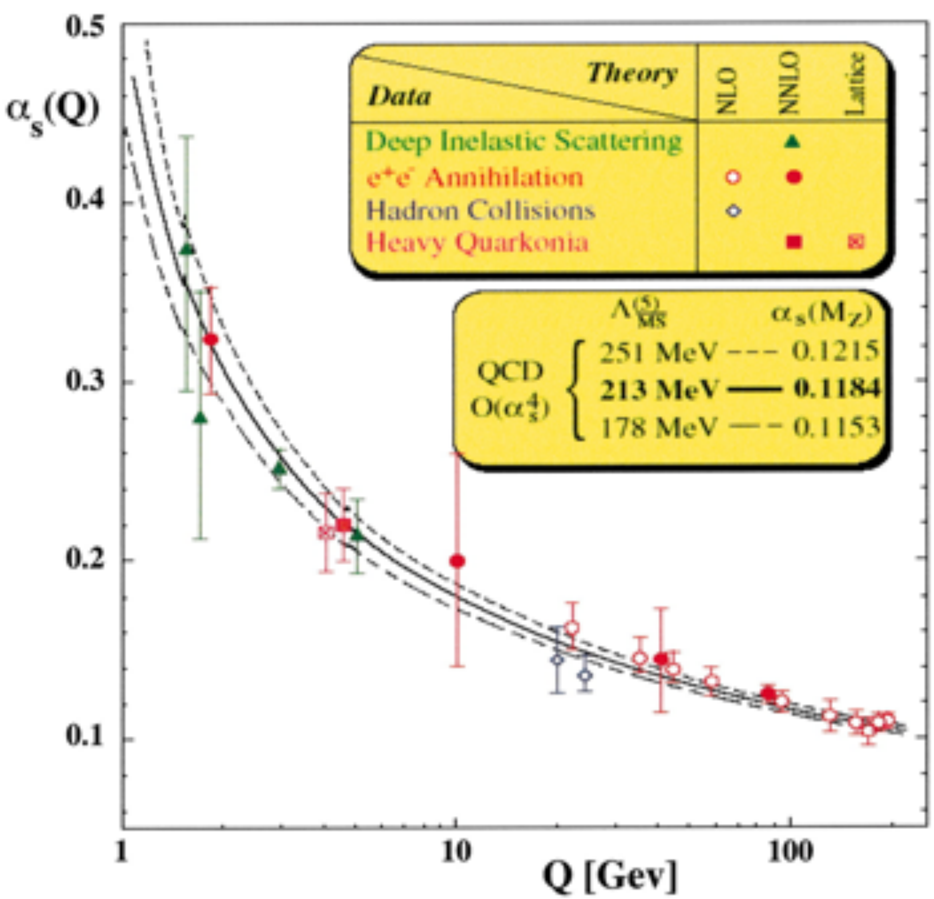
QCD in Heavy-Ion Collisions (for non-experts)

Kenji Fukushima

The University of Tokyo

Student-day Lecture at QM15

Typical Scale of QCD Phenomena



$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2_{\rm QCD})}$$

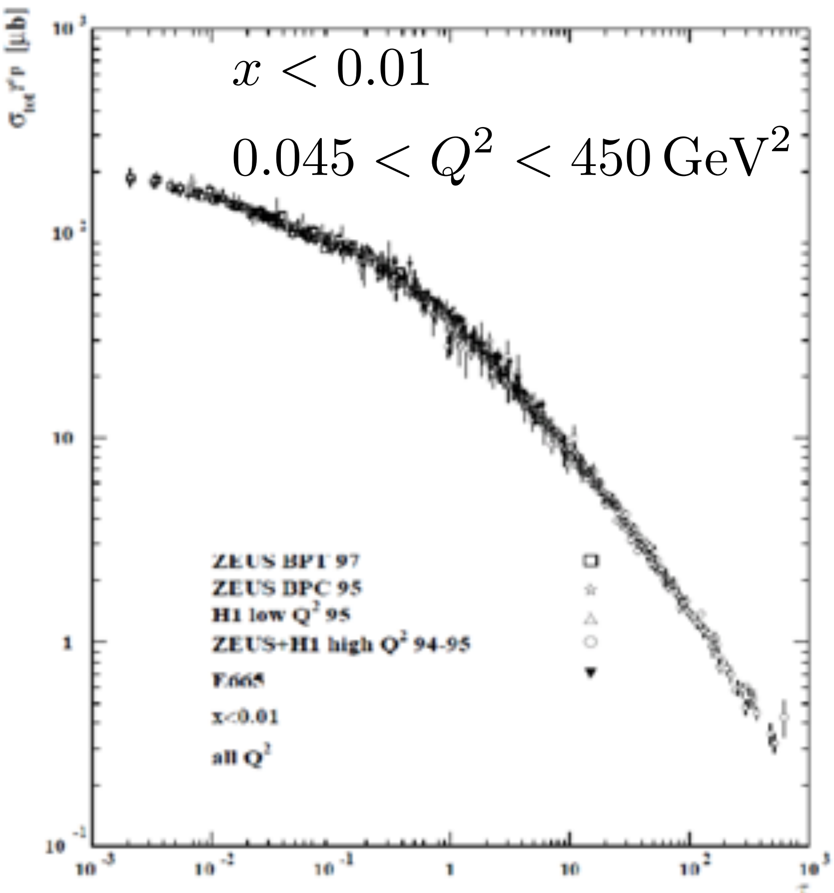
$$\boxed{\Lambda_{\rm QCD} \sim 200 \text{ MeV}}$$

$$M_B \sim N_c \Lambda_{\rm QCD}$$

$$T_c \sim \Lambda_{\rm QCD}$$

$$\rho_B \sim (\Lambda_{\rm QCD})^3$$

Typical Scale of QCD Phenomena



$$\sigma_{\gamma^* p}(x, Q^2) \to \sigma_{\gamma^* p}(Q^2/Q_s^2(x))$$

$$Q_s^2(x) = Q_0^2(x/x_0)^{-\lambda}$$

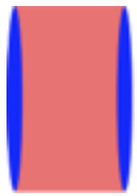
Golec-Biernat-Wuesthoff
Stasto-Golec-Biernat-Kwiecinski Plot

Geometric Scaling

$$Q_s(\mathrm{RHIC}) = 1 \sim 2\,\mathrm{GeV}$$
$$Q_s(\mathrm{LHC}) \sim 2Q_s(\mathrm{RHIC})$$

Λ_{QCD} and Q_s : scheme dependent

Four Regimes in HIC



Color Glass Condensate (CGC)

$$\tau \lesssim 1/Q_s \sim 0.1\mathrm{fm/c}$$

Color Glass + Plasma = Glasma

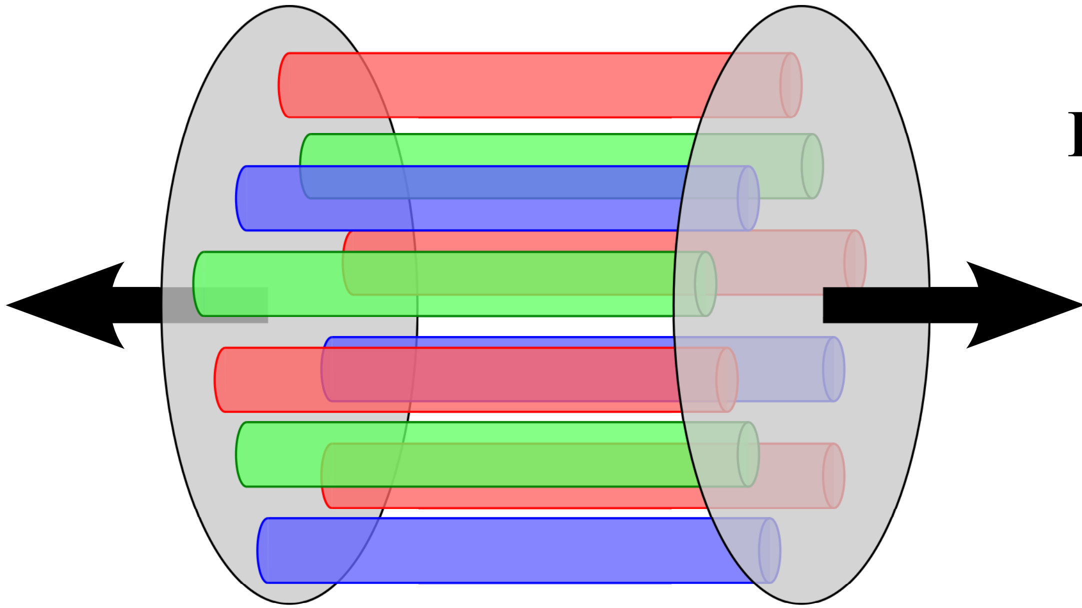
$$\tau \lesssim \tau_0 \sim \Lambda_{\mathrm{QCD}}^{-1}$$

(s) Quark-Gluon Plasma

$$\tau \lesssim \tau_f \sim 10\mathrm{fm/c}$$

Hadronization (quarks → hadrons)

Glasma



Everything scales with $Q_s(x)$

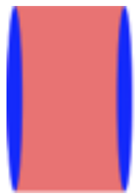
Negative P_L

Flux tubes broken apart by instabilities

→ Positive P_T → Hydrodynamization → Thermalization

Unsolved problems (enjoy talks on this during QM)

Four Regimes in HIC



Color Glass Condensate (CGC)

$$\tau \lesssim 1/Q_s \sim 0.1\mathrm{fm/c}$$

Color Glass + Plasma = Glasma

$$\tau \lesssim \tau_0 \sim \Lambda_{\mathrm{QCD}}^{-1}$$

(s) Quark-Gluon Plasma

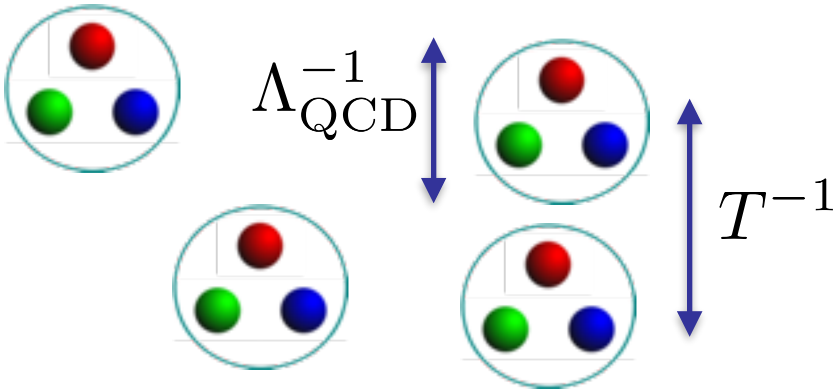
$$\tau \lesssim \tau_f \sim 10\mathrm{fm/c}$$

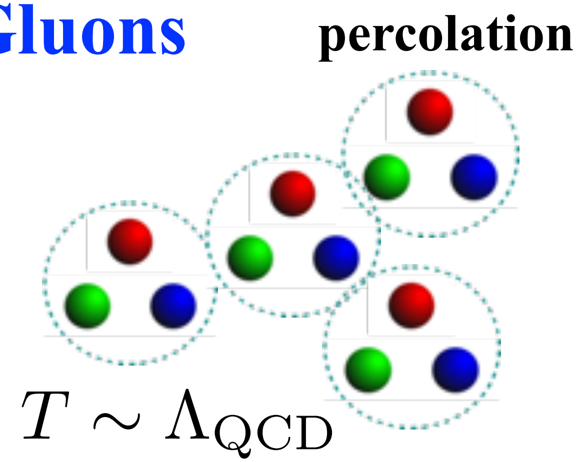
QCD Phase Transitions

Hadronization (quarks → hadrons)

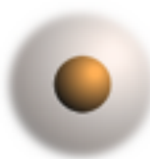
QCD Phase Transitions

Confinement of Quarks and Gluons





Dynamical Generation of Mass (chiral sym.)

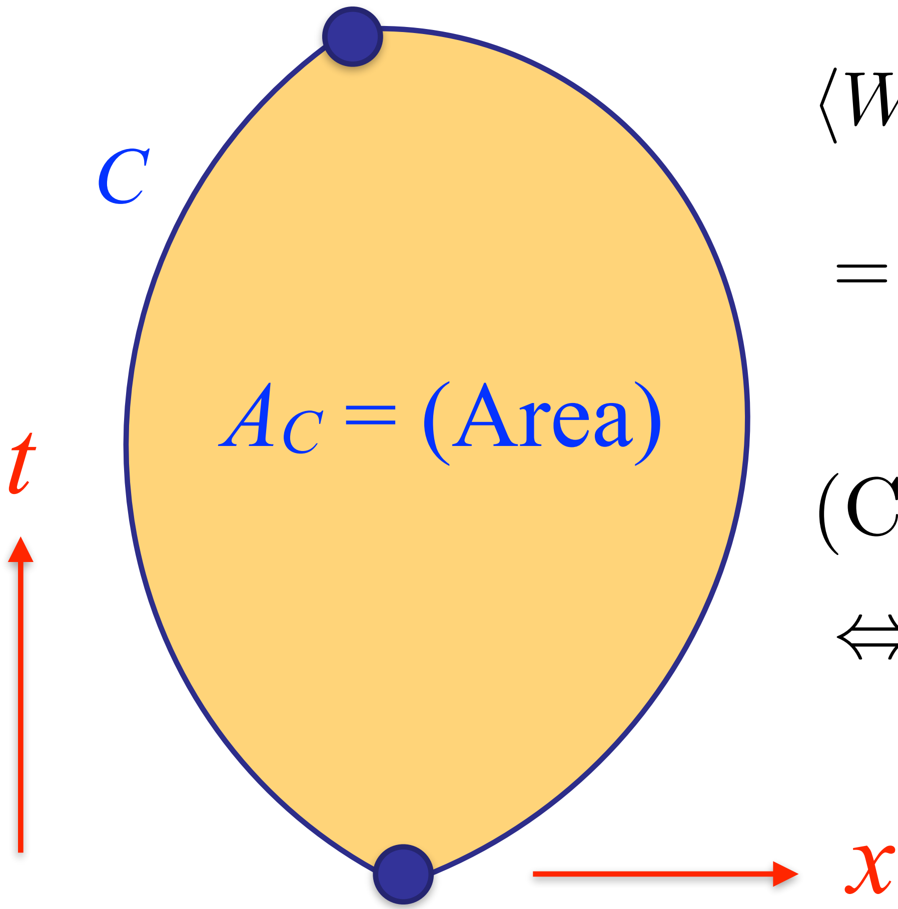


"Constituent" Quark
$M_{\rm q} \sim 350$MeV

"Bare" Quark
$M_{\rm q} \sim 3$~5MeV

Order Parameter — Confinement

Confinement of Quarks (Wilson 1974)



$$\langle W(C)\rangle$$

$$= \left\langle \mathrm{tr} P \exp\left[ig \oint_C dx^\mu A_\nu\right]\right\rangle$$

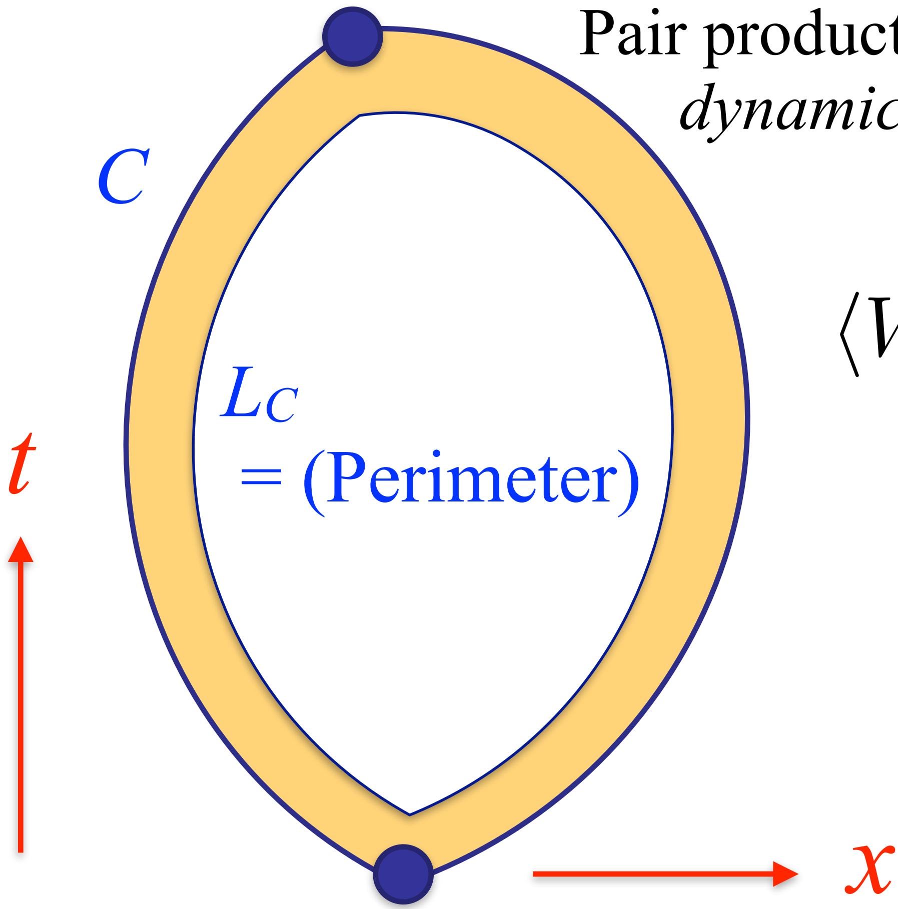
$$(\text{Confinement})$$

$$\Leftrightarrow \langle W(C)\rangle \sim \exp[-\# A_C]$$

$\boxed{\textbf{Area Law}}$

Order Parameter — Confinement

Confinement of Quarks (Wilson 1974)

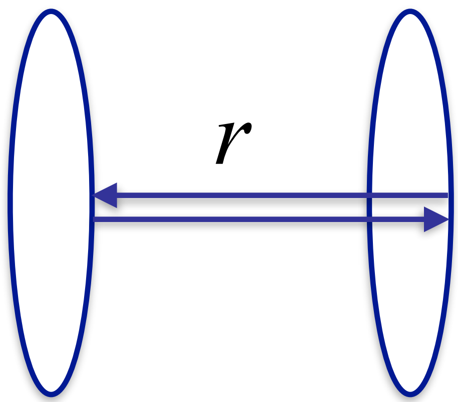


Pair production of
dynamical quarks

$$\langle W(C)\rangle \sim \exp[-\# L_C]$$

$\boxed{\textbf{Perimeter Law}}$

Extension to Finite-T



$$Z = \mathrm{tr}\, e^{-\hat{H}/T}$$

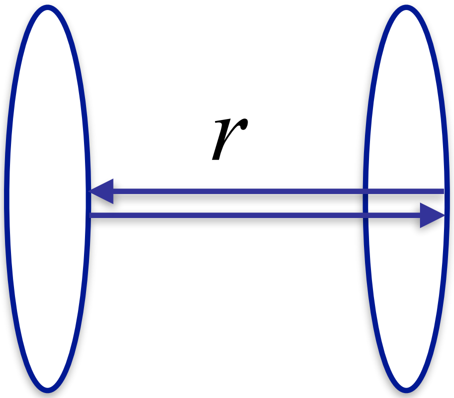
$$it \;\; \Leftrightarrow \tau$$

$$A_\mu(\tau + \beta) = A_\mu(\tau)$$
$$\psi(\tau + \beta) = -\psi(\tau)$$

$$W(C) = \mathrm{tr} L(0)\, \mathrm{tr} L^\dagger(r)$$

$$\begin{aligned}
\langle W(C) \rangle &= \langle \mathrm{tr} L(0) \mathrm{tr} L^\dagger(r) \rangle \\
&= \exp[-f_{q\bar{q}}(r)/T] \\
&\to |\langle \mathrm{tr} L \rangle|^2 \quad (r \to \infty) \\
&= \exp[-2 f_q / T]
\end{aligned}$$

Extension to Finite-T



$$Z = \mathrm{tr}\, e^{-\hat{H}/T}$$

$$it \quad \Leftrightarrow \tau$$

$$A_\mu(\tau+\beta) = A_\mu(\tau)$$

$$\psi(\tau+\beta) = -\psi(\tau)$$

$$W(C) = \mathrm{tr}L(0)\,\mathrm{tr}L^\dagger(r)$$

$$\begin{aligned}\langle W(C)\rangle &= \langle \mathrm{tr}L(0)\mathrm{tr}L^\dagger(r)\rangle \\ &= \exp[-f_{q\bar{q}}(r)/T] \\ &\boxed{\begin{aligned}&\to |\langle \mathrm{tr}L\rangle|^2 \quad (r\to\infty) \\ &= \exp[-2f_q/T]\end{aligned}}\end{aligned}$$

Polyakov Loop

Extension to Finite-T

Quenched Case (no dynamical quarks)

$$f_{q\bar{q}}(r) \sim \sigma r \to \infty \quad (r \to \infty)$$

$$f_q \to \infty \;\; \text{(in conf. phase)}$$

Dynamical Case (quarks with finite mass)

$$f_{q\bar{q}}(r) \to 2\text{(hadron mass)} \quad (r \to \infty)$$

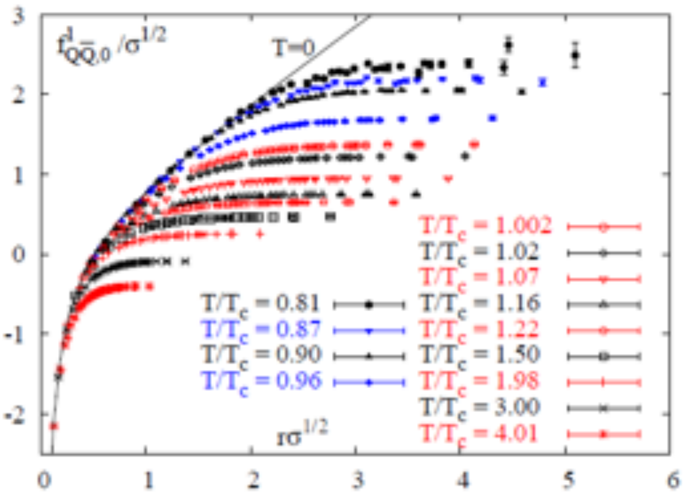
$$f_q \to \text{(hadron mass)} \;\; \text{(in ``conf.'' phase)}$$

Extension to Finite-T

Dynamical Case

$$f_{q\bar{q}}(r) \to 2(\text{hadron mass}) \quad (r \to \infty)$$

$$f_q \to (\text{hadron mass}) \ \ (\text{in “conf.” phase})$$



Linear potential is
“screened” at large distances

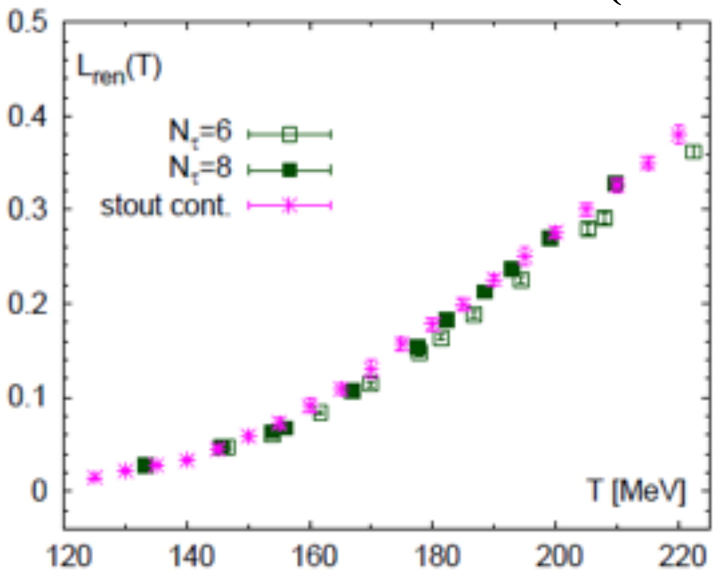
Lattice from Tokyo group

No way to *define* confinement at finite *T*

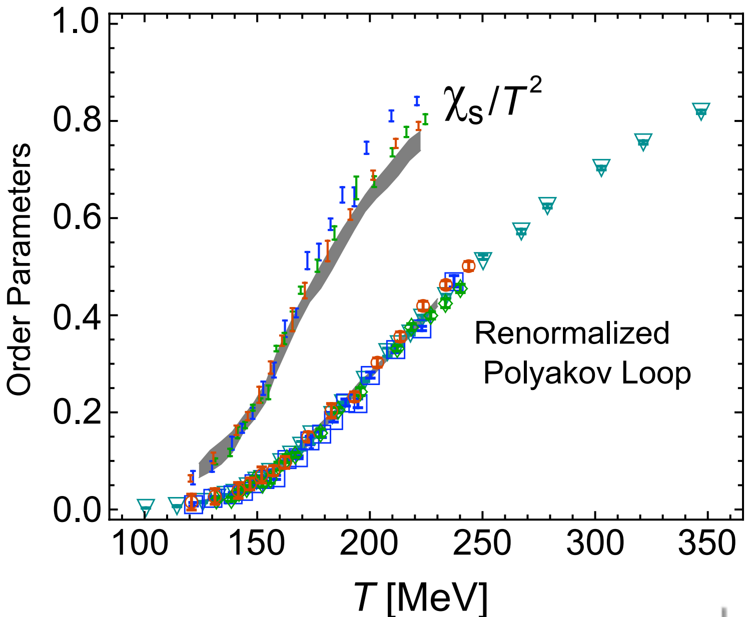
Examples from Lattice-QCD

Polyakov loop increases very smoothly:

Lattice from BNL-Bielefeld (2010)



Lattice from Wuppertal-Budapest (2010)



There is no clear-cut T_c for deconfinement

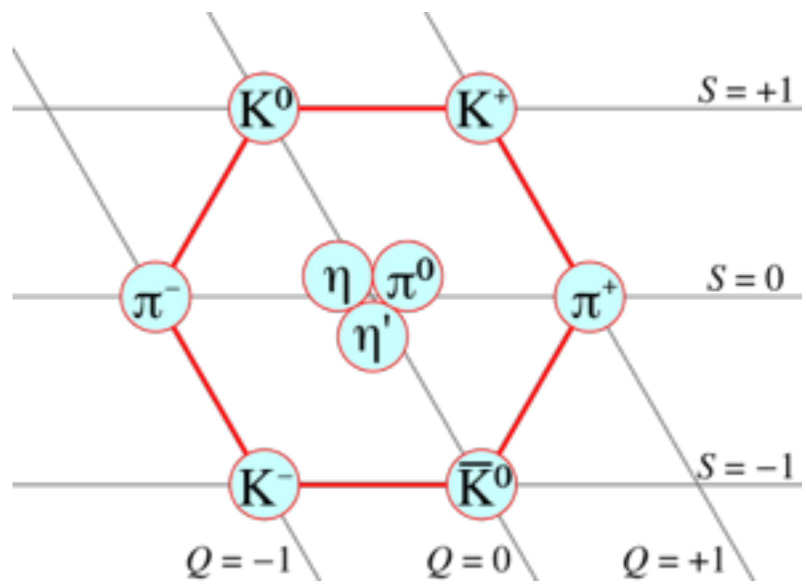
Order Parameter — Chiral Sym.

$$\mathrm{SU}(N_f)_\mathrm{L} \times \mathrm{SU}(N_f)_\mathrm{R} \times \cancel{\mathrm{U}(1)_\mathrm{A}} \;\to\; \mathrm{SU}(N_f)_\mathrm{V}$$

Instantons — η' mass

$3\mathrm{NG}$ modes for $N_f = 2$

$8\mathrm{NG}$ modes for $N_f = 3$

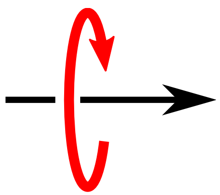


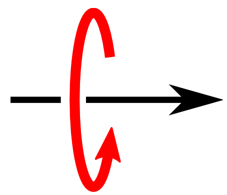
Chiral Condensate

$$\langle \bar{q} q \rangle$$

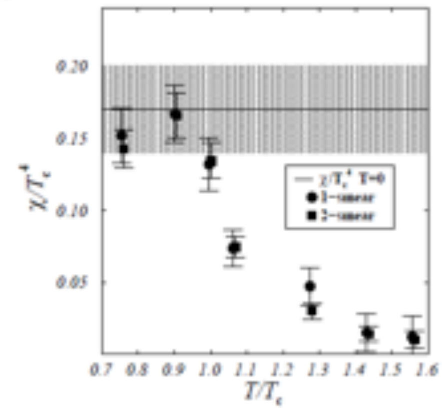
Order Parameter — Chiral Sym.

$$\mathrm{SU}(N_f)_\mathrm{L} \times \mathrm{SU}(N_f)_\mathrm{R} \times \cancel{\mathrm{U}(1)_\mathrm{A}} \;\to\; \mathrm{SU}(N_f)_\mathrm{V}$$





?



Lattice from D'Elia et al.

For $N_\mathrm{f} = 2$

Without axial-U(1)

$$\mathrm{O}(4) \;\to\; \mathrm{O}(3)$$

2nd-order expected

With axial-U(1) (***effective restoration***)

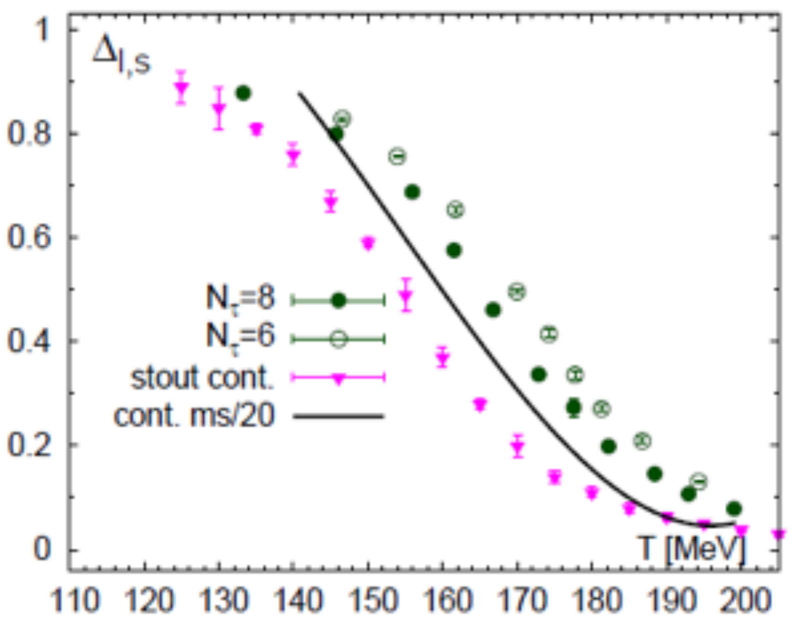
$$\mathrm{O}(4) \times \mathrm{O}(2) \;\to\; \mathrm{O}(3)$$

1st-order expected?

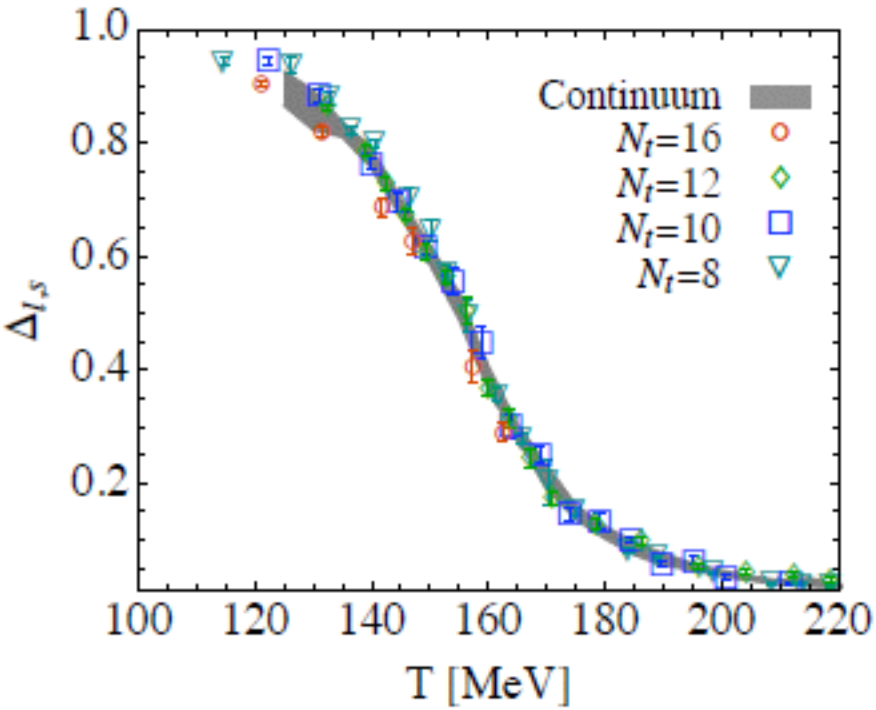
Examples from Lattice-QCD

Chiral condensate decreases (relatively) steeply:

Lattice from BNL-Bielefeld (2010)



Lattice from Wuppertal-Budapest (2010)



$\Delta_{l,s}$: Special combination free from the renormalization

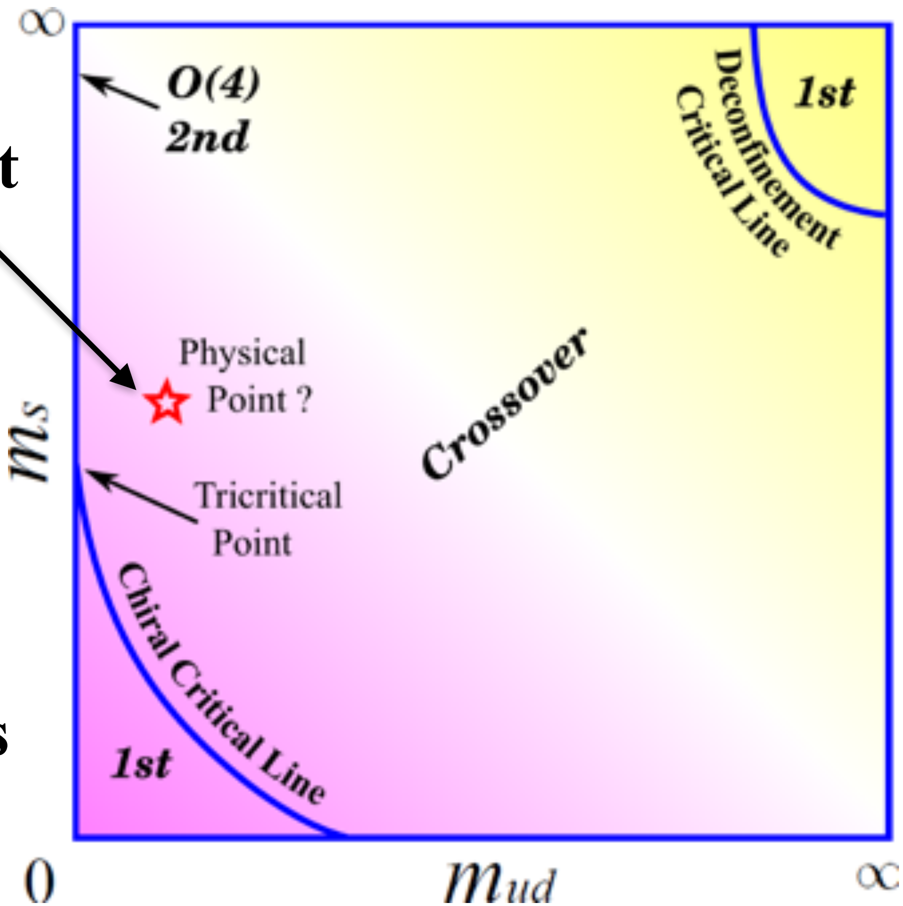
Phase Structure with Quark Masses

**Far from
the quenched 1st**

**Close to
the O(4) 2nd?**

**Crossover
confirmed by
finite-*V* analysis**

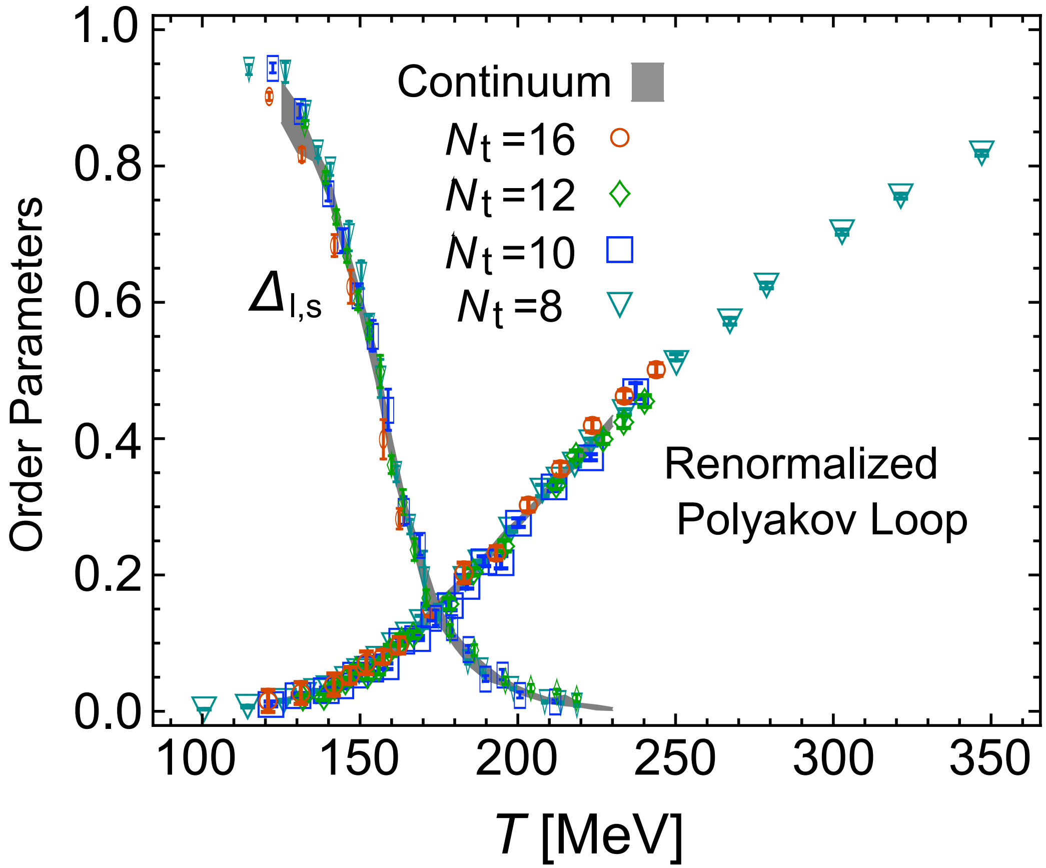
Aoki et al. (2006)



**Quenched
Limit**

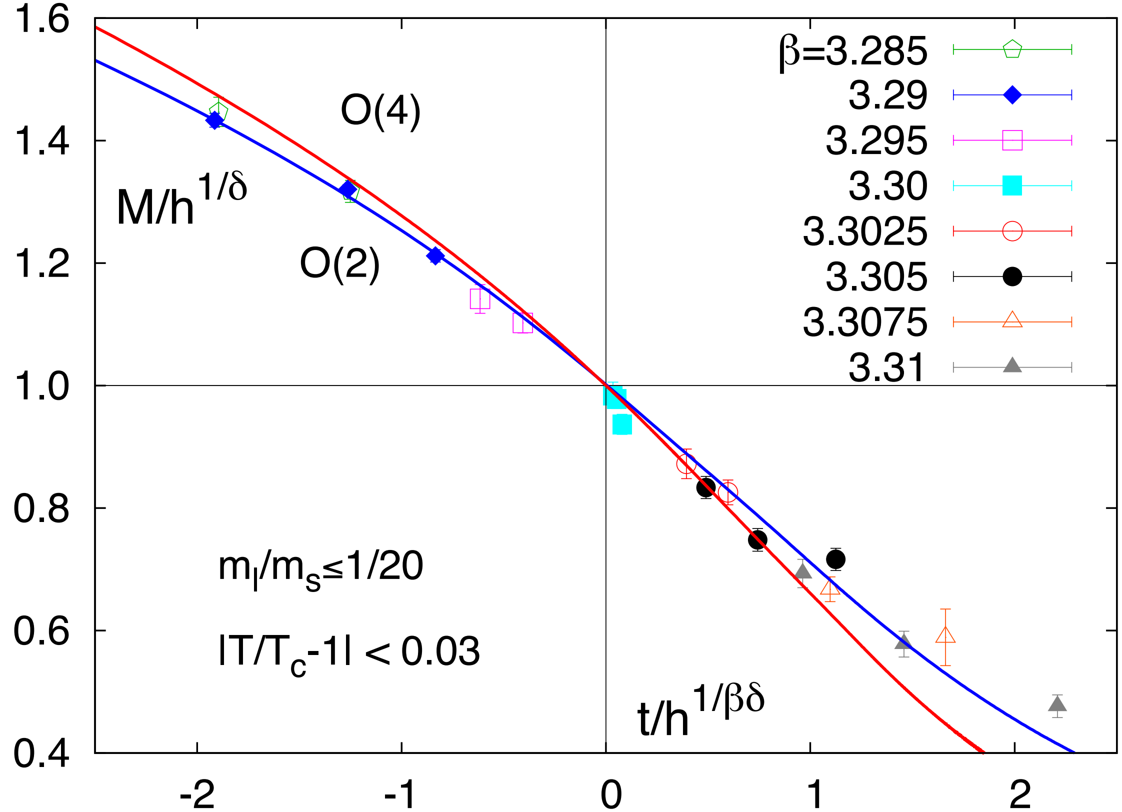
Examples from Lattice-QCD

Chiral restoration is more like a real phase transition



Magnetic Scaling : O(4) vs O(2)

Lattice from BNL-Bielefeld (2009)

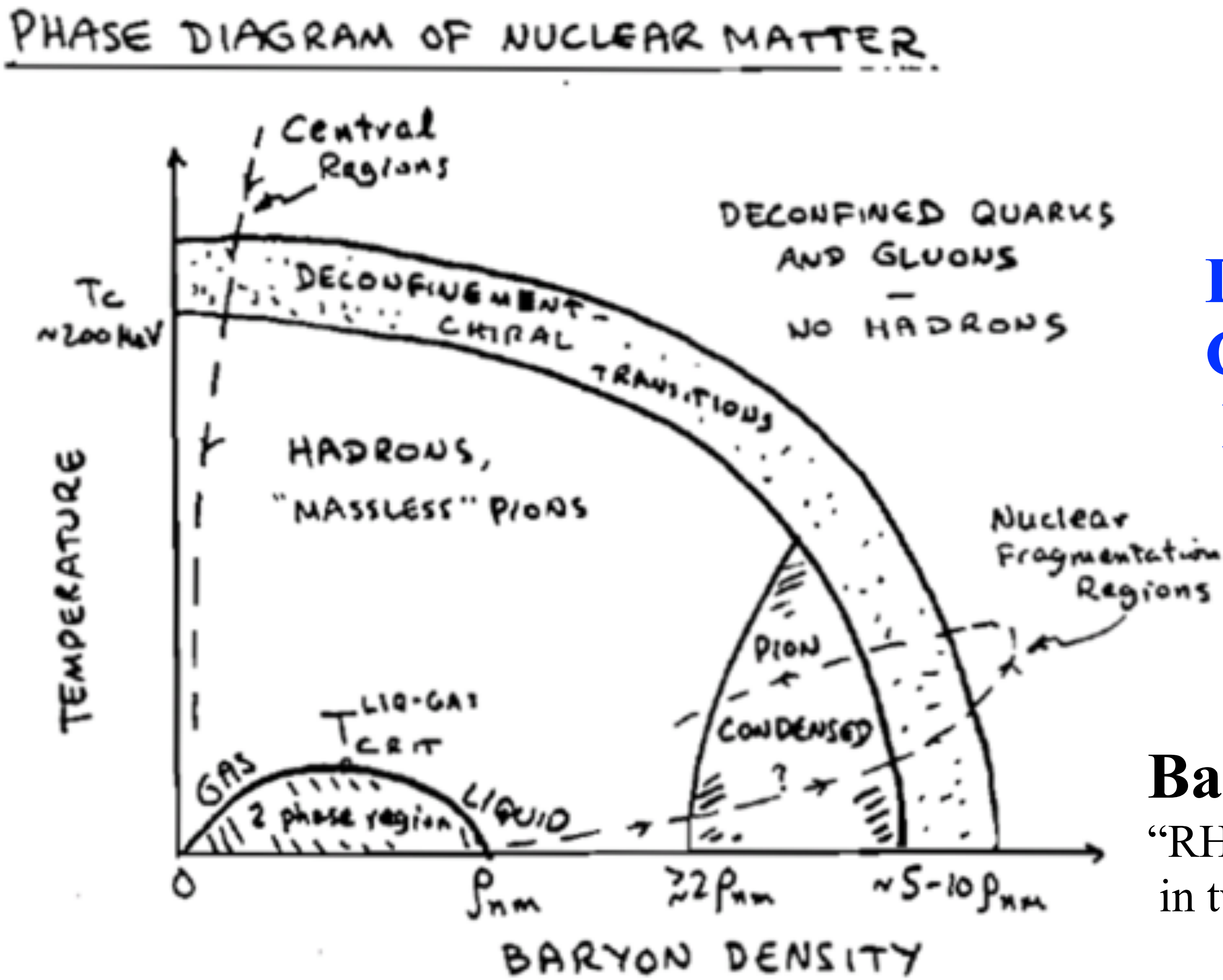


(Scaled) Chiral Cond.

(Scaled) Quark Mass

***T_c* is better-defined for chiral phase transition**

Hypothetical Phase Diagram

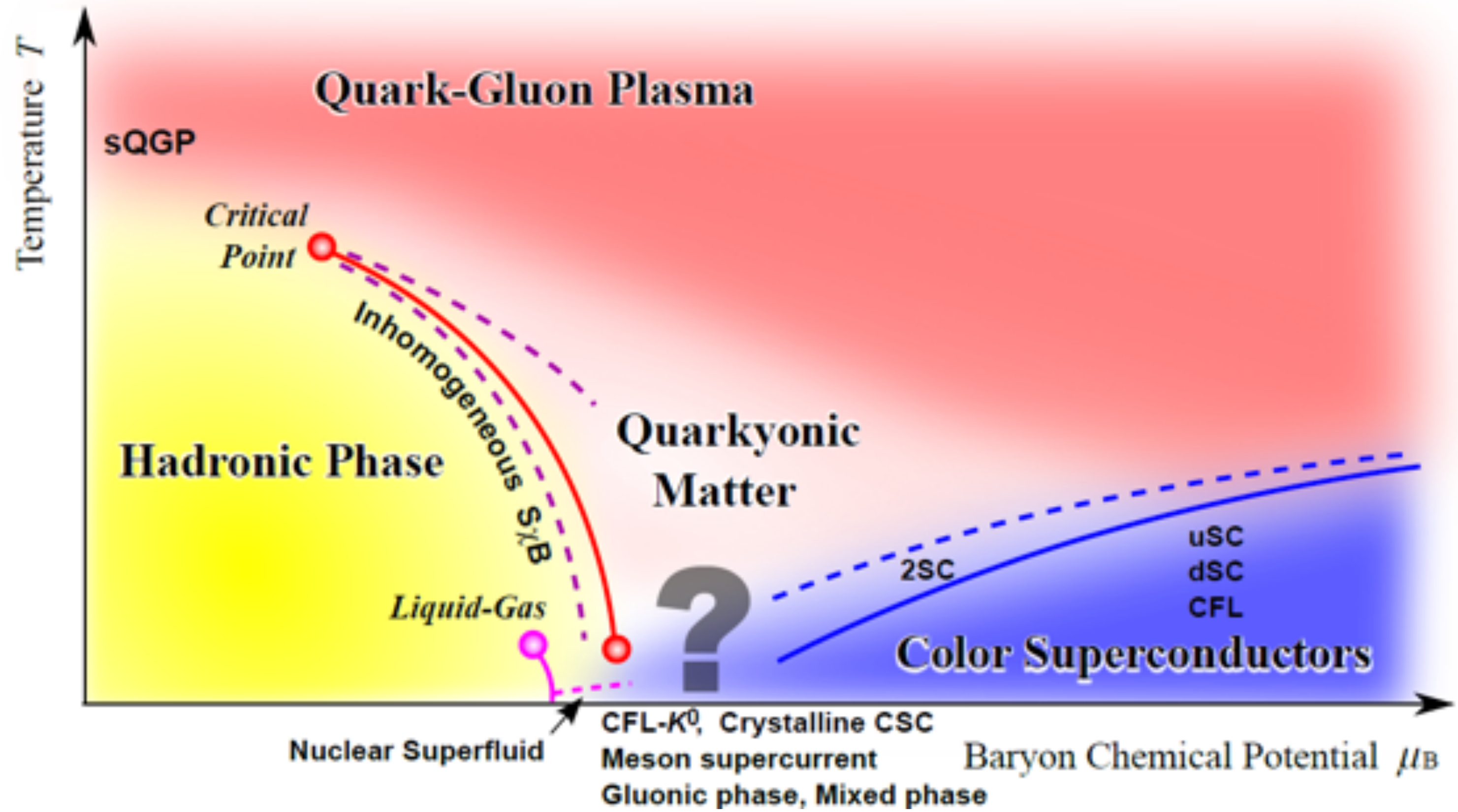


Deconfinement Chiral Transitions located at close *T*

Baym (1984)

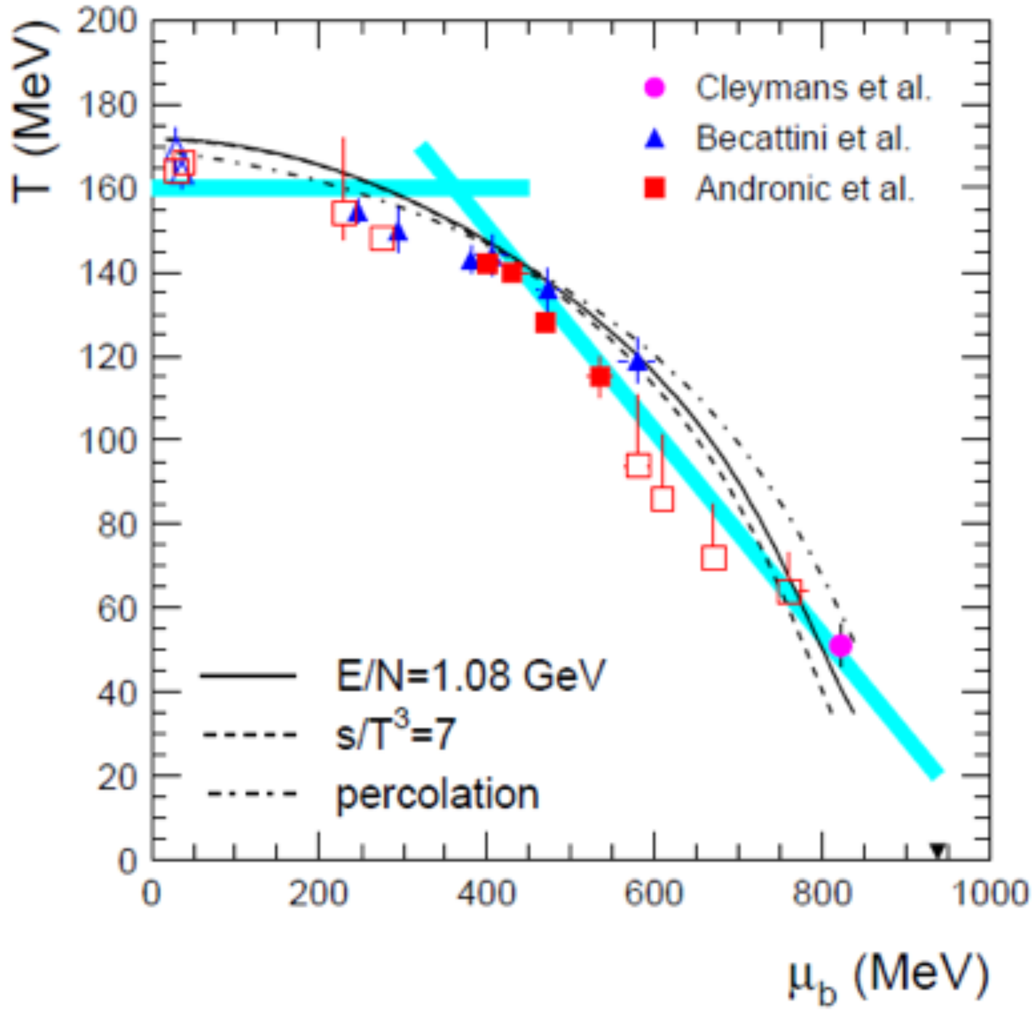
"RHIC:From dreams to beams in two decades," hep-ph/0104138

Modern QCD Phase Diagram



Chiral is rather sharp, while deconfinement is blurred

Experimental Survey

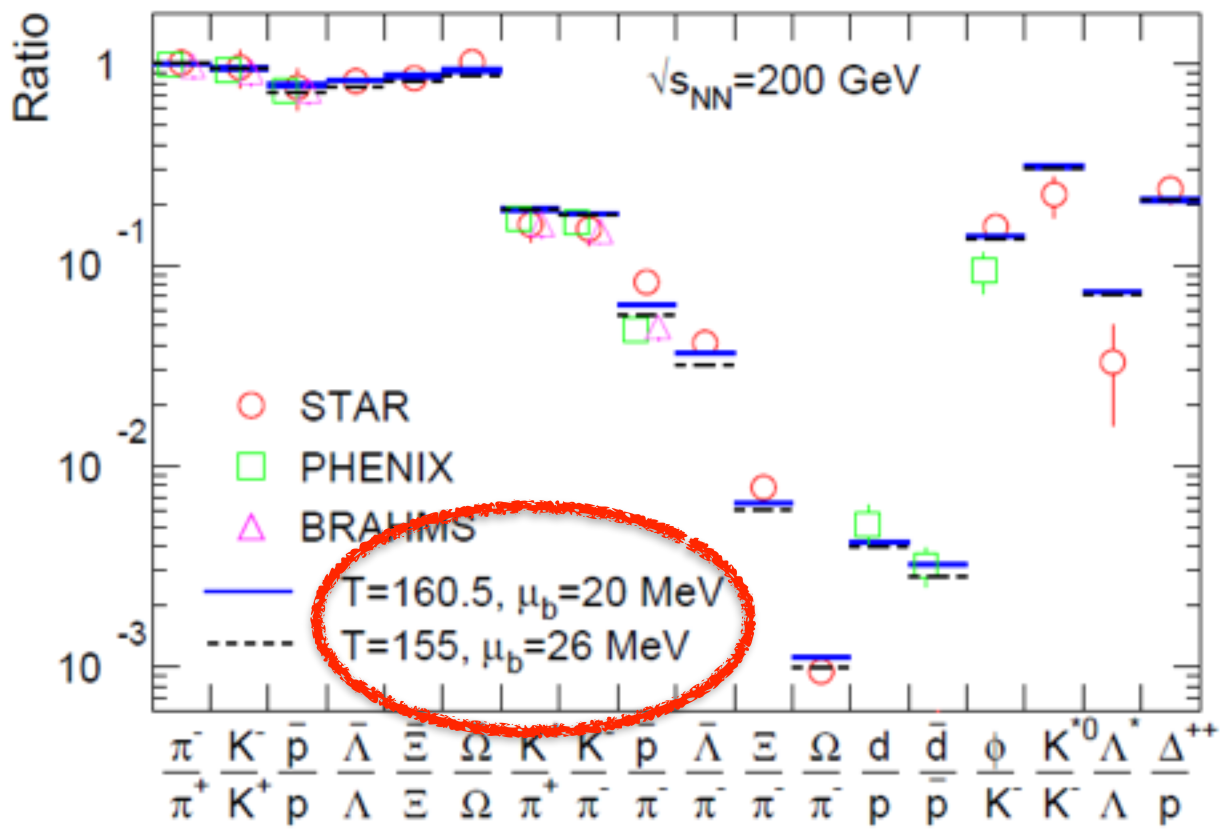


Changing the collision energy the phase boundary is investigated:
— Beam Energy Scan

Andronic et al. (2010)

Thermal Model Fit

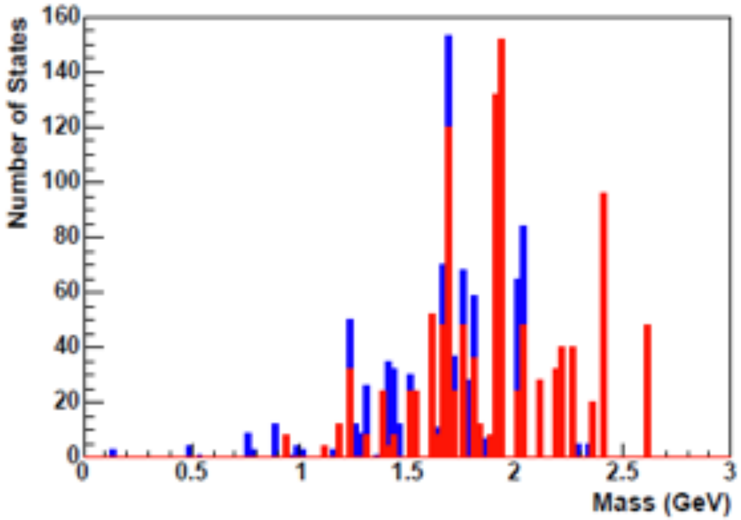
How to determine *T* and *μ* "experimentally"



Andronic
Braun-Munzinger
Stachel…

Thermal Model Fit

μ_Q : **determined from the charge conservation**
μ_S : **determined from zero net strangeness**



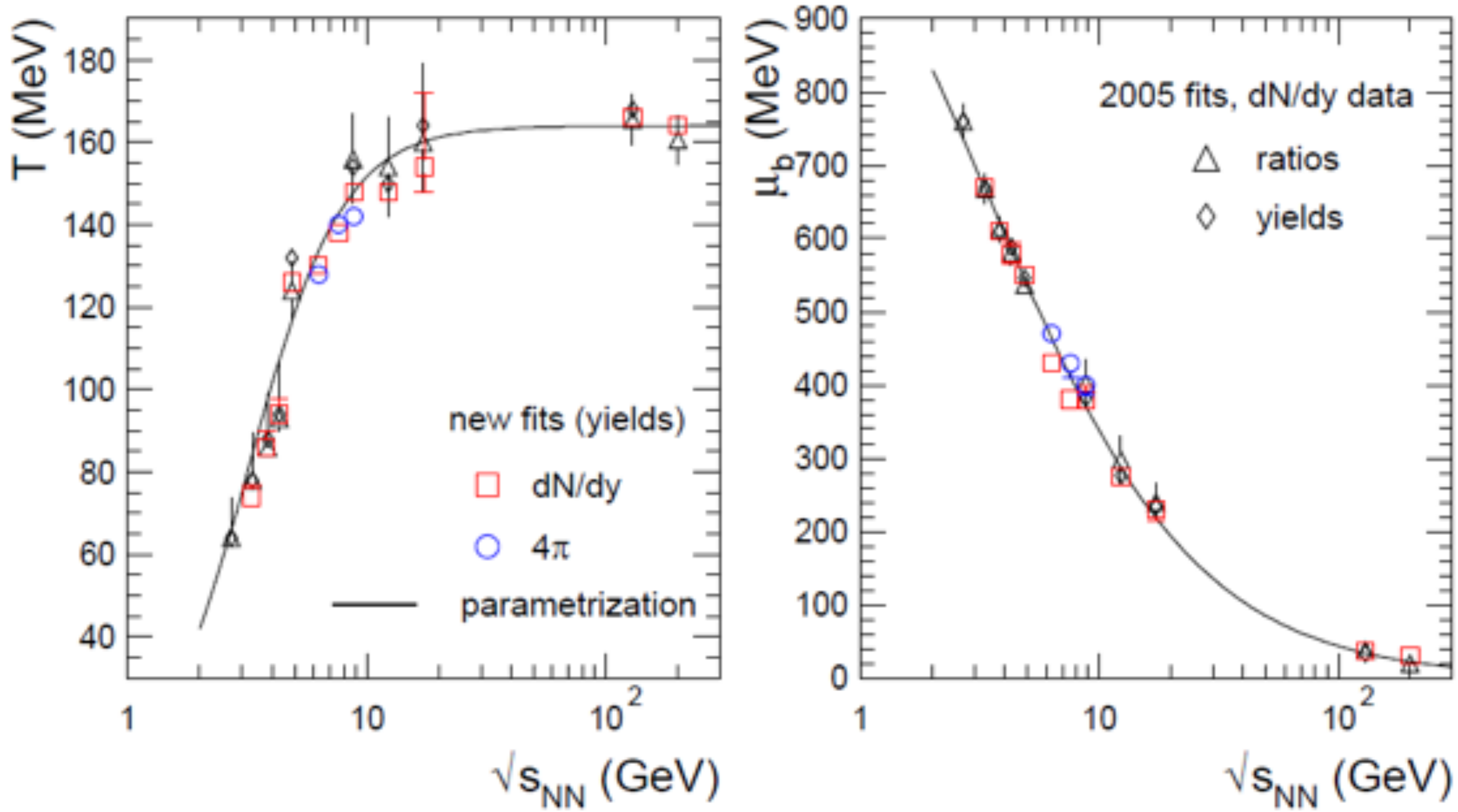
Mesons (blue)
Baryons (red)
contained in
THERMUS2.1
(from manual)

T **and** μ_B **: fitting parameters**

http://www.phy.uct.ac.za/people/wheaton/THERMUS/thermus_index.html
V3.0 is available now…

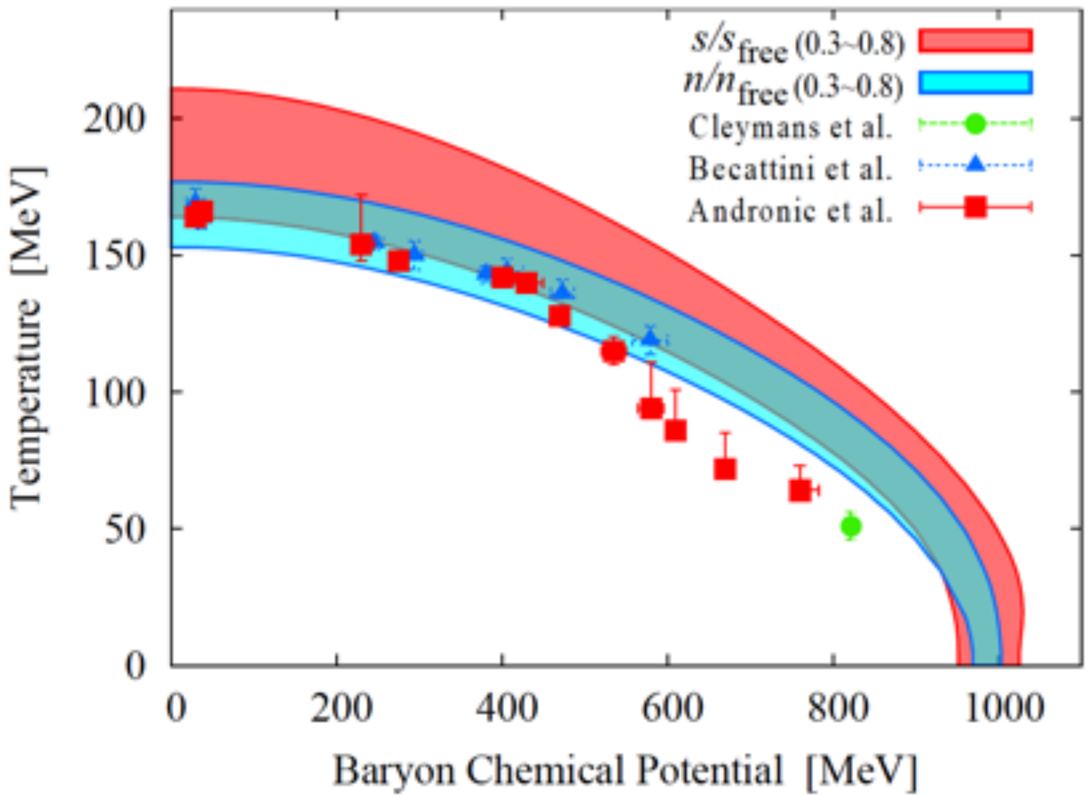
Chemical Freezeout Curve

$$\text{(Mapping) } \sqrt{s_{NN}} \Leftrightarrow T,\ \mu_B$$



Freezeout vs Phase Boundary

Chemical freezeout ~ “Chemical reaction” turned off
~ Inter-particle distance drops down



Thermodynamics from THERMUS

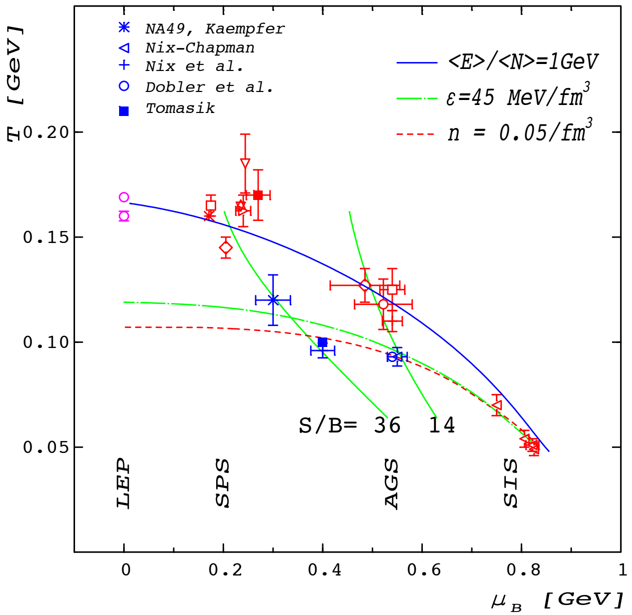
Smallness of $e^{-m/T}$ compensated by entropy

Caution

Do not get confused with the "thermal freezeout"

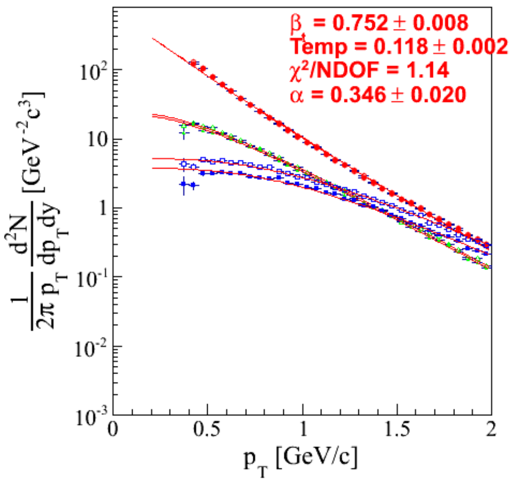
By definition "temperature" is an exponential slope of the particle distribution in momentum space.

Momentum exchange still goes on after the "chemical reaction" stops (elastic scatterings).



Cleymans-Redlich (1999)

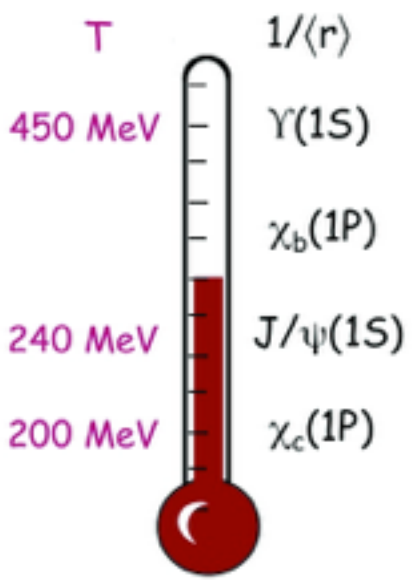
Blast-wave model parameters include T_{kin}



Ristea et al.

Signature for Deconfinement

Melting of heavy quarkonium



A. Mocsy

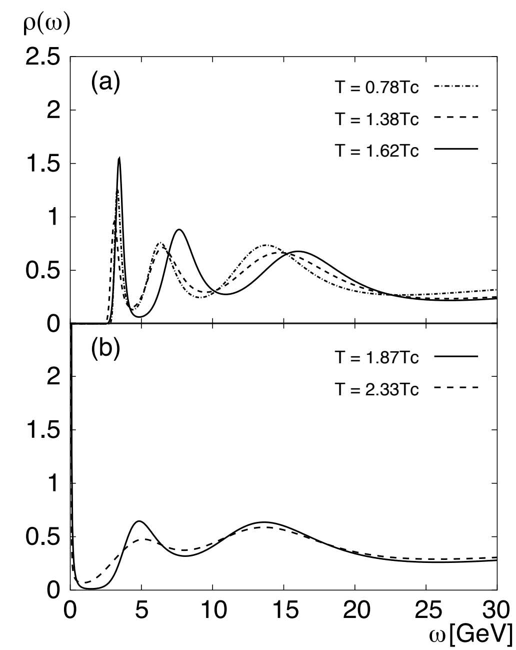
Many (confusing) discussions have been triggered by this…

Static potential model

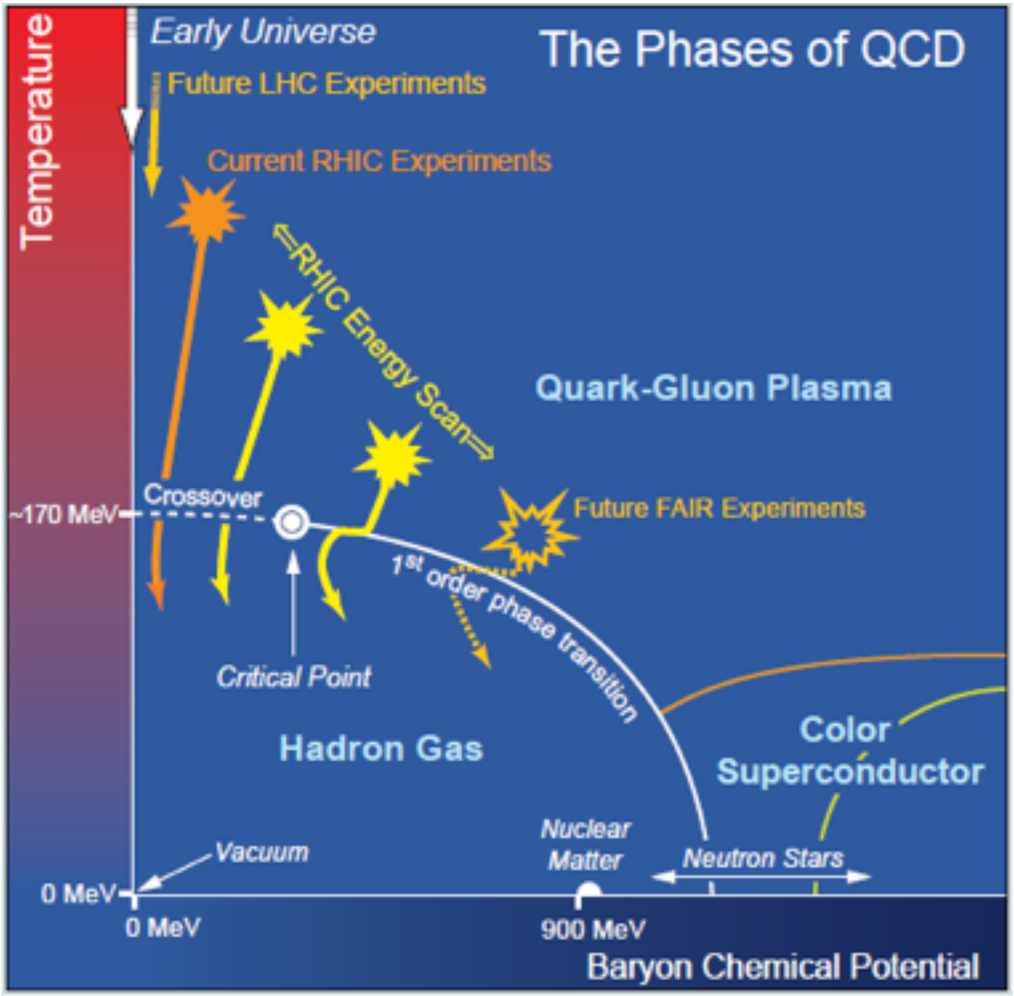
↓

Real-time physics important
Heavy-flavor diffusion
(Langevin dynamics)

Asakawa-Hatsuda (2003)



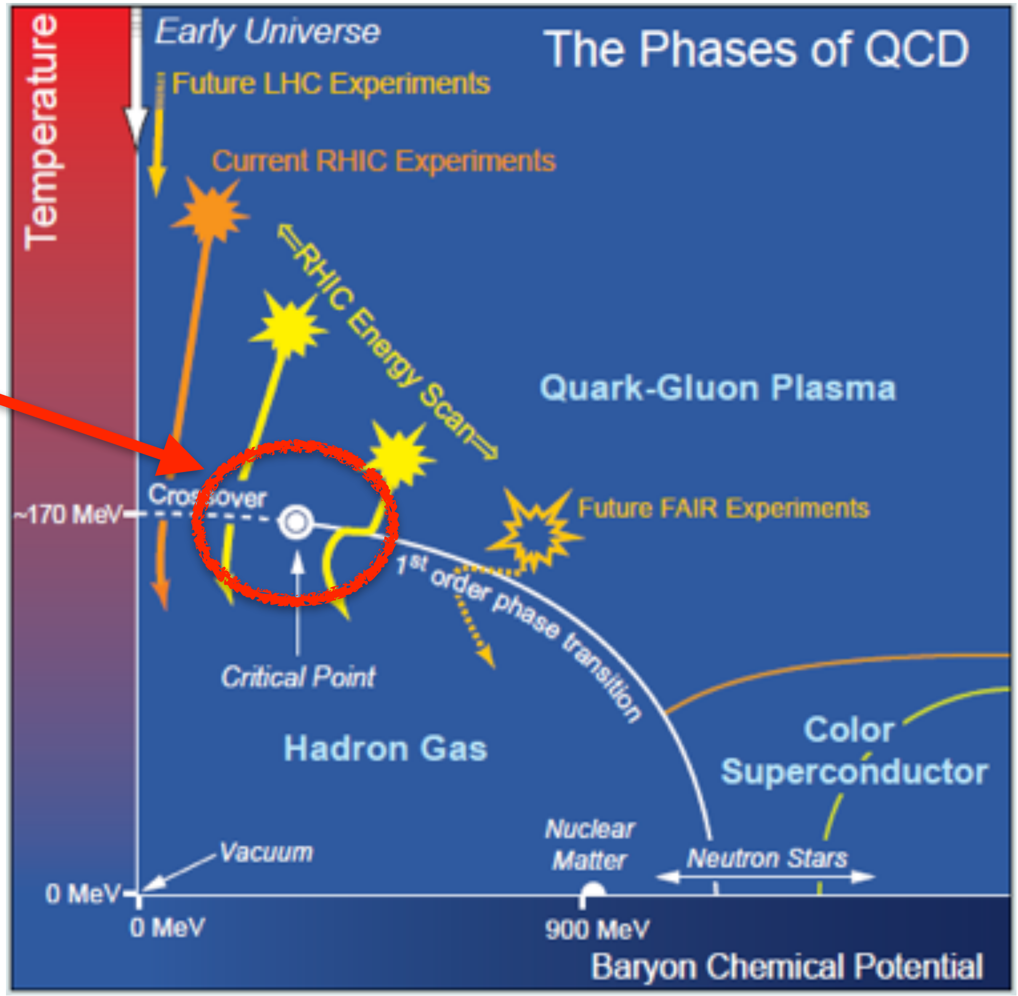
Beam-energy Scan



Beam-energy Scan

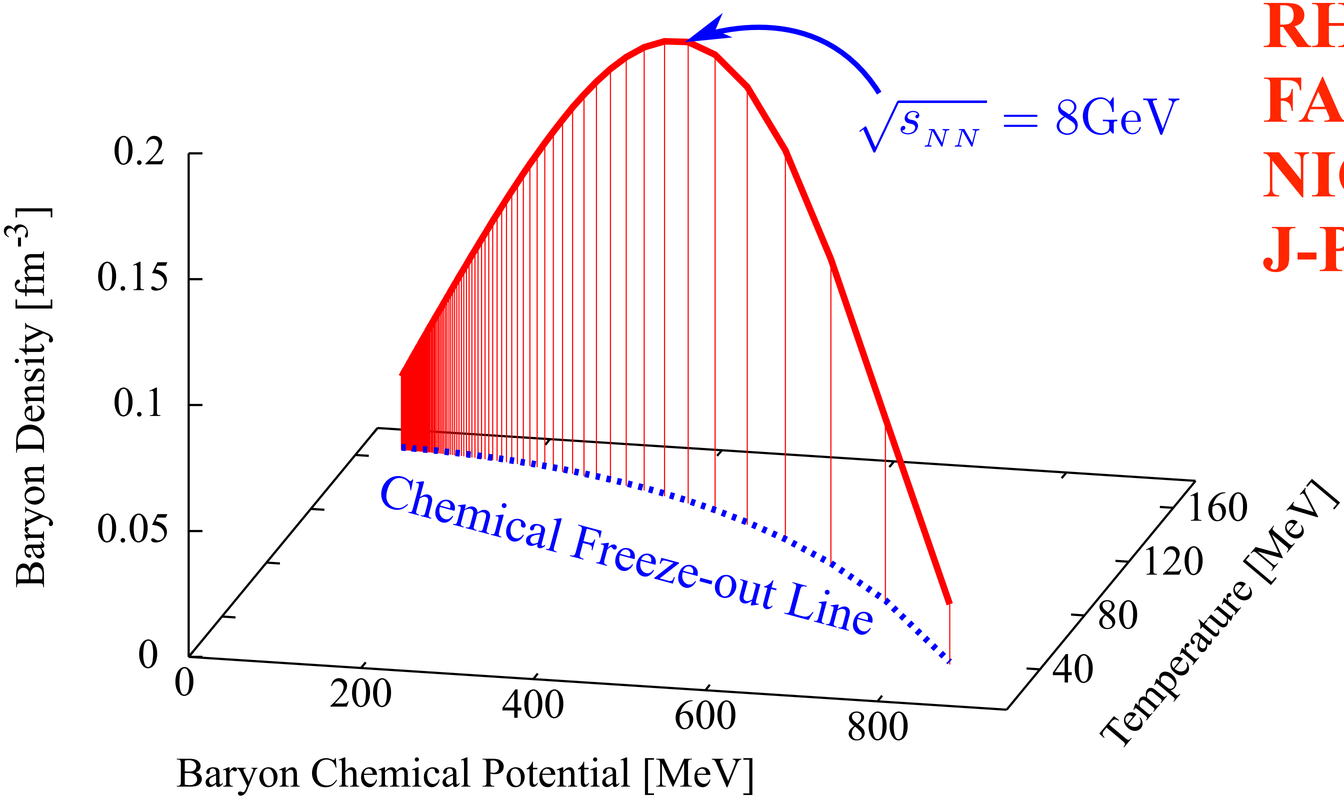
QCD CP

End-point of 1st order phase transition



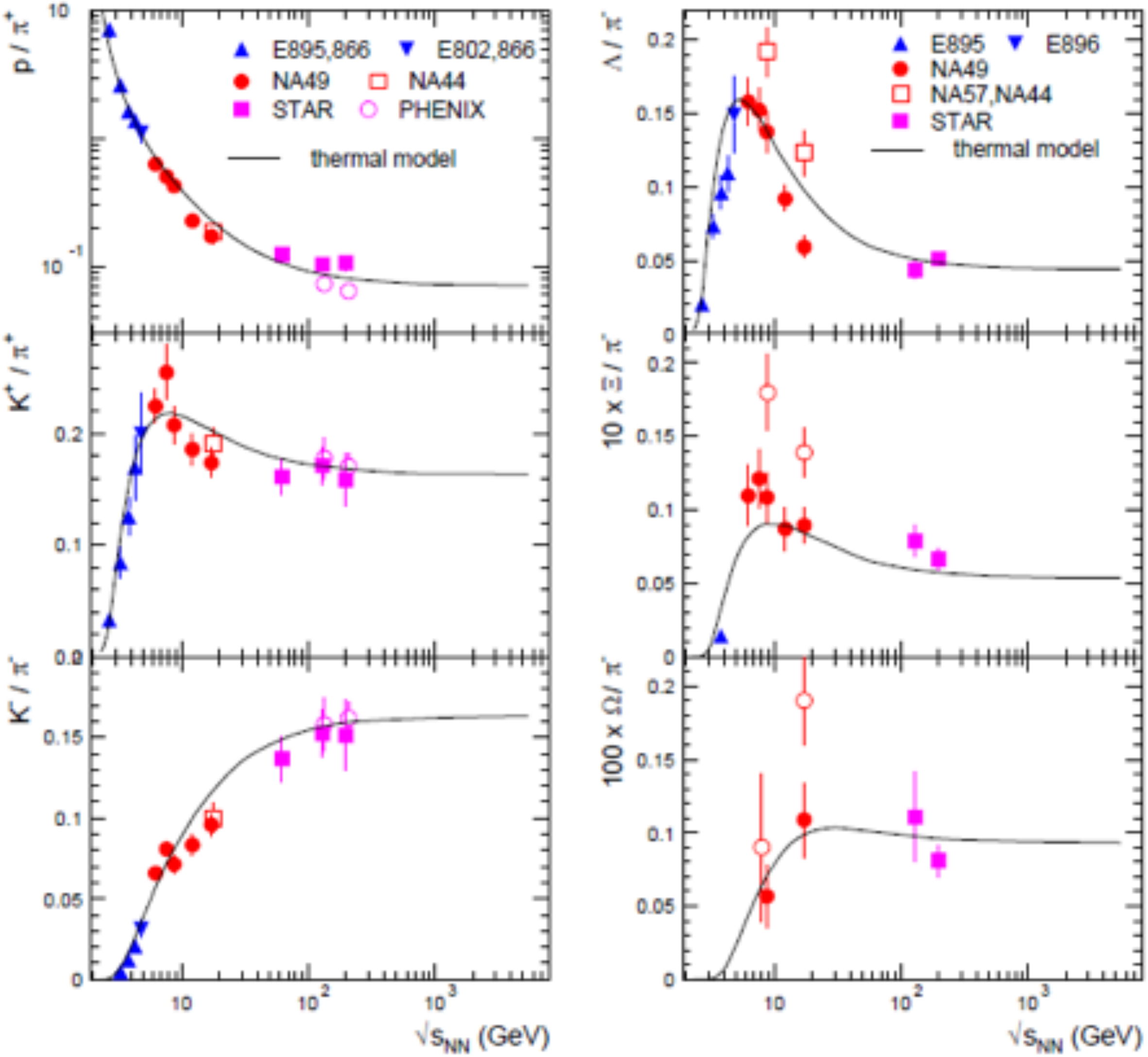
Densest Matter

Estimate from HRG



RHIC BES
FAIR
NICA
J-PARC

“Strangest” Matter



More baryons

↓

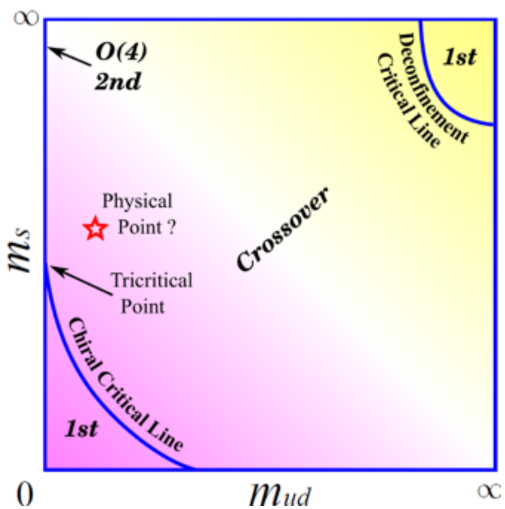
More *Λ*

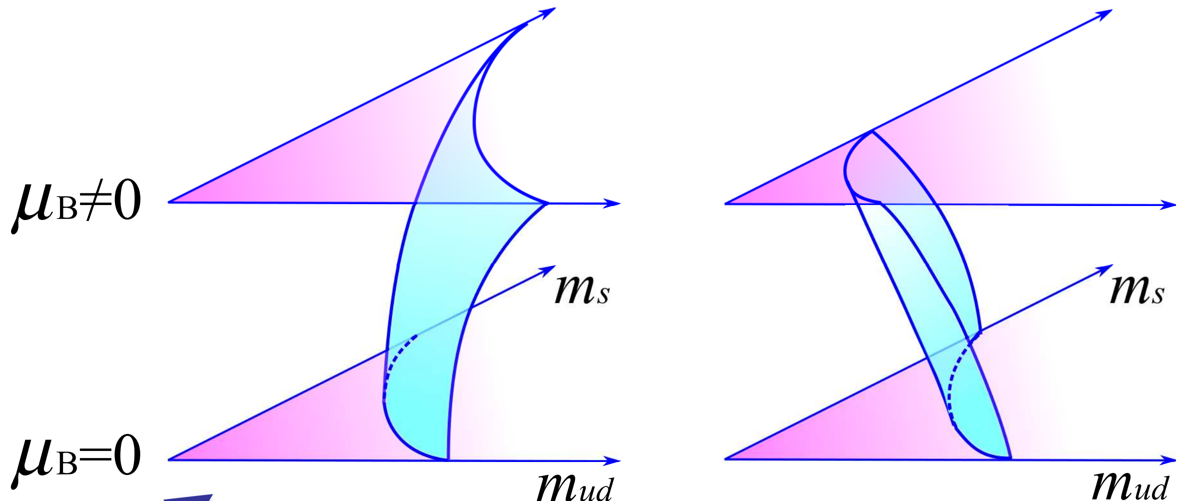
↓

More *K*⁺

($n_s = 0$)

QCD Critical Point



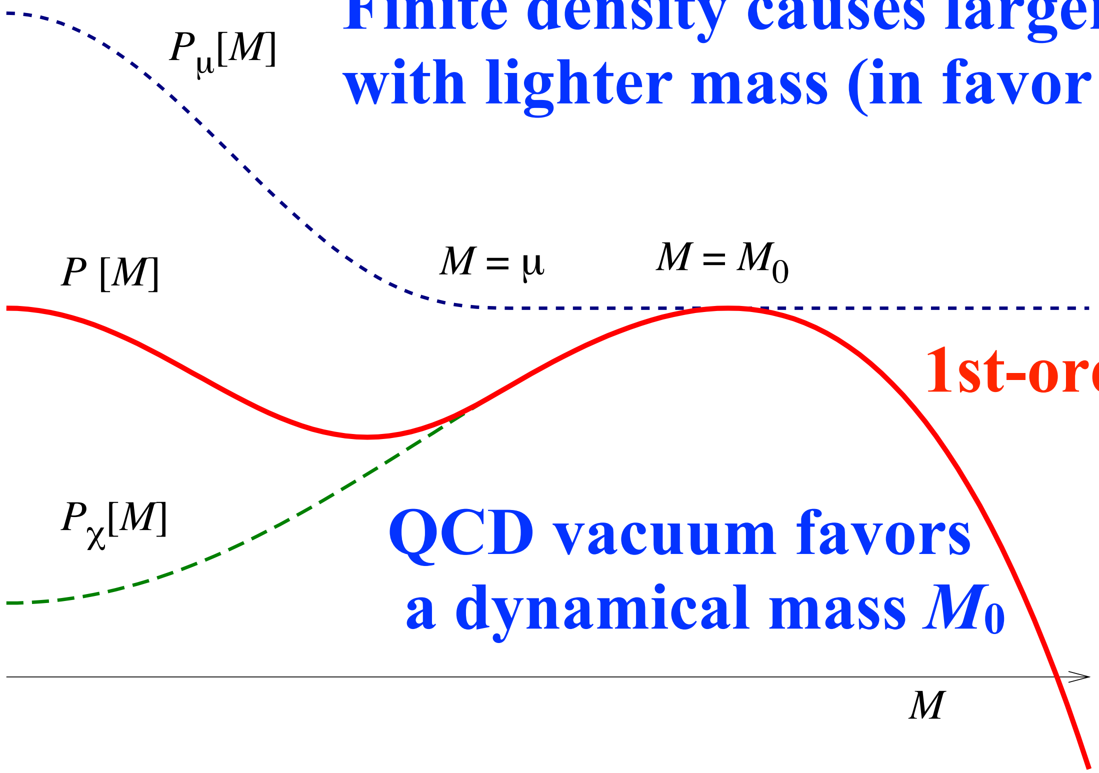


IF this is the case in QCD:
IF the curvature is large enough: → **QCD CP exists**

QCD CP is a hypothesis (needs exp. confirmation)

Why QCD CP ?

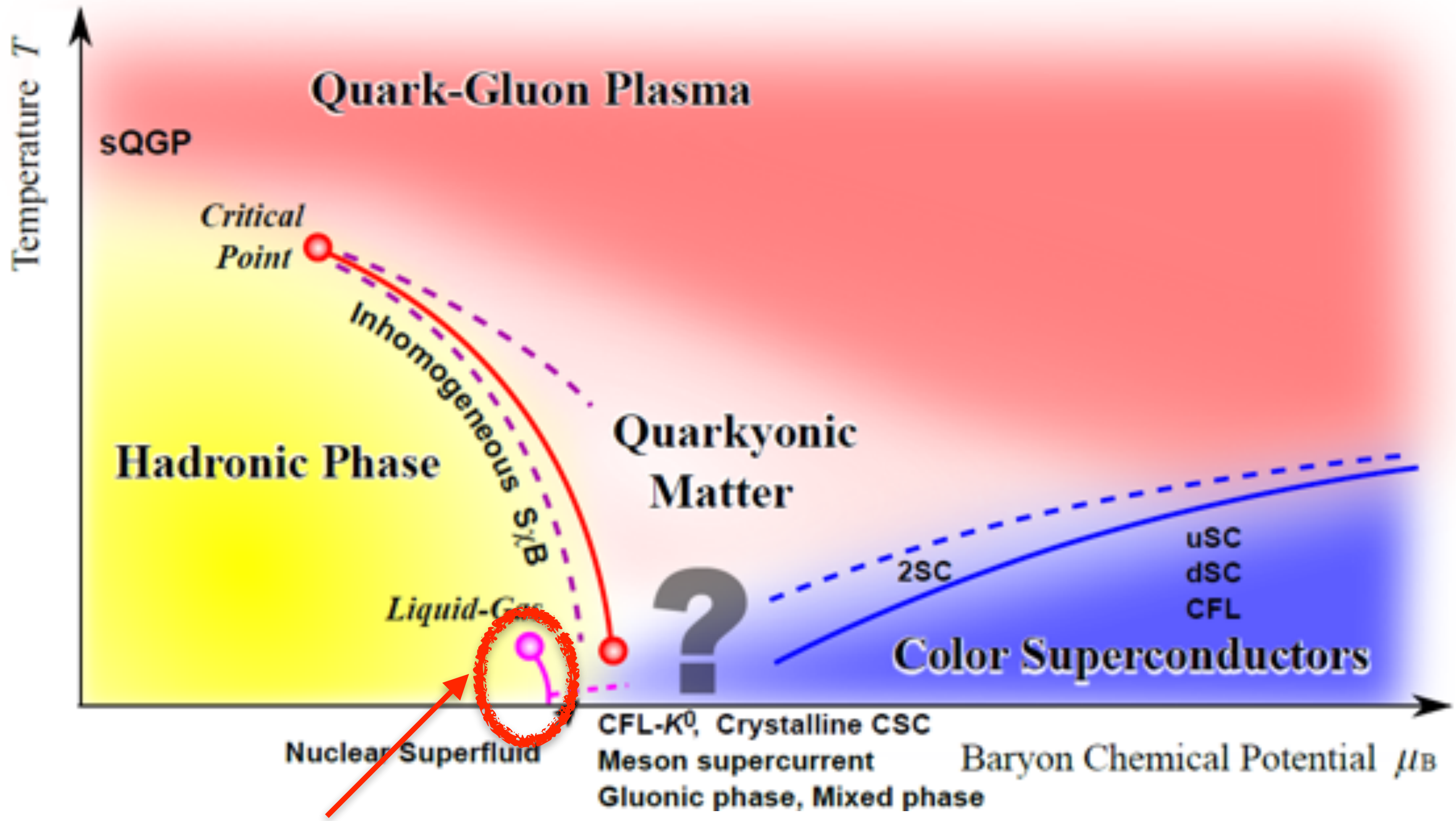
Finite density causes larger pressure with lighter mass (in favor of small *M*)



1st-order transition!

QCD vacuum favors a dynamical mass M_0

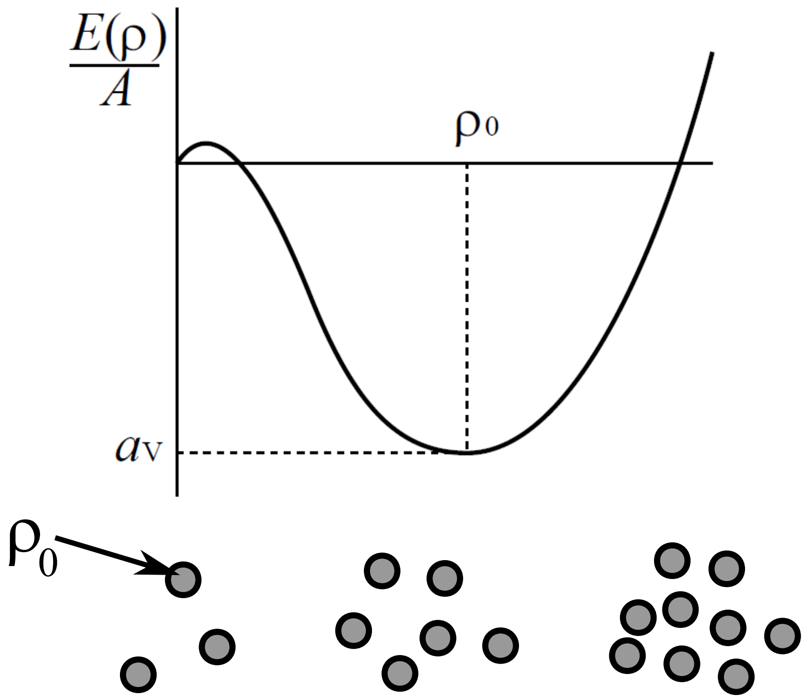
Known CP (nuclear matter)



Liquid-gas phase transition

(Nuclear matter is a self-bound fermionic system)

Mixed Phase

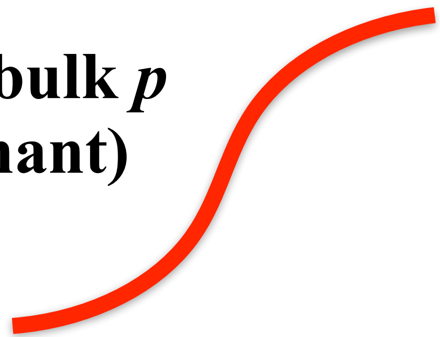


Self-bound fermionic systems have a preferred density.
Diluteness is realized as a "mixed phase" of nuclei.

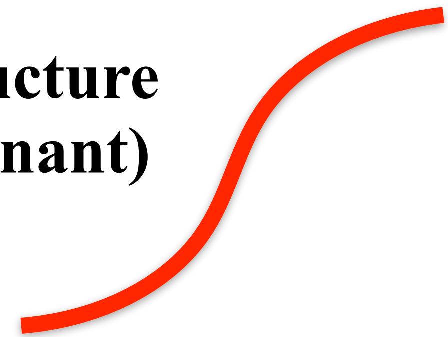
No argument about whether quarks are self-bound?
Quark EoS is constrained by neutron stars > $2M_\odot$

Fluctuations

Smooth bulk *p*
(dominant)



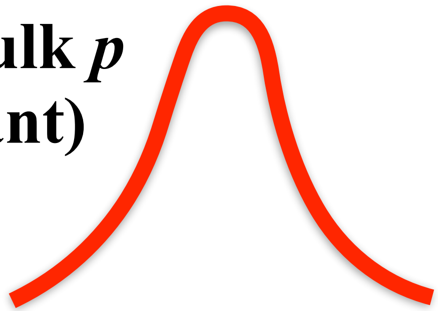
+ Fine structure
(sub-dominant)



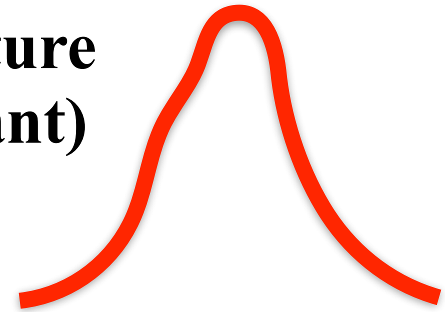
Q : How to extract the difference ?

Fluctuations

Smooth bulk *p*
(dominant)



+ Fine structure
(sub-dominant)



Q : How to extract the difference ?

A : Take the (higher) derivative !

$$\chi^{(n)}_{B,S} \equiv \frac{\partial^n}{\partial(\mu_{B,S}/T)^n}\frac{p}{T^4}$$

enhanced near QCD CP

Fluctuations

$$\frac{\sigma^2}{M} \equiv \frac{\chi_B^{(2)}}{\chi_B^{(1)}} \,, \qquad S\sigma \equiv \frac{\chi_B^{(3)}}{\chi_B^{(2)}} \,, \qquad \kappa\sigma^2 \equiv \frac{\chi_B^{(4)}}{\chi_B^{(2)}}$$

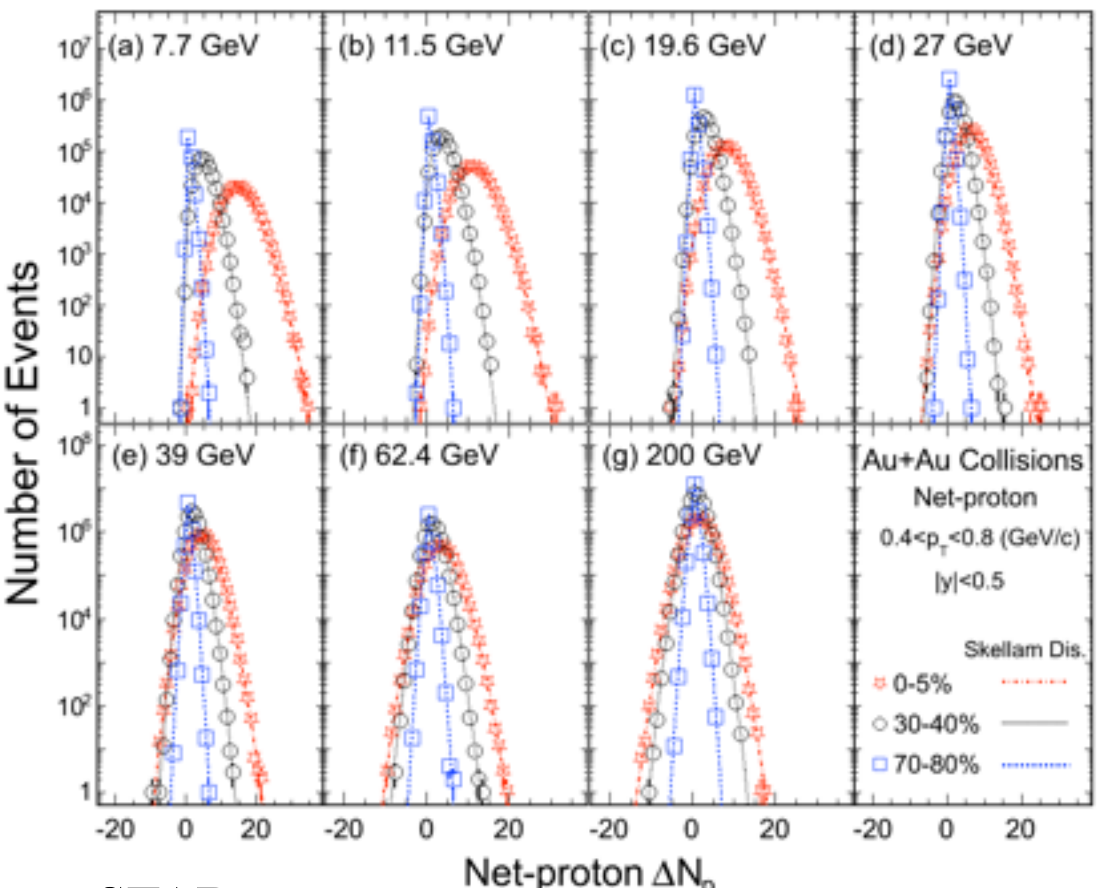
Skewness **Kurtosis**

HRG (non-interacting hadrons) + Boltzmann approx.

$$\boxed{S\sigma = \tanh(\mu_{\mathrm{B}}/T) \,, \qquad \kappa\sigma^2 = 1}$$

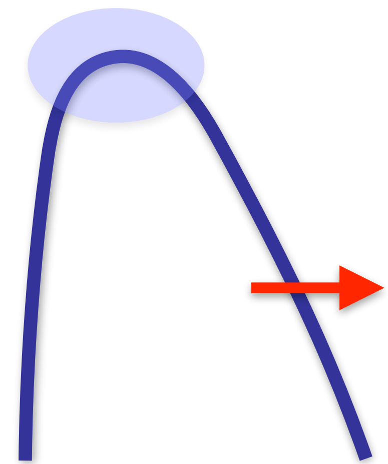
Karsch-Redlich (2011)

Fluctuations



STAR

κ ~ how sharp



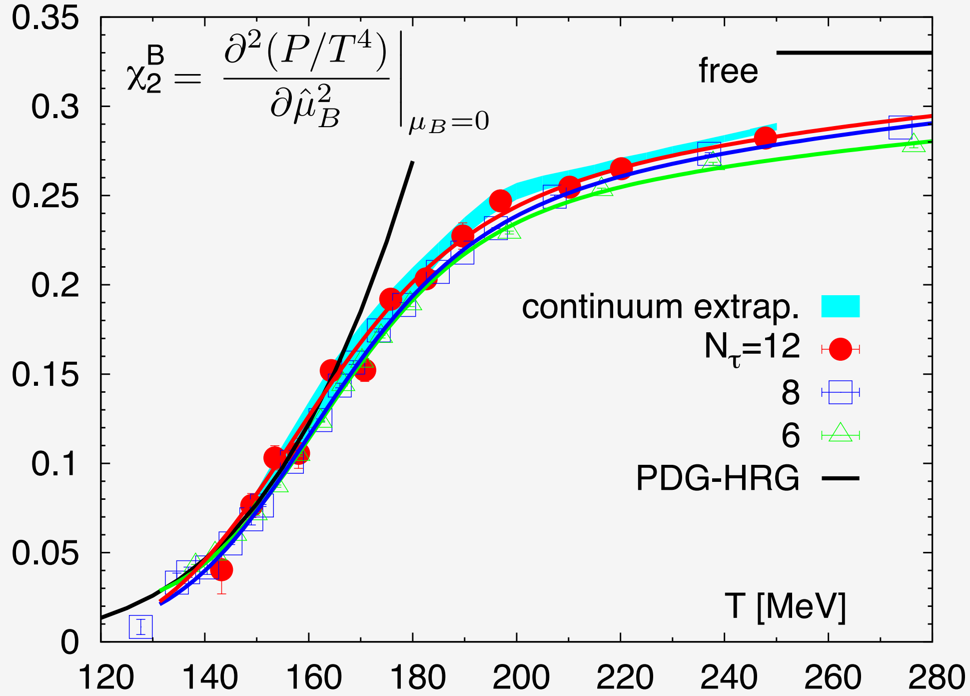
S ~ how distorted

→ Lecture by Nu Xu

Fluctuations on Lattice

Lattice from BNL-Bielefeld (thanks to Maezawa)

Susceptibility

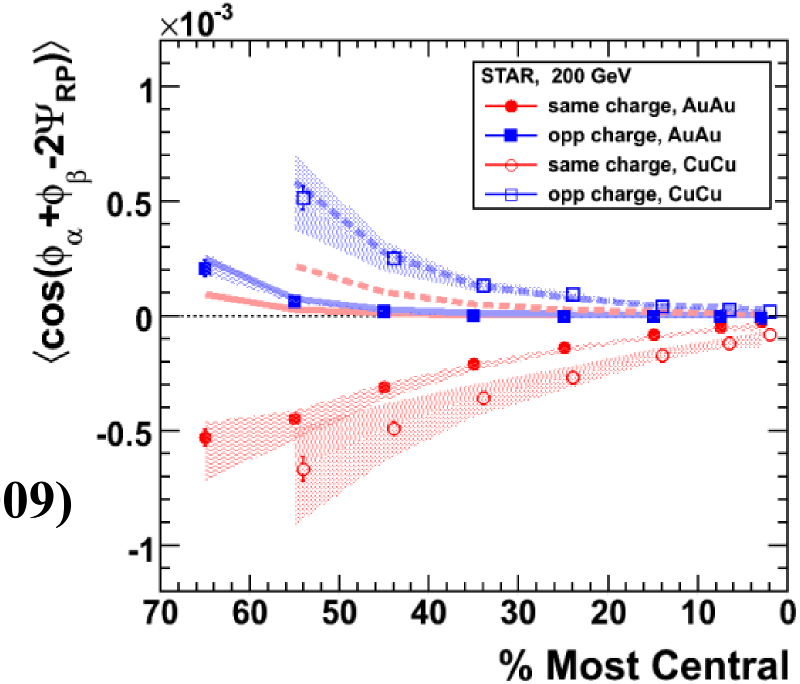


Deviation from HRG

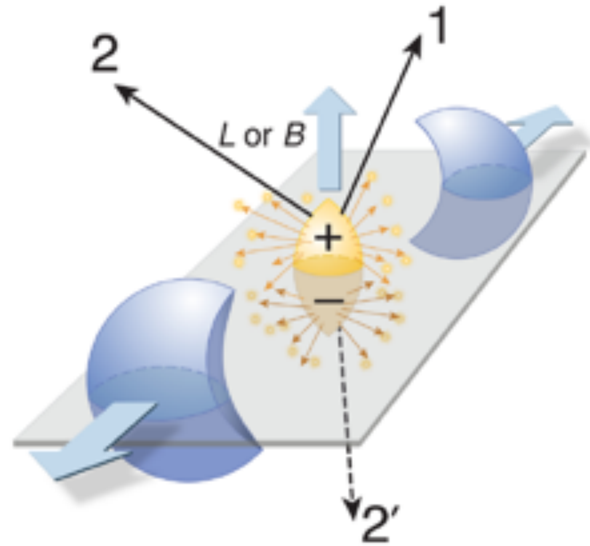
↓

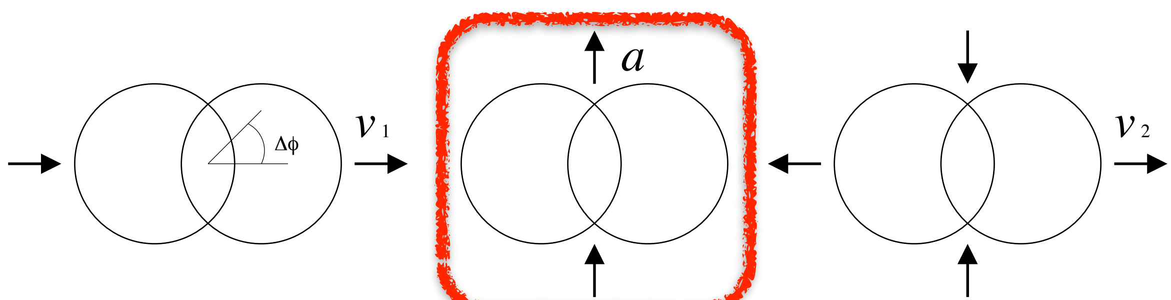
Deconfinement of heavy flavors (strange, charm,…)

Another (P-odd) Fluctuations

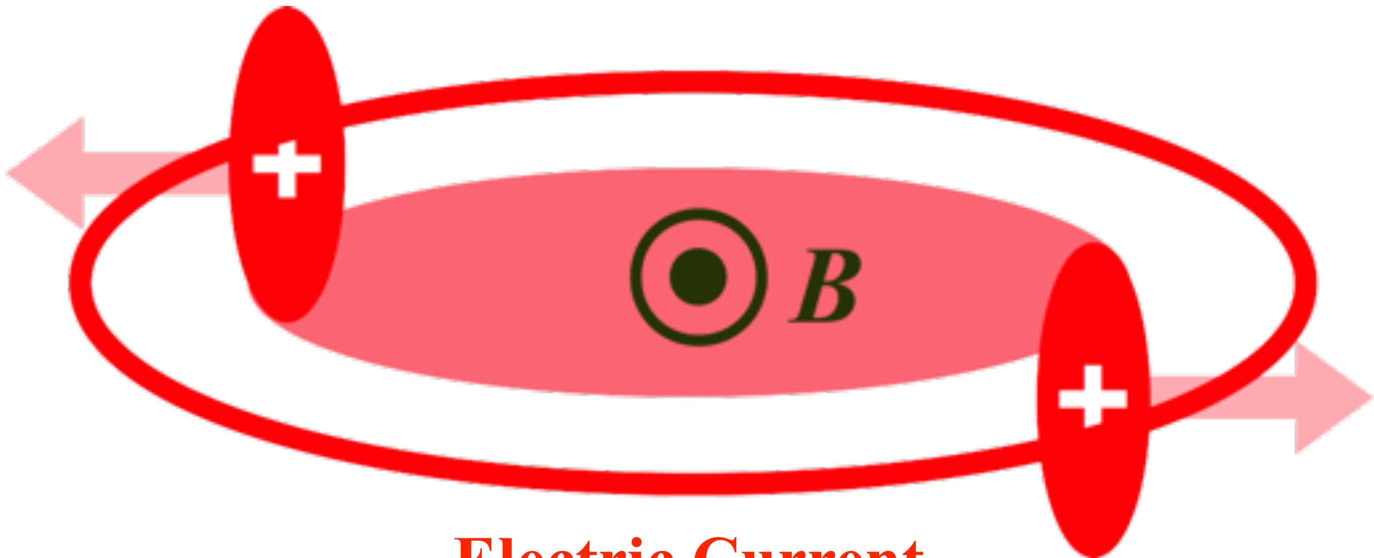


STAR (2009)



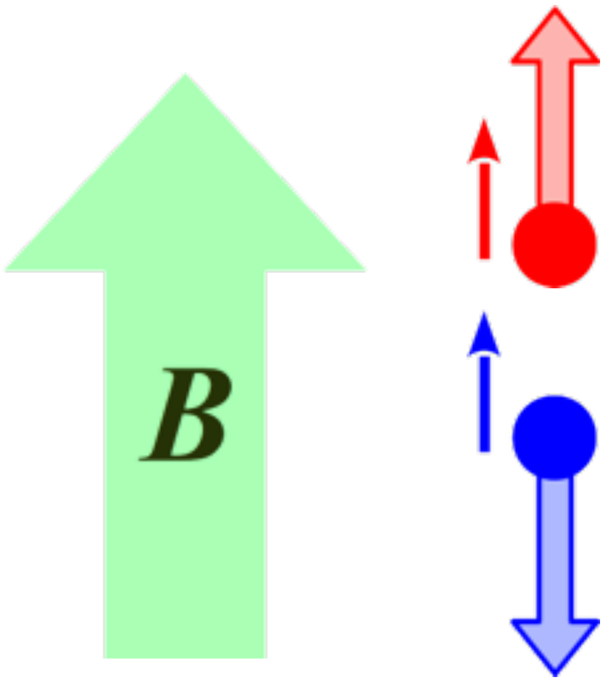


Magnetic Field? Vorticity?



Strong field of the QCD scale
Short life-time (shorter than the QCD scale)
Vorticity with longer life time

Chiral Magnetic Effect



Right-handed particles
Momentum parallel to Spin

Left-handed particles
Momentum anti-parallel to Spin

If topological fluctuations exist in a QGP, it should be reflected in charge-sep. fluct.

CME not confirmed but not excluded in HIC

Q (categorized to QCD) & A

- **The QGP we obtain at LHC is a strongly interacting fluid. Do we expect that due to the asymptotic freedom QGP at some higher collision energies will be an almost ideal gas of quarks and gluons? If yes then how high should be such collision energy?**
- **"strongly interacting" and "strongly correlated" should be distinguished. Resumed pQCD works already at ~3T_c but the dynamics always passes over the sQGP regime near freezeout.**
- **I think that the QCD system is well described by a free gas, the Quark Gluon gas model at high temperature. However, the results of the lattice calculation don't much the results of the Quark Gluon gas model even at high temperature, and I have heard that QGP behaves like a perfect fluid. So I'm interested in an approximation method of the QGP.**
- **Resumed pQCD works at ~3T_c for bulk thermodynamic quantities but does not account for smallness of the shear viscosity. Lattice is marginal and functional RG might be getting better…**

Q (categorized to QCD) & A

- **Where does the Cronin effect comes from and which are its consequences in collisions? Can it be influenced by the shadowing effect?**
- **Redistribution of momenta gives enhanced R_{pA} at small p_T (Cronin effect) that may or may not be influenced by non-linear evolution.**

- **What are the details of pQCD and lattice QCD calculations? I would like to see basic examples leading to more complicated ones.**
- **Example : Resumed pQCD at high T (Hard Thermal Loop)**

$$\Gamma_{\text{eff}} = \int d^4x\, m_E^2 \,\mathrm{tr} A_0^2 + \int \frac{d\Omega}{4\pi} W(gA\cdot\hat{K})$$

$$p \sim T\int d^3p \sim Tm_M^3 \sim g^6T^4 \quad (m_M \sim g^2T)$$

(IR Catastrophe)

Q (categorized to QCD) & A

- **Are there some theoretical and practical evidences to believe that not only scalar-pseudoscalar channel is important for low-energy-QCD models, i.e. should we use Fierz complete approach for calculations or you believe that standard scalar- pseudoscalar ansatz for effective interaction is sufficient?**
- **Just go beyond the mean-field approximation.**
- **What is chiral symmetry and why is it expected to be restored in heavy-ion collisions?**
- **Just like the disappearance of magnetization at Curie temperature.**
- **How many critical points one can expect in the QCD phase diagram?**
- **One we know for sure, two we hope to find, three theory may have.**
- **What is the critical point in the QCD phase diagram and how would it be visible in measurements?**
- **You are supposed to know now after this lecture… aren't you?**

Q (categorized to QCD) & A

- **Is QGP formed in high-multiplicity pPb collisions? By considering the measured particle multiplicity and the small size of the colliding system, it can be deduced that the initial energy density in high-multiplicity pPb events exceeds the one measured in PbPb collisions, and therefore the critical value for the QGP phase transition. However, could such a small and short-lived system reach thermal equilibrium fast enough to form a QGP-like droplet?**
- **This is precisely the hottest topic that will be discussed.**
  Go to the parallel and plenary talks and enjoy them!

Q (categorized to QCD) & A

- **How is the CSC state of QCD described mathematically, and do we expect that it actually manifests itself physically anywhere?**
- **Mathematically it is defined by the chiral symmetry breaking pattern and this is why we can never distinguish CSC from nuclear matter, in principle, in a gauge invariant way. CSC may or may not be realized in the cores of neutron star.**

- **Do we need to go to higher energies in heavy ion collisions i.e. more than LHC energy? If yes then what we would explore in the direction of QGP or QCD?**
- **Depends on physics we are interested in. For small-*x* physics it is nicer and nicer to go to higher and higher energies, but to explore the phase structure physics is dominated at the chemical freezeout which is not changed by the collision energies.**