Open Charm Mesons and QCD Critical Point

Masayuki Asakawa

Department of Physics, Osaka University

February 11, 2023

新学術領域「量子クラスターで読み解く物質の階層構造」領域研究会

High Energy HIC and Clusters

Hadrons: Clusters of Quarks

In this talk, we focus on heavy quarks such as charm and bottom.

Charm quarks and bottom quarks as impurities in QGP

- Observed mainly through *open charm mesons* and *open bottom mesons*

Nowadays, possible to distinguish between c and b at RHIC and LHC (vertex detection)

In the following, we focus on low energy nuclear collisions.

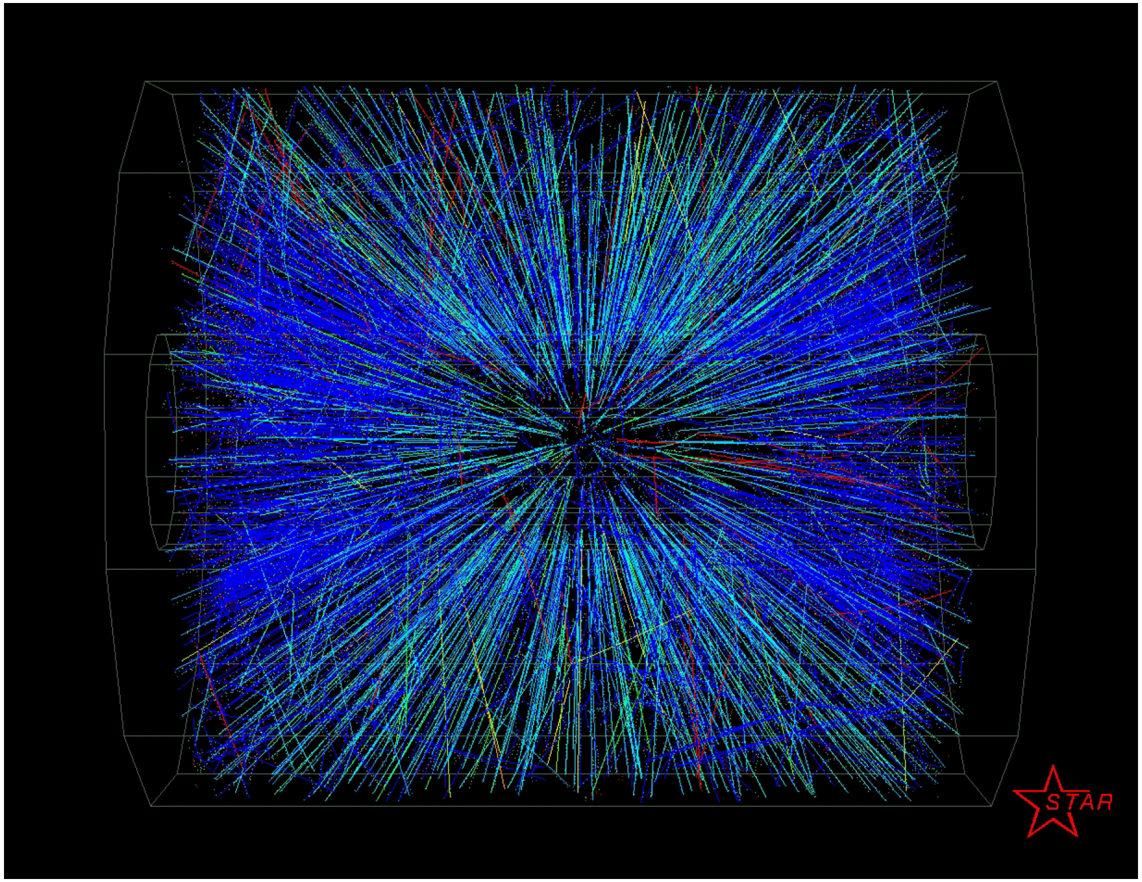
Heavy quarks = Charm quarks

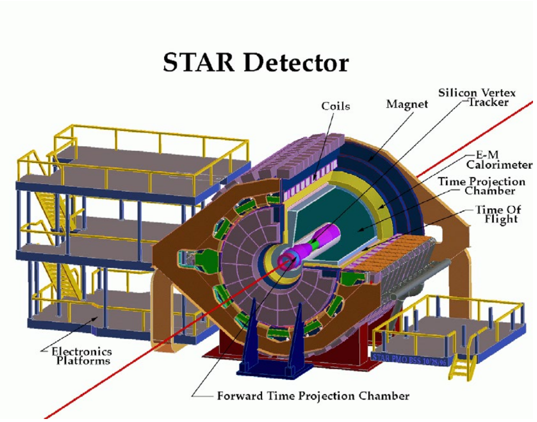
High Energy HIC: Accelerator

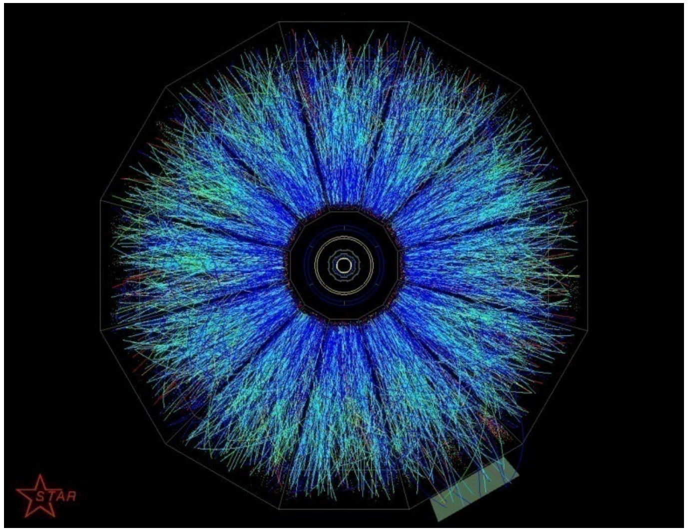
High Energy HIC: Event

STAR at RHIC

One Event: Au+Au collision



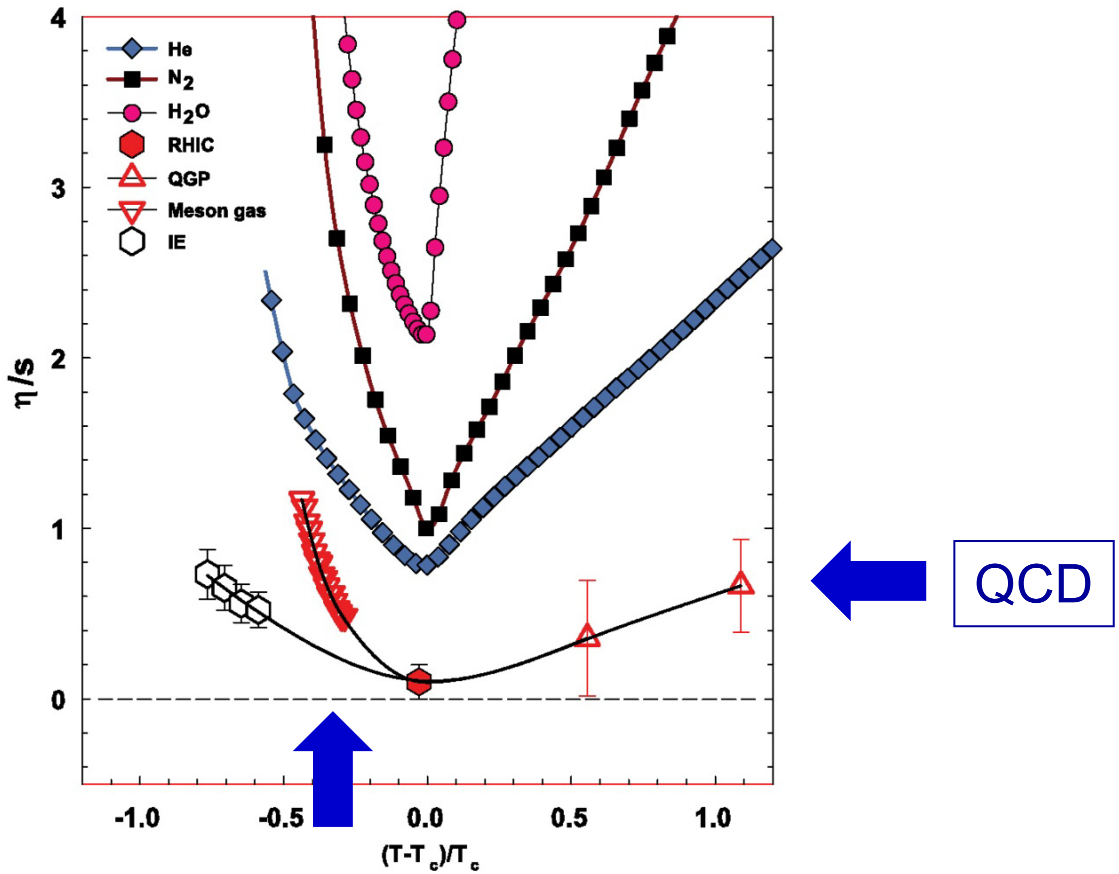




Trajectories of charged particles

Color: Momentum

η/s in QCD (μ_B=0)



Significant increase in hadron phase (cluster formation)

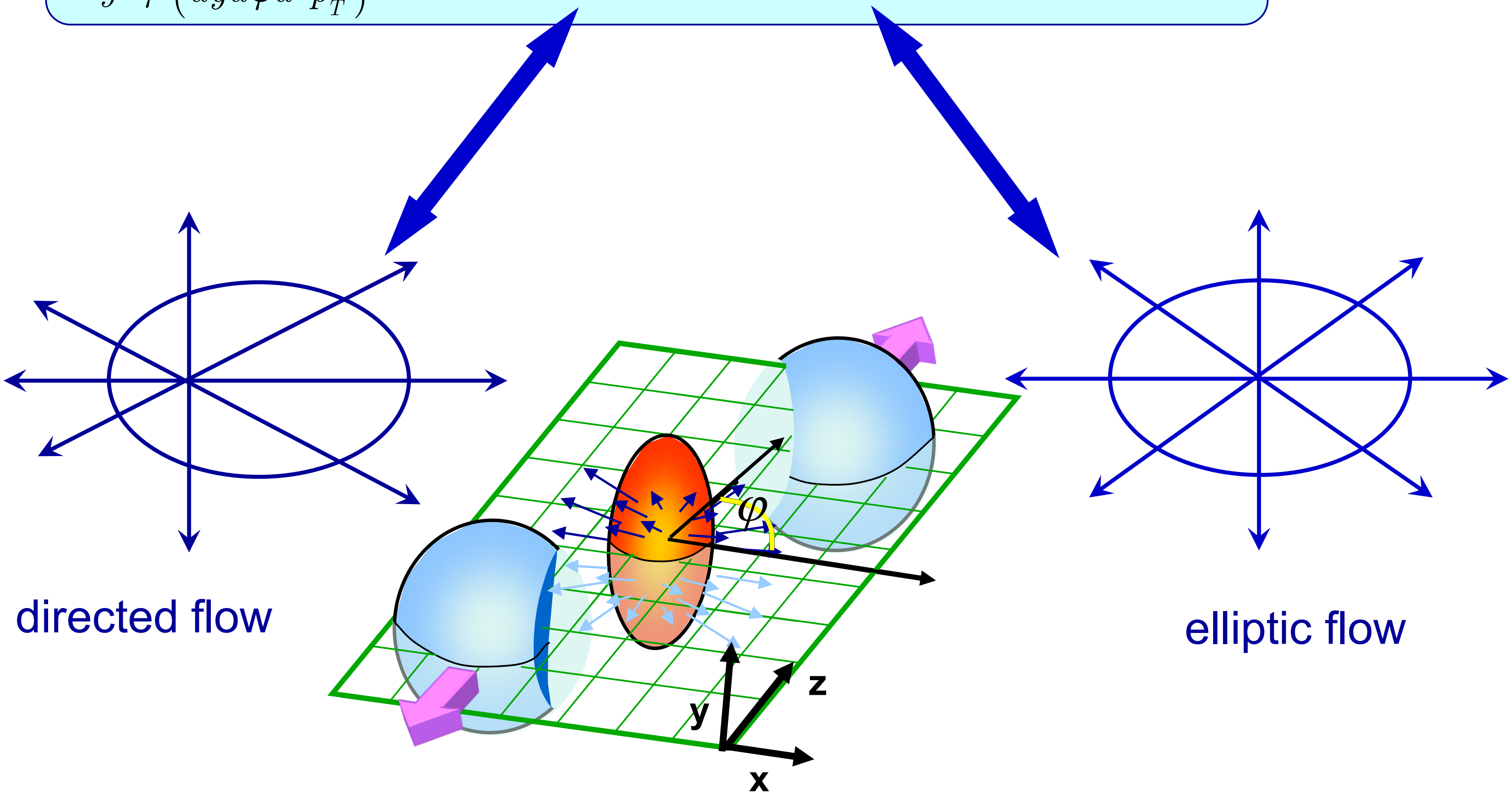
$\eta \sim \frac{1}{3} n \bar{p} \lambda_f, \ n \propto s$ kinetic theory

λ_f increases.

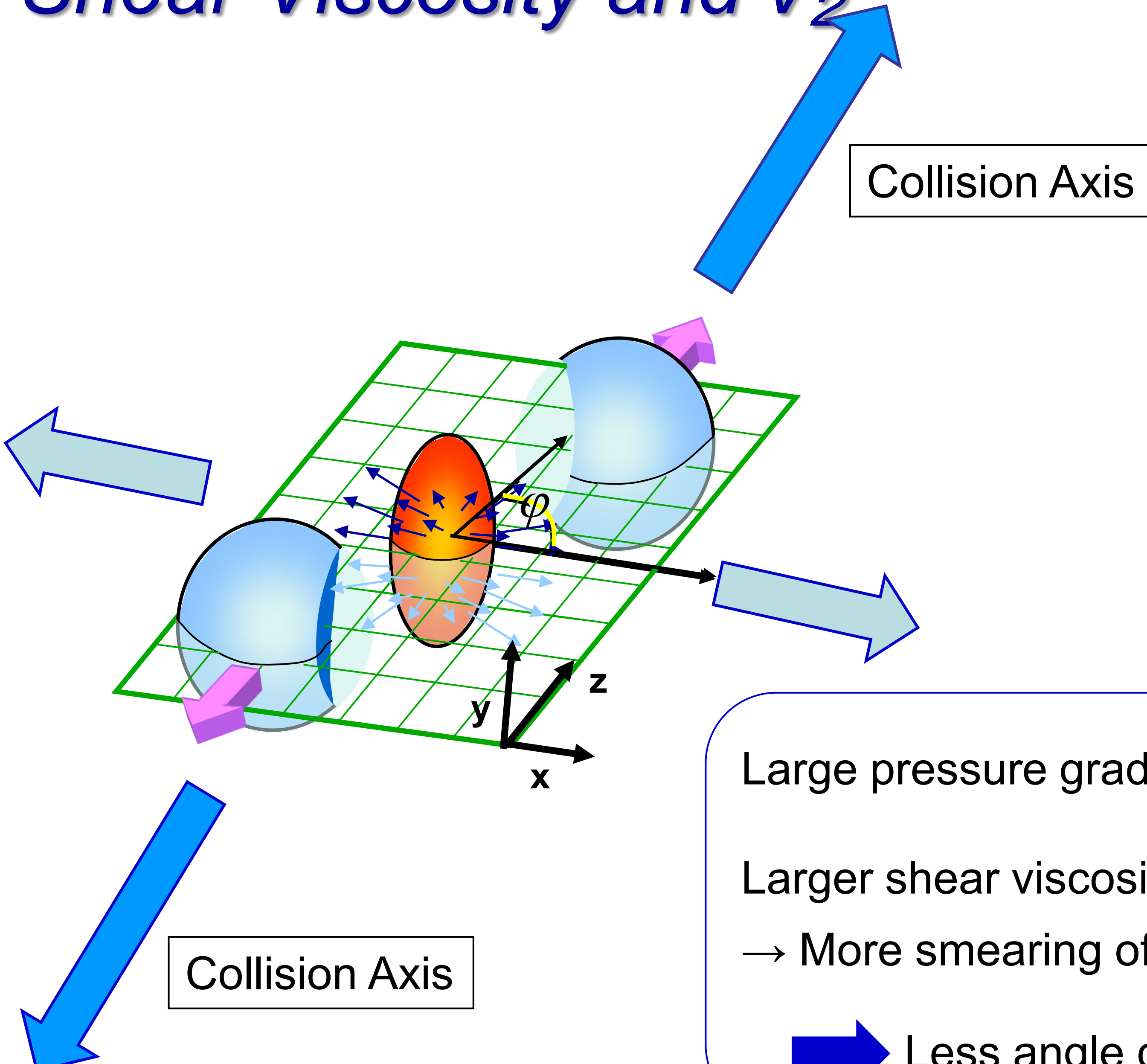
$v_2(v_n)$: Fourier Expansion w.r.t. Flow Angle

Particle distribution as a function of angle measured from reaction plane

$$\frac{dN_i}{dyd\varphi}\left(\frac{dN_i}{dyd\varphi d^2p_T}\right) = N_{i0}\left(1 + 2v_1\cos(\varphi-\varphi_1) + 2v_2\cos 2(\varphi-\varphi_2) + \cdots\right)$$



Shear Viscosity and v_2



Large pressure gradient

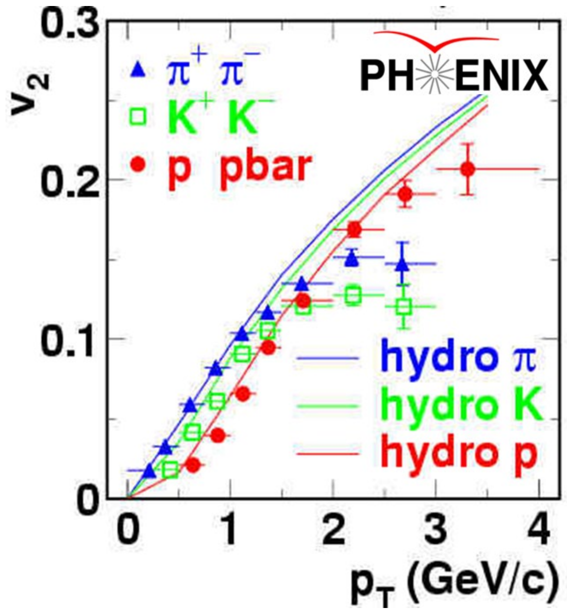
Larger shear viscosity, larger shear stress

→ More smearing of pressure gradient

➡ Less angle dependence of flow

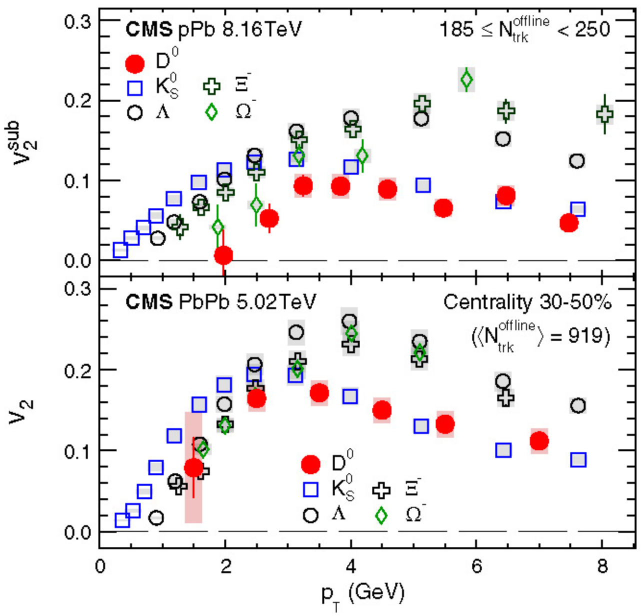
Strongly Interacting QGP

Hydrodynamical feature of QGP ⇒ Strongly interacting QGP



PHENIX(RHIC), PRL (2003)

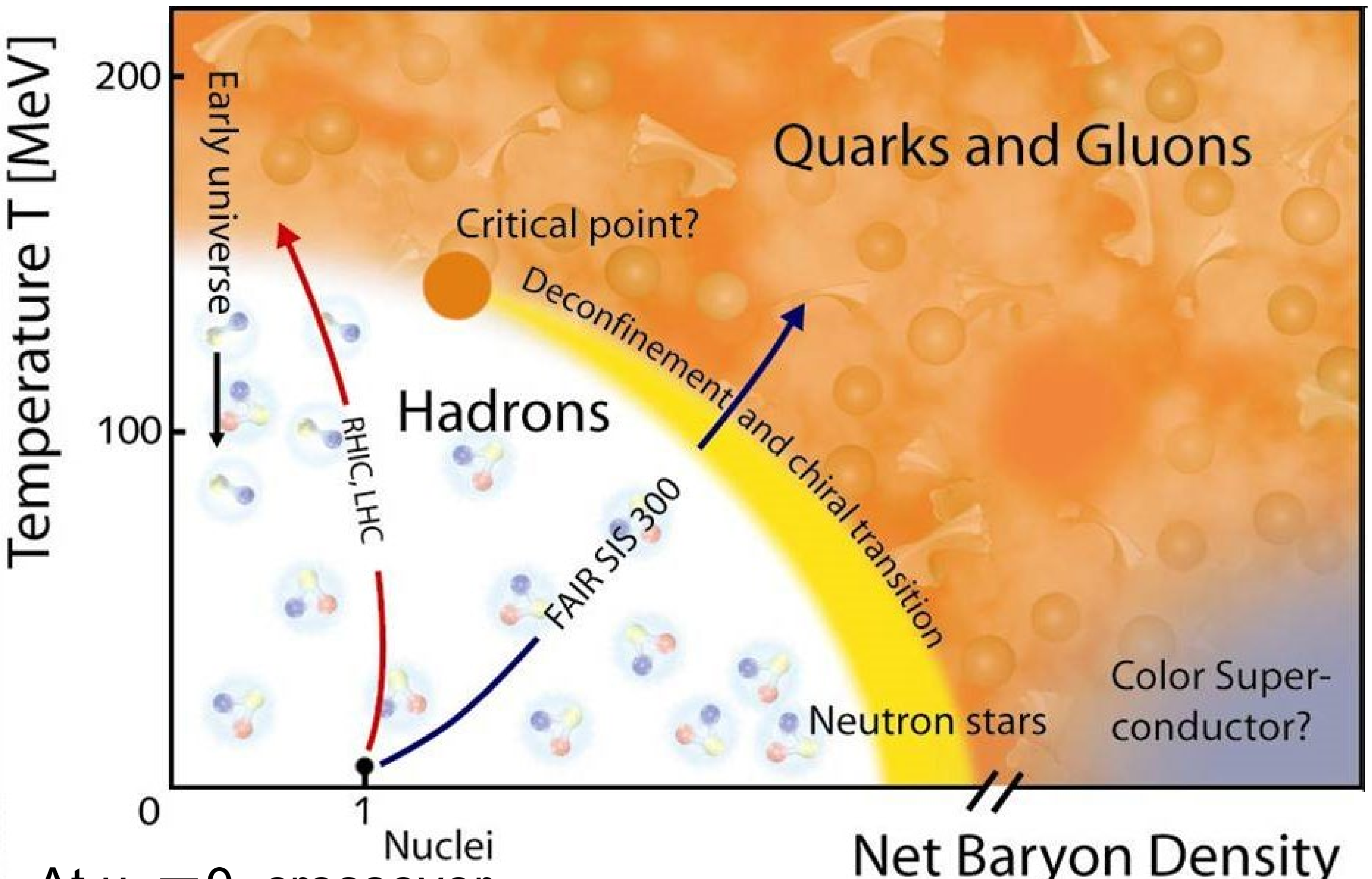
- At SPS, perfect fluid calculation did not explain v_2 so well.
- Hydro calculation revealed physical properties of QGP（RHIC）.



CMS(LHC), PRL(2022)

Charm (D) is also flowing.

QCD Phase Diagram (expected)



GSI

At $\mu_B = 0$, crossover

Recent interests: Critical point, High density and Low T (⇒neutron star)

Beginning of QCD Critical Point Search

Nuclear Physics **A504** (1989) 668–684
North-Holland, Amsterdam

CHIRAL RESTORATION AT FINITE DENSITY AND TEMPERATURE

Masayuki ASAKAWA and Koichi YAZAKI

Department of Physics, Faculty of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

Received 2 May 1988
(Revised 24 April 1989)

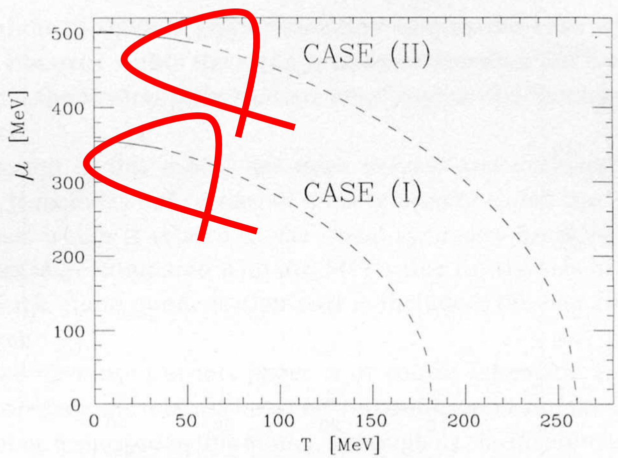
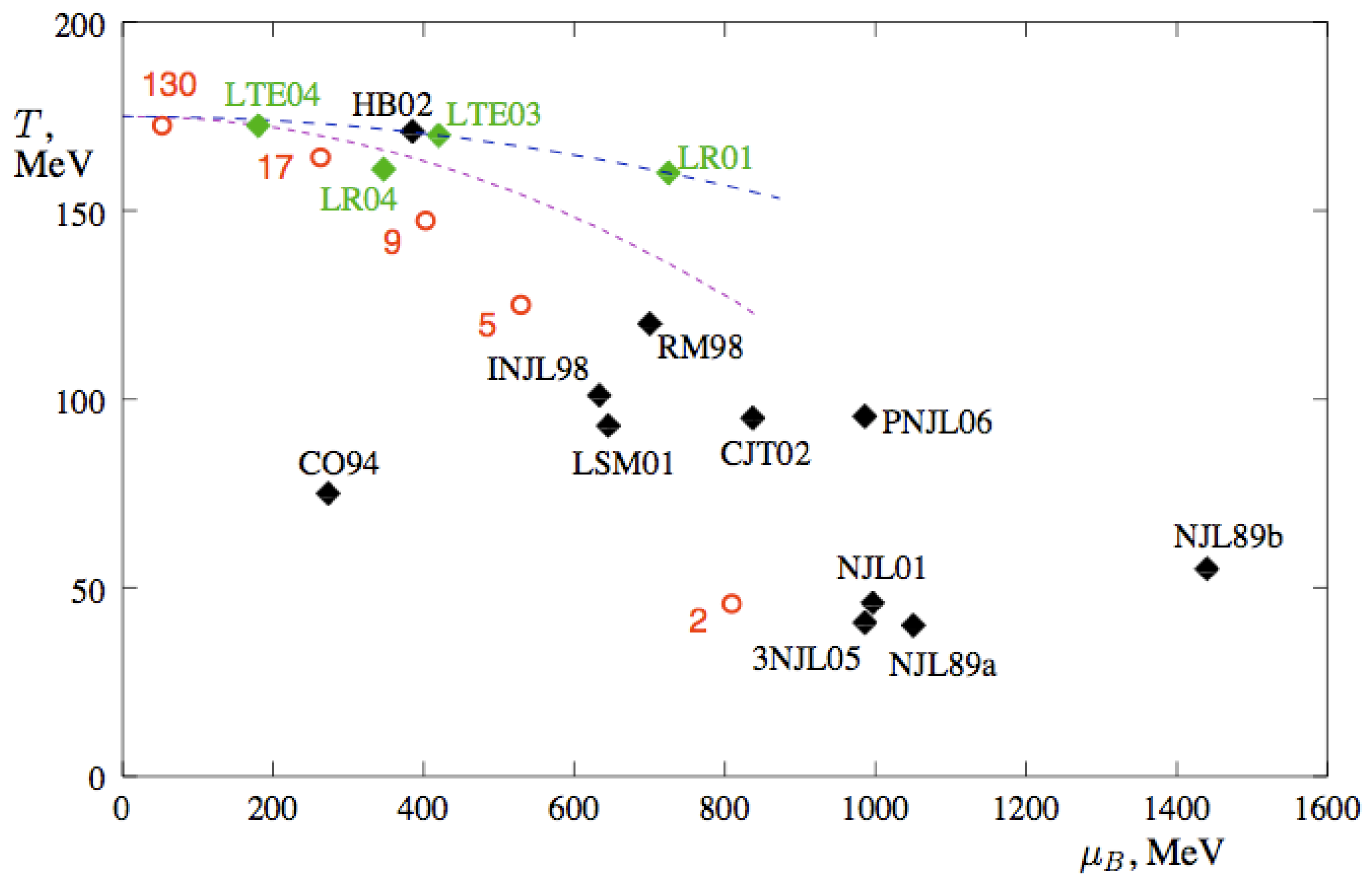


Fig. 8. The phase transition line in the cases (I) and (II).

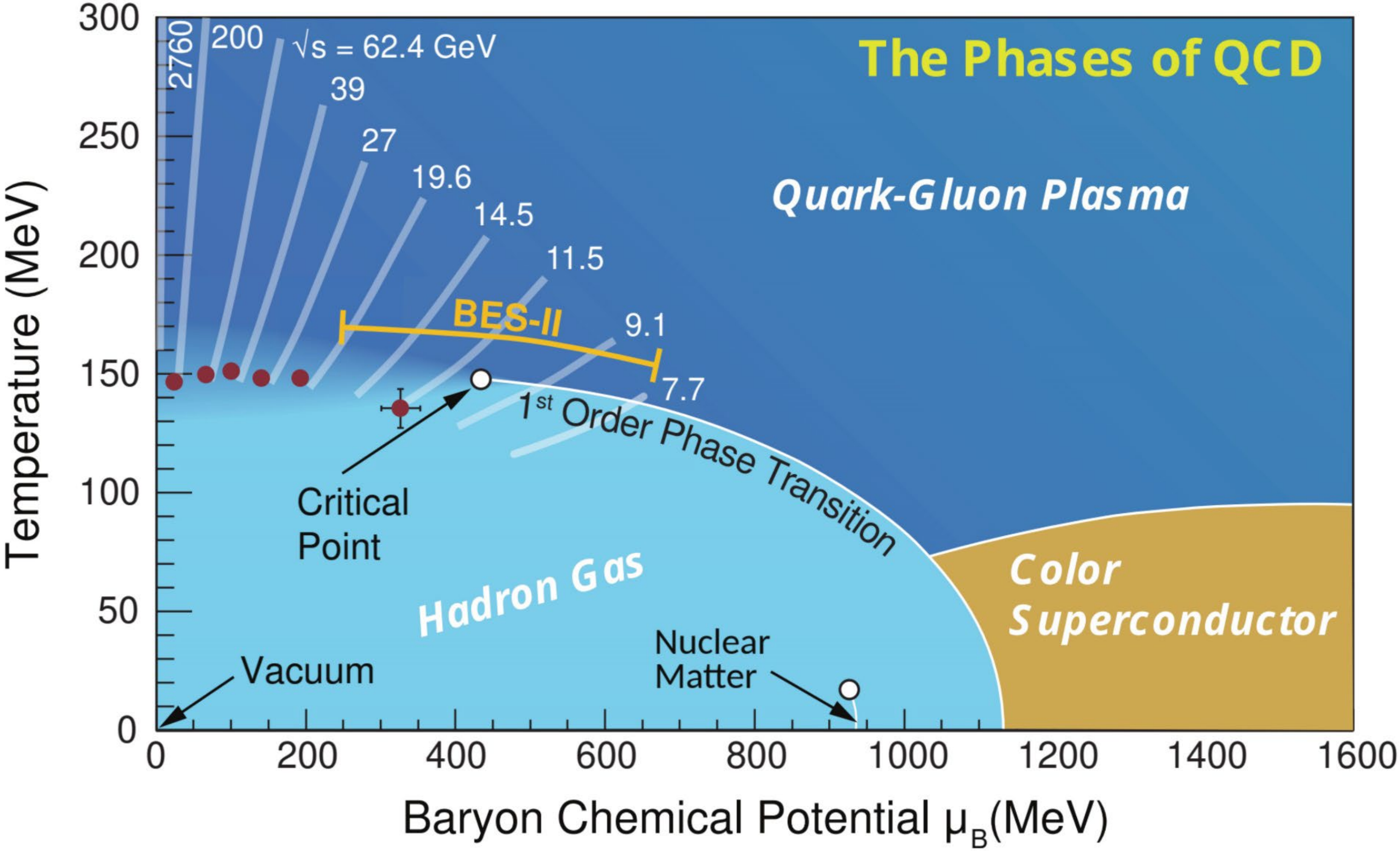
Many Theoretical Calculations for CP



Stephanov,hep-lat/0701002

Experimental Search for Critical Point

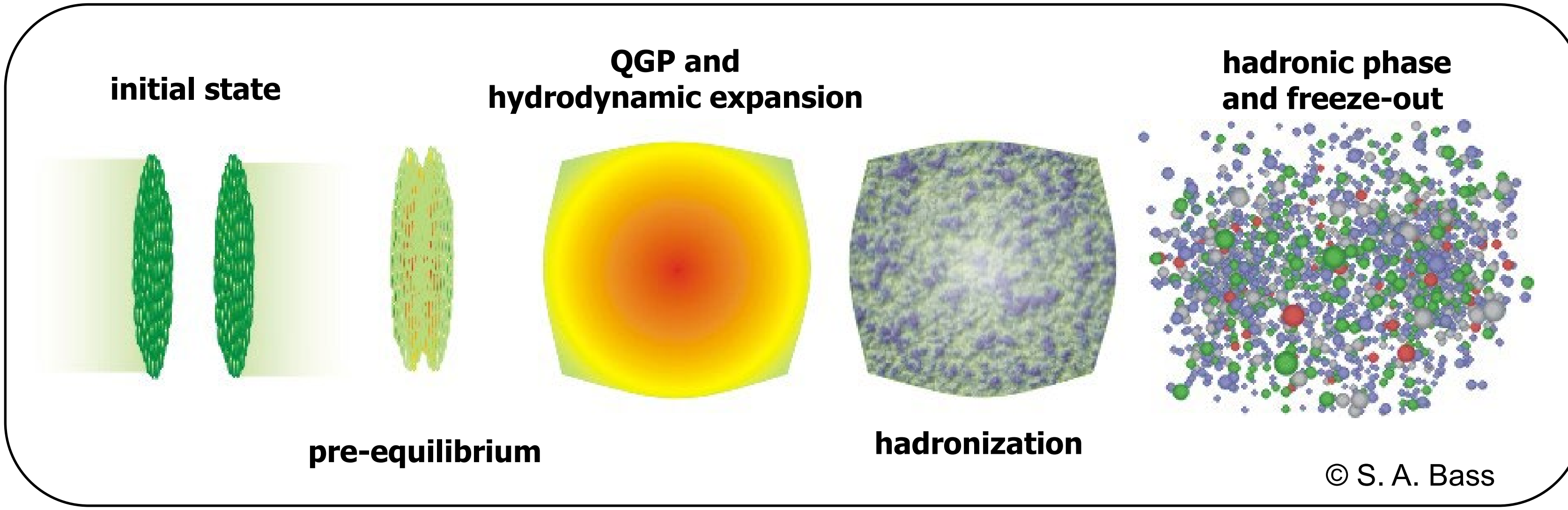
Vary collision energy



Bzdak et al., 1906.00936

RHIC(BES, BES-II), FAIR(GSI), NICA(JINR), J-PARC HI（planned）…

Time Evolution of High Energy HIC



$\sim 10^{-23}$ sec

Interacting quarks, gluons, and hadrons

$\sim 10^{-22}$ sec

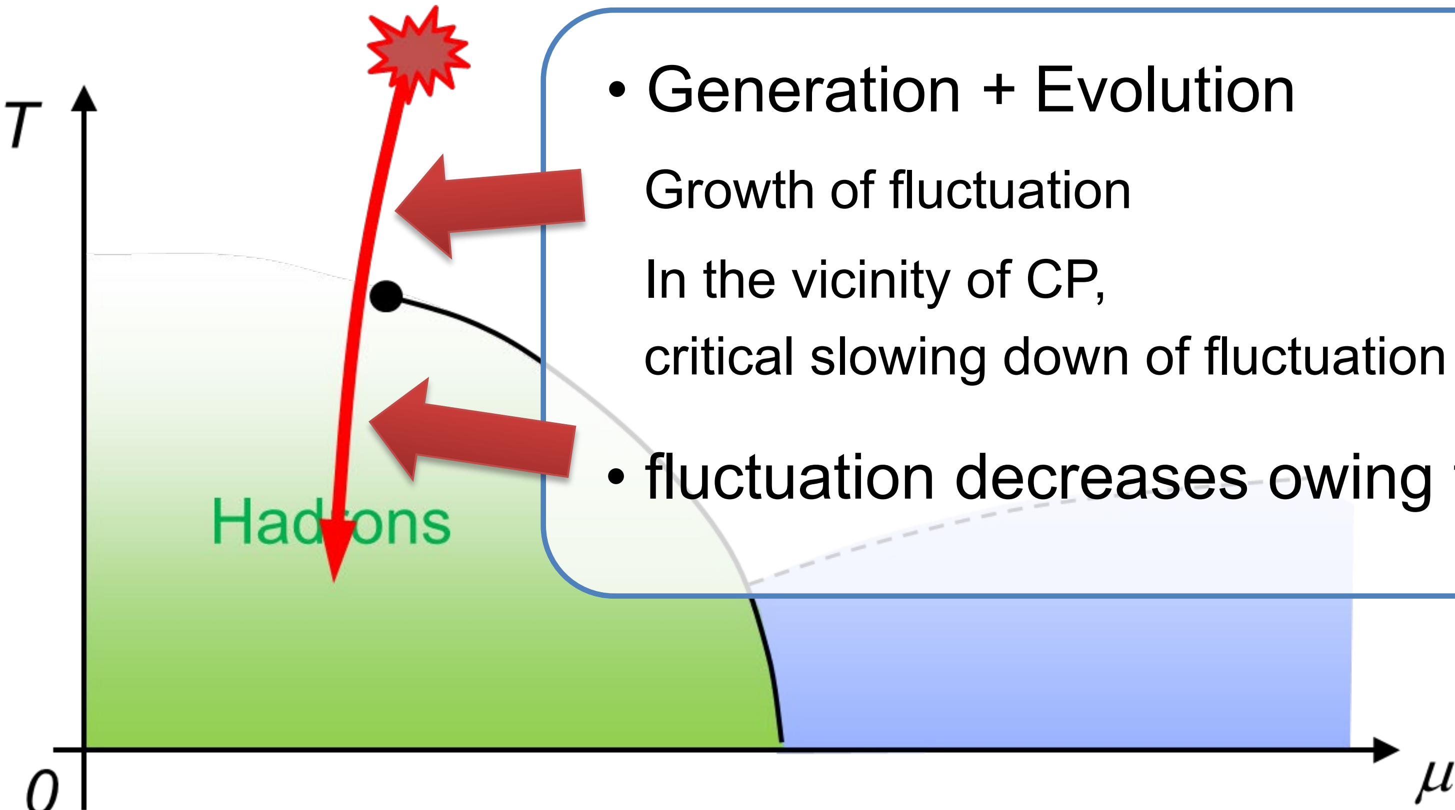
Cooling, phase transition, generation of collective motion···etc.

CP cannot be observed directly.

Critical Phenomena + Time Evolution

- Even if the system passes through CP, diverging fluctuation is not observed.
  ⇒ Finite time effect

- Near CP, critical slowing down is important. (dynamical critical phenomena)



- Generation + Evolution

  Growth of fluctuation

  In the vicinity of CP,
  critical slowing down of fluctuation evolution

- fluctuation decreases owing to diffusion

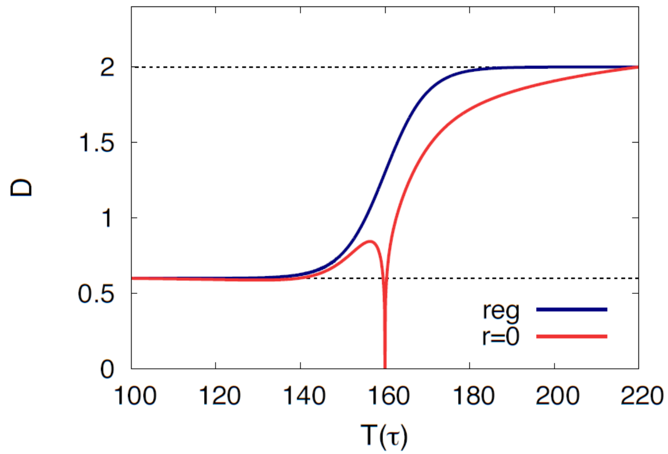
Experimentally, critical fluctuation is not observed directly.

Dynamical Critical Phenomena

- Dynamic Universality:

  QCD belongs to Hohenberg-Halperin's model-H

- Critical slowing down at CP ⇒ Dip of diffusion constant（D）



Increase of drag force（η_D）in Langevin equation

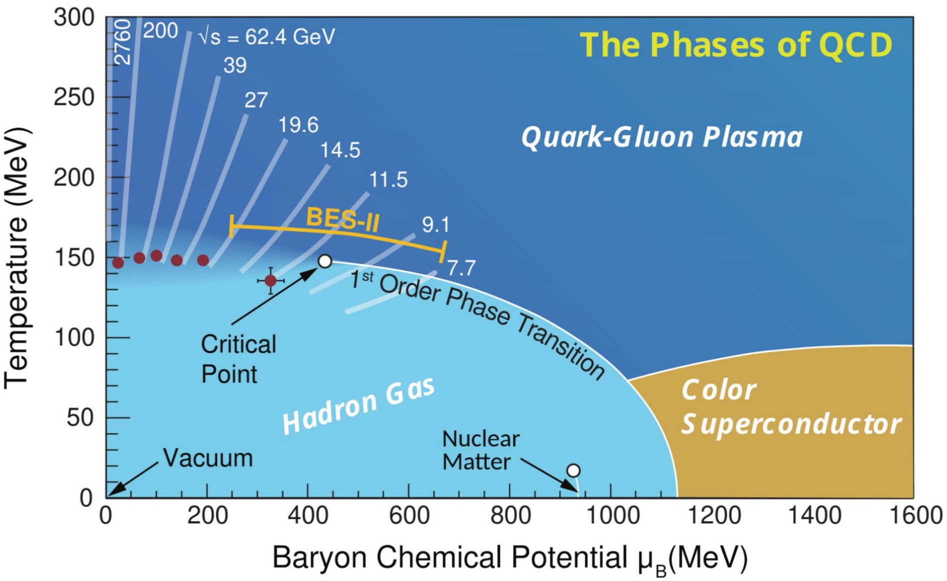
$$m\frac{d^2\vec{x}}{dt^2} = -m\eta_D\frac{d\vec{x}}{dt} + \vec{\xi} \qquad \eta_D = \frac{kT}{mD}$$

- $D \sim \xi^{-1.044}$ This value is for light quarks (within Chiral Symmetry) .

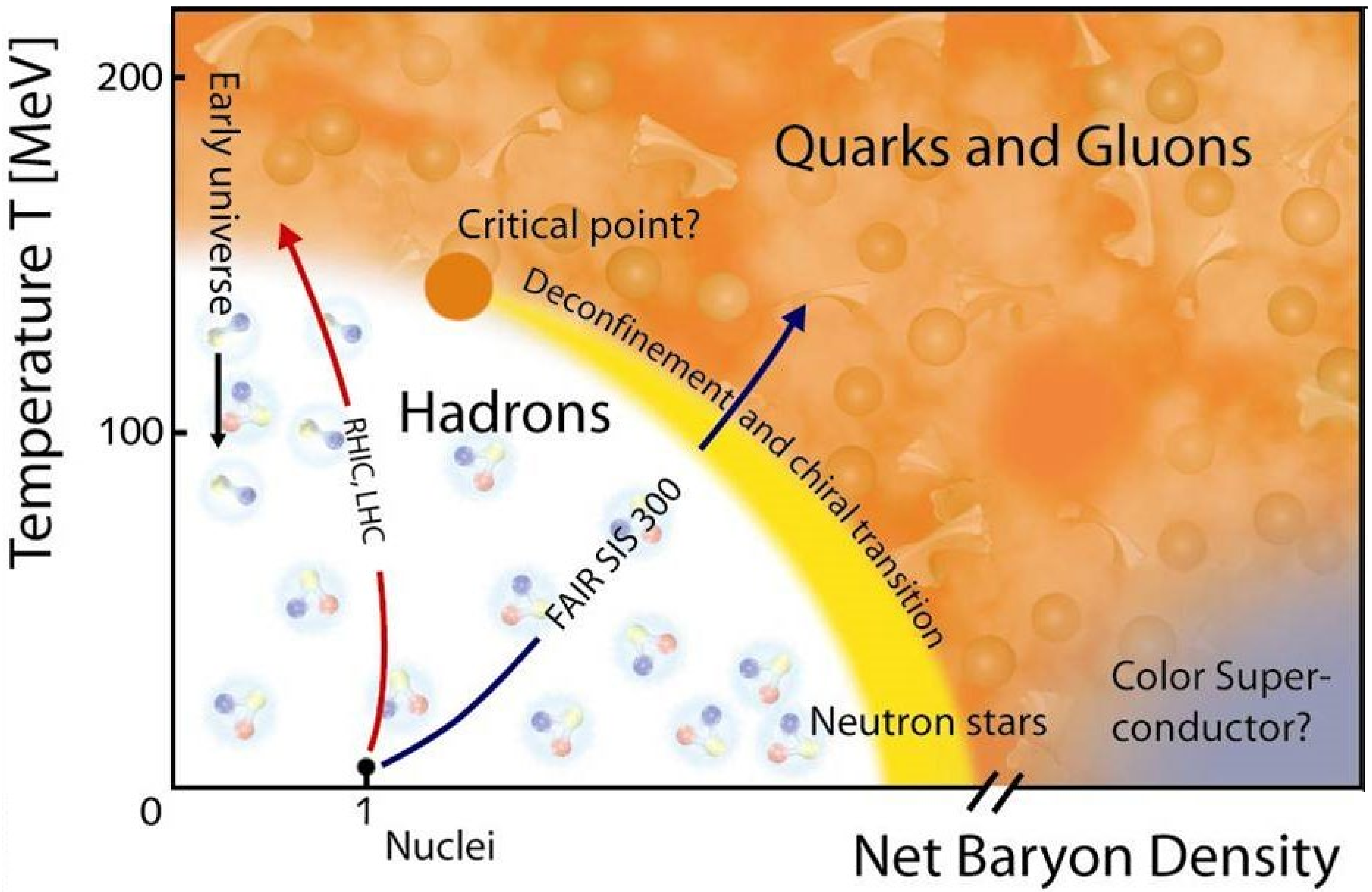
v_2 of Open Charms

- As collision energy decreases, duration of QGP becomes shorter. It is expected difference of v_2's of charm and fluid becomes larger.
- If the system passes the vicinity of CP and drag force for charm increases, v_2's of charm and fluid may get closer to each other.

➡ Non-monotonous change of the ratio of v_2's of open charm and fluid ?



QCD Phase Diagram



GSI

This CP：CP for Chiral Symmetry

Charm as Impurity

This CP : CP for Chiral Symmetry

Chiral Symmetry : Approximate symmetry for light quarks
(up, down, (strange))

Charm Quark : obeys the same interaction as up, down, and strange (QCD),
but stays outside Chiral Symmetry.

Impurity with the same interaction but different symmetry

Behavior of charm diffusion coefficient or drag force
in the vicinity of CP: *non-trivial problem*

Strategy

Dynamic universality class of this CP: Model H

(order parameter, baryon number density, EM tensor)

Effective model: determined by symmetry consideration

$$L_{\mathrm{I}} = -a\sigma Q^{\dagger} Q$$

a: constant

σ: light mode

linear combination of order parameter, baryon number density, energy density

Momentum diffusion constant of heavy quark（~ drag force）

$$\kappa = \frac{a^2}{3}\int_{-\infty}^{\infty} \left\langle \nabla \delta\sigma(\vec{x},t) \cdot \nabla \delta\sigma(\vec{x},0) \right\rangle dt$$

Correlation function: scaling form

$$C(\vec{x},t) = \left\langle \delta\sigma(\vec{x},t)\delta\sigma(\vec{0},0) \right\rangle$$

$$\simeq \frac{1}{|\vec{x}|}\tilde{C}\left(|\vec{x}|/\xi, t/\xi^{z}\right) \qquad z \sim 3 \text{ (Model H)}$$

Result

$$\kappa = \frac{a^2}{3}\int_{-\infty}^{\infty} \langle \nabla\delta\sigma(\vec{x},t)\cdot\nabla\delta\sigma(\vec{x},0)\rangle dt$$

$$\sim a^2\left(\frac{1}{x_0^{d-z+\eta}} - \xi^{z-d-\eta}\right)$$

x_0: UV cut-off, η: small number

Preliminary: Y. Akamatsu and M. A.
in progress

model A: z ~ 2	No increase
model B: z ~ 4	Increase at CP
model H: z ~ 3 (QCD)	Almost const.

Behavior of drag force around CP depends on dynamic universality class.

Impurity with the same interaction but different symmetry

Example in Condensed Matter Physics ?