Baryonic Matter and Beyond

Kenji Fukushima
The University of Tokyo

Summary

Baryonic Matter

- □ Deconfinement at high T
- □ Nuclear matter
- □ Deconfinement at high μ

… and Beyond — Speculative Scenarios

- □ Critical point and/or modulation
- □ Strangeness
- □ Diquark mixture
- □ Chiral ("whatever you like") effect

Summary and Conclusion

Baryonic Matter

- □ Deconfinement at high T *What we believe we know*
- □ Nuclear matter *What we are supposed to know*
- □ Deconfinement at high μ *What we don't know*

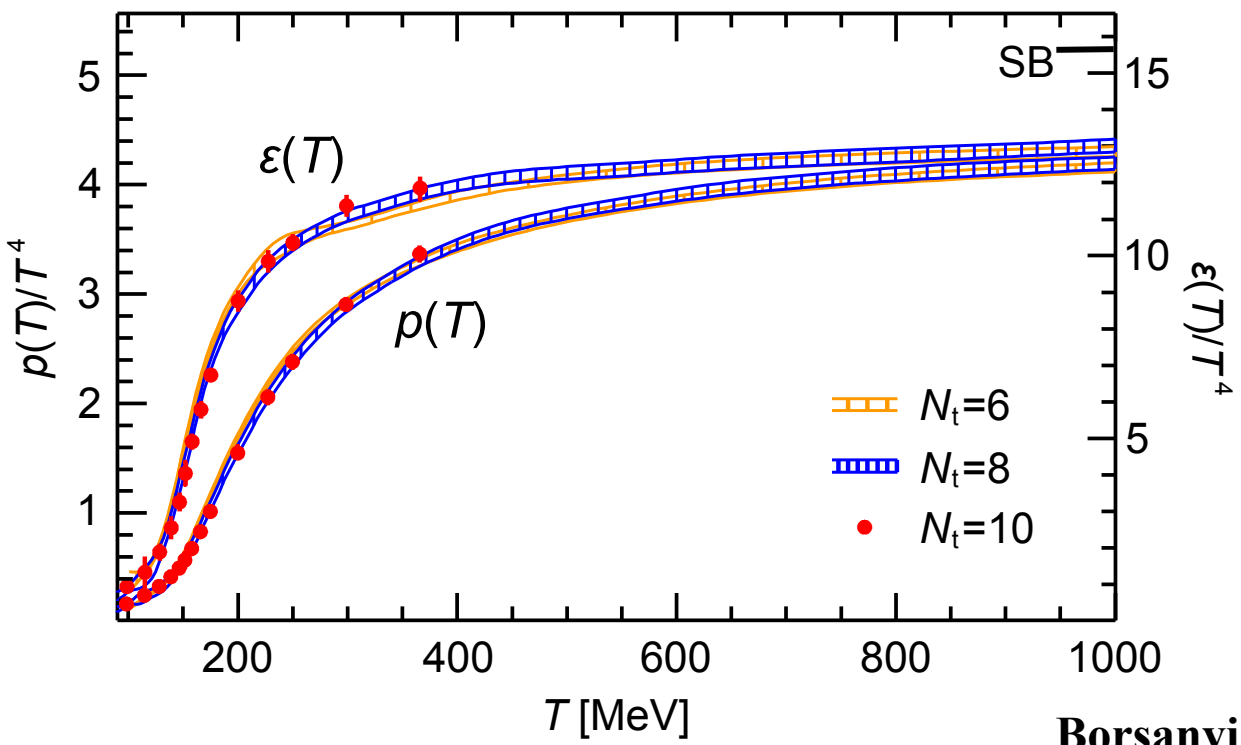
… and Beyond — Speculative Scenarios

- □ Critical point and/or modulation *Chiral symmetry*
- □ Strangeness *Baryon density and deconfinement*
- □ Diquark mixture *Exotic components*
- □ Chiral ("whatever you like") effect *Topological vacua*

Is "quarkyonic matter" real?

Baryonic Matter

Deconfinement at high T



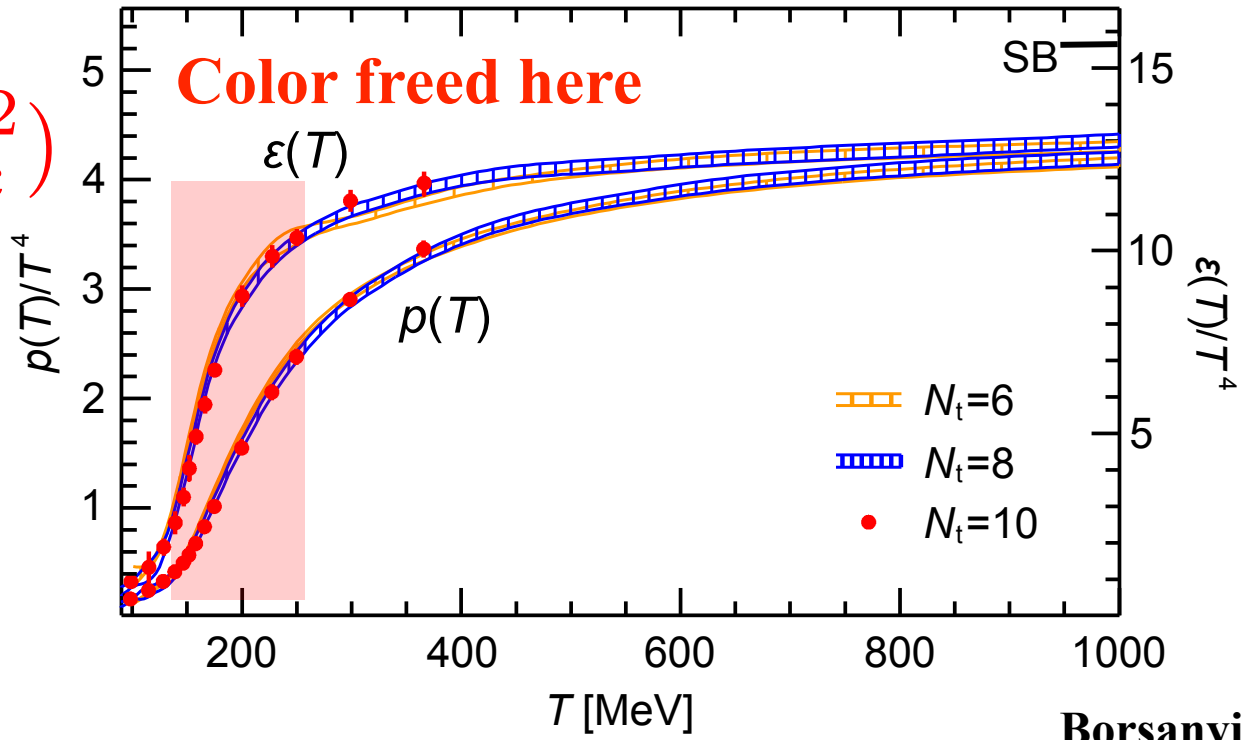
Borsanyi et al. (mod.)

Where would you find deconfinement?

Deconfinement at high T

$\mathcal{O}(N_c^2)$

$\mathcal{O}(1)$

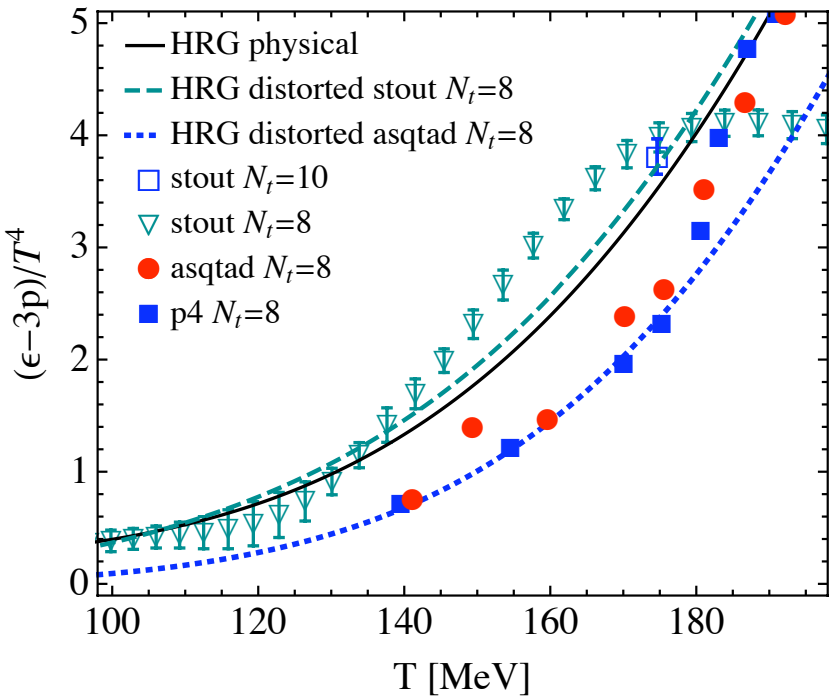


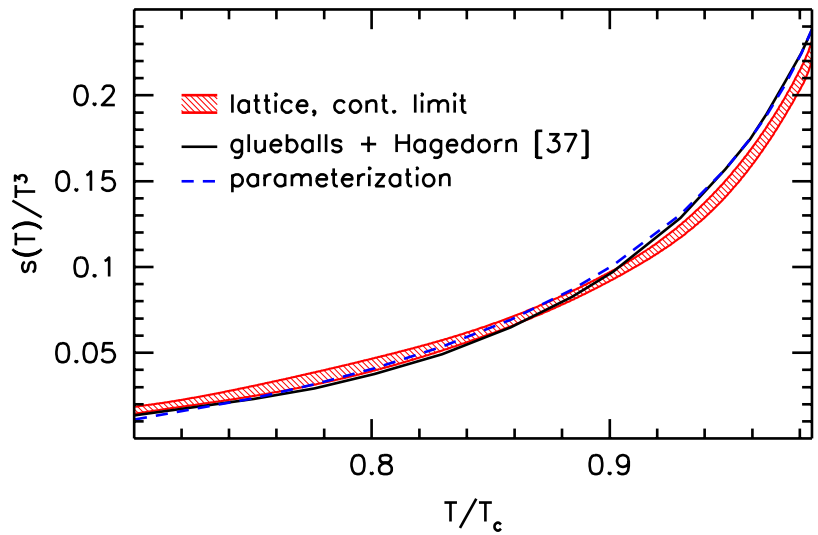
Borsanyi et al. (mod.)

More color → **More pressure**

Deconfinement at high T

Challenged by:



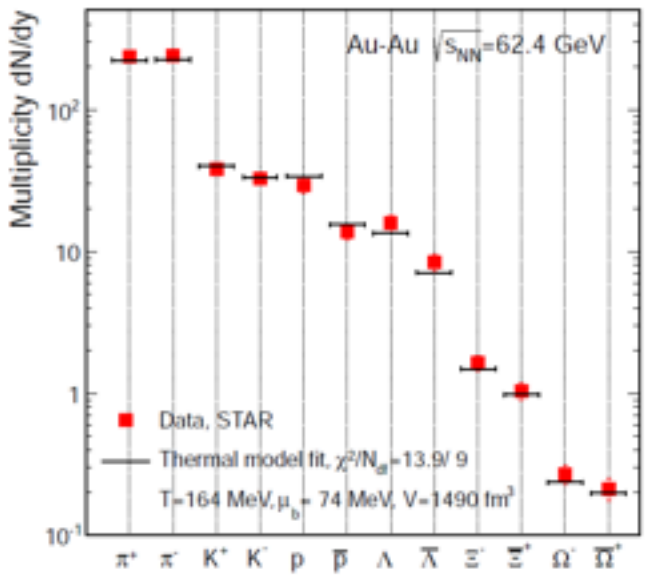


Borsanyi et al.

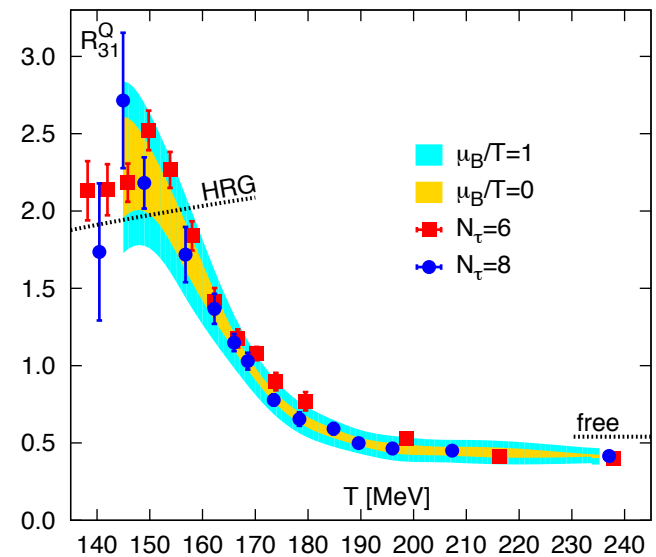
Hadron Resonance Gas (HRG)

Thermal Model Fit

Lattice meets phenomenology



OR

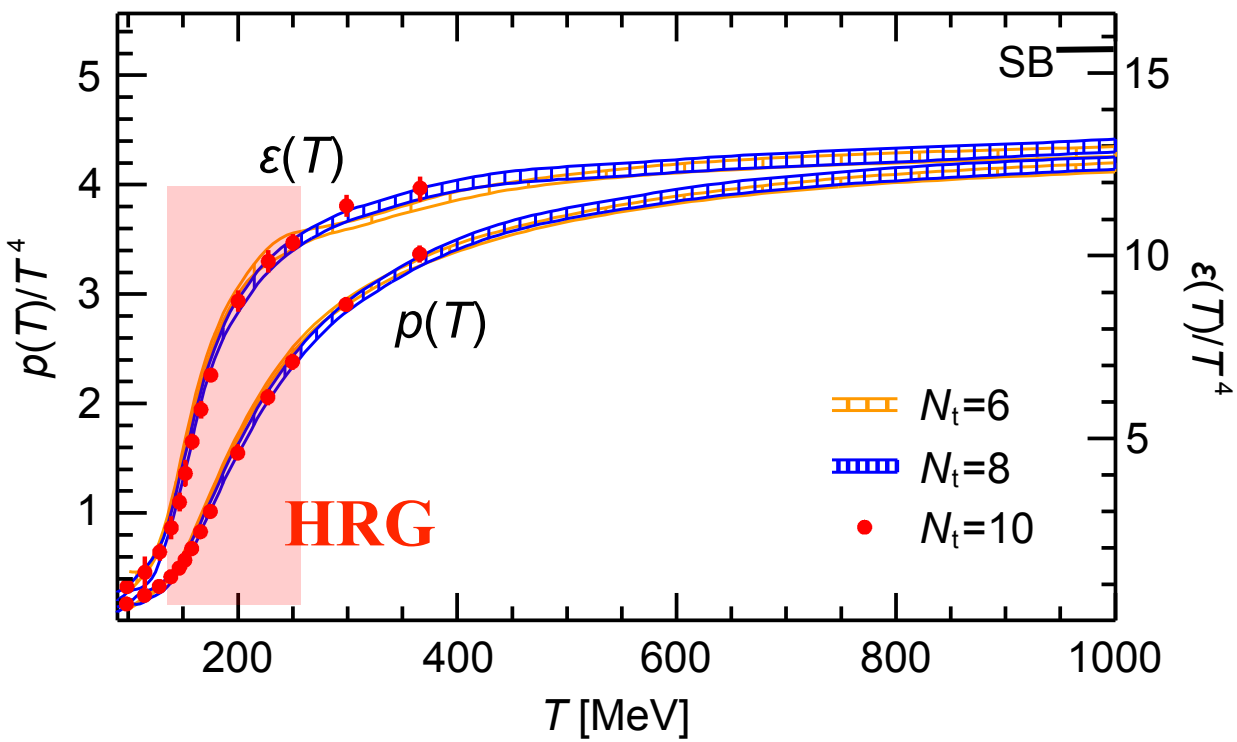


Andronic, Becattini, Cleymans, Redlich, Stachel, Braun-Munzinger, etc…

Bazavov et al.

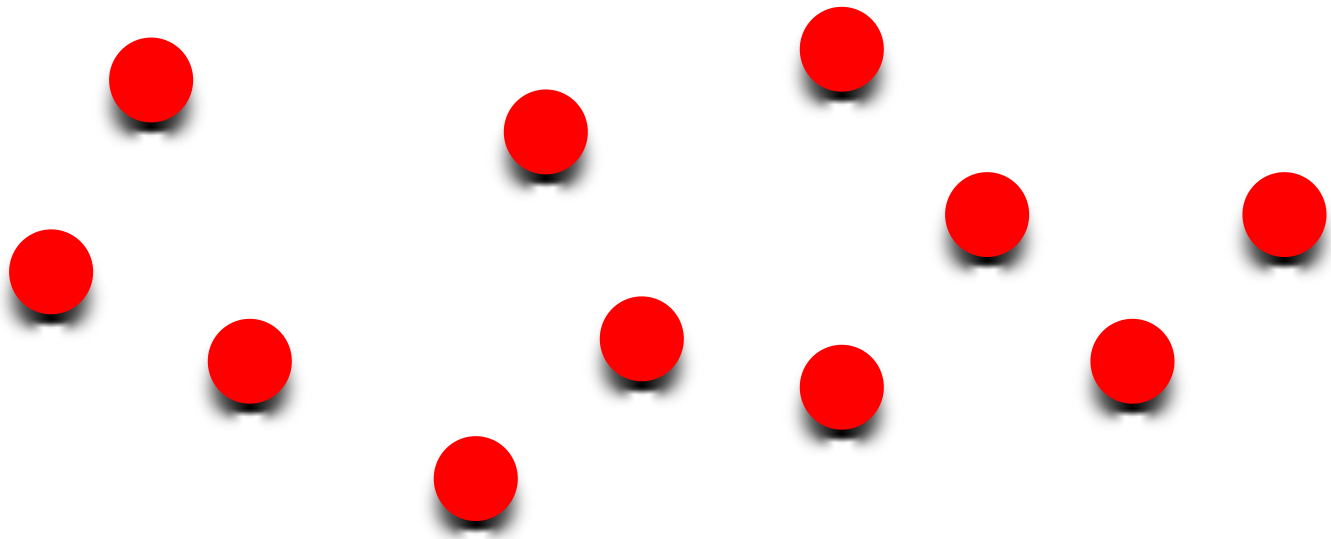
T, μ : fixed by the fit

Deconfinement at high T



More hadrons → **More pressure**

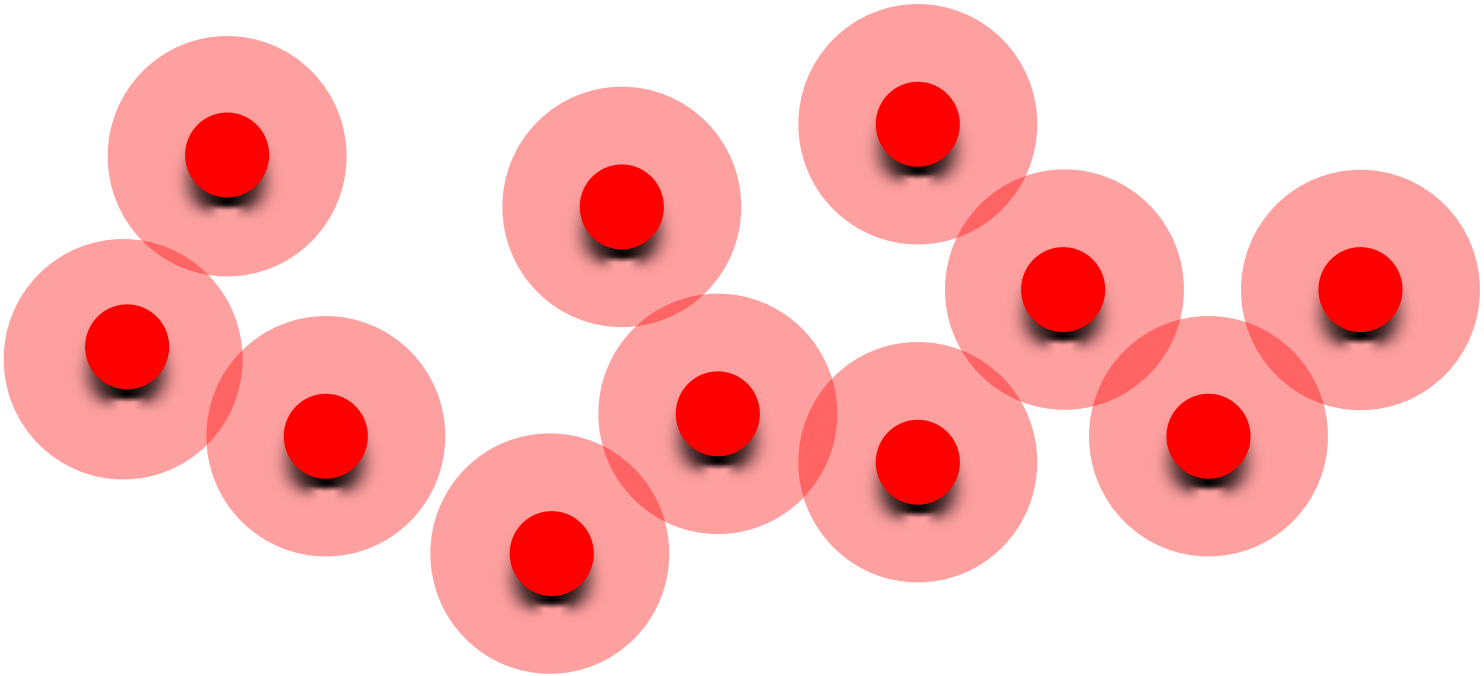
Deconfinement at high T



No interaction → No saturation

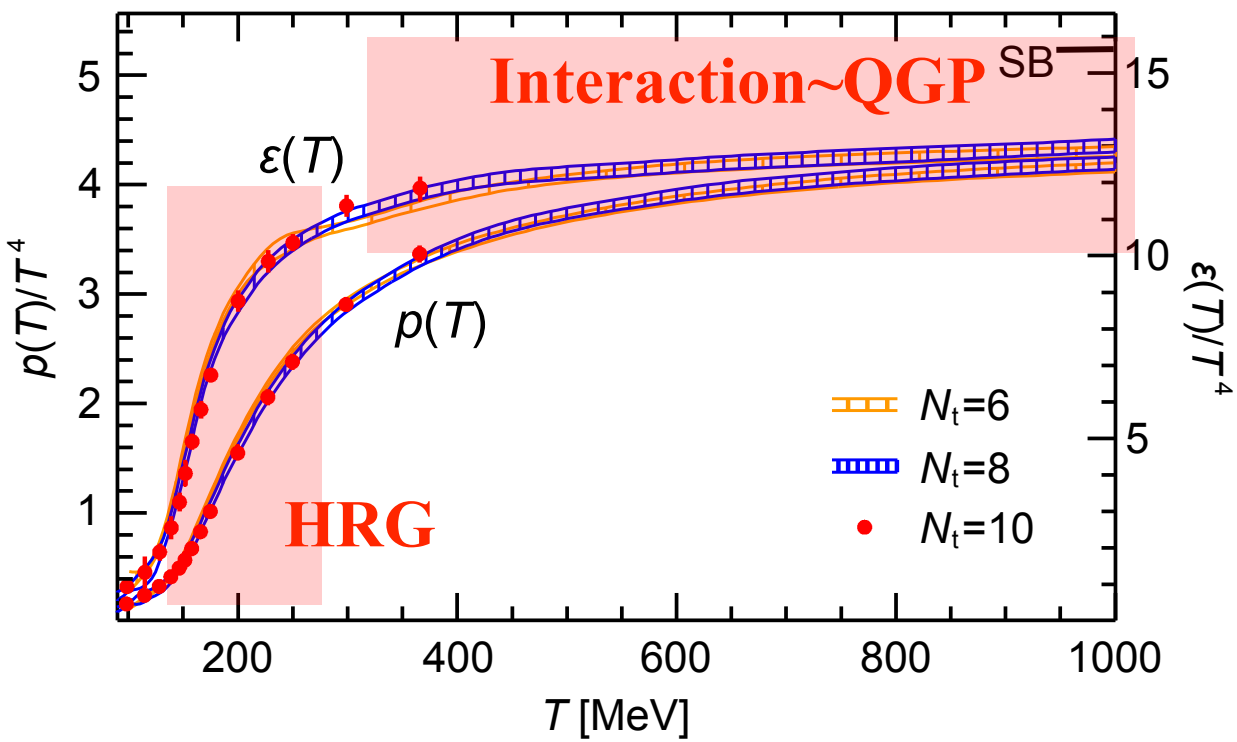
(Large-N_c QCD : Non-interacting mesons)

Deconfinement at high T



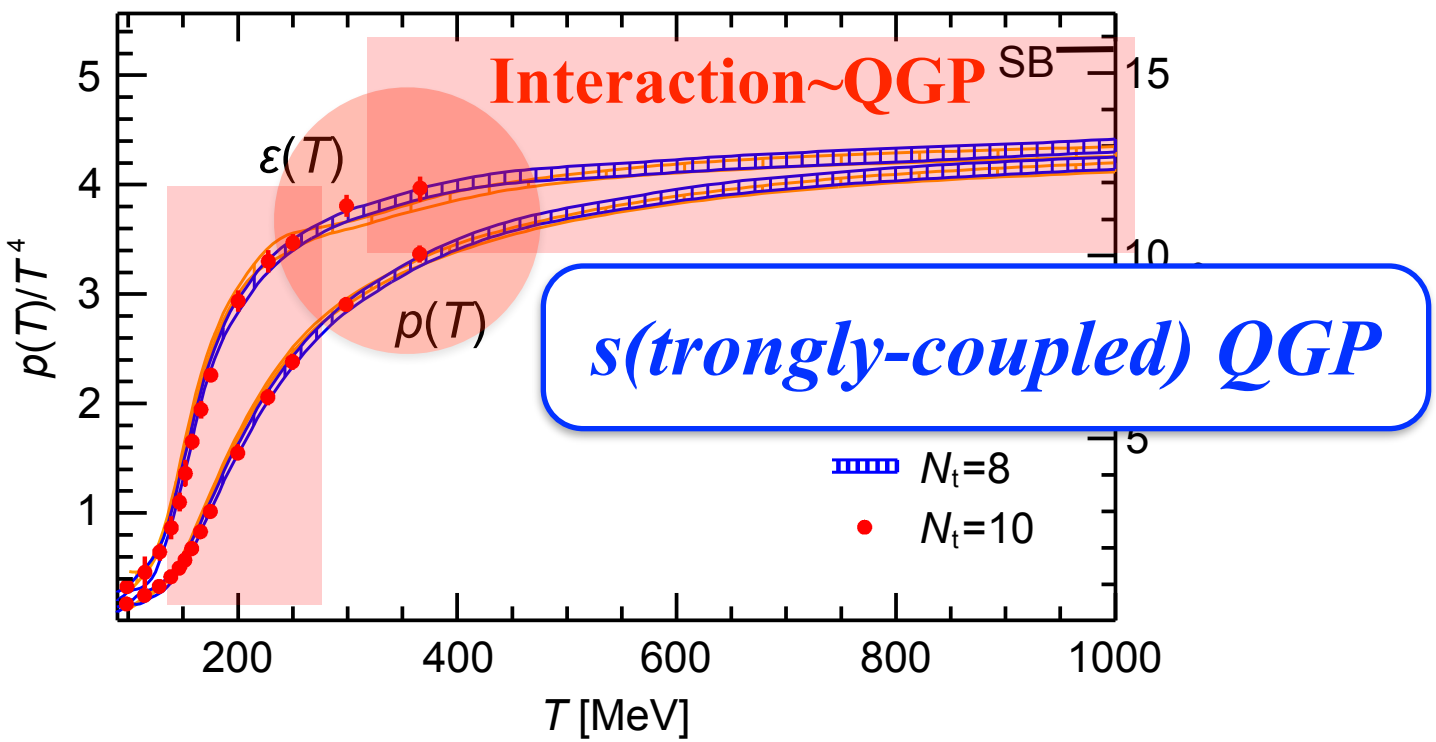
Elementary d.o.f. through interaction

Deconfinement at high T

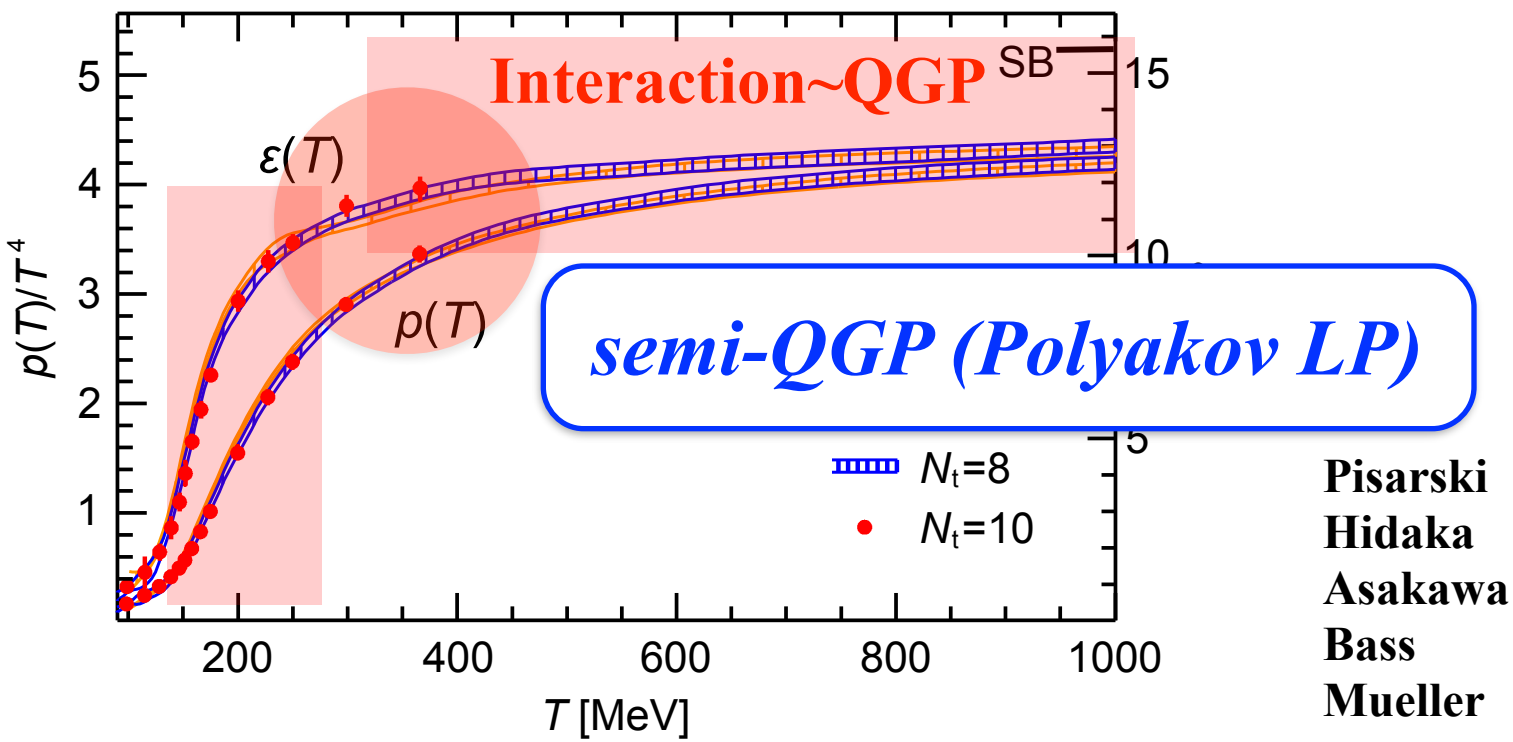


Interaction → Saturation → Deconfinement

Deconfinement at high T



Deconfinement at high T

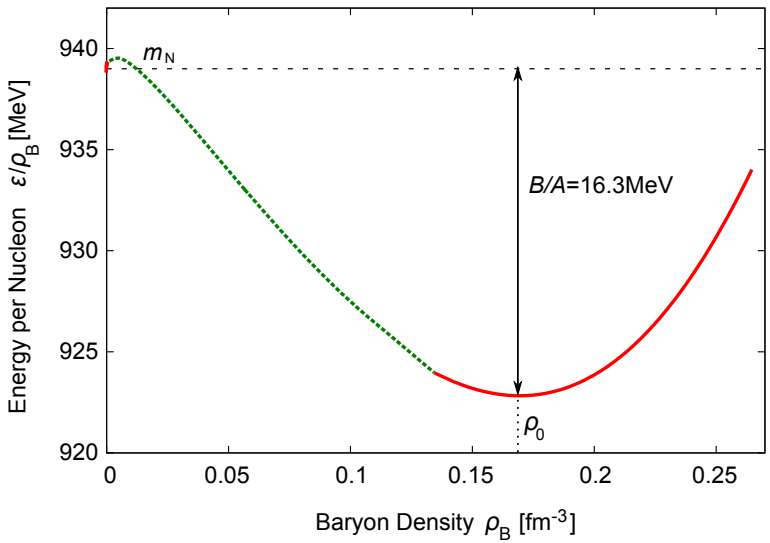


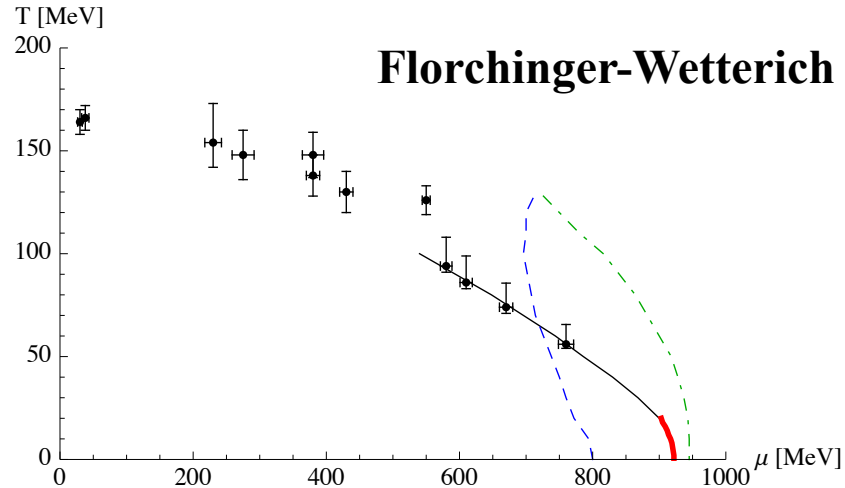
Pisarski
Hidaka
Asakawa
Bass
Mueller

Now ready to go to finite density!

Nuclear matter (symmetric)

Self-bound Fermi System

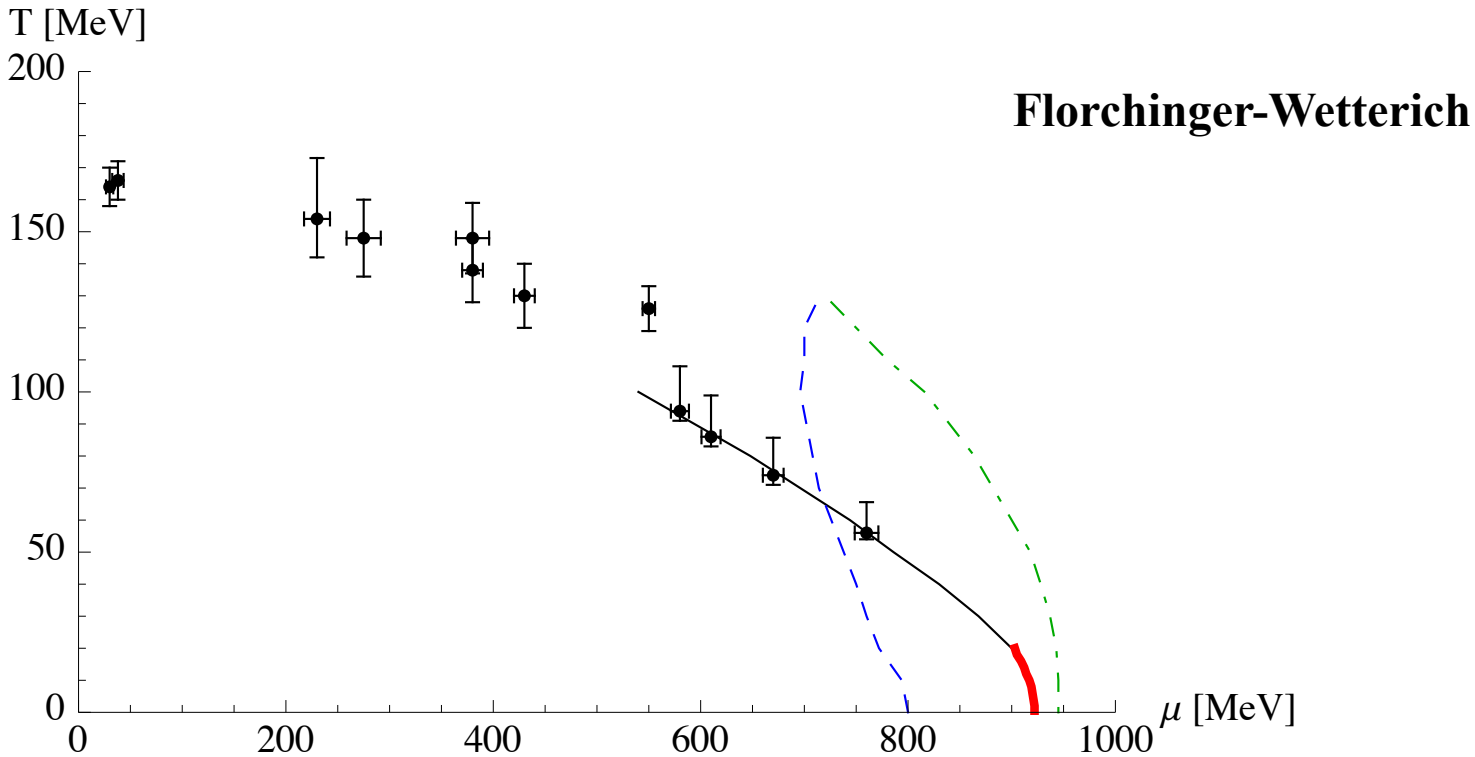




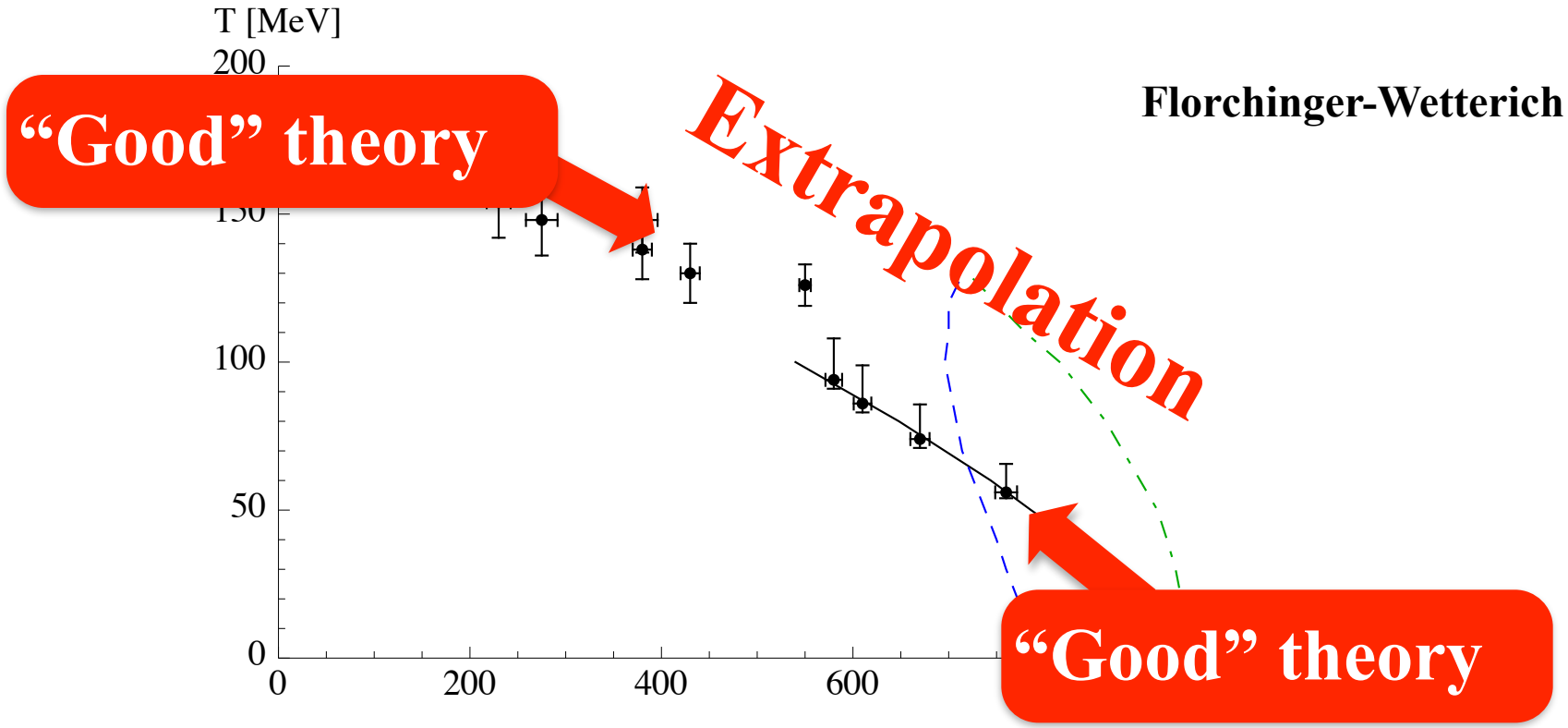
First-order Liquid-Gas

Critical point (Phase diagram)

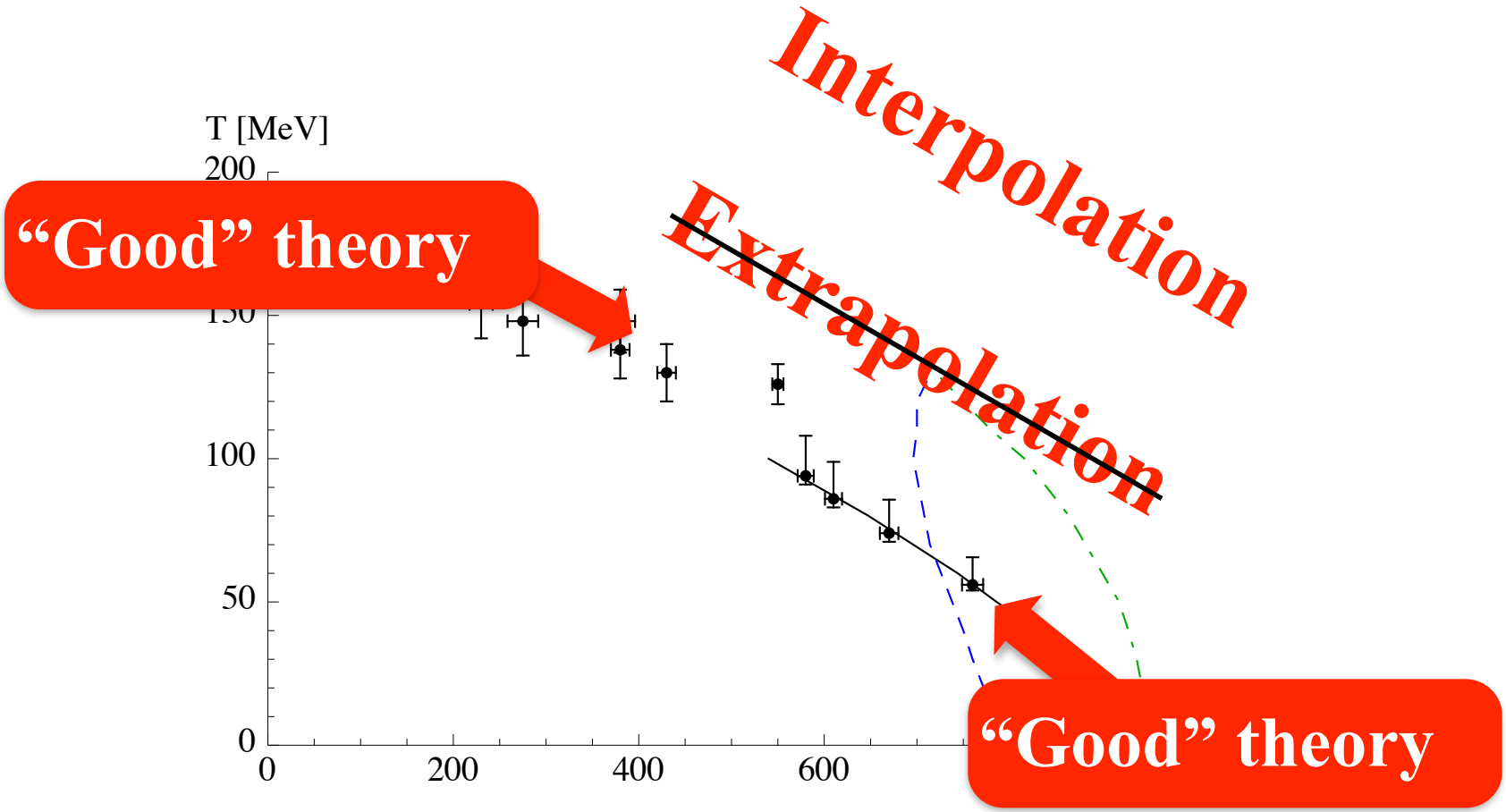
Nuclear matter (symmetric)



Nuclear matter (symmetric)

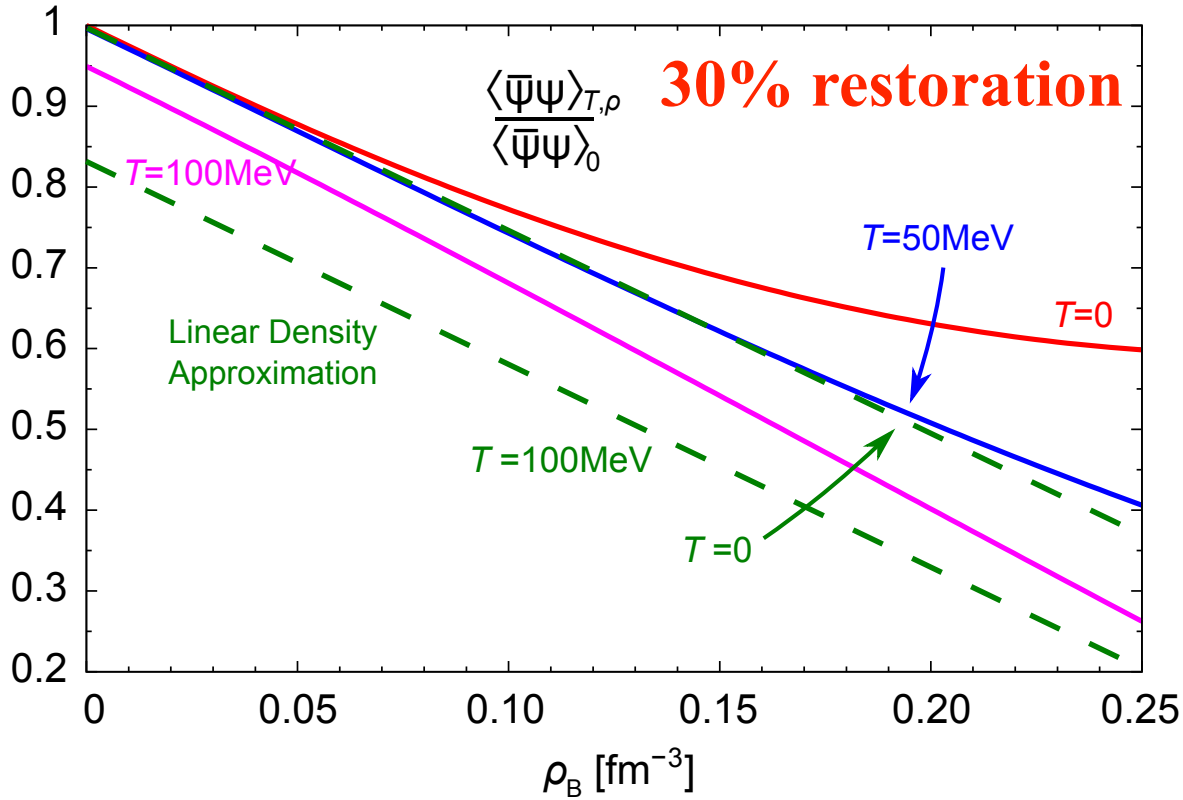


Nuclear matter (symmetric)



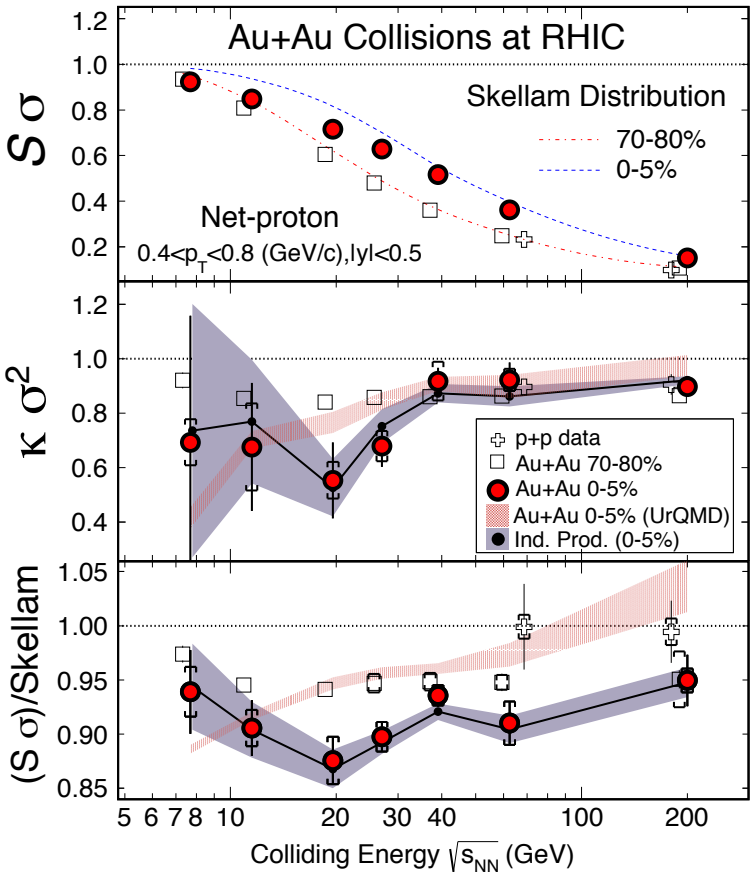
In-medium chiral condensate

"Reliably" calculable with χPhT



Weise et al. (modified)

STAR Beam-Energy-Scan



STAR

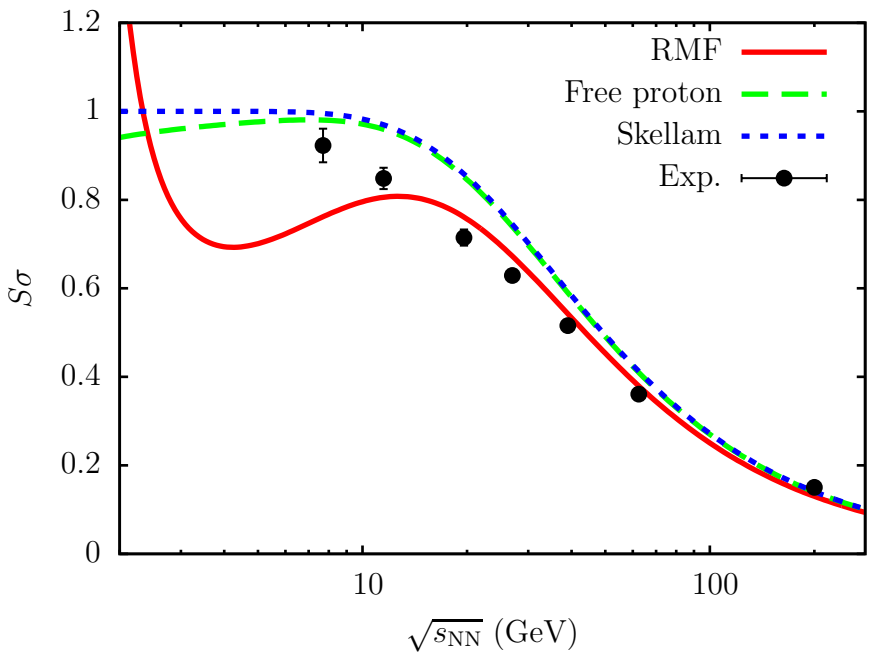
$$N = N_p - N_{\bar{p}}$$

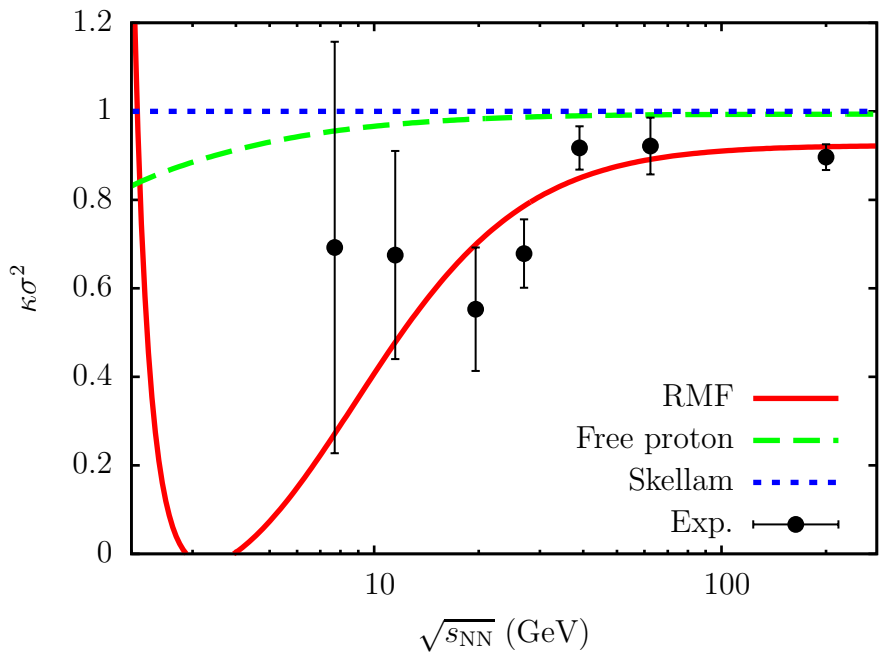
Skellam Poisson Poisson

Skewness	$\tanh(\mu/T)$
Kurtosis	1

Extra(inter)polation from nuclear matter?

STAR Beam-Energy-Scan

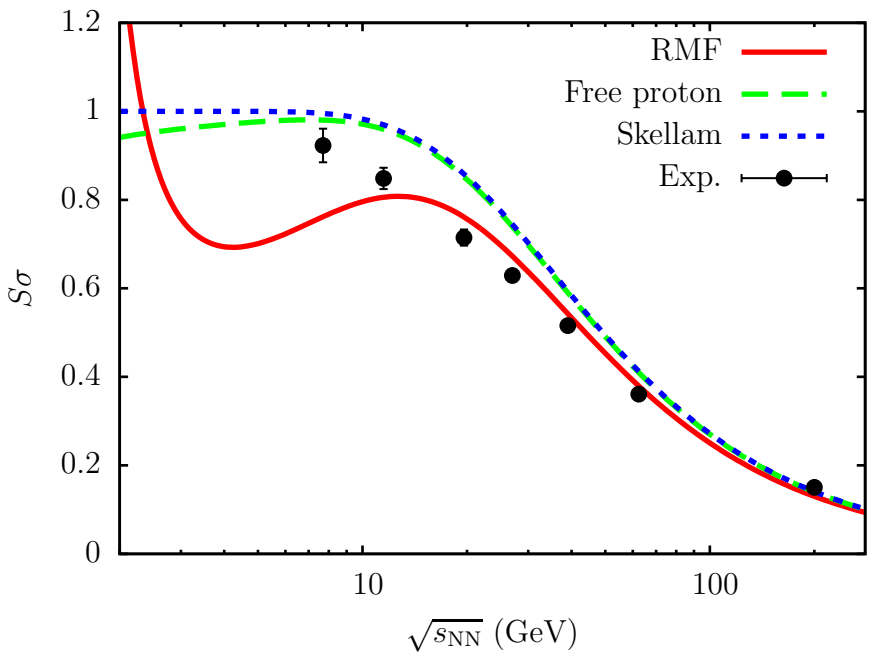


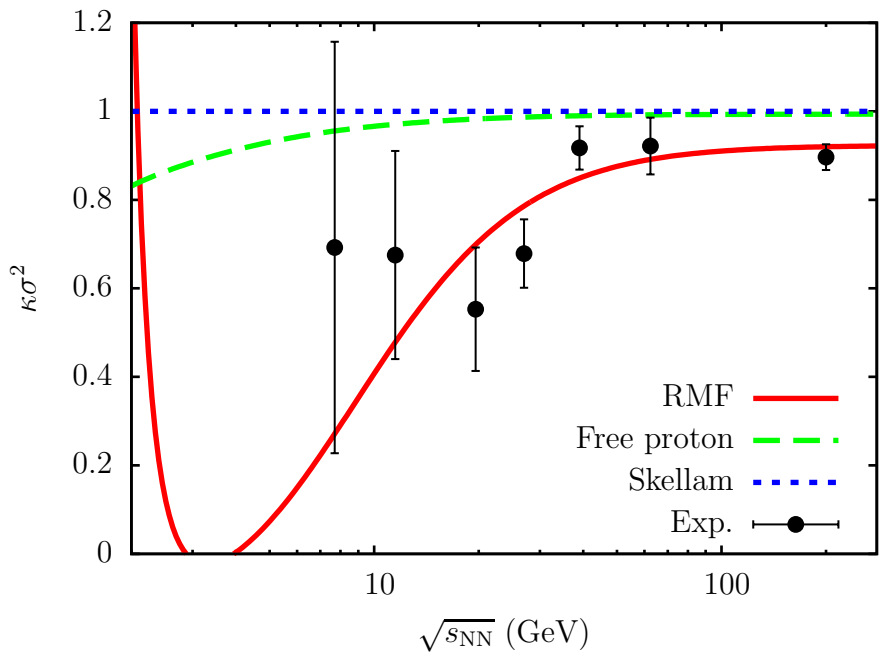


KF-Sasaki

Quasi-particle + Interaction (mean-field)

STAR Beam-Energy-Scan

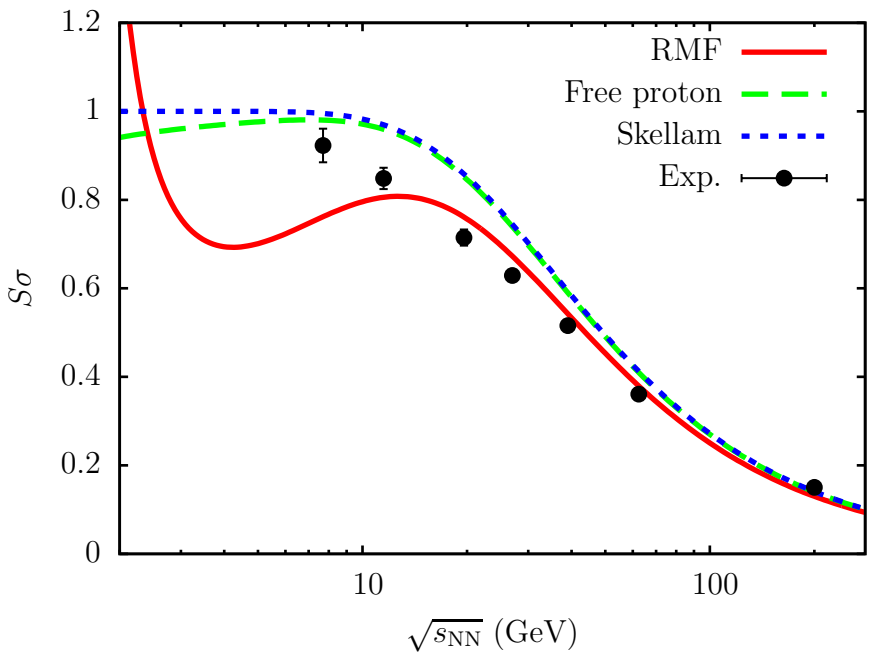


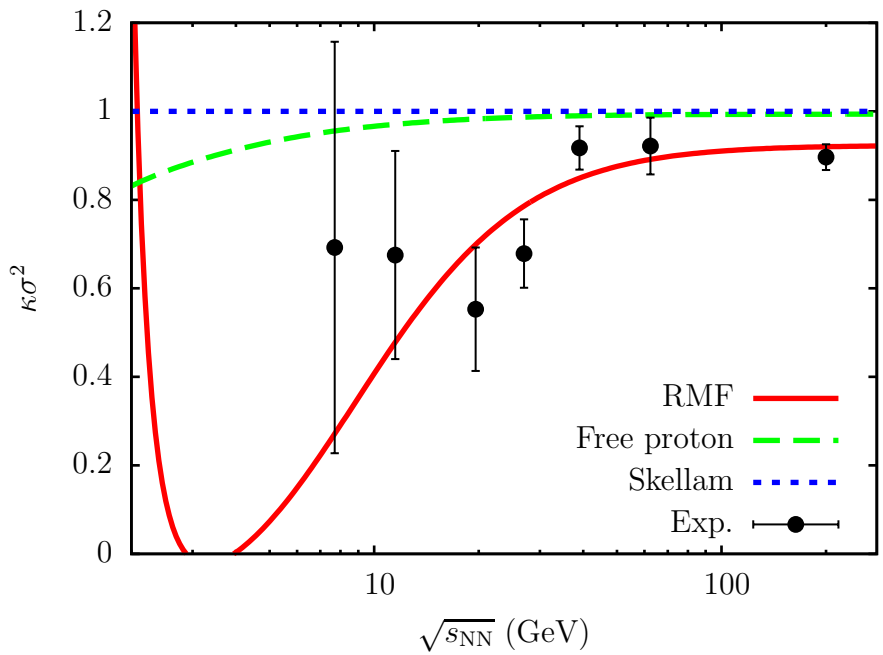


KF-Sasaki

A crazy idea?

STAR Beam-Energy-Scan





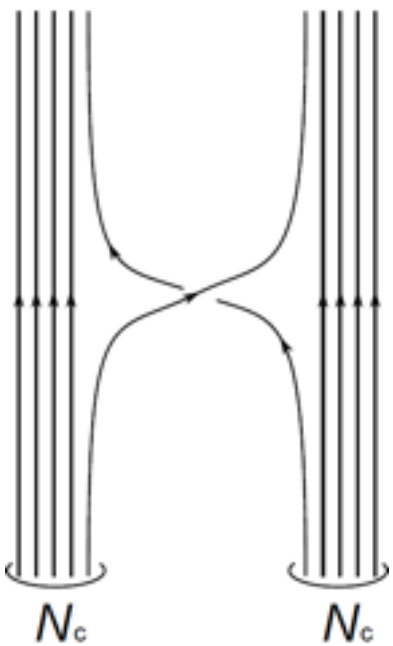
KF-Sasaki

A crazy idea?
Maybe, but not more crazy than …
More calc with χPhT needed

Deconfinement at high μ

Where would you find quarks?

$\mathcal{O}(1) \longrightarrow \mathcal{O}(N_{\rm c})$



$N_{\rm c}\Lambda_{\rm QCD}^4$

(Interacting) Baryonic matter

Quark matter

Deconfinement at high μ

Where would you find quarks?

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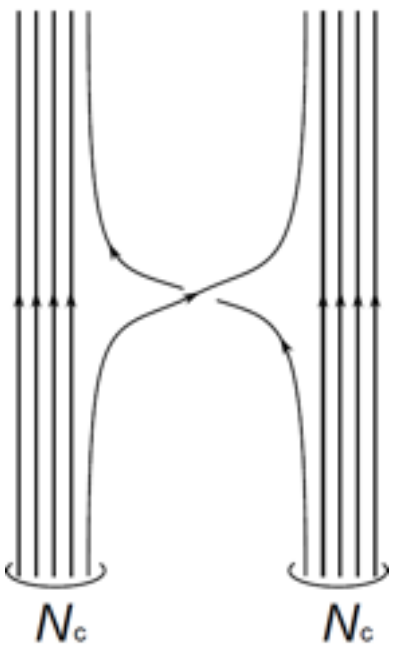


$N_{\rm c}\Lambda_{\rm QCD}^4$

McLerran, Pisarski
Hidaka, Kojo

(Interacting)
Baryonic matter

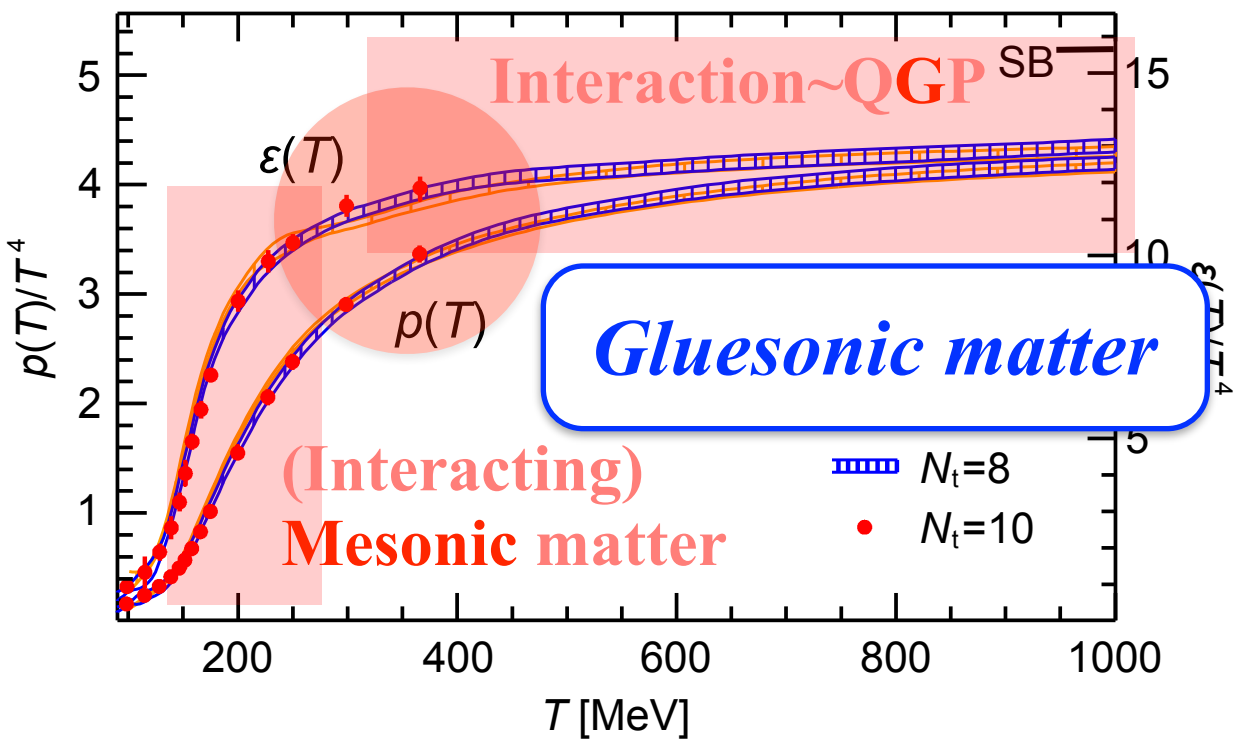
↓

Quarkyonic matter

↓

Quark matter

Deconfinement at high T



Quarkyonic ~ a counterpart of sQGP

Deconfinement at high μ

Coulomb phase / Confining phase ~ Higgs phase

Decofinement ***Hadron*** ***CSC***

- **pQCD at high μ → Color Super Conductivity**

  Fermi surface + Attractive interaction

- **pQCD without CSC → IR catastrophe**

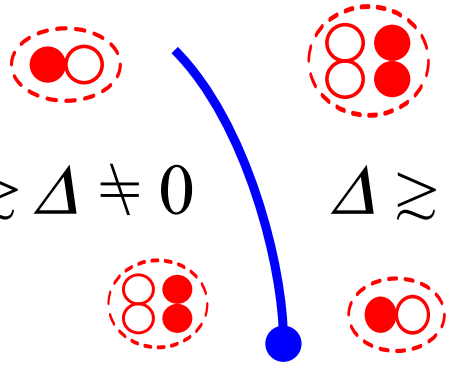
  Non-perturbative for magnetic gluons
  CSC parametrically enhanced

Son

cf. Kurkela-Romatschke-Vuorinen $(\mu_q > 1\ \mathrm{GeV})$

Deconfinement at high μ

U(1)A Broken



We can never see color

$\sigma \gtrsim \Delta \neq 0$ $\Delta \gtrsim \sigma \neq 0$

induced by $\Delta^2\sigma$

quark-hadron continuity

Schafer-Wilczek / Berges et al.
Hatsuda et al.

Superfluid Nuclear Matter
(pairing interaction)

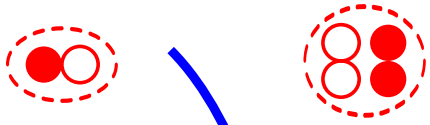
CFL (all gluon screened)

2SC ~ pure YM (confining gluon)

Rischke-Son-Stephanov

Deconfinement at high μ

U(1)A Broken



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CSC **Quarkyonic**

… and Beyond
— Speculative Scenarios —

Critical point and/or modulation

Critical enhancement

- □ Fluctuation measurement (of conserved quantities)

First-order transition

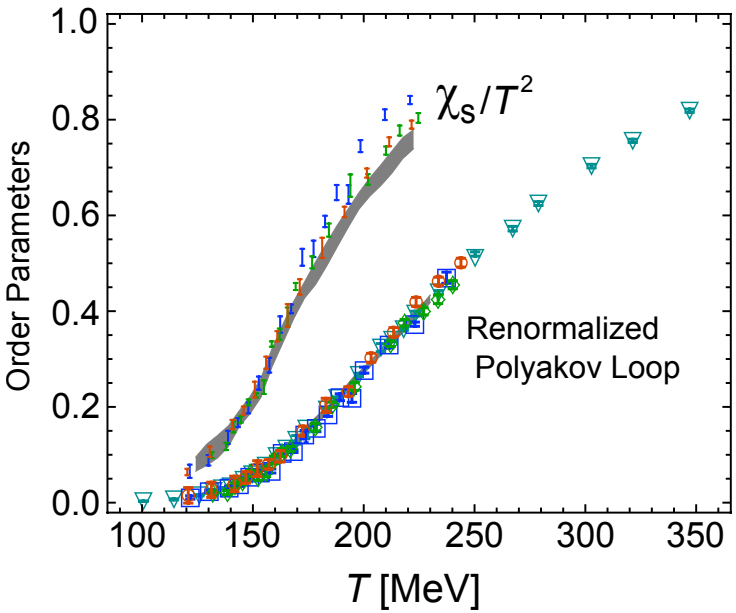
- □ Mixed state ~ Inhomogeneity (no practical difference)
- □ Density bubbles — fluctuations and harmonics
- □ **Caloric flattening, Fisher/Δ scalings (interacting nucleons ~ non-interacting fragments)**

Chiral symmetry restoration

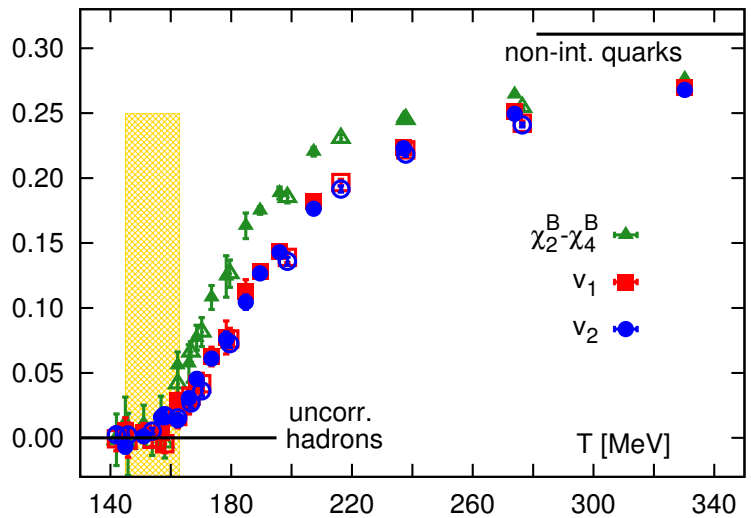
- □ In-medium hadron properties (V-A mixing / sum rules)
- □ Physics of not gluons but quarks — topological effect

Strangeness

Measure of Quark Deconfinement



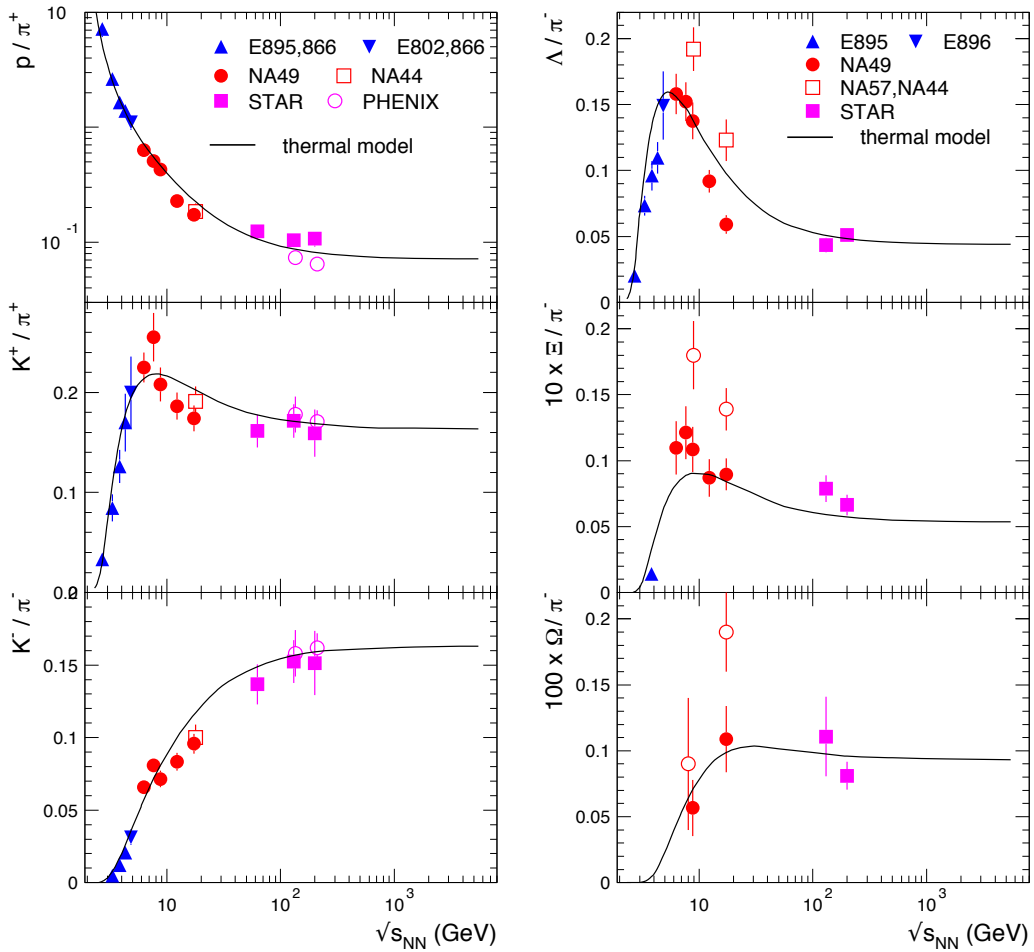
Borsanyi et al. (modified)



Bazavov et al.

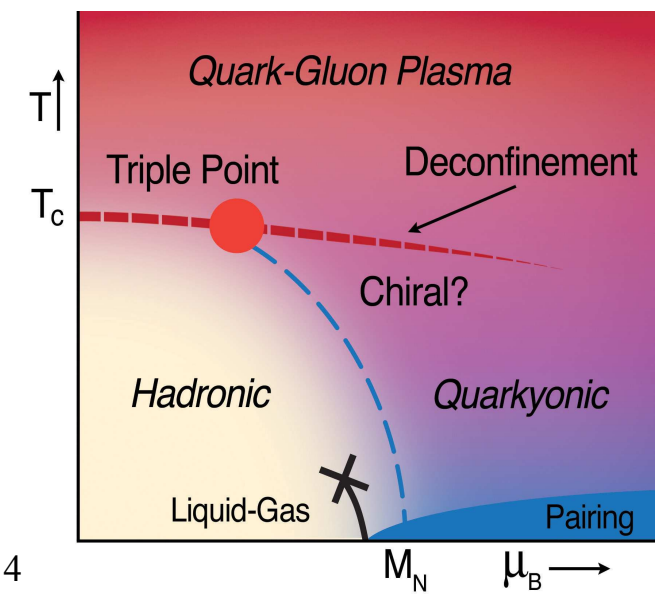
Strangeness

Measure of Baryon Density

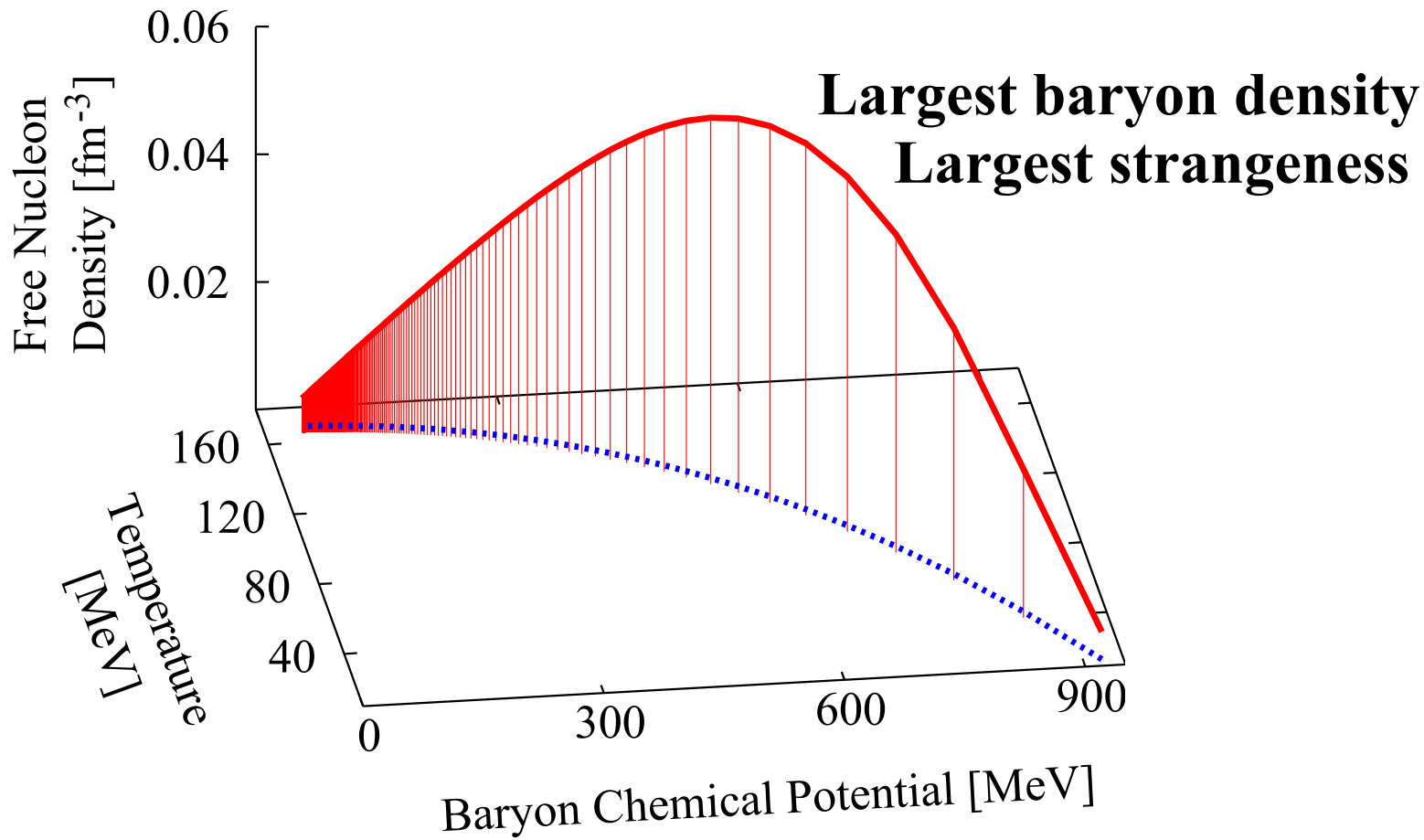


Baryon density

- → **More Λ (s)**
- → **Canceled by anti-s**
- → **Strangeness μ_s**



Non-trivial trivial



Deconfinement at high μ

Higher Density

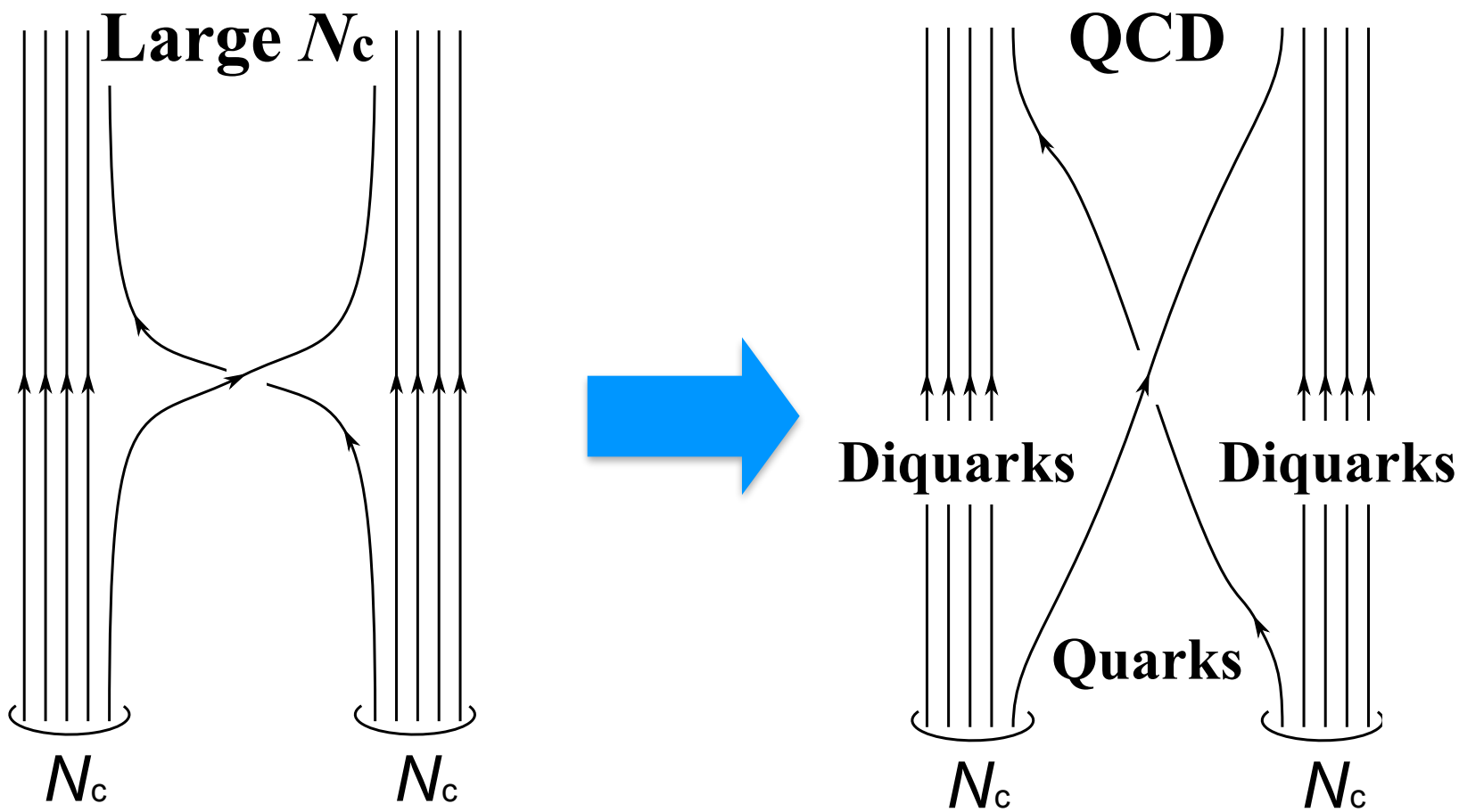
→ **More Strangeness**

→ **Smoother Deconfinement**

(cf. center symmetry)

Quarkyonic (counterpart of sQGP) widened

Diquark mixture



Diquark mixture

Nuclear matter = Quark + Diquark matter

A model easily built
… but …
Difficult to avoid diquark cond.

Bentz, Ishii, Yazaki
Baym, Kojo, Pawlowski
etc…

Who is in trouble if CSC lives close to NM?

Diquark mixture

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Diquarks strike back?

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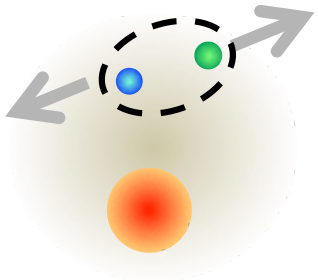
Who is in trouble if CSC lives close to NM?

Diquarks strike back?

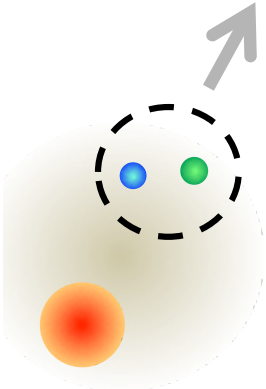
💕 CSC 💗 Quarkyonic 💕

cf. Diquark search at J-PARC

ρ-mode



λ-mode



Hosaka et al.

Spectroscopy of Q-(qq) system (~ Λc)

3-body geometry probed with Q

Chiral XXX Effects

$$\theta \, \boldsymbol{E} \cdot \boldsymbol{B}$$

Magnetoelectric Effect

$$\boldsymbol{E} \quad \Rightarrow \quad \boldsymbol{B}$$

$$\boldsymbol{B} \quad \Rightarrow \quad \boldsymbol{E}$$

Topological Insulator $\theta = \pi \quad (\mathrm{Cr_2O_3})$

Chiral XXX Effects

$$\theta \, \boldsymbol{E} \cdot \boldsymbol{B}$$

Magnetoelectric Effect

In-medium θ, why not in HIC?

Topological Insulator $\theta = \pi \quad (\mathrm{Cr_2O_3})$

Chiral XXX Effects

Temperature is a geometrical effect

Density is a gauge effect ~ A_0

$$\boldsymbol{j} \propto \mu_5 \boldsymbol{B}$$

$$\boldsymbol{j}_5 \propto \mu \boldsymbol{B}$$

Local Parity Violation — zero net effect

Chiral Imbalance — finite net effect

Chiral XXX Effects

Zero-density

$$\langle \boldsymbol{j} \rangle = 0$$

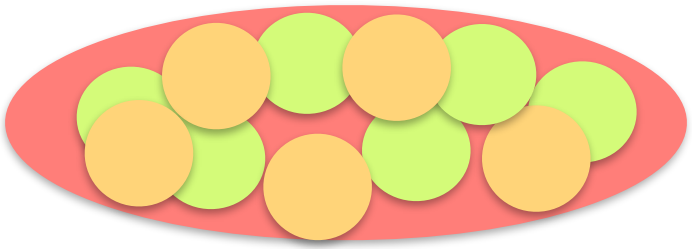
$$\boxed{\langle \boldsymbol{j}^2 \rangle \neq 0}$$

Finite-density

$$\langle \boldsymbol{j}_5 \rangle \neq 0$$

$$\langle \boldsymbol{j}_5^2 \rangle \neq 0$$

Parity / Charge-parity even quantity



Chiral XXX Effects

Zero-density

$$\langle \boldsymbol{j} \rangle = 0$$

$$\langle \boldsymbol{j}^2 \rangle \neq 0$$

Finite-density

$$\langle \boldsymbol{j}_5 \rangle \neq 0$$

$$\langle \boldsymbol{j}_5^2 \rangle \neq 0$$

Chiral Magnetic Wave

Kharzeev-Yee

Finite density ~ More protons ~ Charge imbalance
Difficult to subtract the background effects

Chiral XXX Effects

Zero-density

$$\langle \boldsymbol{j} \rangle = 0$$

$$\langle \boldsymbol{j}^2 \rangle \neq 0$$

Finite-density

$$\boxed{\langle \boldsymbol{j}_5 \rangle \neq 0}$$

$$\langle \boldsymbol{j}_5^2 \rangle \neq 0$$

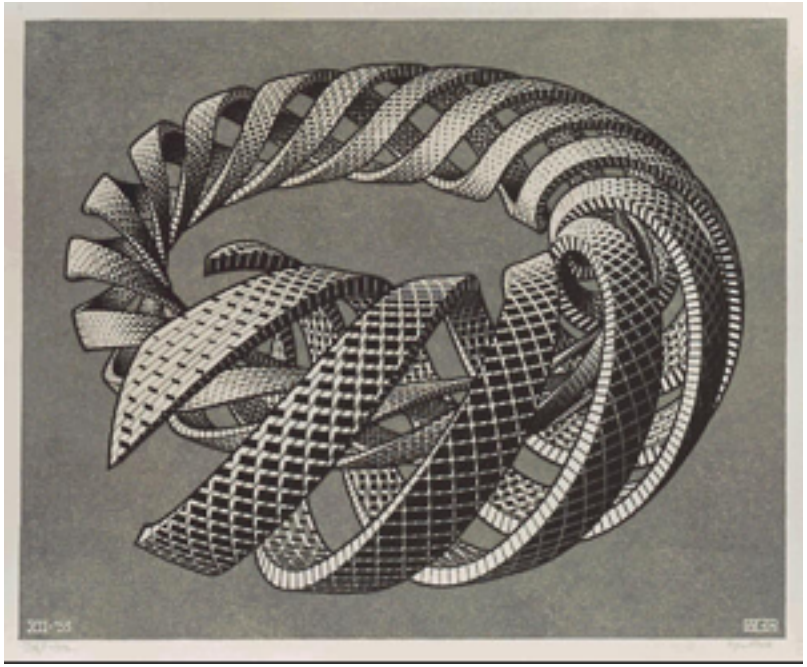
Axial-vector condensation (polarization)
Helicity transmutation (chiral symmetry)

Ohnishi-Yamamoto

Observable?

Chiral XXX Effects

Chiral (solitonic) Spiral

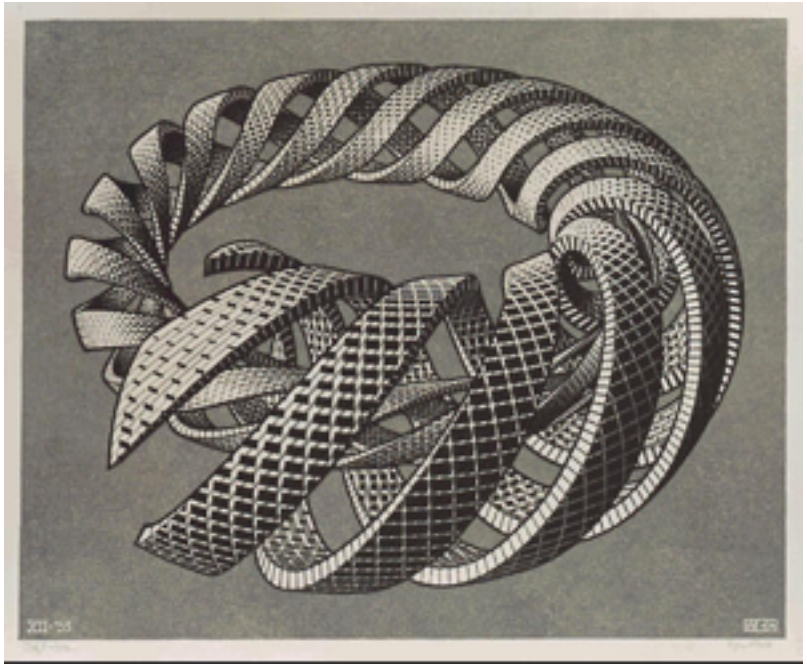


v.s. $\boldsymbol{j}_5 \neq 0$

Buballa, Carignano, Nakano, Tatsumi, etc etc…
Yamamoto (Lattice-QCD)

Chiral XXX Effects

Chiral (solitonic) Spiral



v.s. $j_5 \neq 0$

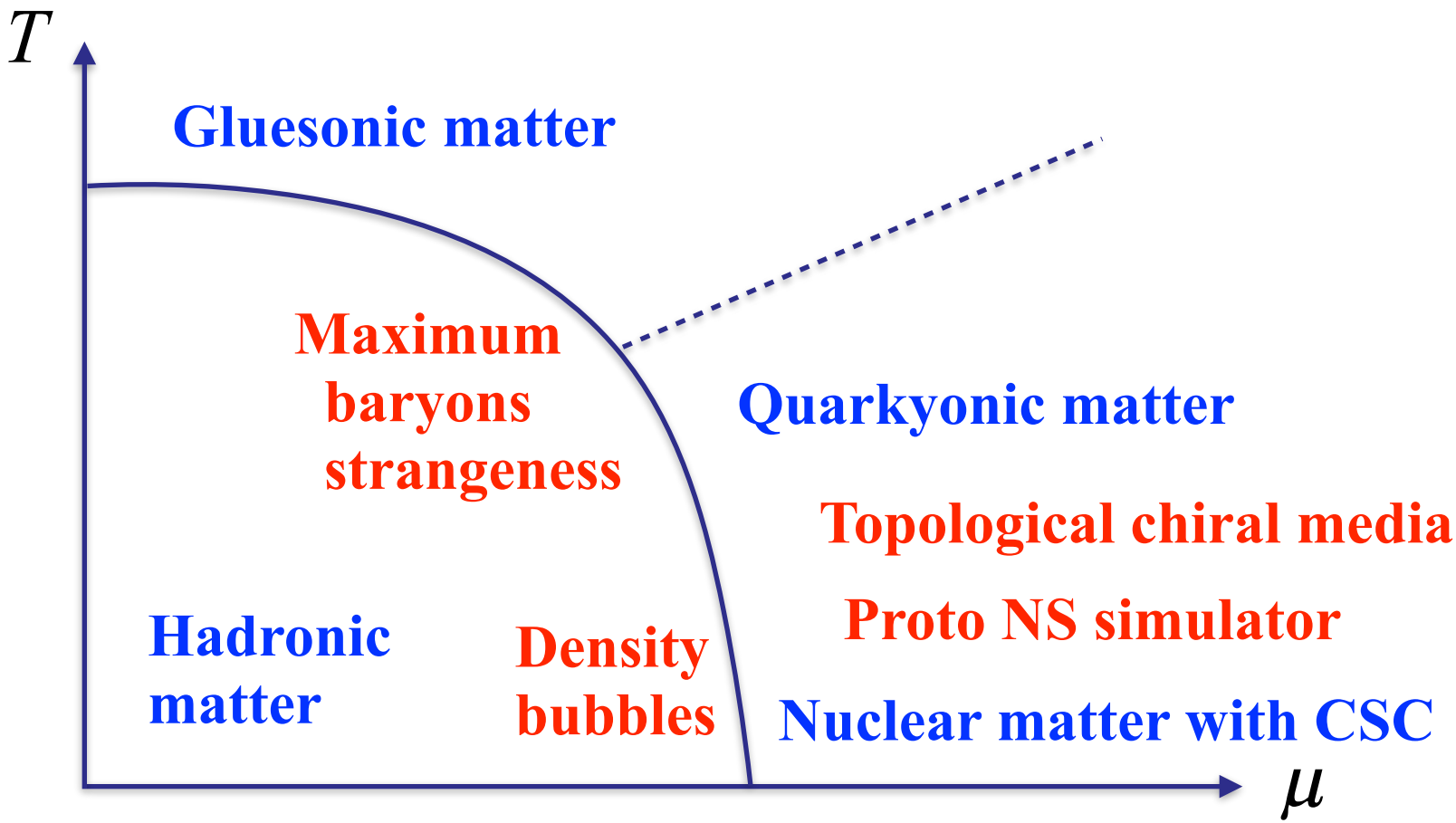
affects the spiral

KF-Morales

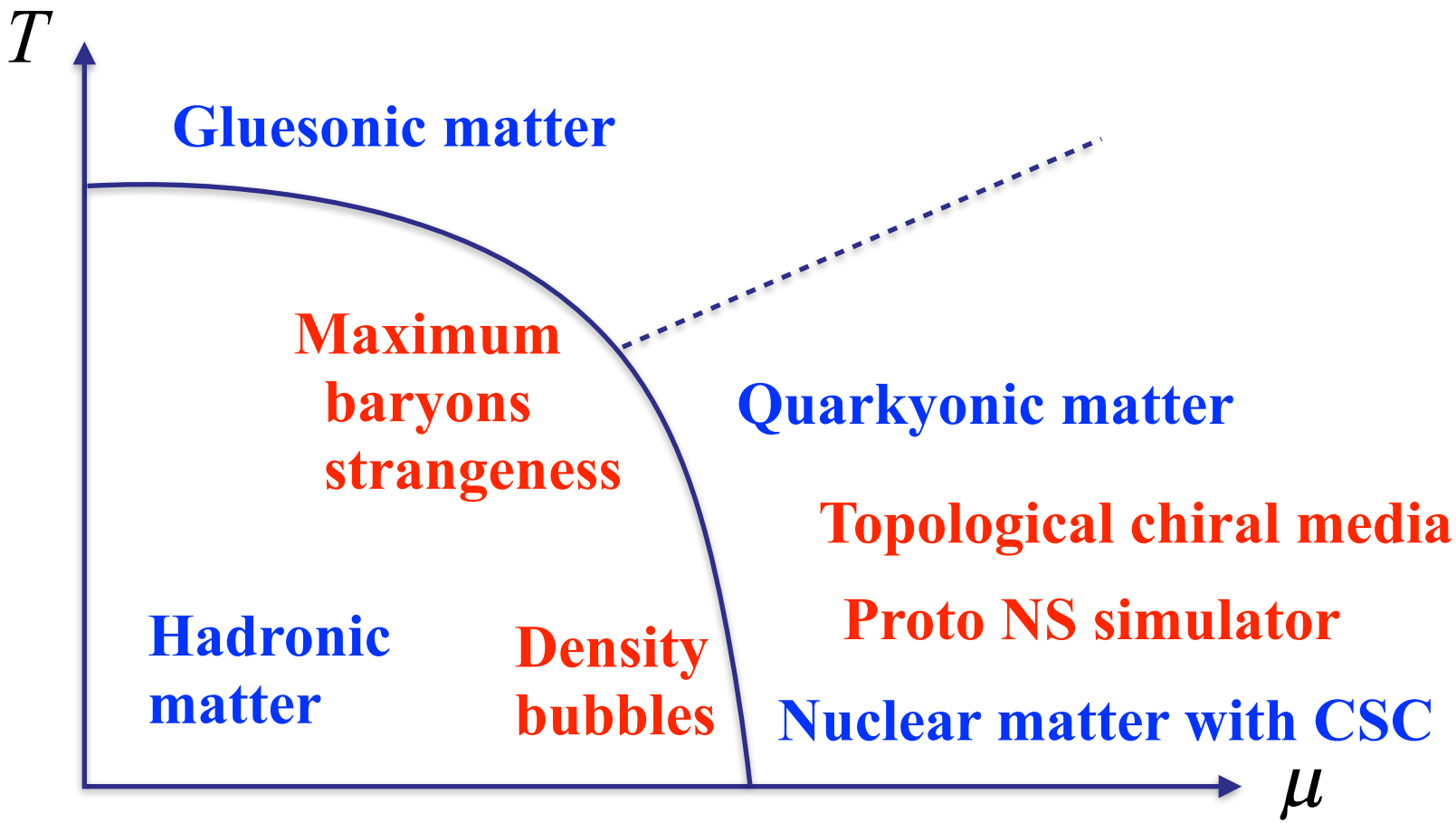
Buballa, Carignano, Nakano, Tatsumi, etc etc…
Yamamoto (Lattice-QCD)

Summary

Phase diagram of "concepts"



Phase diagram of "concepts"



Place where QCD and Nuclear Physics meet