New proposal: HAD_03

Observing Critical Fluctuations in the Dynamics of Heavy Ion Collisions

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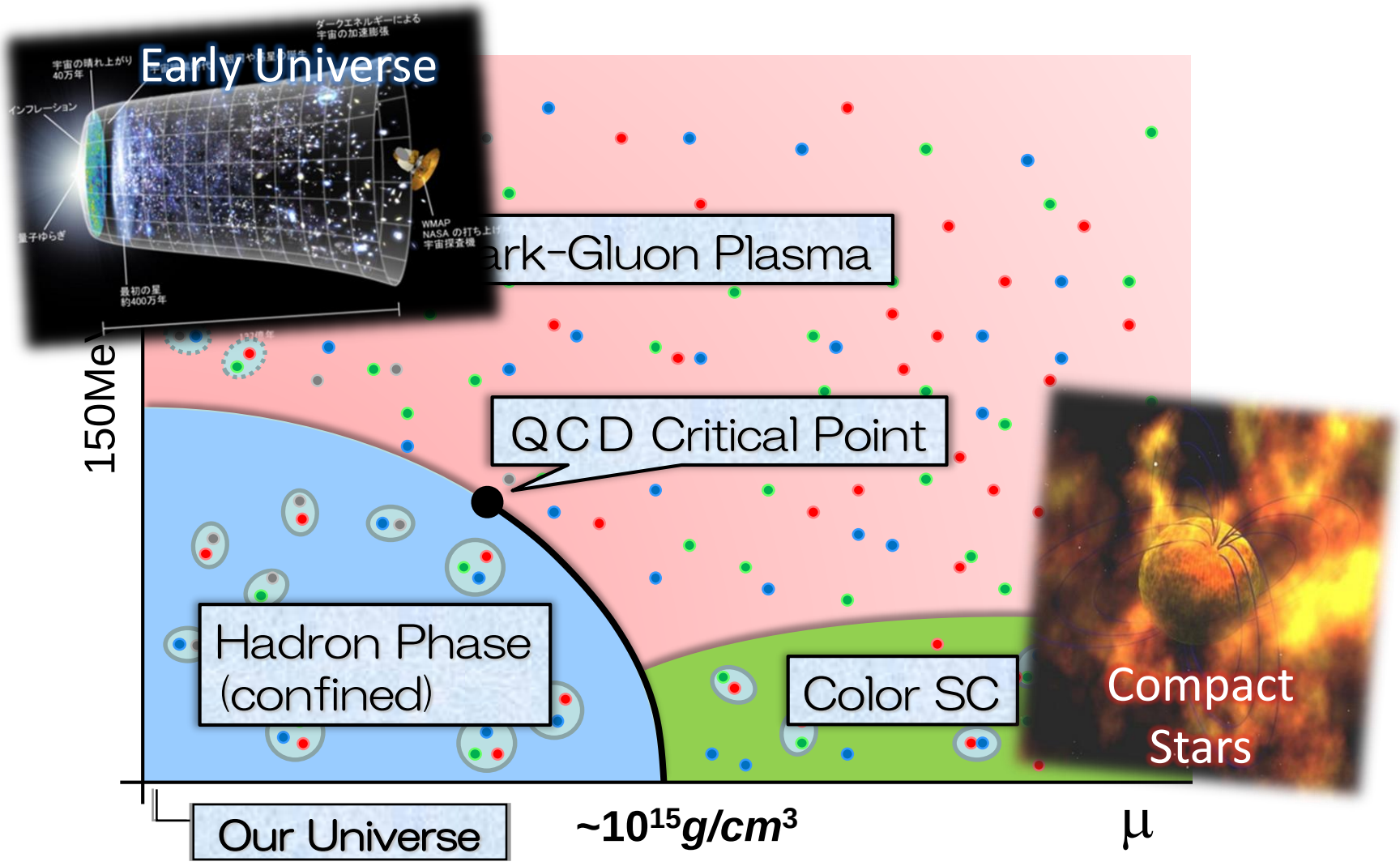
with

Marlene Nahrgang

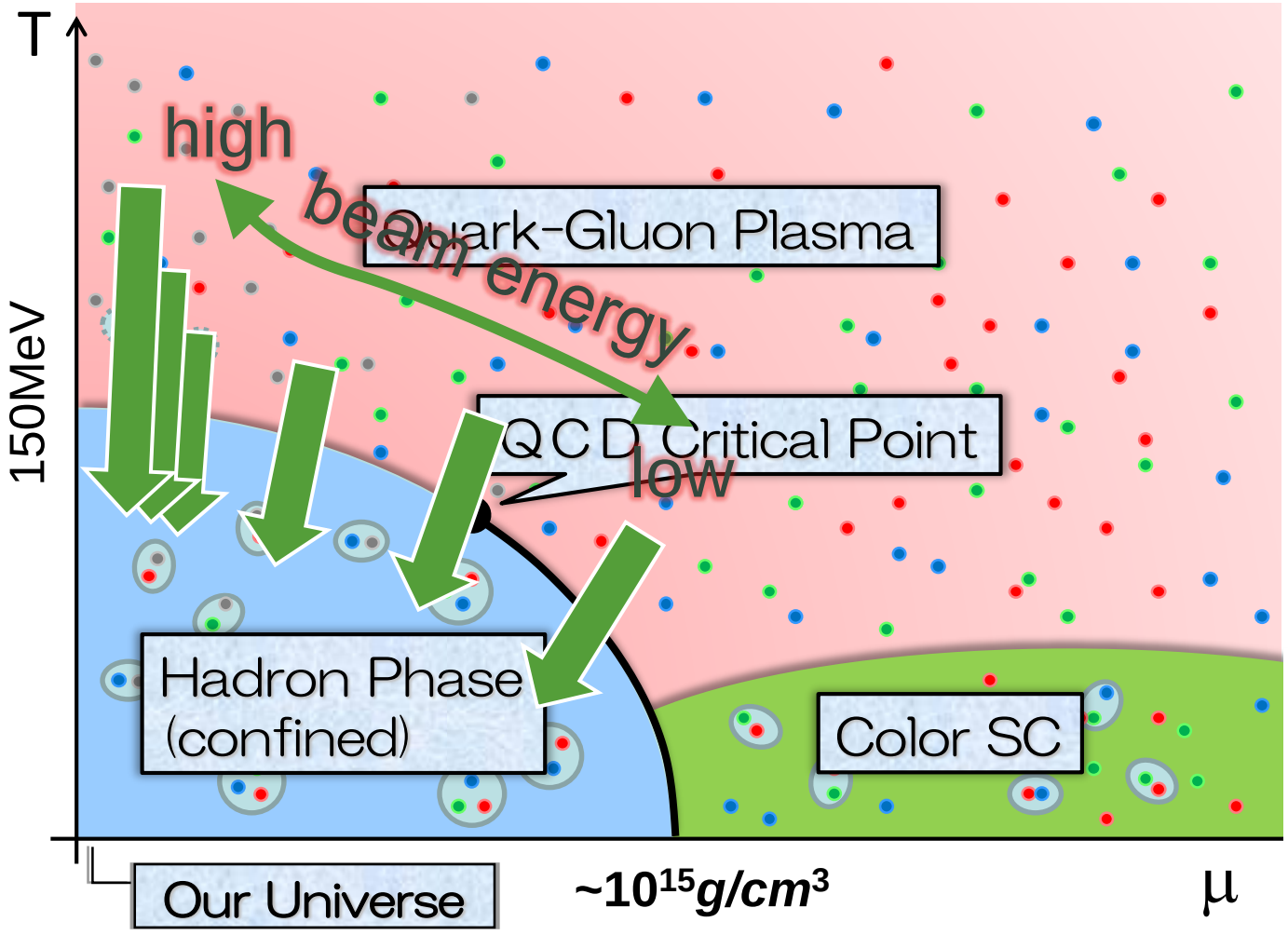
(SUBATECH, Nantes)

TYL/FJPPL, FKPPL workshop, Nara, May. 9, 2018

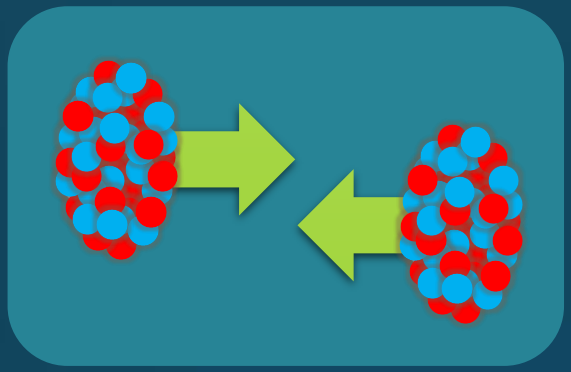
QCD Phase Diagram



Beam-Energy Scan Program in Heavy-Ion Collisions



Beam-Energy Dependence



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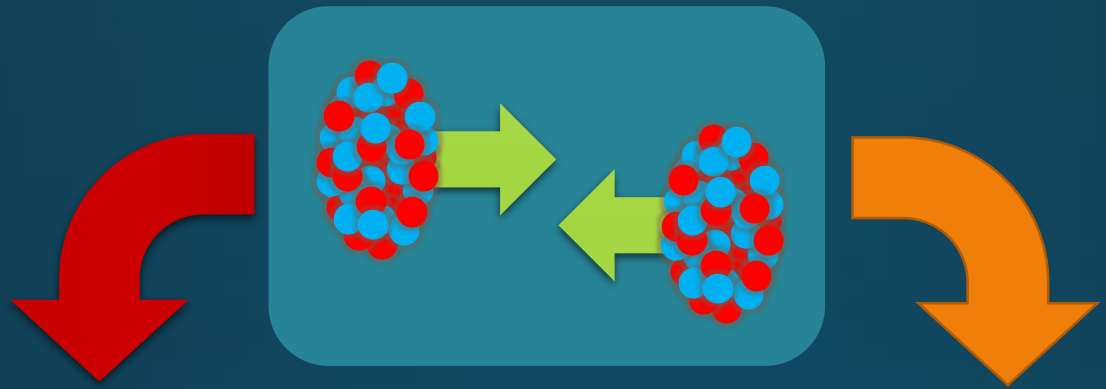
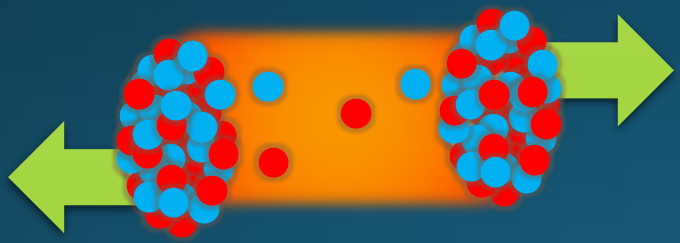
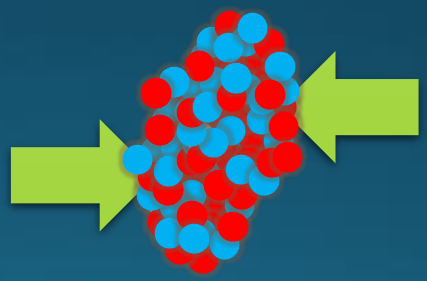


High energy

Low energy





Nuclear transparency

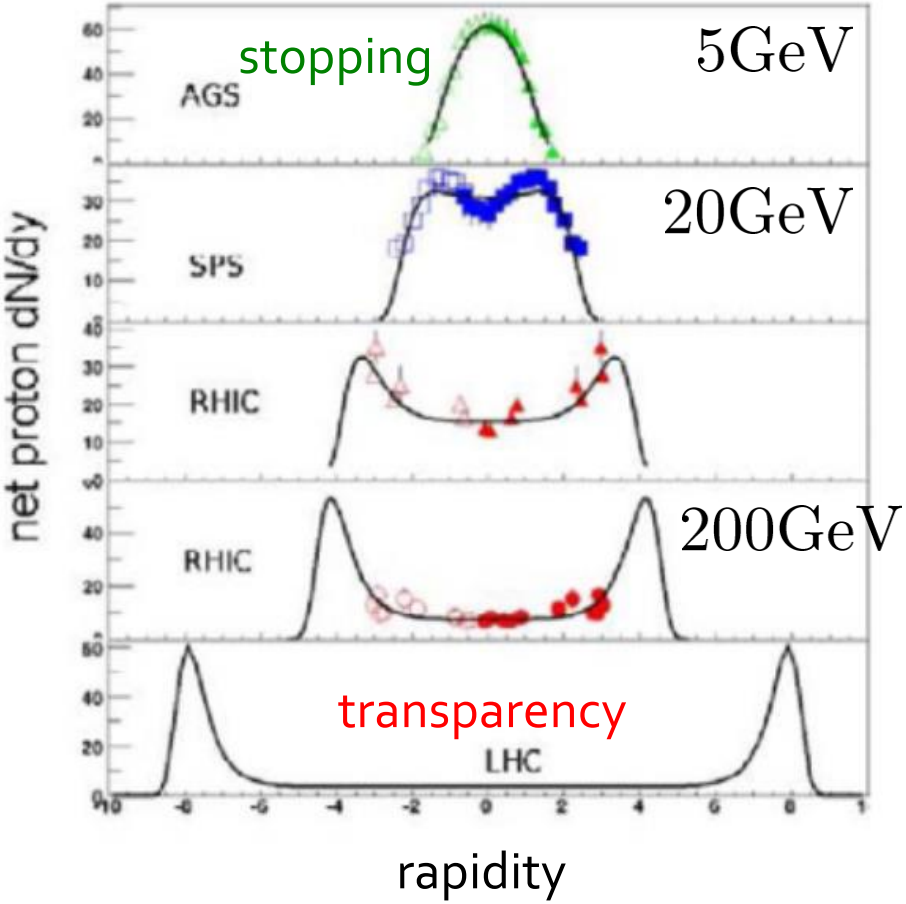
net-baryon #: small

Baryon stopping

net-baryon #: large

Baryon Stopping

rapidity dep. of net-proton #

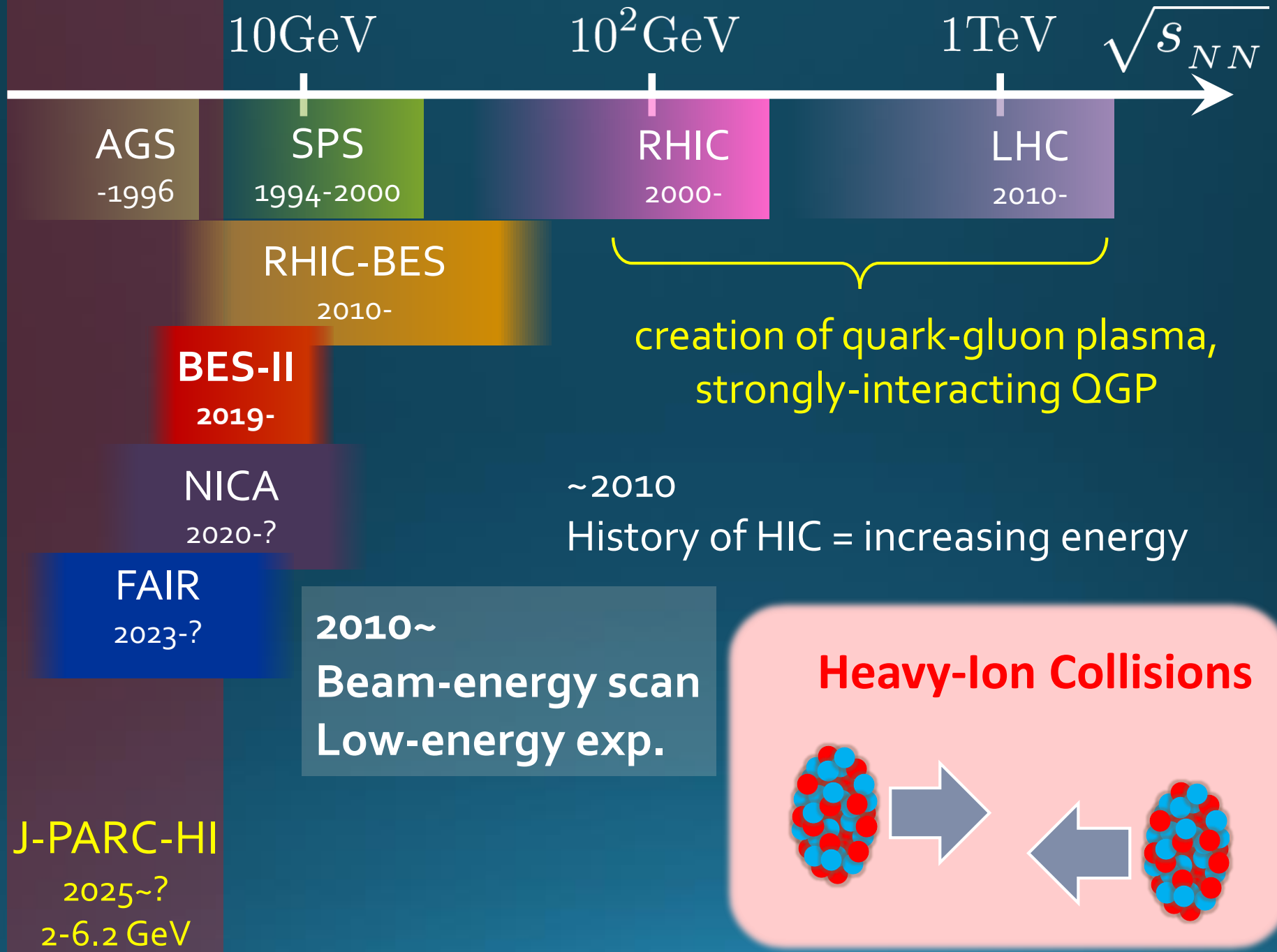


$\sqrt{s_{NN}} \simeq 4 - 6\mathrm{GeV}$

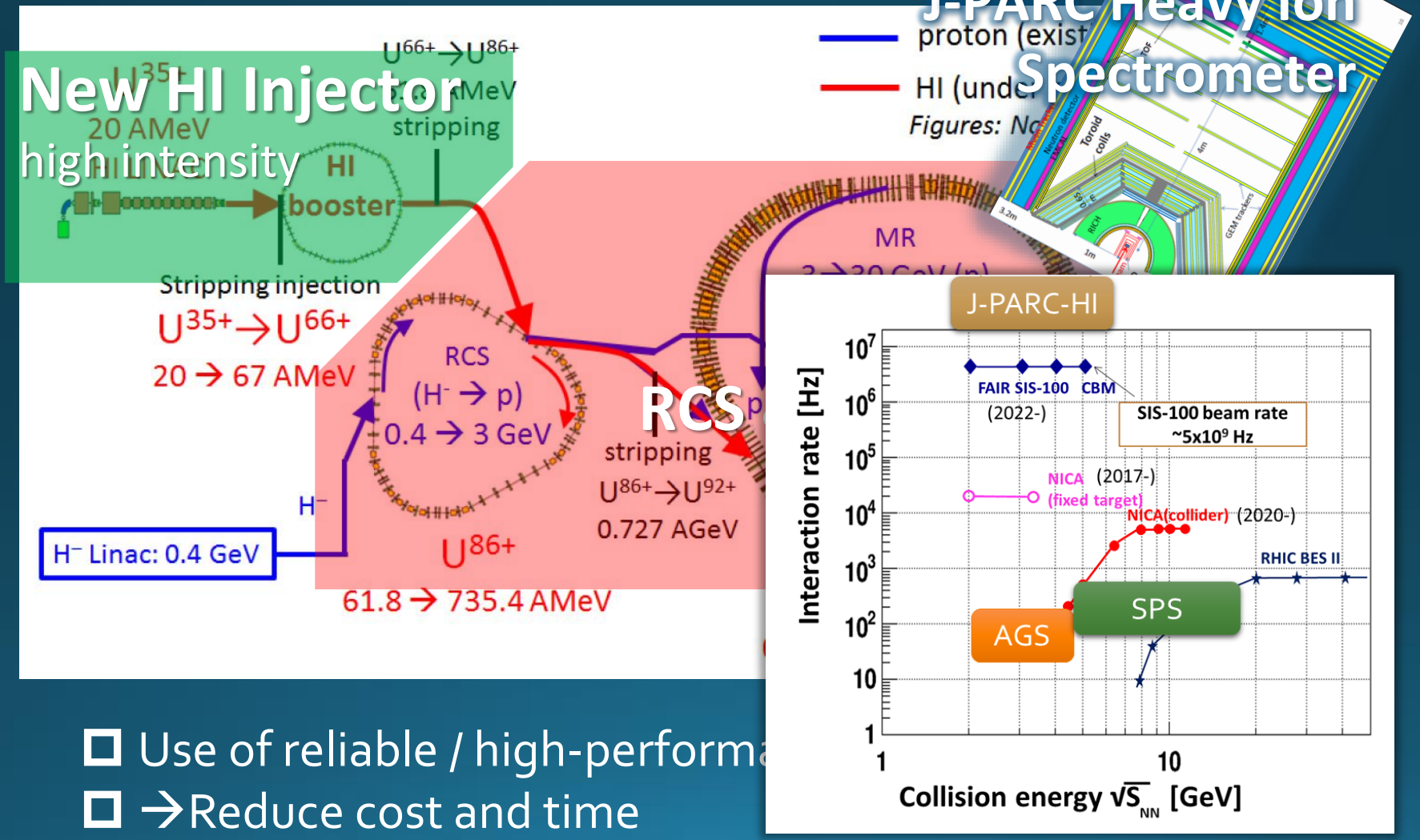
Baryons stop at collision point

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

Baryons pass through

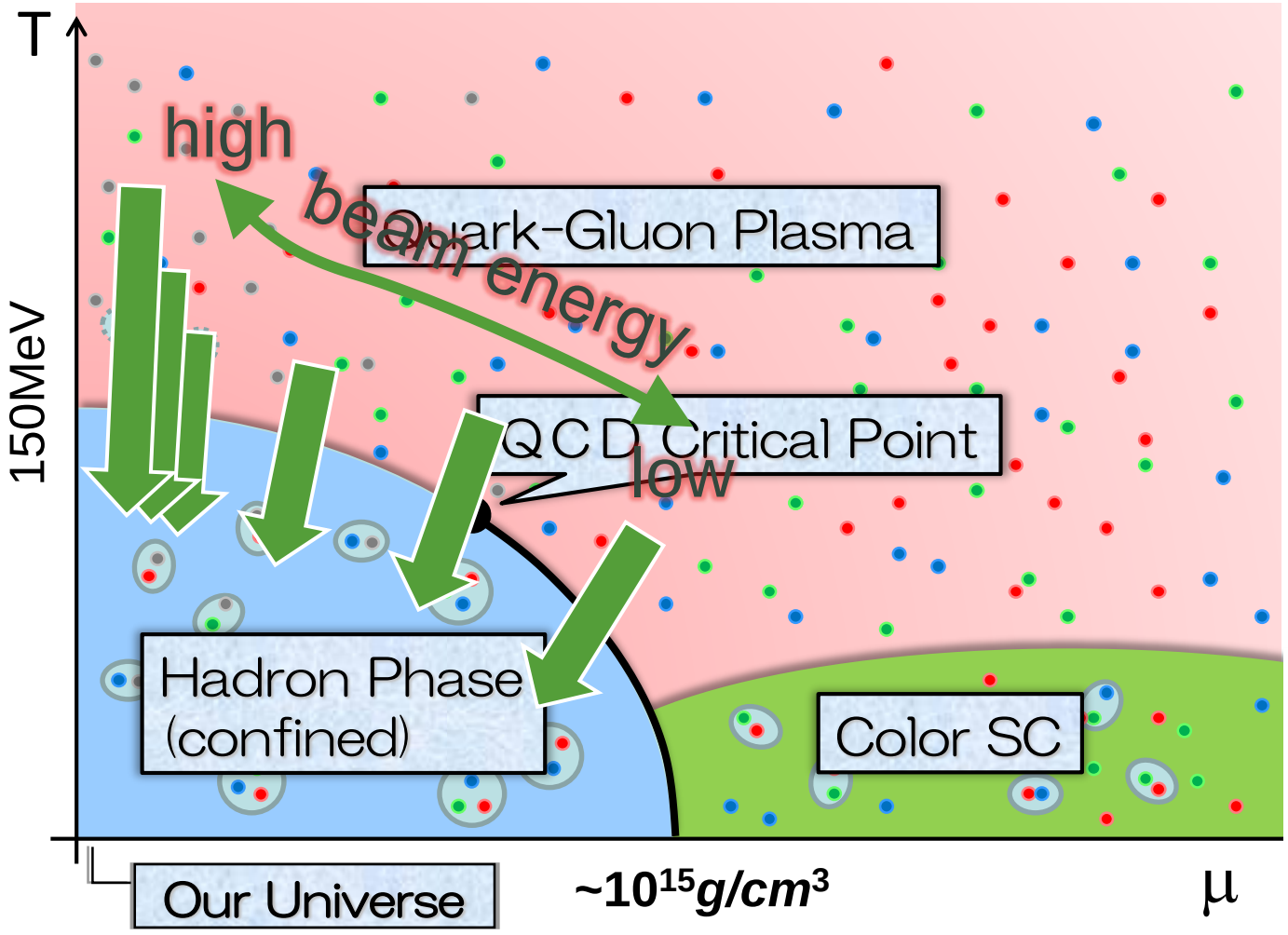

10GeV
10^2GeV
1TeV
$\sqrt{s_{NN}}$
AGS
-1996
SPS
1994-2000
RHIC
2000-
LHC
2010-
RHIC-BES
2010-
BES-II
2019-
NICA
2020-?
FAIR
2023-?
J-PARC-HI
2025~?
2-6.2 GeV
creation of quark-gluon plasma,
strongly-interacting QGP
~2010
History of HIC = increasing energy
2010~
Beam-energy scan
Low-energy exp.
Heavy-Ion Collisions

HI Acceleration @ J-PARC



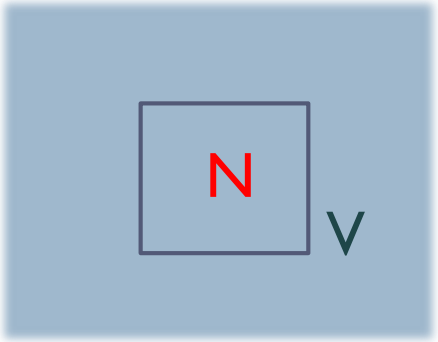
- Use of reliable / high-performa
- →Reduce cost and time

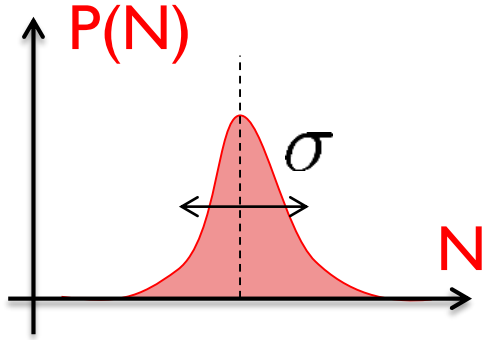
Searh for QCD Phase Structure with Fluctuation Observables



Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.





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

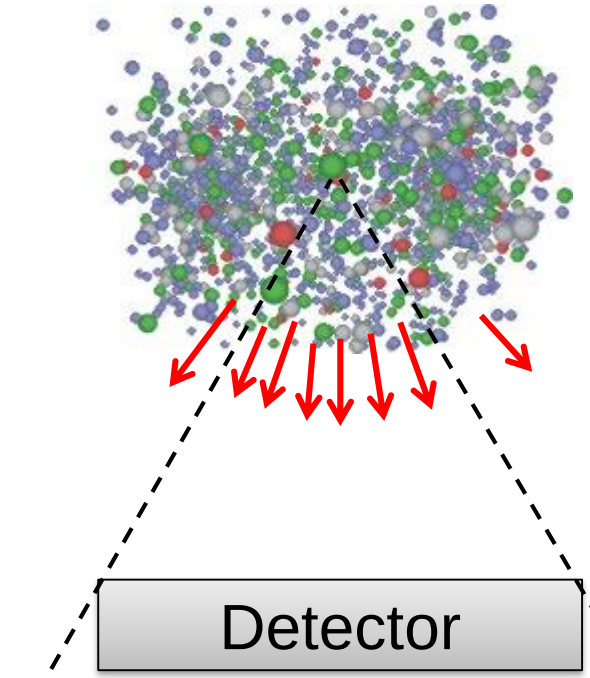
Stephanov, PRL (2009); Asakawa, Ejiri, MK, PRL (2009)

Review: Asakawa, MK, PPNP**90** (’16)

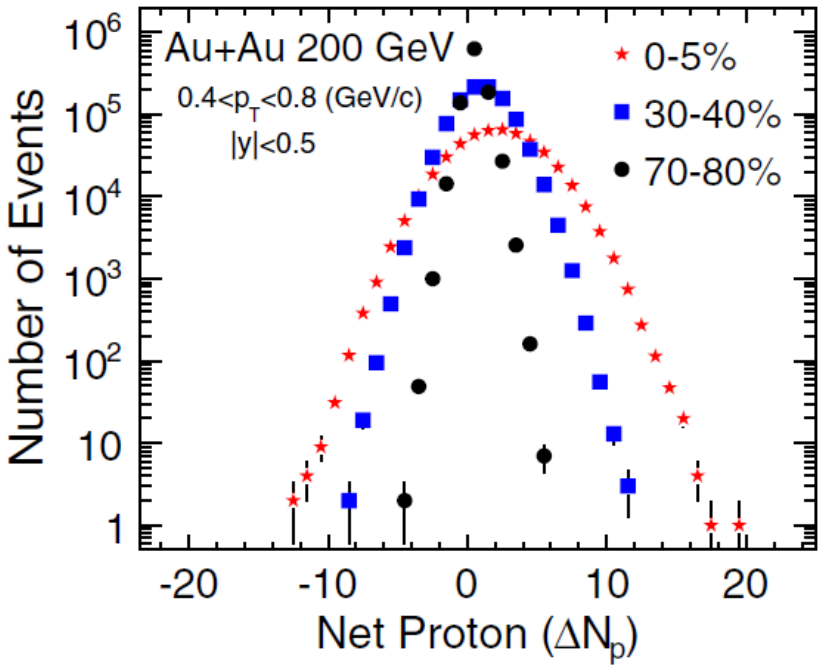
Event-by-Event Fluctuations

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

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



STAR, PRL**105** (2010)

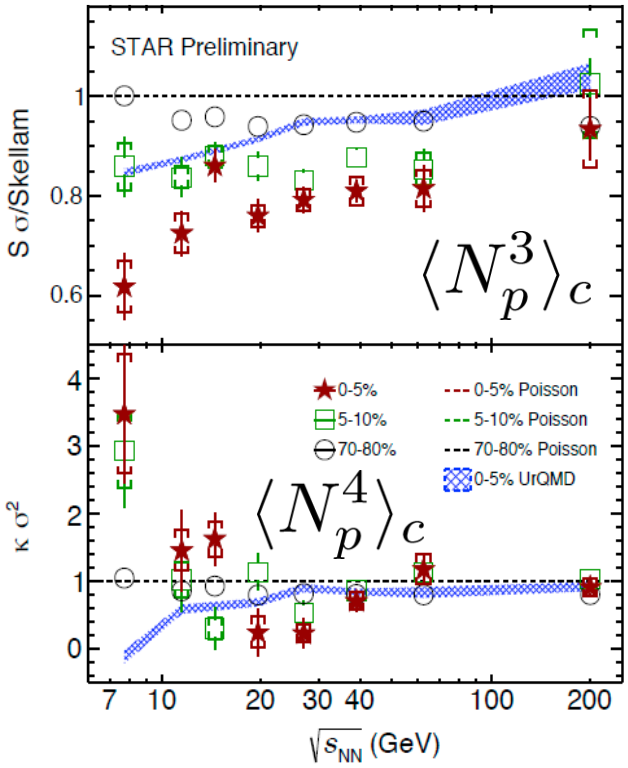


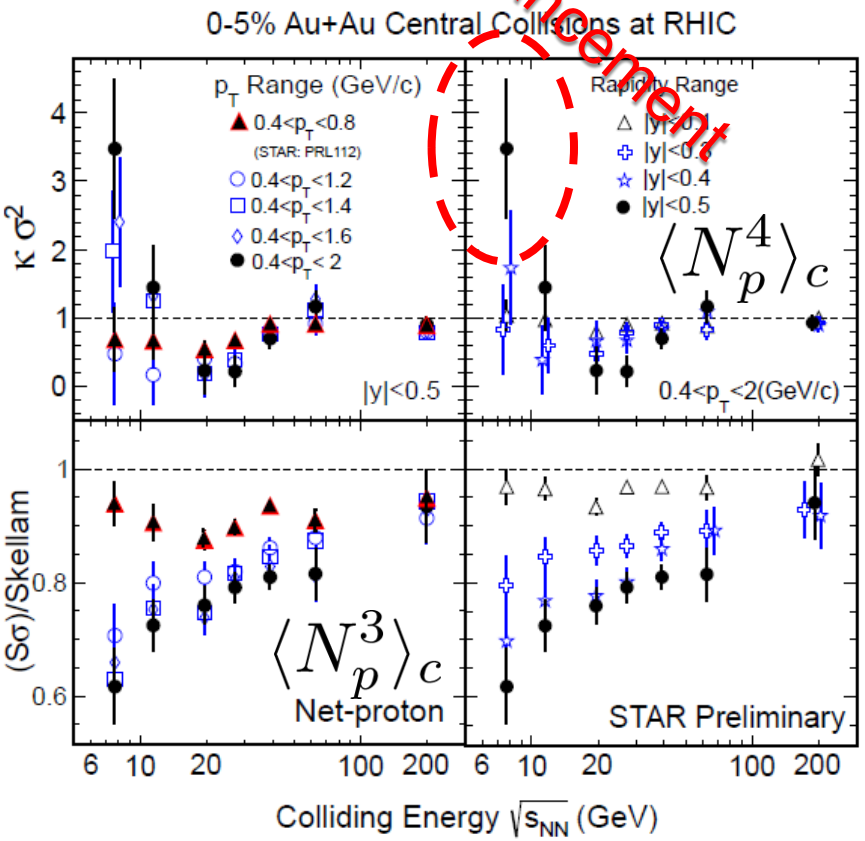
Cumulants

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

Higher-Order Cumulants

STAR Collab.
2010~



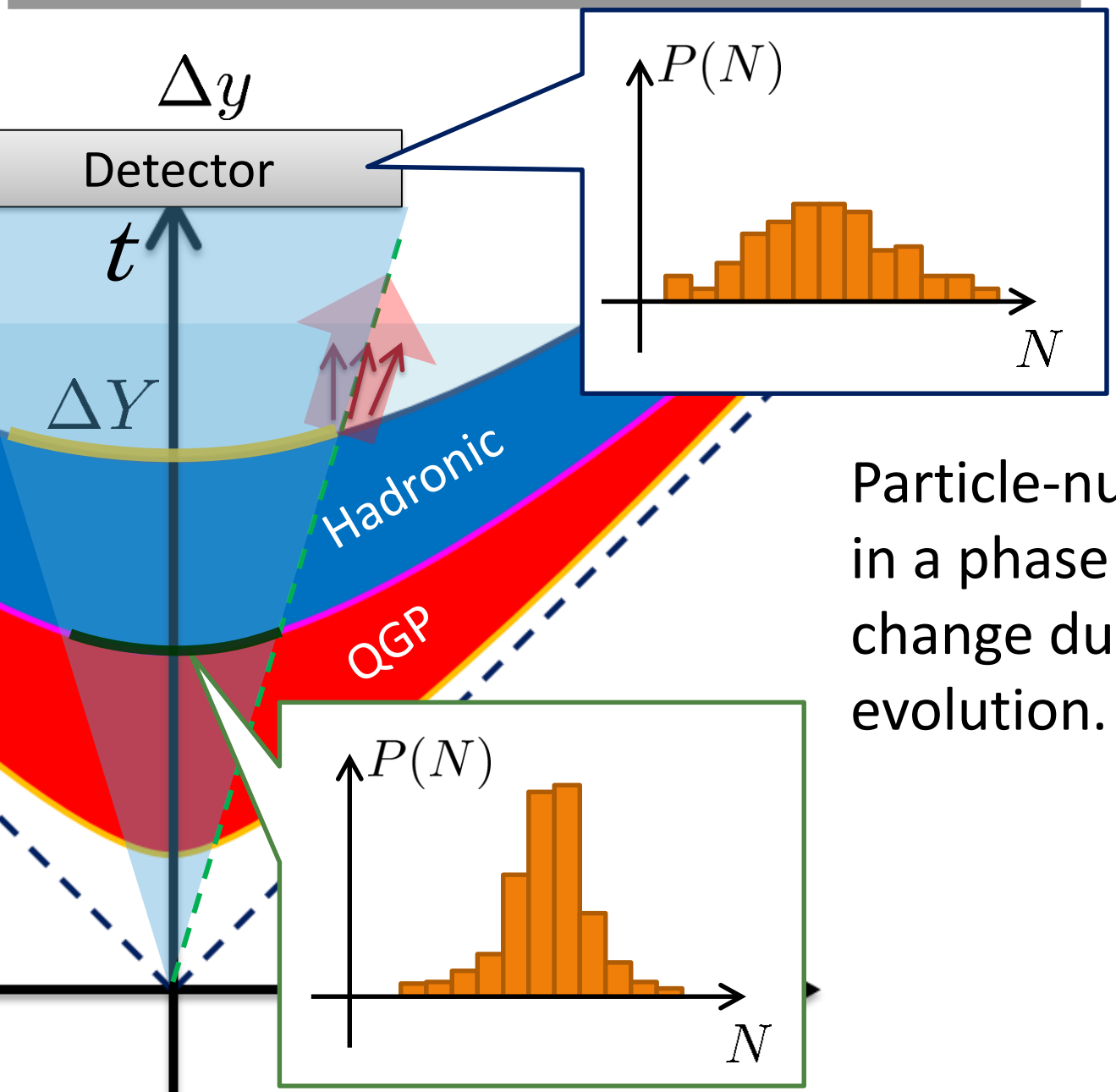


Enhanement in non-Gaussian cumulants has been observed!

Have we measured critical fluctuations?

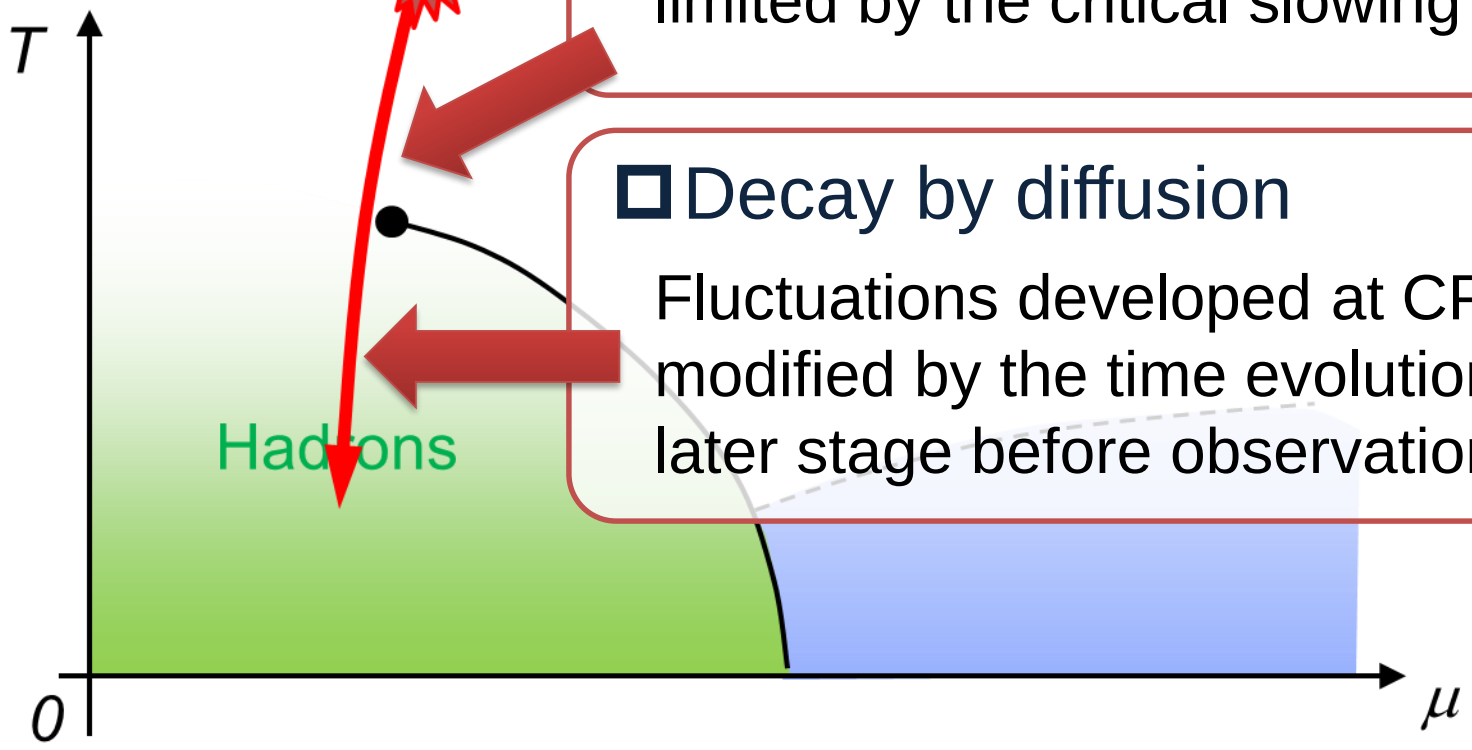
Time Evolution of Fluctuations

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



Particle-number fluctuations in a phase space continue to change during the time evolution.

Effect of Dynamical Evolution



Growth

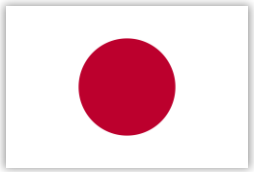
Growth of the critical fluctuation is limited by the critical slowing down.

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



Osaka

Nantes

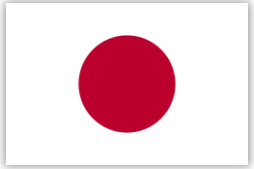
Masakiyo Kitazawa
(Osaka University/KEK)

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

Stochastic Diffusion Equation



Sakaida, MK, et al.
PR**D95**, 064905 (2017)

- 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

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

$$\langle \xi(\eta_1)\xi(\eta_2)\rangle \sim \chi\delta(\eta_1-\eta_2)$$

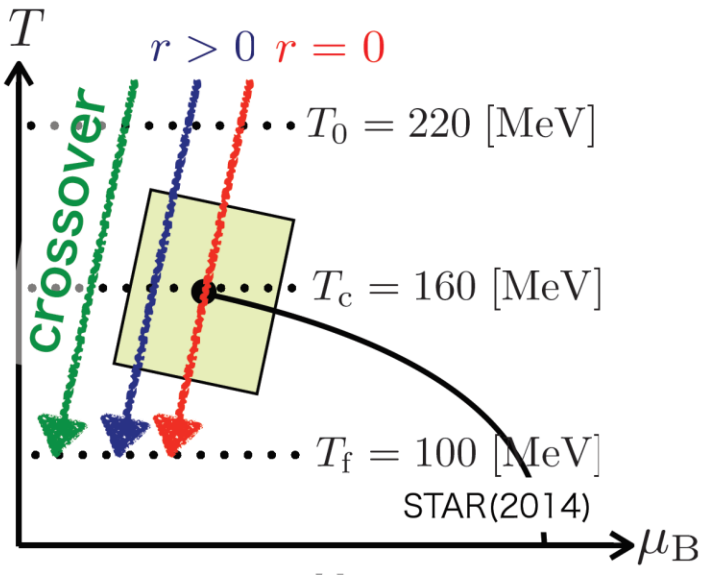
- Describe a relaxation toward fluctuating uniform state
- Only Gaussian fluctuations

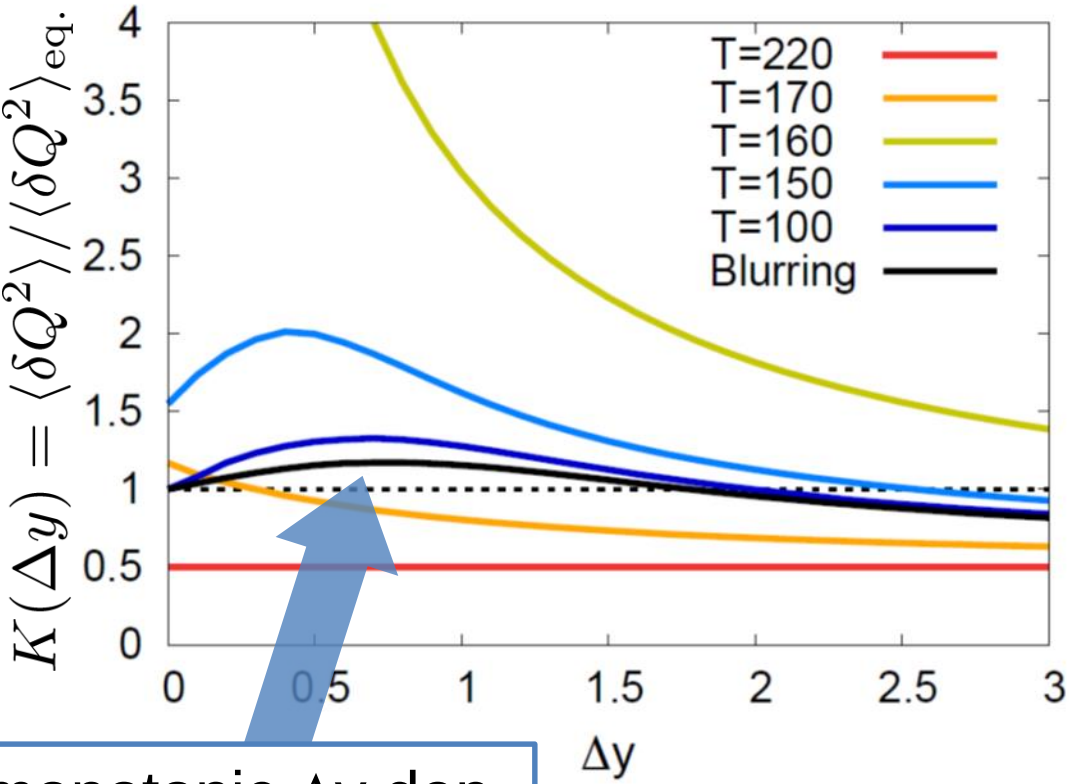
Review: Asakawa, MK, PPNP **90** (2016)

Evolution of Fluctuation

Sakaida, MK, et al.
PR**D95**, 064905 (2017)

Solve the time evolution **analytically** for Gaussian fluctuations





Non-monotonic Δy dep. as a signal of QCD-CP

Extension to Non-Gaussianity

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

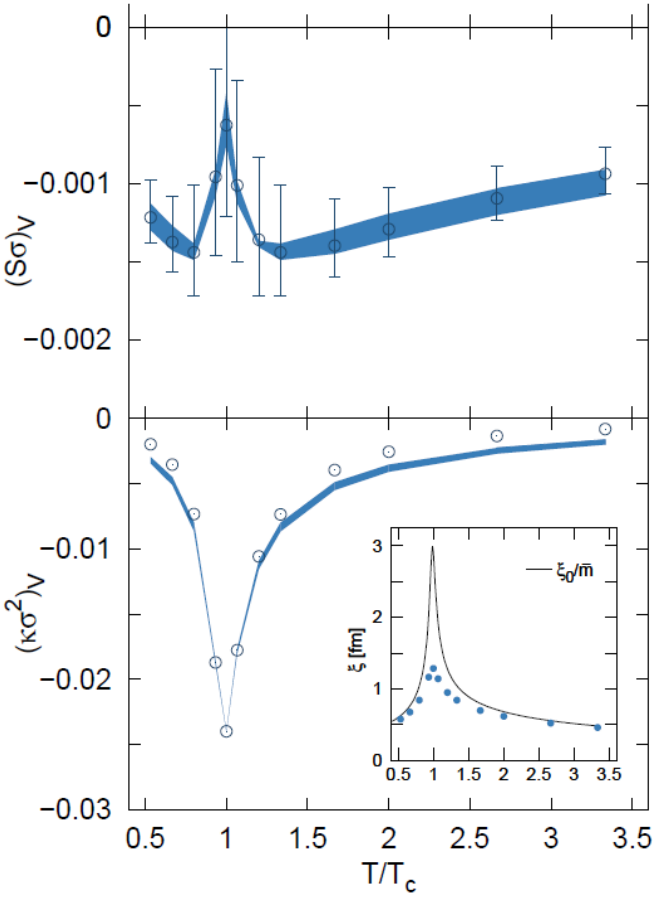
Nahrgang, Bluhm, et al.
arXiv:1804.05728

Include non-linear effects

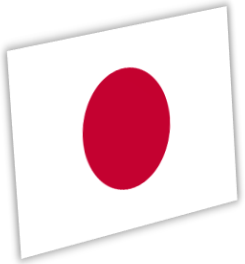
$$\partial_\tau n = D\partial_\eta^2 \frac{\delta F(n)}{\delta n} + \partial_\eta \xi(\eta,\tau)$$

$$F(n) = n^2 + an^3 + bn^4 + cn^6$$

Solve the time evolution **stochastically** including **non-Gaussian** fluctuations



Many Things To Do

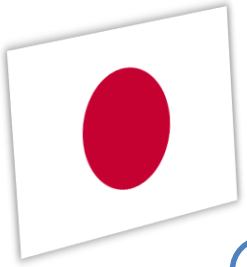


Gaussian
Analytic

Stochastic diffusion model

Non-Gaussian
Stochasitc

Many Things To Do



Gaussian
Analytic

Non-Gaussian
Stochasitc

Stochastic diffusion model

analytic result
for non-Gaussian

parameter
dependence

Comparison

Deeper understanding
on dynamics of fluctuations

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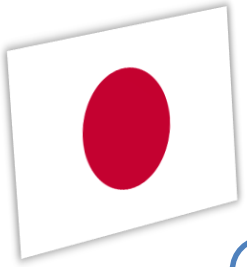

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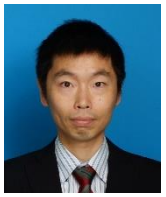
Diffusion on
Brownian particle
model

Coupling to
chiral condensate
in chiral-fluid model



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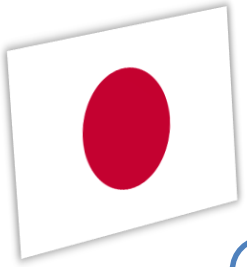

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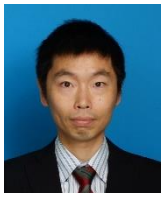
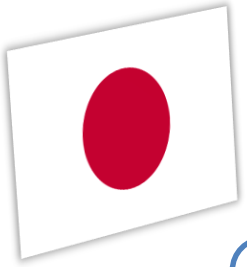


Dynamical evolution in
realistic space-time evolution

Many Things To Do



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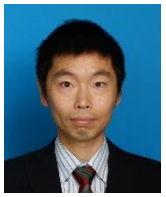

Dynamical evolution in
realistic space-time evolution

- 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…