Exploring Phases of Dense QCD in Heavy-Ion Collisions

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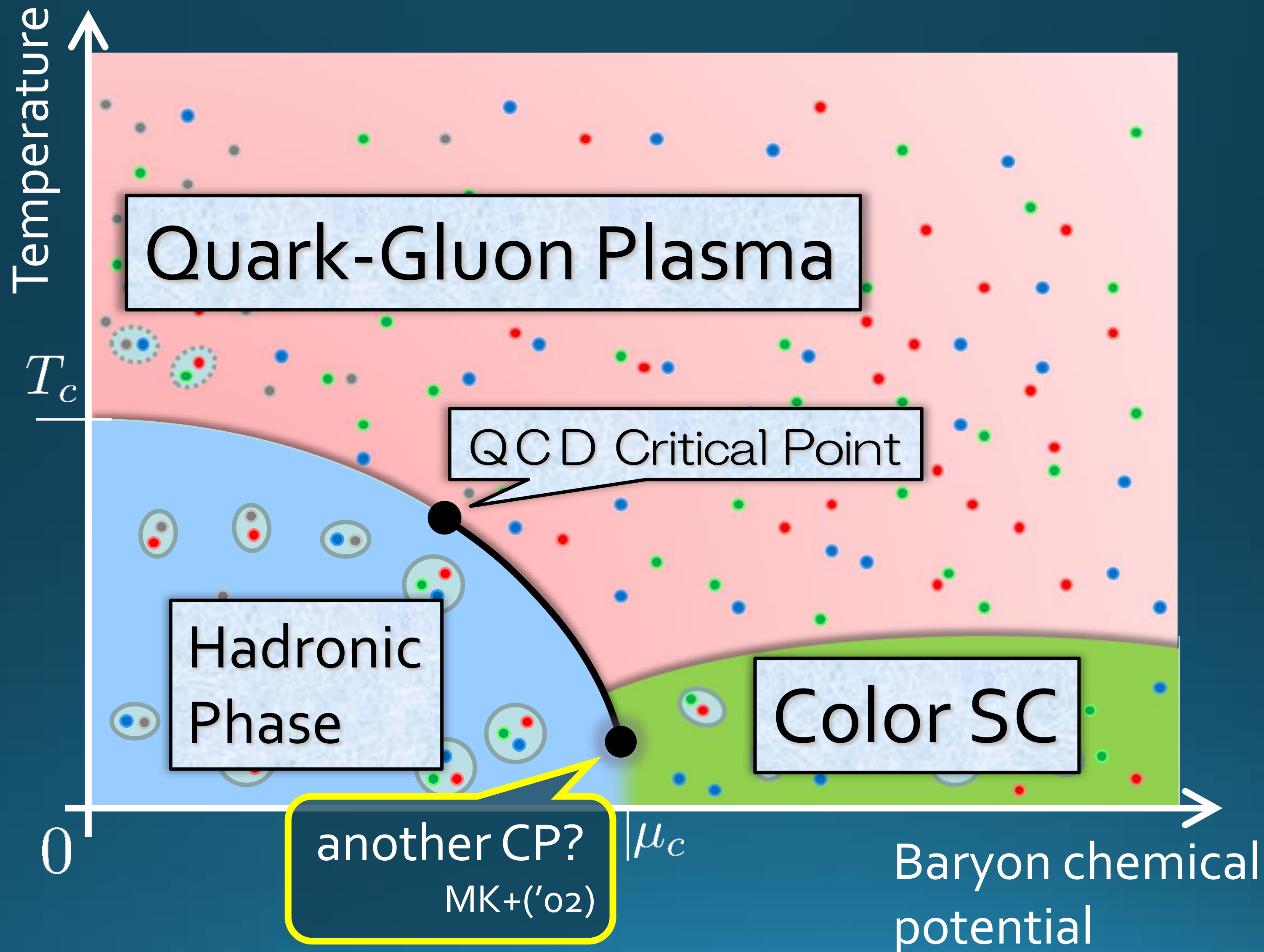
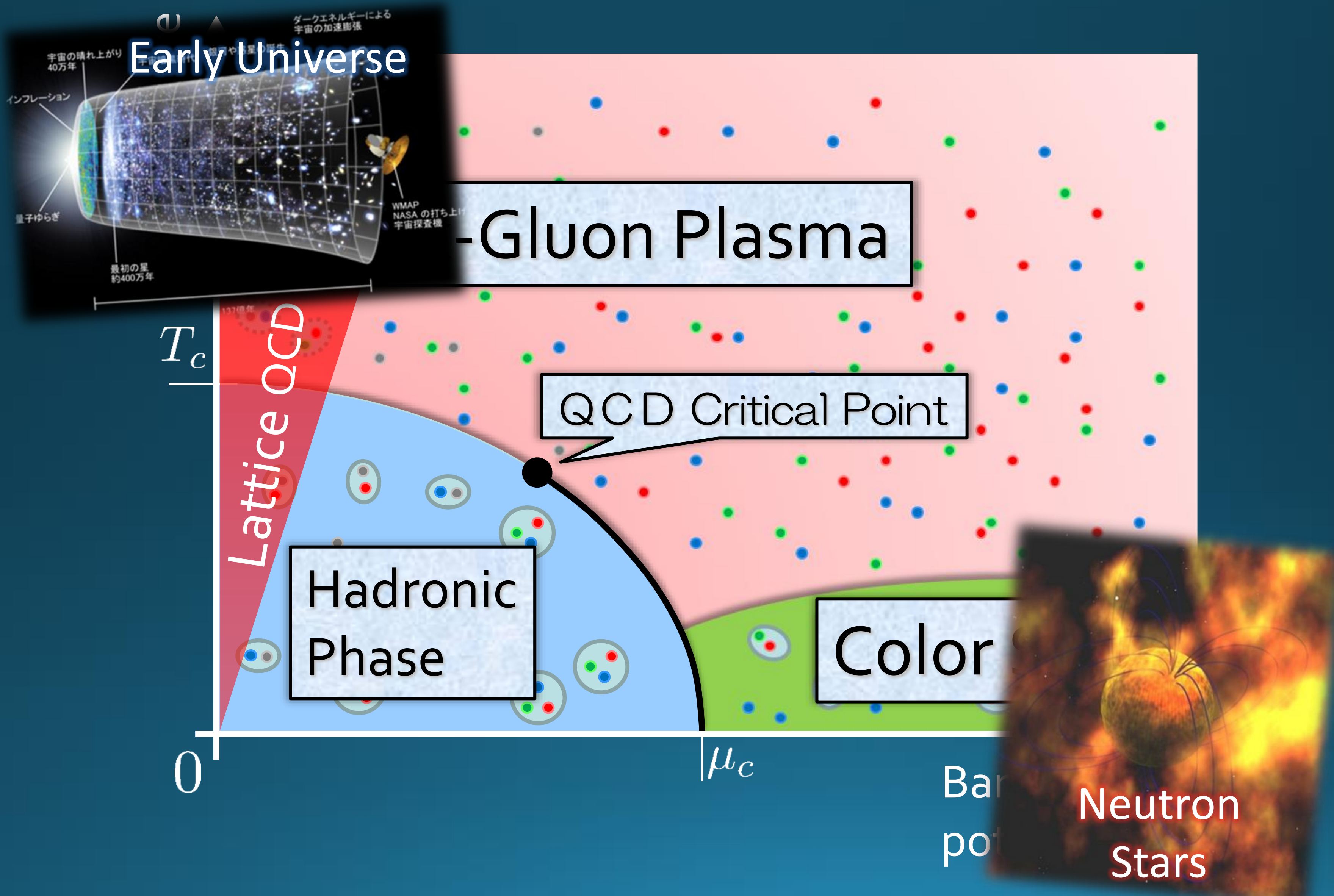
(Osaka U.)

Reimei Workshop "Hadrons in dense matter at J-PARC"
KEK, Tokai, 2022/Feb./23

QCD Phase Diagram

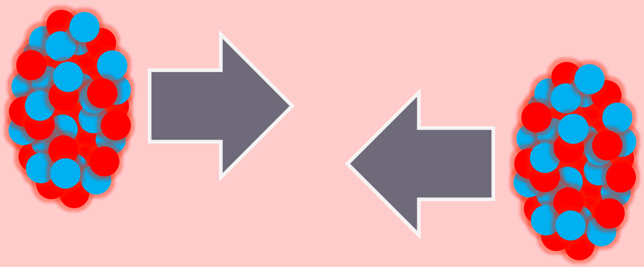


QCD Phase Diagram



Relativistic Heavy-Ion Collisions

Collide 2 heavy nuclei



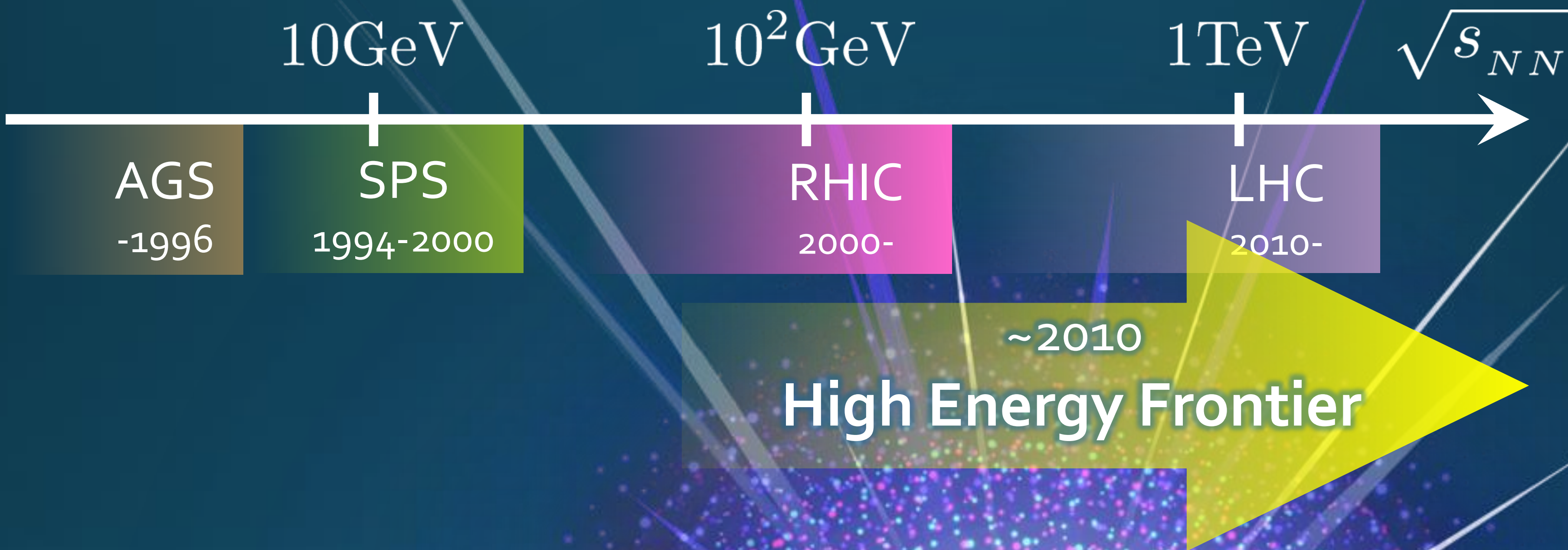
RHIC (2000~)
QGP Formation
Strongly coupled QGP

LHC (2010~)
Precision measurement of the QGP

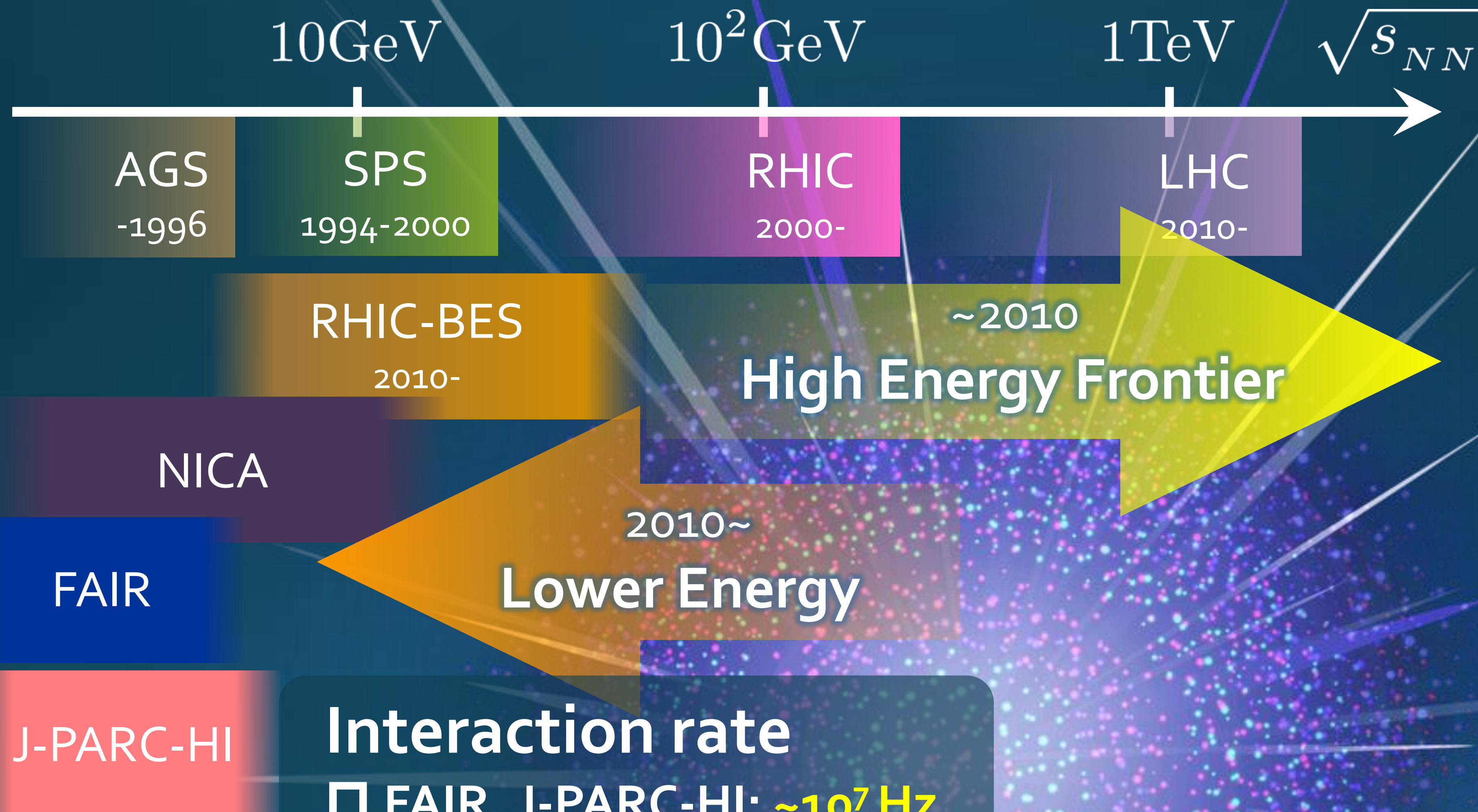
Physics

- ☐ Hot & dense medium
- ☐ Early Universe
- ☐ Quark-gluon plasma
- ☐ QCD phase structre

Brief History of Relativistic HIC



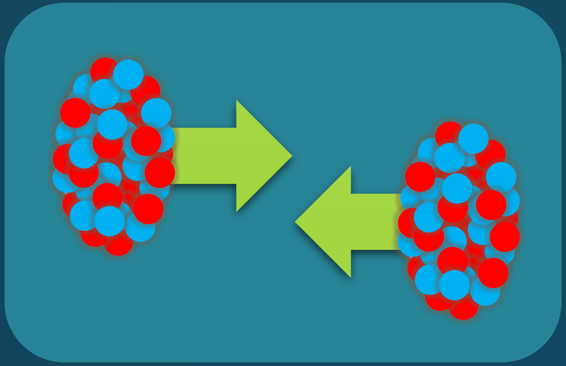
Brief History of Relativistic HIC



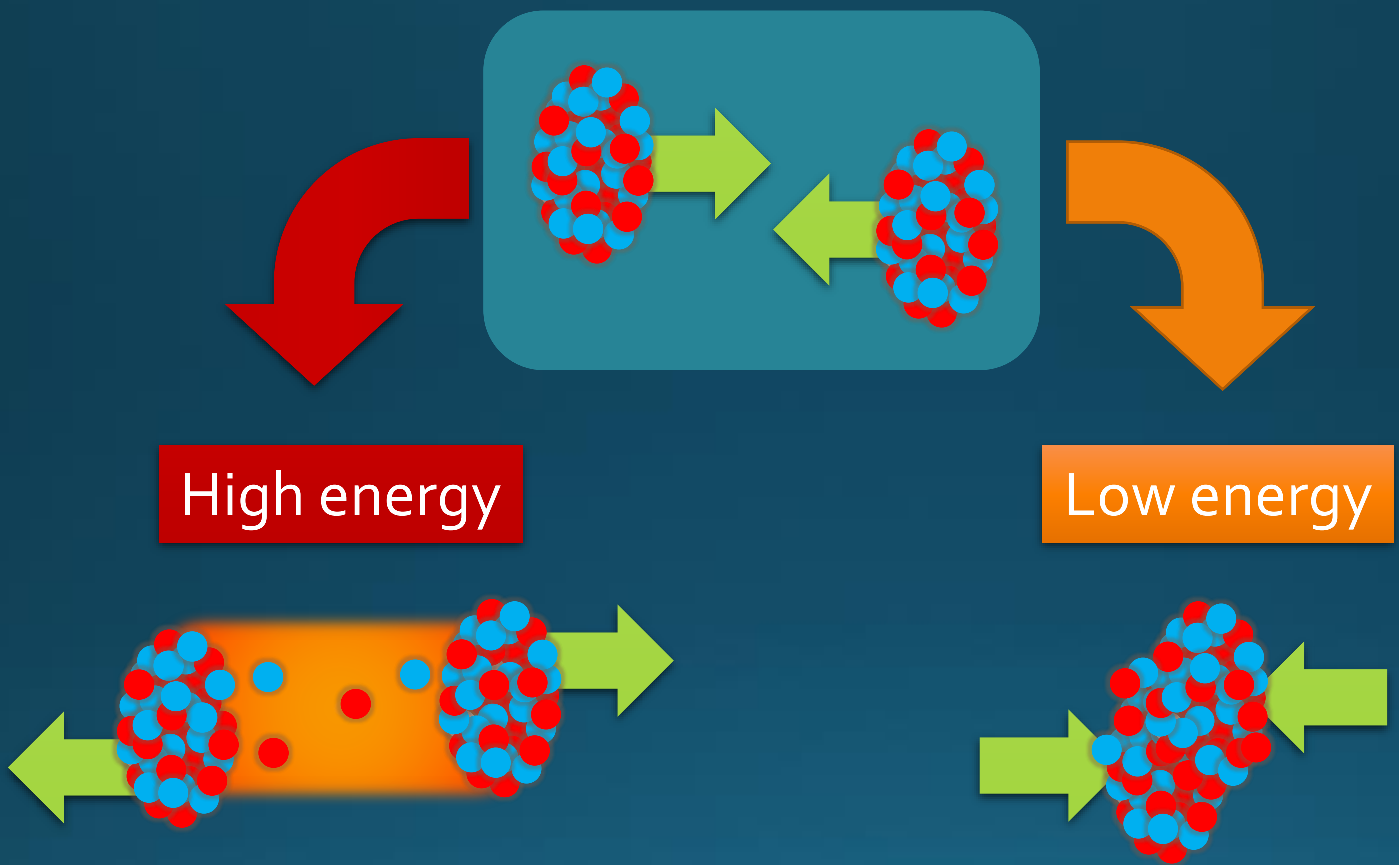
Interaction rate

- ☐ FAIR, J-PARC-HI: **~10^7 Hz**
- ☐ AGS, SPS: ~10^2 Hz

Beam-Energy Dependence



Beam-Energy Dependence



Nuclear transparency

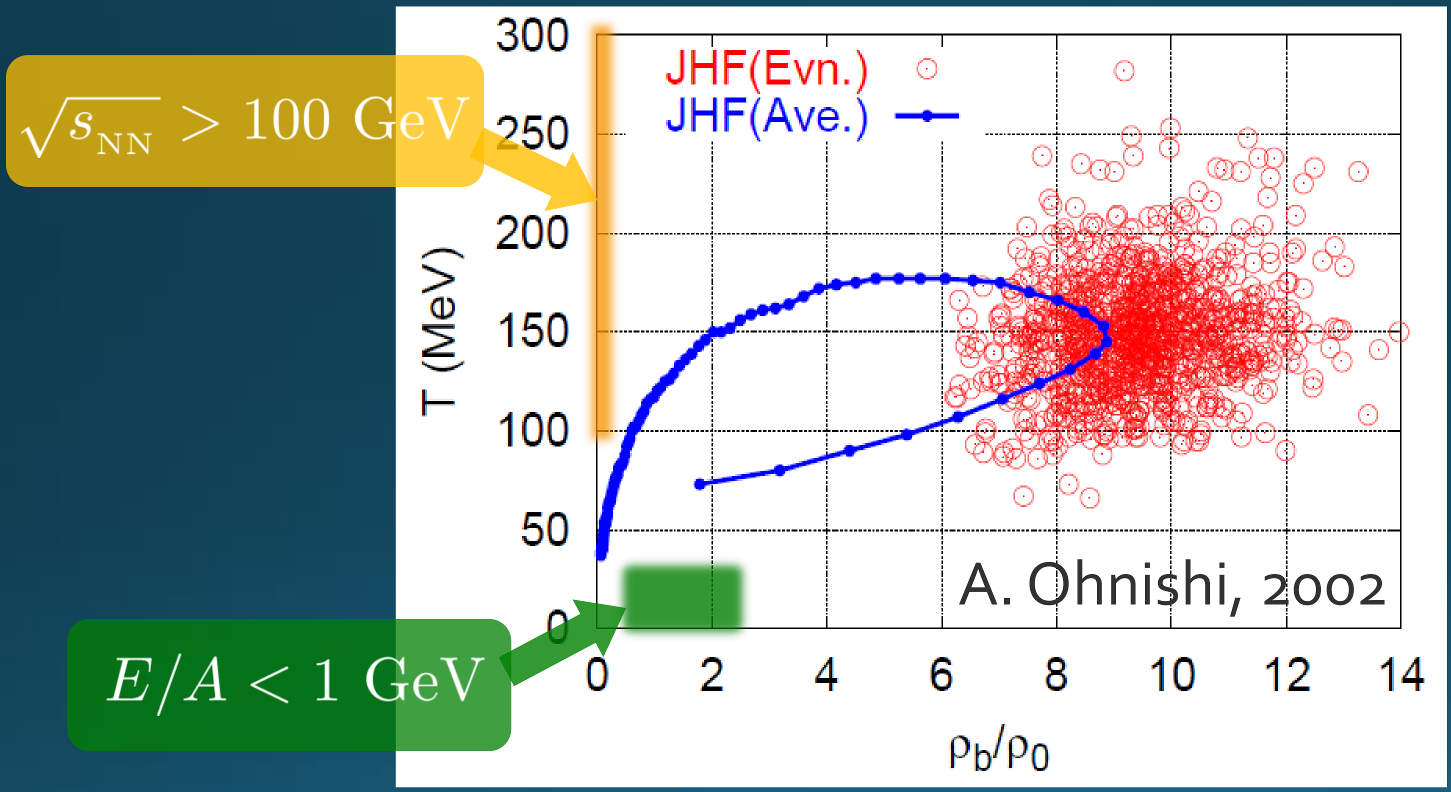
net-baryon #: small

Baryon stopping

net-baryon #: large

Maximum Density

Time evolution in *T*-ρ plane by JAM

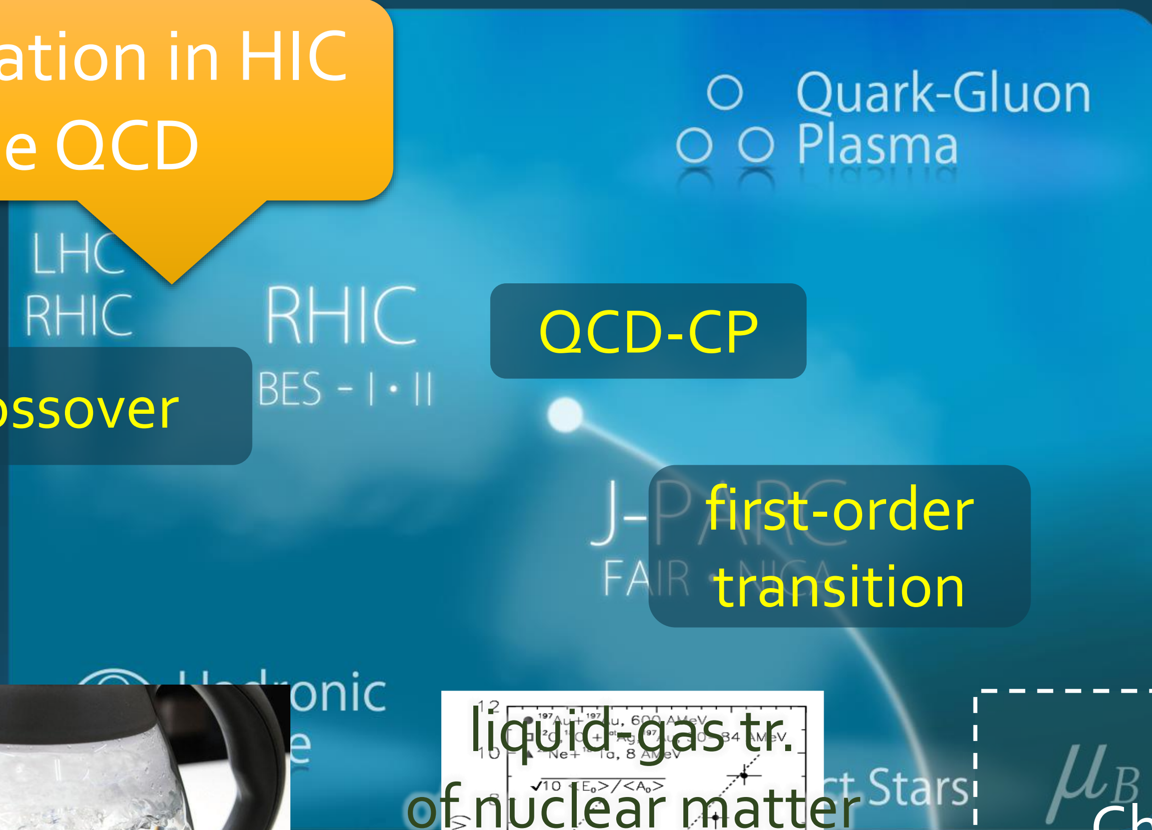


$E/A = 20\text{GeV}$

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

- Maximum density 5~10ρ_0 @ E/A~20GeV
- Large event-by-event fluctuations?

First-order Transition
at Highest Density in the Universe



QGP formation in HIC
Lattice QCD

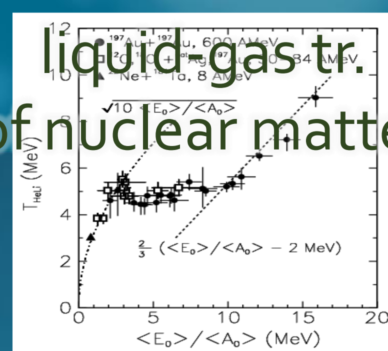
crossover

QCD-CP

first-order
transition

boiling water

$1 g/cm^3$



liquid-gas tr.
of nuclear matter

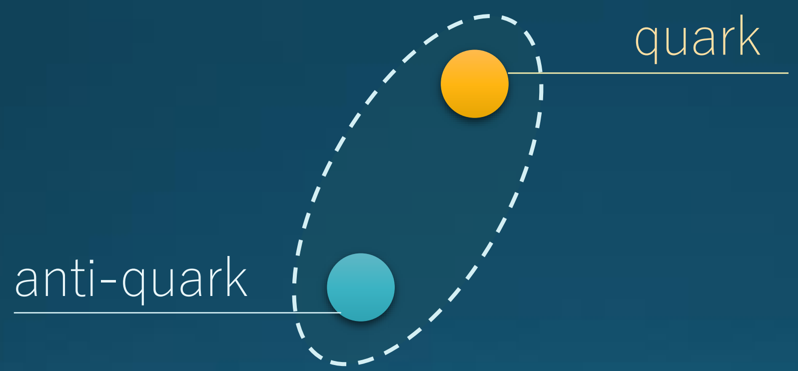
$10^{14} g/cm^3$

Chiral
Transition

$10^{15} g/cm^3$

Collapse of Vacuum

Our vacuum is filled with the quark condensate.



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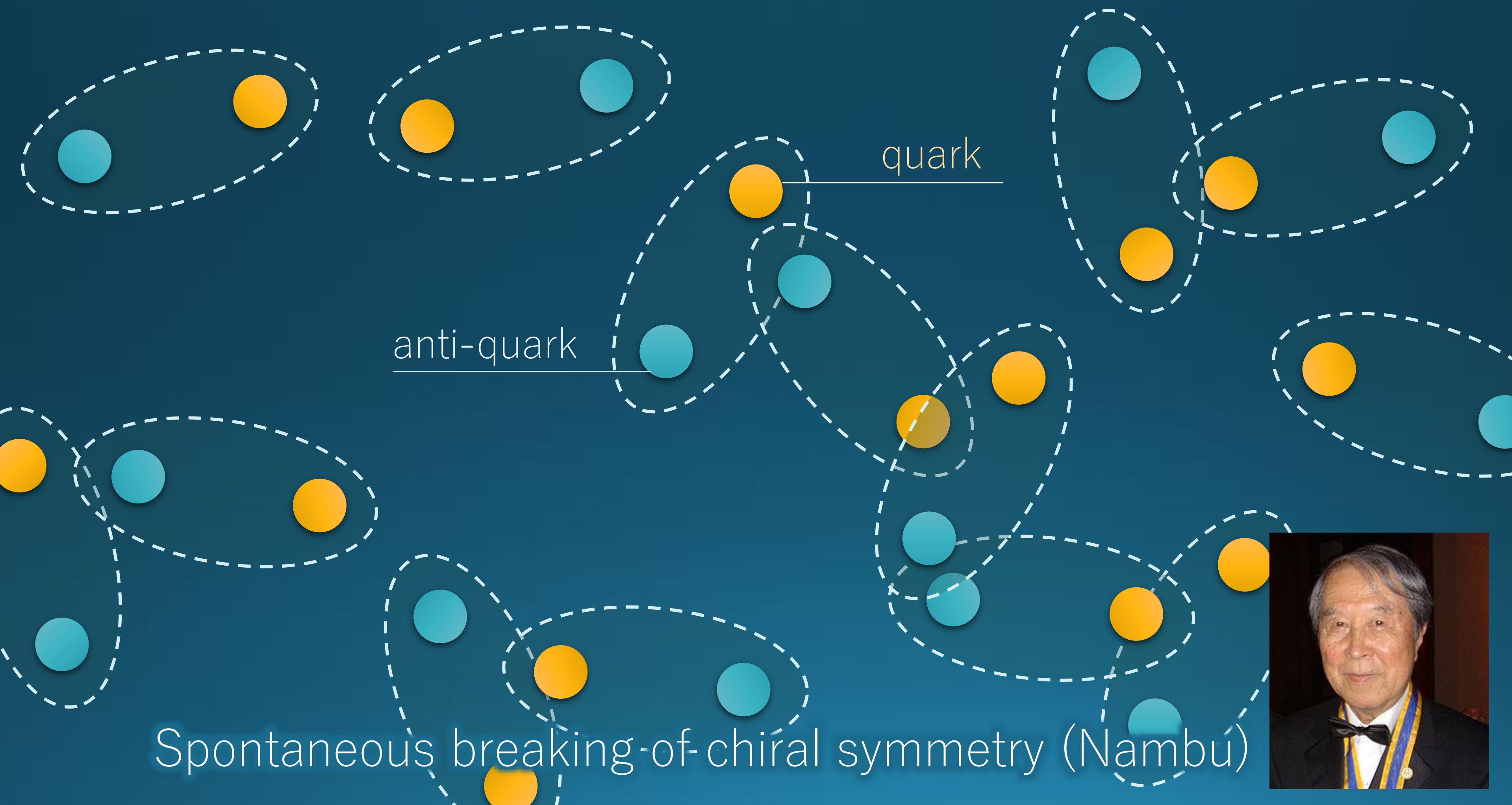
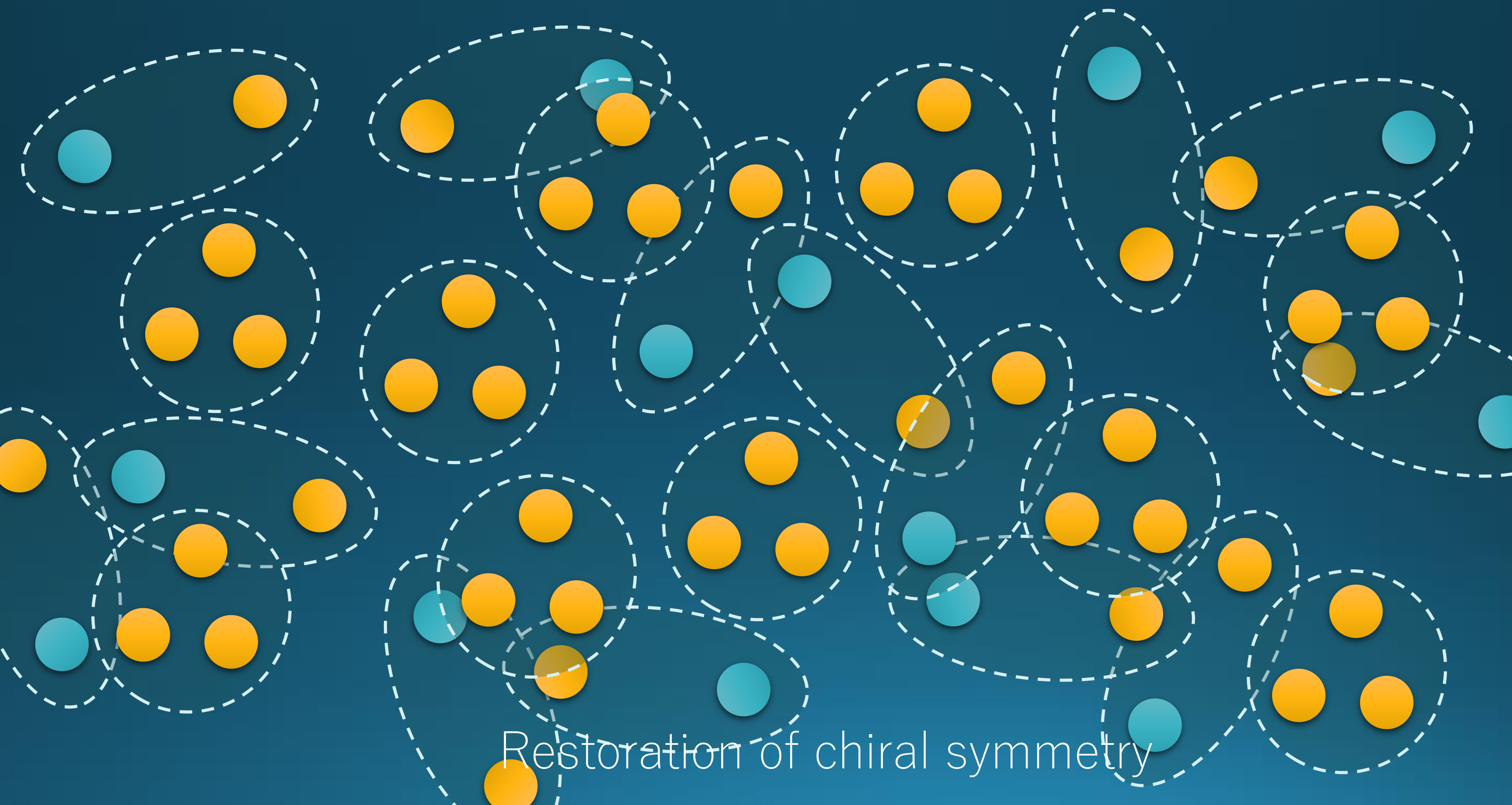


Spontaneous breaking of chiral symmetry (Nambu)

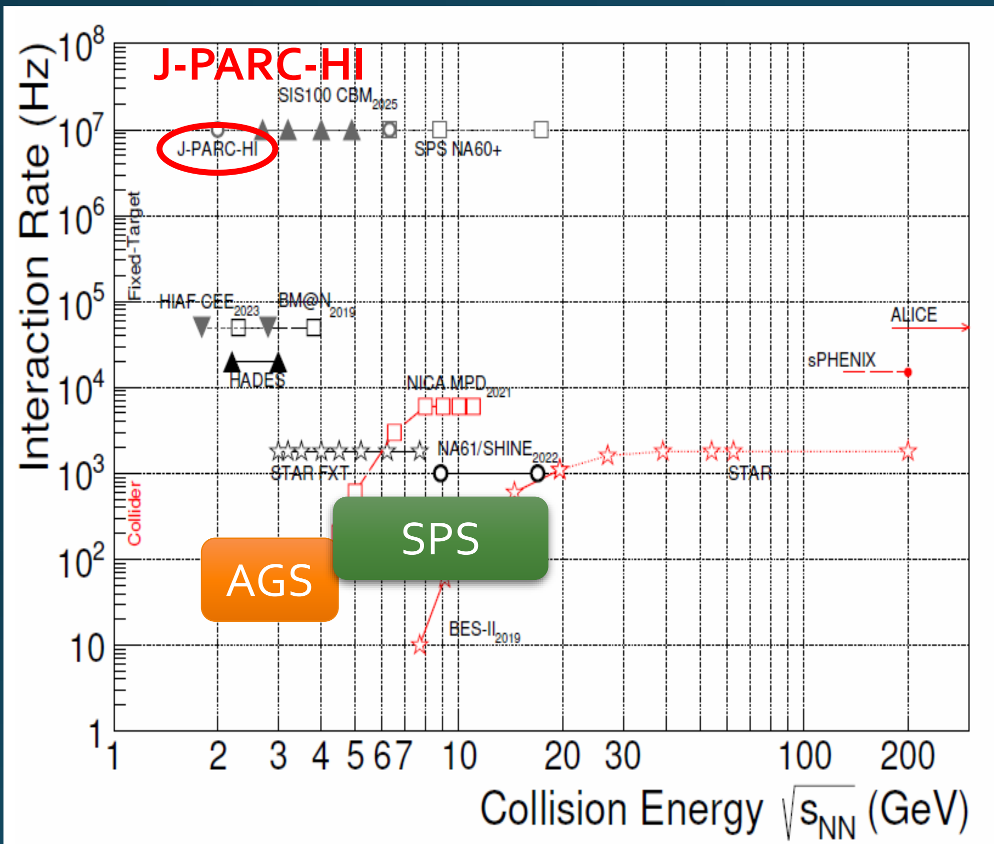
Collapse of Vacuum

Matter modifies the vacuum.



Restoration of chiral symmetry

Collision Rate



Galatyuk, NPA982,163 (2019)

J-PARC-HI:

High-luminosity x Fixed target

→World highest rate～10^8Hz

5-order higher than AGS,SPS

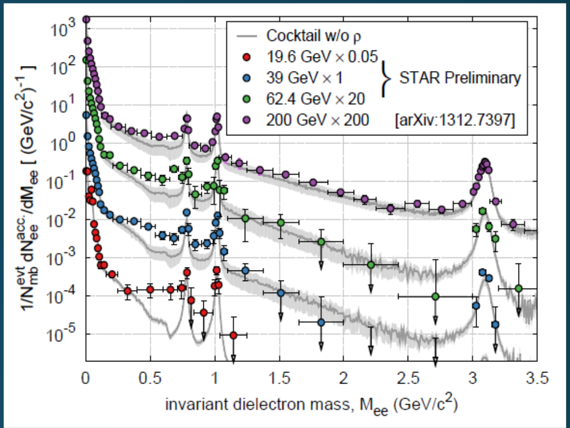
AGS, SPS 1 year	=	J-PARC-HI 5 min.

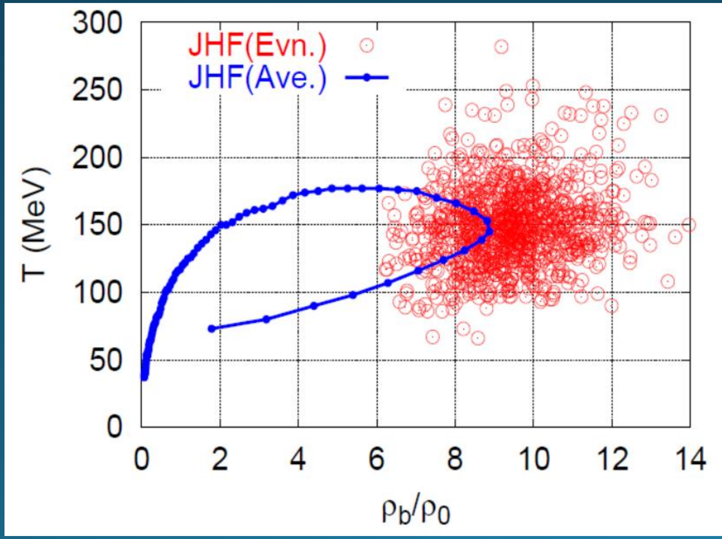
- ☐ High-statistical exp.
- ☐ various event selections
- ☐ higher order correlations
- ☐ search for rare events

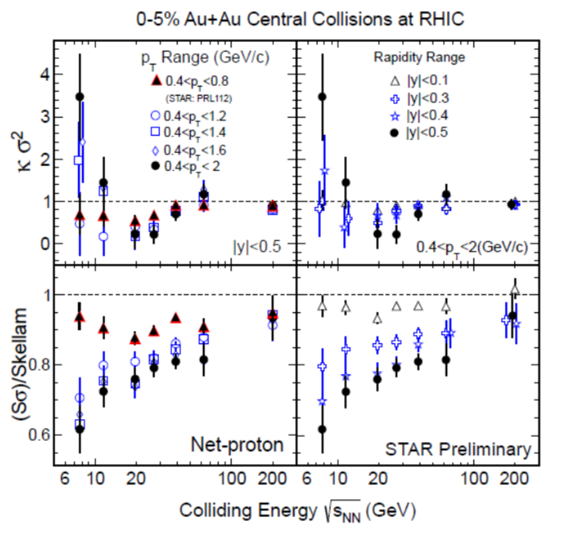
Various Observables

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

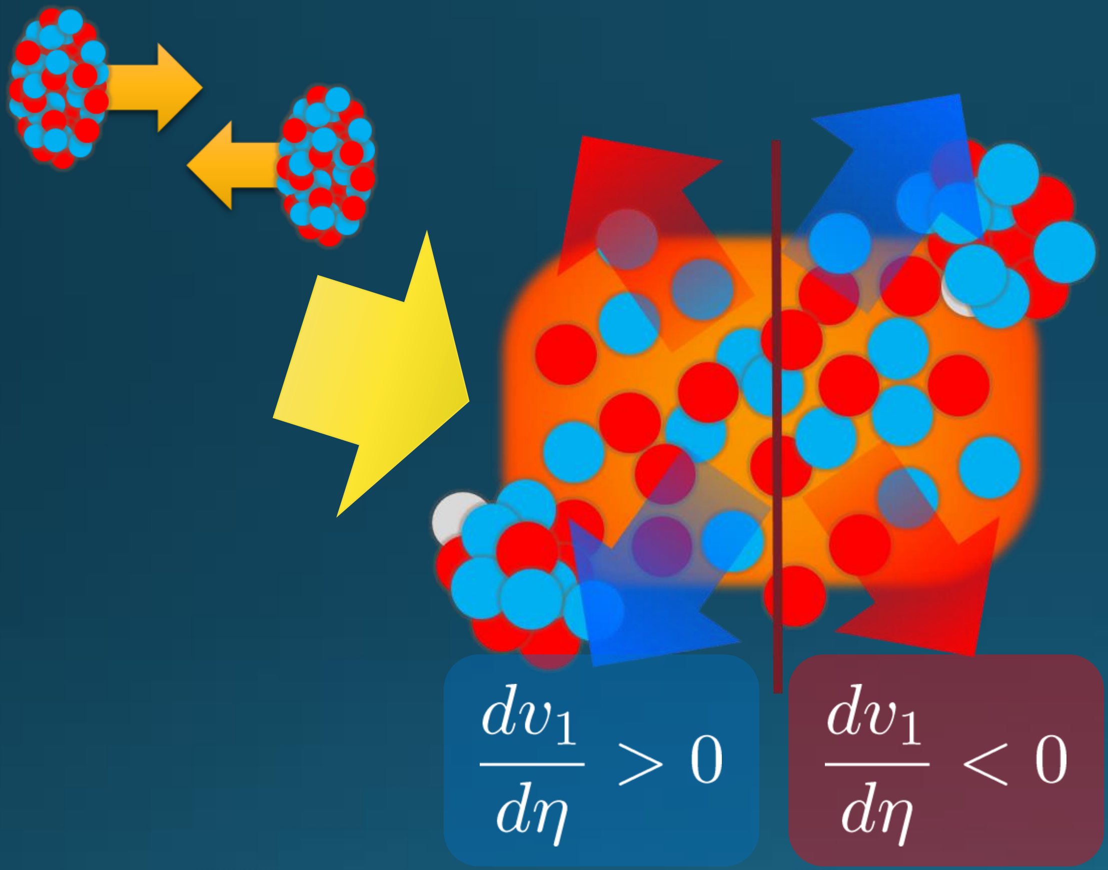
- Sophisticated event selections
- Various correlations



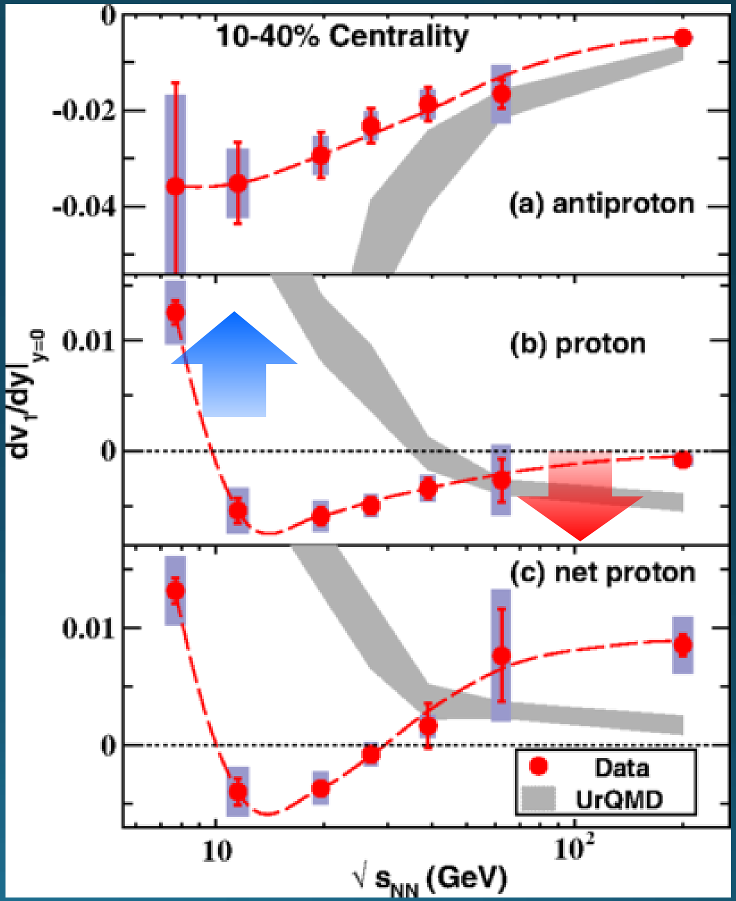




Directed Flow



$dv_1/d\eta$

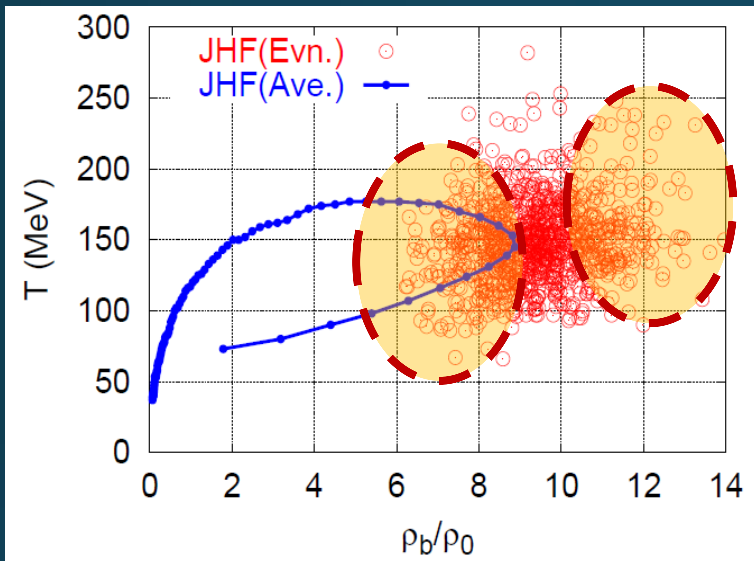


Reproduction of $\sqrt{s_{NN}}$ dependence

Nara, Ohnishi, PRC ('22)

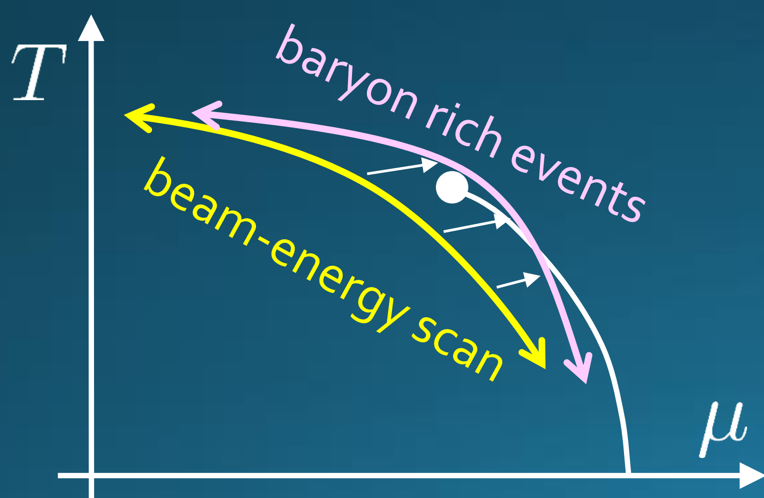
STAR, PRL('14)

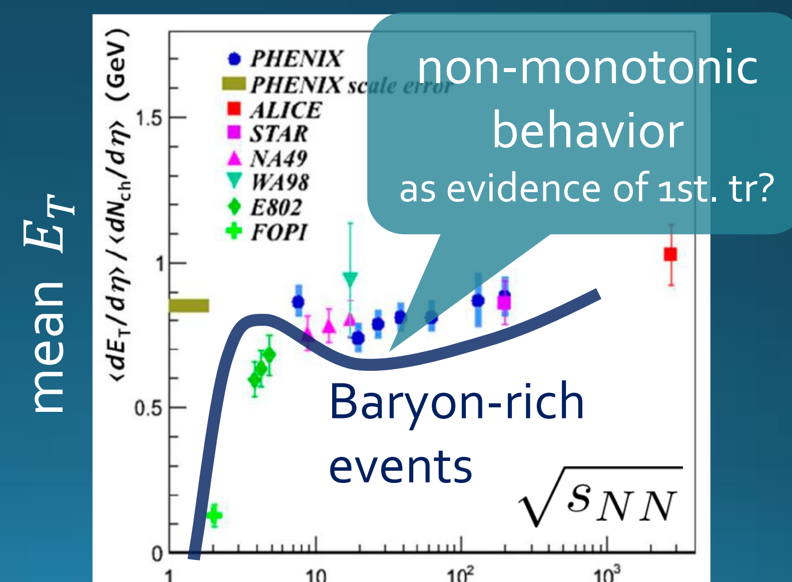
Event Selection



Large fluctuations in highest density

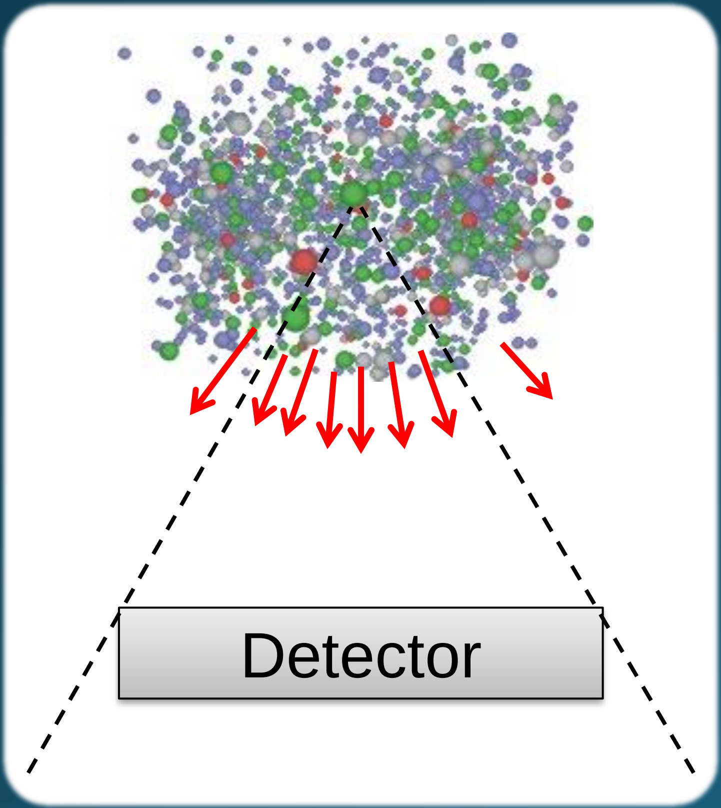
"Density scan" by event selection?



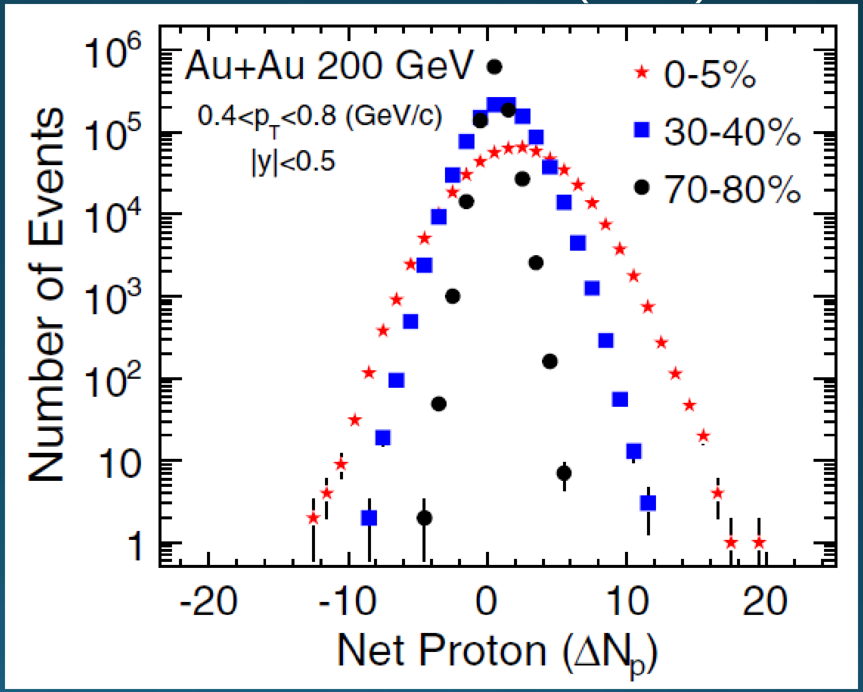


Event-by-Event Fluctuations

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



STAR, PRL**105** (2010)



Cumulants

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

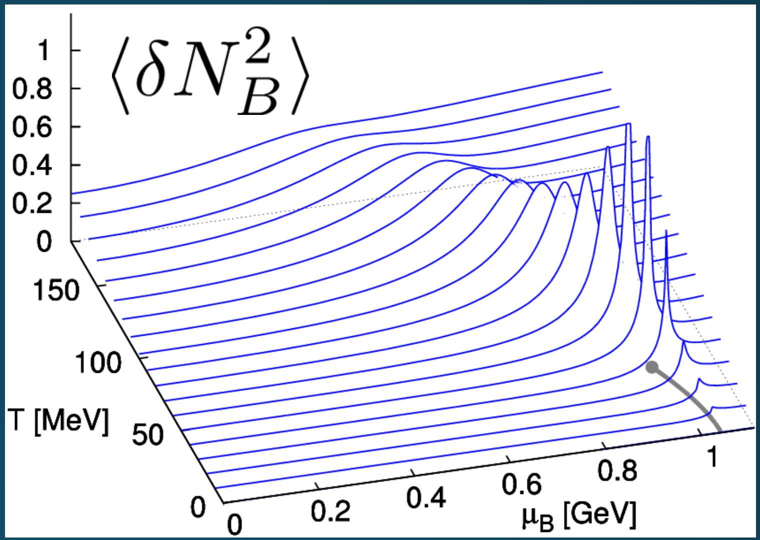
Non-Gaussian Cumulants

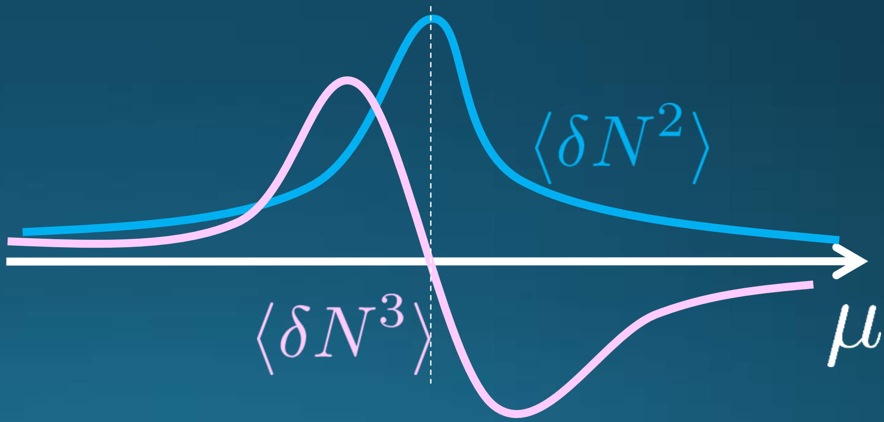
Gaussian fluctuations diverge at the QCD-CP

- Higher order cumulants change sign at the phase boundary

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

Asakawa, Ejiri, MK, 2009



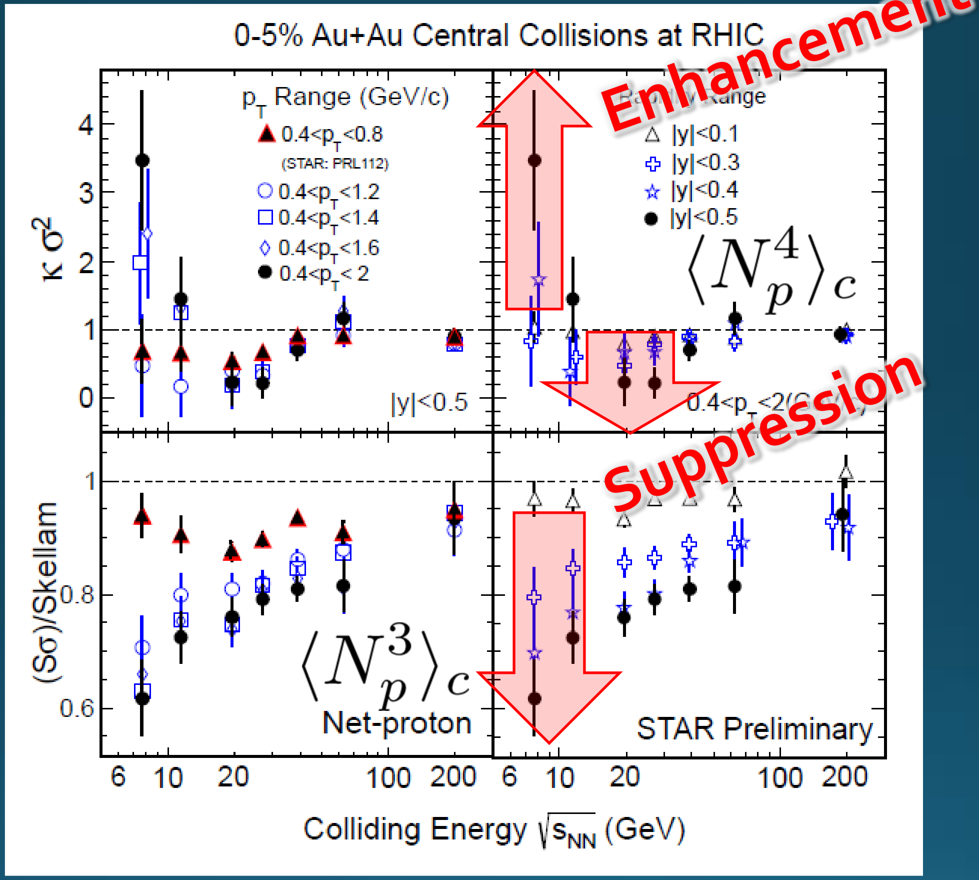


- Steeper divergence for higher-order cumulants Stephanov, 2009

Experimental Results

$$\frac{\langle N_{\rm p}^4\rangle_c}{\langle N_{\rm p}^2\rangle_c}$$

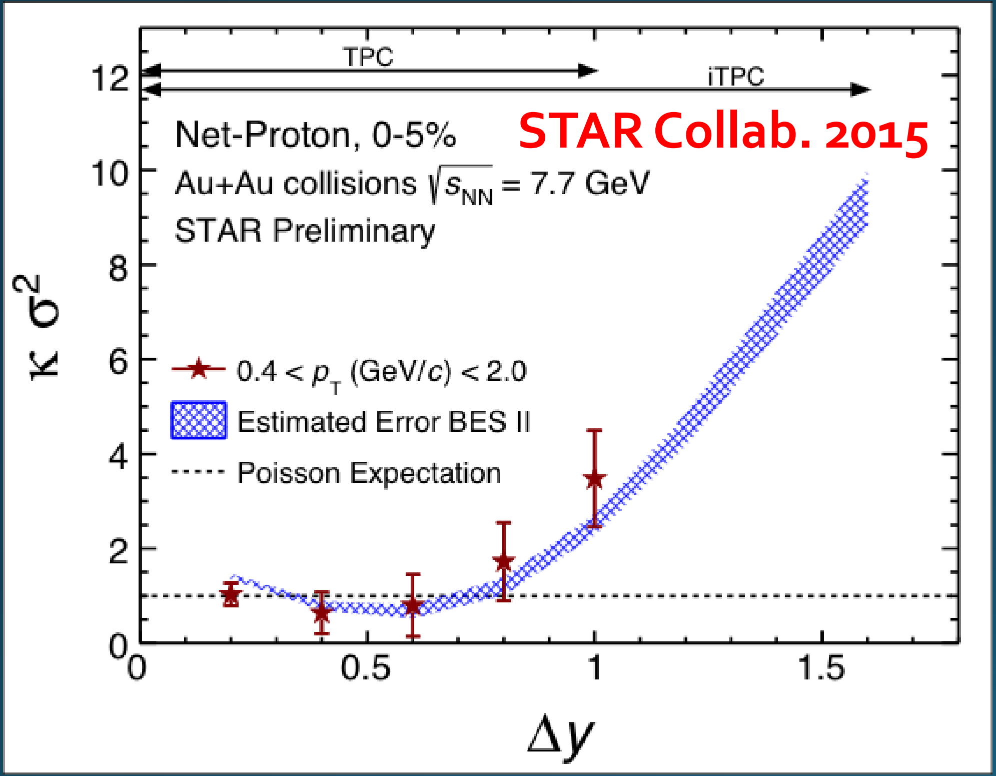
$$\frac{\langle N_{\rm p}^3\rangle_c}{\langle N_{\rm p}^2\rangle_c}$$

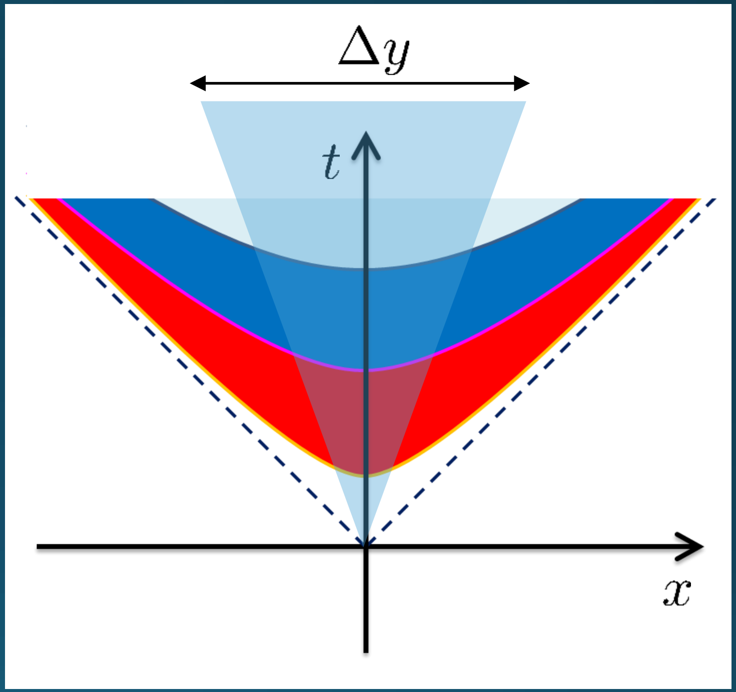


STAR Collab.
2010~

Enhancement & Suppression of non-Gaussian cumulants! → Have we observed QCD critical point?

Rapidity Window Dependence

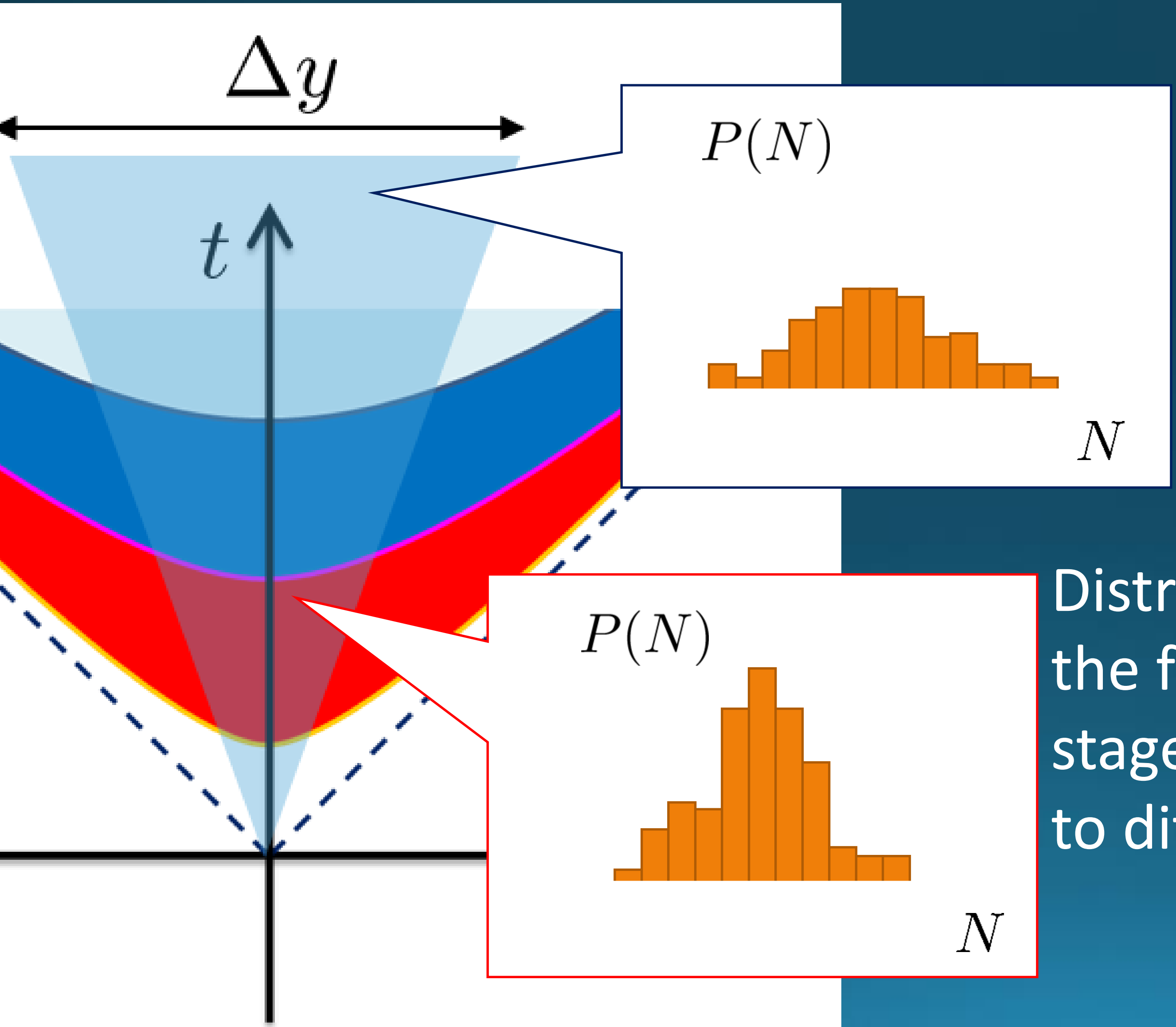




- Non-Gaussian Cumulants have been observed as a function of rapidity window Δy.
- Some results have non-monotonic Δy dependence.

Diffusion of Fluctuations

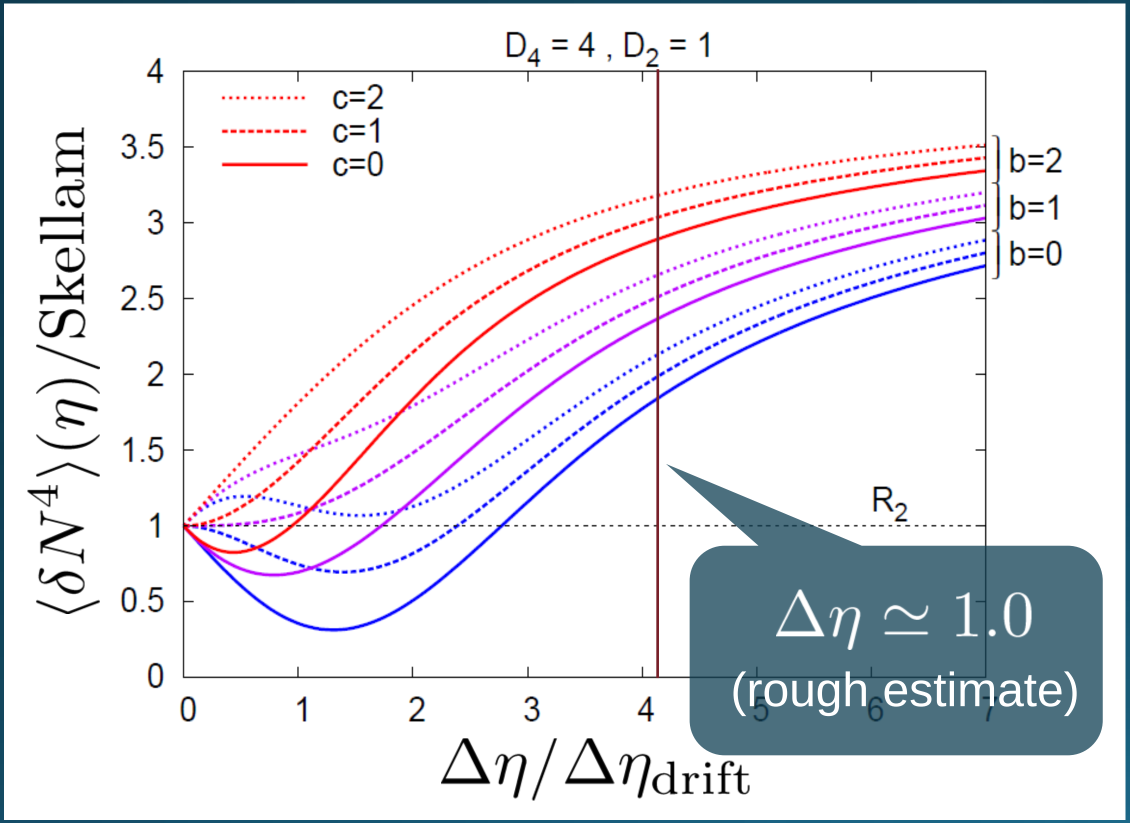
MK, Ohno, Asakawa 2014
MK 2015



Distributions in Δy in the final state and early stage are different due to diffusion.

Rapidity Window dependence
as a Result of Diffusion

MK+ (2014); MK (2015)



Parameters

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

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

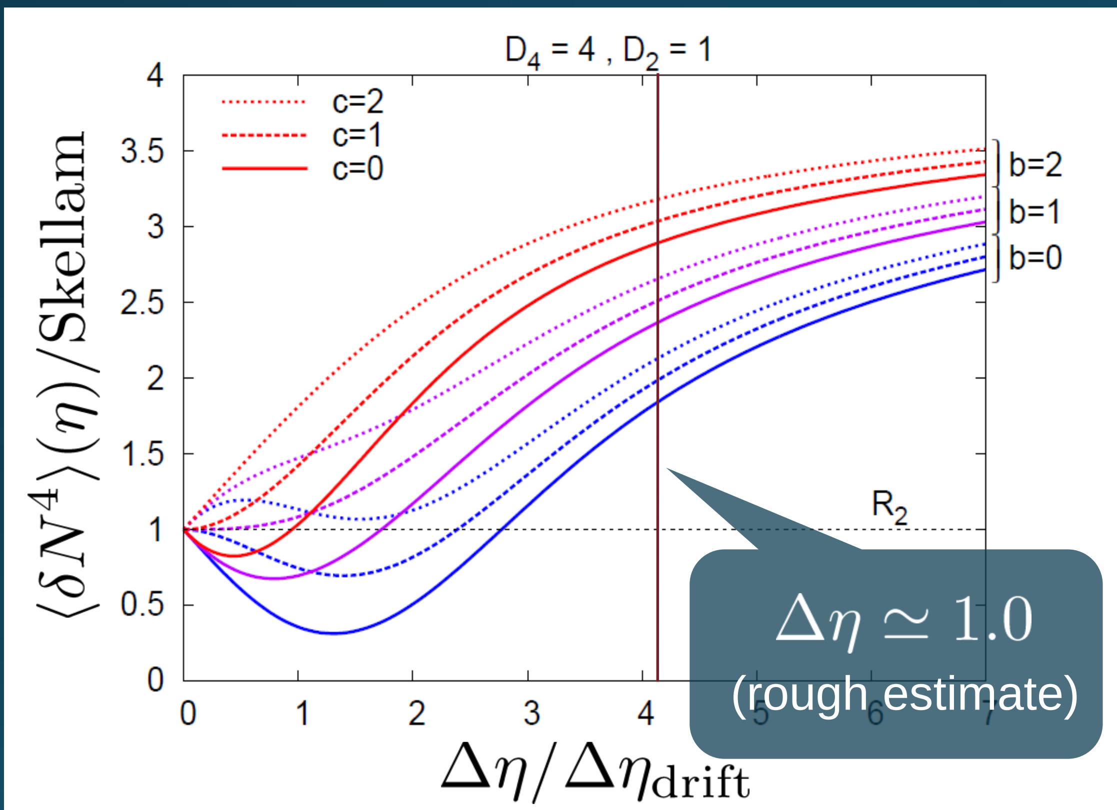
$$b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{net})} \rangle}$$

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

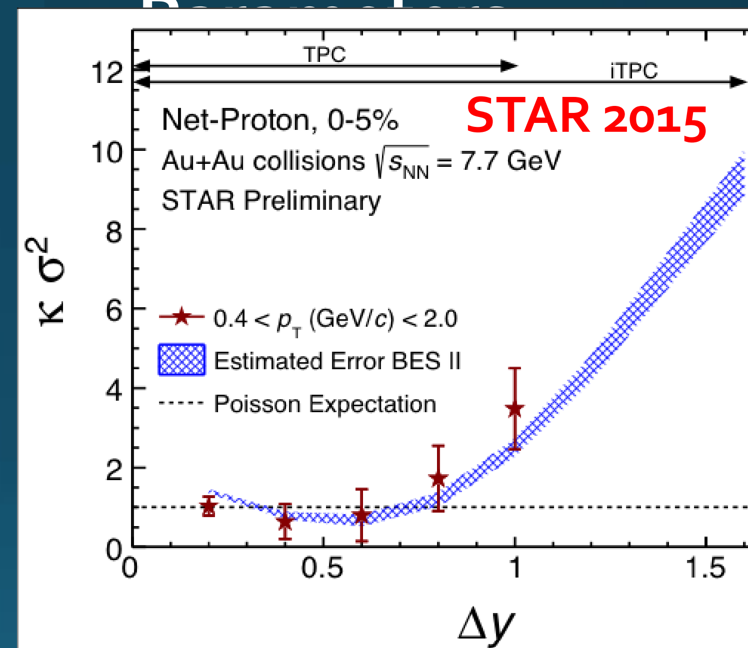
- Higher order cumulants can behave non-monotonically.
- $\Delta\eta$ dependence encodes history of time evolution.

Rapidity Window dependence
as a Result of Diffusion

MK+ (2014); MK (2015)



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



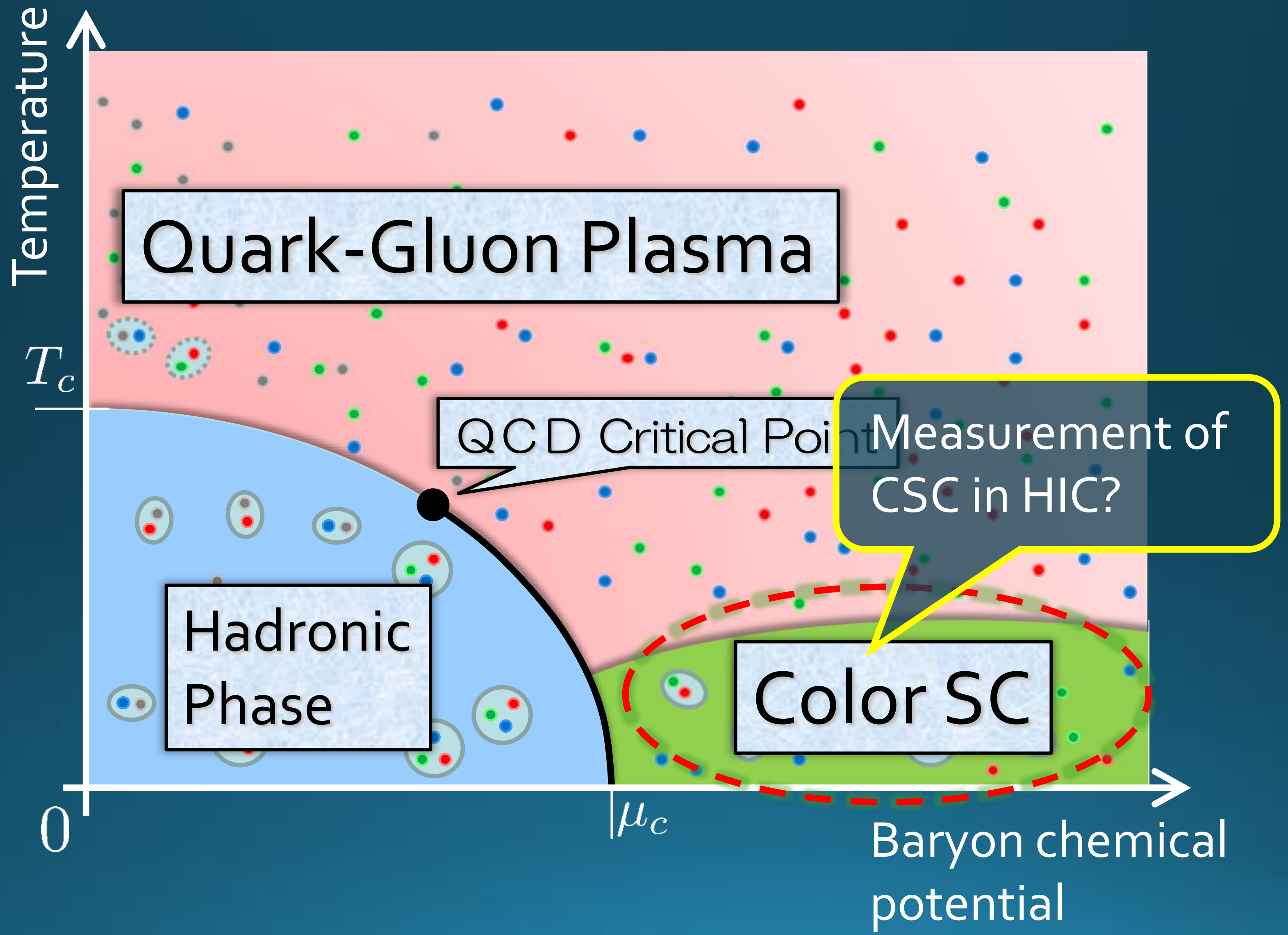
$c = \frac{\quad}{\langle Q_{(\mathrm{tot})} \rangle}$

- Higher order cumulants can behave non-monotonically.
- Δη dependence encodes history of time evolution.

Search for **CSC Phase Transition** using dilepton production rates

Nishimura, MK, Kunihiro, arXiv:2201.01963

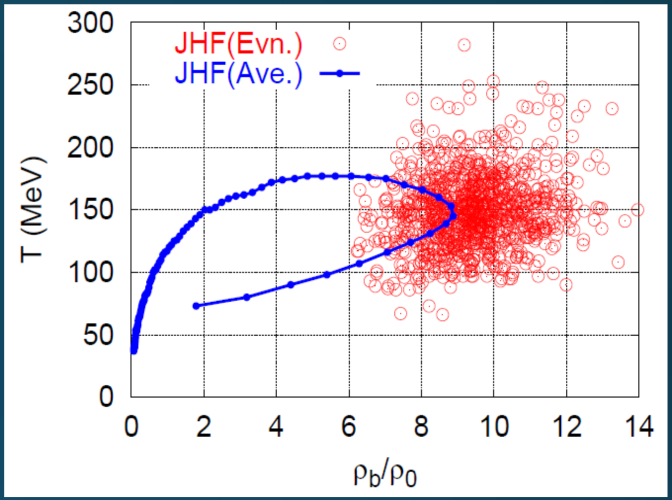
Color Superconductivity



Observing CSC in HIC?

Difficulties

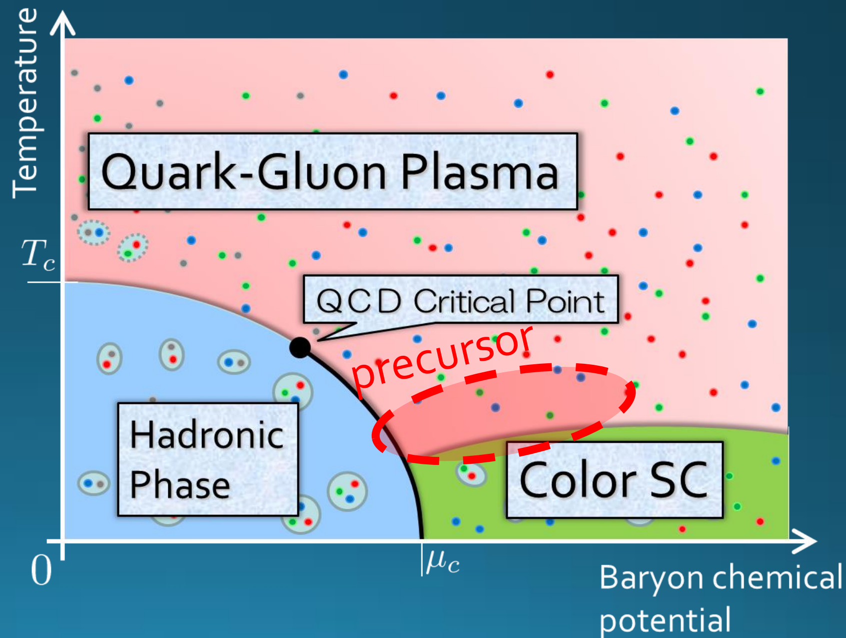
1) Creation of CSC itself would be impossible.
2) CSC would be realized only in the early stage.



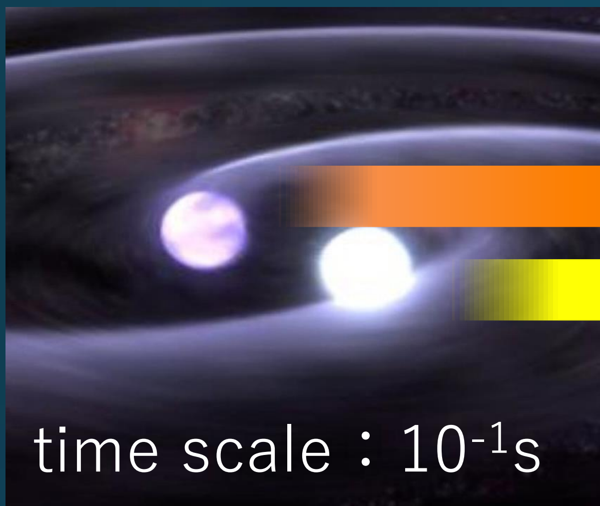
Solution

1) Focus on **precursor of CSC**
2) Use **dilepton production**

Nishimura, MK, Kunihiro, 2201.01963

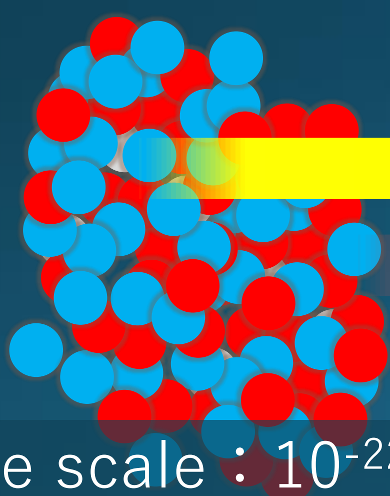


Multi-Messenger Observation

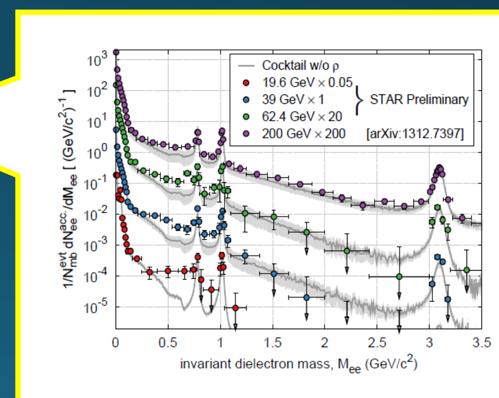


gravitational waves

electromagnetic waves



leptons,
photons

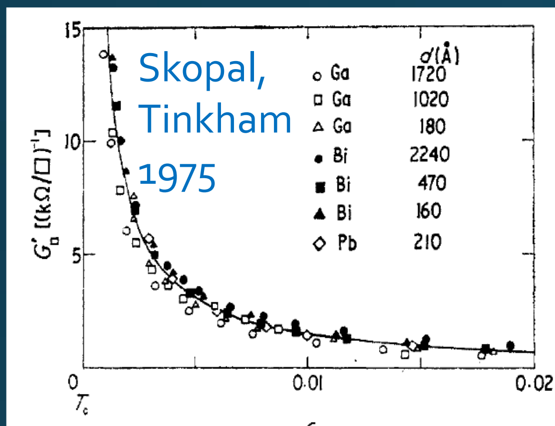


hadronic observables

Precursory Phenomena

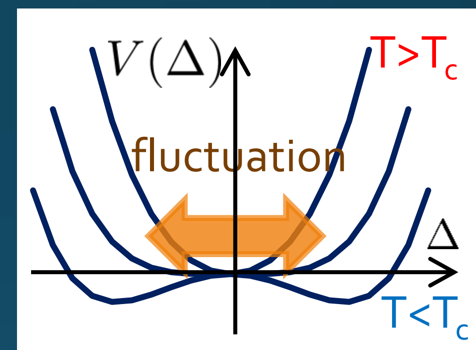
= anomalous behavior of observables near but above T_c

Electric conductivity in metals



$$\varepsilon = \frac{T - T_c}{T_c}$$

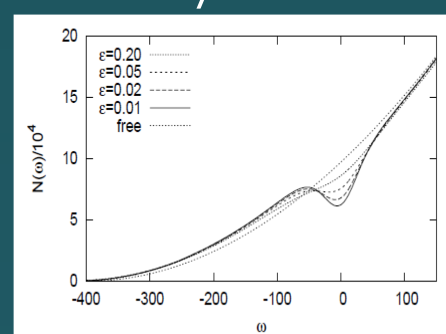
Landau's Free Energy



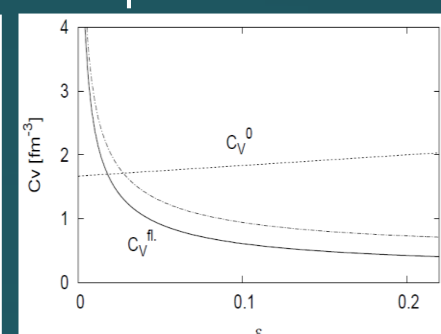
Precursor of CSC

- **Pseudogap** = Depression in the density of states
- Specific heat
- etc.

Density of States



Specific Heat



MK, Koide, Kunihiro, Nemoto, '03, '05

Model

NJL model (massless 2-flavor)

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + \mathcal{L}_S + \mathcal{L}_C$$

$$\mathcal{L}_S = G_S\big((\bar{\psi}\psi)^2 + (\bar{\psi} i\gamma_5 \tau \psi)^2\big)$$

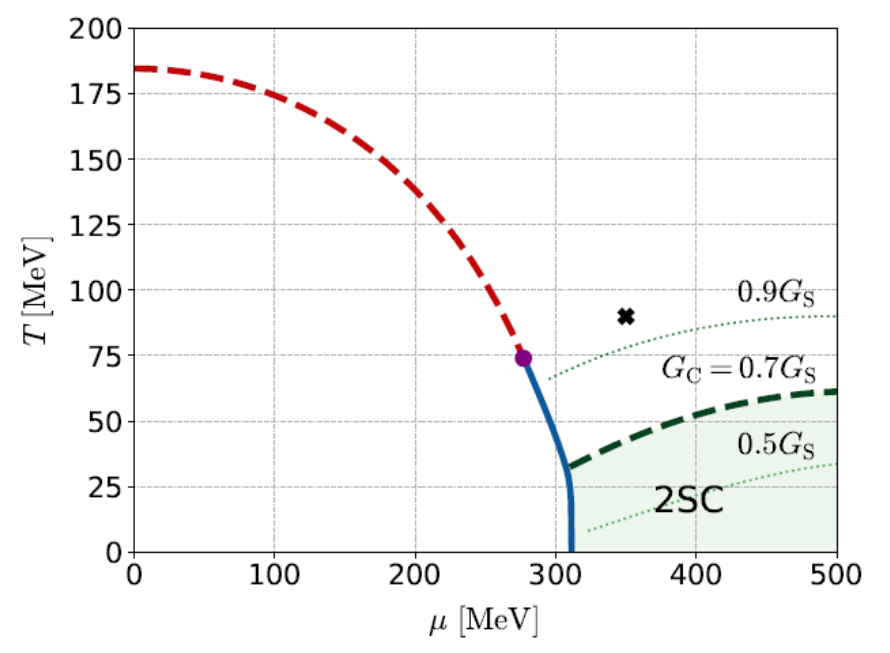
$$\mathcal{L}_C = G_C\big((\bar{\psi} i\gamma_5 \tau_A \lambda_A \psi^C)(\text{h.c.}\big)$$

diquark interaction

$$G_S = 5.01\ \text{GeV}^{-2}, \quad \Lambda = 650\text{MeV}$$

- G_C: free parameter

Phase Diagram in MFA



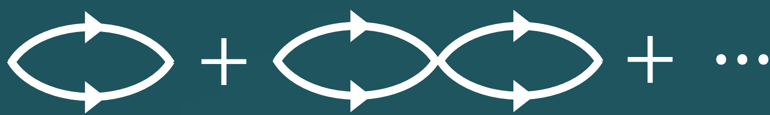
Order of CSC phase transition
Matsuura+('04), Giannakis+('04)
Noronha+('06), Fejos, Yamamoto('19)

Diquark Mode

Diquark Propagator (T-matrix)

in random-phase approximaion

$$\Xi^R(\boldsymbol{k},\omega) =$$

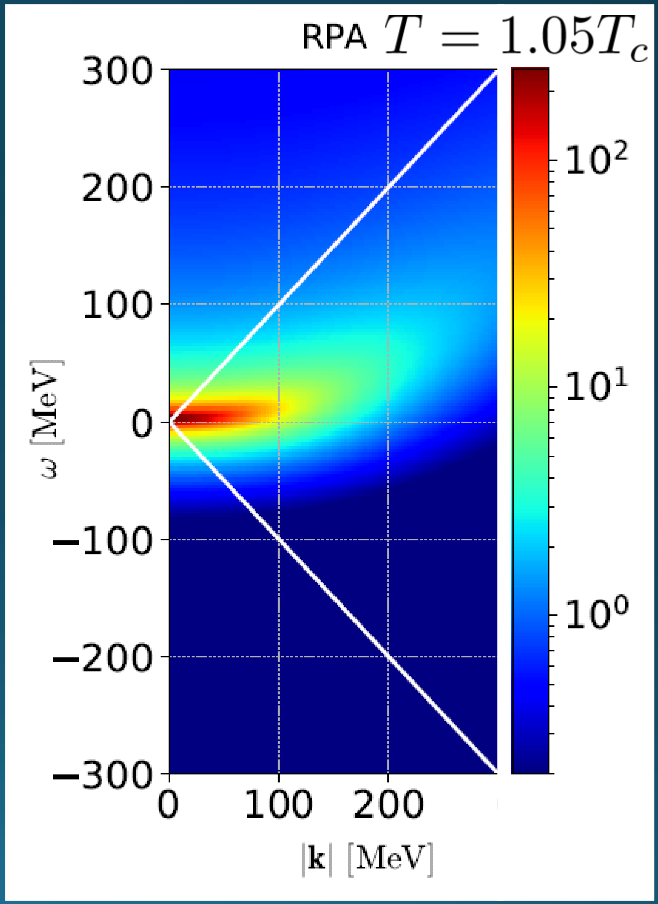


$$= \frac{Q^R(\boldsymbol{k},\omega)}{1 + G_C Q^R(\boldsymbol{k},\omega)}$$

- Massless at T=T_c as a soft mode of CSC transition
- Strength in the space-like region

MK, Koide, Kunihiro, Nemoto, ’01,’05

Dynamical Structure Factor

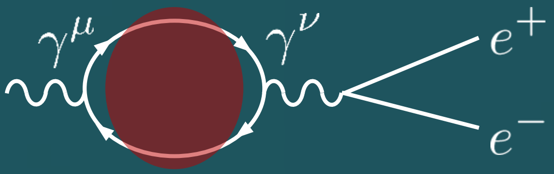


Photon Self-Energy

Dilepton Production Rate

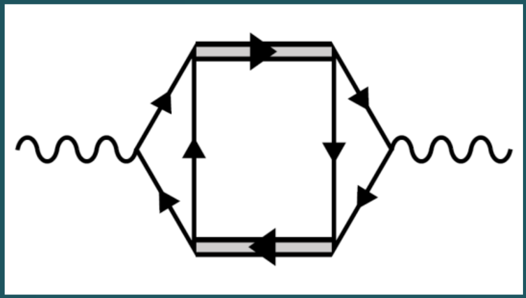
$$\frac{d^4\Gamma}{dk^4} = \frac{\alpha}{12\pi^4}\frac{1}{k^2}\frac{1}{e^{\beta\omega-1}}\mathrm{Im}\Pi^{R\mu}_{\mu}(k)$$

$$\Pi^{\mu\nu}(k) =$$

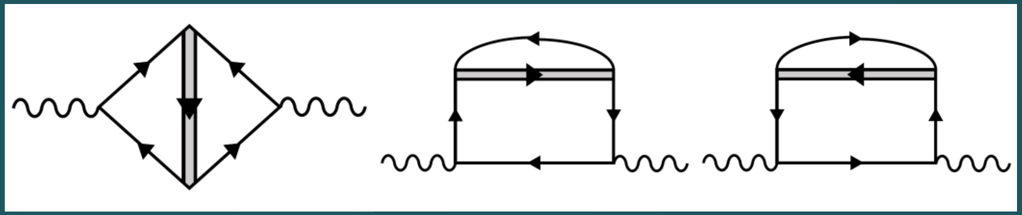


Terms included in $\Pi^{\mu\nu}$

Aslamasov-Larkin



Maki-Thompson, Density of states

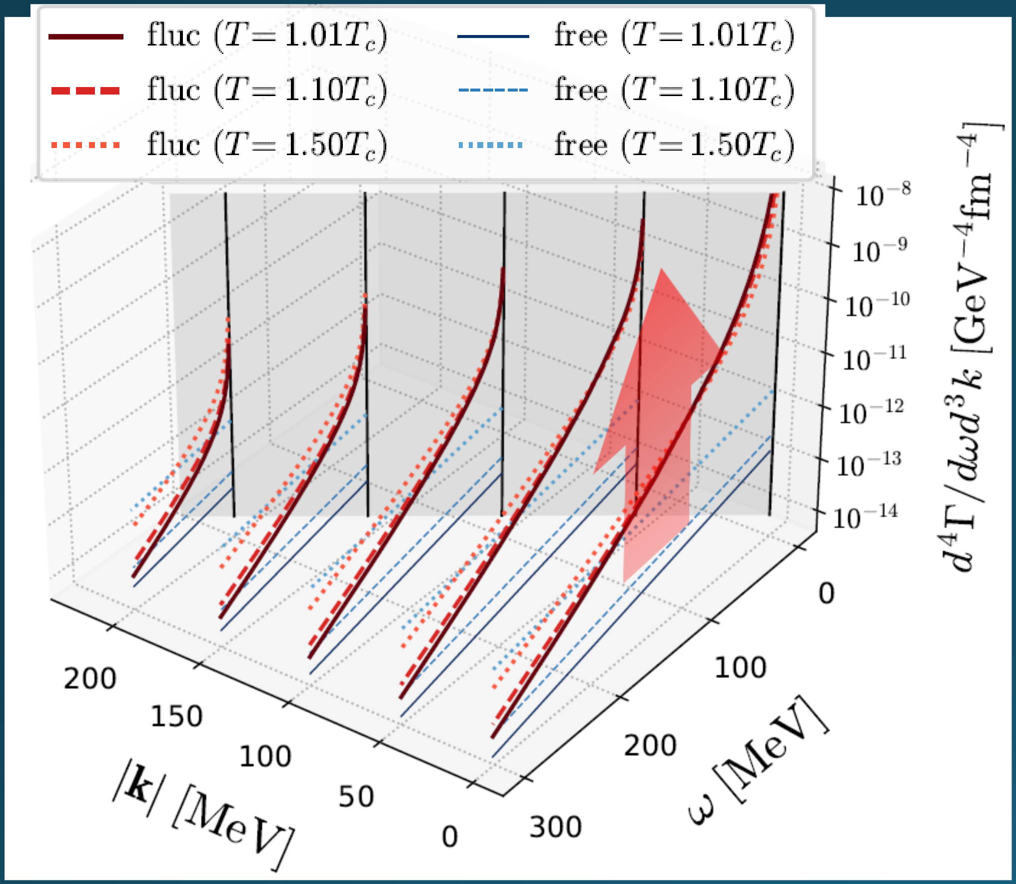


 = diquark propagator

- common in metallic superconductors (conductivity)
- time-dependent GL approx. for diquark field
- gauge-invariant construction

Nishimura, MK, Kunihiro, 2201.01963

Dilepton Production Rates



$$\frac{d^4\Gamma}{dk^4}(\omega, k)$$

Red: fluctuation contribution
Blue: free quarks

$\mu = 350$ MeV

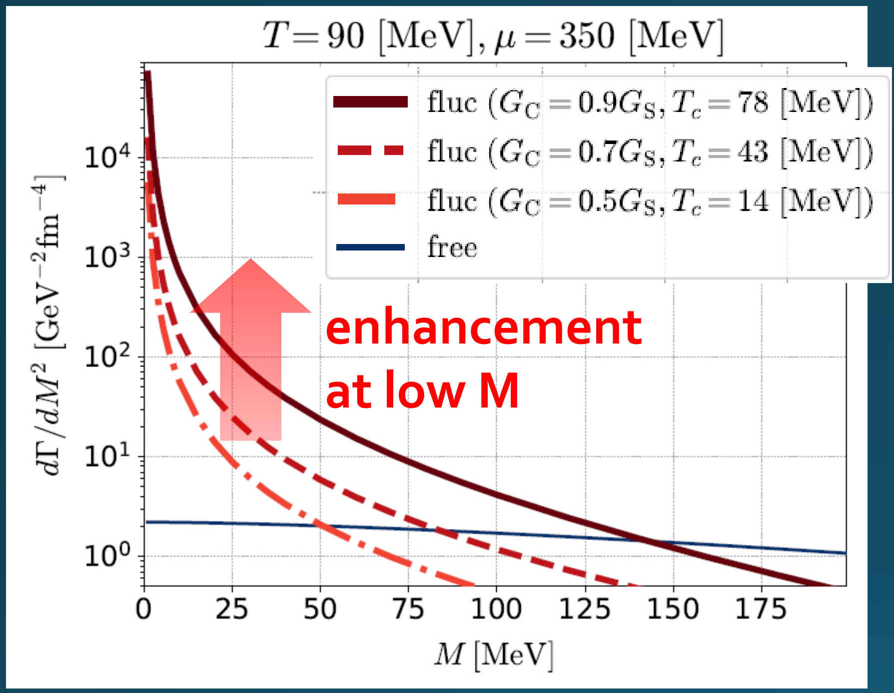
$G_C = 0.7 G_S, \quad (T_c \simeq 43\ \text{MeV})$

Nishimura, MK, Kunihiro,
2201.01963

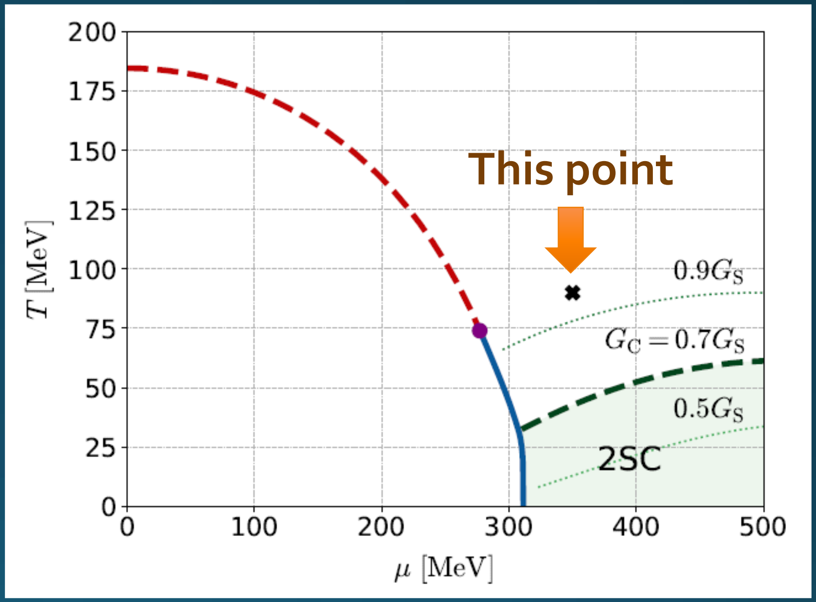
- Diquark fluctuations give rise to anomalous enhancement in the low energy-momentum region for $T < 1.5T_c$.

Invariant-Mass Spectrum

Fixed Temperature



$$\frac{d\Gamma}{dM^2} = \int \frac{d^3k}{2\omega} \frac{d^4\Gamma}{dk^4}\bigg|_{\omega=E_k}$$



- Strong enhancement at low invariant mass, though the range of M is narrower than the previous results.
- **Observable in the HIC?**

Nishimura, MK, Kunihiro, 2201.01963

Summary

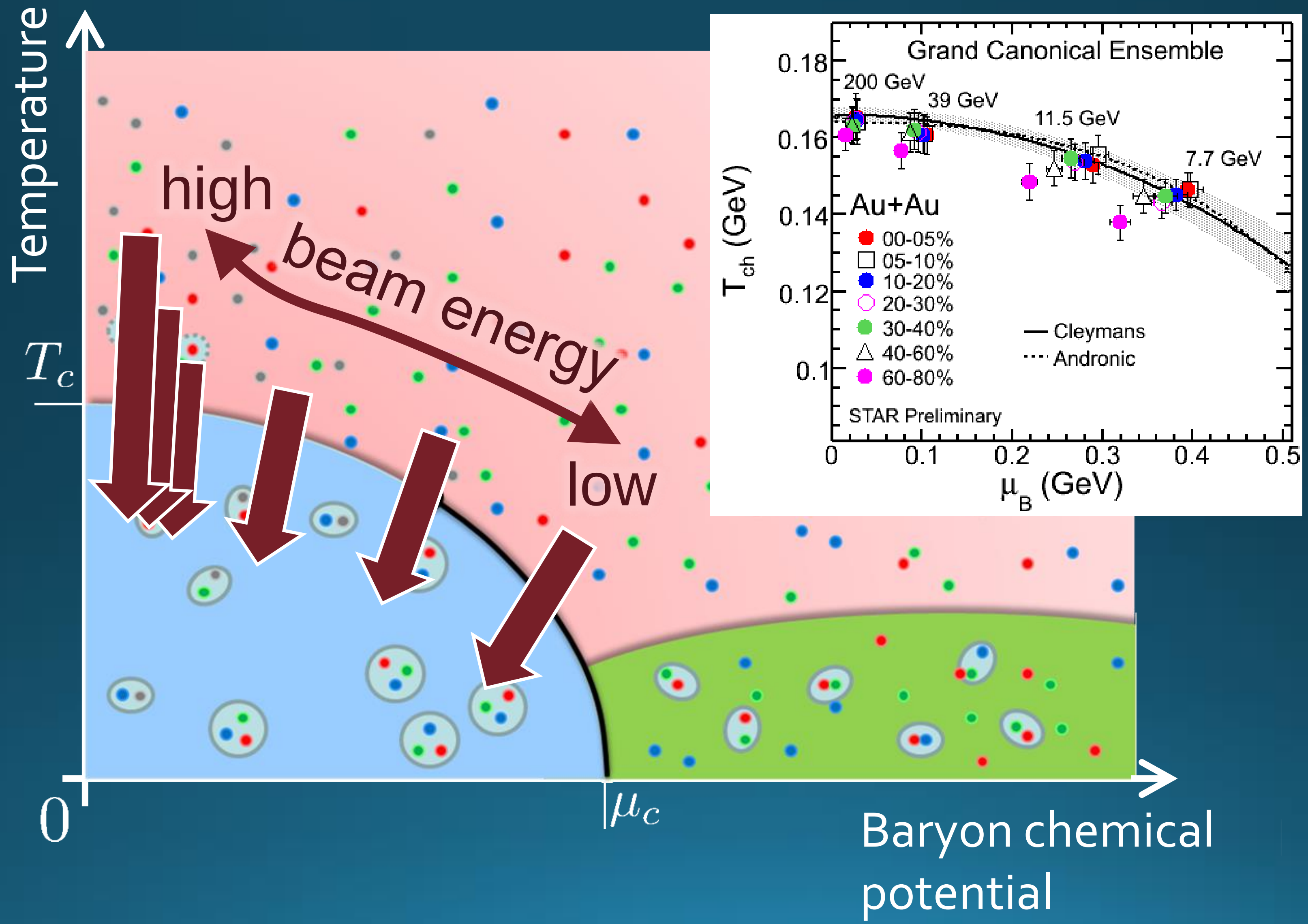
- Exploring dense medium in relativistic heavy-ion collisions is a hot topic in this field. The beam-energy scan is ongoing, and many new experiments will start in near future!

- Among them, search for
  - the QCD critical point using fluctuation observables
  - the color superconductivity using dileptons

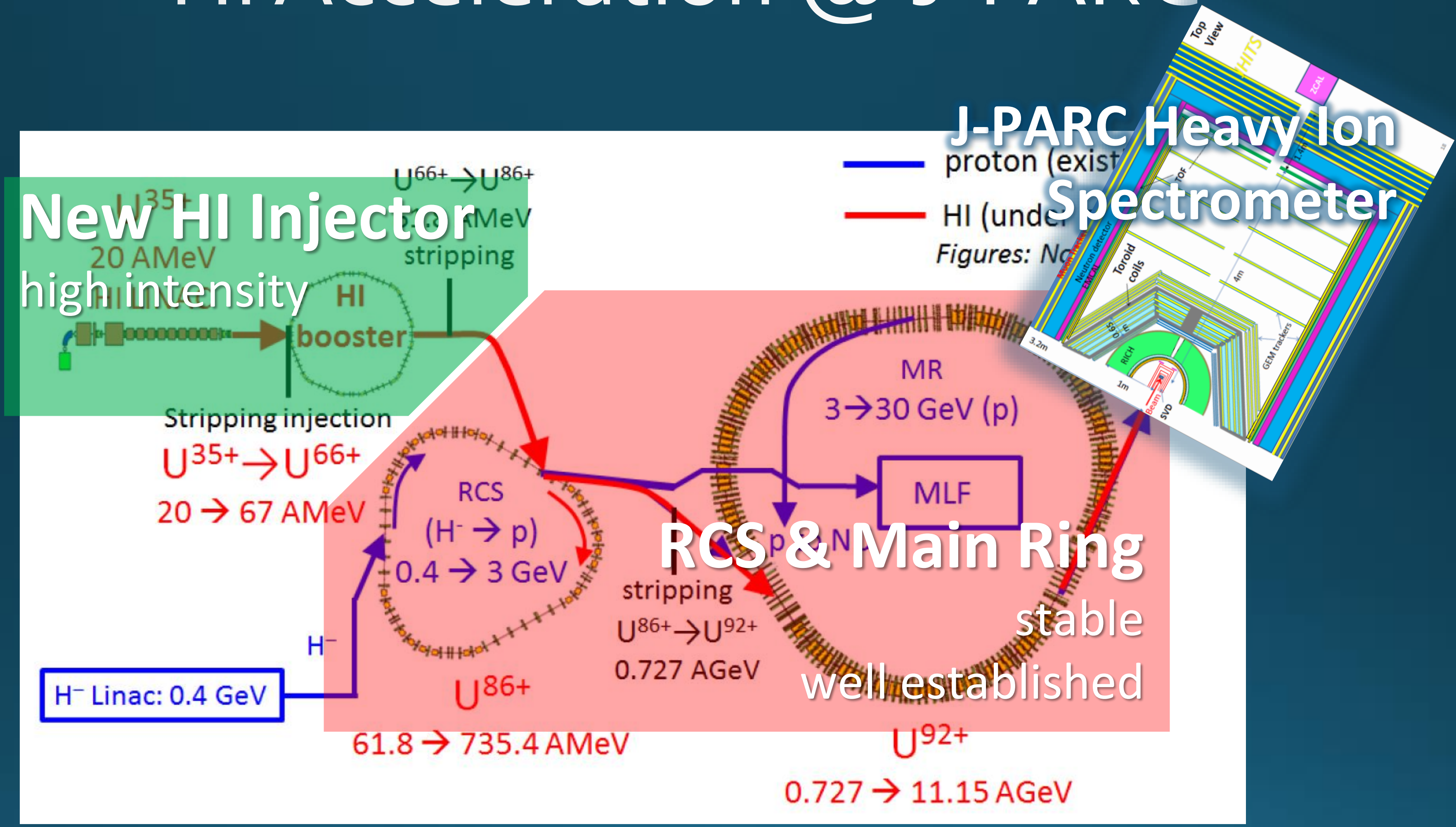
  are especially interesting and important subjects.

- Heavy-ion collisions at J-PARC will play important roles in pursuing these subjects.

Beam-Energy Scan



HI Acceleration @ J-PARC



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