Exploring Dense Nuclear Matter in Heavy-ion Collisions

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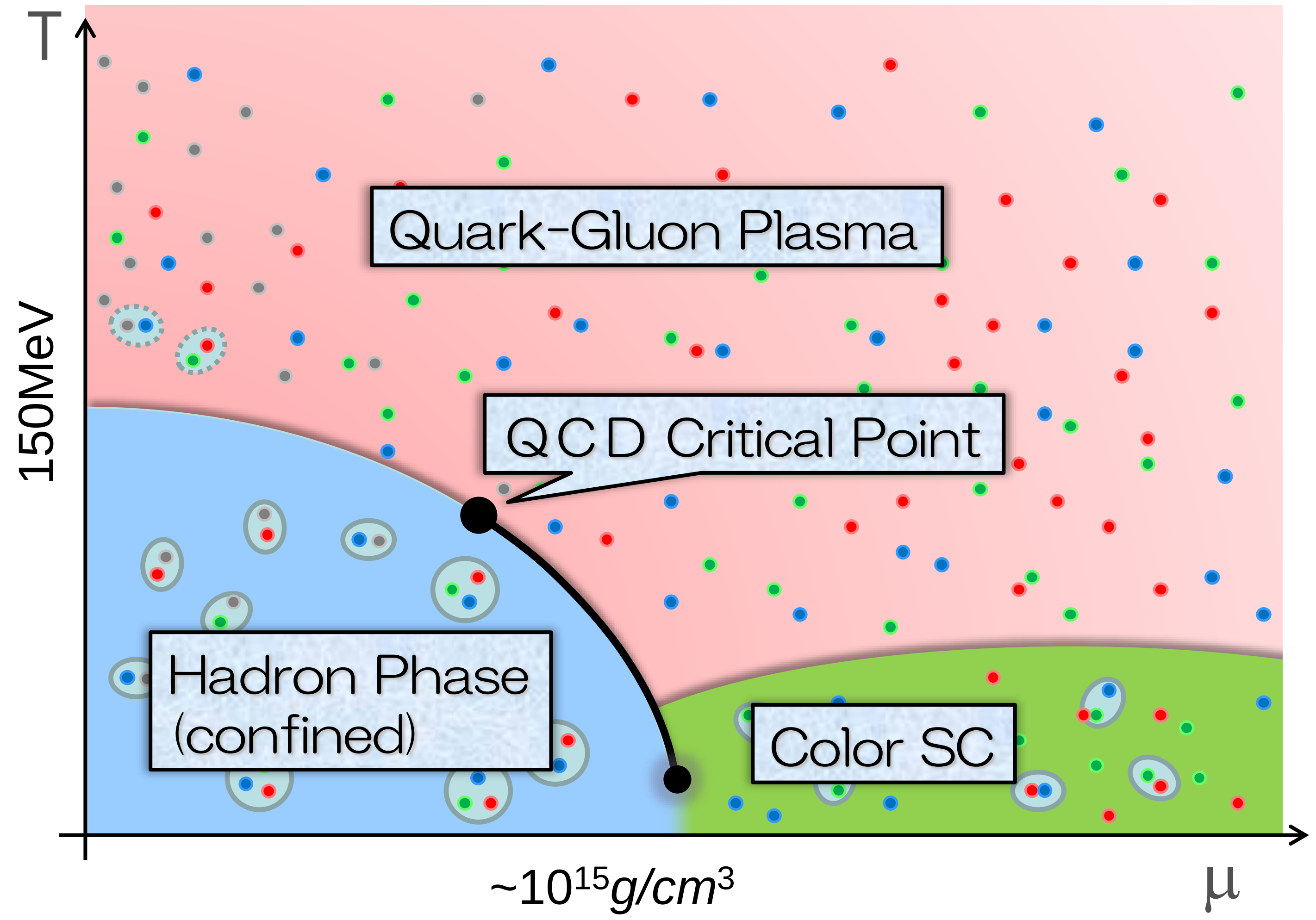
Taya, Jinno, MK, Nara, Nishimura, in preparation.
Nishimura, MK, Kunihiro, arXiv:2405.09240 [hep-ph]; PTEP 2023, 053D01; PTEP 2022, 093D02

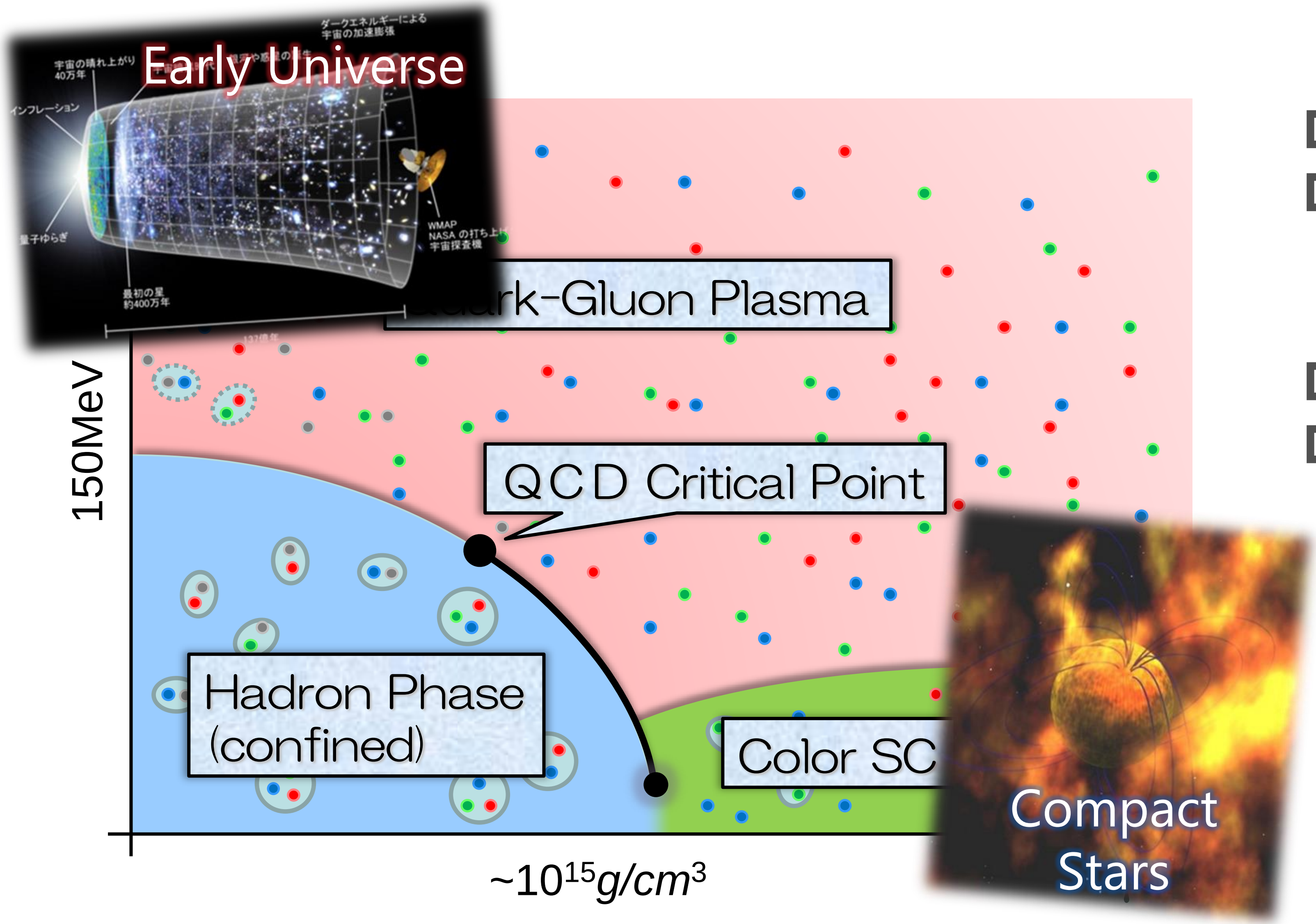
Hadron interactions with strangeness and charm, 2024/6/28, Jeju Korea

QCD Phase Diagram



- Crossover at $\mu = 0$
- Possible first-order transition and QCD critical point in dense region
- Multiple QCD-CP? MK+ ('02)
- Color superconducting phases in dense and cold quark matter

QCD Phase Diagram



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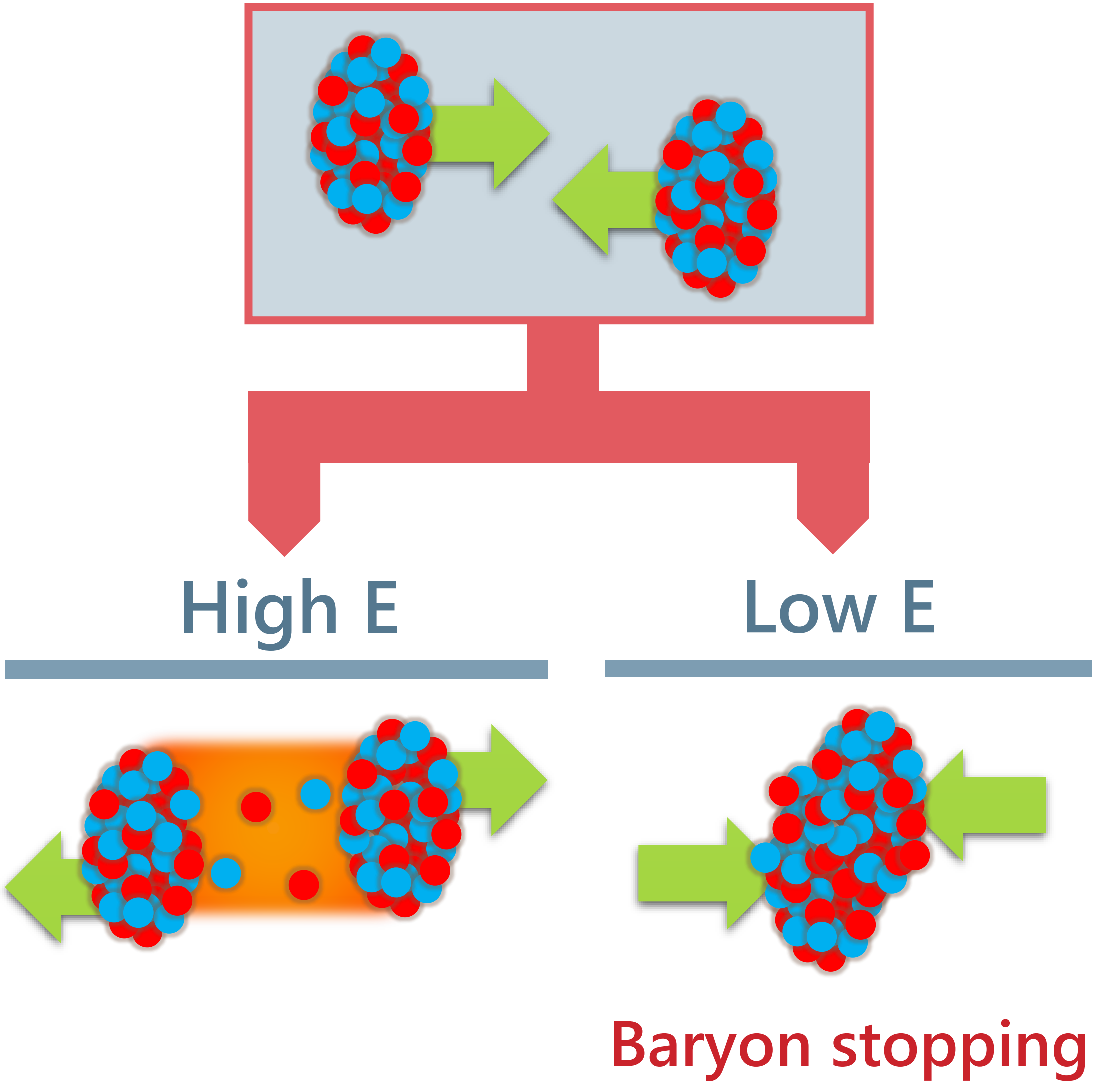
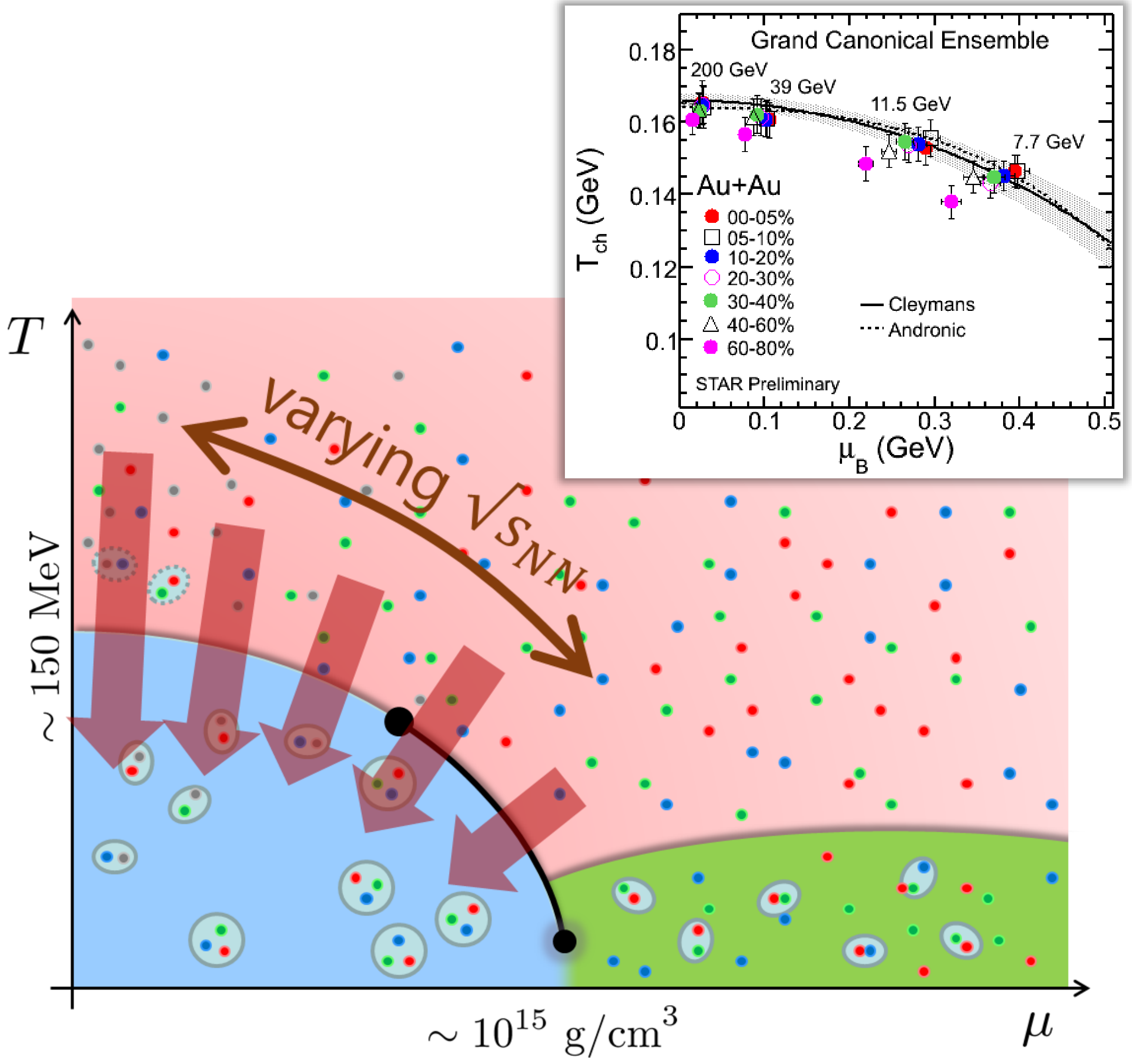
- Color superconducting phases in dense and cold quark matter

Beam-Energy Scan



STAR, 2012



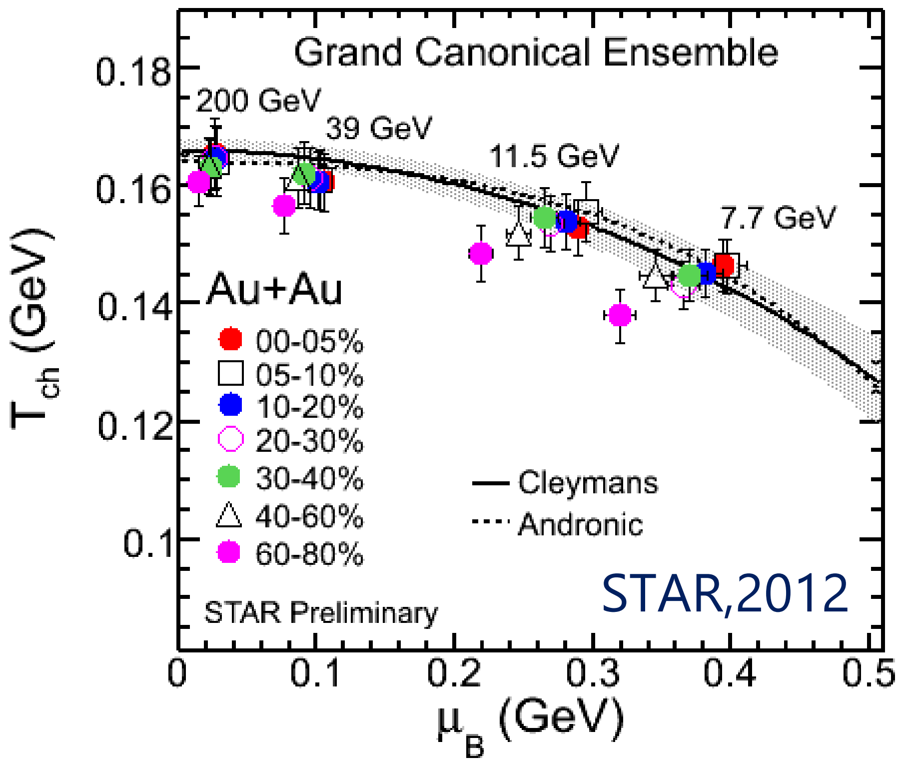
Questions

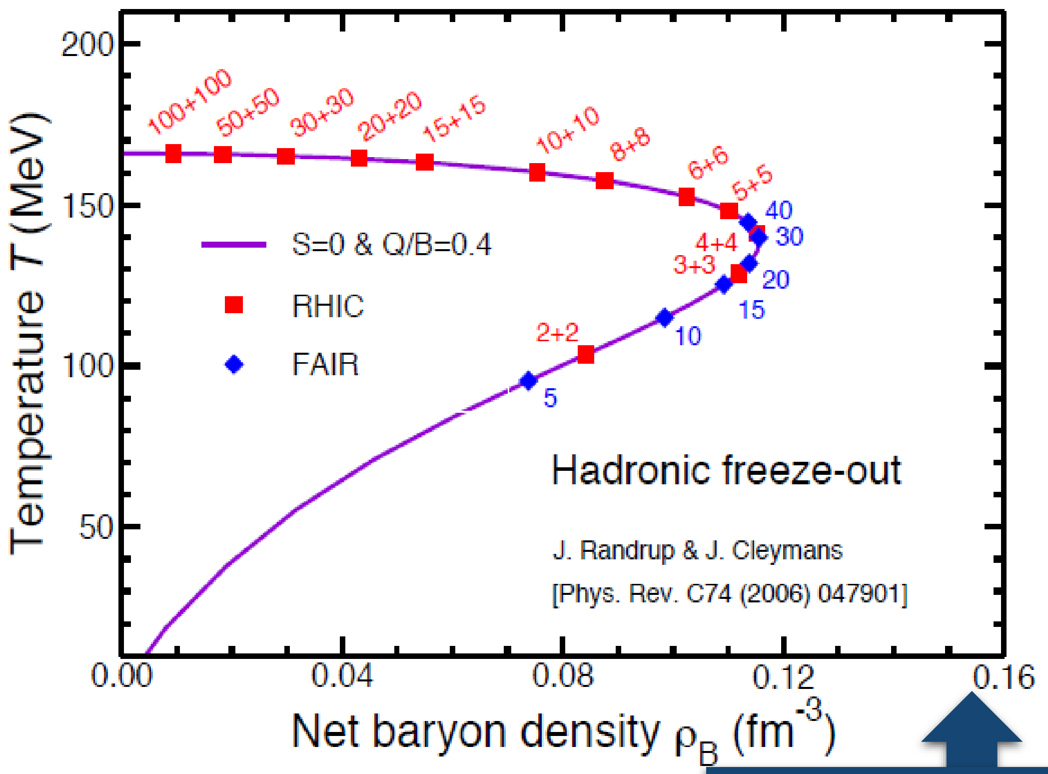
- What is the best collision energy to explore the baryon-rich matter?
- How high density are accessible?
- How to investigate their properties?

Quantitative estimates on the size/lifetime of high density region

Taya, Jinno, MK, Nara, Nishimura, in prep.

Chemical Freezeout



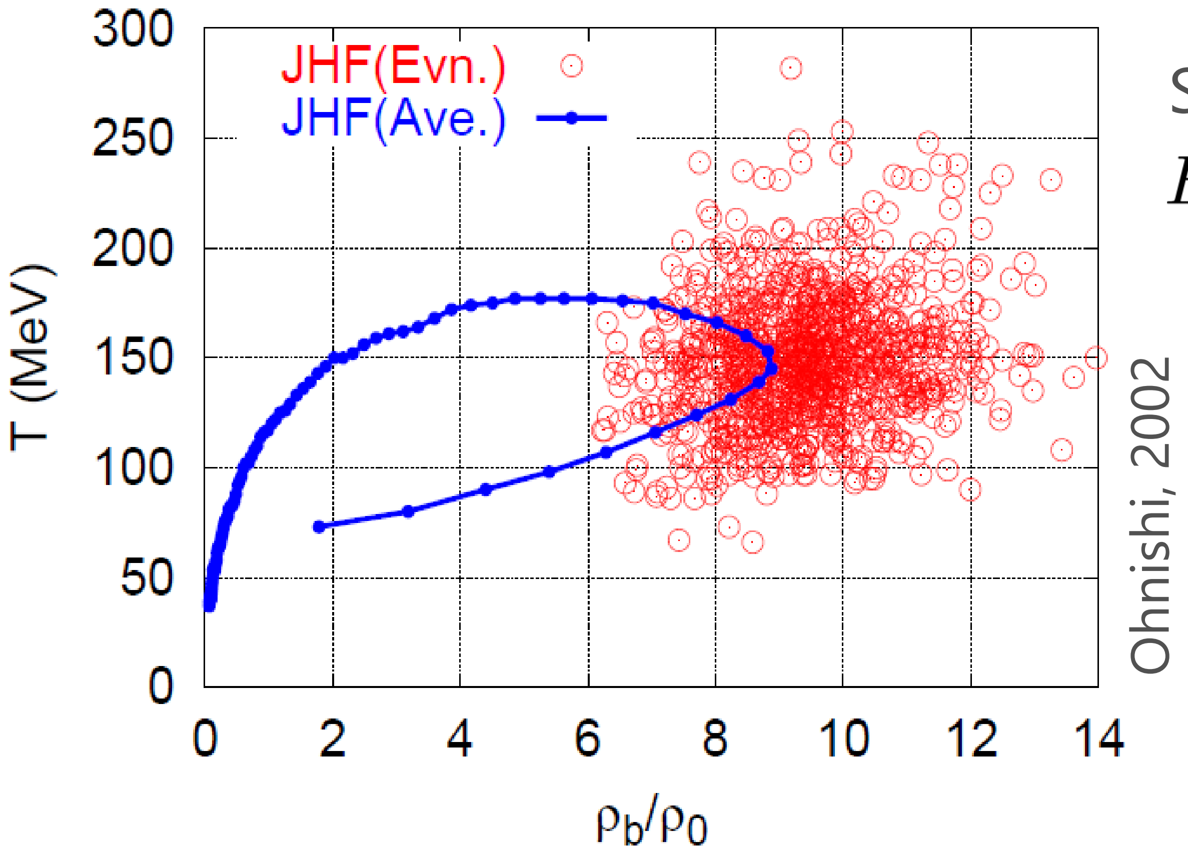


Nuclear density ρ_0

— Highest baryon density at chemical freezeout at $\sqrt{s_{NN}} \simeq 6 - 10$ GeV?

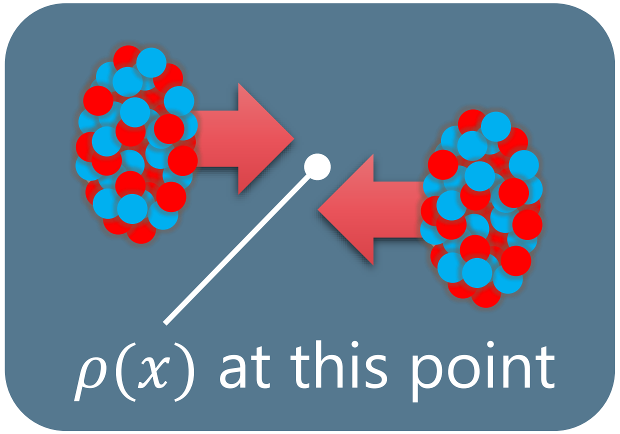
— Density at earlier stage? ➤ Analysis in dynamical models

Baryon Density at the Collision Point



Simulation by JAM

$E/A = 20\text{GeV}, \ \sqrt{s_{NN}} \simeq 6\text{GeV}$



— Maximum baryon density exceeds $\rho/\rho_0 \simeq 8$!
— Large event-by-event fluctuations?
— How large is the high-density region? How long is the lifetime?

Volume of Dense Region

The volume where the local baryon density is larger than a threshold value $\rho_{\rm th}$

$$V_3(\rho_{\rm th}, t) = \int_{\rho(x)>\rho_{\rm th}} d^3\boldsymbol{x}\gamma$$

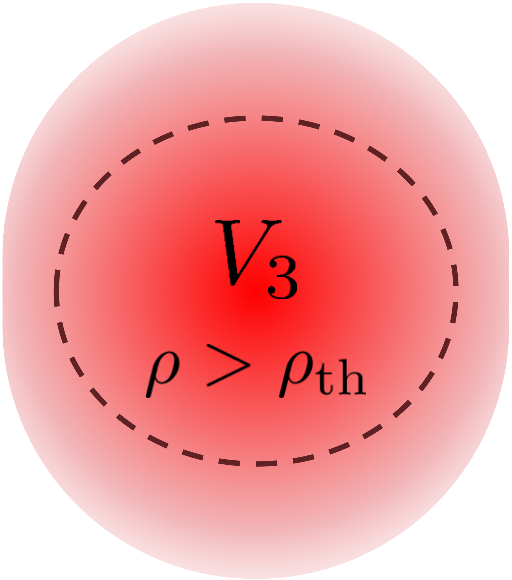
Baryon current $J^\mu(x)$

Baryon density $\rho(x) = \sqrt{J^\mu(x)J_\mu(x)}$

Lorentz factor $\gamma = (1-(\boldsymbol{J}/J_0)^2)^{-1/2}$

Note:

— Event-by-event basis density
— Directly calculable in a dynamical model.
— We do not care about local thermalization.
  — V_3 is the upper limit of thermalized volume.
  — Even non-thermal, dense region is interesting!



Simulation Setup in JAM

- Au+Au collision for $2.4 \le \sqrt{s_{NN}} \le 20$ GeV
- Impact parameter $b \le 3$ fm : top 5% centrality

- Momentum-dependent mean field (MF2) Nara, Ohnishi, 2022
  - Setup reproducing v_1 and v_2 flows

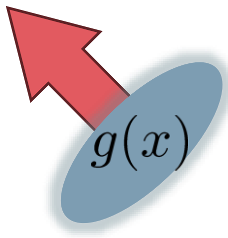
Smeared baryon current

JAM: discrete particle distribution ➔ continuous current by smearing

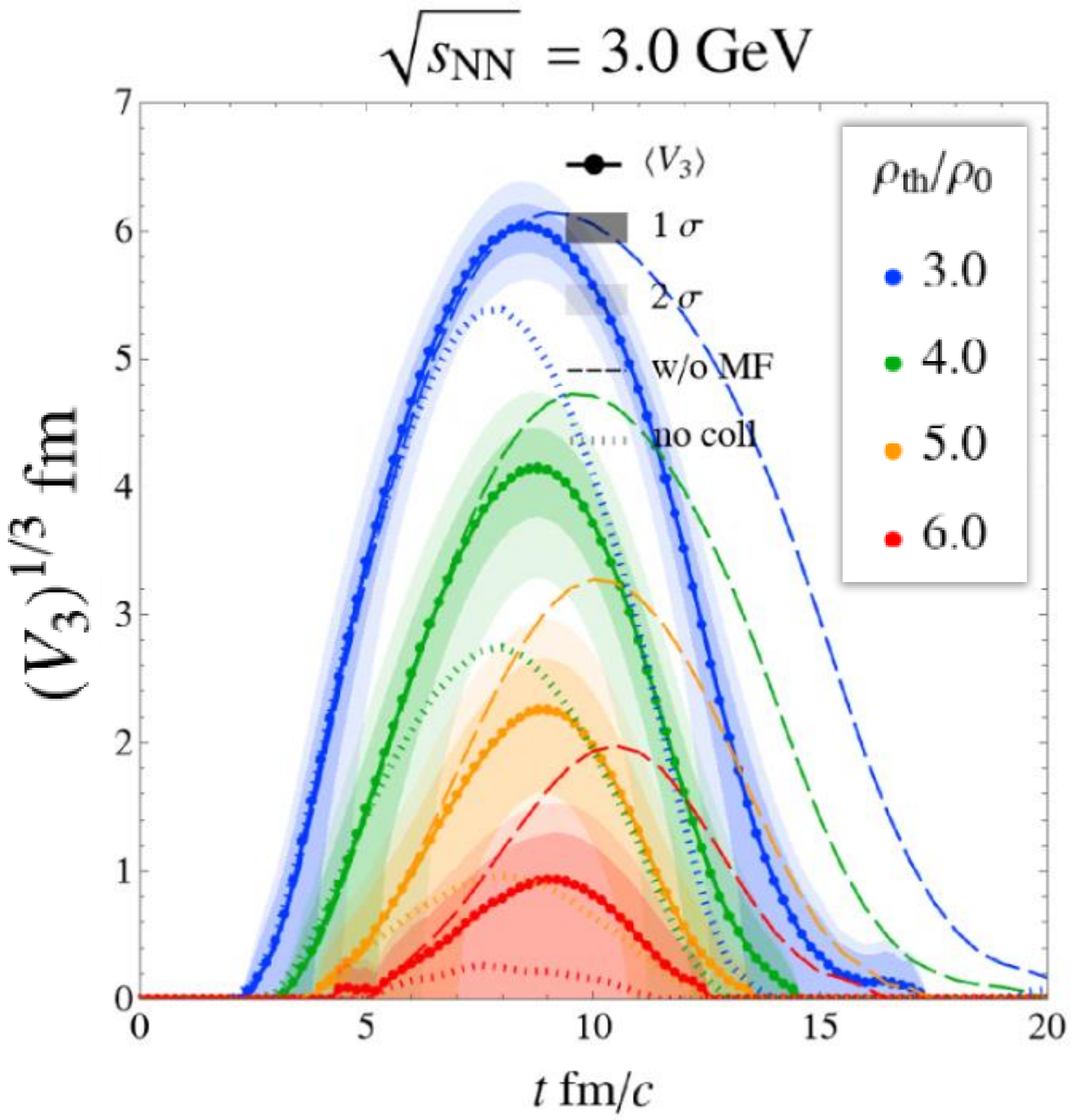
$$J^\mu(x) = \sum_{i \in \text{baryons}} B_i g(x; X_i, P_i) \frac{P_i^\mu}{P_i^0}$$

$$g(x; X, P) := \frac{\gamma}{(\sqrt{2\pi} r)^3} \mathrm{e}^{-\frac{|\boldsymbol{x}-\boldsymbol{X}|^2 + (\gamma \boldsymbol{V} \cdot (\boldsymbol{x}-\boldsymbol{X}))^2}{2r^2}}$$

$$r = 1 \text{ fm}$$



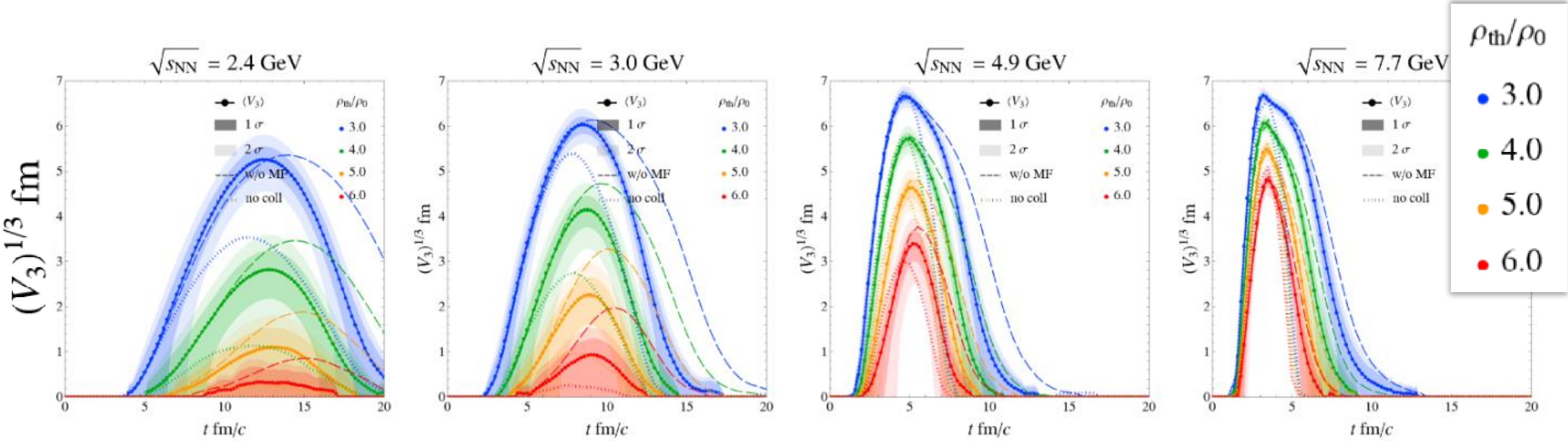
V_3 in JAM



— **solid: JAM+MF** Nara, Ohnishi, 2022
— shaded band: 1σ and 2σ e-v-e fluct.
— dashed: JAM cascade mode
— dotted: no-collision

- Formation of dense region:
  - $V_3(3\rho_0, t) = (6\text{ fm})^3$
  - $V_3(4\rho_0, t) = (4\text{ fm})^3$
- Compression owing to interaction
- Repulsive MF → weaker compression
- Large e-v-e fluctuations

V_3 for various $\sqrt{s_{NN}}$



As $\sqrt{s_{NN}}$ becomes larger,

- ☐ $\max V_3(\rho_{th}, t)$ becomes larger.
- ☐ The lifetime of the dense region becomes shorter.
- ☐ E-v-e fluctuations are more suppressed.

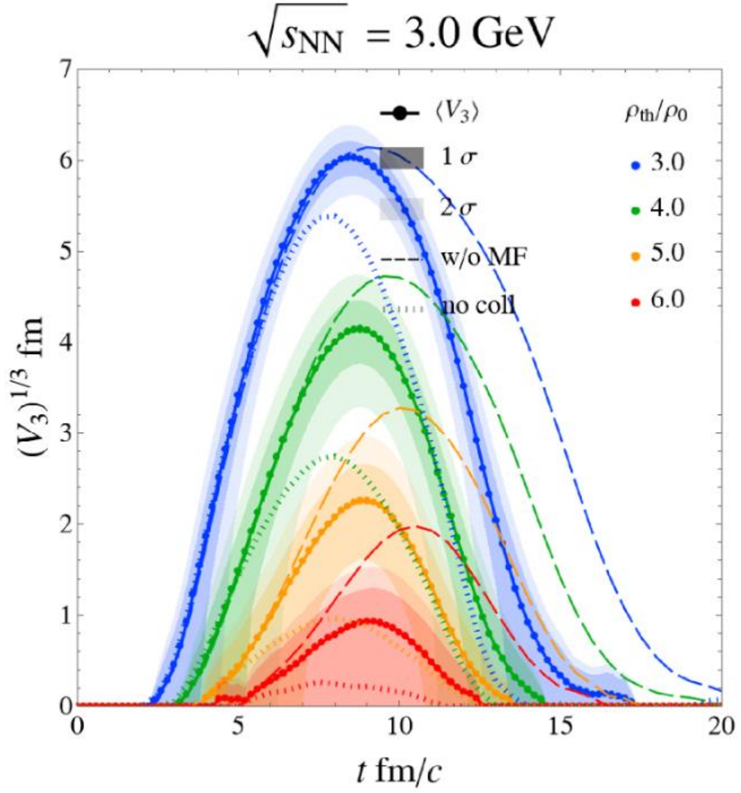
Four-Volume & Lifetime

Four Volume

$$V_4(\rho_{\rm th}) = \int_{-\infty}^{\infty} dt \int_{\rho(x)>\rho_{\rm th}} d^3\boldsymbol{x}$$

Lifetime

$$\tau(\rho_{\rm th}) = \frac{V_4(\rho_{\rm th})}{\max V_3(\rho_{\rm th}, t)}$$

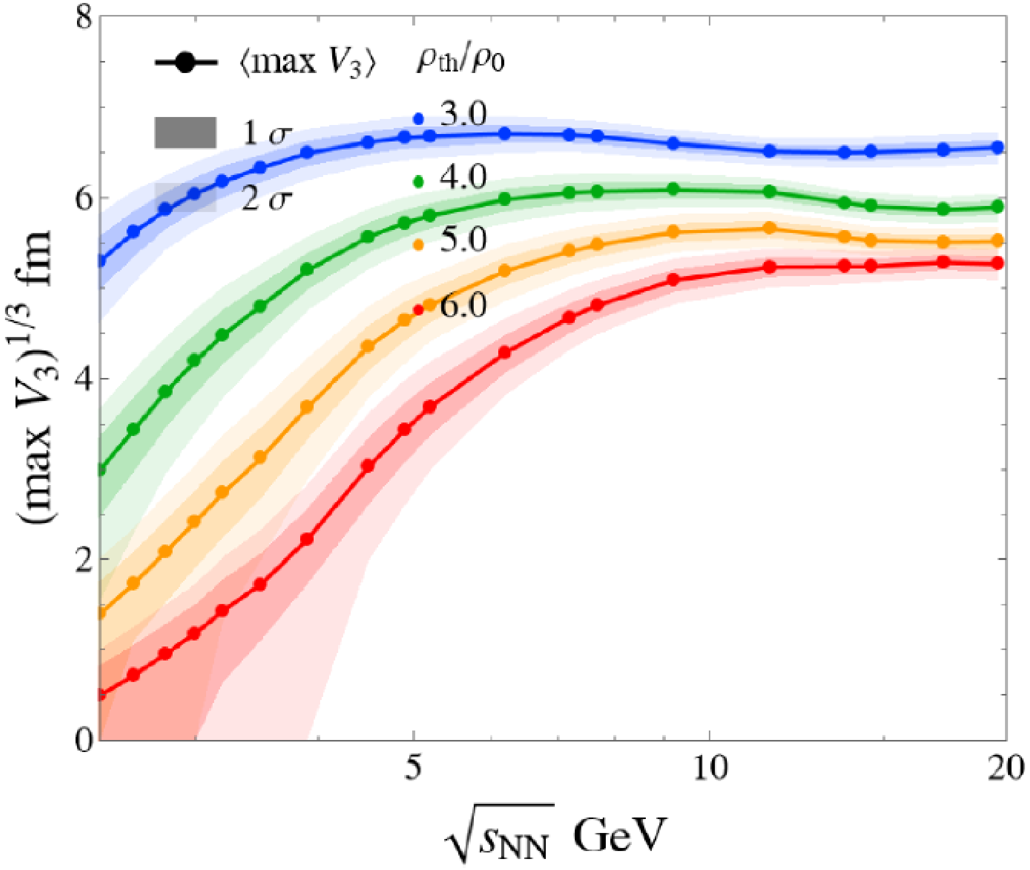


Note

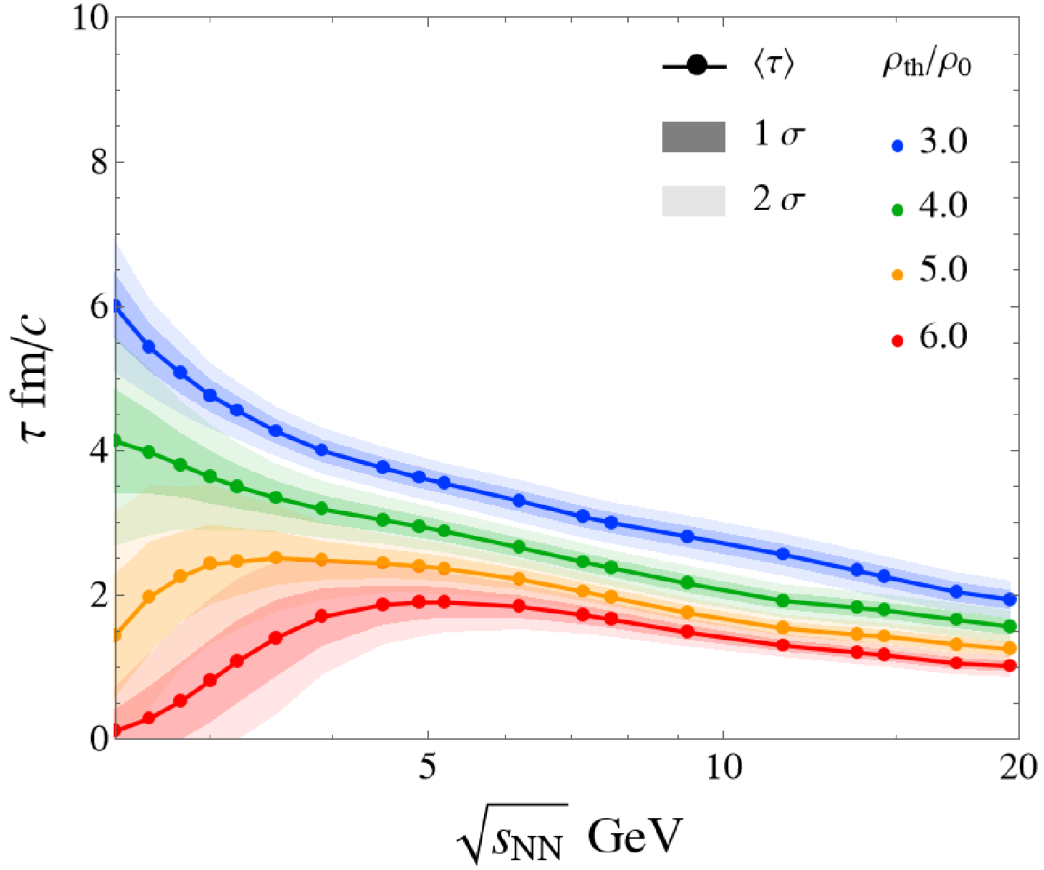
V_4 may be relevant for the dilepton production rate.

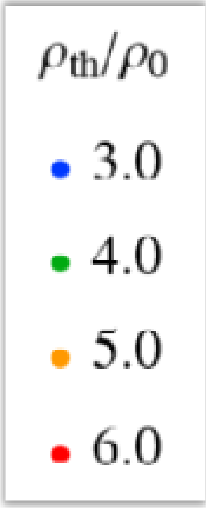
$\sqrt{s_{NN}}$ Dependence

max V_3

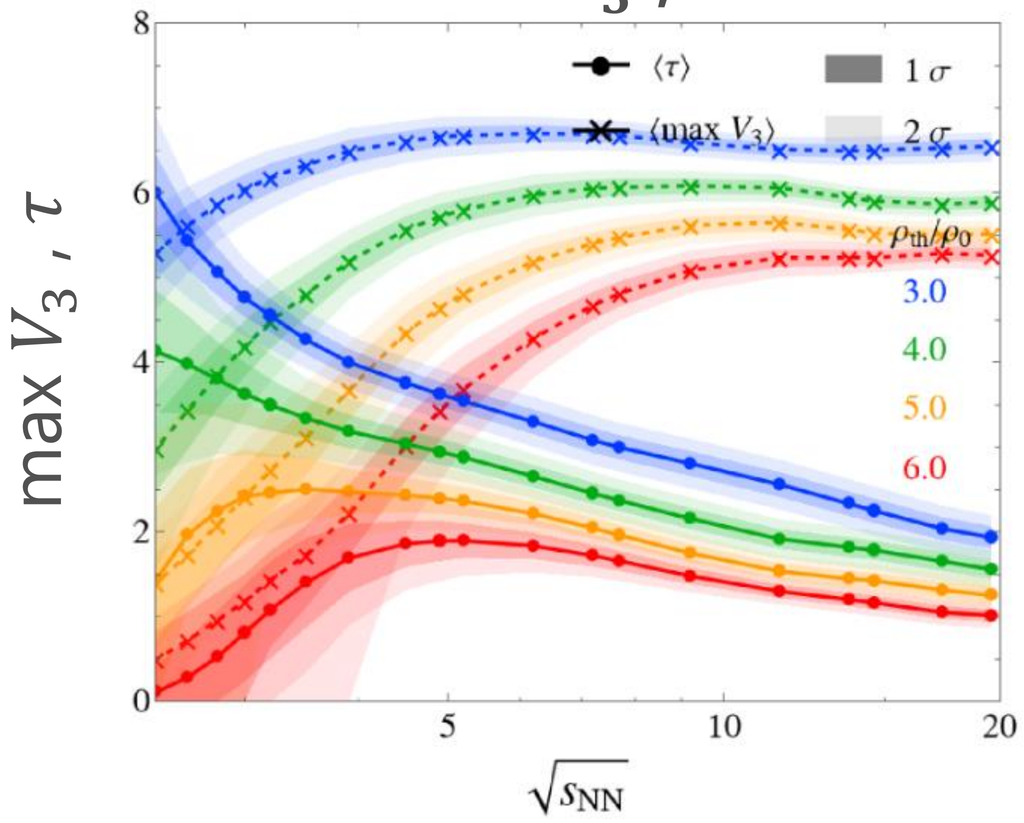


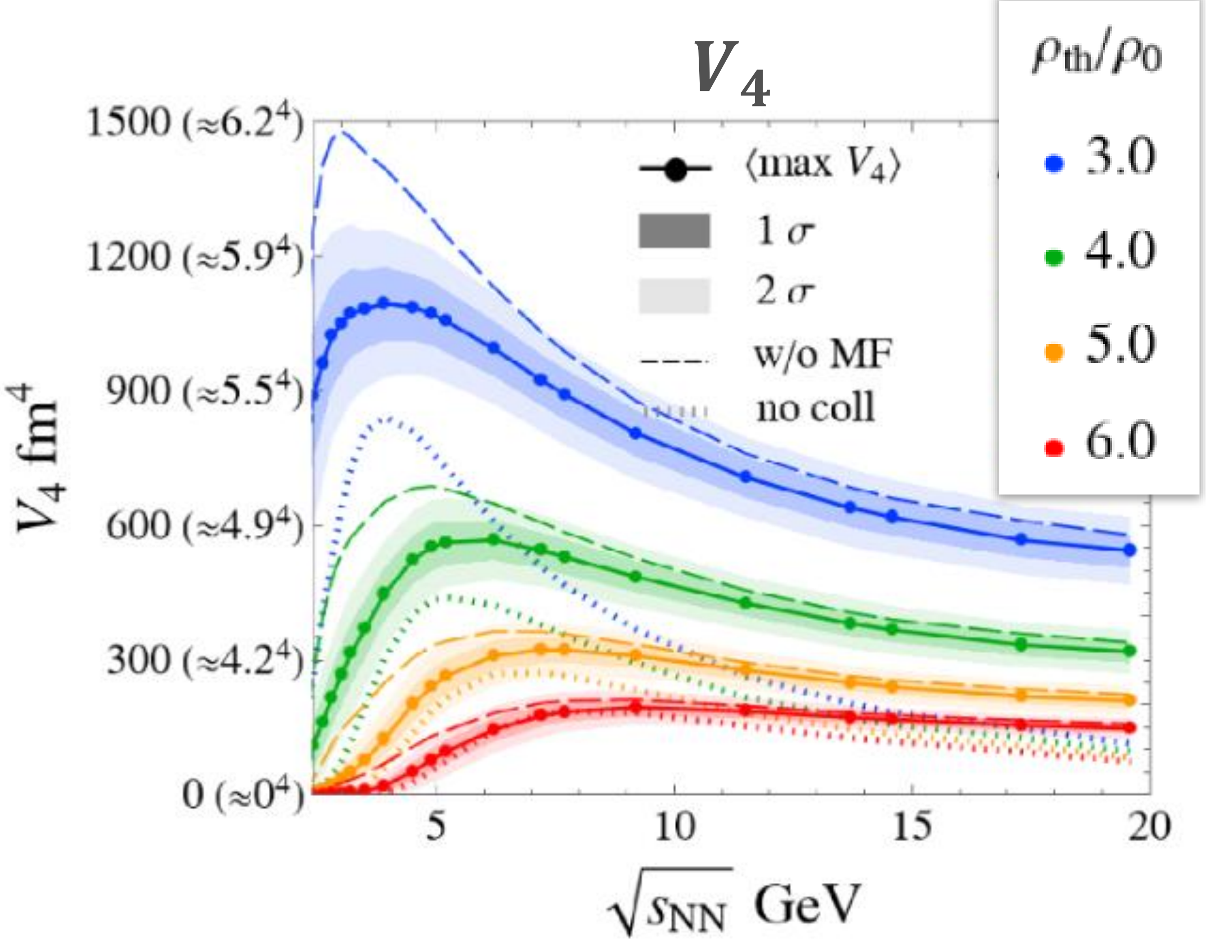
Lifetime





$\sqrt{s_{NN}}$ Dependence





- ☐ $\sqrt{s_{NN}} \simeq 3$ GeV would be the best energy to create $\rho = 3 \sim 4\rho_0$ with large V_3 and τ.
- ☐ Lower $\sqrt{s_{NN}}$ is suitable to create colder matter.
- ☐ All results have large e-v-e fluctuations ➔ Event selection by density?

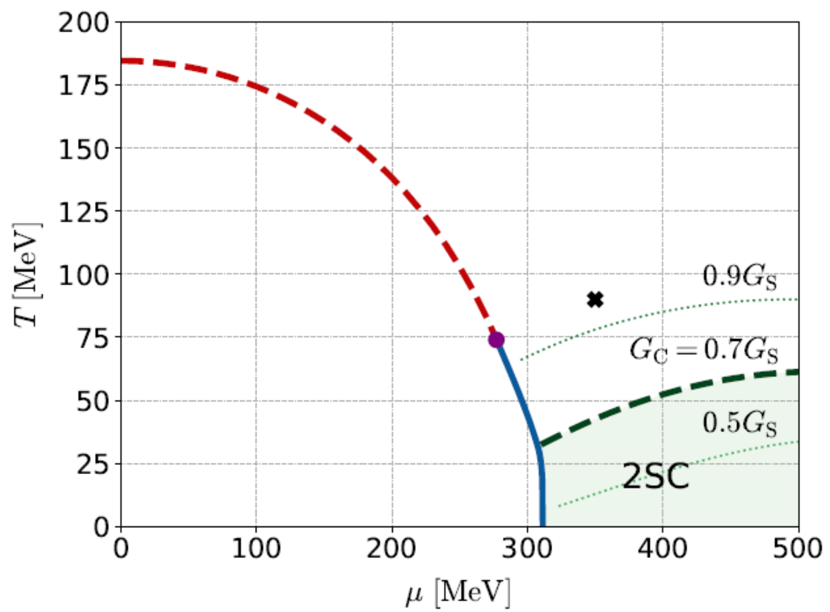
Dilepton Production
as experimental observables of
Color Superconductivity & QCD-CP

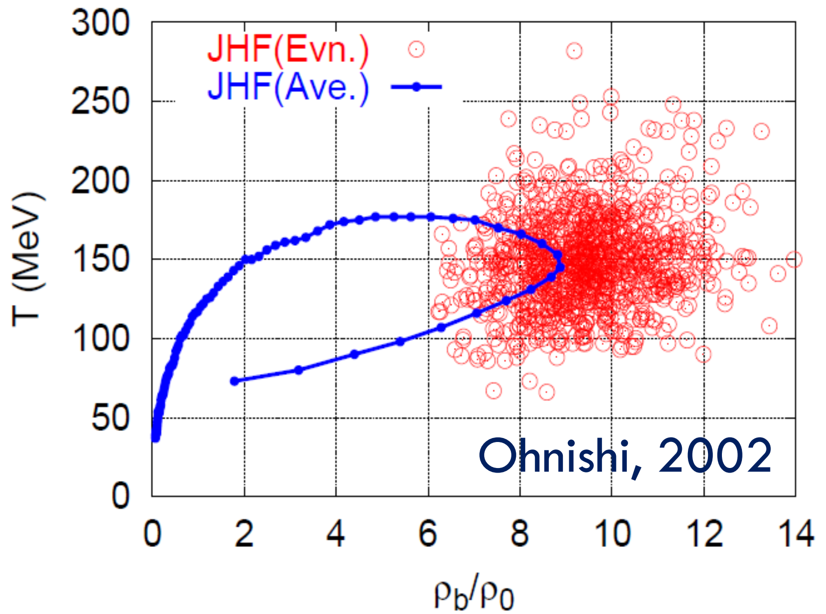
Nishimura, MK, Kunihiro, PTEP2022, 093D02; PTEP2023, 053D01; arXiv:2405.09240

Observing CSC in HIC

- **Difficulties**
  - CSC would not be created if Tc is not high enough.
  - Even if created, its lifetime would be short.
  - Since CSC is created in the early stage, its signal would be blurred during the evolution in later stage.

- **Strategy** in our study:
  - Focus on precursory phenomena of CSC
  - Use dilepton production as an observable



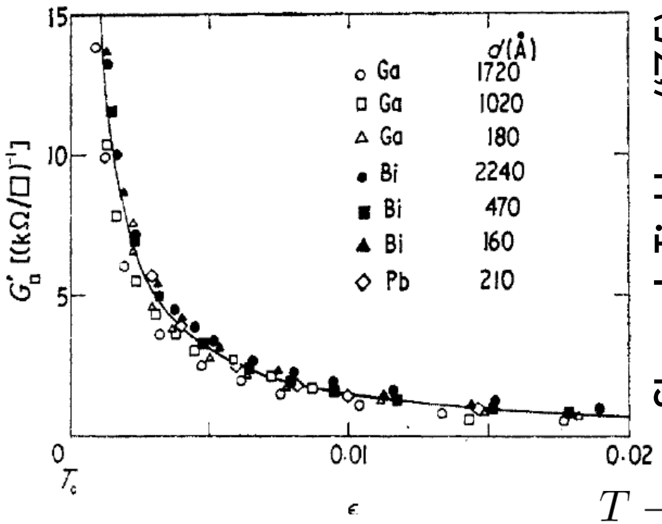


Precursor of CSC

- **Anomalous behavior of observables near but above Tc of SC**
  - electric conductivity
  - magnetic susceptibility
  - pseudogap

- Enhanced pair fluctuations is one of the origins of precursory phenomena.
- More significant phenomena in strongly-coupled systems.

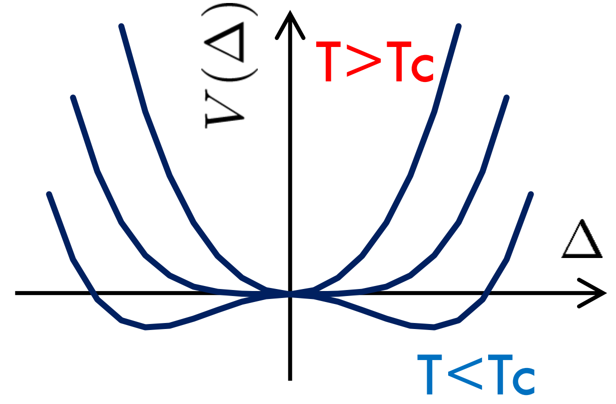
Electric conductivity



Skopal, Tinkham('75)

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

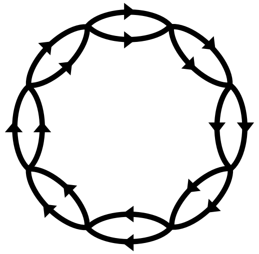
Landau's free energy



Precursor of Color Superconductivity

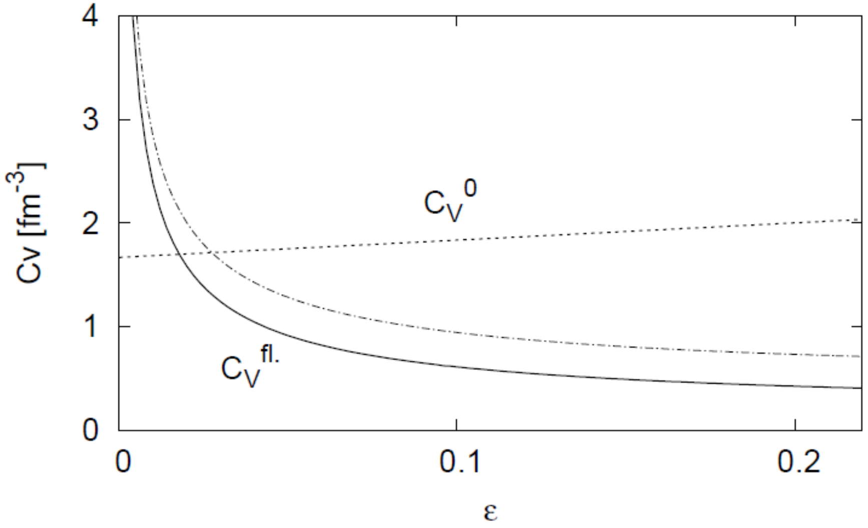
MK, Koide, Kunihiro, Nemoto, '03, '05

☐Thermodynamic Potential

$\Omega =$ 

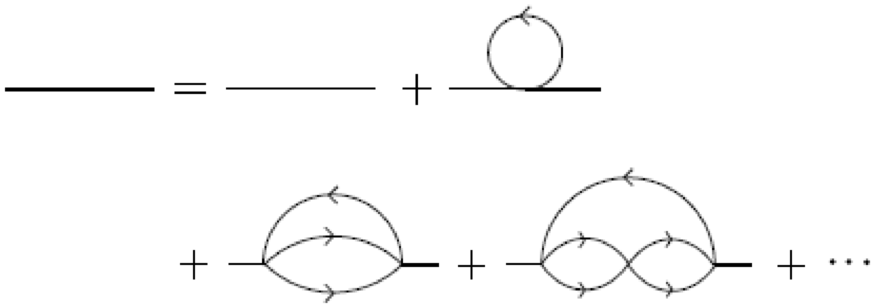
Specific heat

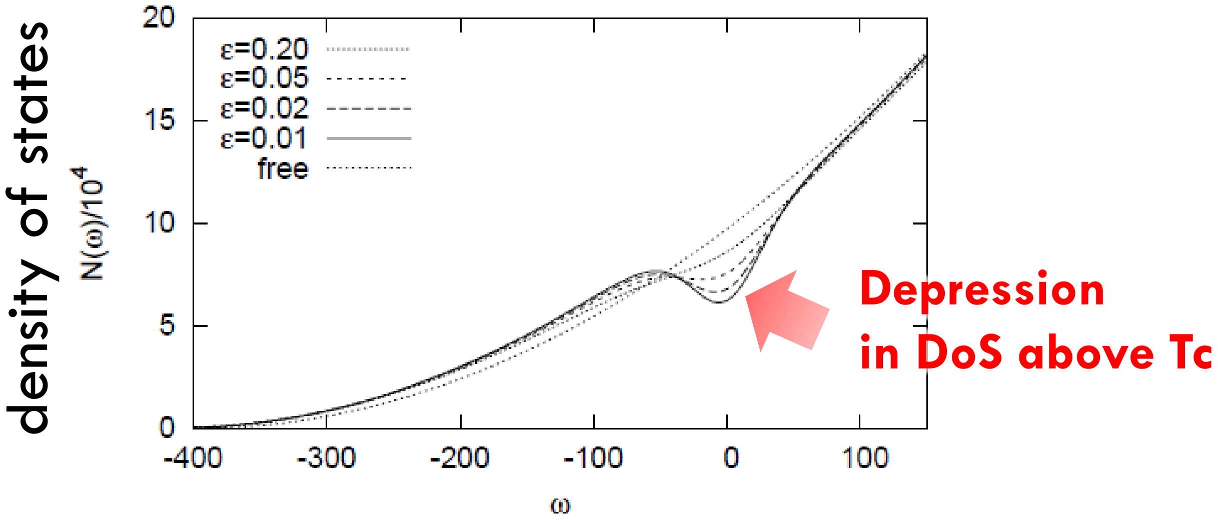
$$c = -T\frac{\partial^2\Omega}{\partial T^2}$$



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

☐Pseudogap





Model

NJL model (2-flavor)

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

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

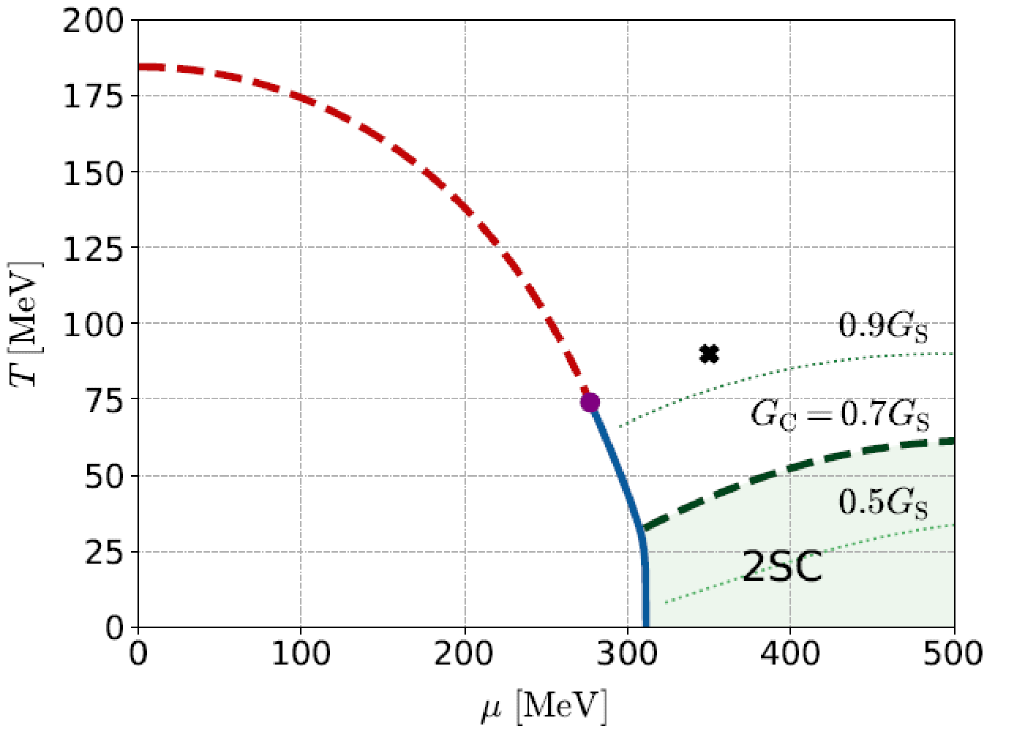
$$\mathcal{L}_C = G_C \left((\bar{\psi} i \gamma_5 \tau_A \lambda_A \psi^C)(\text{h.c.}) \right)$$

diquark interaction

Parameters

$$G_S = 5.01 \text{ GeV}^{-2}, \quad \Lambda = 650\text{MeV}, \quad m_q = 0$$

Phase Diagram in MFA



- Order of phase transition
  - 2nd in the MFA
  - can be 1st due to gauge fluctuation

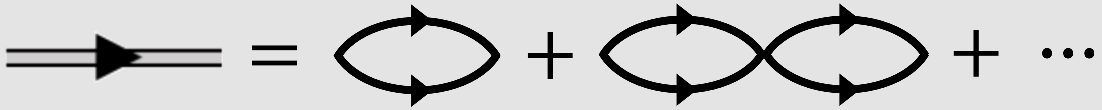
Matsuura+('04), Giannakis+('04)
Noronha+('06), Fejos, Yamamoto('19)

Di-quark Fluctuations

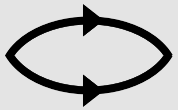
□ Diquark Propagator

$$D^R(x) = \langle [\Delta^\dagger(x), \Delta(0)] \rangle \theta(t) =$$ 

- □ Random Phase Approximaion



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

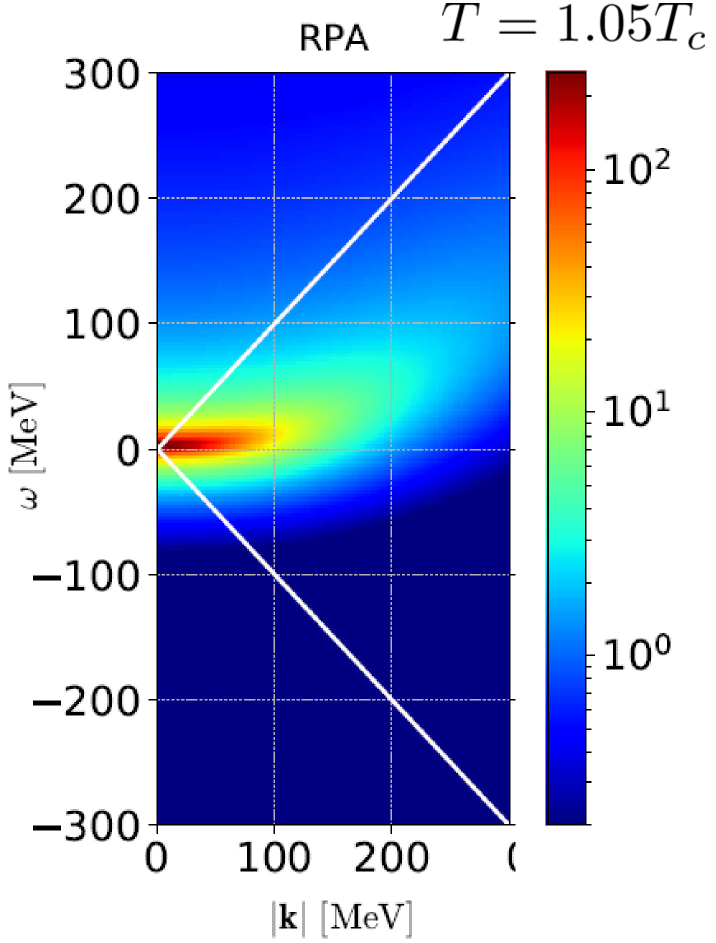
$$Q^R(\boldsymbol{k},\omega) =$$ 

- □ Diquark field becomes massless at T=Tc
- □ Soft mode of CSC transition
- □ Strength in the space-like region

MK, Koide, Kunihiro, Nemoto, '01,'05

Dynamical Structure Factor

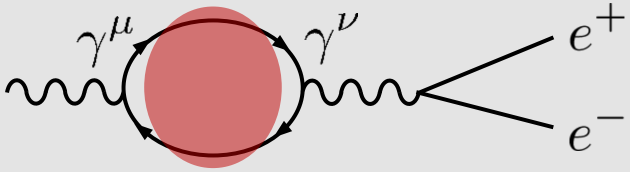
$$S(\boldsymbol{k},\omega) = -\frac{1}{\pi}\frac{1}{1-e^{-\beta\omega}}\mathrm{ImD^R(k,\omega)}$$



Photon Self-Energy: Precursor of CSC

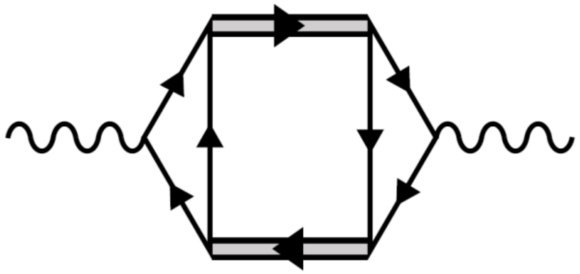
□ Dilepton Production Rate

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

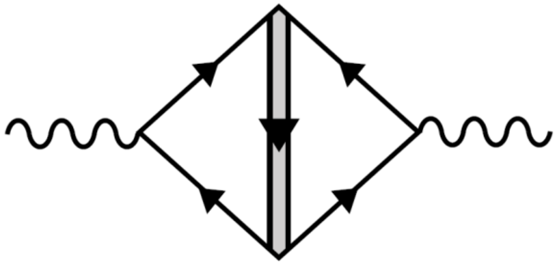


□ Effect of Di-quarks on $\Pi^{\mu\nu}(k)$

Aslamasov-Larkin term



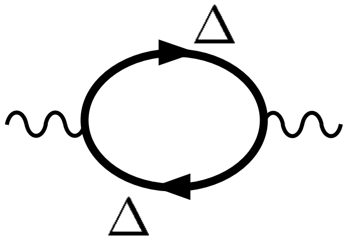
Maki-Thompson term

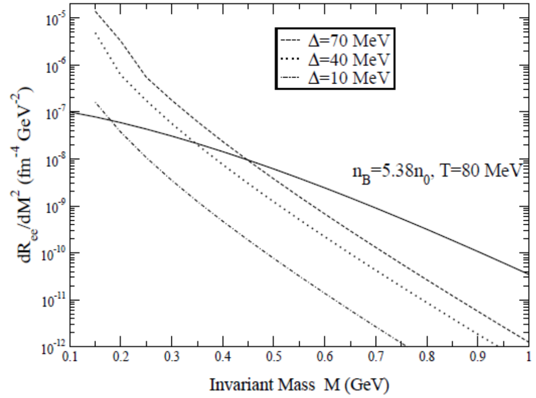


Well-known diagrams in metallic SC
for describing paraconductivity

□ DPR from CFL phase

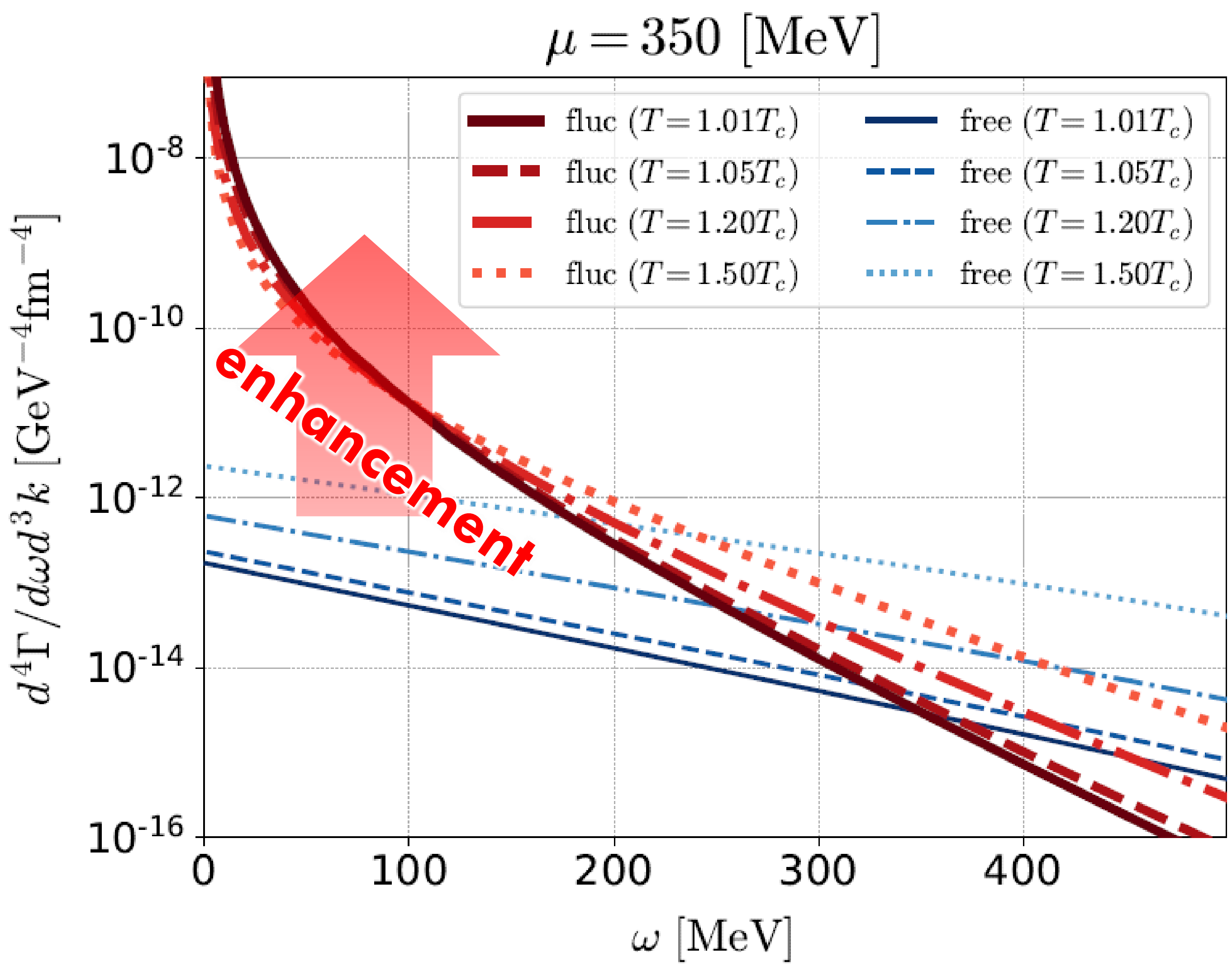
Jaikumar, Rapp, Zahed ('02)





Production Rate at $\boldsymbol{k} = 0$

Nishimura, MK, Kunihiro ('22)



Red: fluctuation contribution

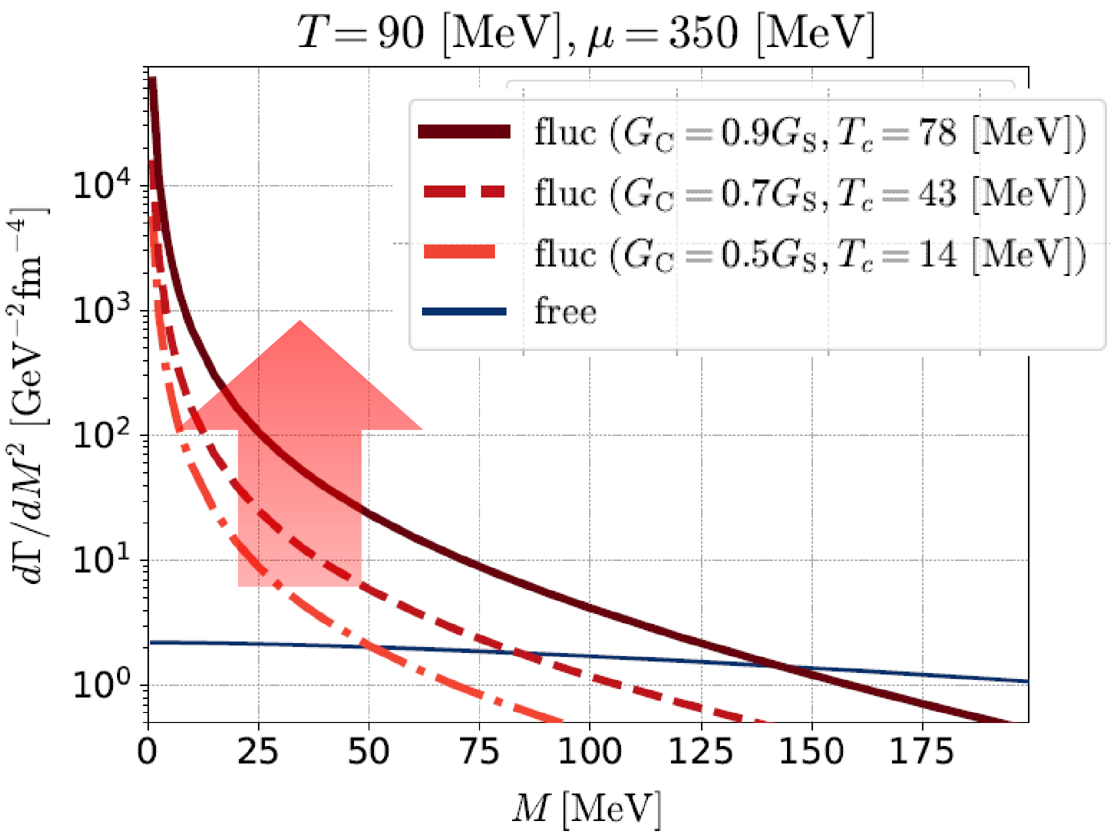
Blue: free quarks

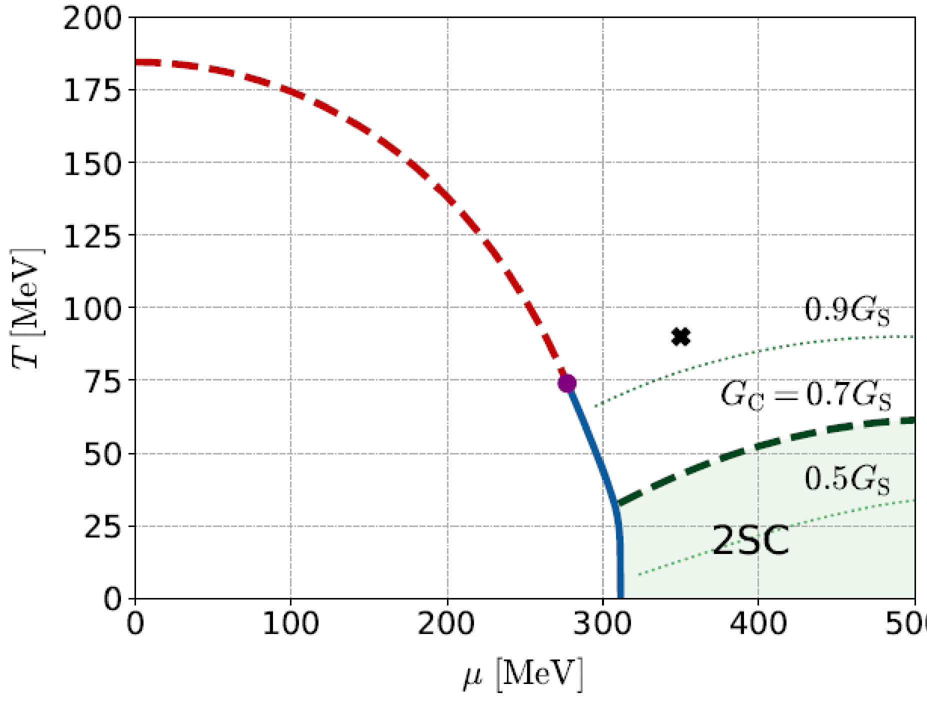
$G_C = 0.7G_s, T_c \simeq 45$ MeV

- Di-quark fluctuations give rise to large enhancement in the low energy region $\omega < 200$ MeV and $T < 1.5T_c$.
- Anomalous enhancement is not sensitive to T.

Invariant-Mass Spectrum

Nishimura, MK, Kunihiro ('22)





- ☐ Strong enhancement at low invariant mass.
- ☐ **Observable in the HIC?**

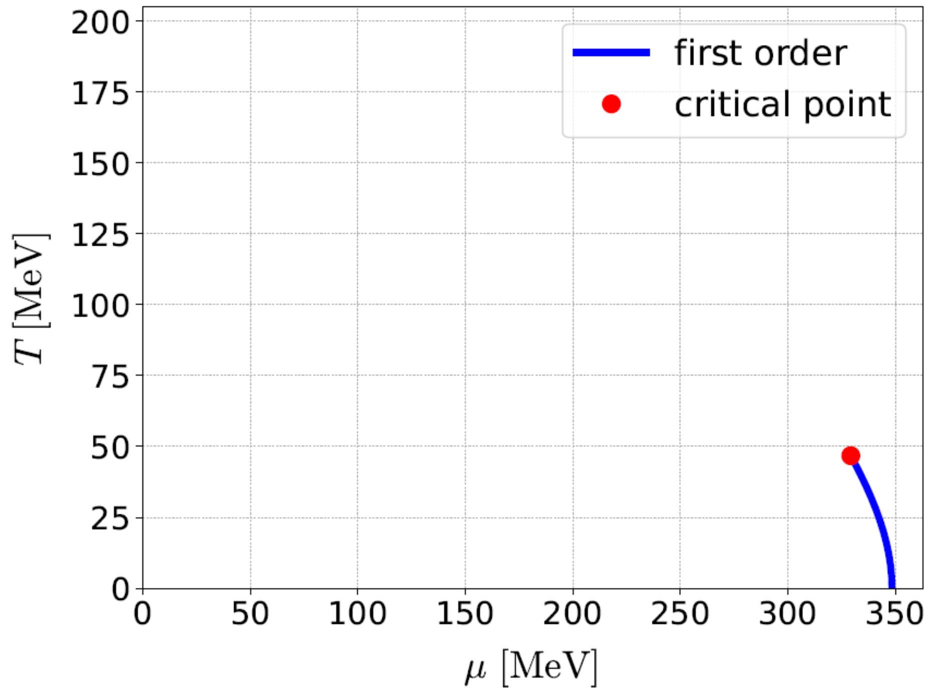
Dileptons from QCD Critical Point

NJL model (2-flavor)

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + G_S\left((\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right)$$

Parameters

$$G_S = 5.5\ \mathrm{GeV}^{-2},\ \Lambda = 631\mathrm{MeV},\ m_q = 5.5\ \mathrm{MeV}$$

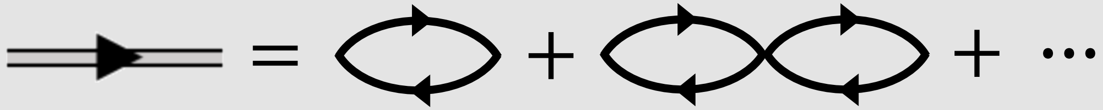


Soft Mode of QCD-CP

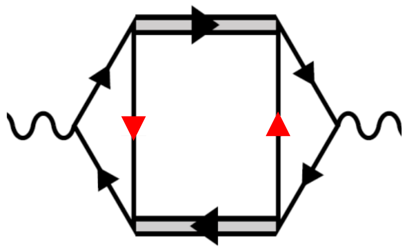
= fluctuation of scalar $(\bar{q}q)$ channel

$$D^R(x) = \langle[\bar{\psi}\psi(x), \bar{\psi}\psi(0)]\rangle\theta(t) =$$ 

- Random Phase Approximaion



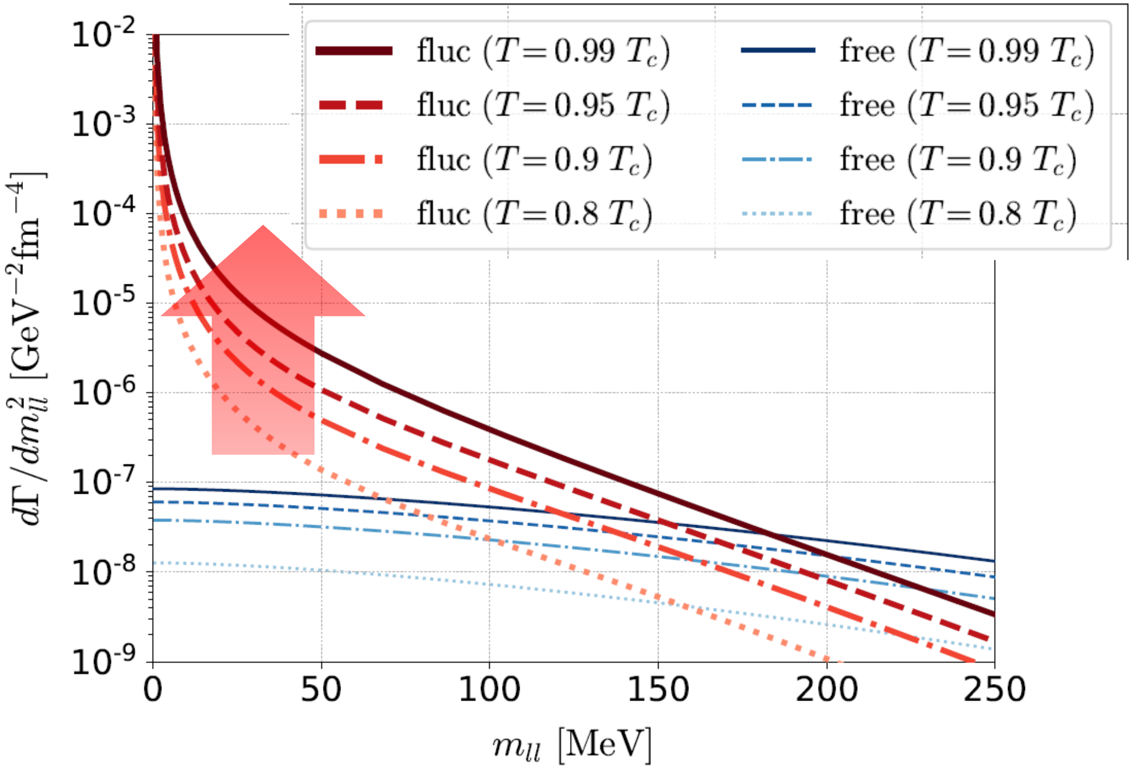
Modification of dilepton production through

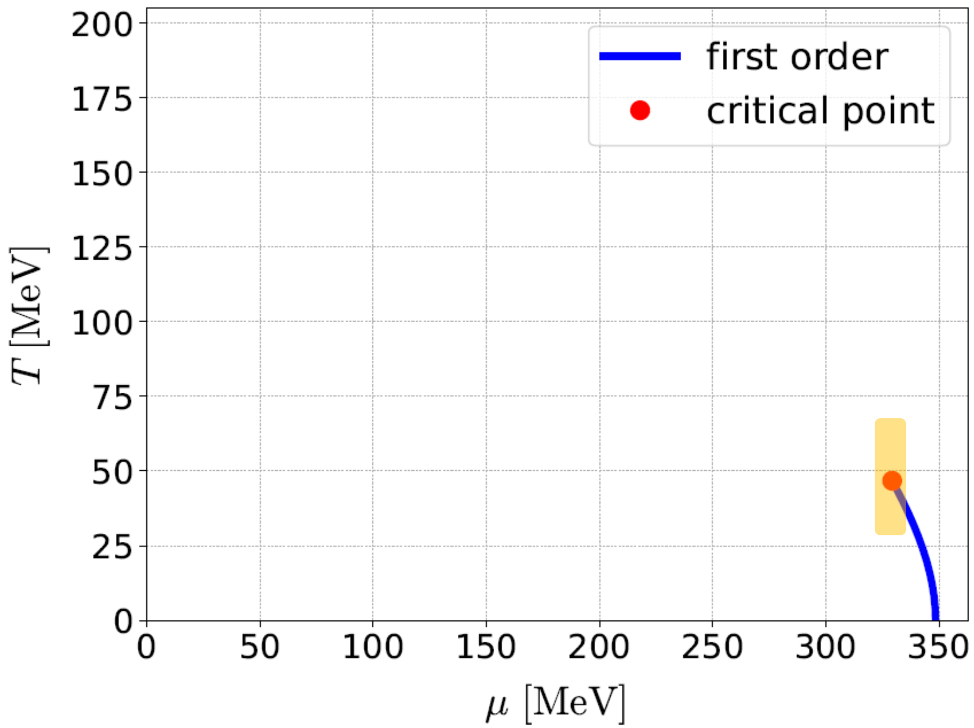


Dilepton production rate near QCD-CP

Nishimura, MK, Kunihiro ('23)

Invariant mass spectrum

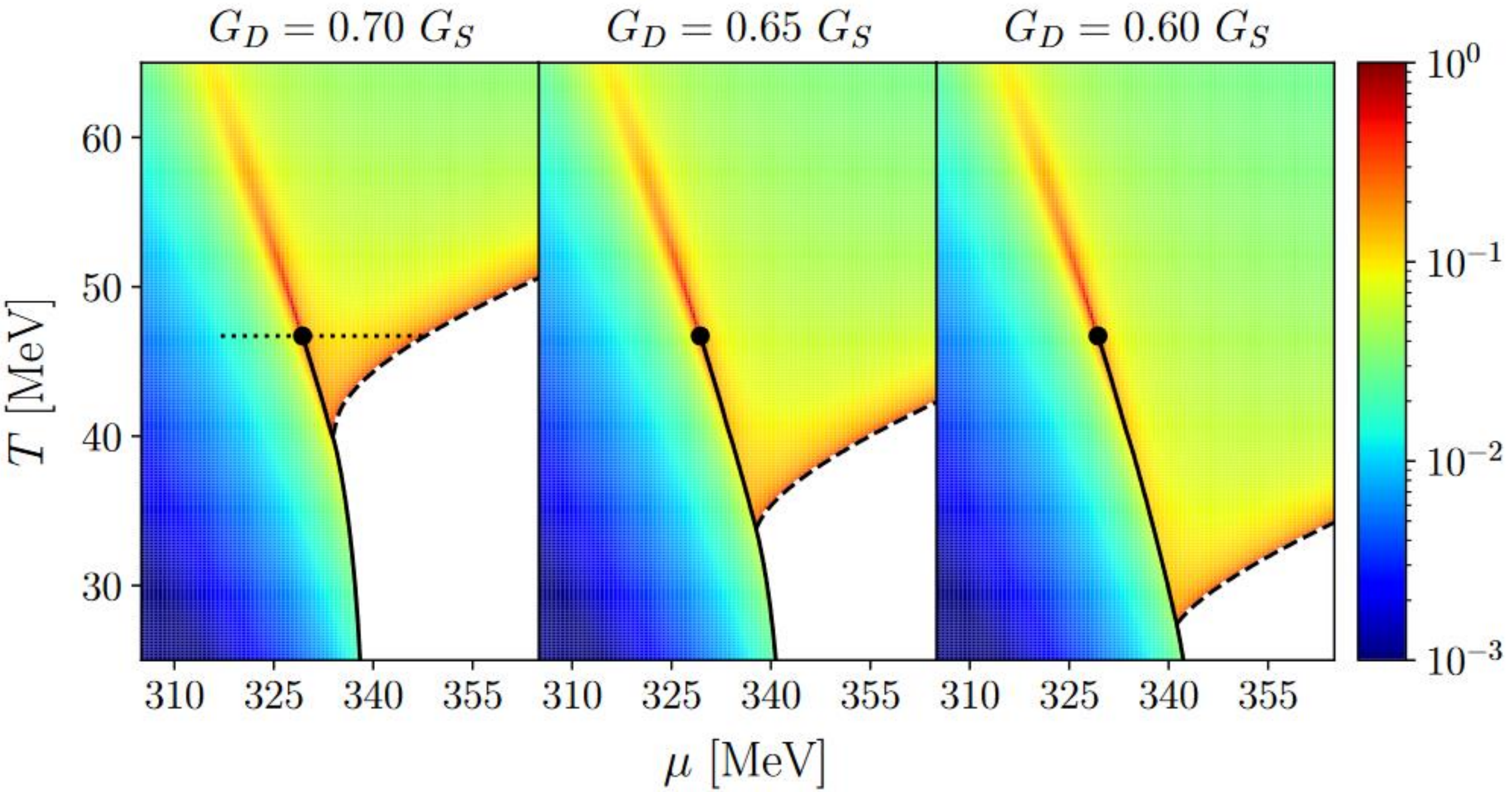




for fixed chem. pot.: $\mu = \mu_c$

- ☐ Enhancement at low M_{ll} region near QCD-CP
- ☐ Distinguishment from diquark soft mode may be difficult.

Electric Conductivity on QCD Phase Diagram



Nishimura, MK, Kunihiro ('24)

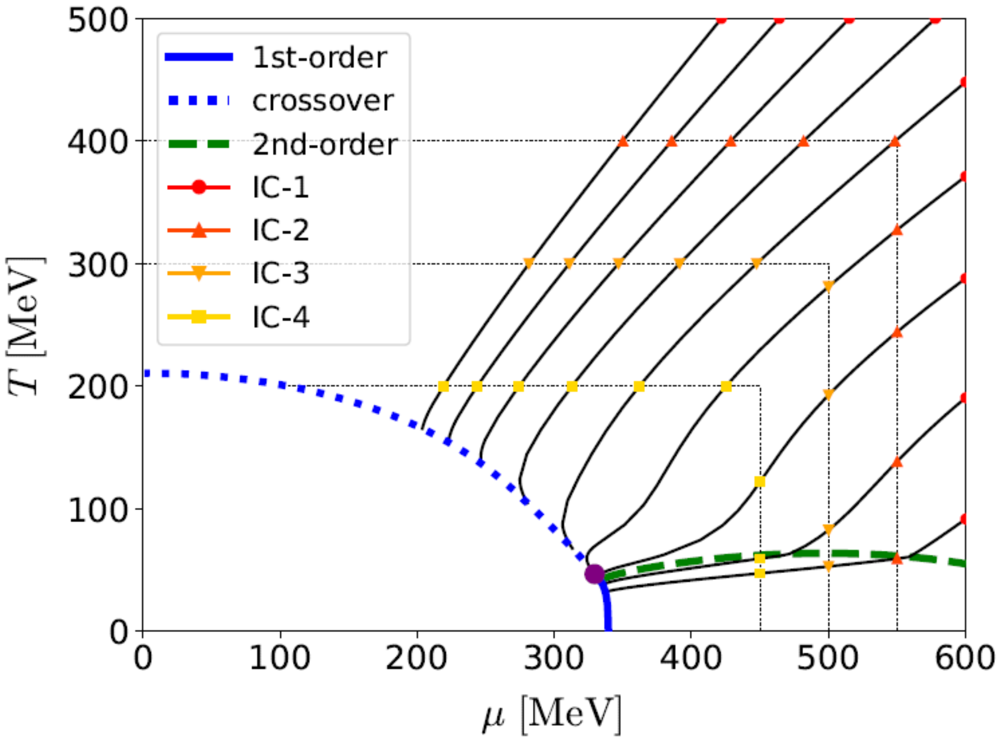
- DPR in the low-energy limit = electric conductivity
- Two "hot spots" on the T-μ plane

Dilepton Yields: Beam-Energy Scan

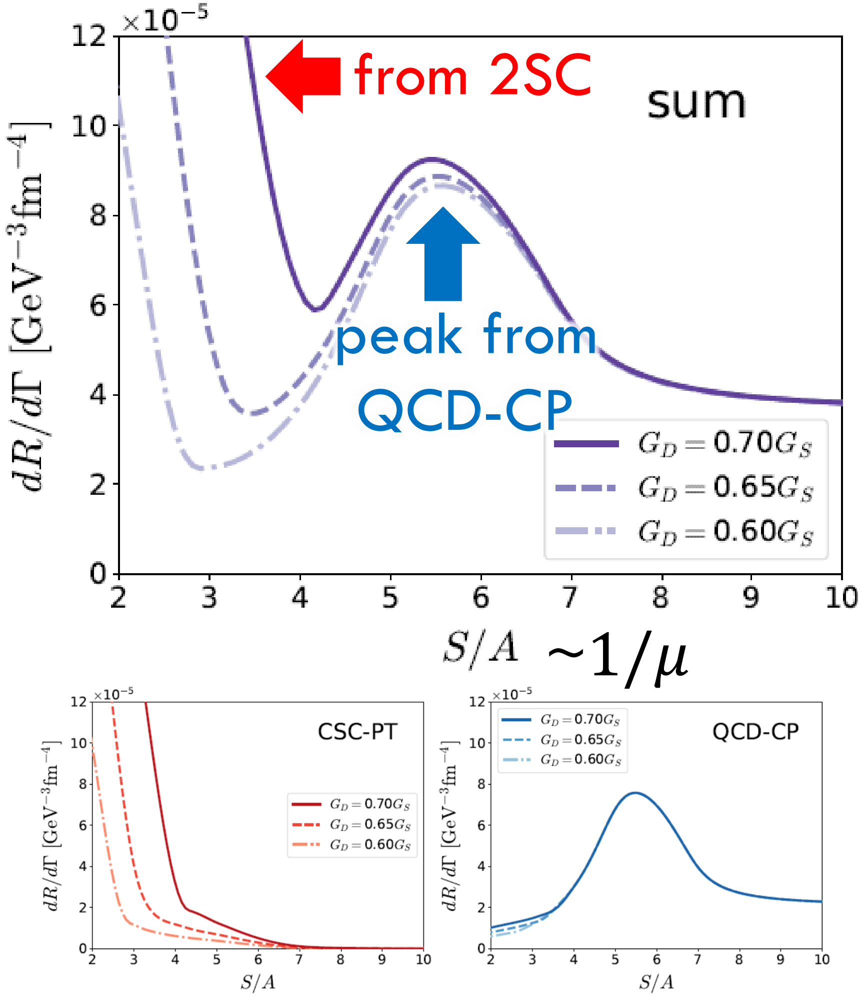
Dilepton yields
$\simeq$ integrated rate along isentropic lines

Nishimura, Nara, Steinheimer, Eur.Phys.J.A 60, 2024

Isentropic lines in NJL model



Dilepton Yields $50 < M < 100$ MeV



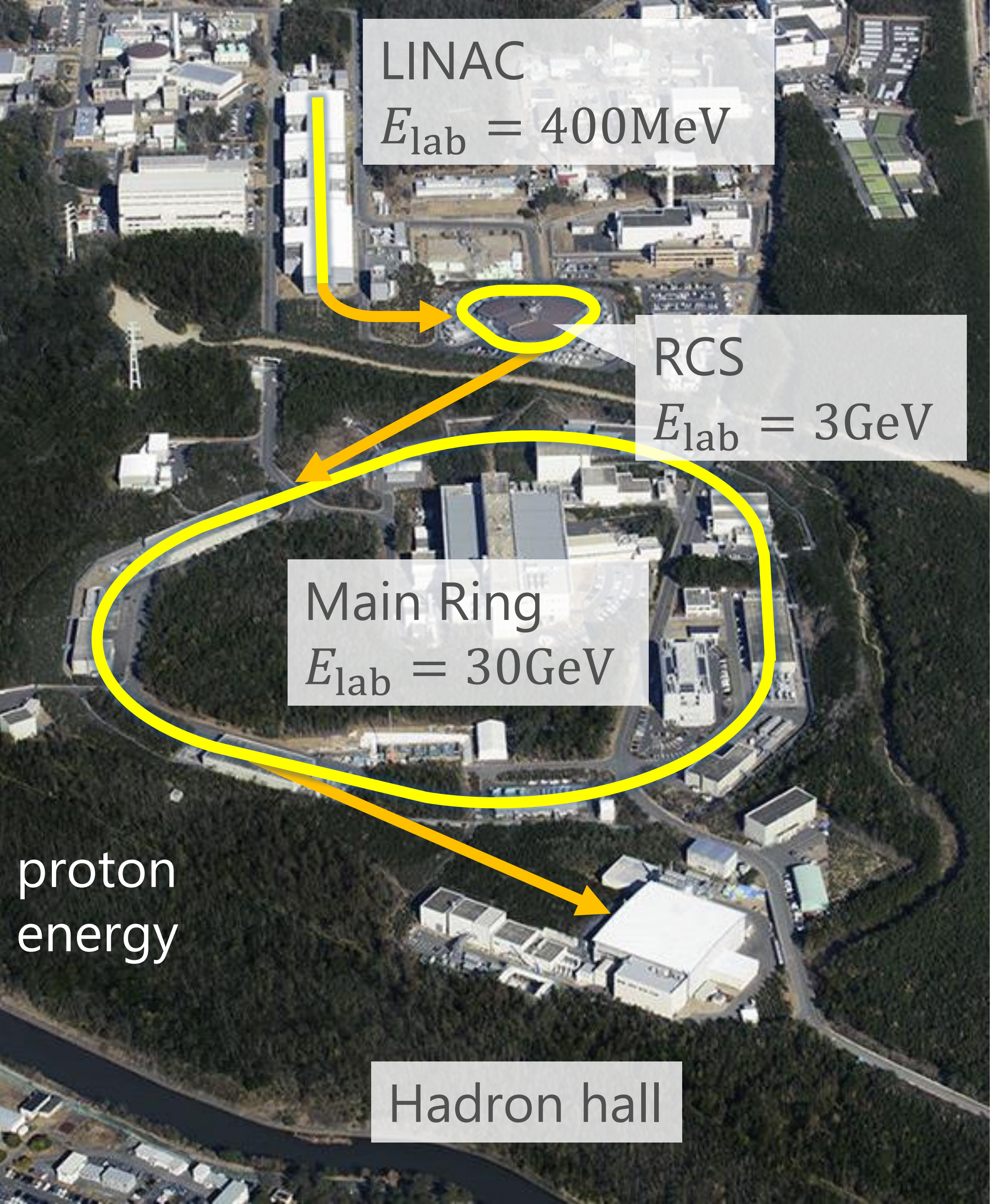
Summary

- QCD phase diagram has rich structures especially in the high-density region, such as the QCD critical point and color superconductivity.
- The beam-energy scan will reveal them.

- We performed a quantitative anaysis of the size and lifetime of the dense region.
  - $\sqrt{s_{NN}} \simeq 3\ \mathrm{GeV}$ may be optimal to investigate $\rho = 3{\sim}4\rho_0$.

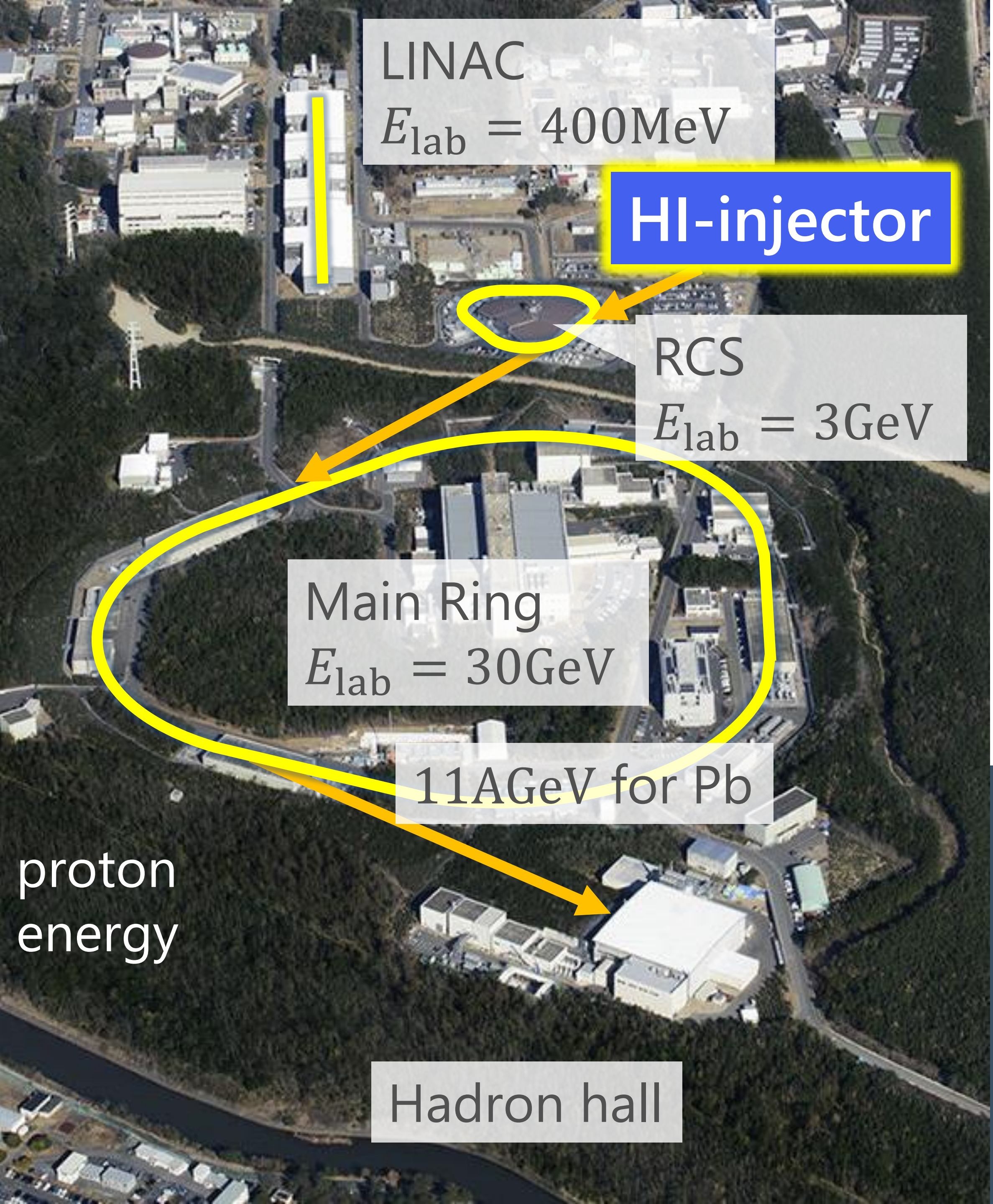
- Phase transitions in dense quark matter may be detectable as the enhancement of the dilepton production rate at ultra-low-mass-region.

J-PARC



Accelerators
- LINAC
- RCS
- Main Ring(MR)
- High intensity $I = 1\mathrm{MW}$

Purposes
- Hadron/Nuclear physics
- Neutrino physics
- Material/Life science



J-PARC

Accelerators
- LINAC
- RCS
- Main Ring(MR)
- High intensity $I = 1\text{MW}$

Purposes
- Hadron/Nuclear physics
- Neutrino physics
- Material/Life science

J-PARC-HI

J-PARC Heavy Ion Program

High intensity × Intermediate energy

J-PARC-HI Staging Plan

Phase-I

- KEK-BS booster
- E16+α spectrometer

Phase-II

- NEW HI booster
- NEW spectrometer