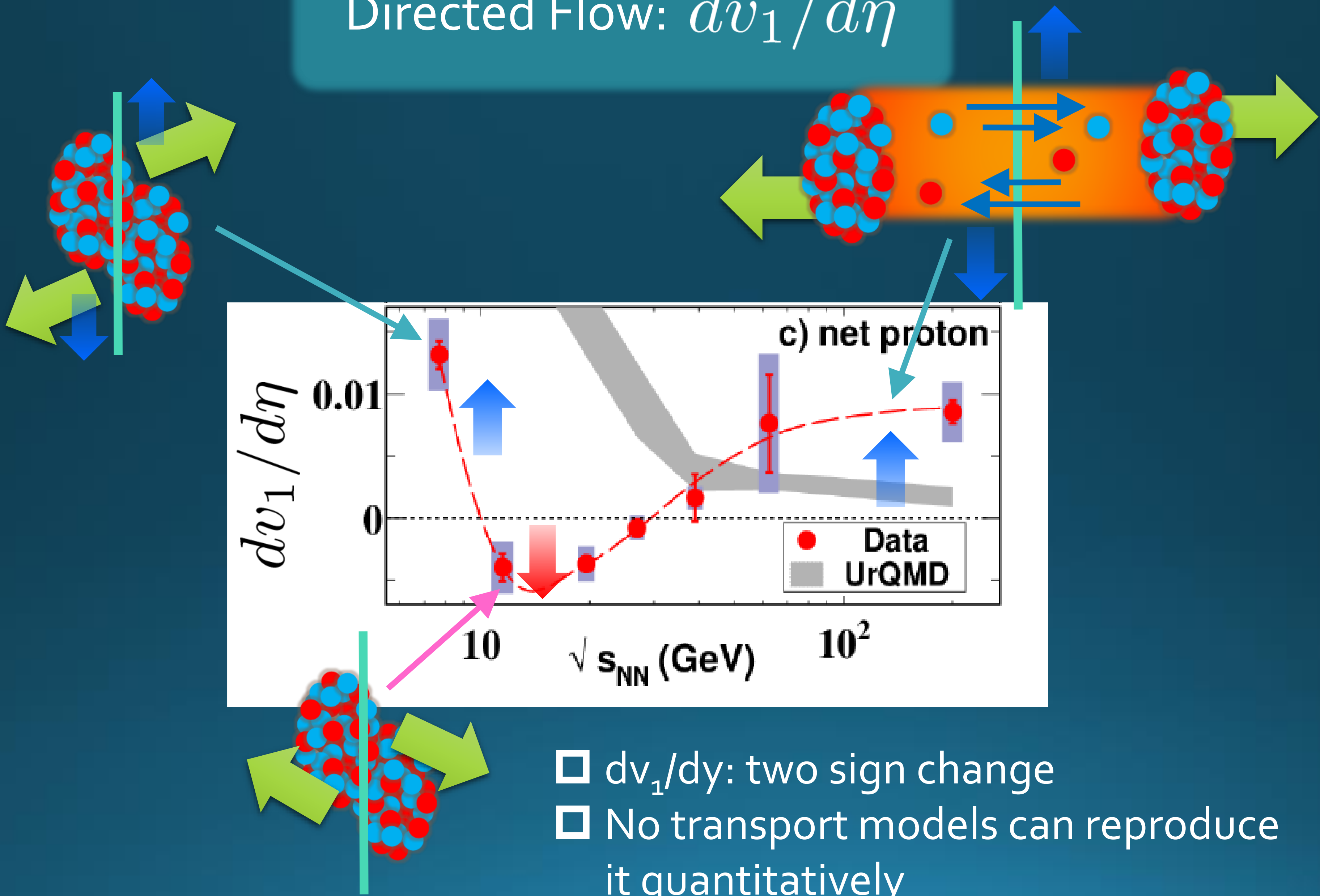
高エネルギー



低エネルギー

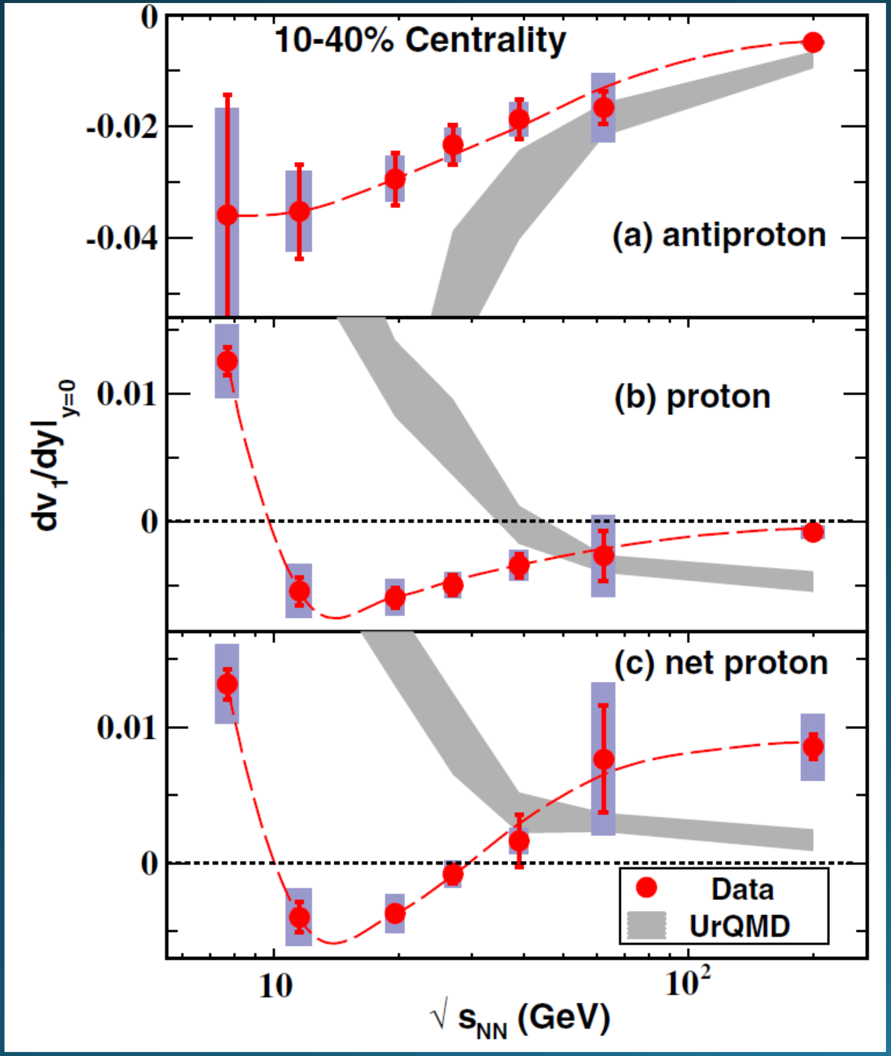


Directed Flow: $dv_1/d\eta$

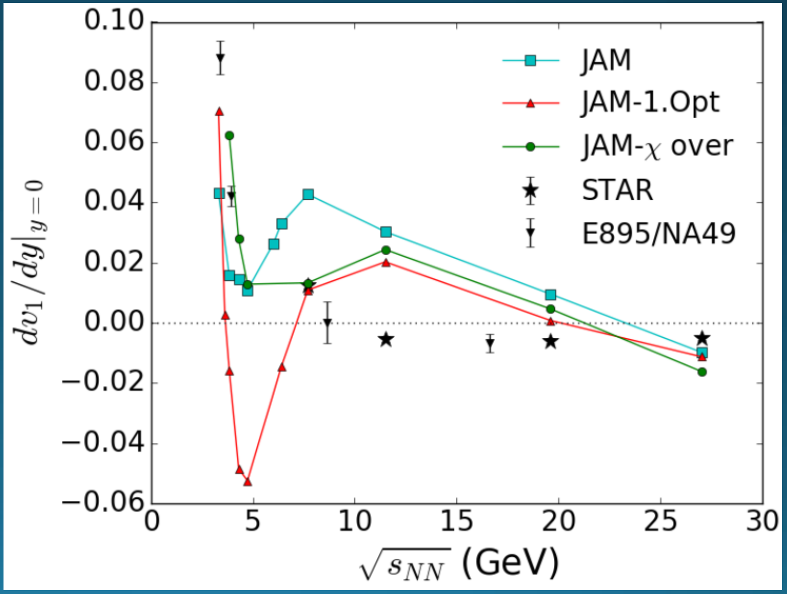


- ☐ dv_1/dy: two sign change
- ☐ No transport models can reproduce it quantitatively

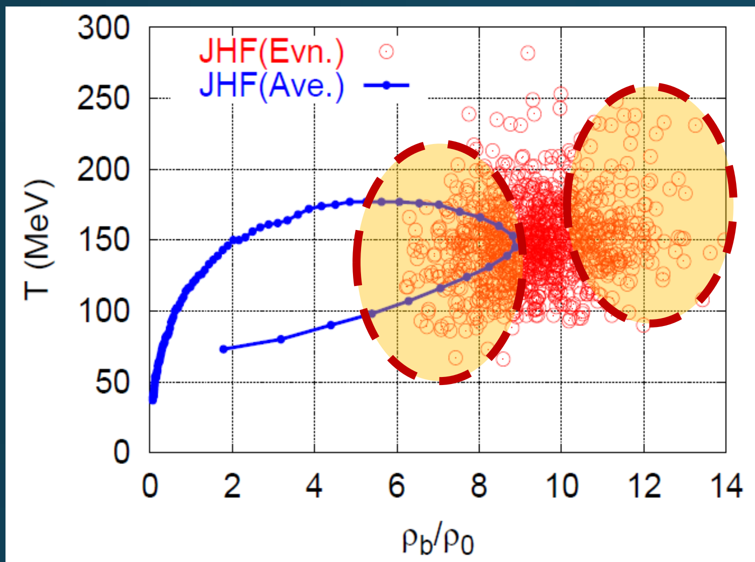
dv_1/dy: Signal of 1st Phase Tr.?



Negative v_1
= signal of softening
≅1st order transition??

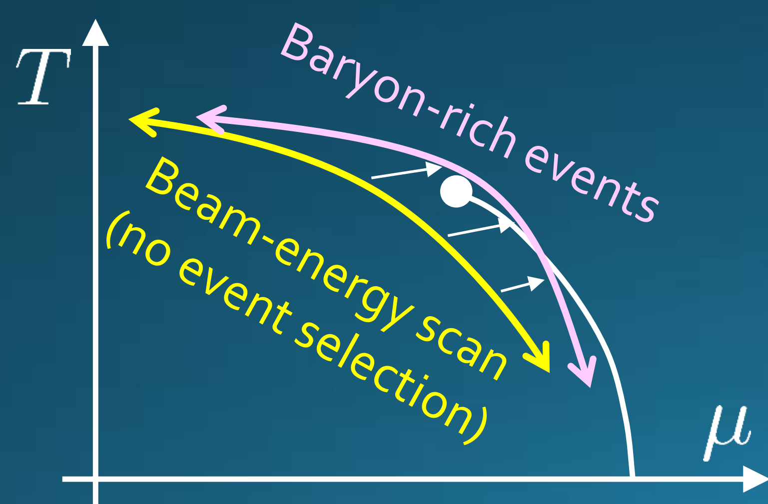


Maximum Density Scan?

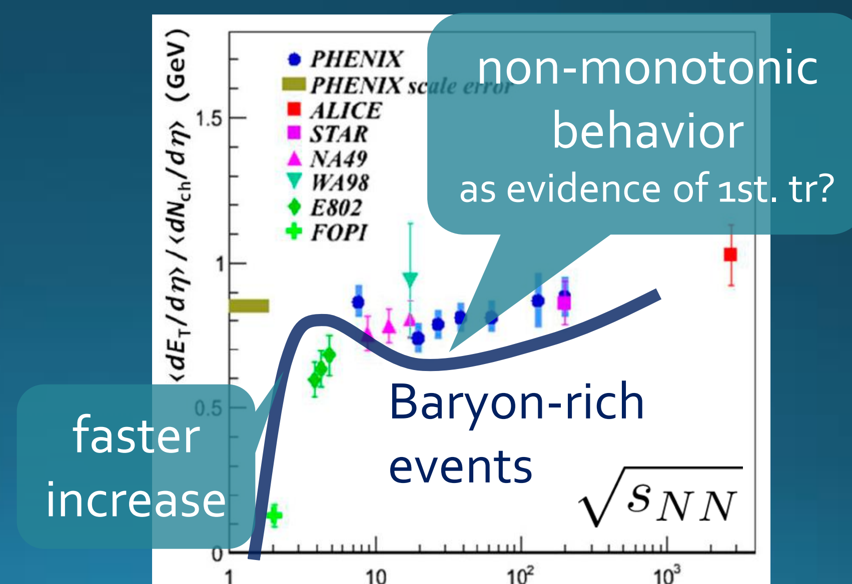


Large event-by-event fluctuations even with fixed centrality.

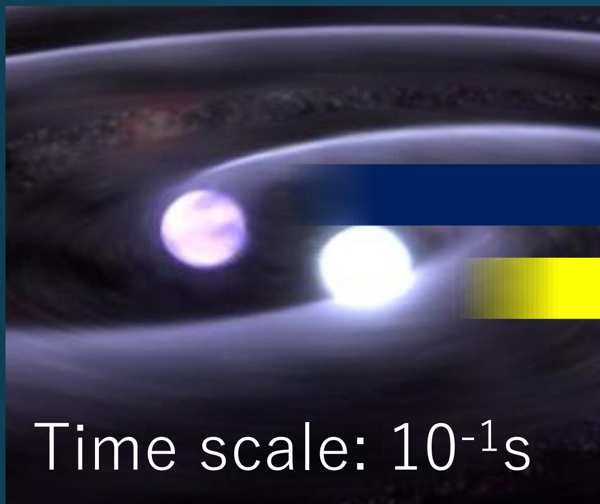
"Maximum density" dependence may be studied experimentally.



average transverse energy

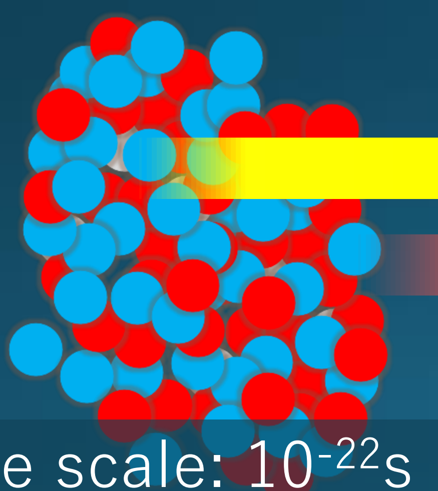


Lepton & Photon: Hierarchical Observation



gravitational wave

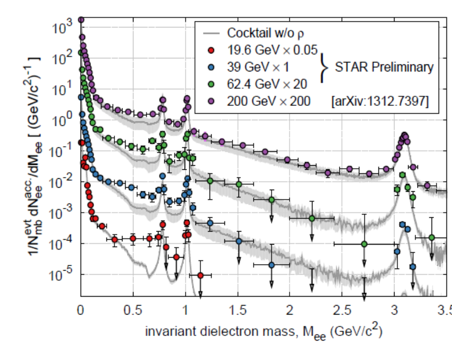
photons



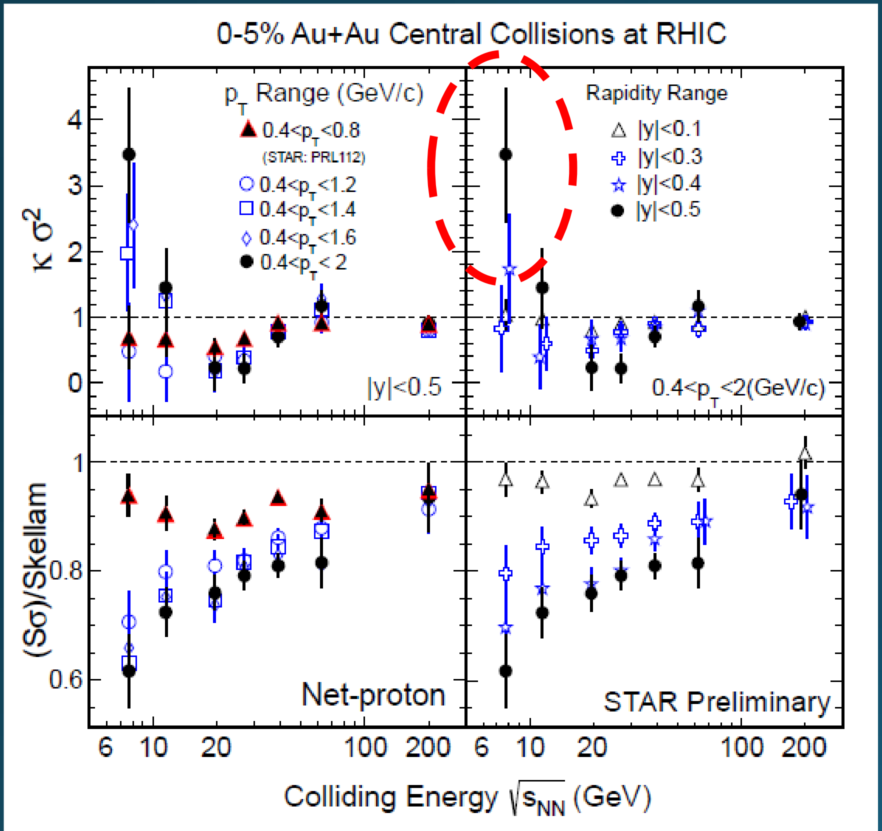
EM probes

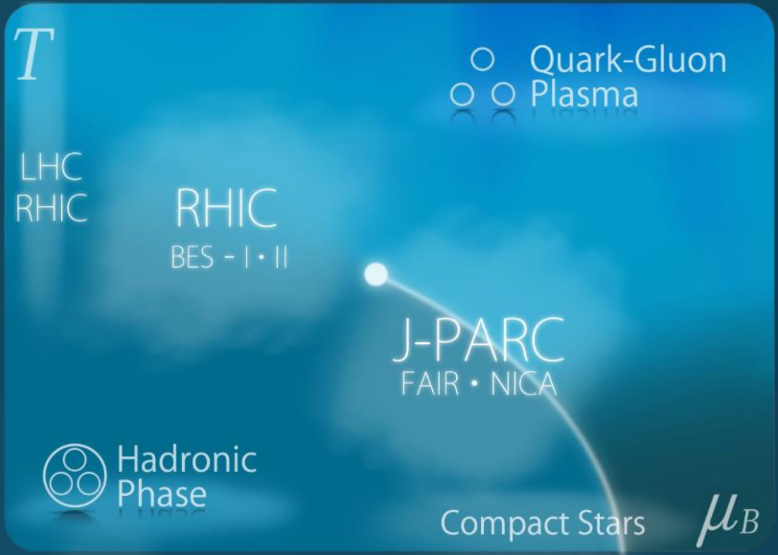
hadronic observables

di-lepton yield



Fluctuations & QCD Critical Point





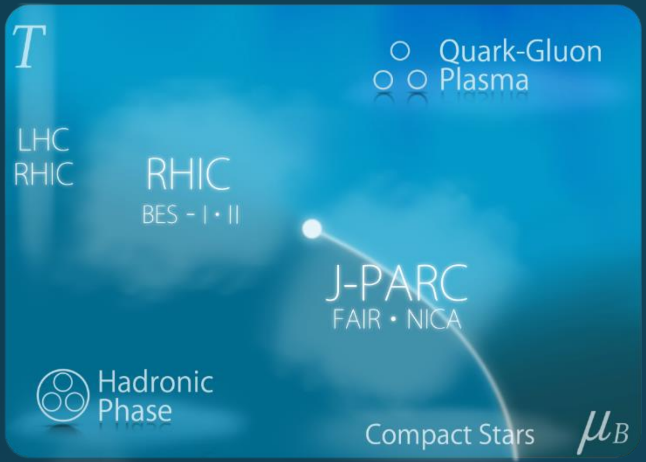
Is the signal of QCD-CP indicated in fluctuation observables??

Careful theor./exp. analyses are needed!

Non-eq. effects / rapidity dependences / experimental cuts / etc.

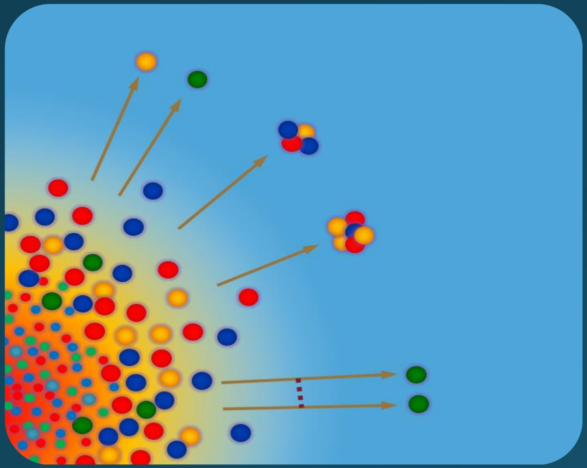
Asakawa, MK, Prog. Part. Nucl. Phys. (2016)

2 Main Goals of J-PARC-HI



Exploring Dense Medium

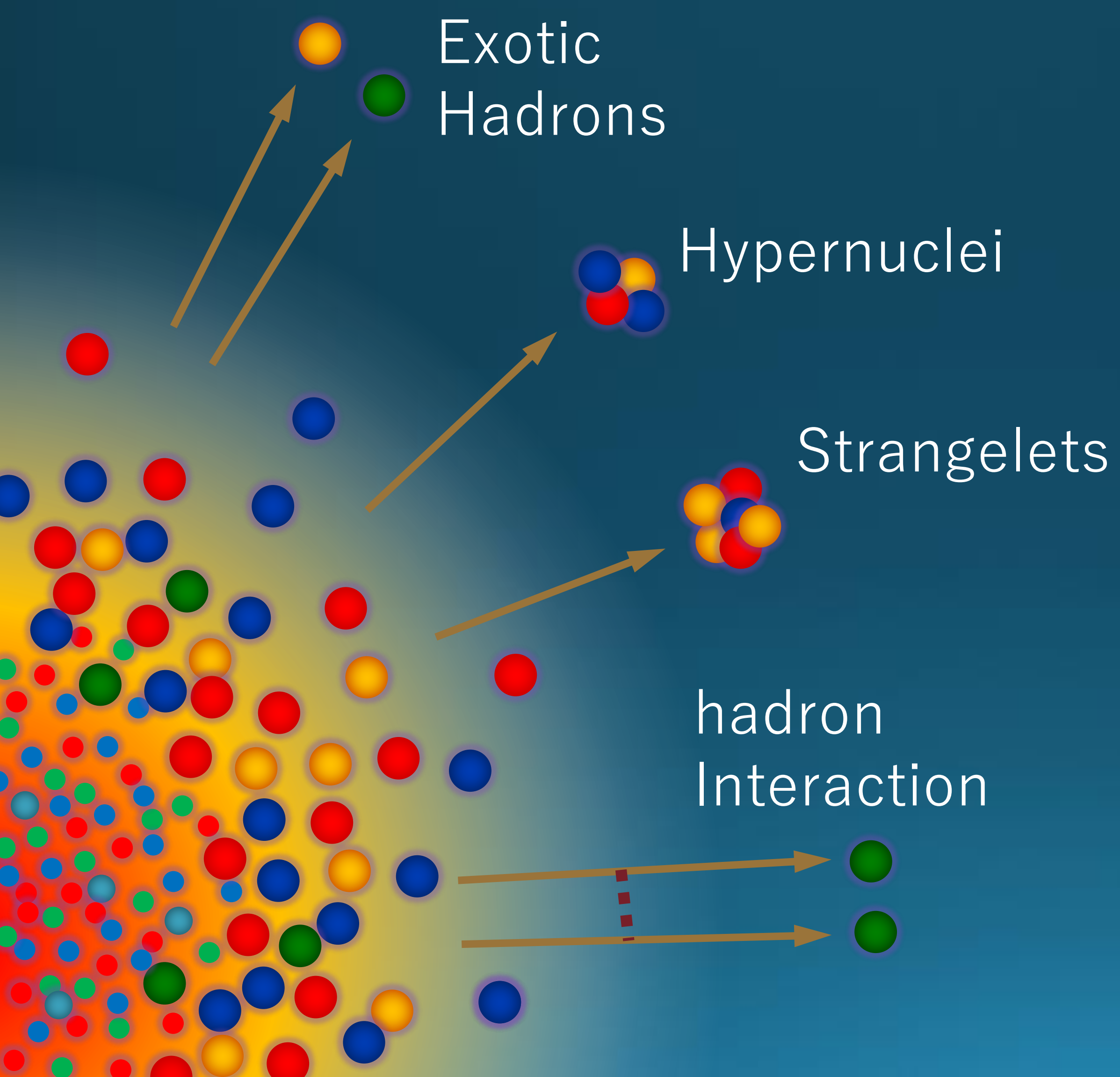
- QCD phase diagram
- 1st order phase transition
- equation of state



Rare-event Factory

- hyper nuclei
- exotic hadrons
- hadron interaction

Search of Rare Events

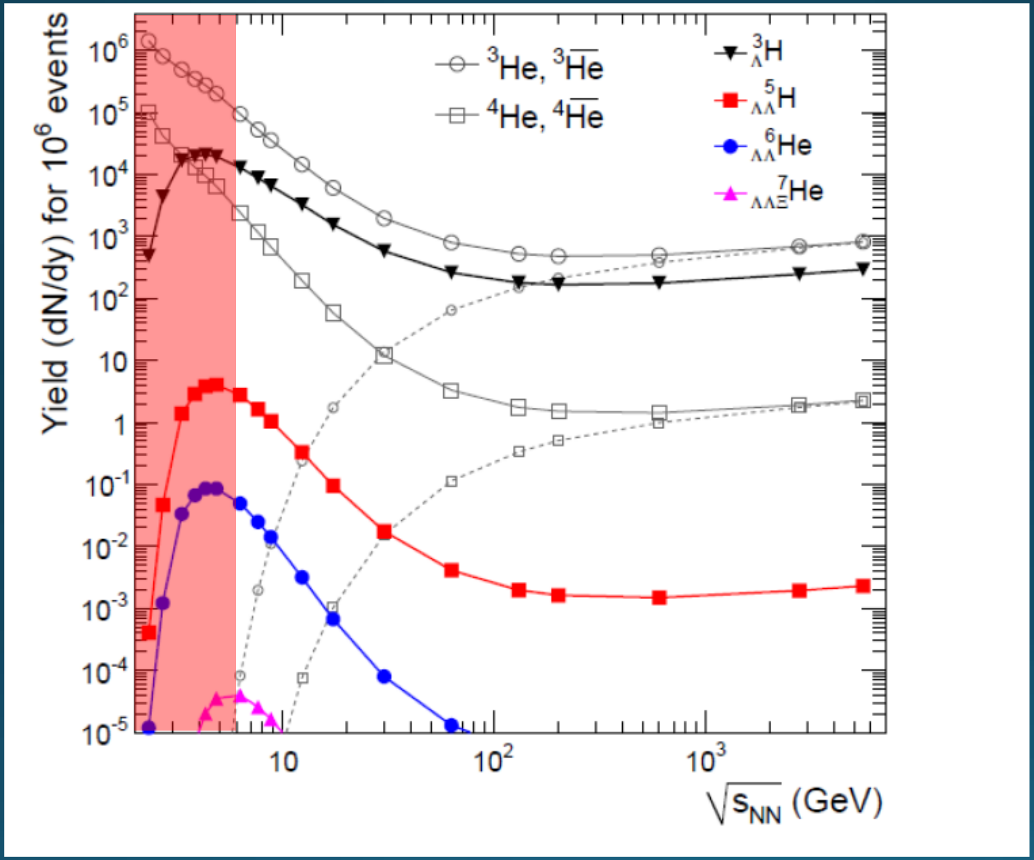


- High density
- High luminosity
- High strange yield

Rare-event Factory

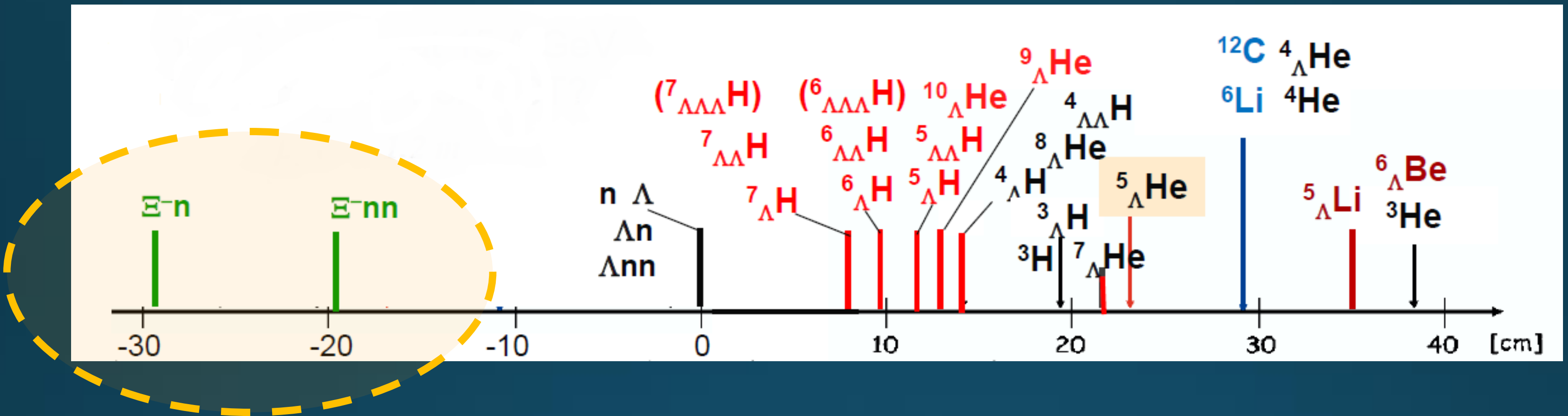
- creation
- properties
- interaction

J-PARC-HI = Strangeness Factory



Particle yields having strangeness have maximum at J-PARC energy

Hyper-Nuclear Phyics @ J-PARC

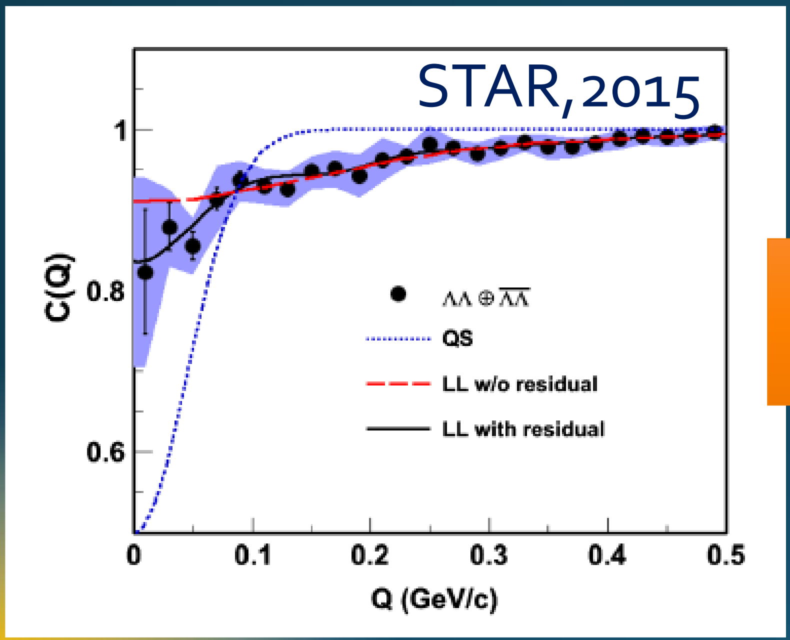


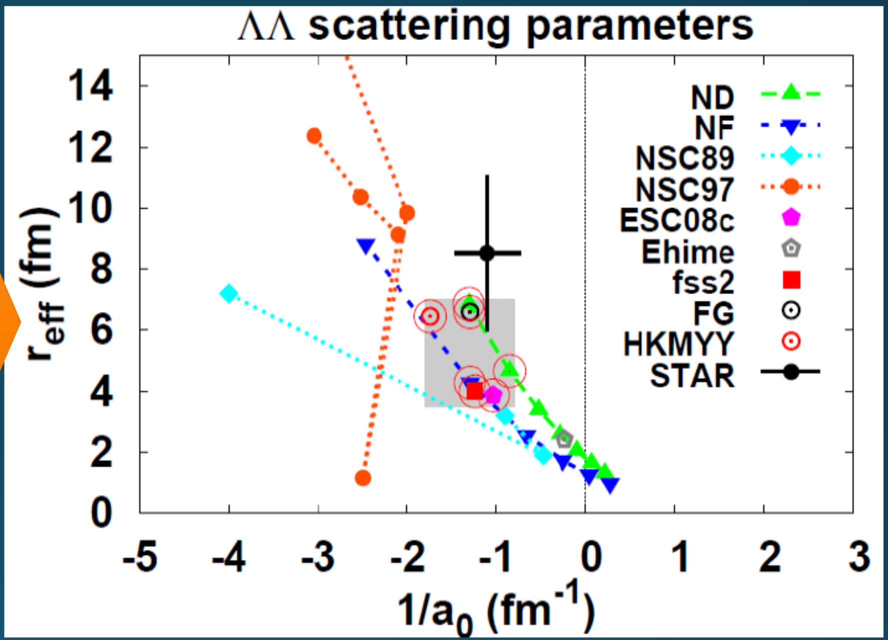
- Negatively-charged hypernuclei (Ξ^-n, Ξ^-nn, …)
- Nuclear strangelets
- n-rich / p-rich hypernuclei

- Measurement of magnetic moments

Hadron-hadron Interaction

ΛΛ Correlation function





Hadron interaction can be studied from correlation function.

emission source func. + relative wave func.

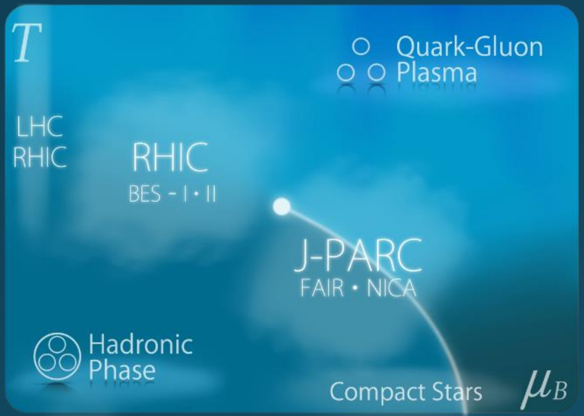
Morita, Furumoto, Ohnishi, 2015

ここまでのまとめ

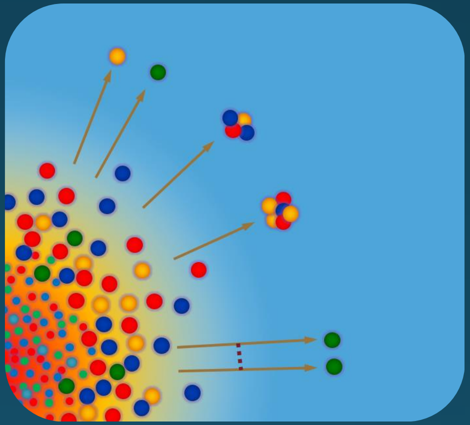
J-PARC-HI = 地上で行うミニ中性子星合体

世界最強度ビームで探る**宇宙最高密度**

2つの重要課題



高密度物質探索

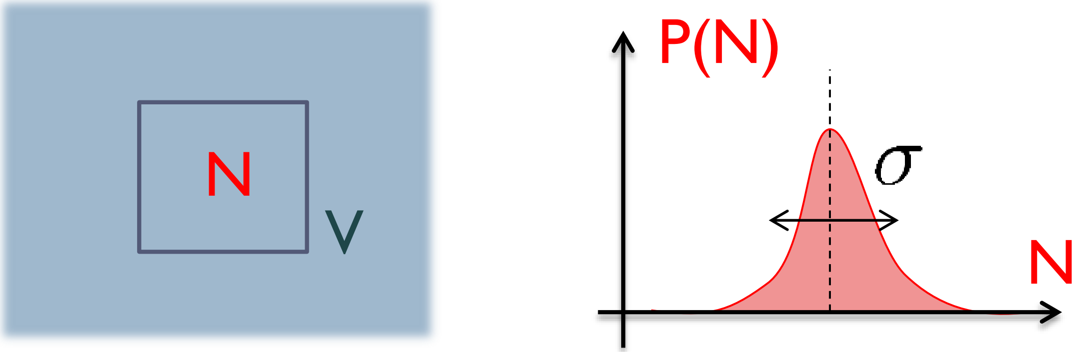


希少粒子生成工場

Fluctuations

Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.



Thermal Fluctuations

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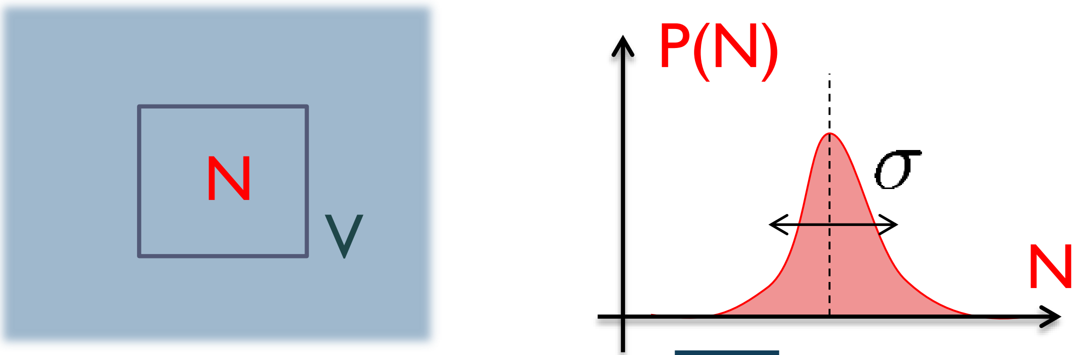


- Variance: $\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$
- Skewness: $S = \dfrac{\langle \delta N^3 \rangle}{\sigma^3}$
- Kurtosis: $\kappa = \dfrac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$

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

Non-Gaussianity

The noise is the signal.

R. Landauer
1998

A Coin Game

① Bet 250 JPY
② You get head coins of

A. 100 x 5 JPY

B. 50 x 10 JPY

Same expectation value.

A Coin Game

① Bet 250 JPY
② You get head coins of

A. 100 x 5 JPY

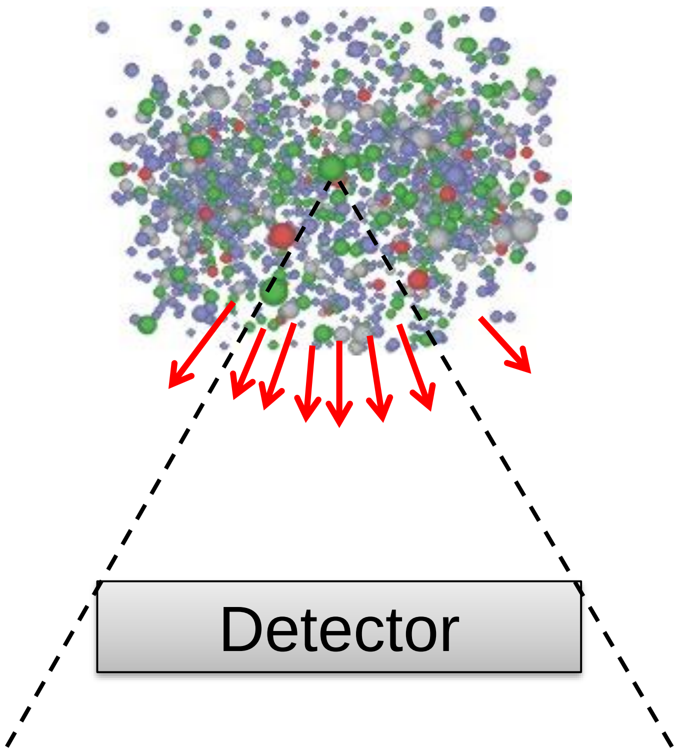
B. 50 x 10 JPY

C. 1 x 500 JPY

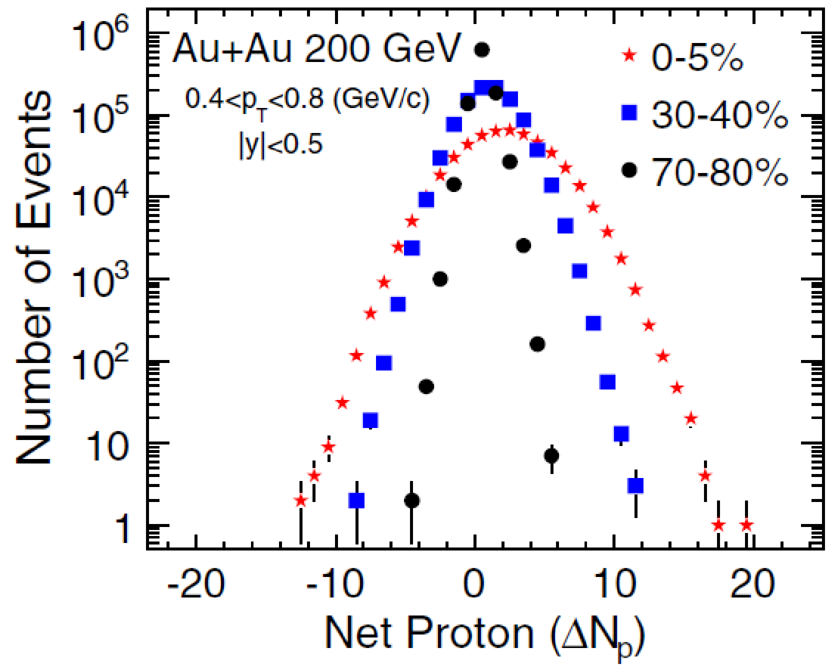
Same expectation valu
But, different fluctuation

Event-by-Event Analysis @ HIC

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



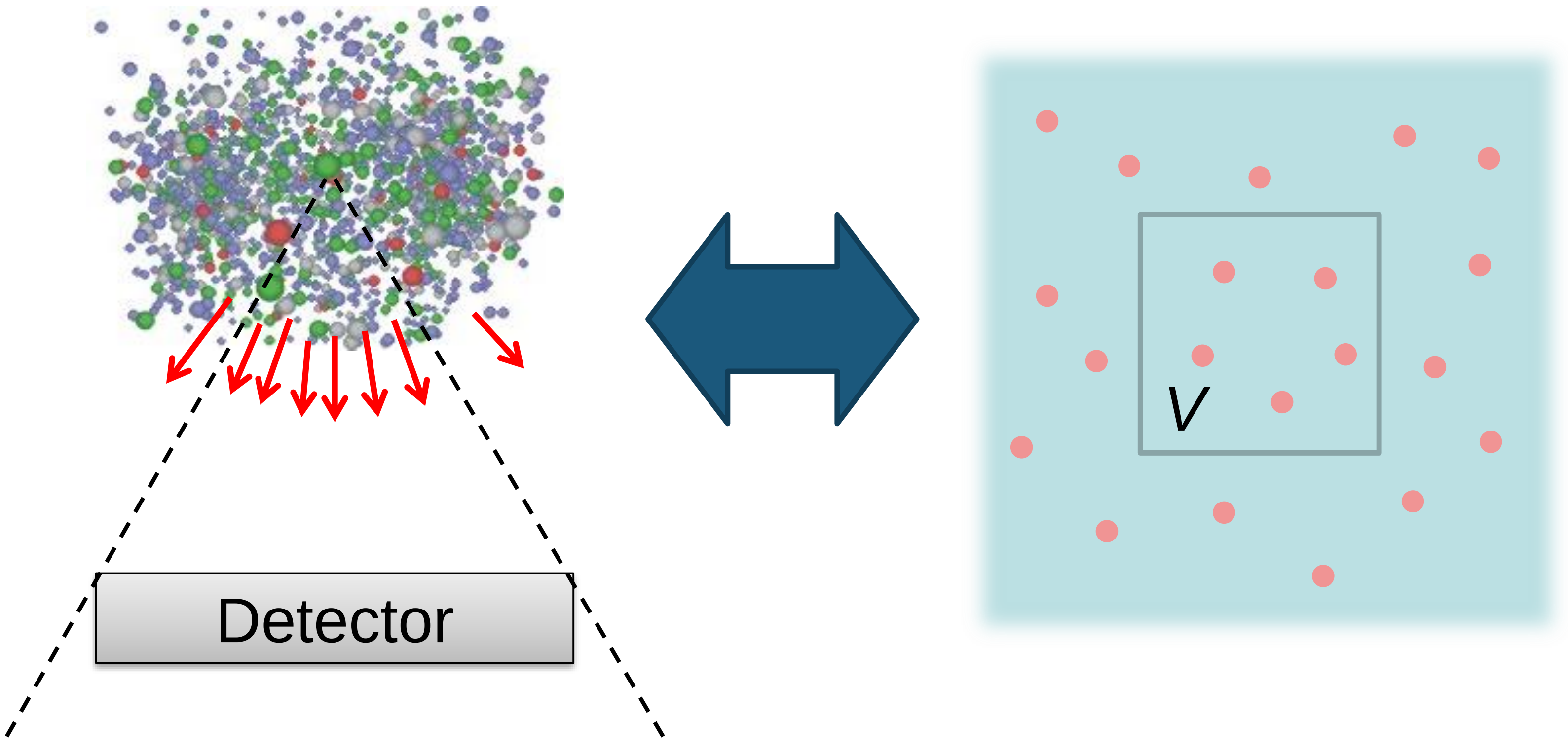
STAR, PRL**105** (2010)



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

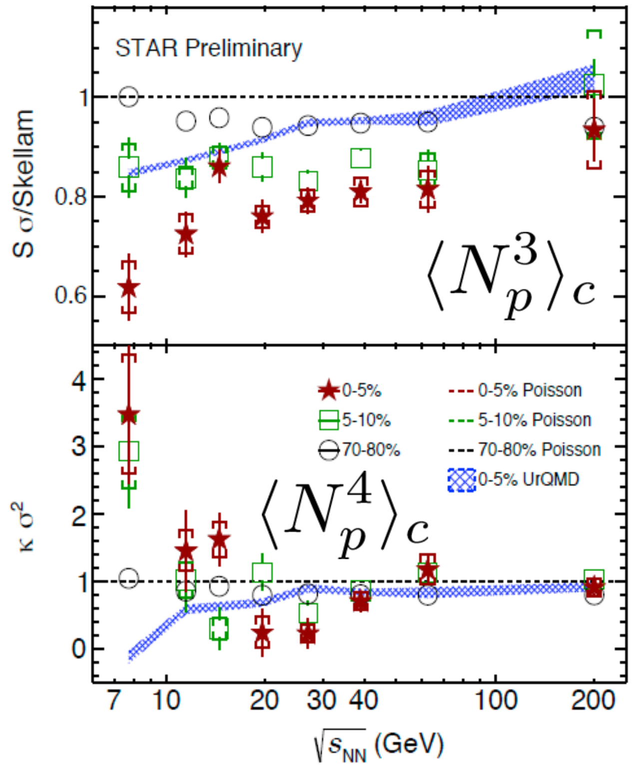
Event-by-Event Analysis @ HIC

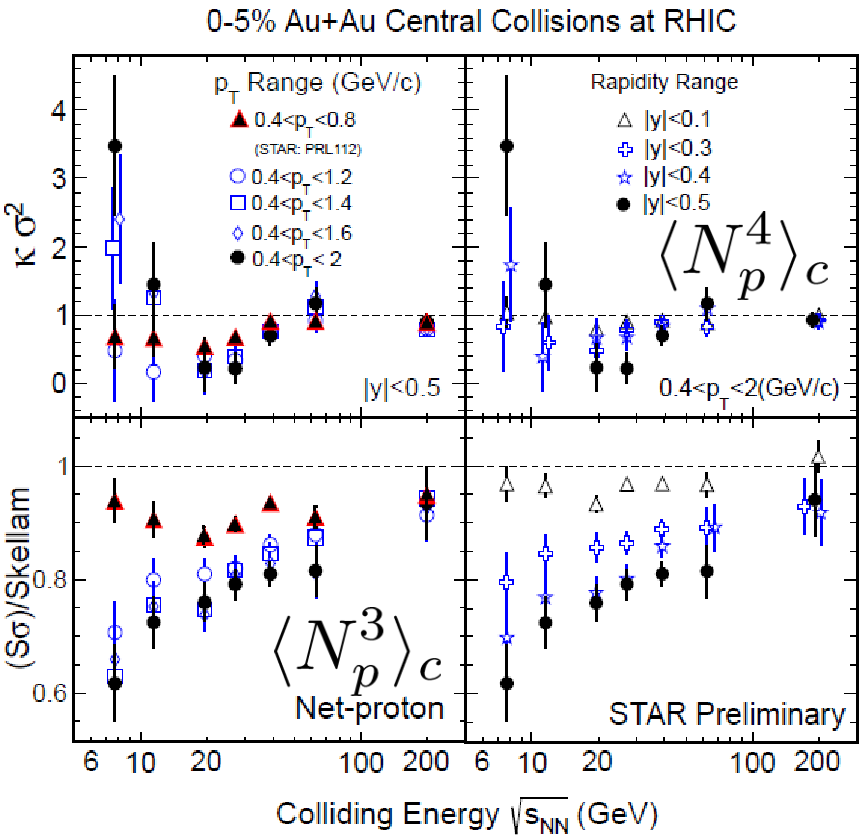
Fluctuations can be measured by e-by-e analysis in experiments.



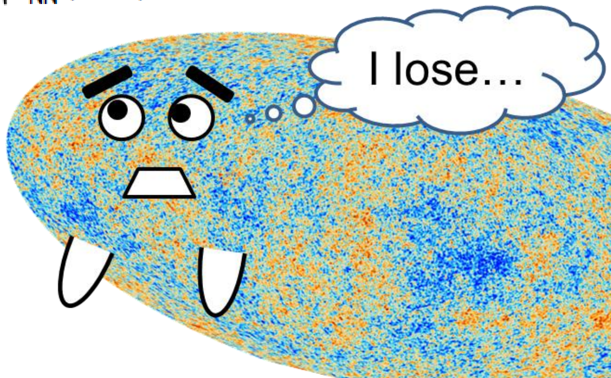
Non-Gaussianity in Exp.

X. Luo+, STAR Collab.
2010~



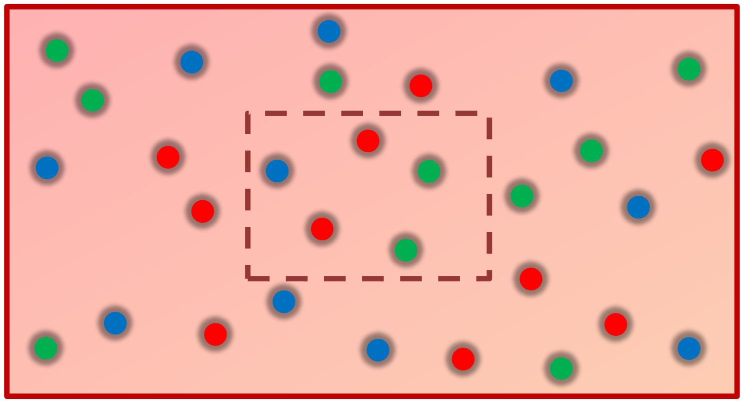


Non-zero **non**-Gaussian cumulants have been established!



Fluctuations and Elemental Charge

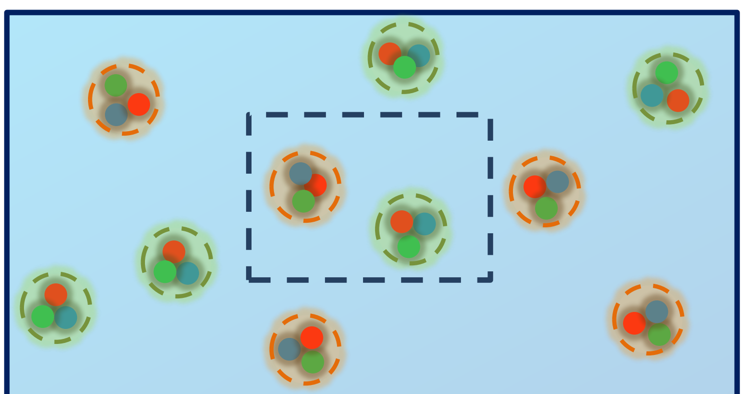
Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000
Ejiri, Karsch, Redlich, 2005



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

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

$$3N_B = N_q$$



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

Free Boltzmann → Poisson

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

Fluctuations and Elemental Charge

Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000
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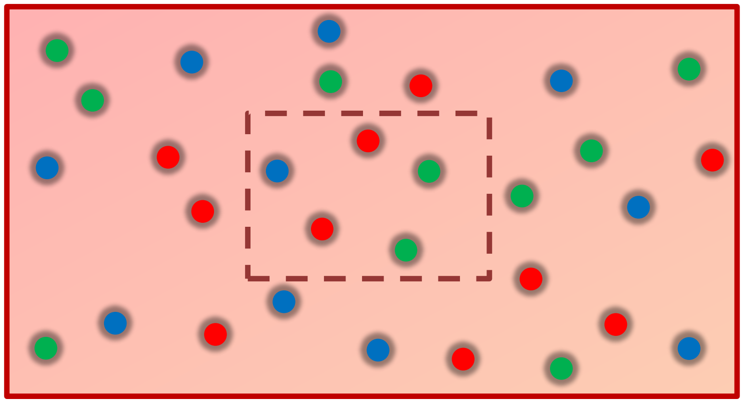

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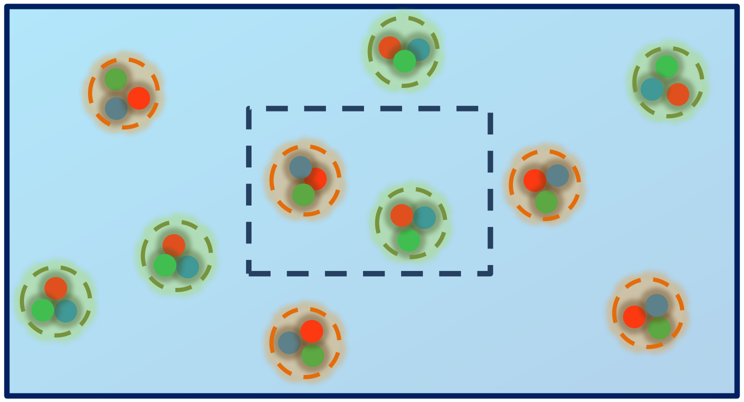
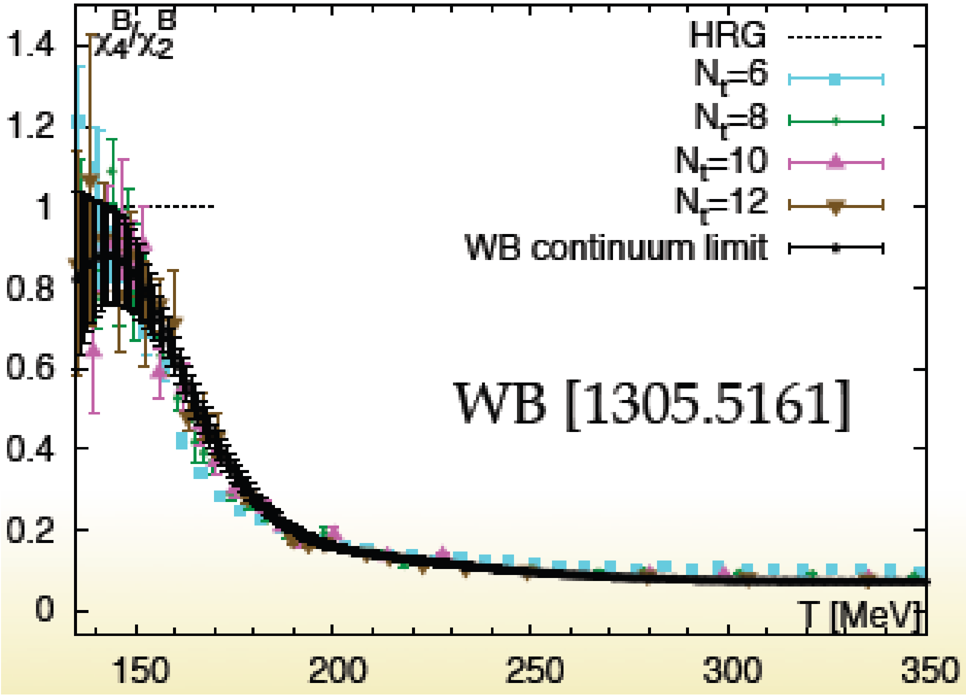
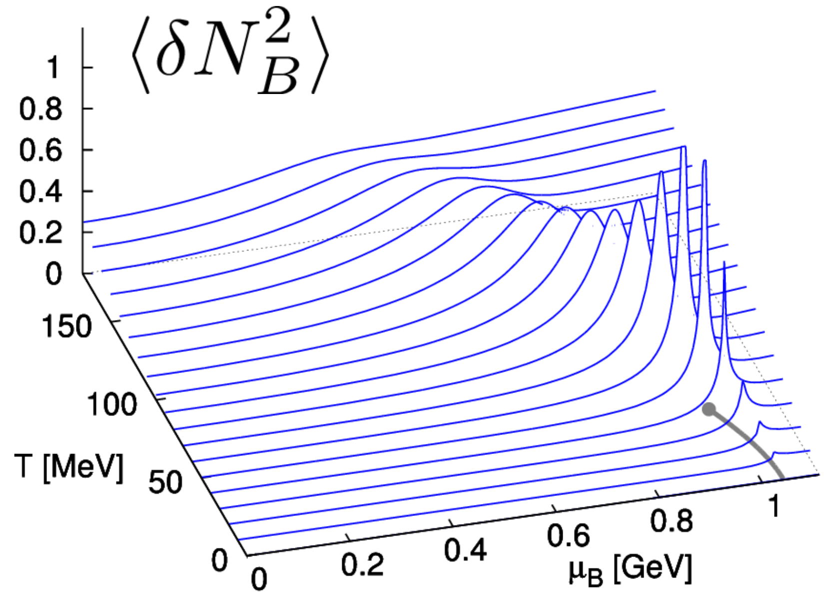




Fluctuation and QCD Critical Point

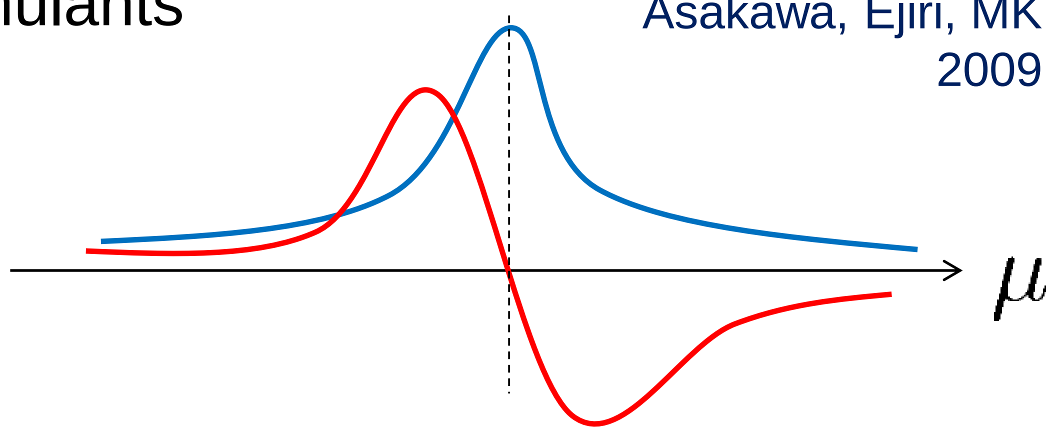
Fluctuations diverge at the QCD critical point



Asakawa, Ejiri, MK 2009

- Geometric interpretation to signs of higher order cumulants

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

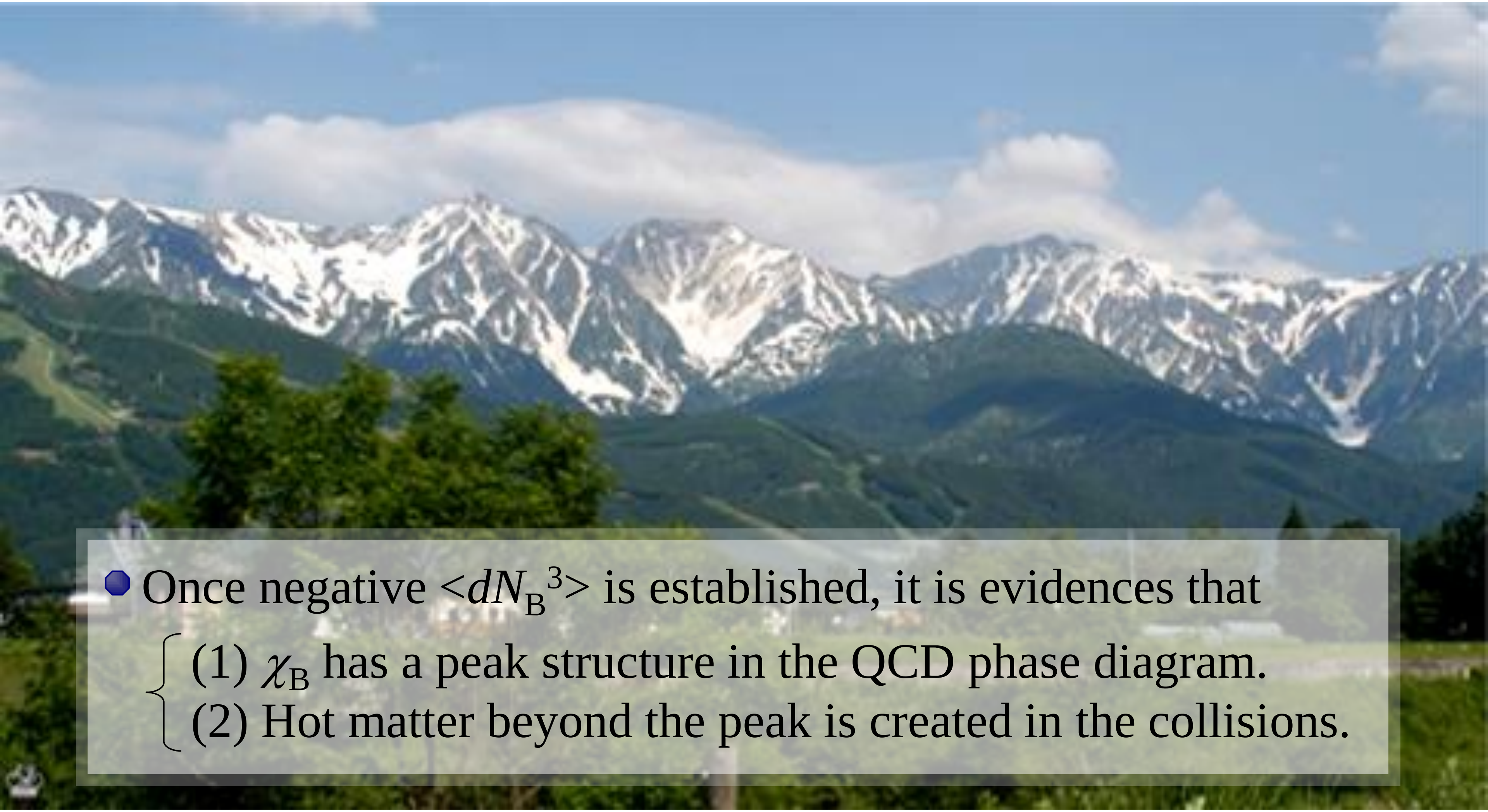


- More severe divergence for higher-order cumulants

Stephanov, 2009

Impact of Negative Third Moments

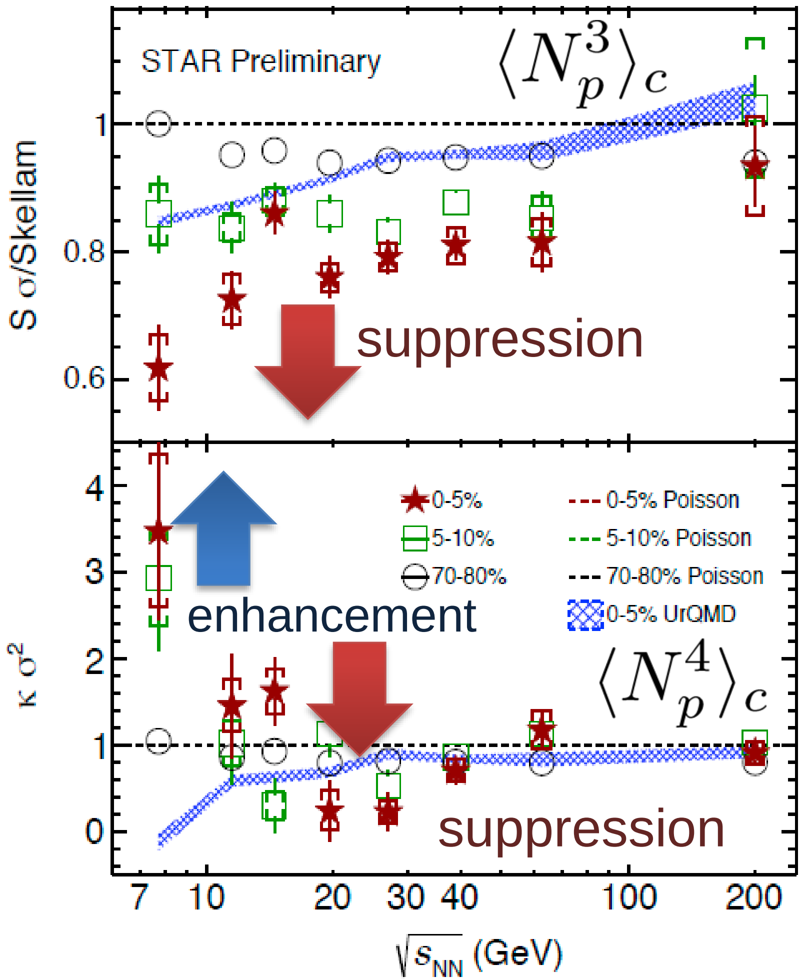
Asakawa, Ejiri, MK, 2009



- 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}).

How do Experimental Data Behave?



3rd-order:
suppression,
but no sign change

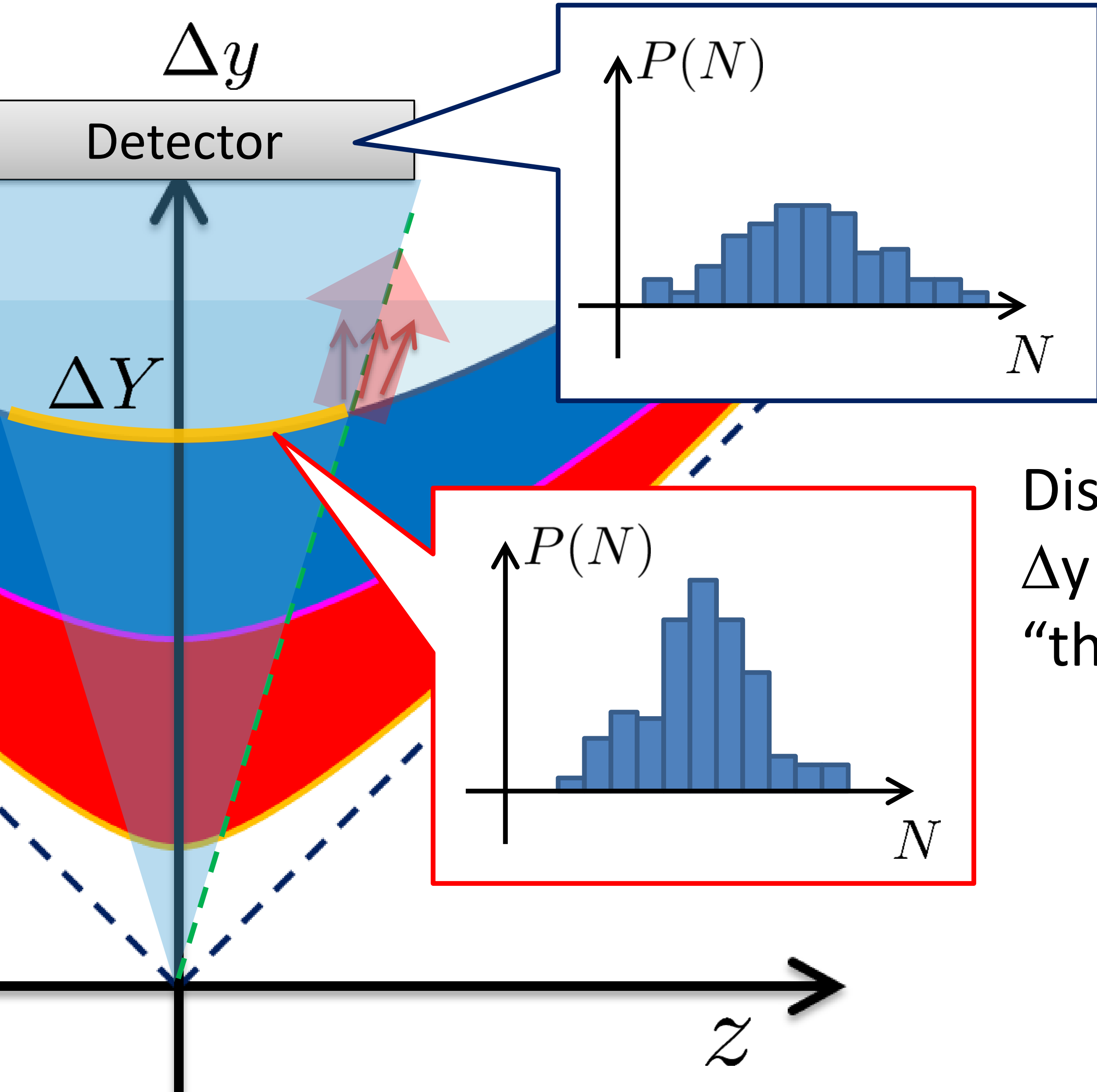
4th-order:
non-monotonic behavior

More careful study is needed

- Are fluctuations generated near the CP?
- Detector's efficiency effects

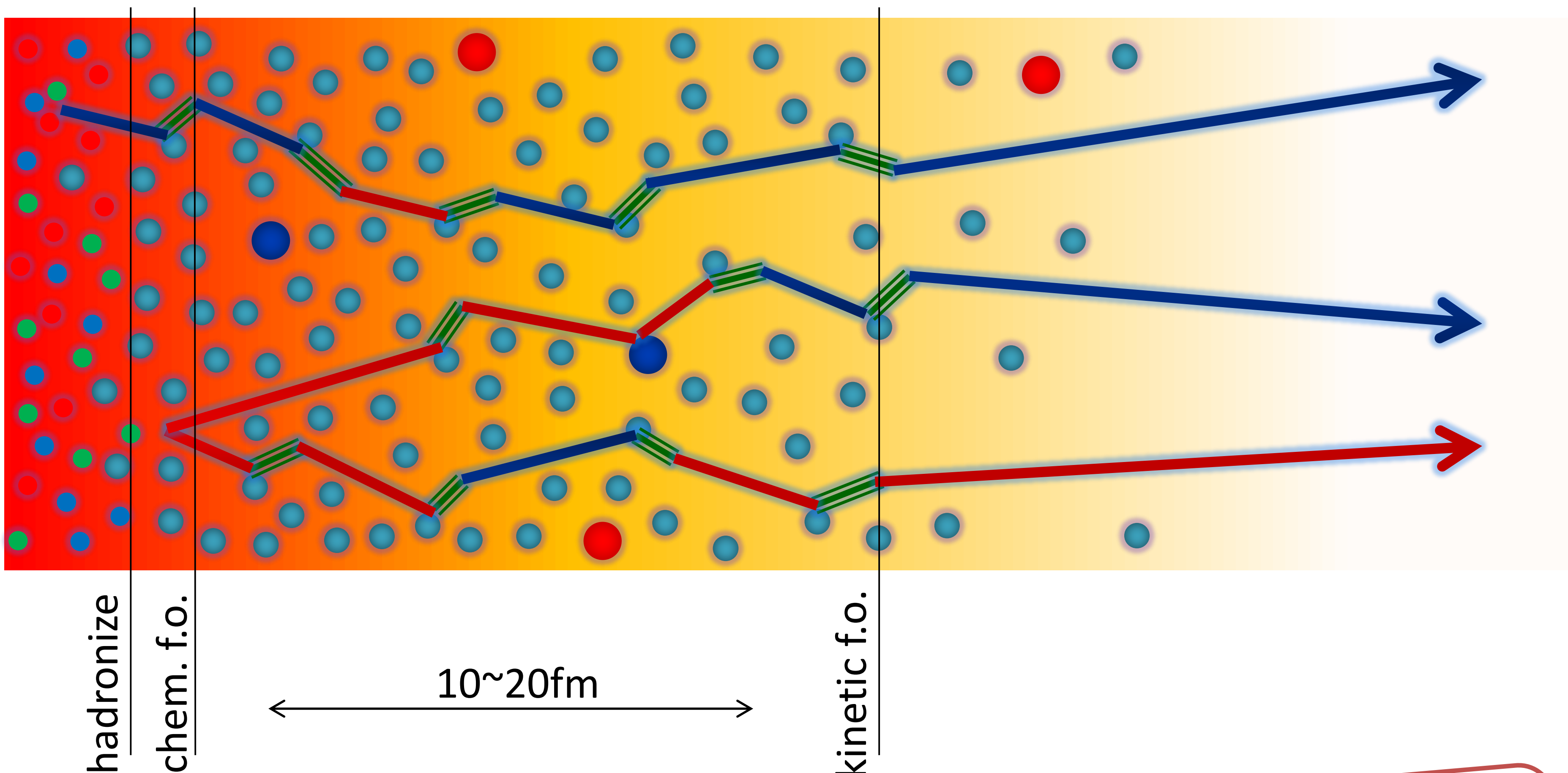
Thermal Blurring

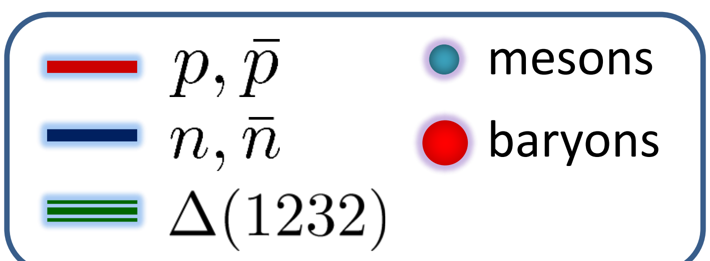
Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000



Distributions in ΔY and Δy are different due to "thermal blurring".

Baryons in Hadronic Phase

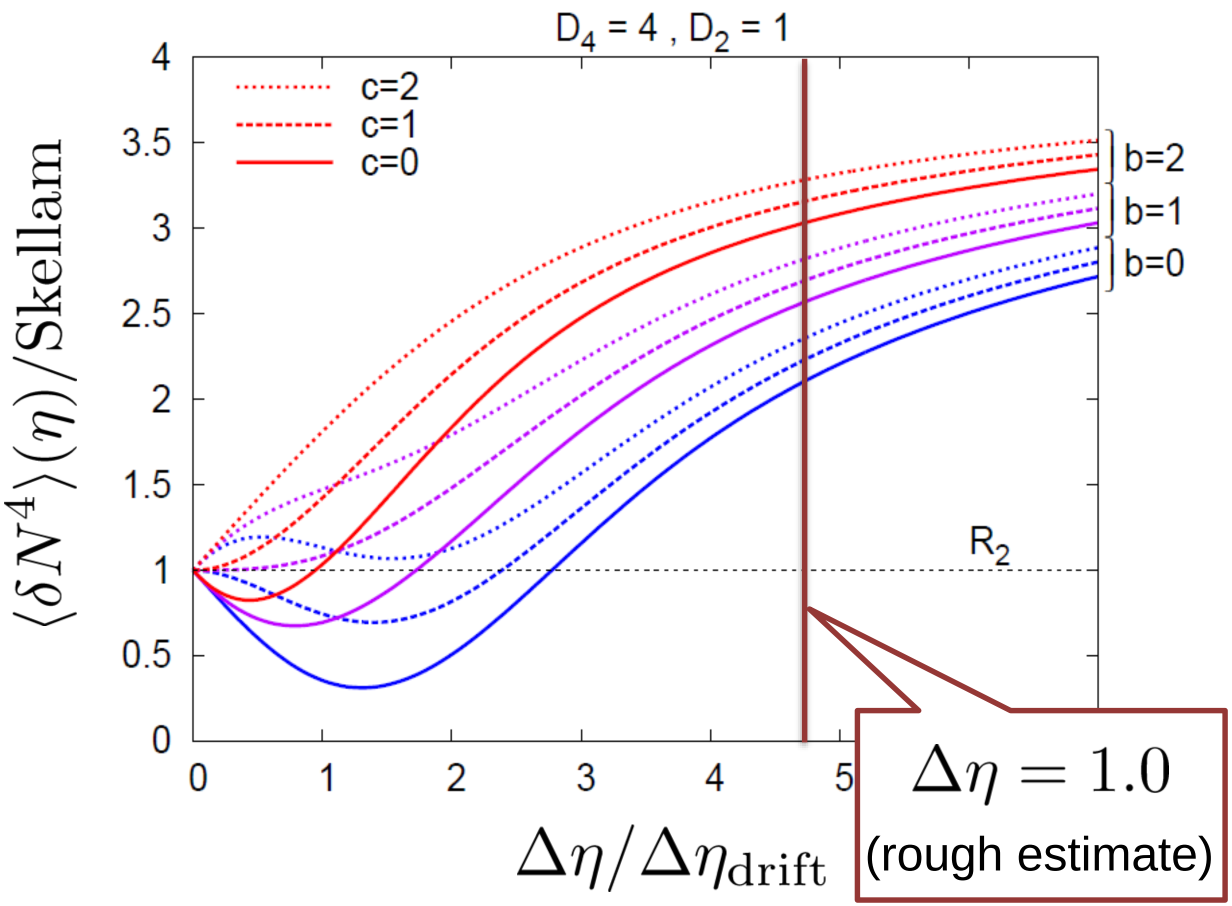




Baryons behave like Brownian pollens in water

4^{th} order : w/ Critical Fluctuation

MK+ (2014)
MK (2015)



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.

Rapidity Window Dep.

4^{th}-order cumulant

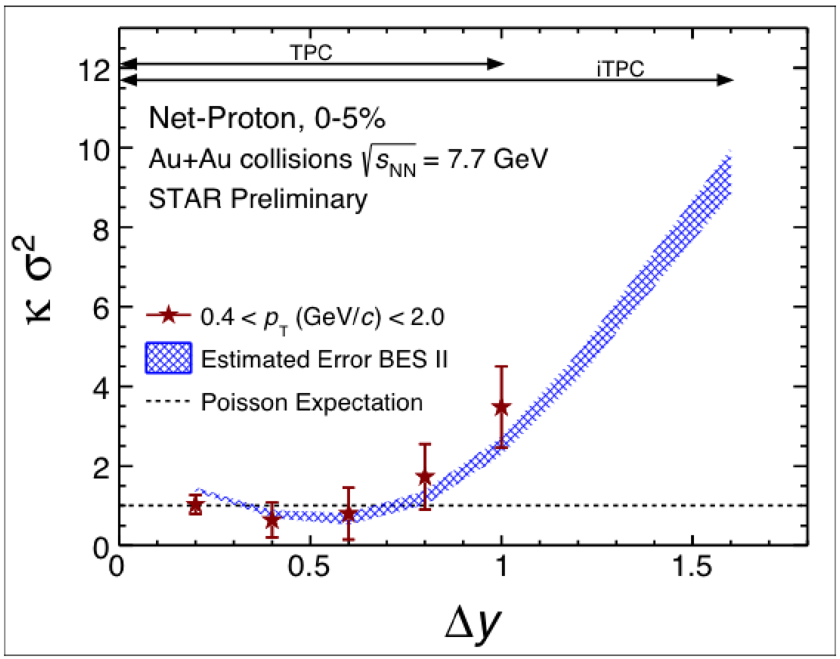
MK+, 2014
MK, 2015

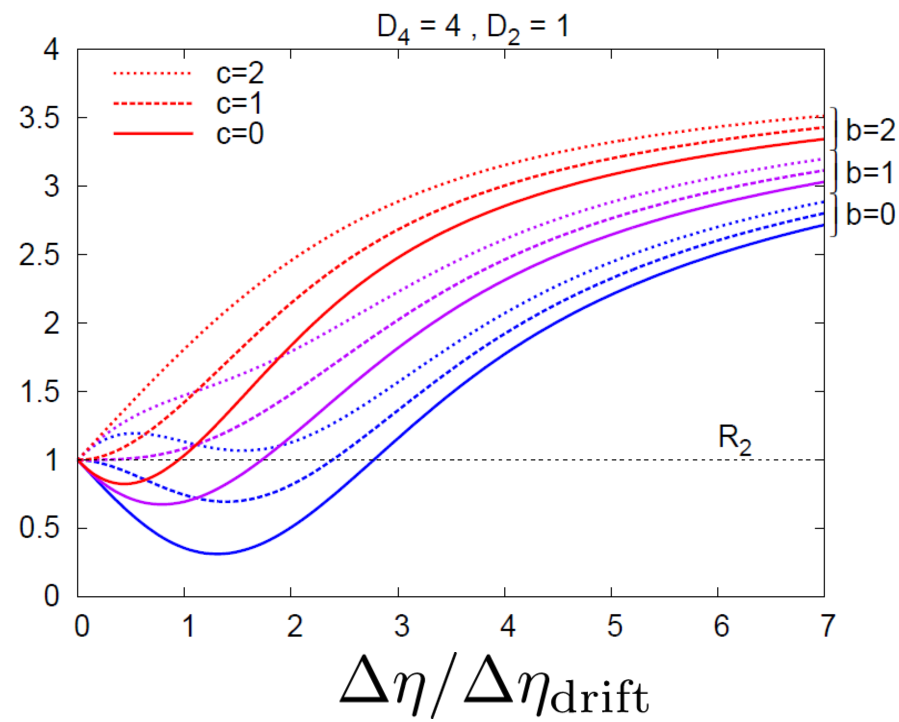
Initial Conditions

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

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

STAR Collab. (X. Luo, CPOD2014)

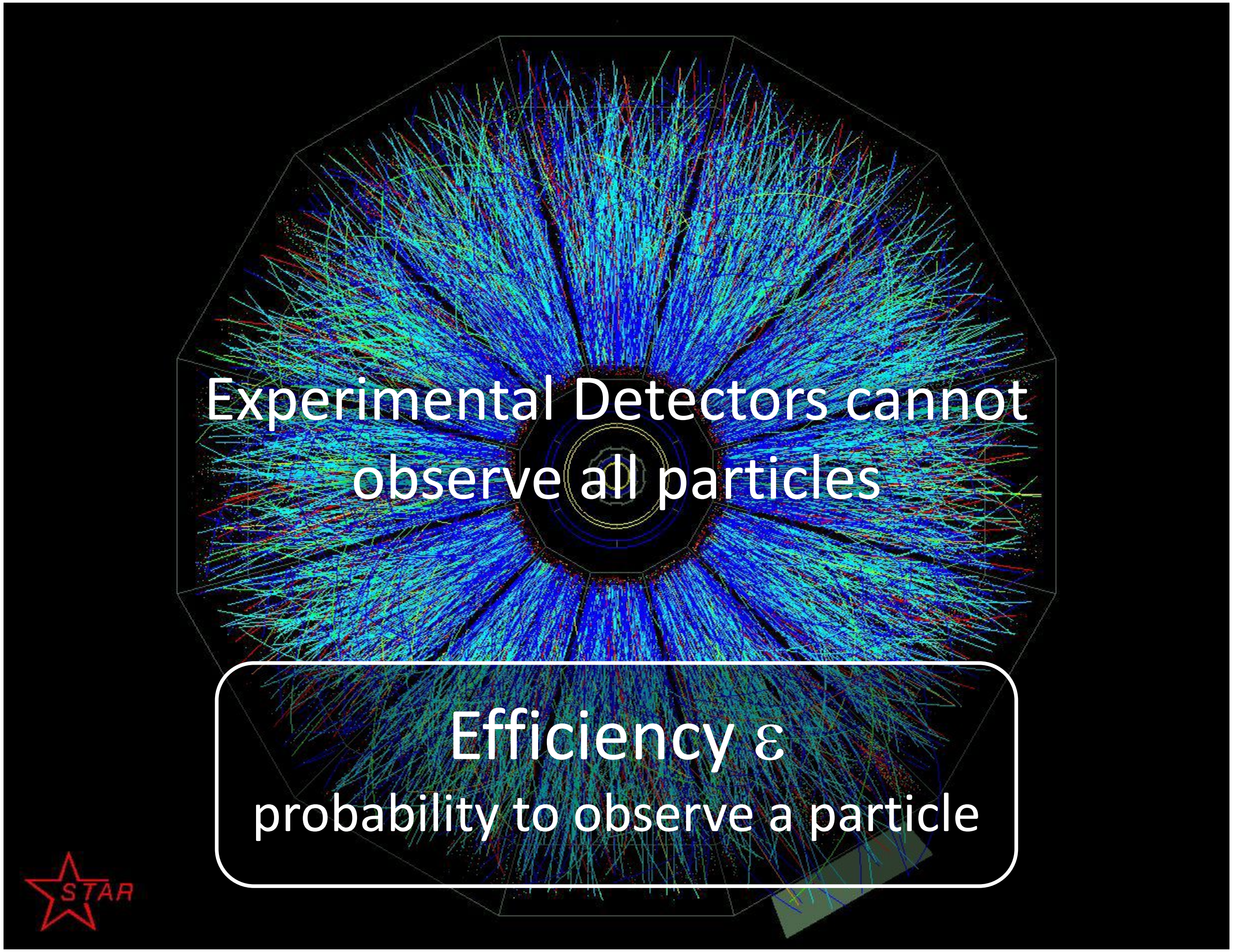




- Different initial conditions give rise to different characteristic Δη dependence. → Study initial condition
- Non-monotonic behaviors can appear in Δη dependence.

Finite volume effects: Sakaida+, PRC90 (2015)

Efficiency Correction

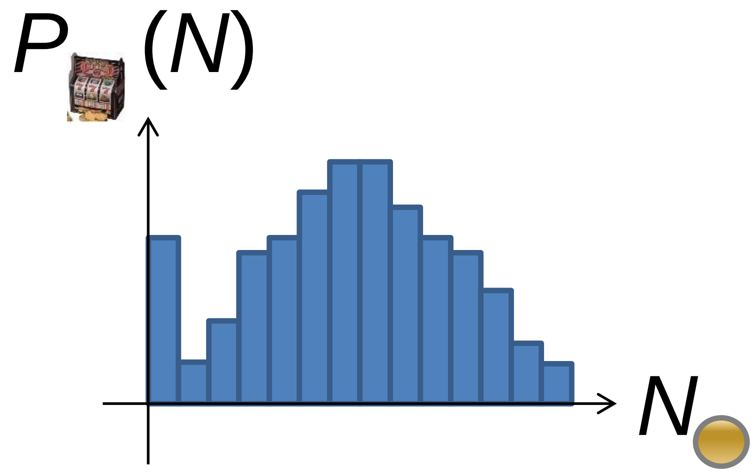


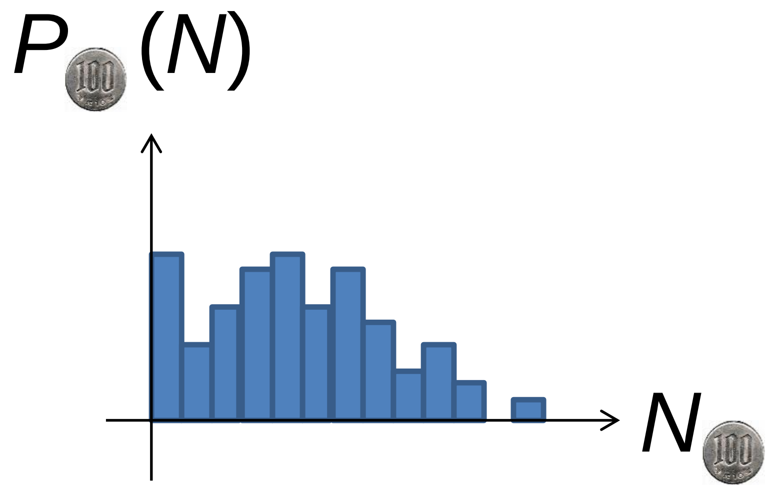
Experimental Detectors cannot observe all particles

Efficiency ε
probability to observe a particle

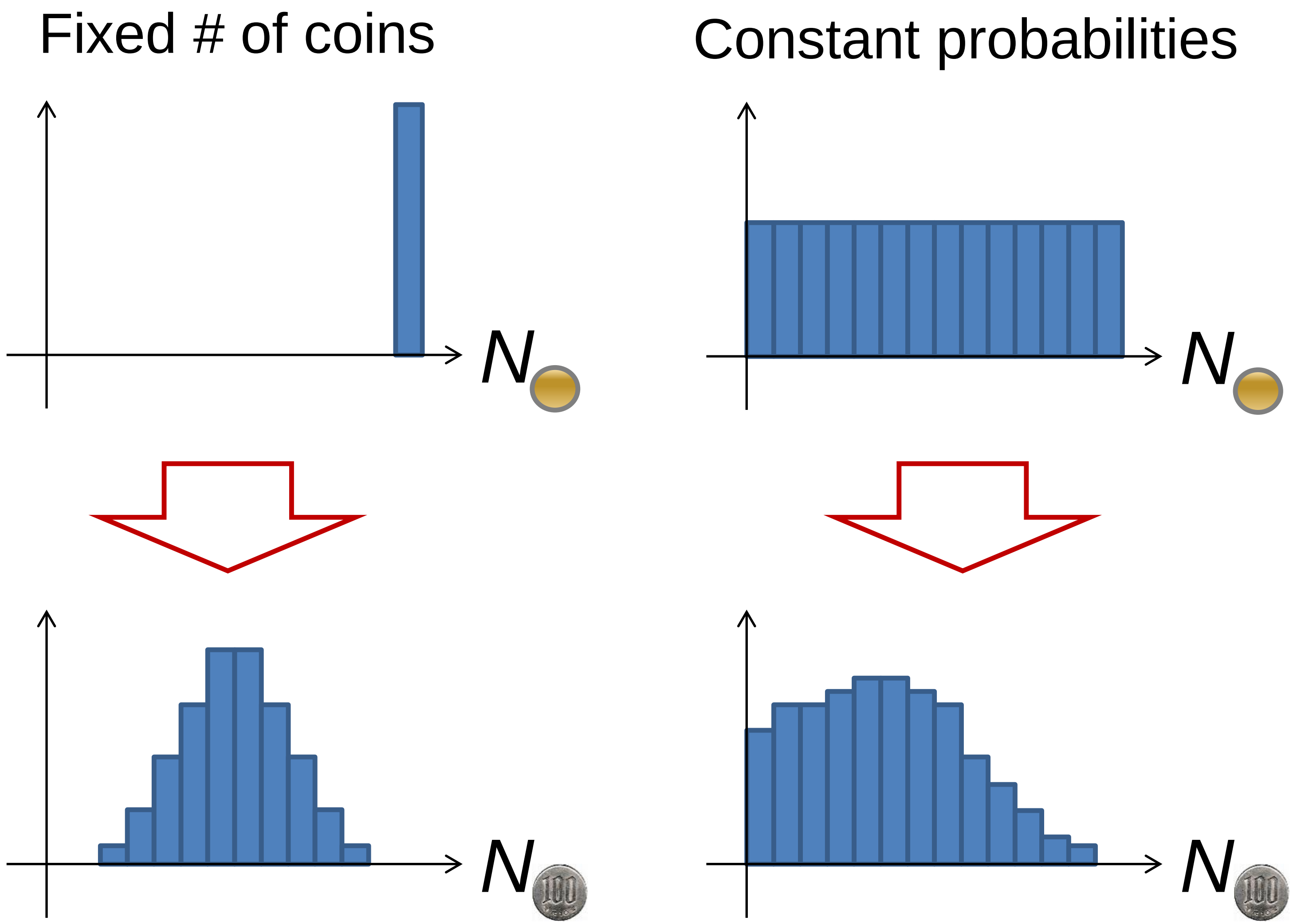
Efficiency correction is indispensable in experimental analyses!

Slot Machine Analogy





Slot Machine Analogy



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

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

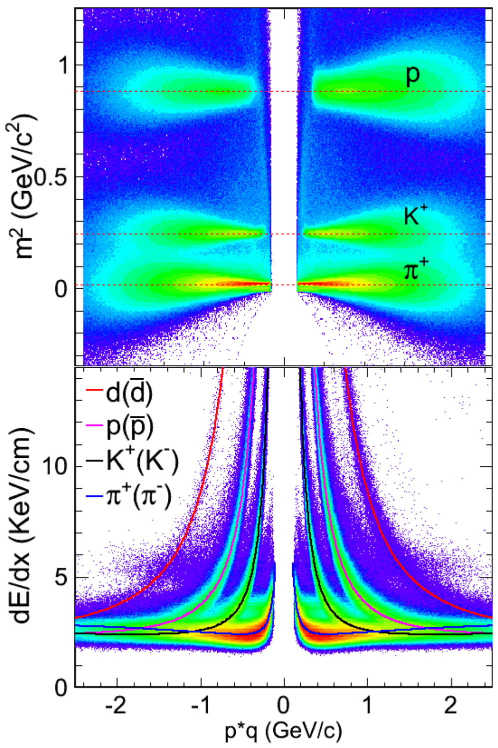
Caveat: Effects of nonvanishing correlations: Holtzman+ 2016

Multi-efficiency Bin Problem

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

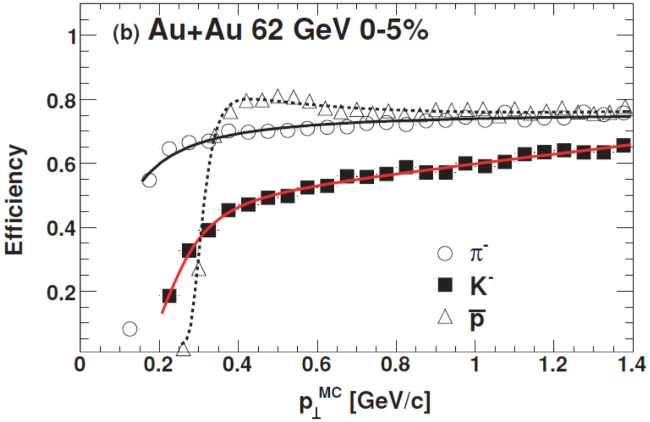
STAR, net proton

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



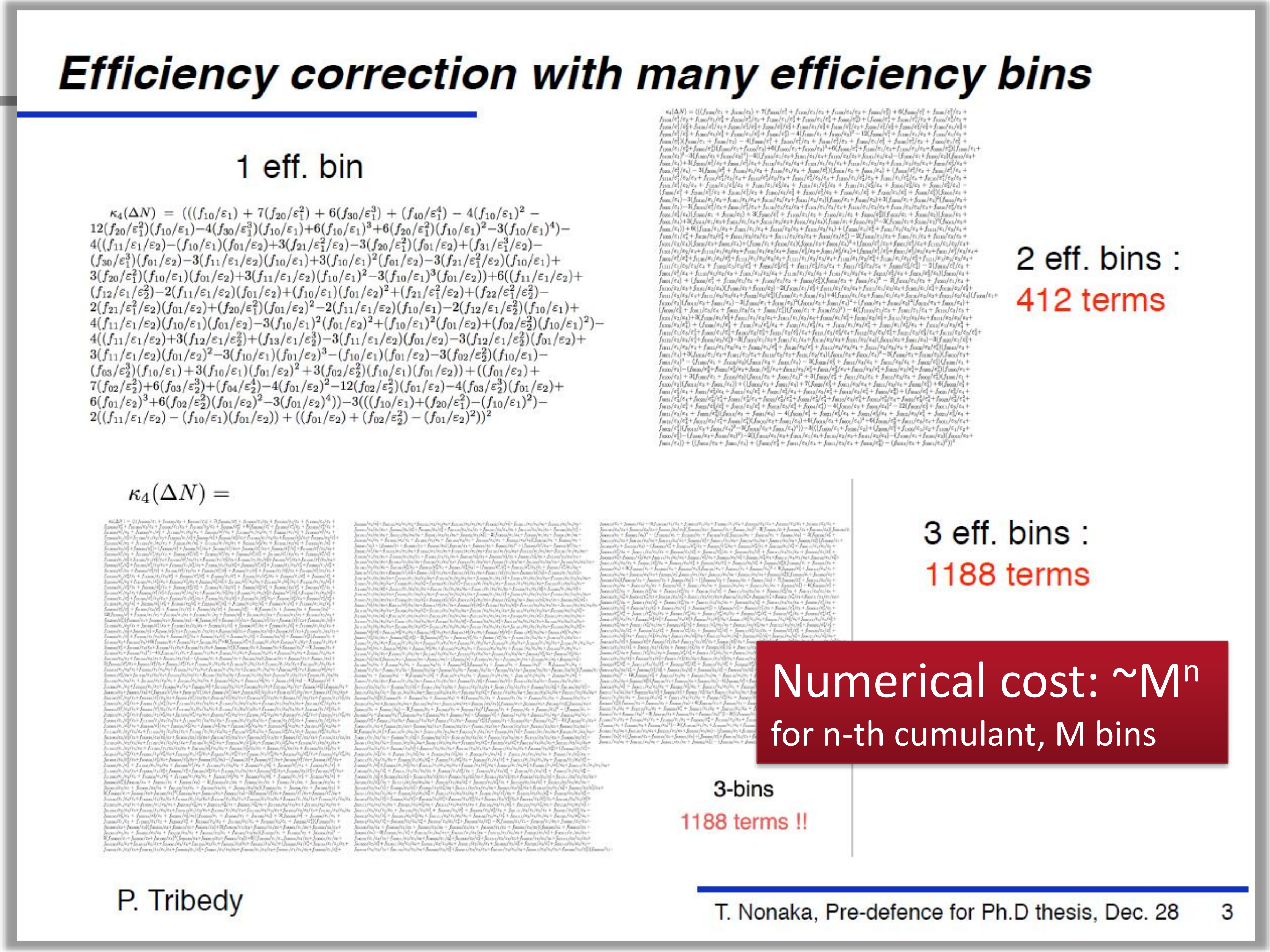
- Multi-variable efficiency correction

A method was proposed, but too large numerical costs



Luo, 2014

Bzdak, Koch, 2015



Slide provided from T. Nonaka

Efficient Formulas for Efficiency Correction

◻Cumulant expansion method MK,2016

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

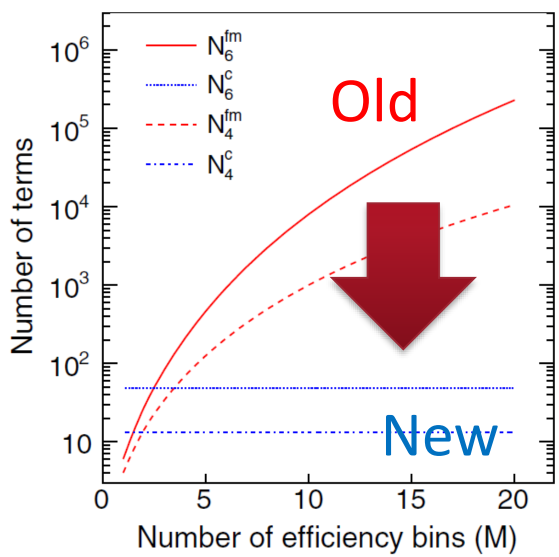
Number of terms is drastically reduced!

Substantial reduction of numerical cost

◻Factorial cumulant method Nonaka, MK, Esumi, 2017

Systematic procedure with the use of factorial cumulants

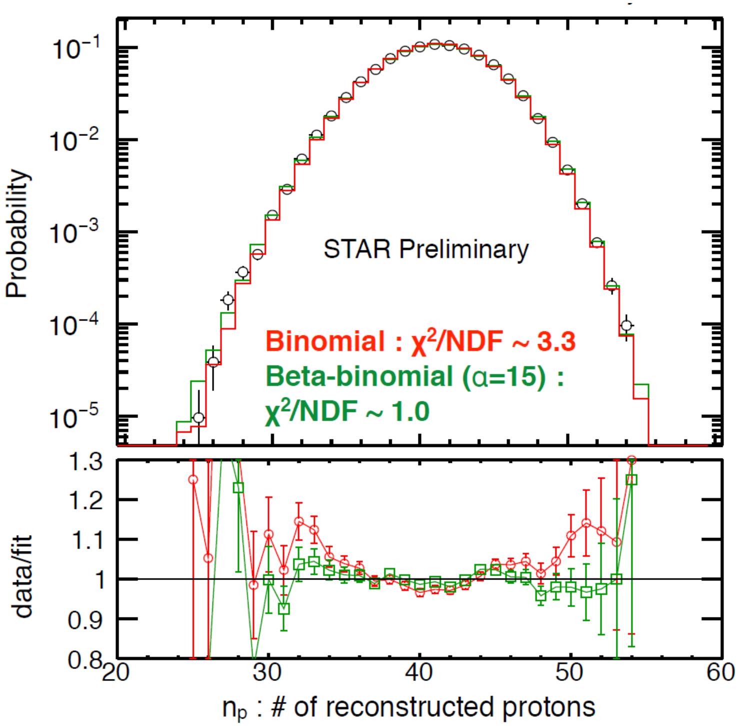
Numerical Cost



Violation of Binomial Model

Typical detectors have clear deviation from the binomial response.

Estimates of systematic uncertainty arising from this deviation are needed!



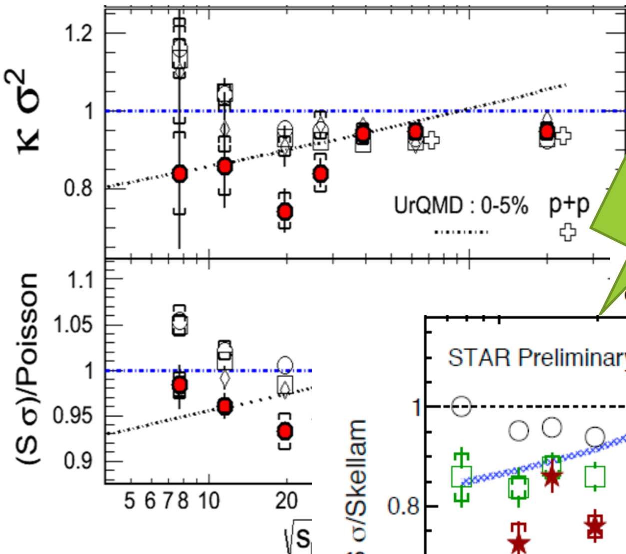
☐ **General procedure for efficiency correction** Nonaka, MK, Esumi, 2018

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

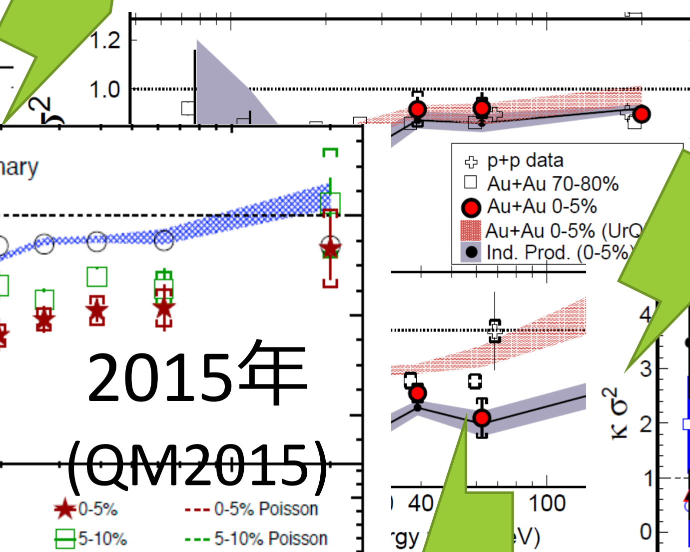
- Efficiency correction for **any** response matrix R(n,N)
- We must understand the property of the detector

4th Order Cumulant: History

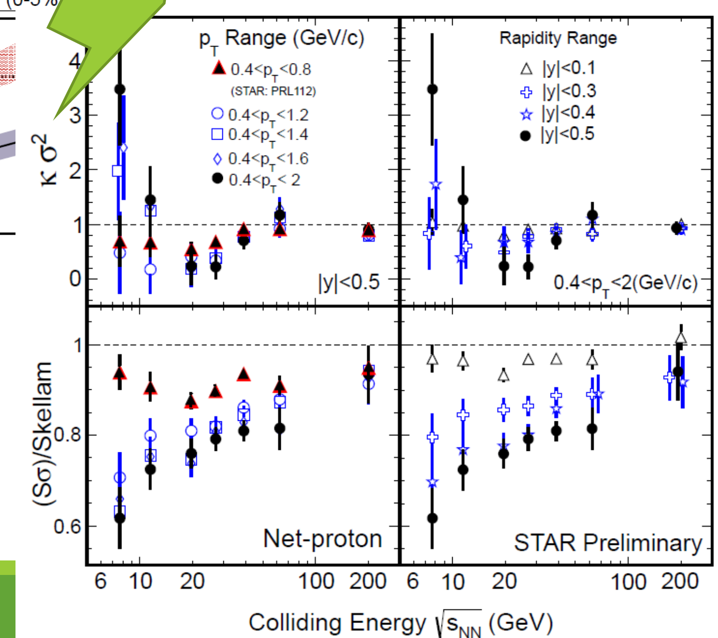
2013年
(PRL(2014))



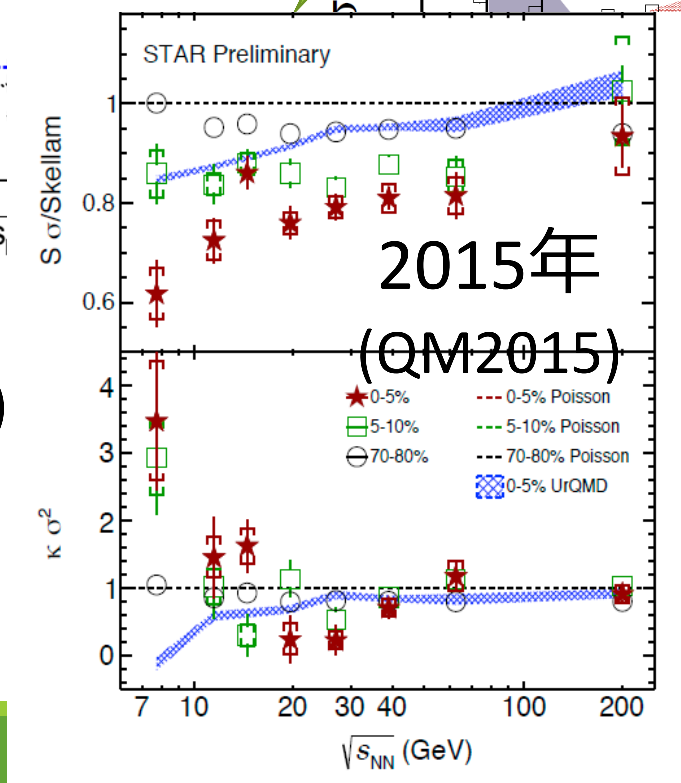
2012年
(QM2012)



2014年
(CPOD2014)

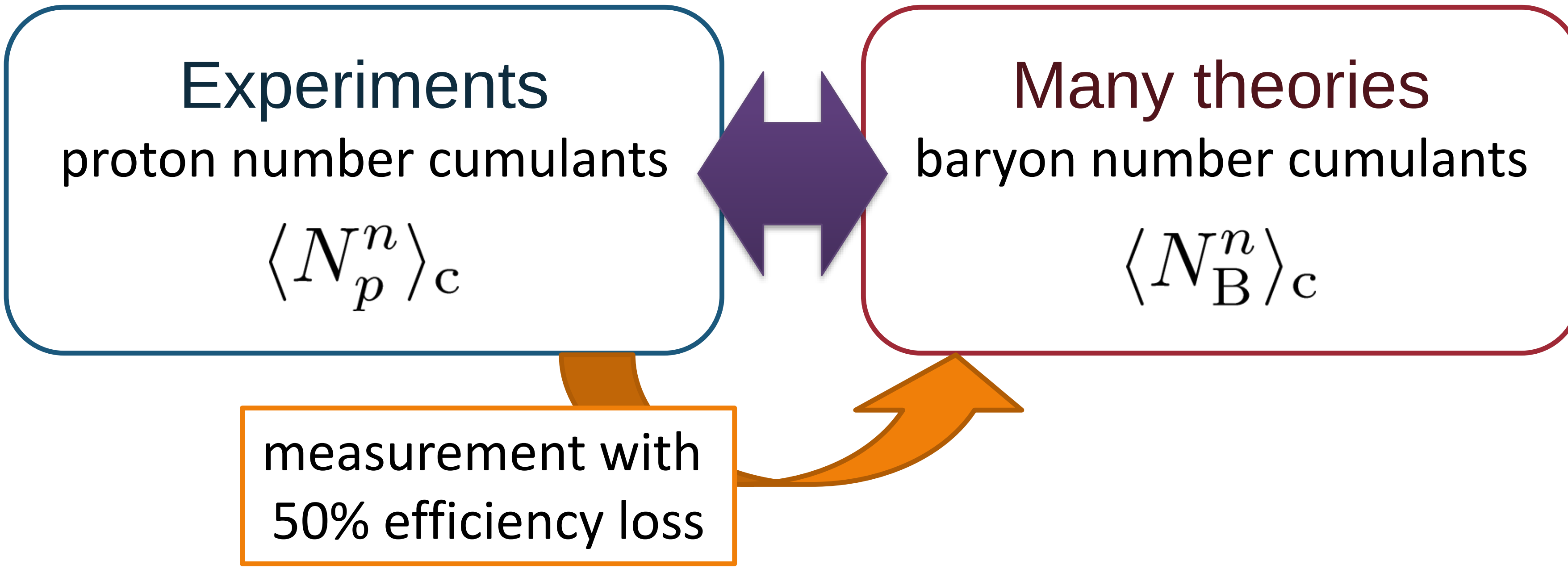


2015年
(QM2015)



Proton v.s. Baryon Number Cumulants

MK, Asakawa, 2012; 2012



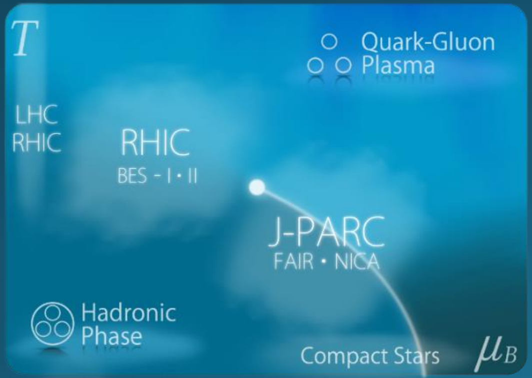
- The difference would be large.
- Reconstruction of $\langle N_B^n \rangle_c$ is possible using the binomial model.
- The use of binomial model is justified by "isospin randomization."

Summary

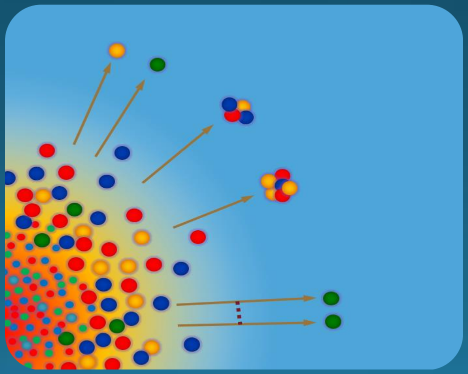
Summary

- J-PARC-HI will explore extremely dense medium with world's highest statistics.

- It will reveal many interesting aspects of

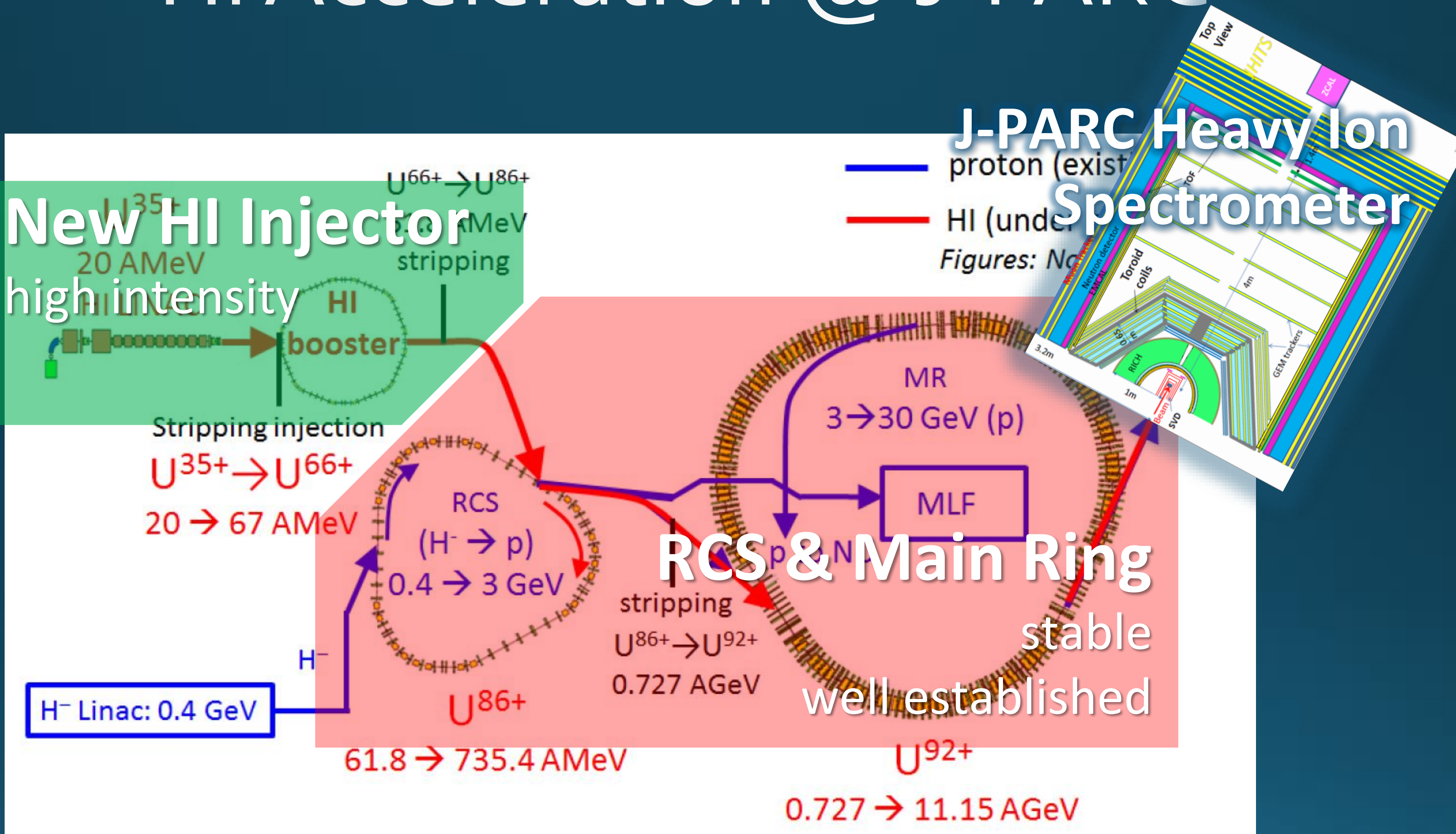


Dense medium



Rare events

HI Acceleration @ J-PARC



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