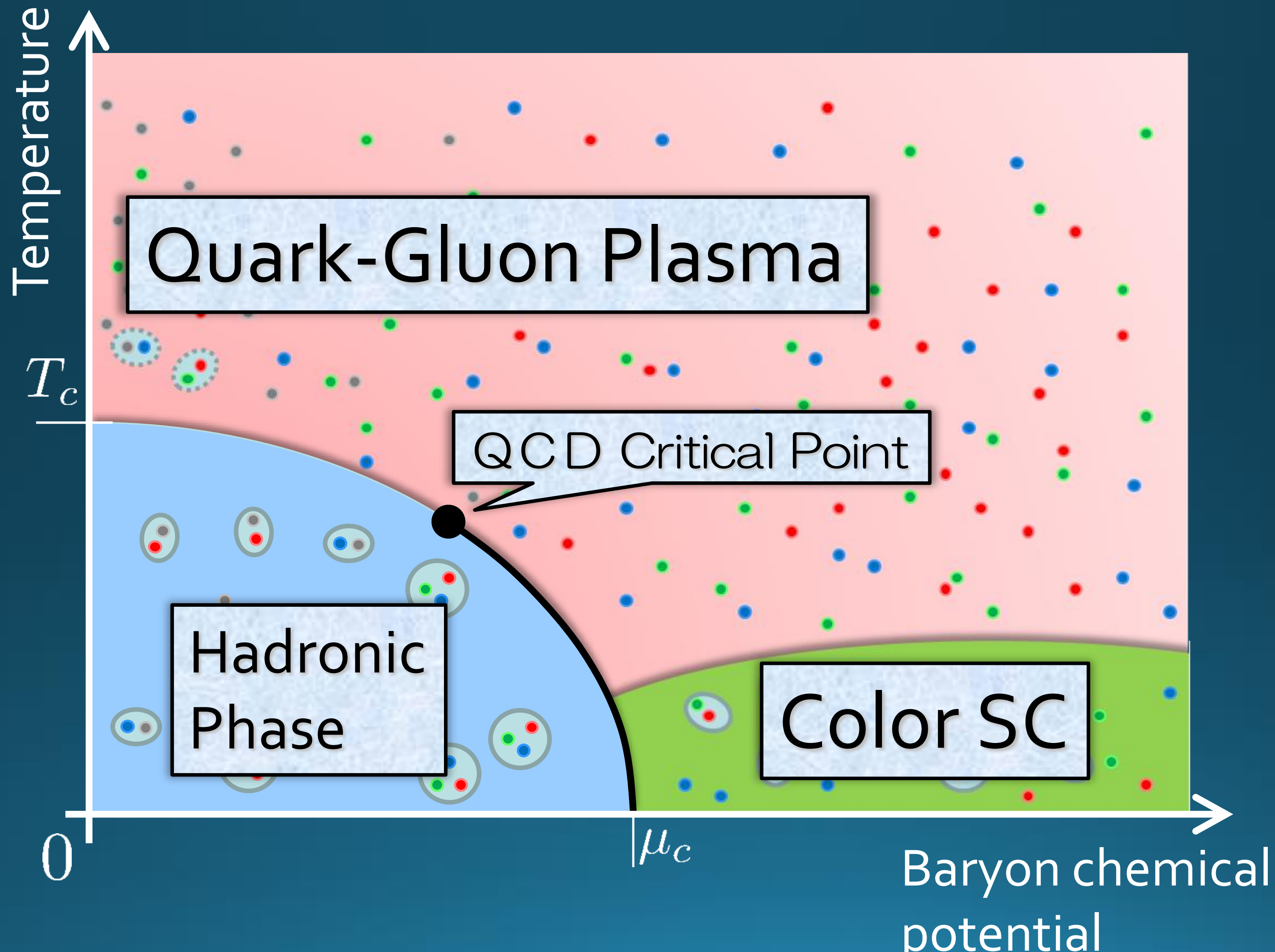
Theoretical Study of QGP and Phase Transition in RHIC

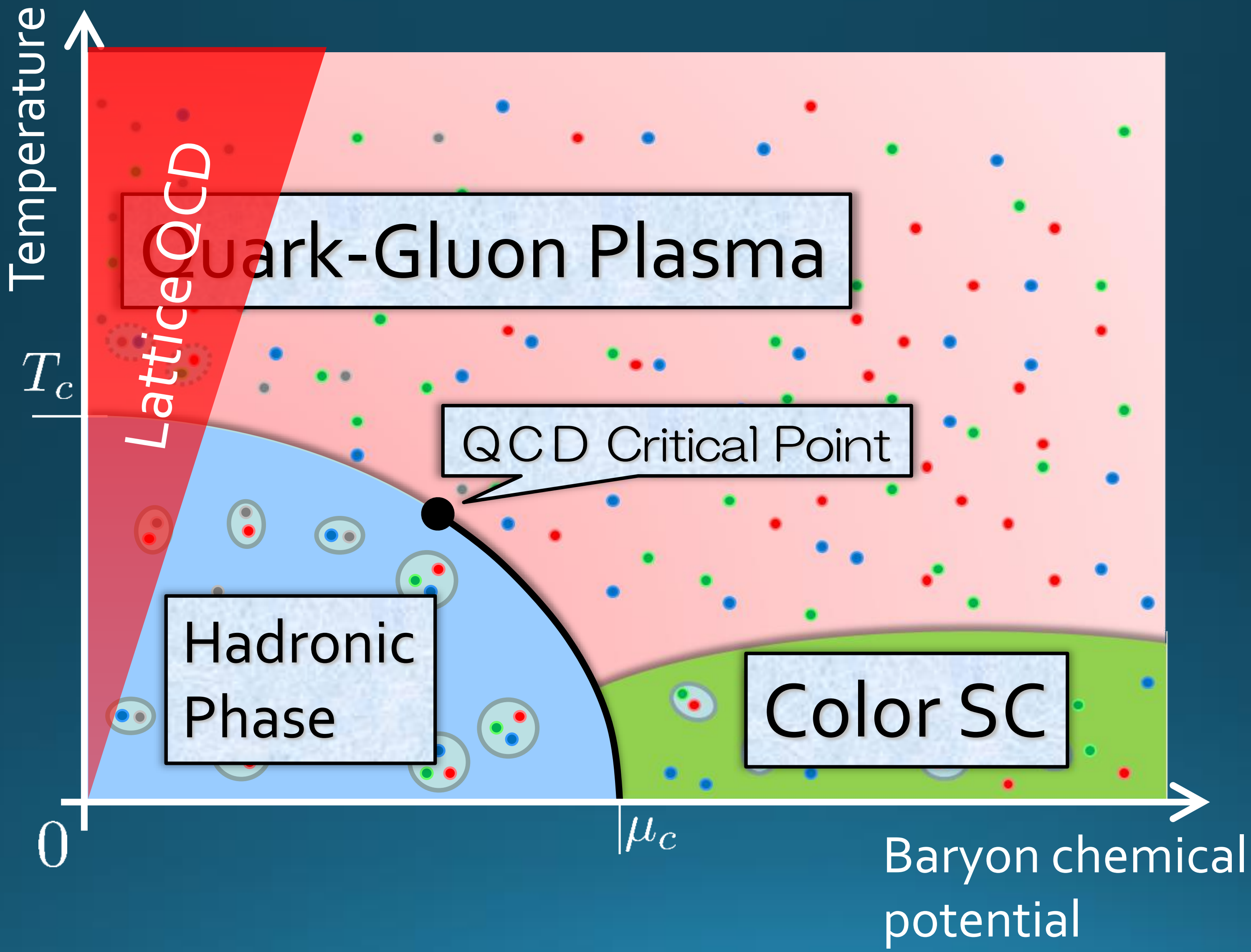
Masakiyo Kitazawa
(Osaka U.)

14th ANPhA Board meeting and Symposium in Korea
Seogwipo KAL Hotel, Korea, 27/June/2019

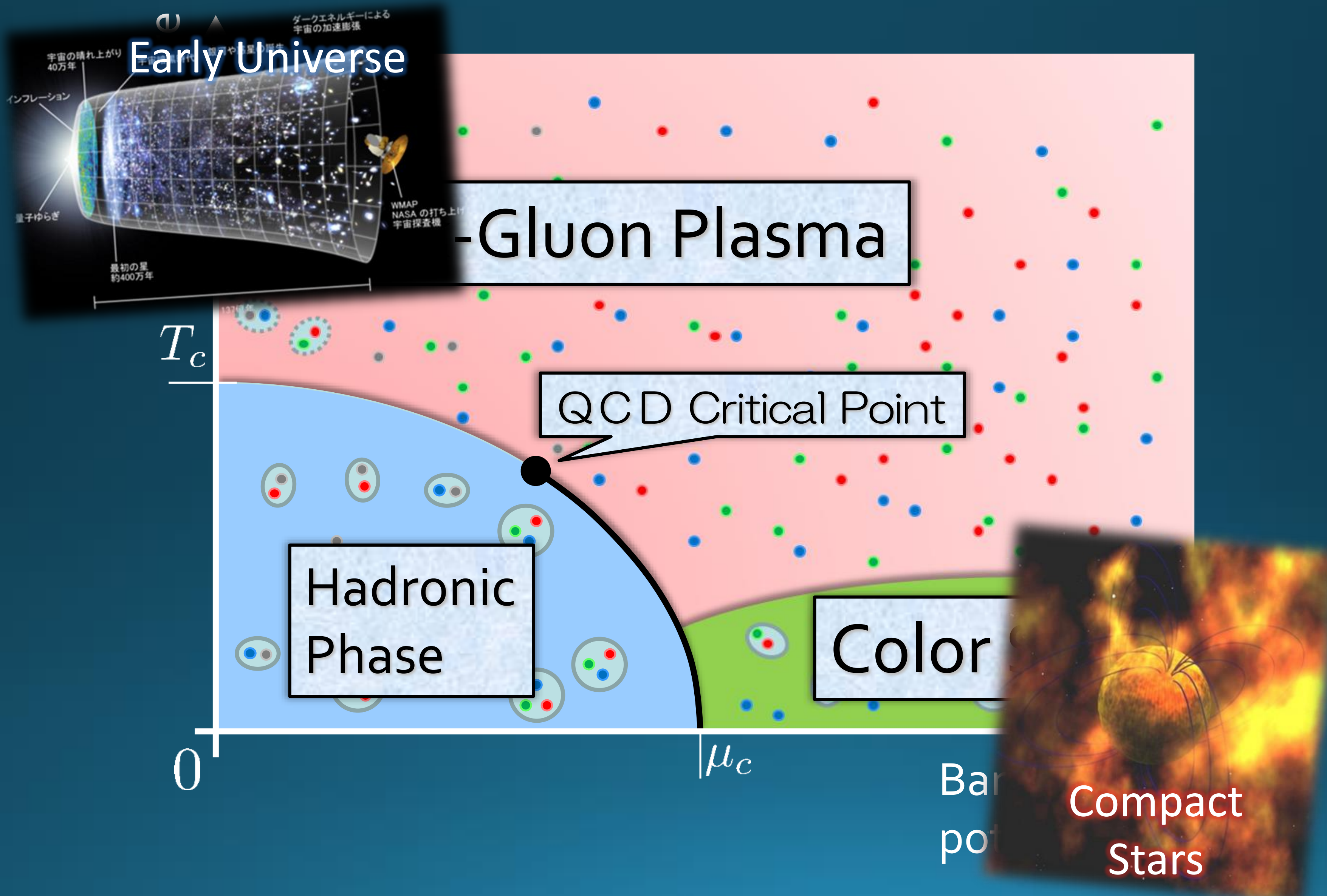
QCD Phase Diagram



QCD Phase Diagram

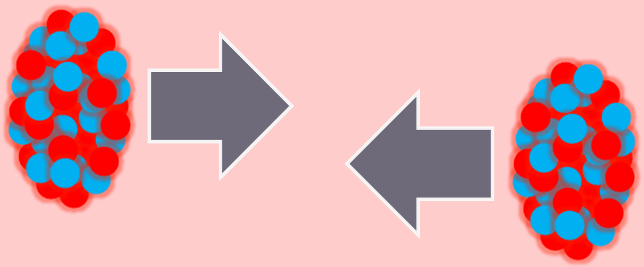


QCD Phase Diagram



Relativistic Heavy-Ion Collisions

Collide 2 heavy nuclei



Physics

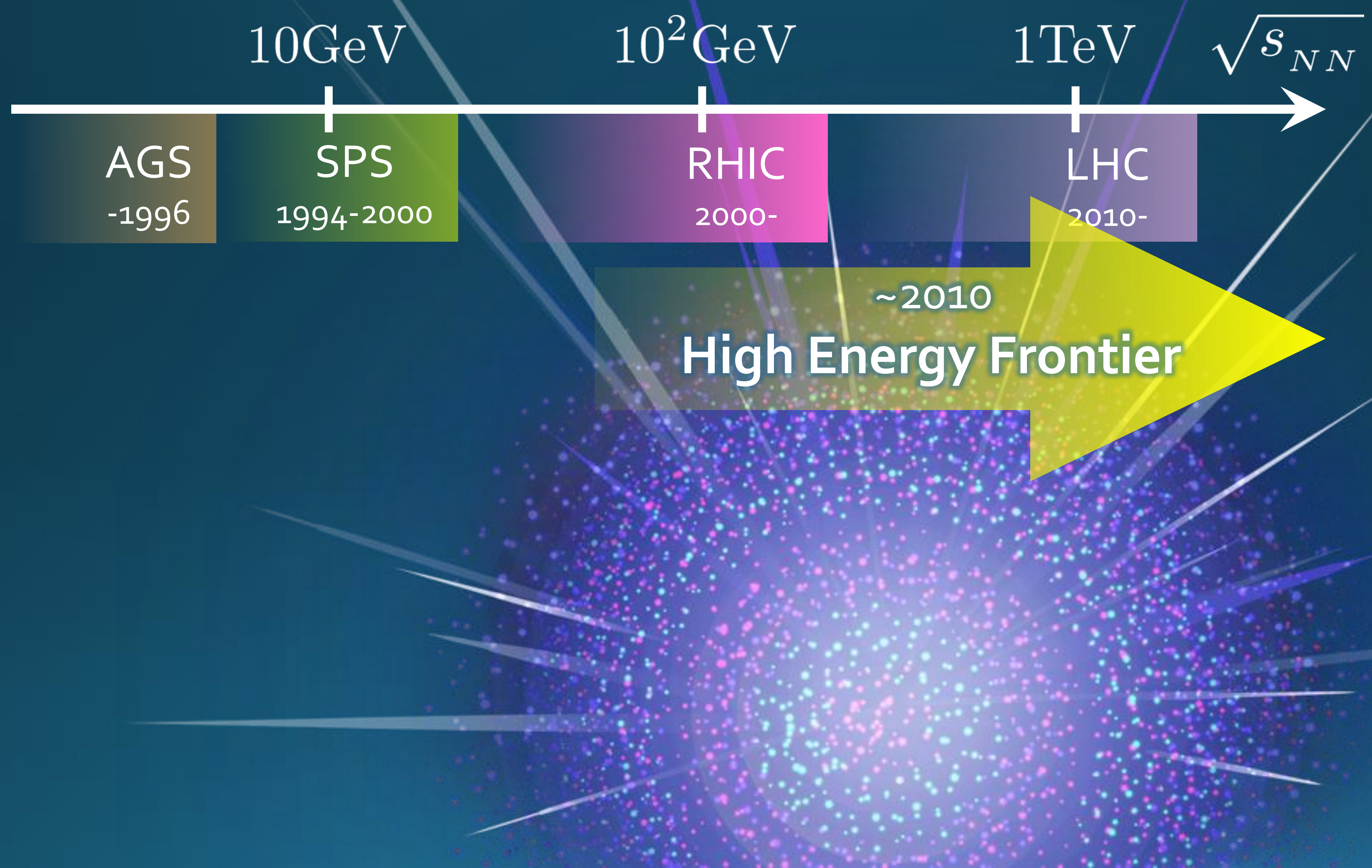
- ☐ Hot & dense medium
- ☐ Early Universe
- ☐ Quark-gluon plasma
- ☐ QCD phase structre

RHIC (2000~)
QGP Formation
Strongly coupled QGP

LHC (2010~)
Precision measurement of the QGP

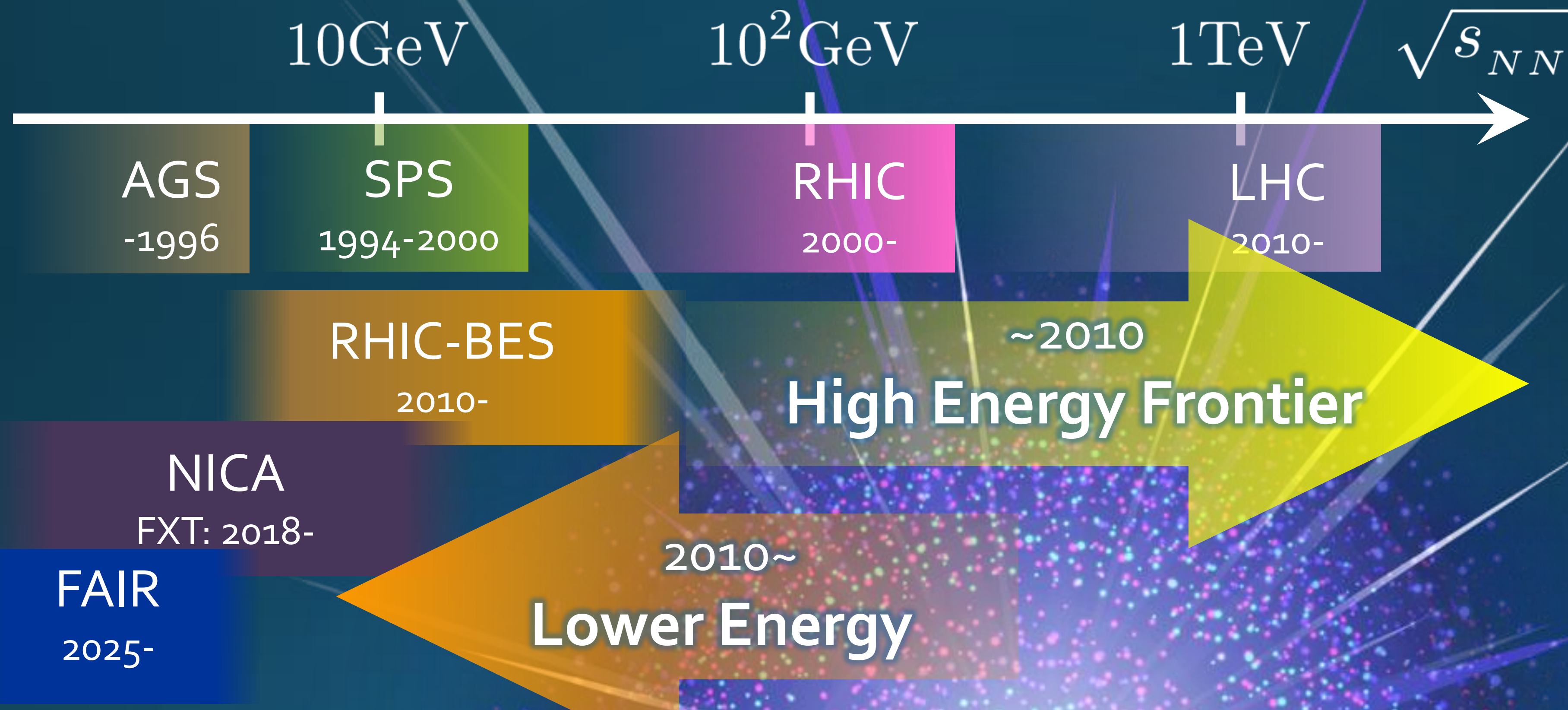
Picture of fireball by Soushi Nonaka

Brief History of Relativistic HIC



Picture of fireball by Soushi Nonaka

Brief History of Relativistic HIC

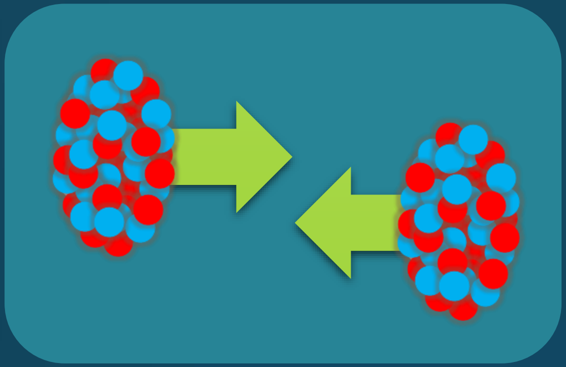


Interaction rate

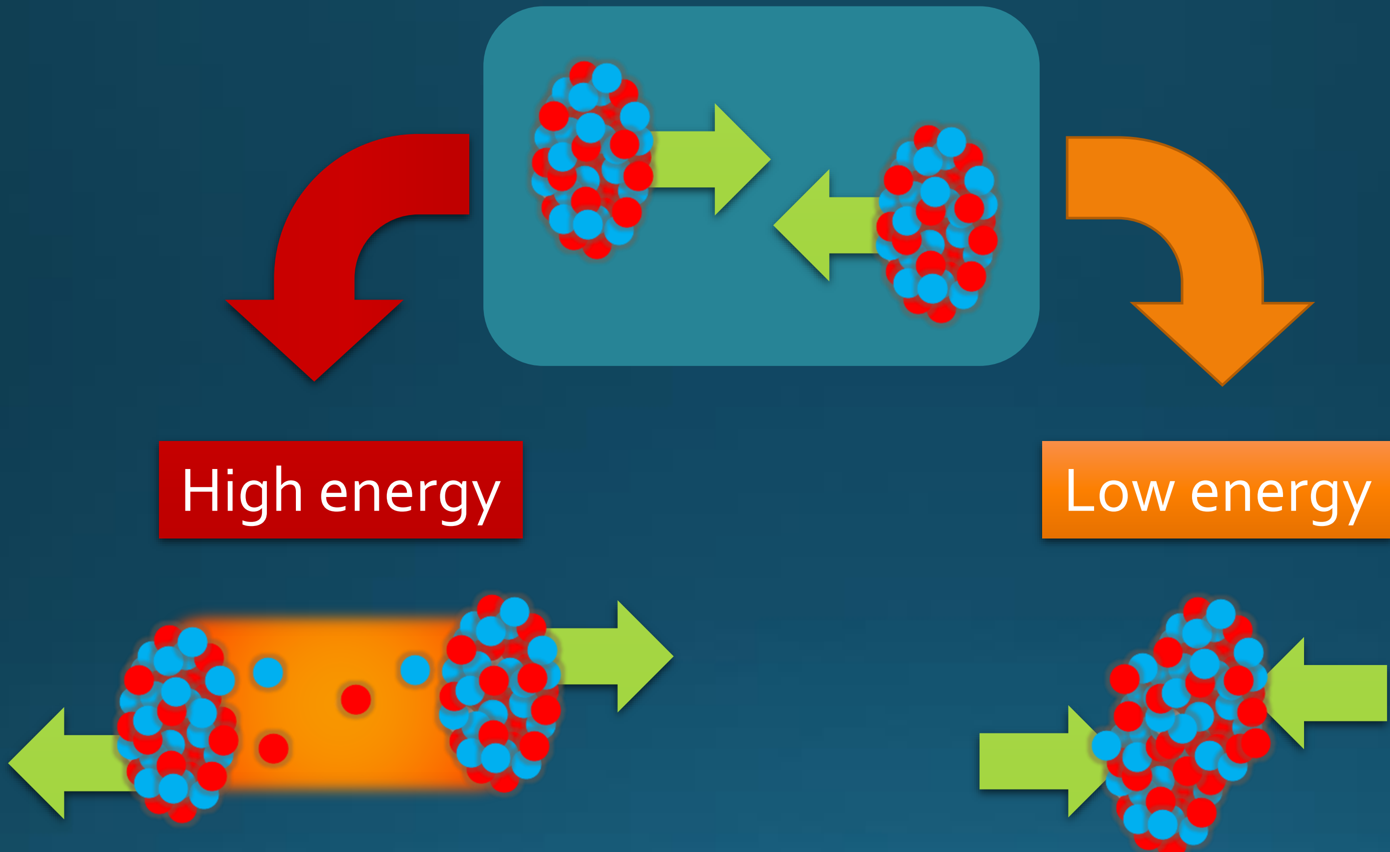
- ☐ **FAIR, J-PARC-HI: ~10^7 Hz**
- ☐ AGS, SPS: ~10^2 Hz

Picture of fireball by Soushi Nonaka

Beam-Energy Dependence



Beam-Energy Dependence



Nuclear transparency

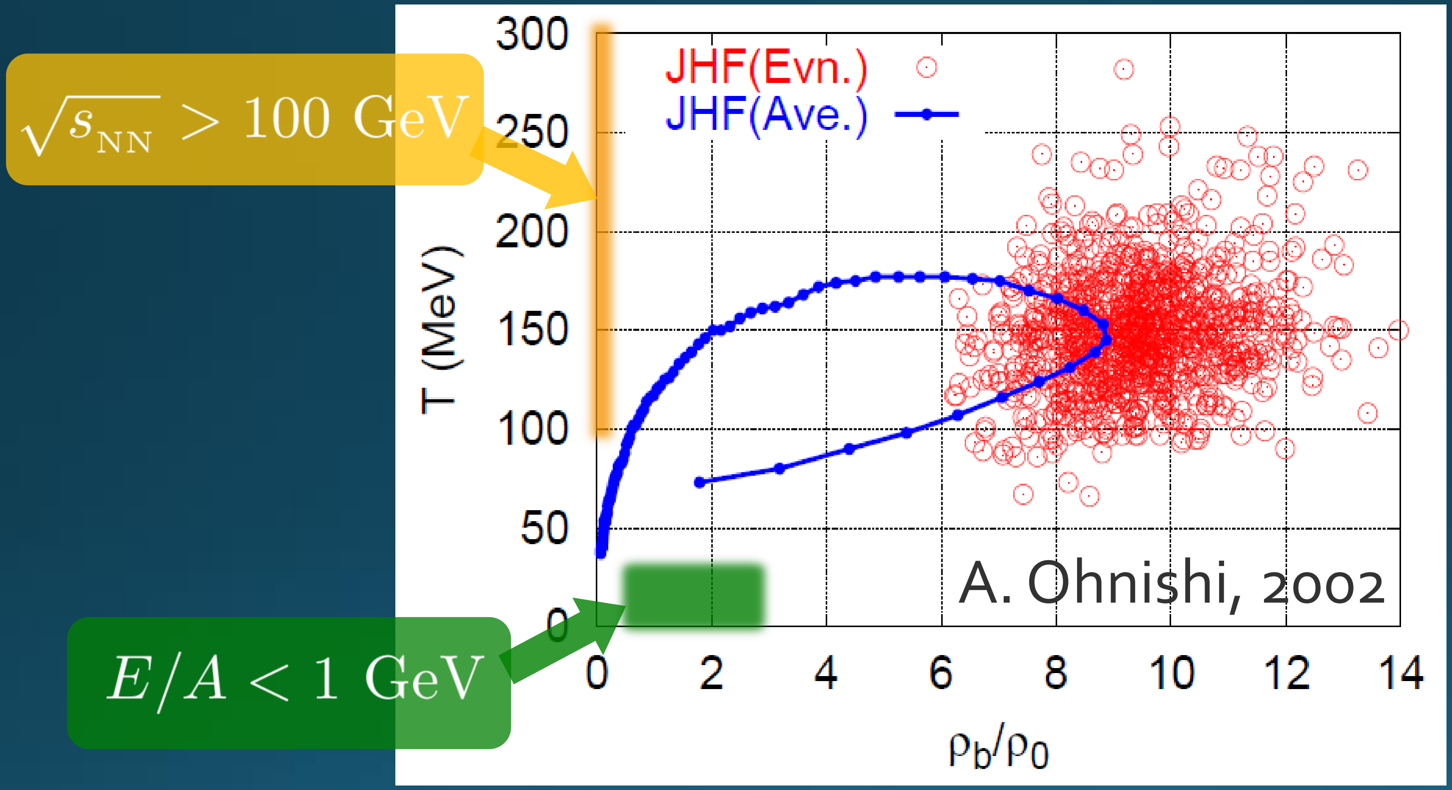
net-baryon #: small

Baryon stopping

net-baryon #: large

Maximum Density

Time evolution in *T*-ρ plane by JAM

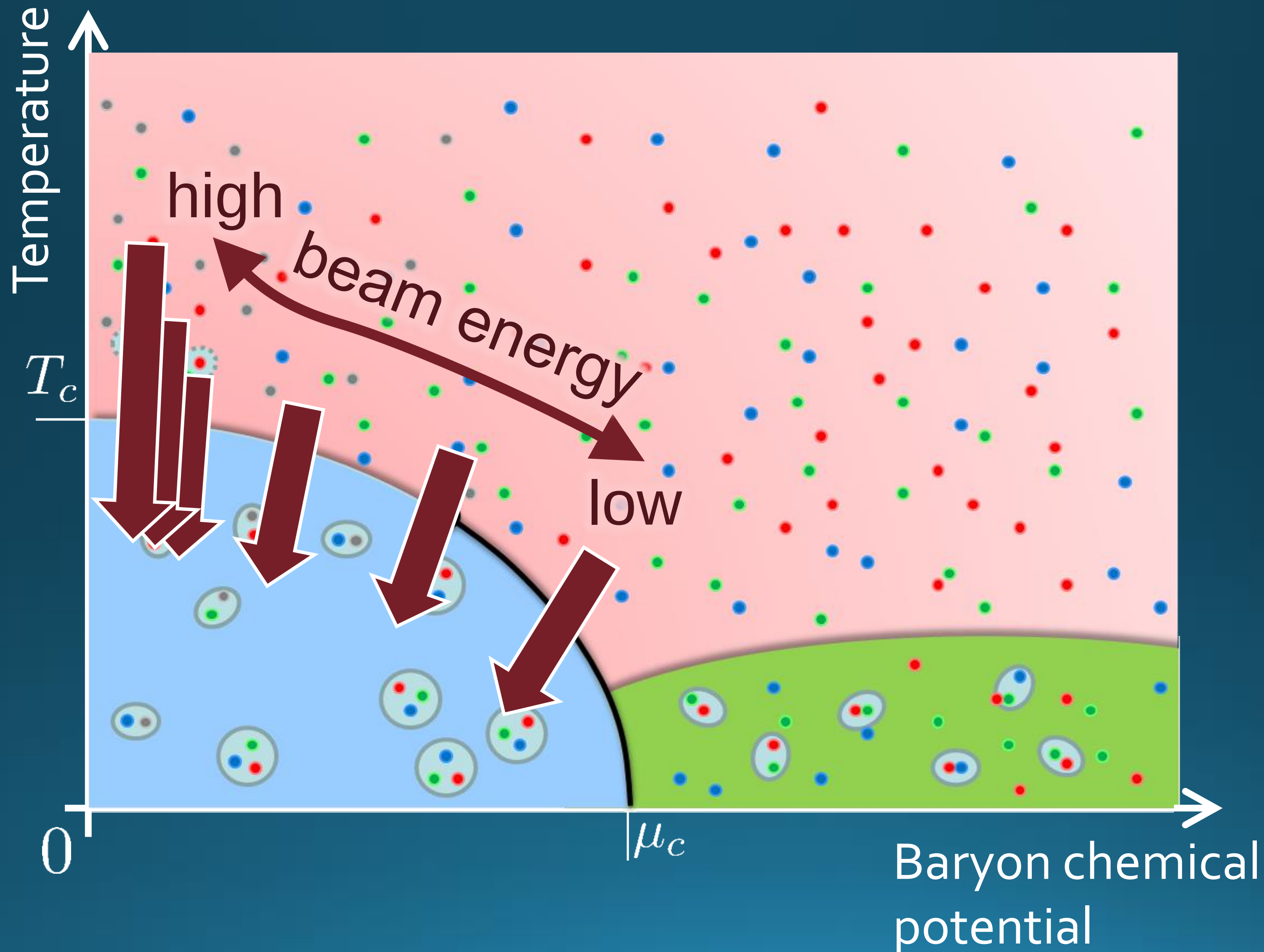


$E/A = 20\mathrm{GeV}$

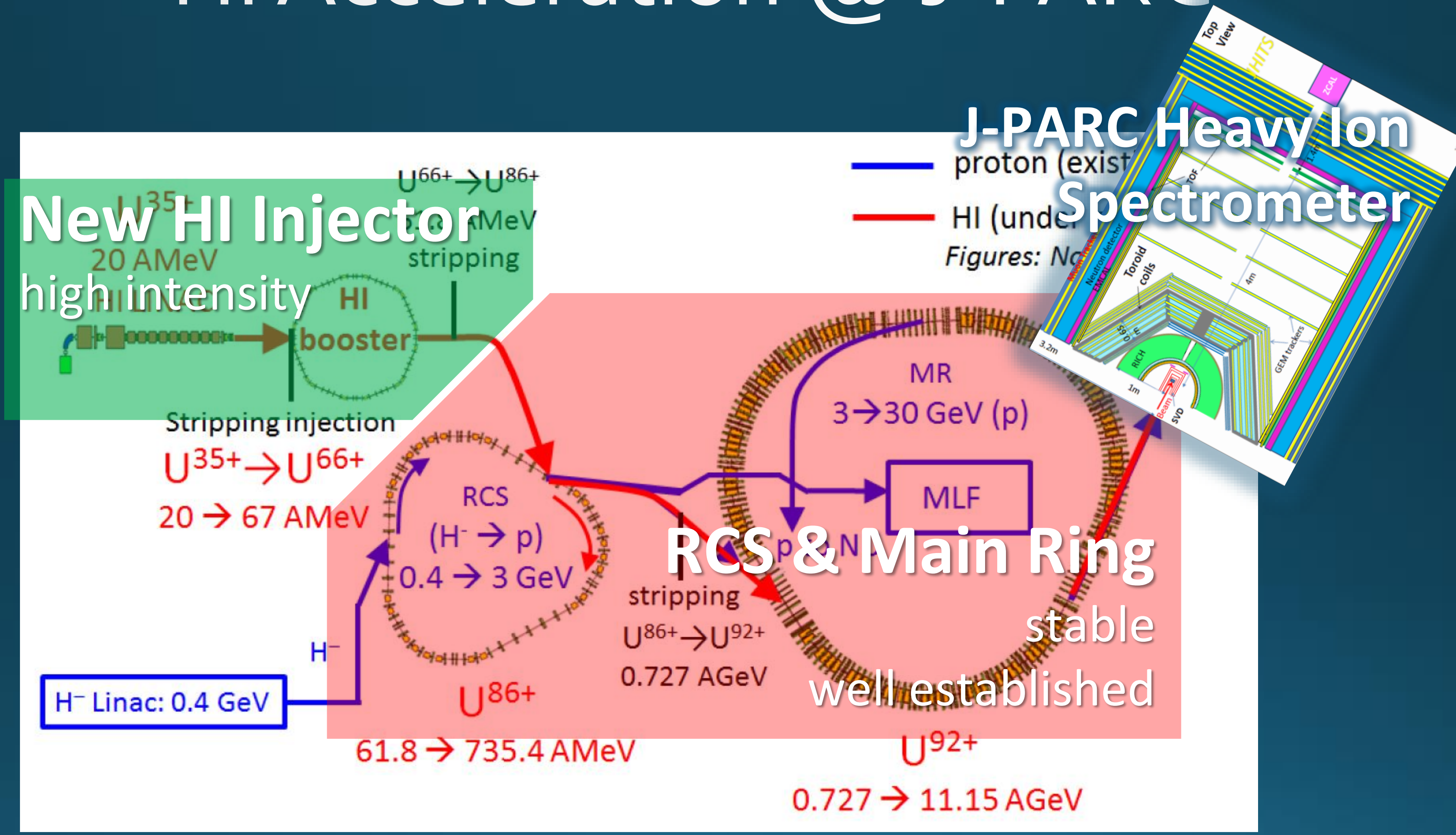
$\sqrt{s_{NN}} \simeq 6\mathrm{GeV}$

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

Beam-Energy Scan

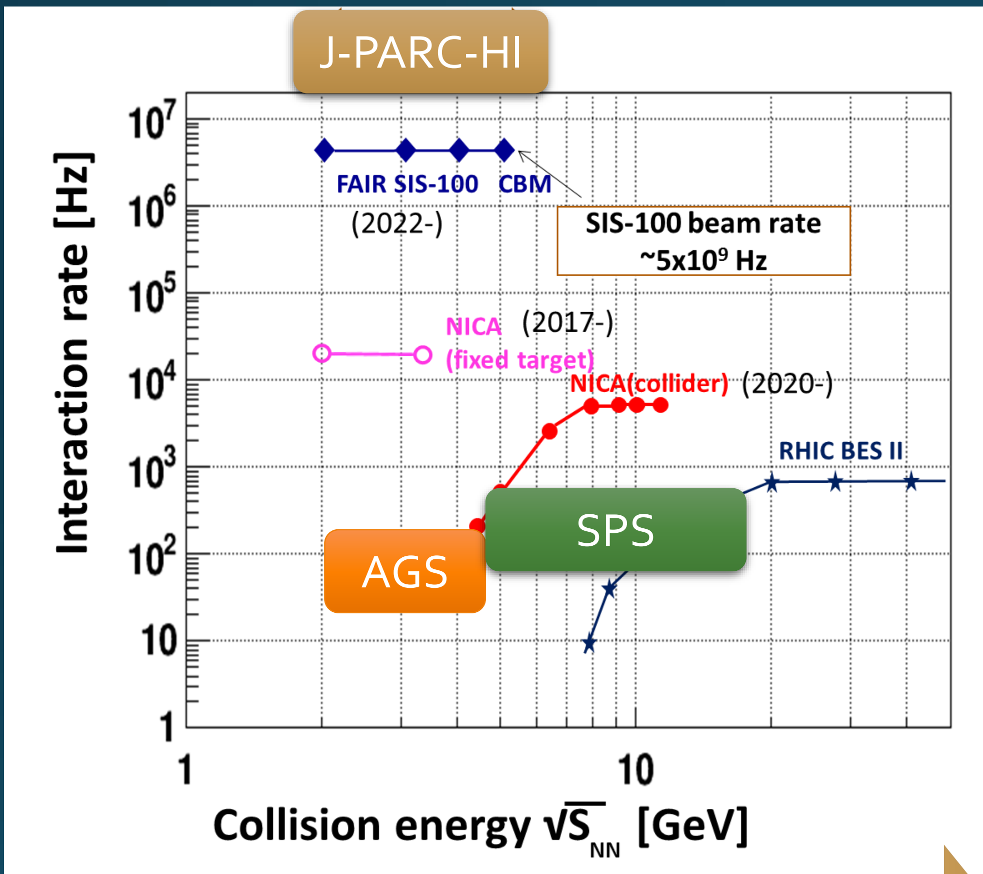


HI Acceleration @ J-PARC



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

Collision Rate



J-PARC-HI:

High-luminosity X Fixed target

→World highest rate～10^8Hz

5-order higher than AGS,SPS

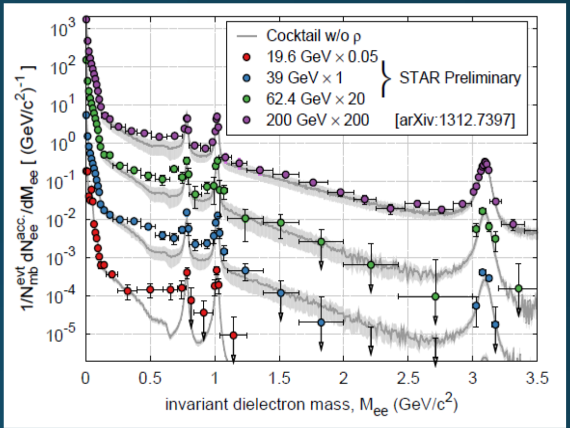
AGS, SPS 1 year	=	J-PARC-HI 5 min.

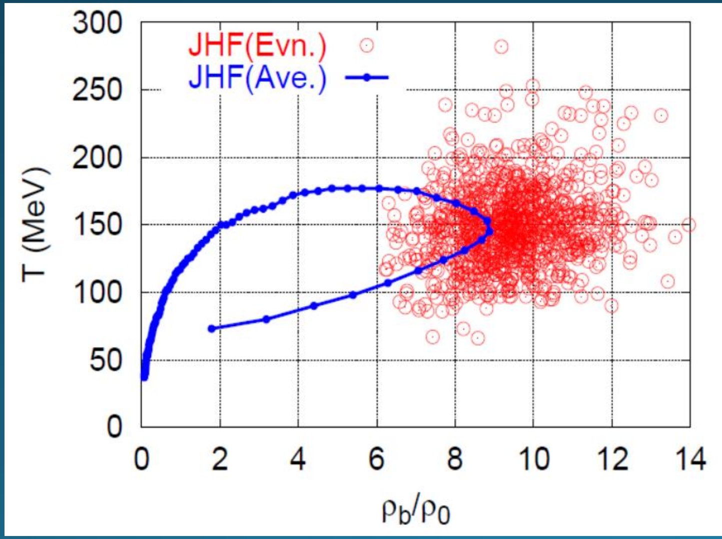
- ☐ High-statistical exp.
- ☐ various event selections
- ☐ higher order correlations
- ☐ search of rare events

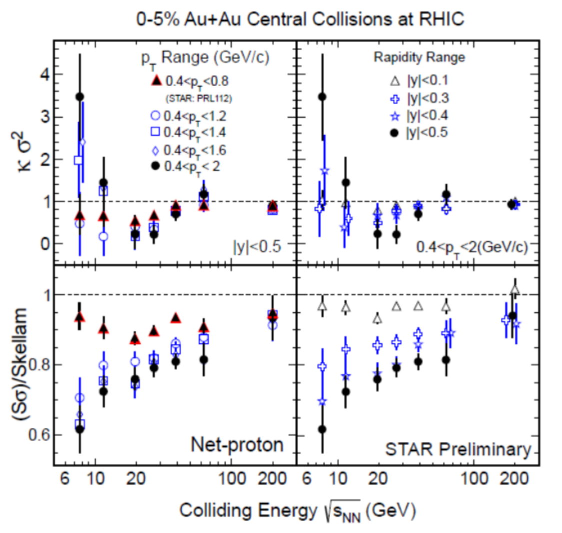
Various Observables

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

- Sophisticated event selections
- Various correlations

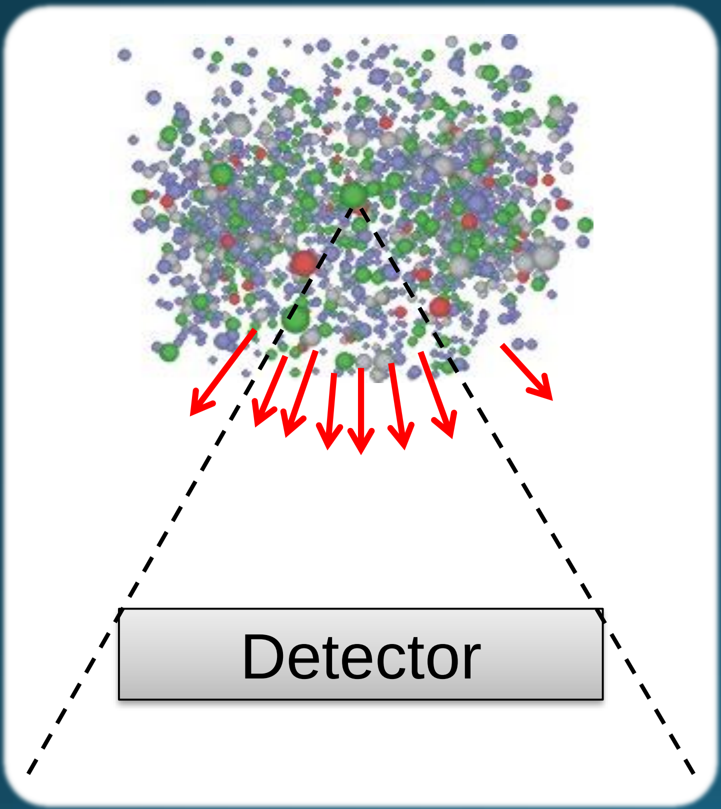




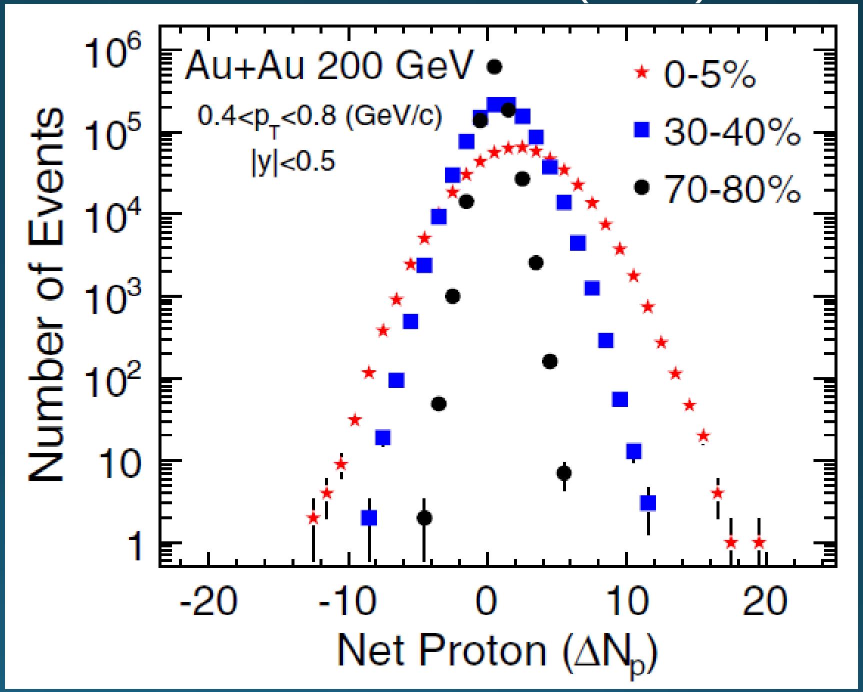


Event-by-Event Fluctuations

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



STAR, PRL**105** (2010)



Cumulants

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

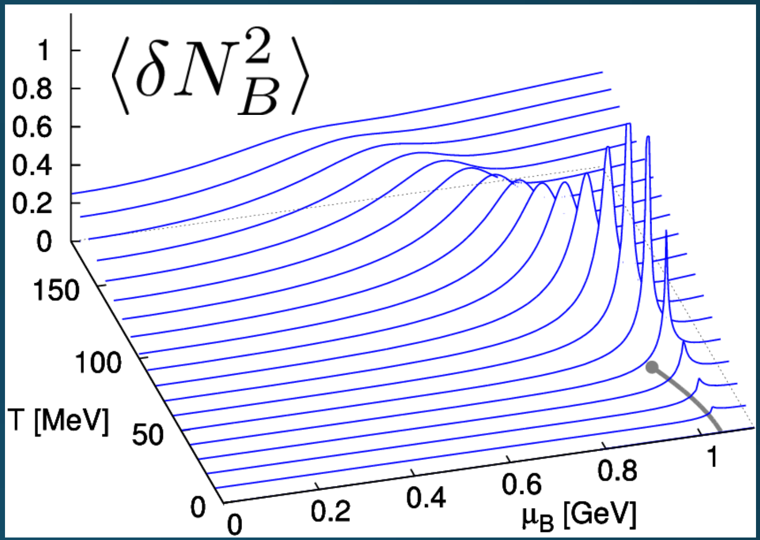
Non-Gaussian Cumulants

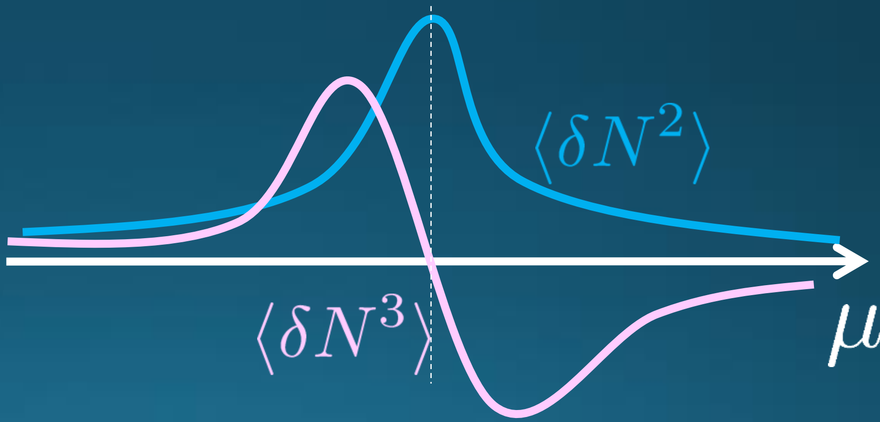
Gaussian fluctuations diverge at the QCD-CP

- Higher order cumulants change sign at the phase boundary

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

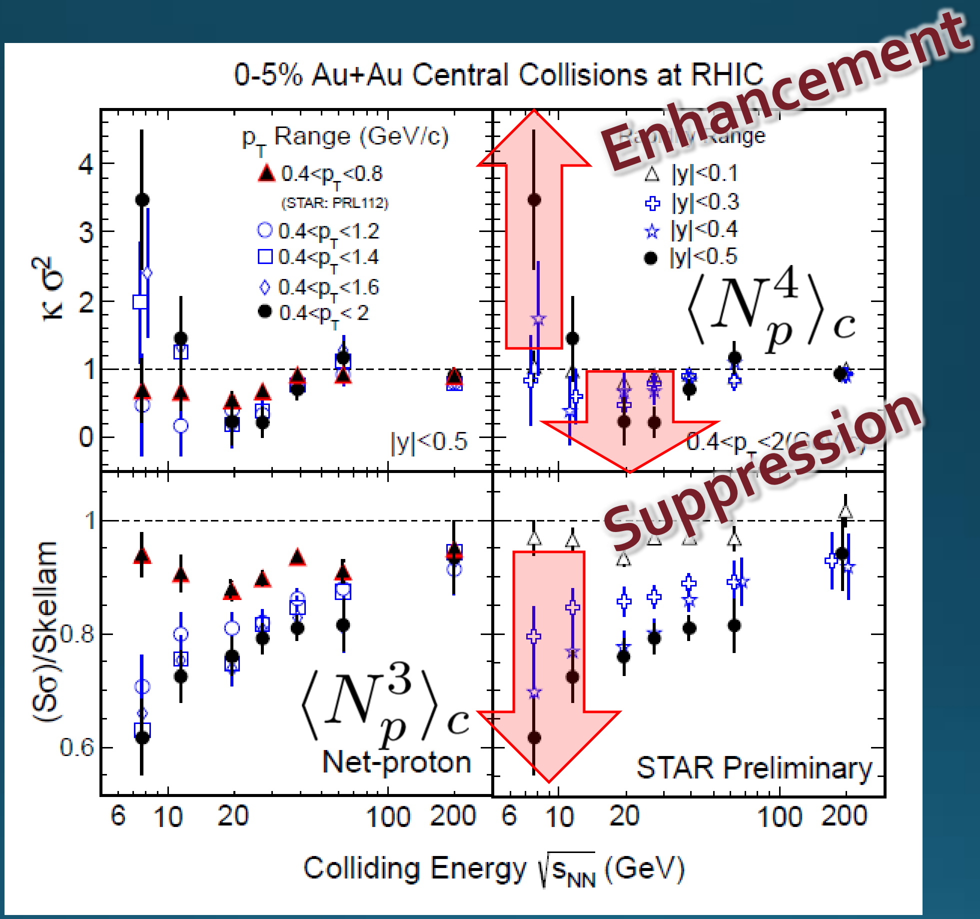
Asakawa, Ejiri, MK, 2009





- Steeper divergence for higher-order cumulants Stephanov, 2009

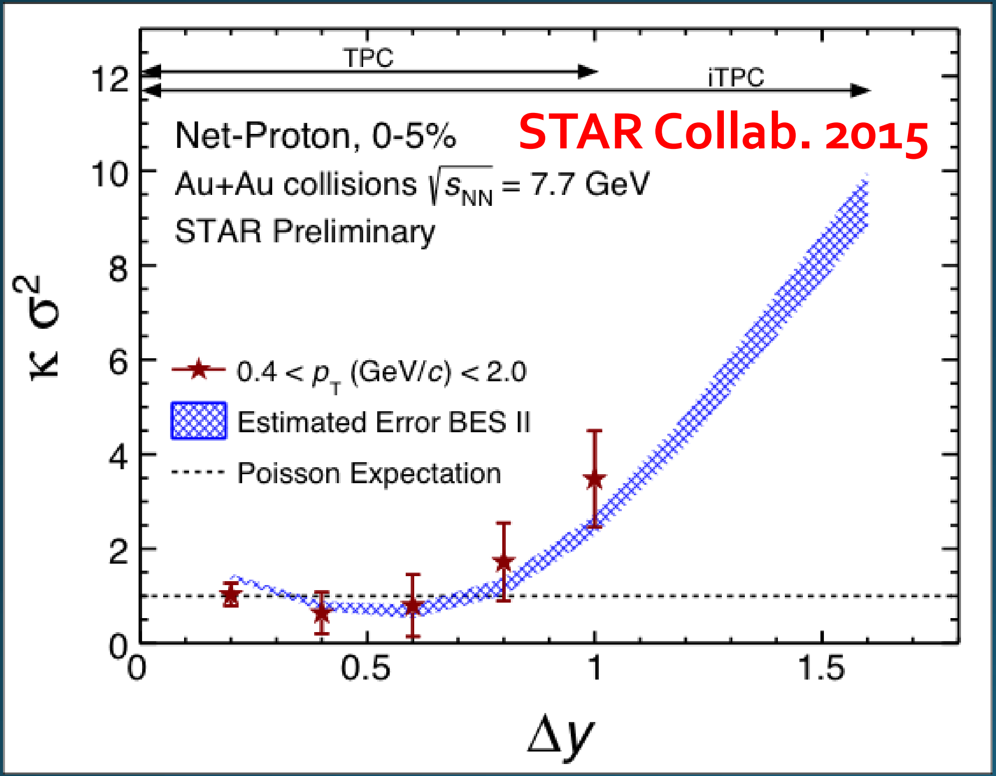
Experimental Results

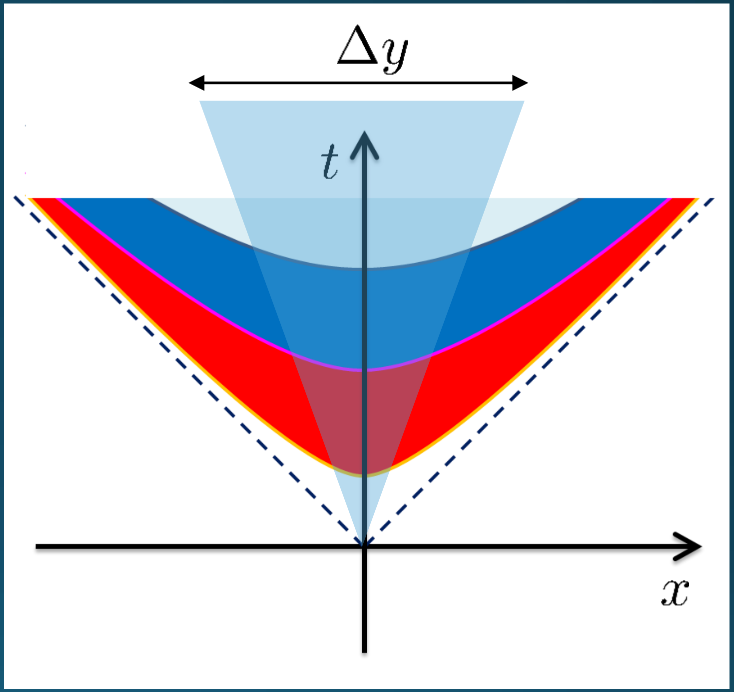


STAR Collab.
2010~

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

Rapidity Window Dependence

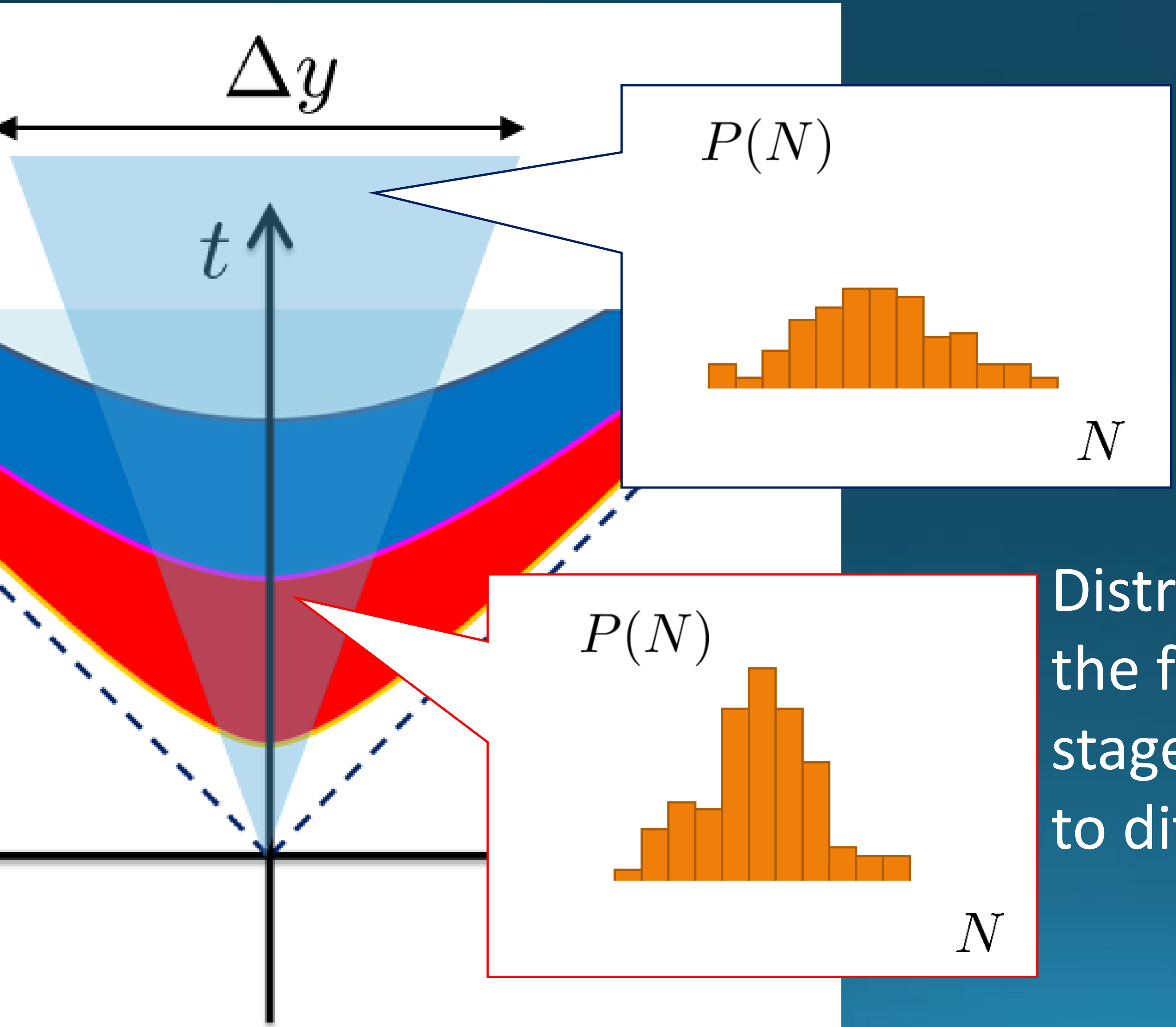




- ☐ Non-Gaussian Cumulants have been observed as a function of rapidity window Δy.
- ☐ Some results have non-monotonic Δy dependence.

Diffusion of Fluctuations

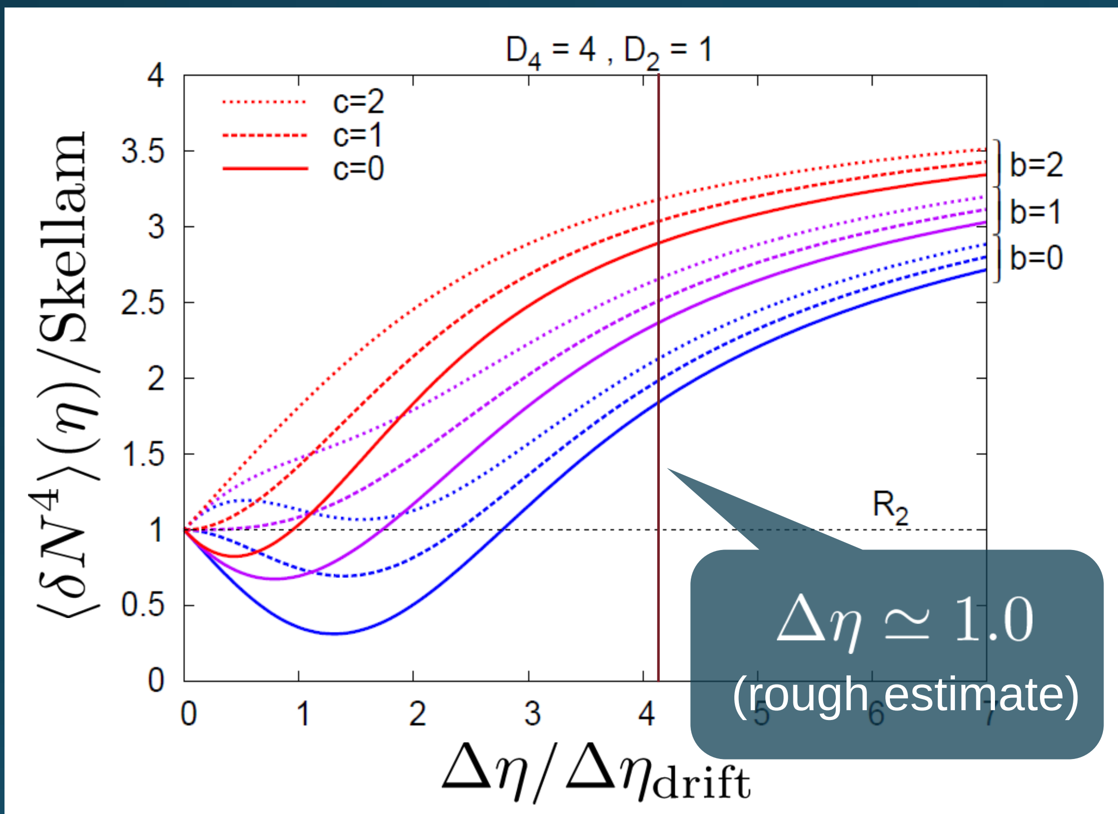
MK, Ohno, Asakawa 2014
MK 2015



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

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

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

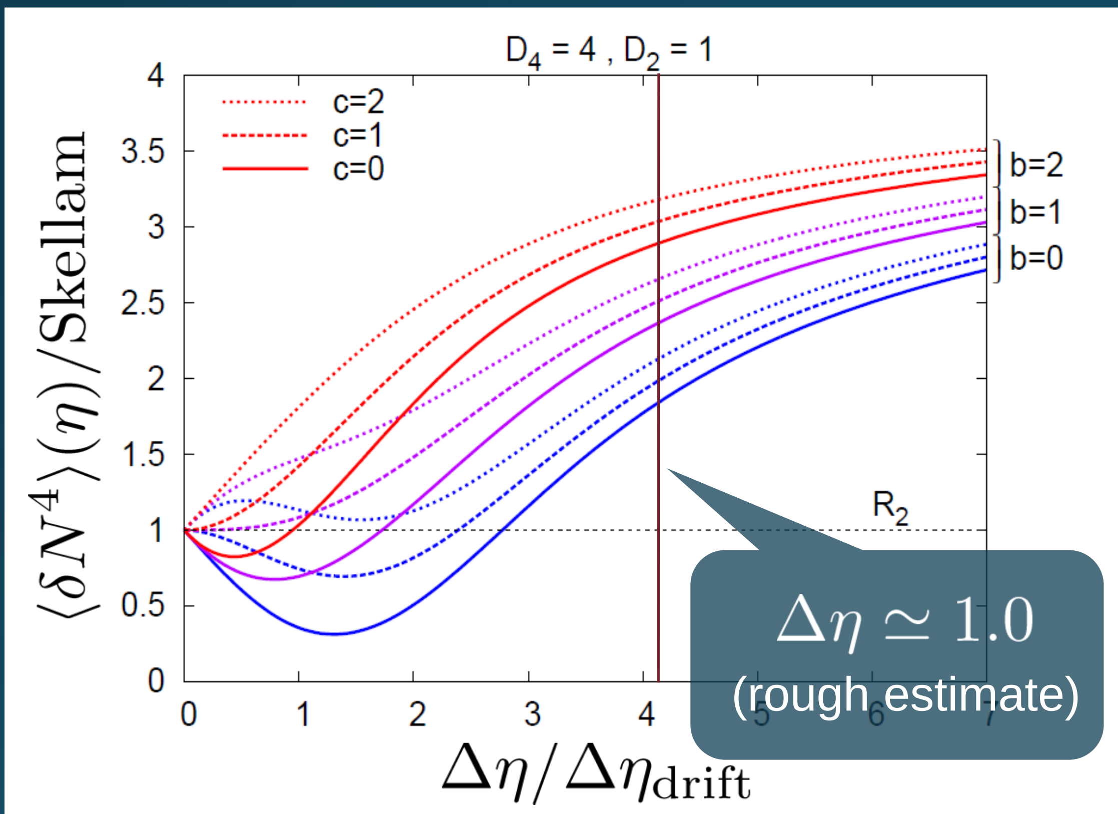
$$b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})}\rangle_c}{\langle Q_{(\mathrm{net})}\rangle}$$

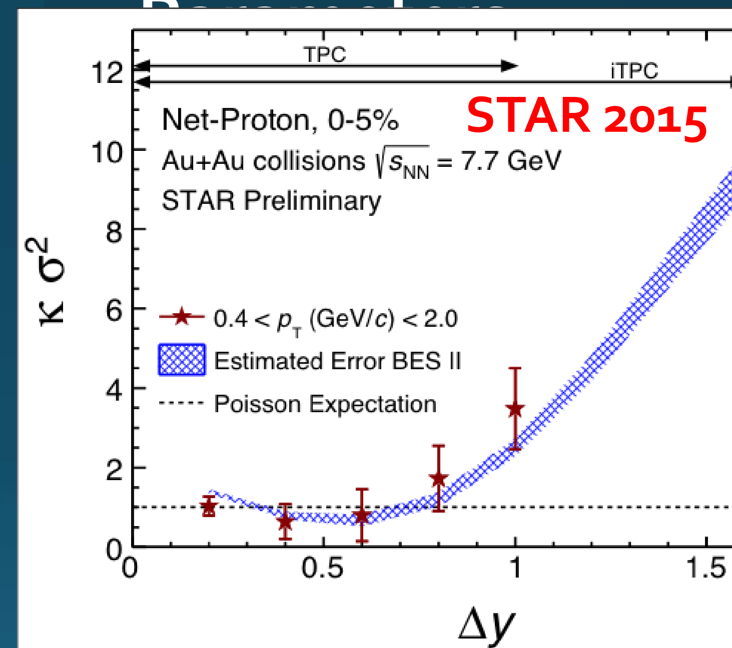
$$c = \frac{\langle Q^2_{(\mathrm{tot})}\rangle_c}{\langle Q_{(\mathrm{tot})}\rangle}$$

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

Rapidity Window dependence
as a Result of Diffusion

MK+ (2014); MK (2015)



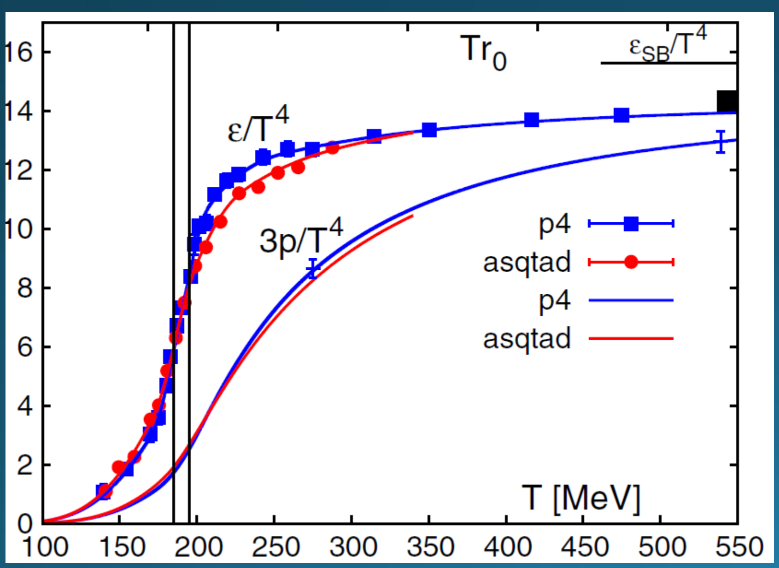


- ☐ Higher order cumulants can behave non-monotonically.
- ☐ Δη dependence encodes history of time evolution.

Numerical Experiments

Lattice QCD simulations on supercomputers

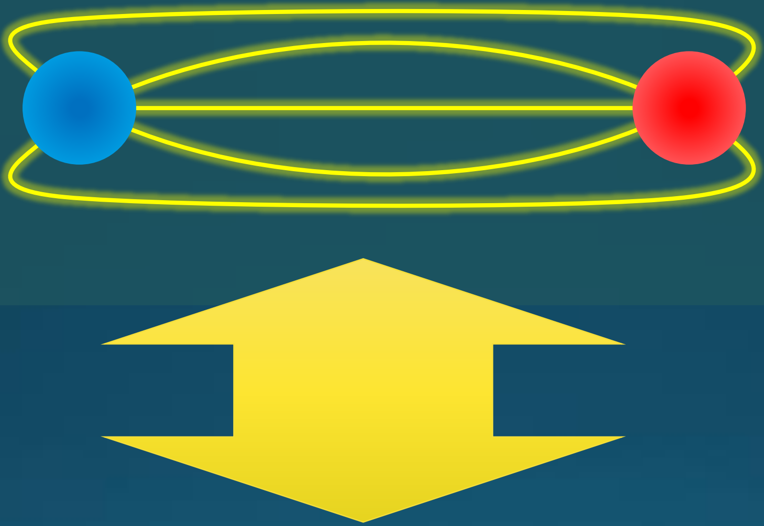
☐ Example: Equation of State



Important inputs for understanding the experimental data in heavy-ion collisions

Confinement / Deconfinement

Single quarks have never been observed.

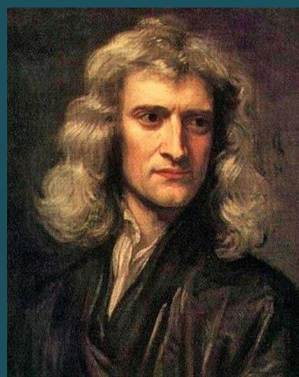


In QGP, liberated quarks are fundamental d.o.f.

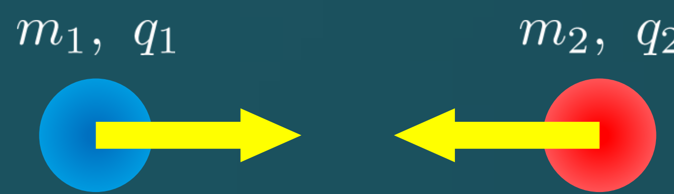
We explore local propagation of the confinement force

Force

Action-at-a-distance



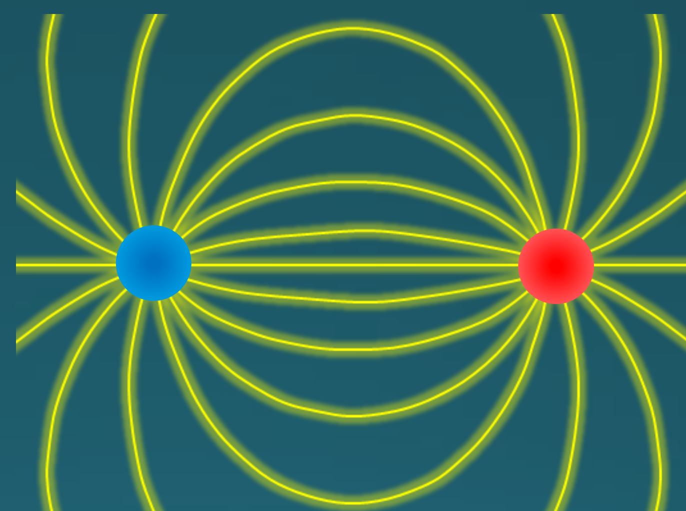
Newton
1687



$$F = -G\frac{m_1 m_2}{r^2} \qquad F = -\frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}$$

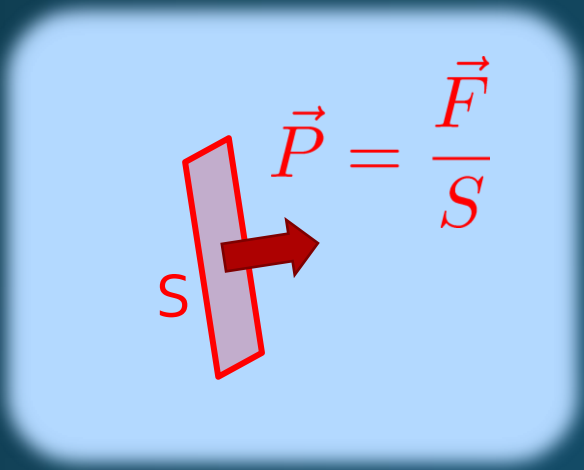
Local interaction

Faraday
1839



Stress = Force per Unit Area

Pressure

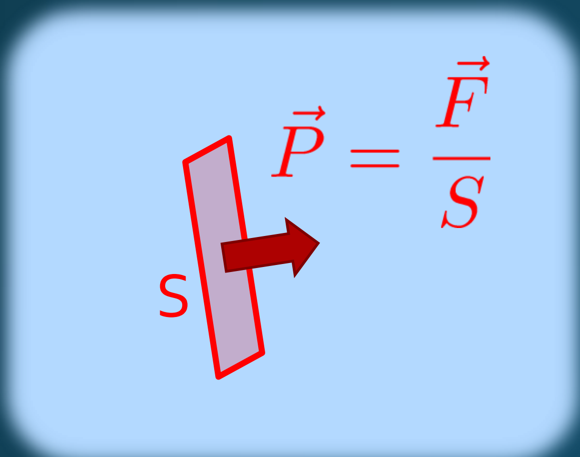


$$\vec{P} = \frac{\vec{F}}{S}$$

$$\vec{P} = P\vec{n}$$

Stress = Force per Unit Area

Pressure

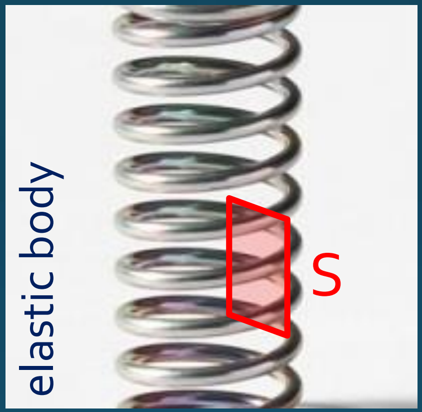


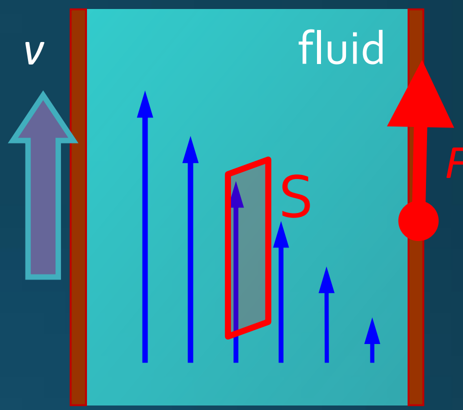
$$\vec{P} = P\vec{n}$$

In thermal medium

$$T_{ij} = P\delta_{ij}$$

Generally, F and n are not parallel





$$\frac{F_i}{S} = \sigma_{ij} n_j$$

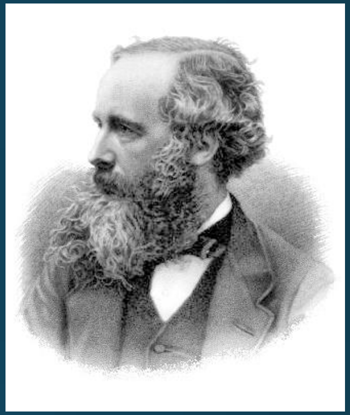
Stress Tensor

$$\sigma_{ij} = -T_{ij}$$

Landau
Lifshitz

Maxwell Stress
(in Maxwell Theory)

$$\sigma_{ij} = \varepsilon_0 E_i E_j + \frac{1}{\mu_0} B_i B_j - \frac{1}{2}\delta_{ij}\left(\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2\right)$$

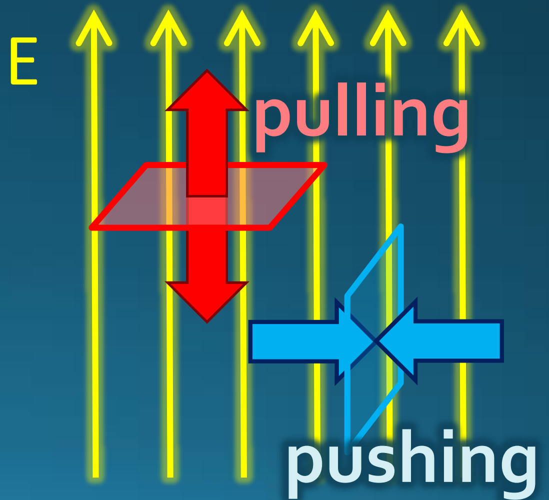


Maxwell

$$\vec{E} = (E, 0, 0)$$

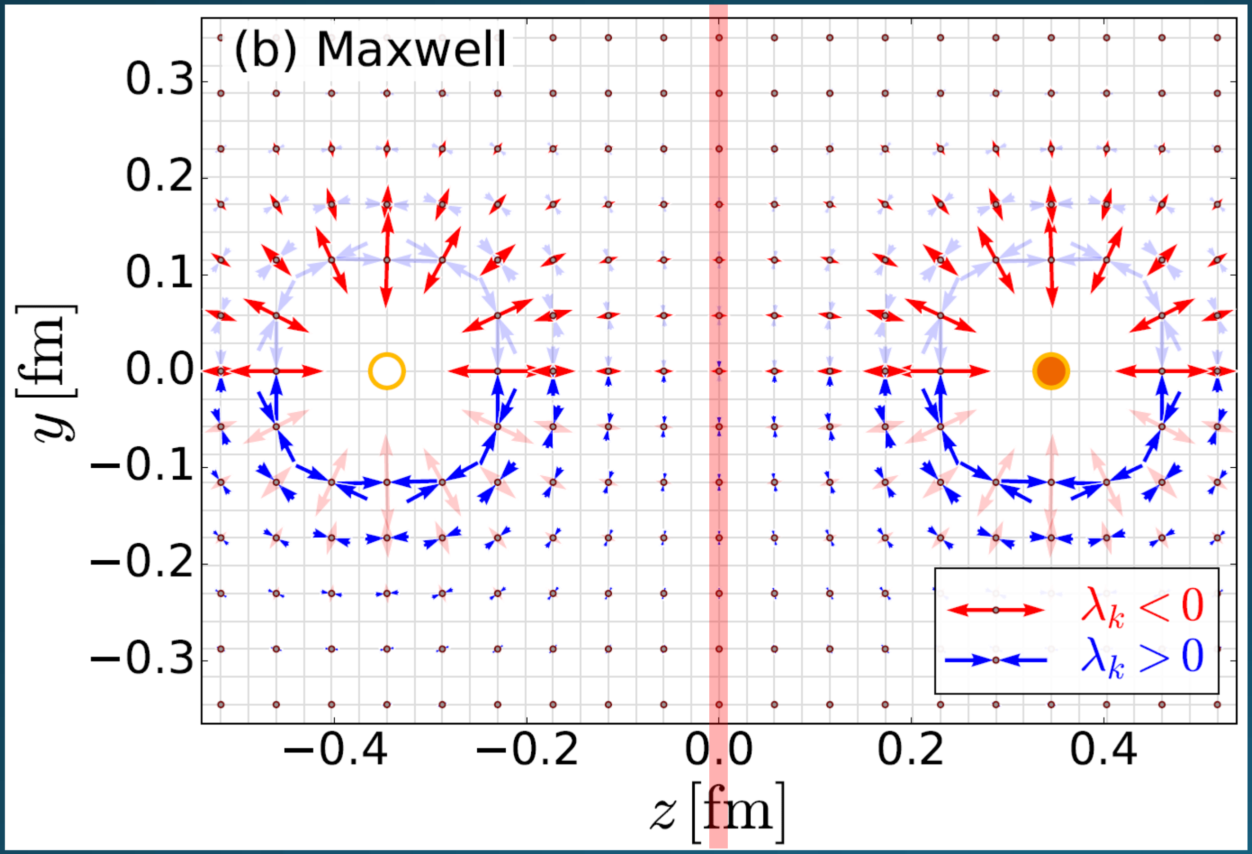
$$T_{ij} = \begin{pmatrix} -E^2 & 0 & 0 \\ 0 & E^2 & 0 \\ 0 & 0 & E^2 \end{pmatrix}$$

- Parallel to field: **Pulling**
- Vertical to field: **Pushing**



Maxwell Stress

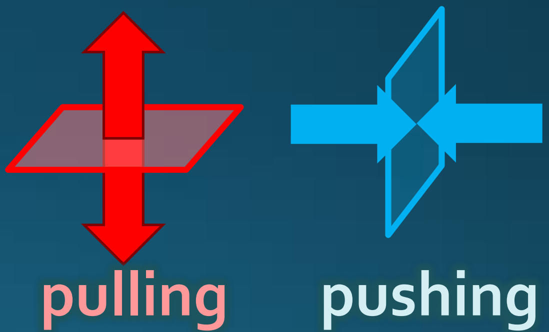
(in Maxwell Theory)



$$T_{ij} v_j^{(k)} = \lambda_k v_i^{(k)}$$

$$(k = 1, 2, 3)$$

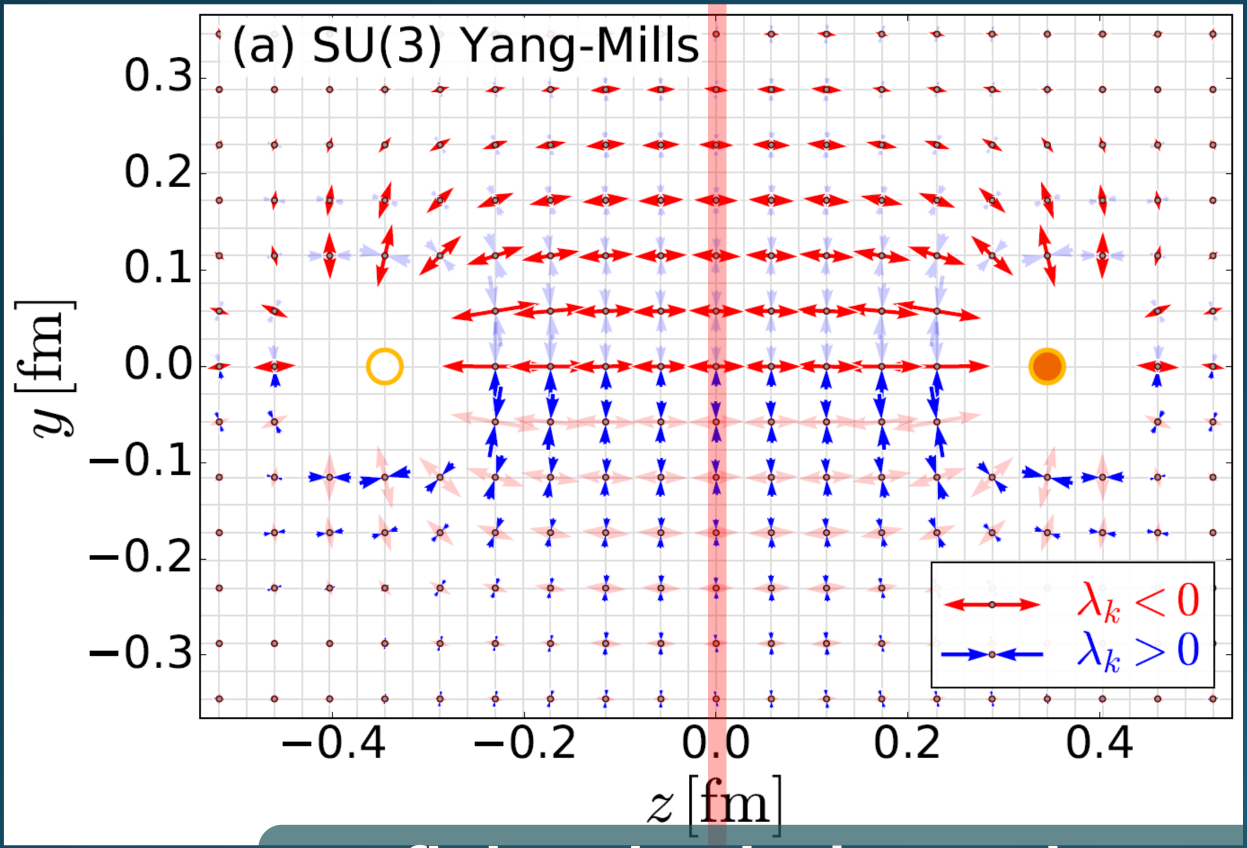
length: $\sqrt{|\lambda_k|}$



Definite physical meaning

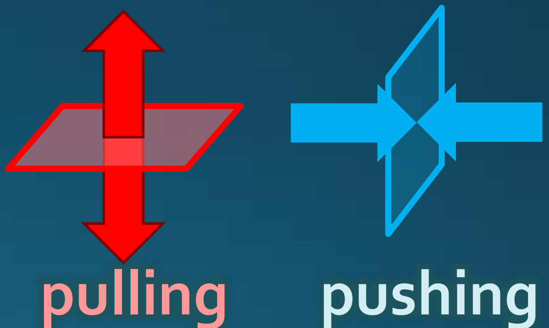
- ☐ Distortion of field, line of the field
- ☐ Propagation of the force as local interaction

Stress Tensor in $Q\bar{Q}$ System



Yanagihara+, PLB 2019

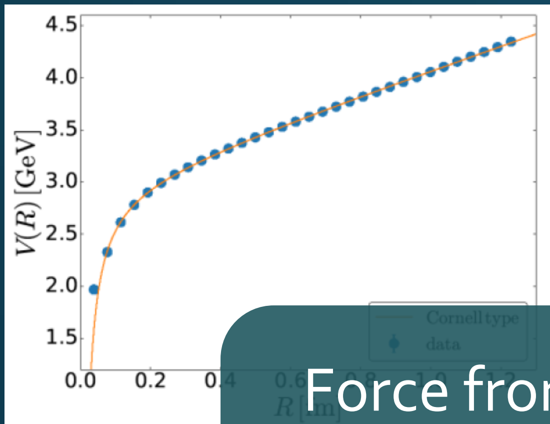
Lattice simulation
SU(3) Yang-Mills
a=0.029 fm
R=0.69 fm
t/a^2=2.0

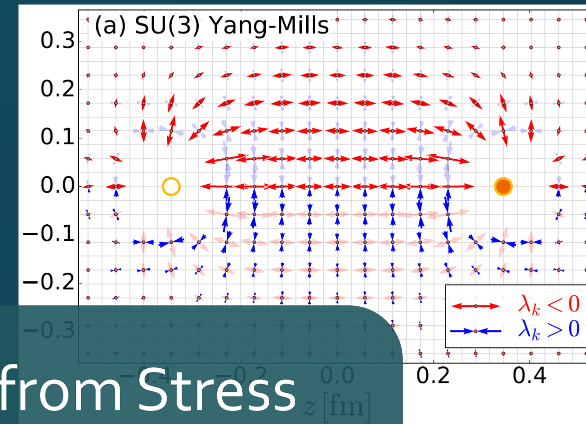


Definite physical meaning

- ☐ Distortion of field, line of the field
- ☐ Propagation of the force as local interaction
- ☐ Manifestly gauge invariant

Force





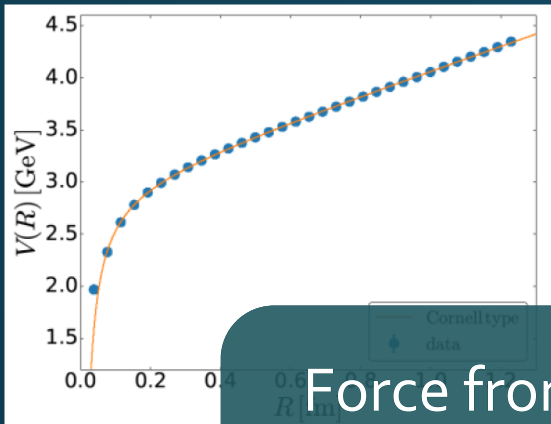
Force from Potential

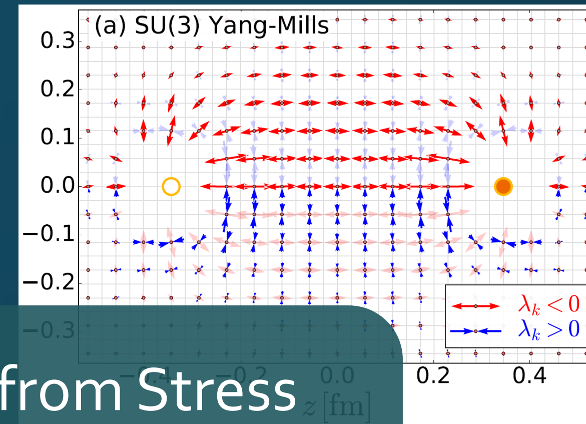
$$F_{\mathrm{pot}} = -\frac{dV}{dR}$$

Force from Stress

$$F_{\mathrm{stress}} = \int_{\mathrm{mid.}} d^2x T_{zz}(x)$$

Force



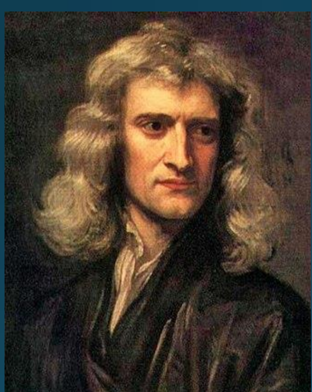


Force from Potential

$$F_{\text{pot}} = -\frac{dV}{dR}$$

Force from Stress

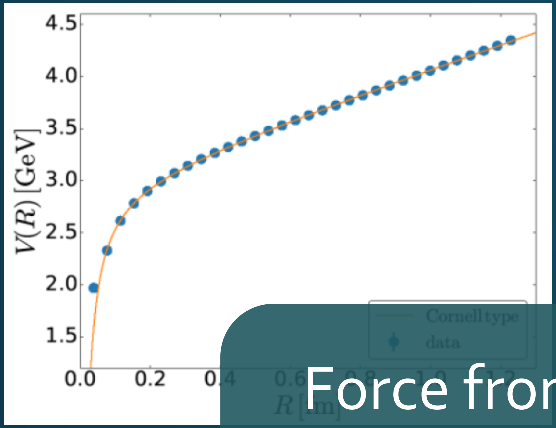
$$F_{\text{stress}} = \int_{\text{mid.}} d^2x T_{zz}(x)$$

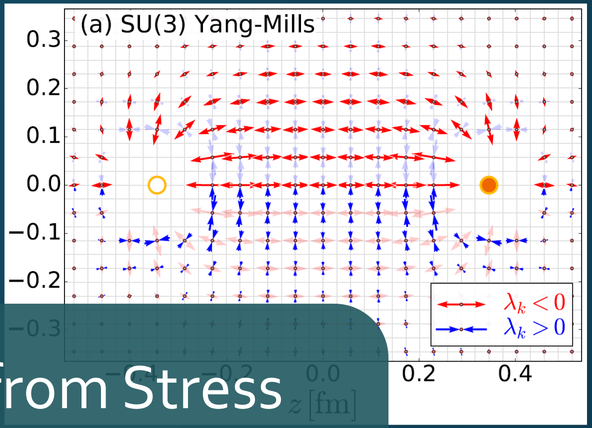


Newton
1687

Faraday
1839

Force



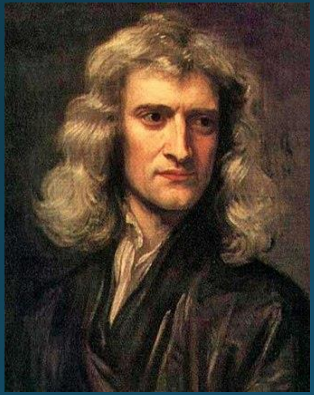


Force from Potential

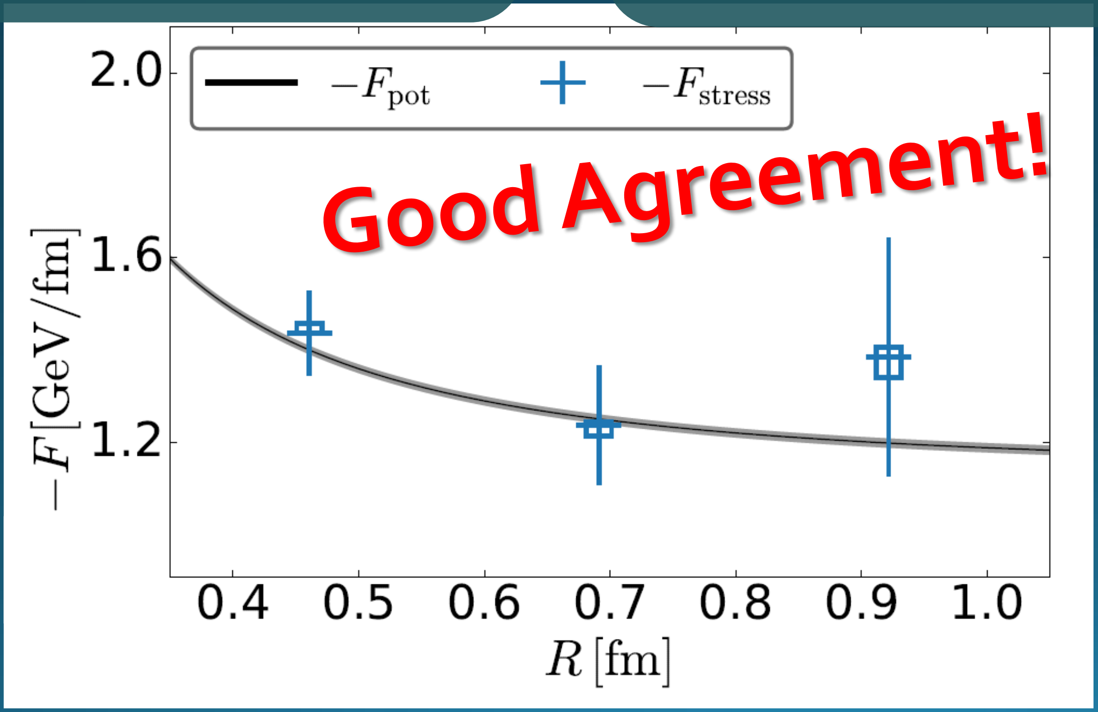
$$F_{\text{pot}} = -\frac{dV}{dR}$$

Force from Stress

$$F_{\text{stress}} = \int_{\text{mid.}} d^2x T_{zz}(x)$$



Newton
1687



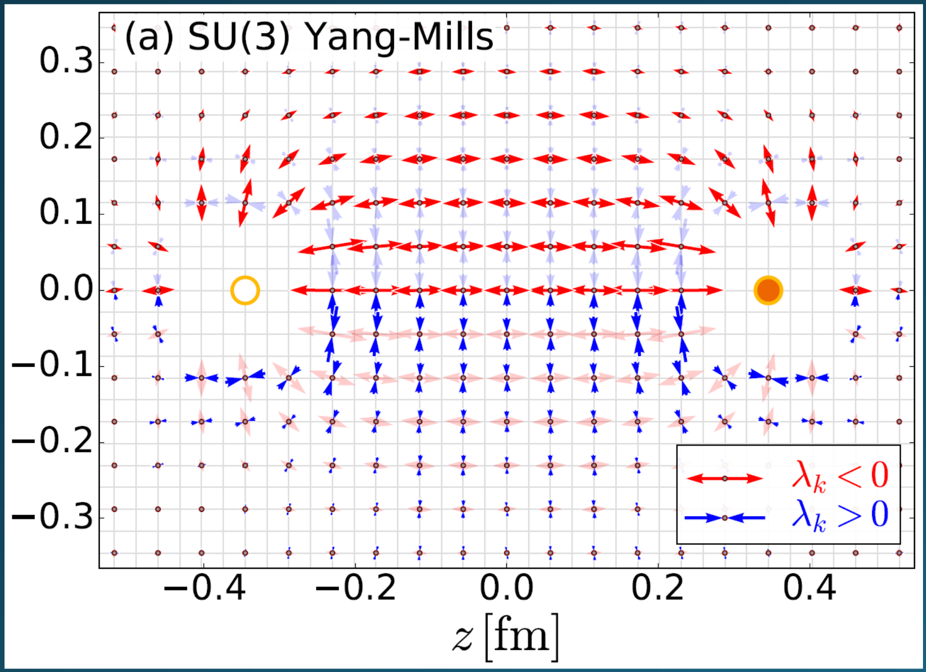
Faraday
1839

Temperature Dependence

Yanagihara+, in prep.

Vacuum

(Current Universe)



QGP

(Early Universe)

?

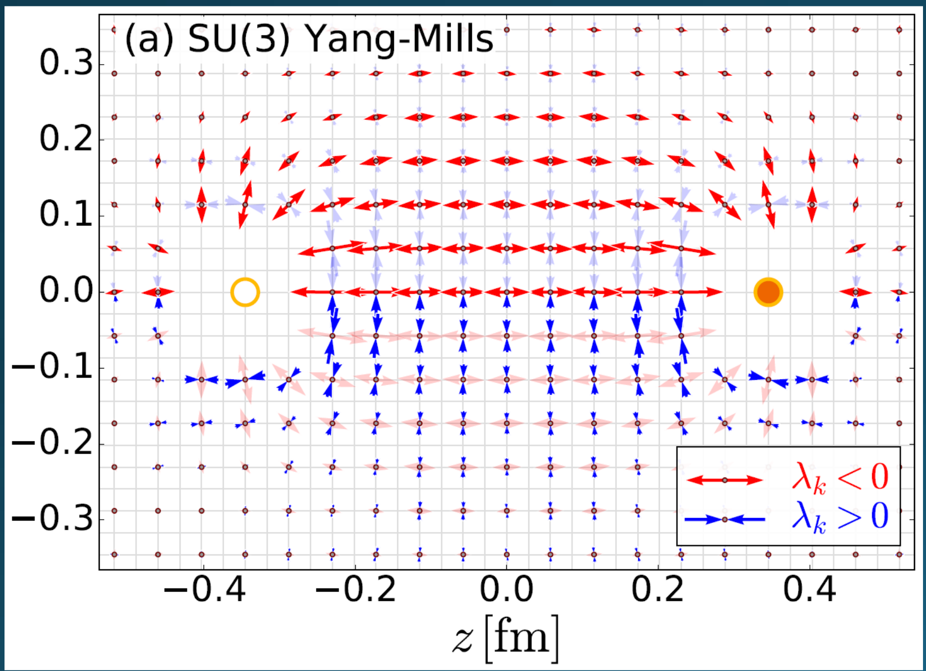
$$\langle T_{\mu\nu}(x)\rangle_{\mathrm{Q\bar{Q}}} = \frac{\langle \delta T_{\mu\nu}(x)\delta\Omega(y)\Omega^\dagger(z)\rangle}{\langle \Omega(y)\Omega^\dagger(z)\rangle}$$

Temperature Dependence

Yanagihara+, in prep.

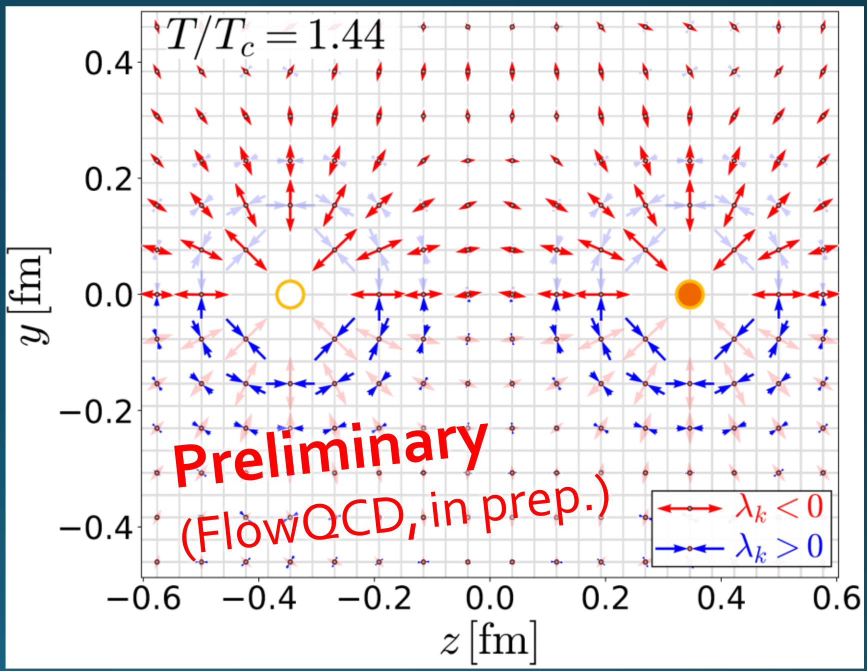
Vacuum

(Current Universe)



QGP

(Early Universe)



$T=1.44T_c$

- Singlet projection for $T=1.44T_c$
- Flux-tube structure is screened above T_c.

Summary

- Exploring dense medium in relativistic heavy-ion collisions is one of the hottest topics in this field. Many new experiments will start in the near future!

- Fluctuations are promising observables for the search for the phase structure of QCD.

- Lattice QCD numerical simulations are another important virtual experiments to explore the hot and dense medium.