# Non-Gaussian fluctuations in relativistic heavy ion collisions

Masakiyo Kitazawa

# 一本の草も涼風宿りけり

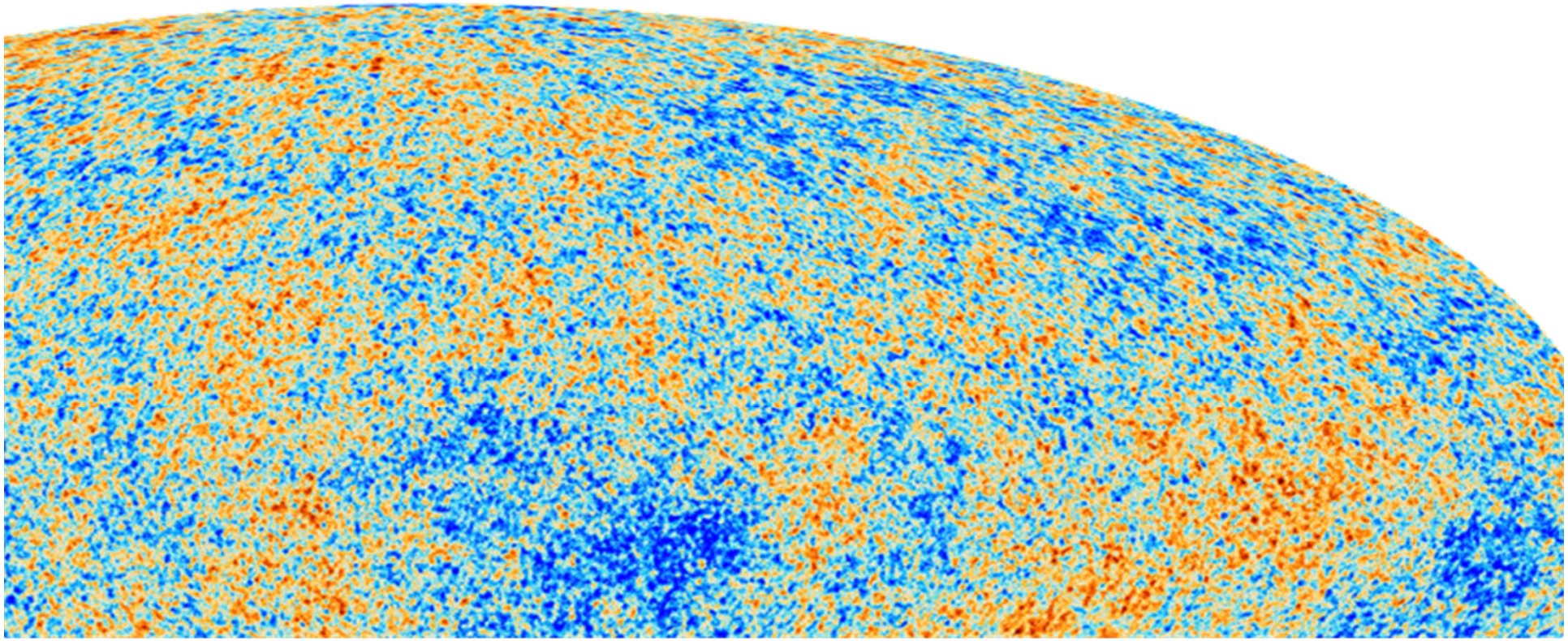
even on one blade of grass the cool wind lives

小林一茶

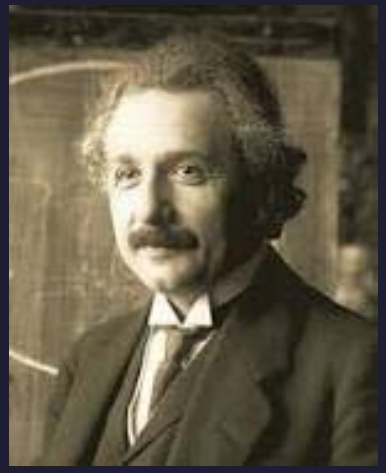
Issa Kobayashi

1814

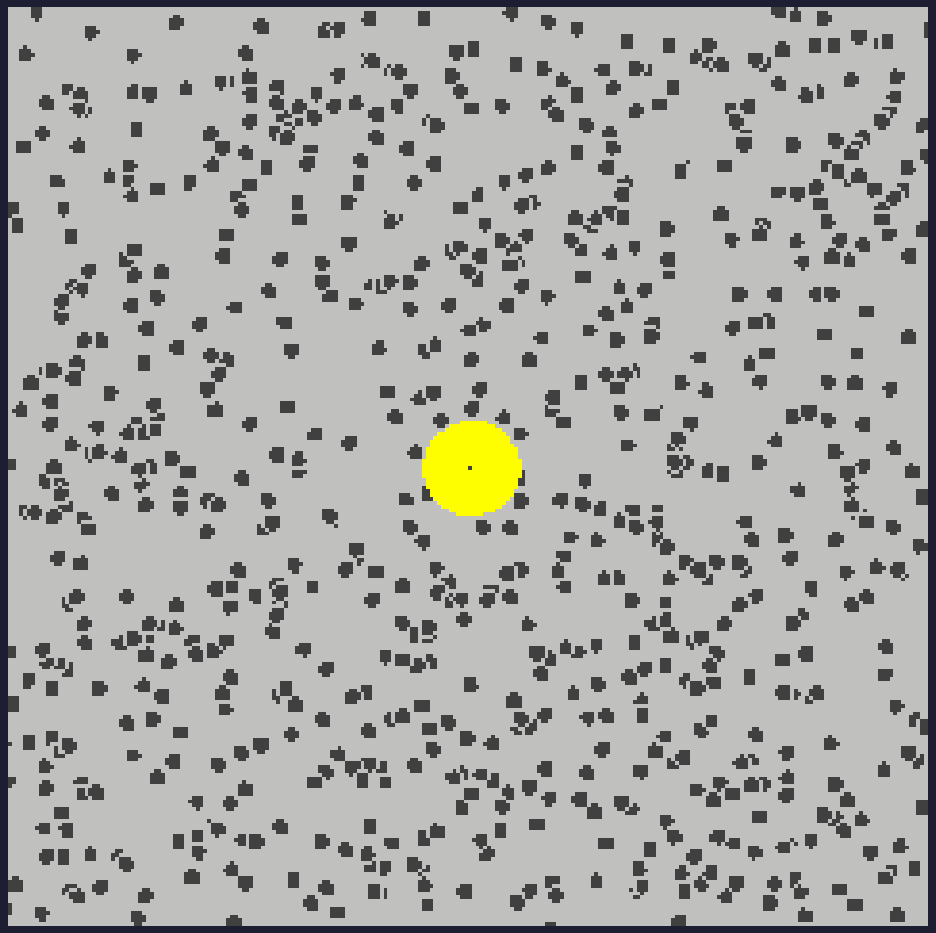
Physicits can feel hot early Universe
13 800 000 000 years ago
in tiny fluctuations of
cosmic microwave



Physicists can feel the existence of microscopic atoms behind random fluctuations of Brownian pollens



A. Einstein
1905



quarks

Feel quarks behind fluctuations
in relativistic heavy ion collisions

2014

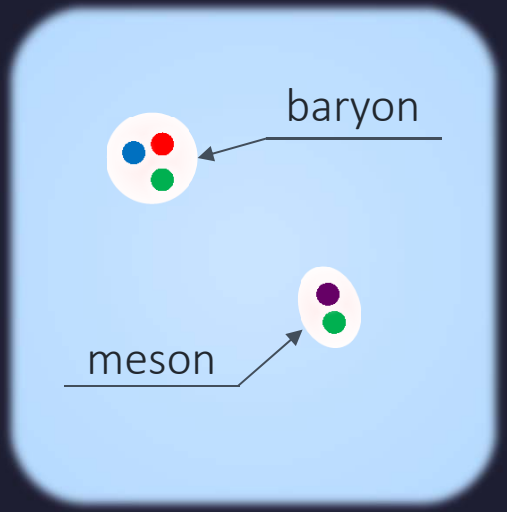
# Non-Gaussian Fluctuations in Relativistic Heavy Ion Collisions

Masakiyo Kitazawa (Osaka U.)

Frontiers of Theoretical Science, Kavli IPMU, Nov. 6, 2014

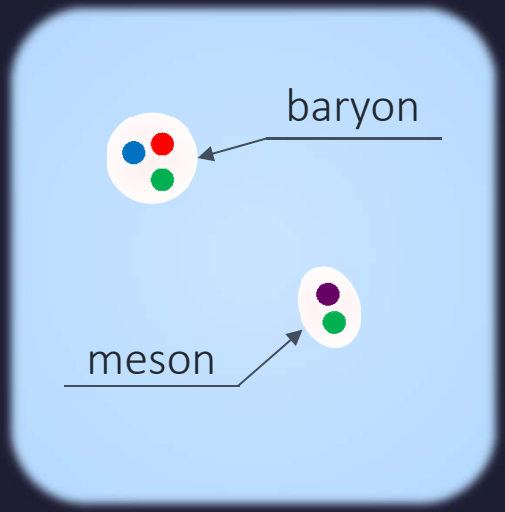
# Quark-Gluon Plasma

vacuum



# Quark-Gluon Plasma

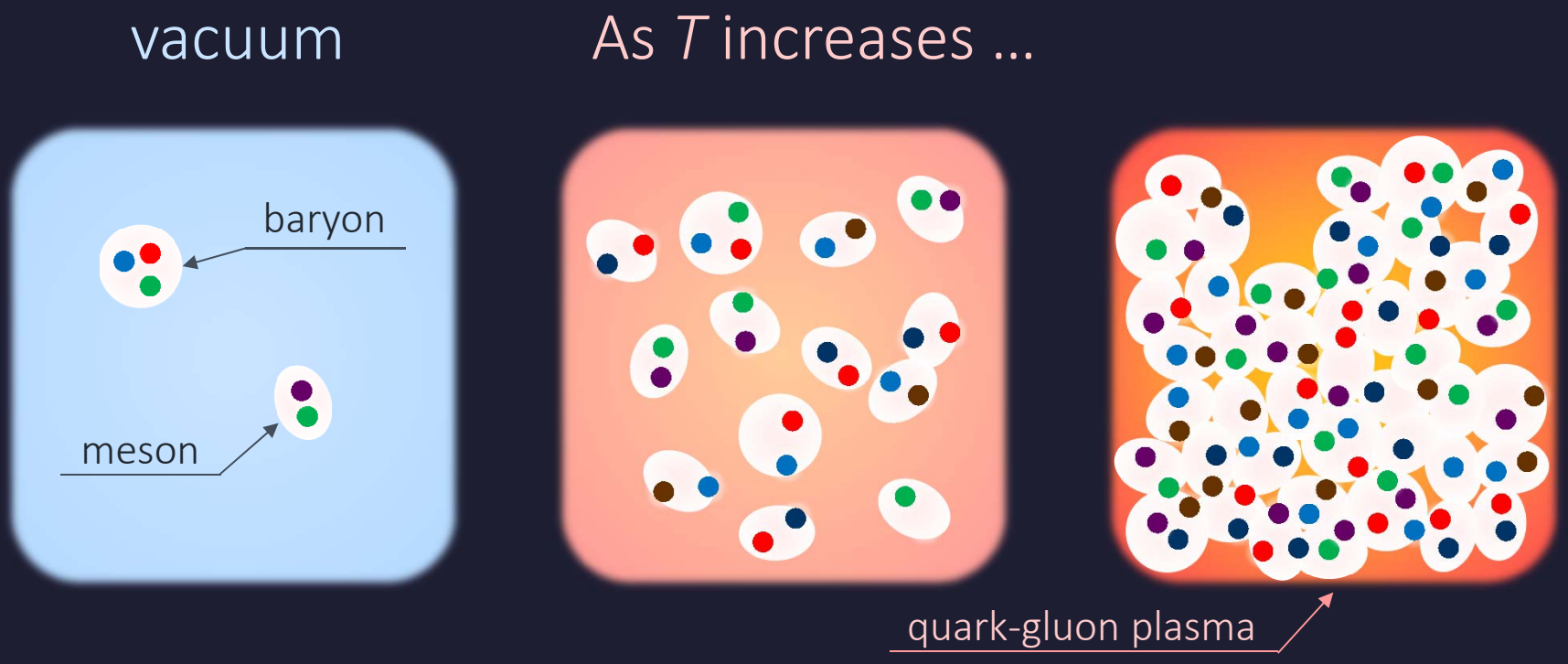
vacuum



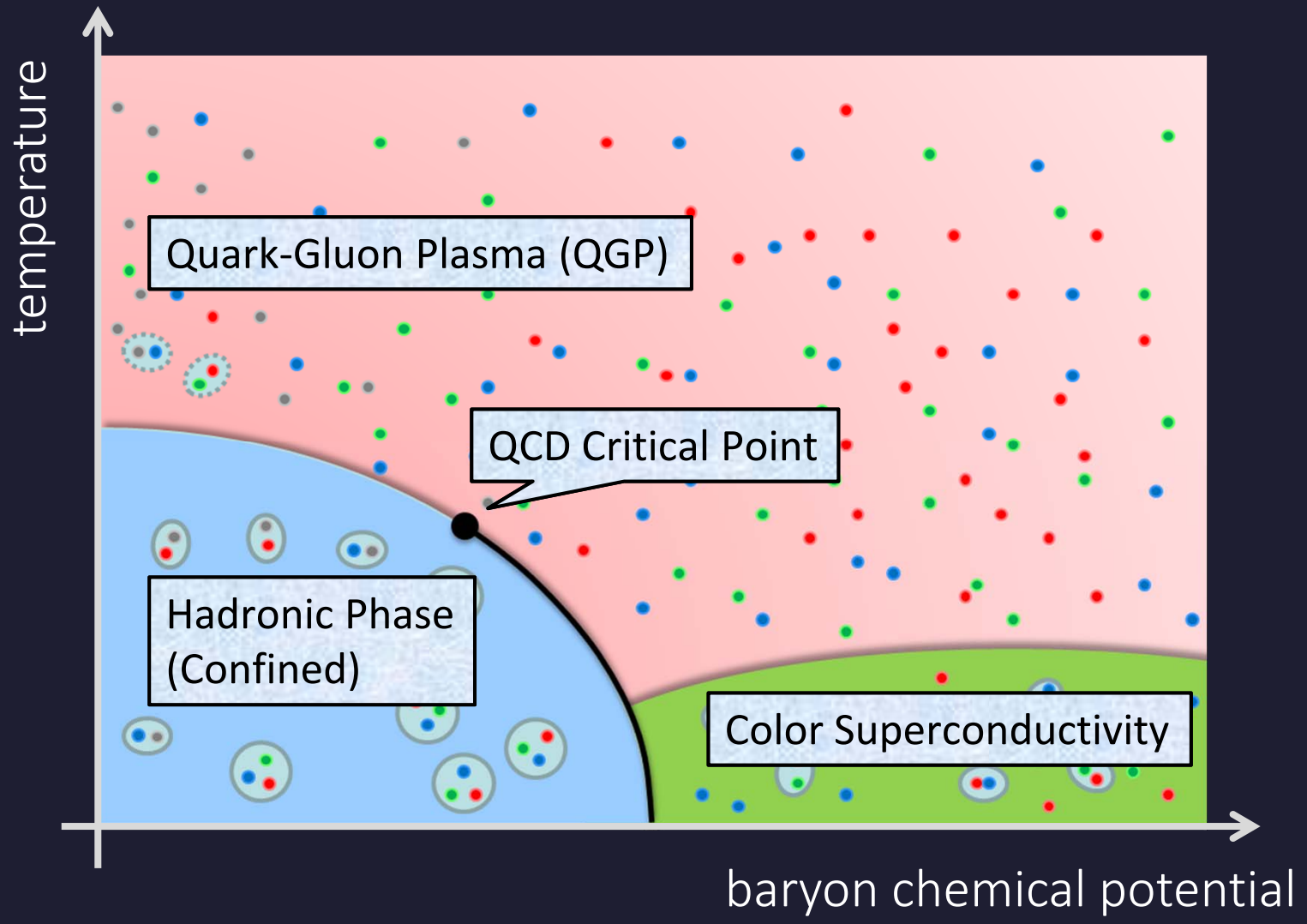

As *T* increases …

Early Universe

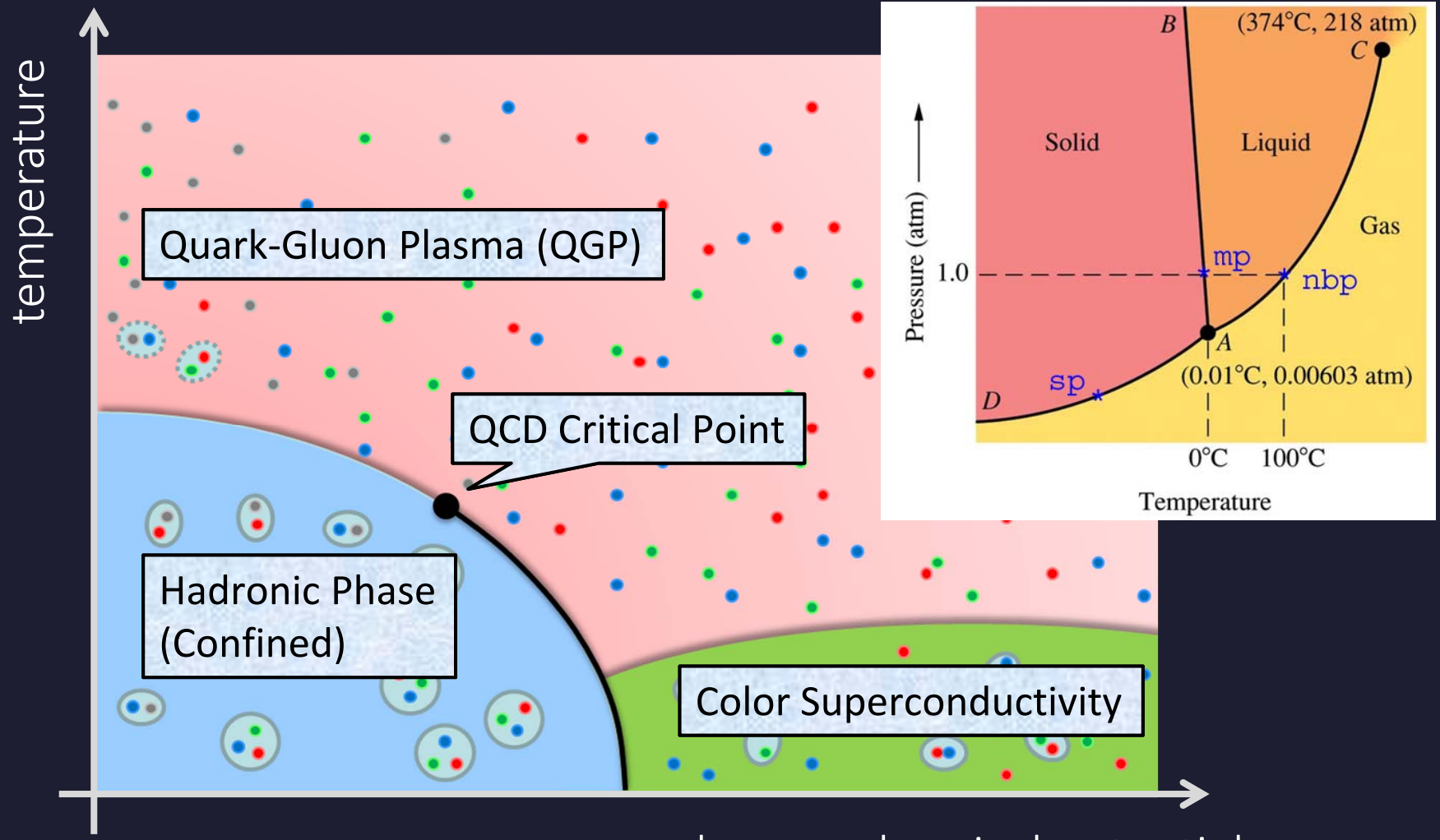
# Quark-Gluon Plasma (QGP)



# QCD Phase Diagram



# QCD Phase Diagram



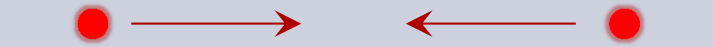

Phase diagram of water

# Relativistic Heavy Ion Collisions

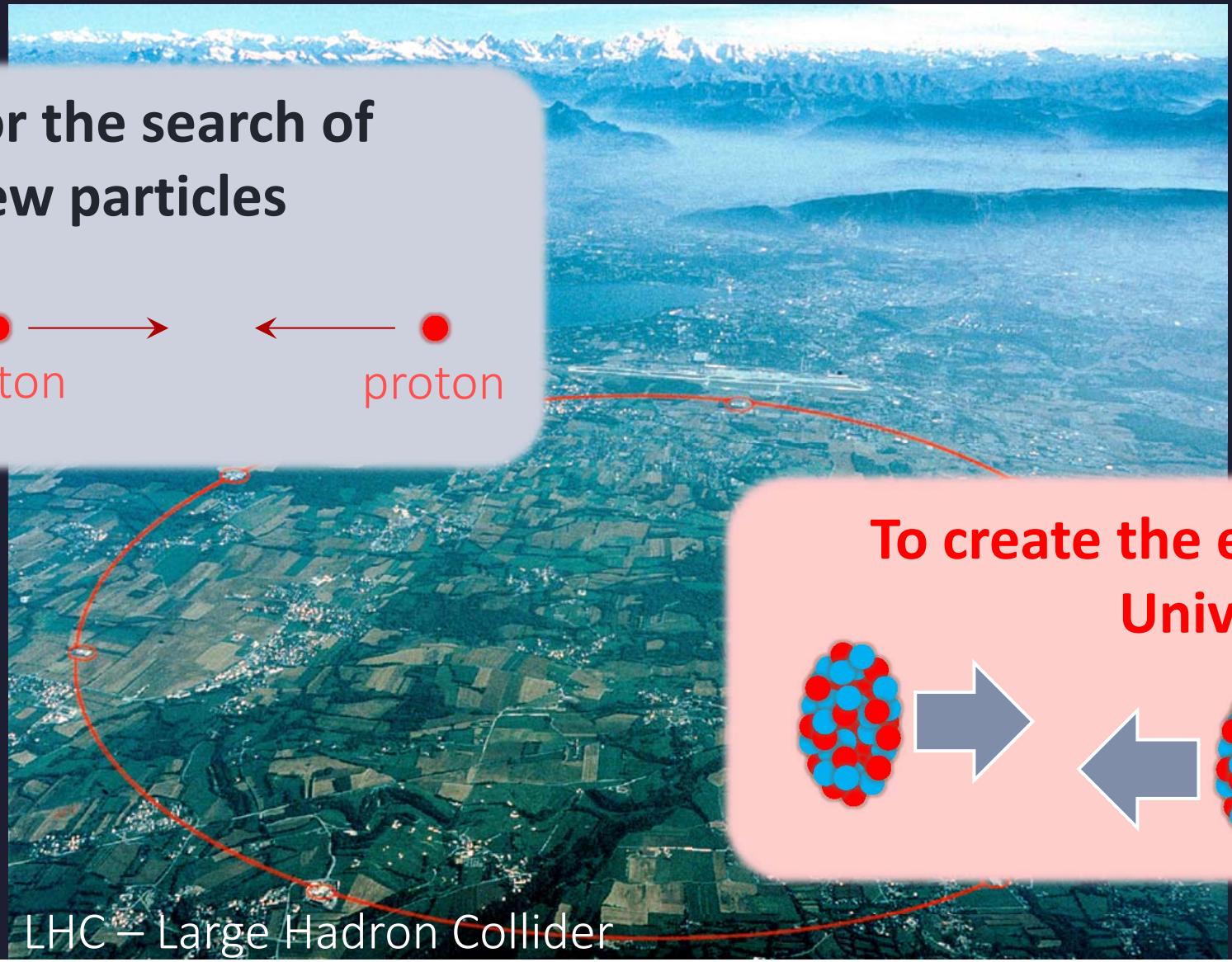
LHC – Large Hadron Collider

# Relativistic Heavy Ion Collisions

**For the search of new particles**



# Relativistic Heavy Ion Collisions

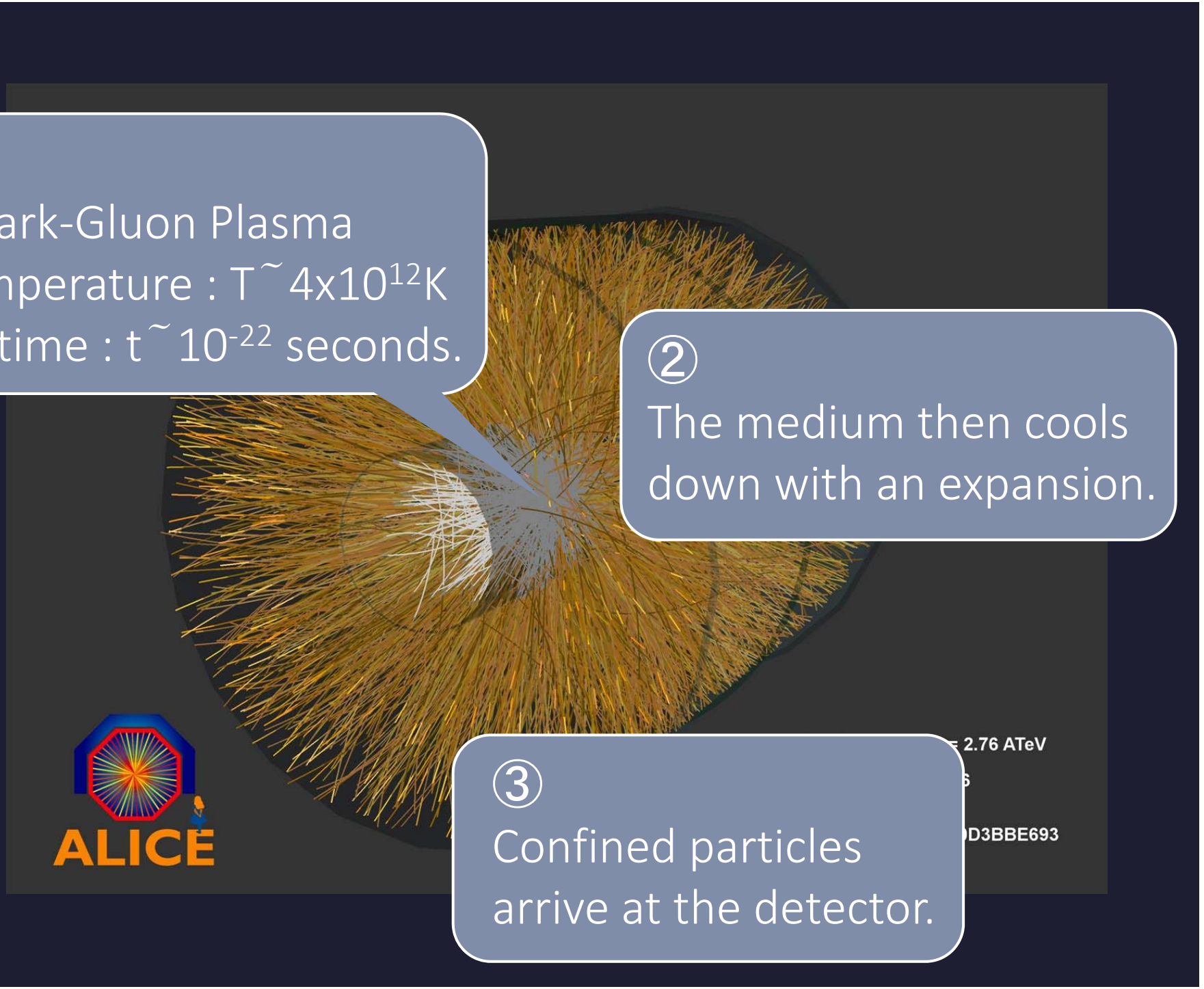


**For the search of new particles**

proton proton

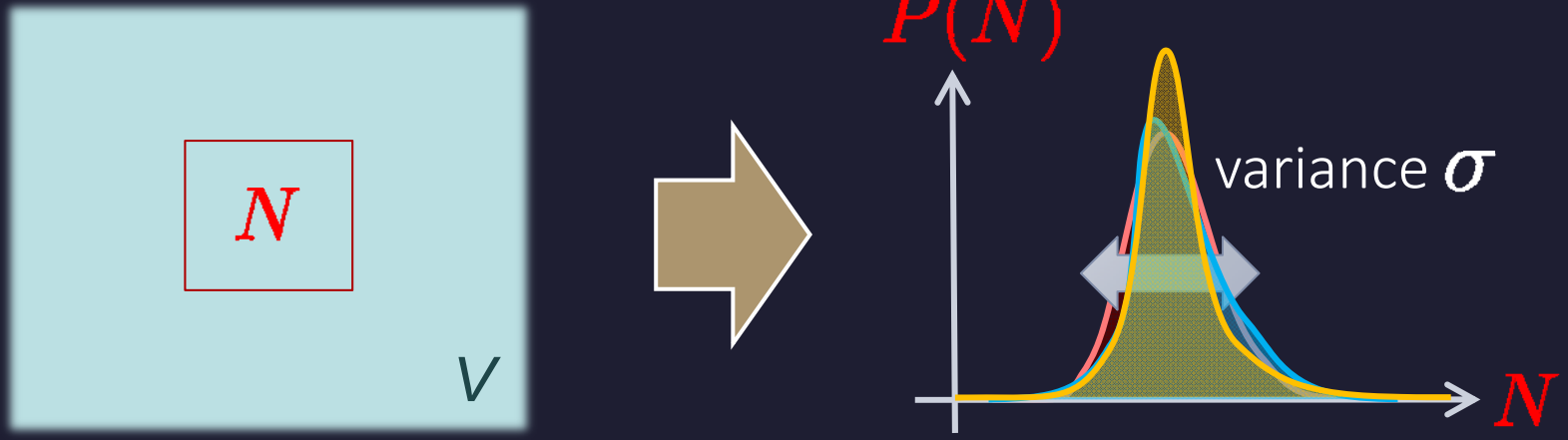
**To create the early Universe**

LHC – Large Hadron Collider


①
Quark-Gluon Plasma
temperature : T~4x10^12K
lifetime : t~10^-22 seconds.
②
The medium then cools
down with an expansion.
③
Confined particles
arrive at the detector.
= 2.76 ATeV
D3BBE693
ALICE

# Thermal Fluctuations

Observables in equilibrium are fluctuating!




$$\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$$

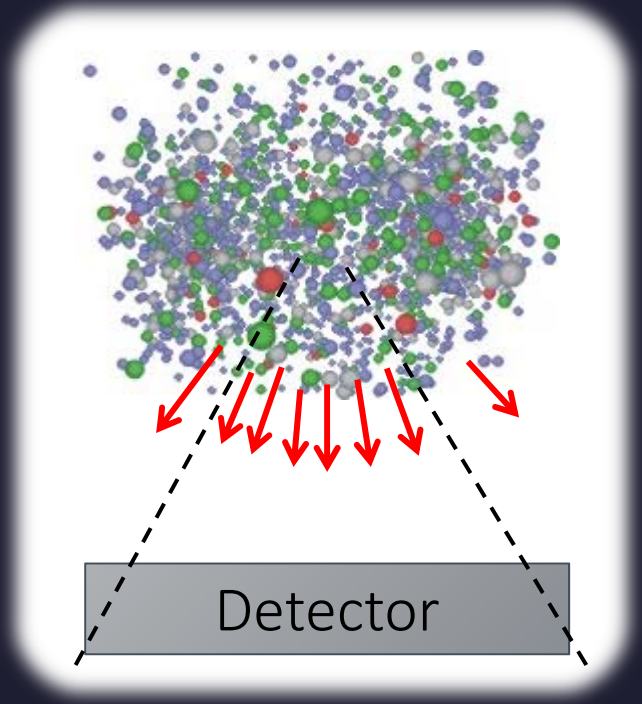
$$S = \frac{\langle \delta N^3 \rangle}{\sigma^3}$$

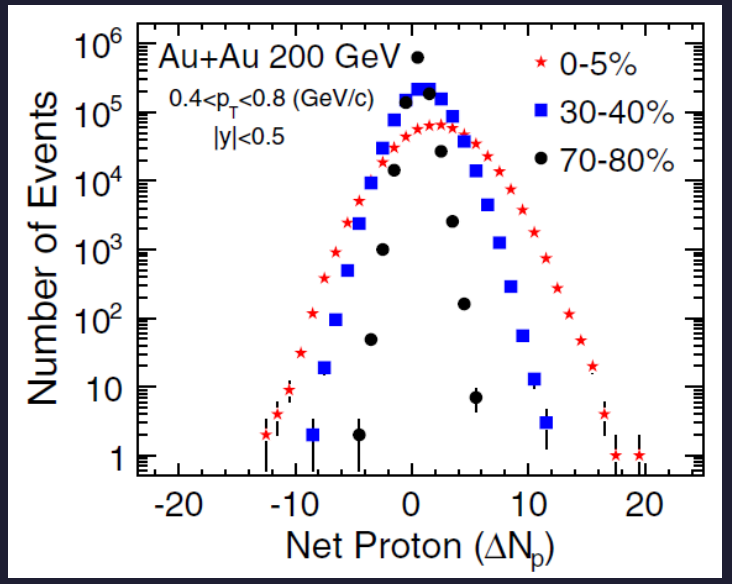
$$\kappa = \frac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$$

Gaussian

non-Gaussianity

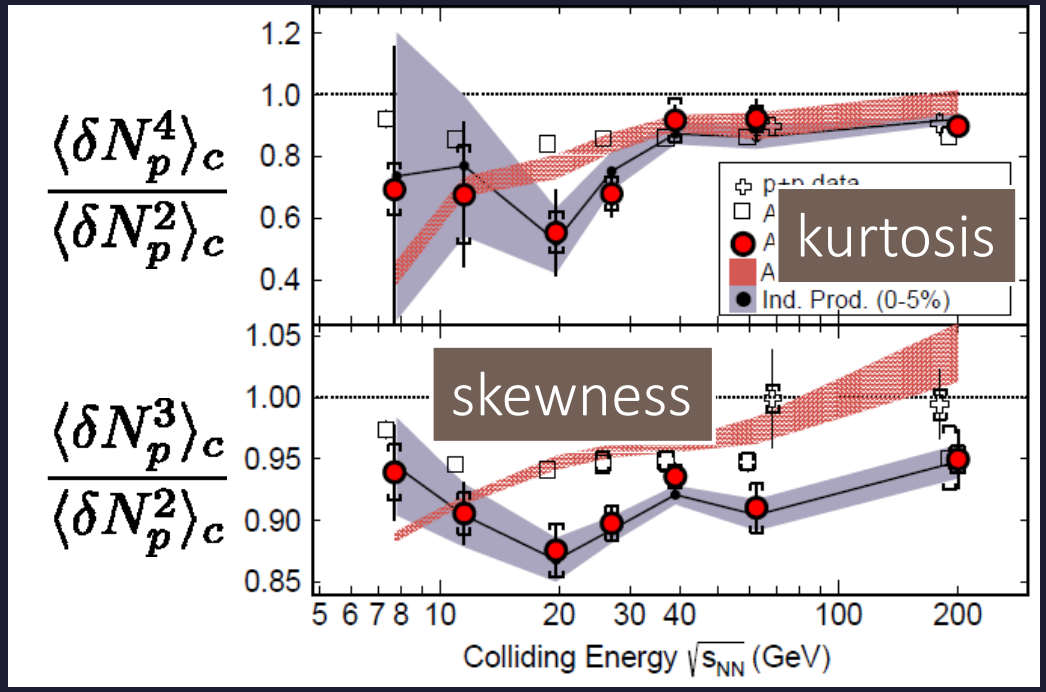
# Event-by-Event Measurement



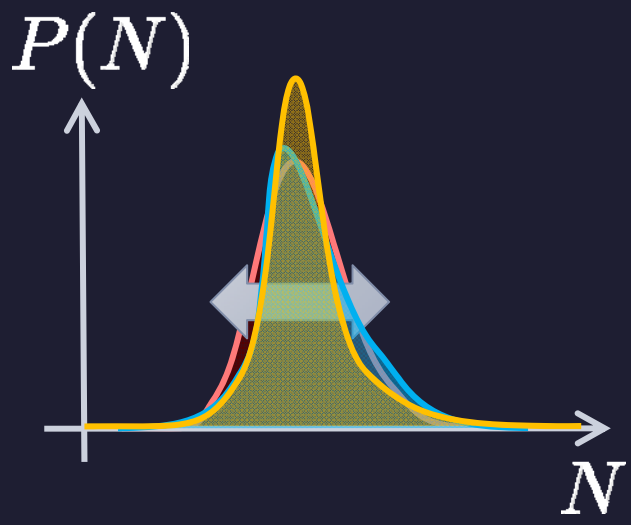




STAR Collaboration, PRL 2010

# Non-Gaussianity @ RHIC

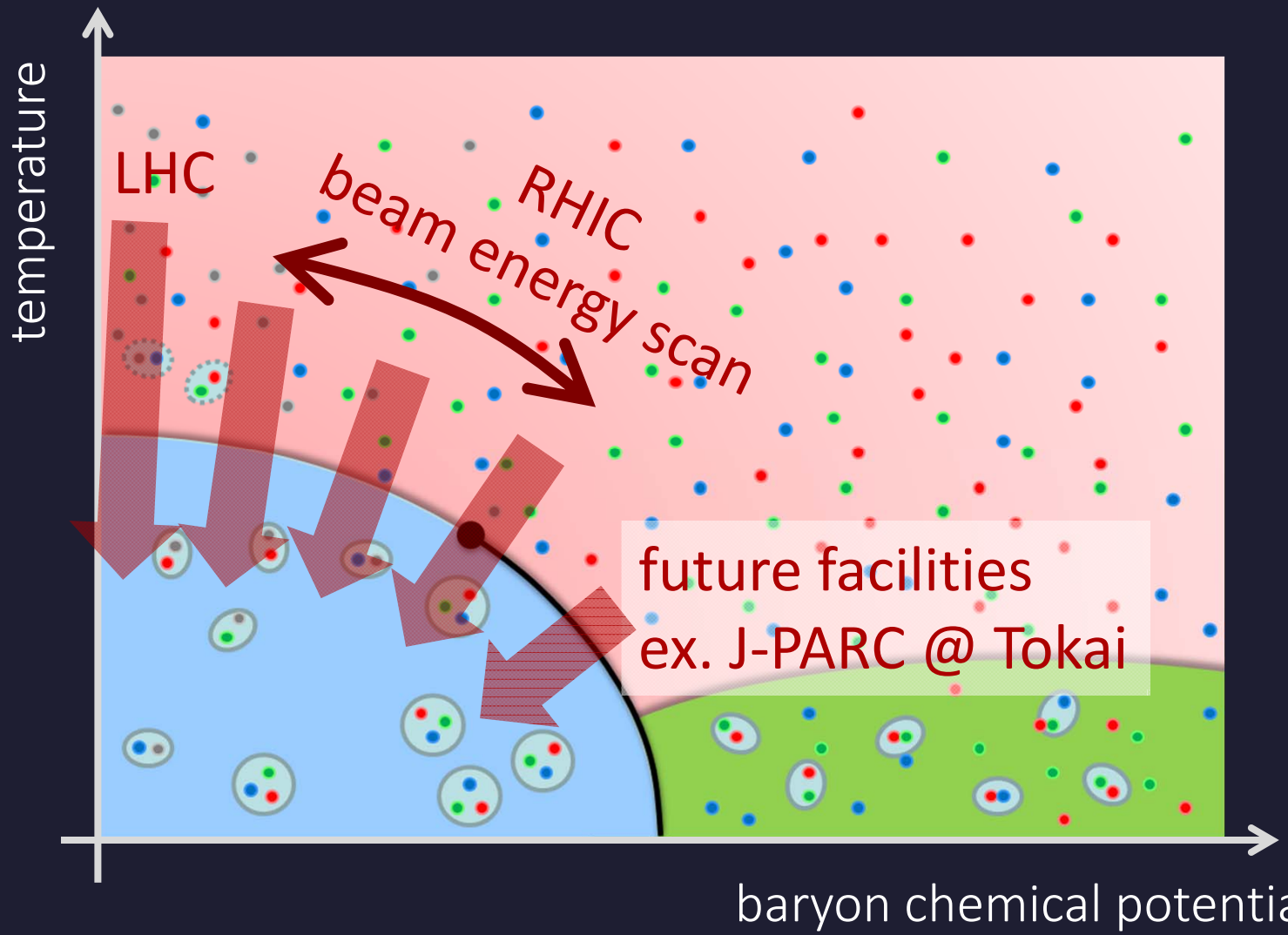



STAR Collaboration, PRL 2014




- Nonzero higher-order cumulants of conserved charges (skewness and kurtosis)
- They are not far from Poissonian values.

# Search for QCD Phase Structure



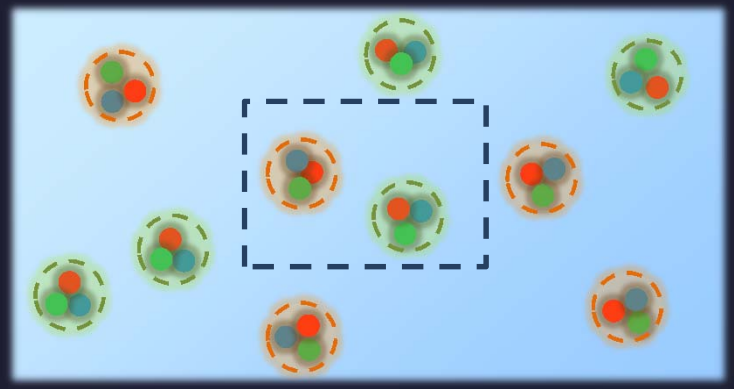

LHC
2010~

RHIC-BES
Phase I
2010~2013
Phase II
2015~

J-PARC
2018~ ??

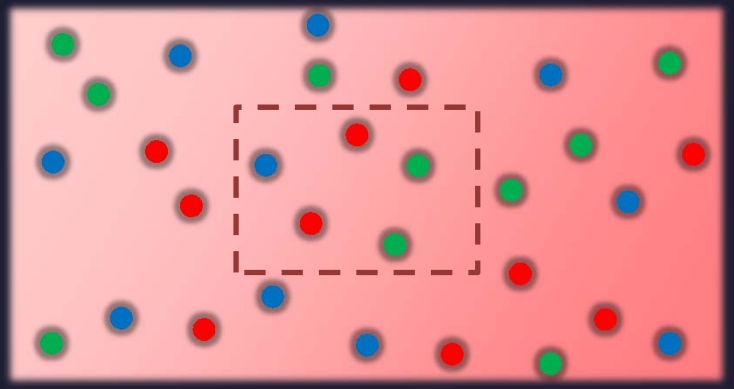
# Signal of Quark Deconfinement

Hadronic



$|q_B| = 0, 1, \ |q_Q| = 0, 1$

Quark-Gluon



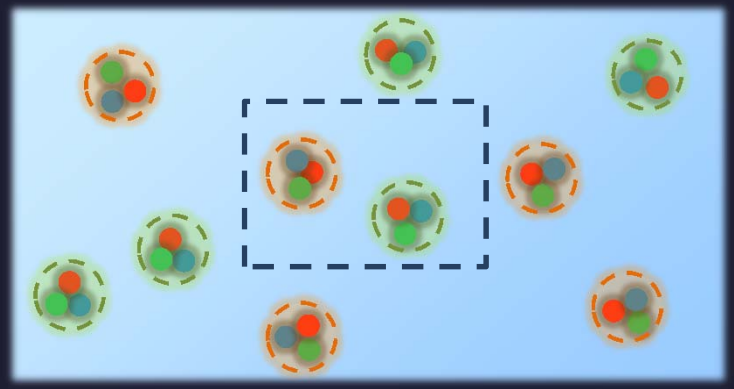
$|q_B| = 1/3, \ |q_Q| = 1/3, 2/3$

Elemental charge carried by quasi-particles decreases in QGP

Asakawa, Heinz, Muller PRL (2000); Jeon, Koch, ibid.

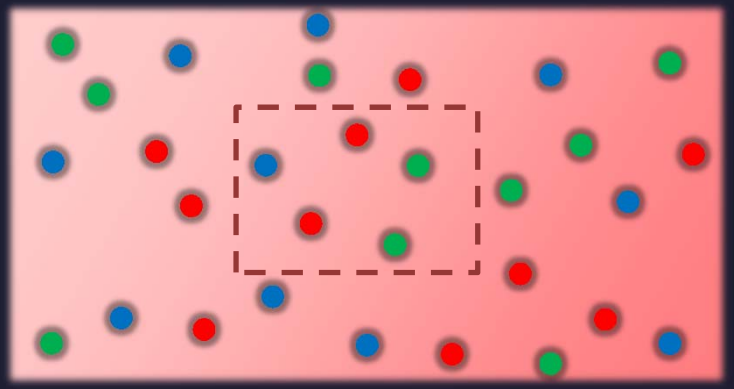
# Signal of Quark Deconfinement

Hadronic



$|q_B| = 0, 1, \ |q_Q| = 0, 1$

Quark-Gluon



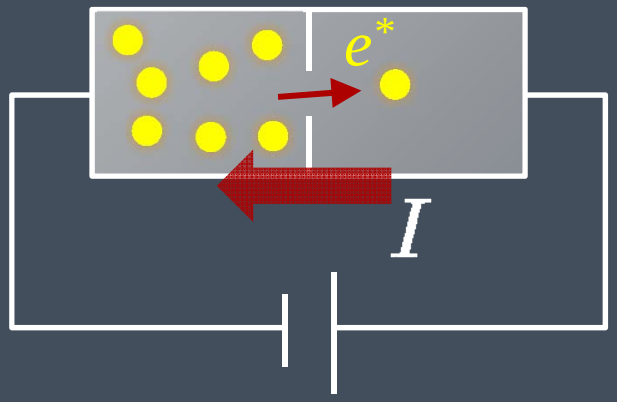
$|q_B| = 1/3, \ |q_Q| = 1/3, 2/3$

Elemental charge carried by quasi-particles decreases in QGP

Corresponding thermal fluctuations decrease in QGP

Asakawa, Heinz, Muller PRL (2000); Jeon, Koch, ibid.

# Shot Noise

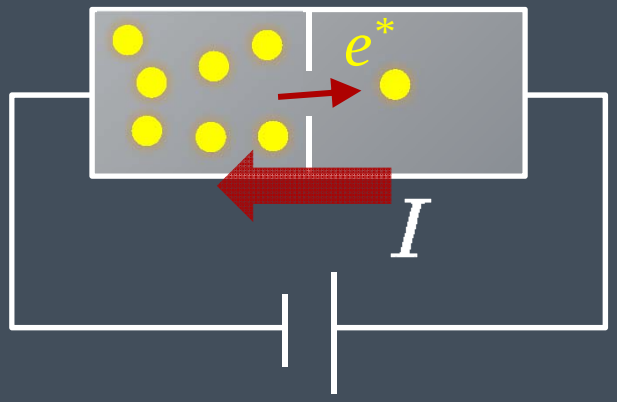



$$S_{\text{shot}} \sim \langle \delta I^2 \rangle$$

$$S_{\text{shot}} = 2e^* \langle I \rangle$$

charge of quasi-particles

# Shot Noise




$$S_{\mathrm{shot}} \sim \langle \delta I^2 \rangle$$

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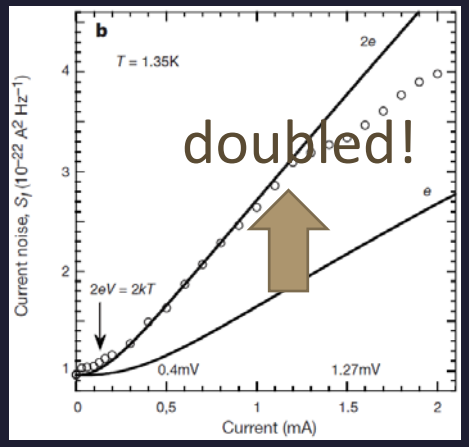
charge of quasi-particles

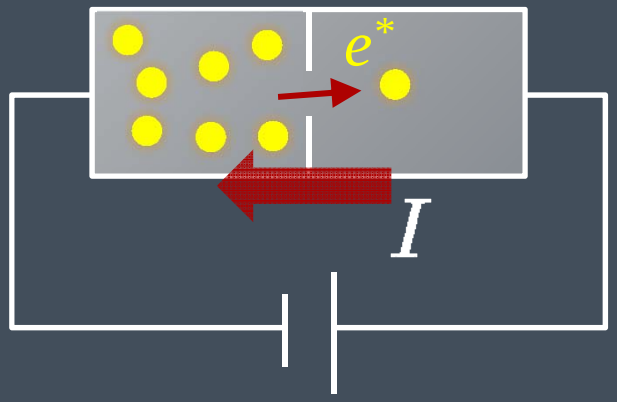
Superconductors with Cooper Pairs

$$e^* = 2e$$

Jehl+, Nature **405**,50 (2000)



# Shot Noise

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## Superconductors with Cooper Pairs

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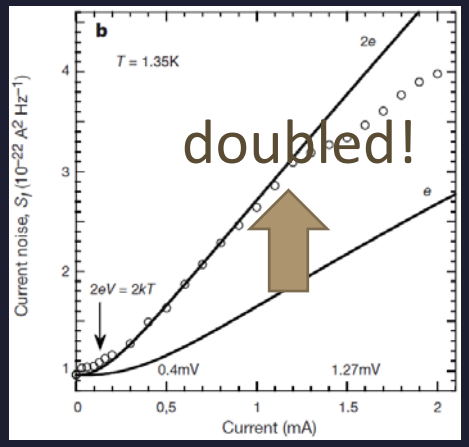
Jehl+, Nature **405**,50 (2000)

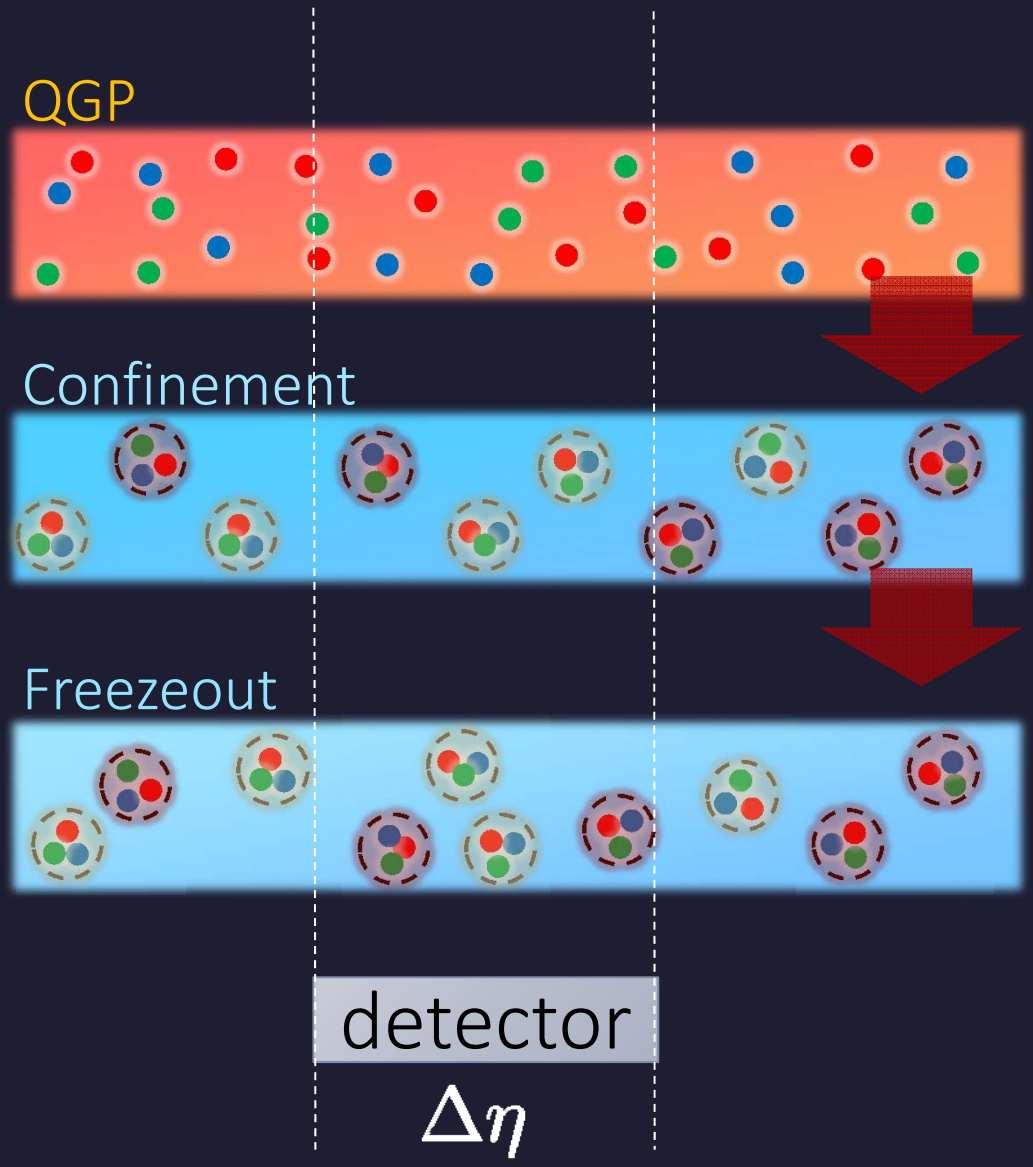



## Fractional Quantum Hall Systems

$$e^* = \frac{q}{p} e$$

Saminadayar+, PRL**79**,2526 (1997)

# Diffusion of Fluctuations



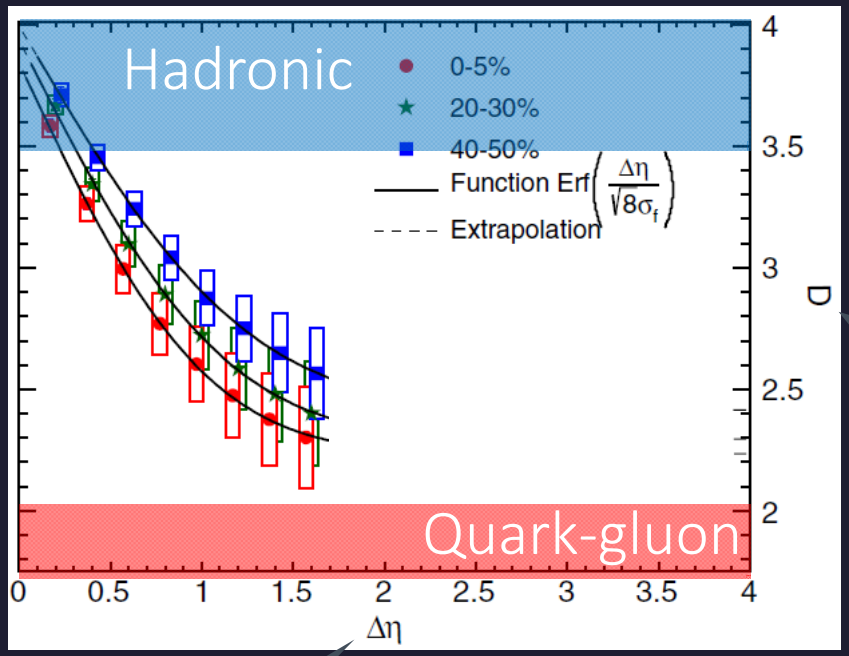

Experiments can vary
spatial volume
to measure fluctuations

The larger $\Delta\eta$,
the earlier fluctuations

# Electric Charge Fluctuations @ LHC

ALICE Collaboration,
PRL **110**, 152301 2013

一本の草も涼風
宿りけり
一茶




$\sim V$

$\sim \frac{\langle \delta N_Q^2 \rangle}{V}$

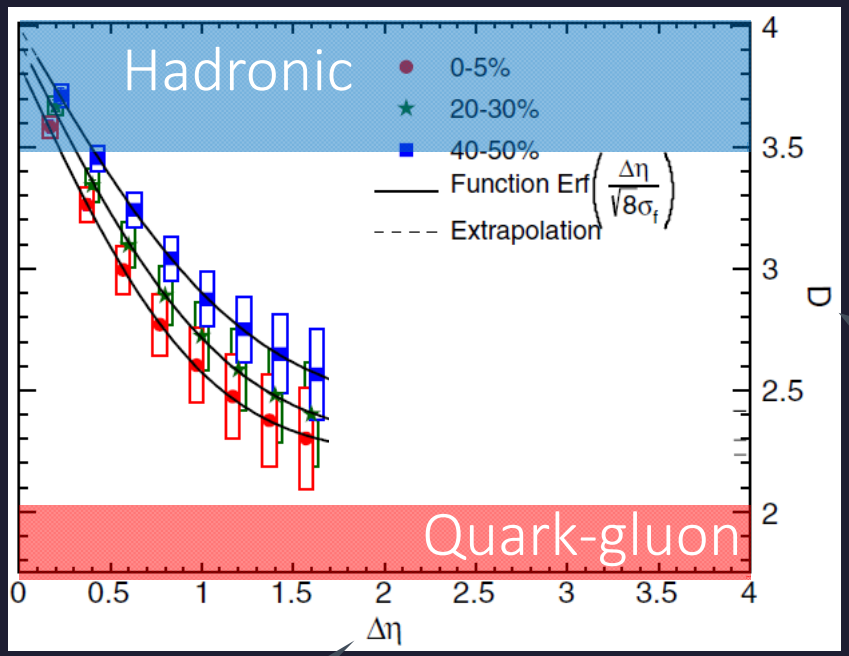
Fluctuation is more QGP-like as *V* becomes larger.
The Δη dependence encodes history of the medium!

# Diffusion of non-Gaussianity

MK,Asakawa,Ono,PLB**728**,386(2014)

# Electric Charge Fluctuations @ LHC

ALICE Collaboration,
PRL **110**, 152301 2013




$\sim \frac{\langle \delta N_Q^2 \rangle}{V}$

$\sim V$

- Experimental results only for 2nd order fluctuation
- No results on $\Delta\eta$ dependence of higher-order cumulants

# Stochastic Formalism

- Fluctuating hydrodynamics
  (stochastic hydrodynamics)

Landau, Lifshitz,
Statistical Mechanics II

- Counterpart for diffusive processes

Stochastic diffusion equation

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

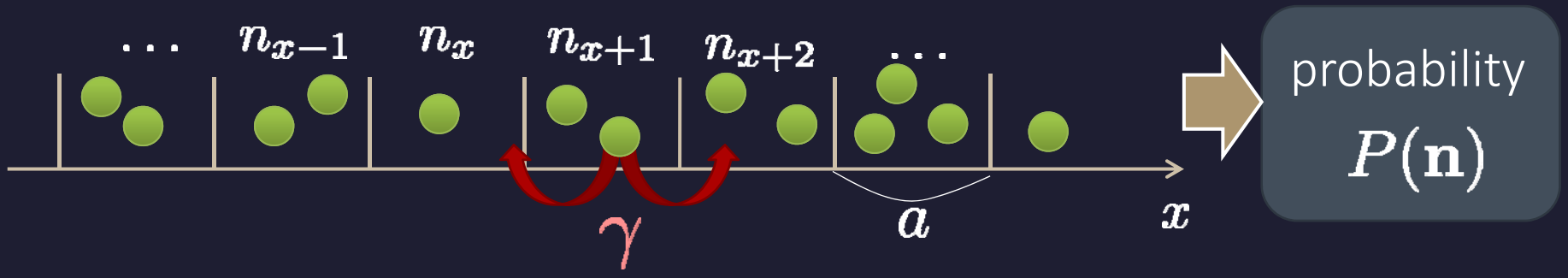
Random force determined by FDR

This formalism cannot describe non-Gaussianity!

# Diffusion Master Equation

MK,Asakawa,Ono,PLB**728**,386(2014)

Divide spatial coordinate into discrete cells



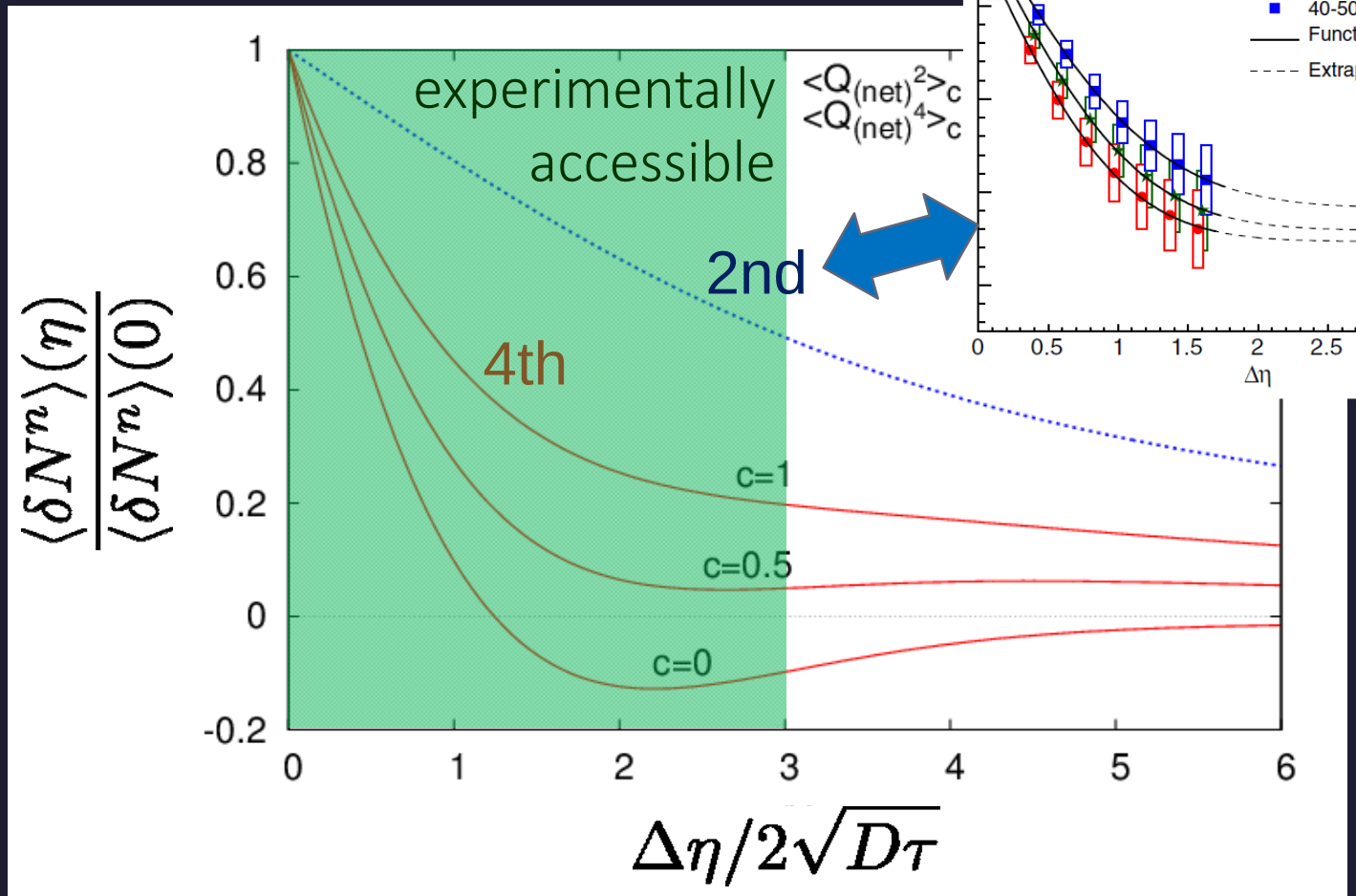

## Master Equation

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

Solve the DME exactly, and take $a \to 0$ limit

# Our Predictions

ALICE Collaboration, 2013




Volume dep. of non-Gaussianity encodes more information!

# Summary

- Fluctuations are invaluable tools in physics, as well as in our daily life.
- Fluctuations acquires much attention in relativistic heavy-ion collisions. In particular, their non-Gaussianity is one of the latest topics in this realm.

1998
Rolf Landauer

The noise is the signal

A poet said

一本の草も涼風宿りけり

even on one blade of grass the cool wind lives

小林一茶

Issa Kobayashi

1814

A physicist said

1998

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The noise is the signal