Relation between color deconfinement and chiral restoration

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References: K. Fukushima Phys. Lett. B553, 38 (2003)
K. Fukushima Phys. Rev. D68, 045004 (2003)
K. Fukushima hep-ph/0310121
Y. Hatta and K. F. hep-ph/0307068, hep-ph/0311267

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Question and Conclusion

- Question
  - What is the QCD phase transition like?

    Deconfinement or Chiral restoration

    Well-defined at $m_q = \infty$ (Deconfinement)

    Well-defined at $m_q = 0$ (Chiral restoration)

  - What happens for $0 < m_q < \infty$?
- Conclusion
  - There is only one phenomenon for any m_q.

    Simultaneous transitions are really simultaneous.

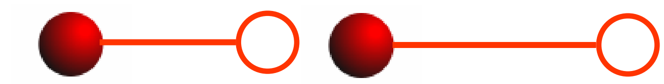
Some Basics

- "Confinement" cannot be recognized.

$m_q = \infty$

x $\quad f_q(x) = \infty \quad$ $x = \infty$

$m_q < \infty$



x $\quad f_q(x) \approx 2m_{\mathrm{meson}} \quad$ $x = \infty$

$l = e^{-f_q/T}$

$l = 0 \rightarrow l \neq 0$ at high T

always $l \neq 0$

- Chiral restoration is approximately realized.

$<q\bar{q}> \neq 0 \ \rightarrow \ <q\bar{q}> \approx 0$ at $m_q \approx 0$ and high T

One might think…

There is only one phenomenon, *i.e.*, chiral restoration.

l reflects the singularity of $<q\bar{q}>$ due to mixing effects.

That means…

- The deconfinement phase transition is so smeared that we cannot see its remnant.
- Then…the QCD phase transition is nothing more than a chiral phase transition?

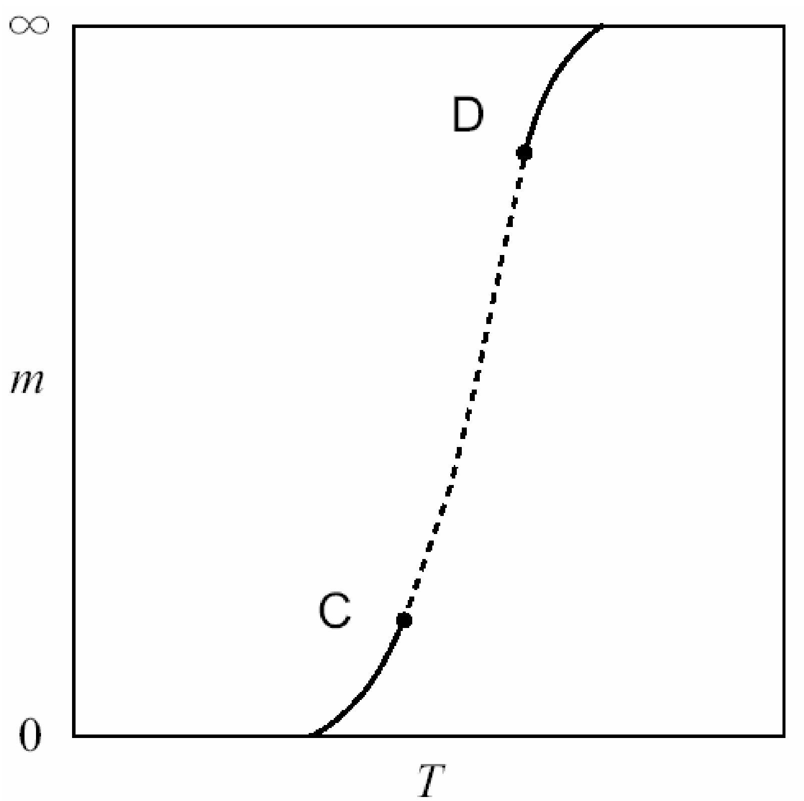
However…

- Even though we have no rigorous definition, the notion of "deconfinement" is indispensable to understand the QCD phase transition.
  - Thermodynamic quantities (e.g. entropy)

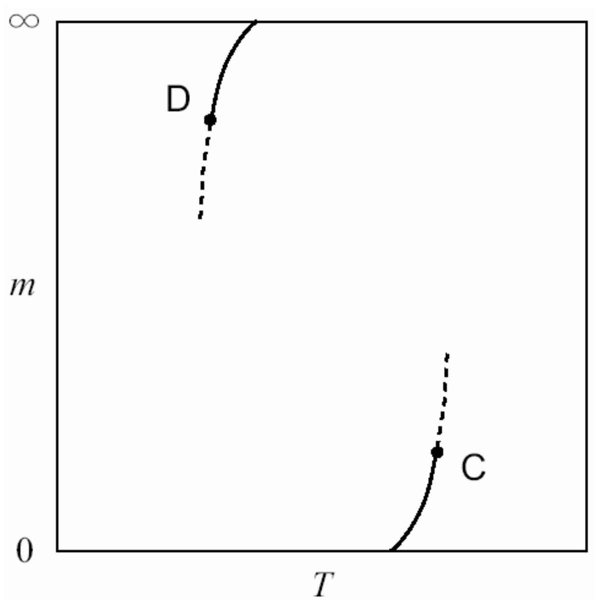
Linking deconfinement and chiral phase transitions

- Two true phase transitions are connected.

  (This is the fact observed in the lattice QCD simulation.)



Not disconnected like



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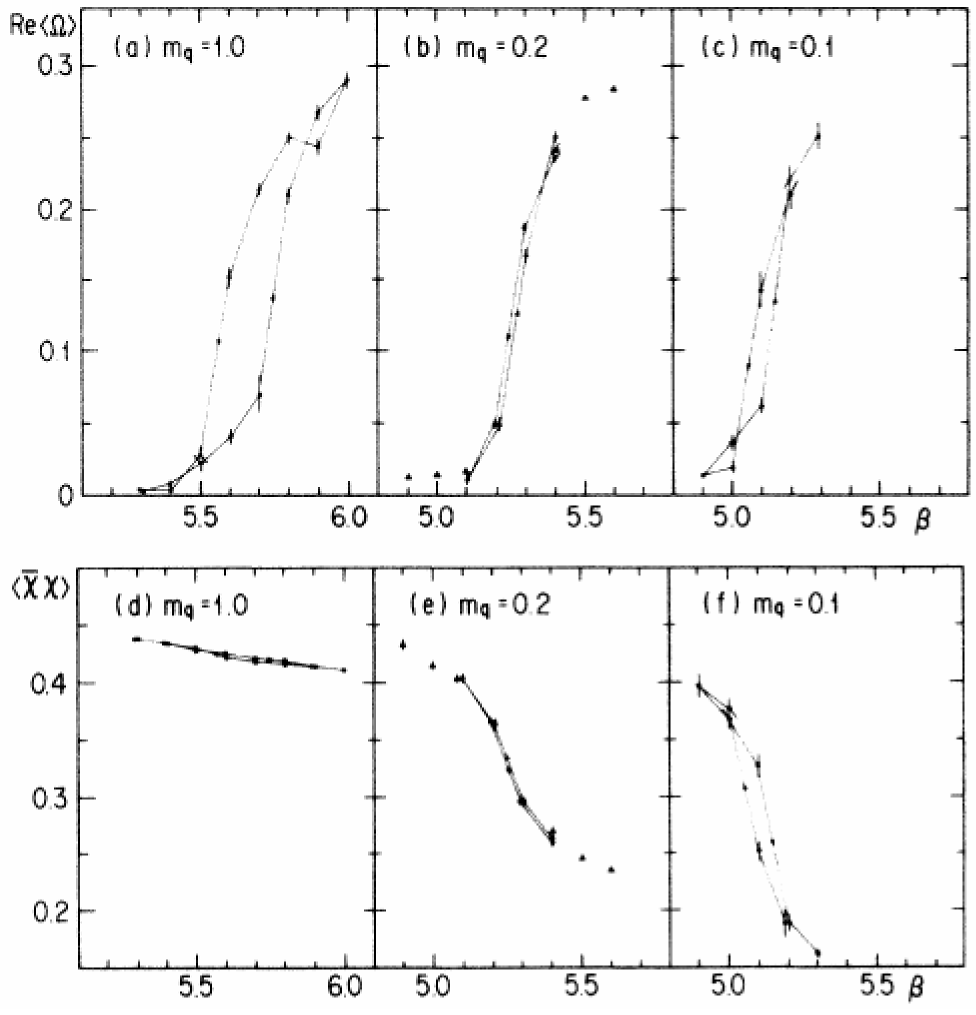
Evidence

- Fukugita, Ukawa
  PRL57, 503 (1986)



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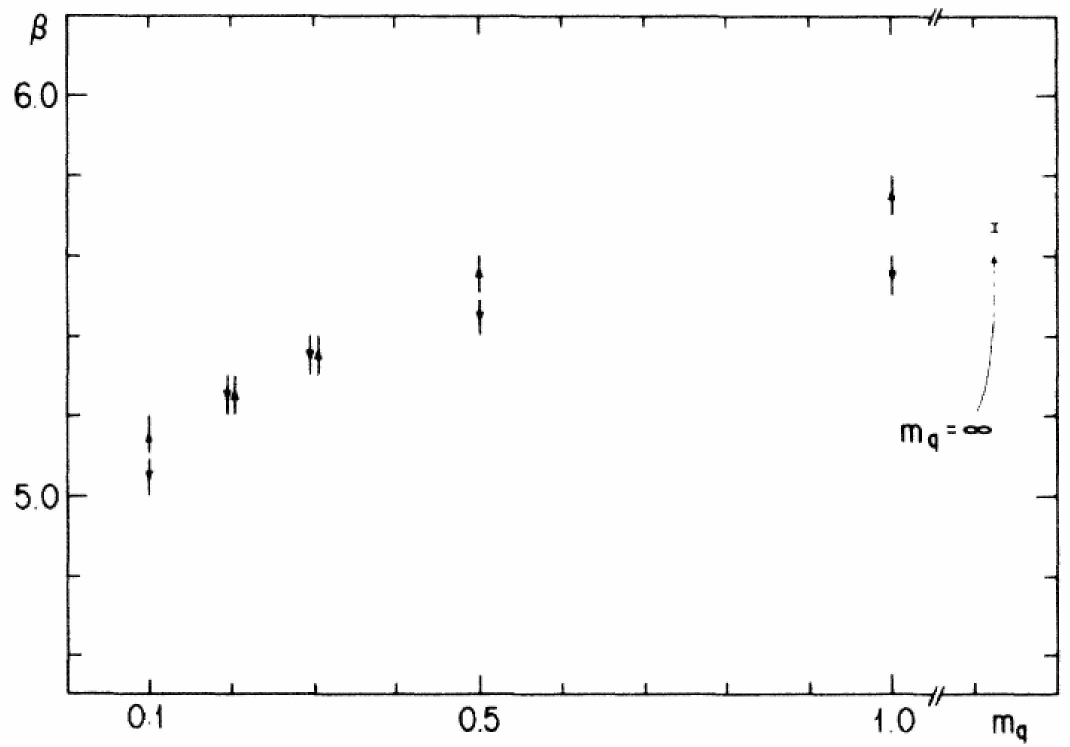


"The deconfining and chiral transitions occur at the same temperature. The strength of transition weakens initially as the quark mass decreases from infinity, but at small quark masses it strengthens again …"

Effective Potential

$$V_{\mathrm{eff}} = V_{\mathrm{glue}}[l; m_{\mathrm{q}}] + V_{\mathrm{chiral}}[\sigma; m_{\mathrm{q}}] + V_{\mathrm{int}}[l, \sigma; m_{\mathrm{q}}]$$

Around C, l sees the singularity of σ in V_{chiral} through V_{int}

Around D, σ sees the singularity of l in V_{glue} through V_{int}

To link C and D, V_{int} must have special properties.

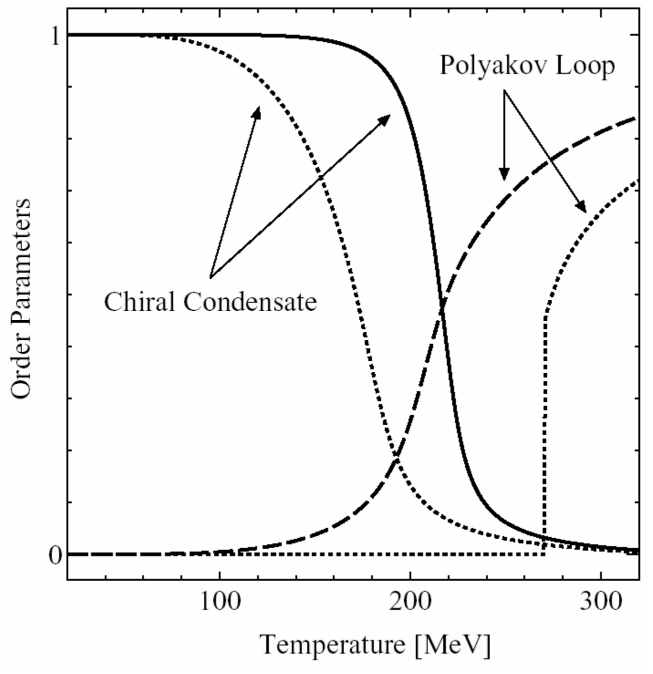
Polyakov loop, l, couples with σ through quasi-quark excitations.

$V_{\mathrm{int}}\left[l, E_p = \sqrt{p^2 + M^2}\right]$ then the mixing $\partial^2 V_{\mathrm{eff}} / \partial l \partial \sigma \propto M$

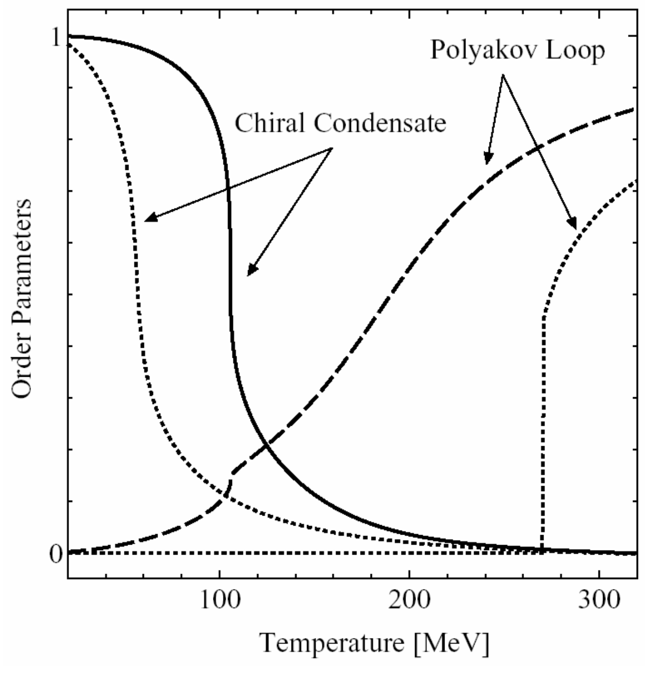
A simple mixing argument is challenged.

Model

$$\sim T\int\frac{d^3p}{(2\pi)^3}\,\mathrm{Tr_c}\,\ln\left[1+L\,e^{-(E_p-\mu)/T}\right]+\mathrm{Tr_c}\,\ln\left[1+L^{+}\,e^{-(E_p+\mu)/T}\right]$$



$\mu = 0$



$\mu = 312\,\mathrm{MeV}$

Soft Mode

$$V_{\text{eff}} \to V[\phi, \phi']$$

$$\begin{aligned} \phi &= \cos\theta \cdot \sigma + \sin\theta \cdot l && \text{(soft-mode)} \\ \phi' &= -\sin\theta \cdot \sigma + \cos\theta \cdot l && \text{(heavy} \to \text{decouple)} \end{aligned}$$

l does not correspond to physical excitations.
Electric glueballs, G_{E}, couple to *l* to be a soft-mode.
Alternatively we can define

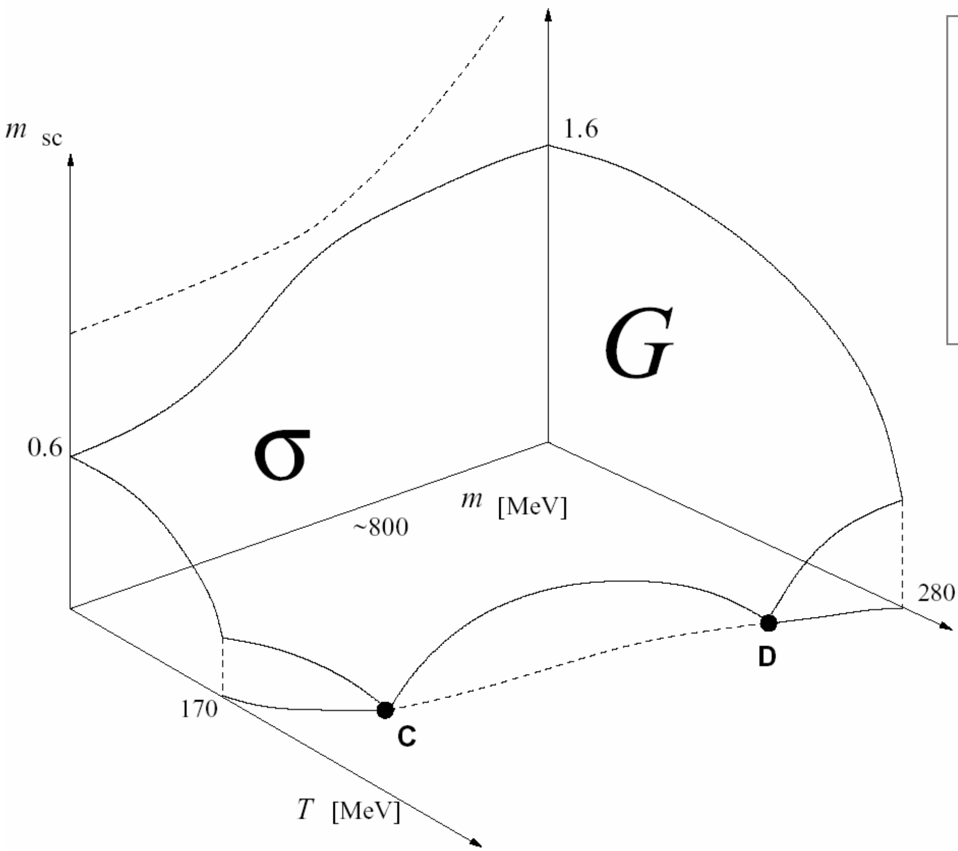
$$\begin{aligned} \phi &= \cos\theta \cdot \sigma + \sin\theta \cdot G_{\mathrm{E}} \\ \phi' &= -\sin\theta \cdot \sigma + \cos\theta \cdot G_{\mathrm{E}} \end{aligned}$$

where $G_{\mathrm{E}} = (l - \langle l \rangle)^2$ should be distinguished from G_{M}

It is proven that G_{E} becomes massless at D.

Level Repulsion

- Schematic picture of soft ϕ mode

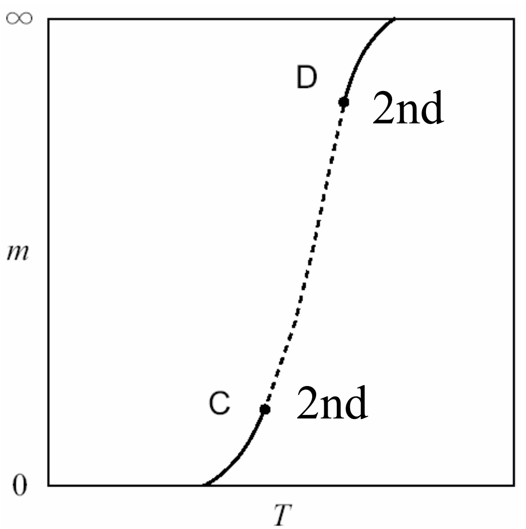


If level repulsion between ϕ and ϕ' is strong enough, only ϕ becomes a soft-mode and ϕ' remains heavy.

Conclusion again

- Chiral and Deconfinement phase transitions are extreme manifestations of one phenomenon characterized by one soft-mode.

Deconfinement transition



Chiral phase transition

Simultaneous transitions indicate not only mixing effects but also true simultaneous realization of remnants of two transitions.