Chiral Symmetry and Heavy-Ion Collisions

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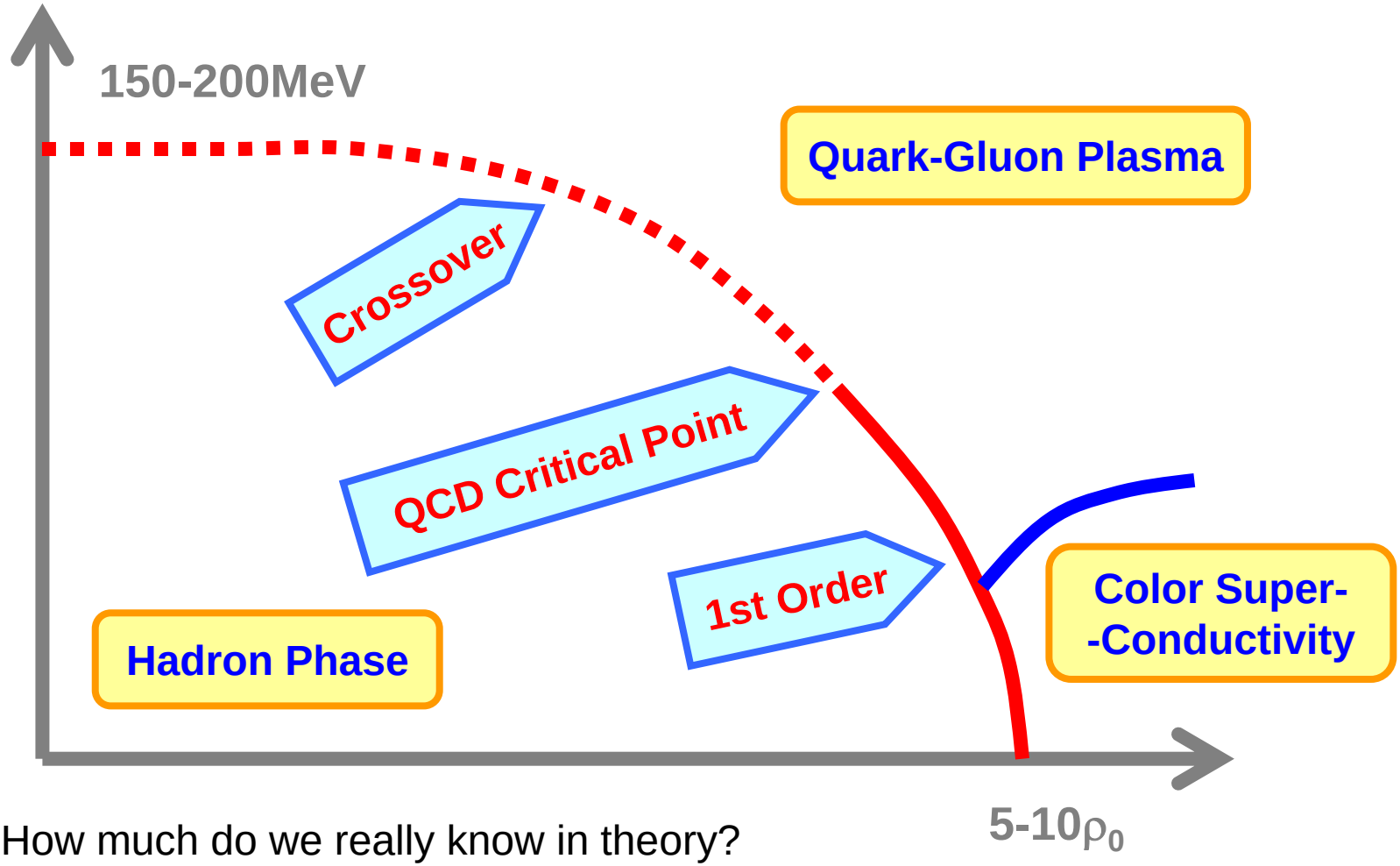
*So-called "**QCD Phase Diagram**"*



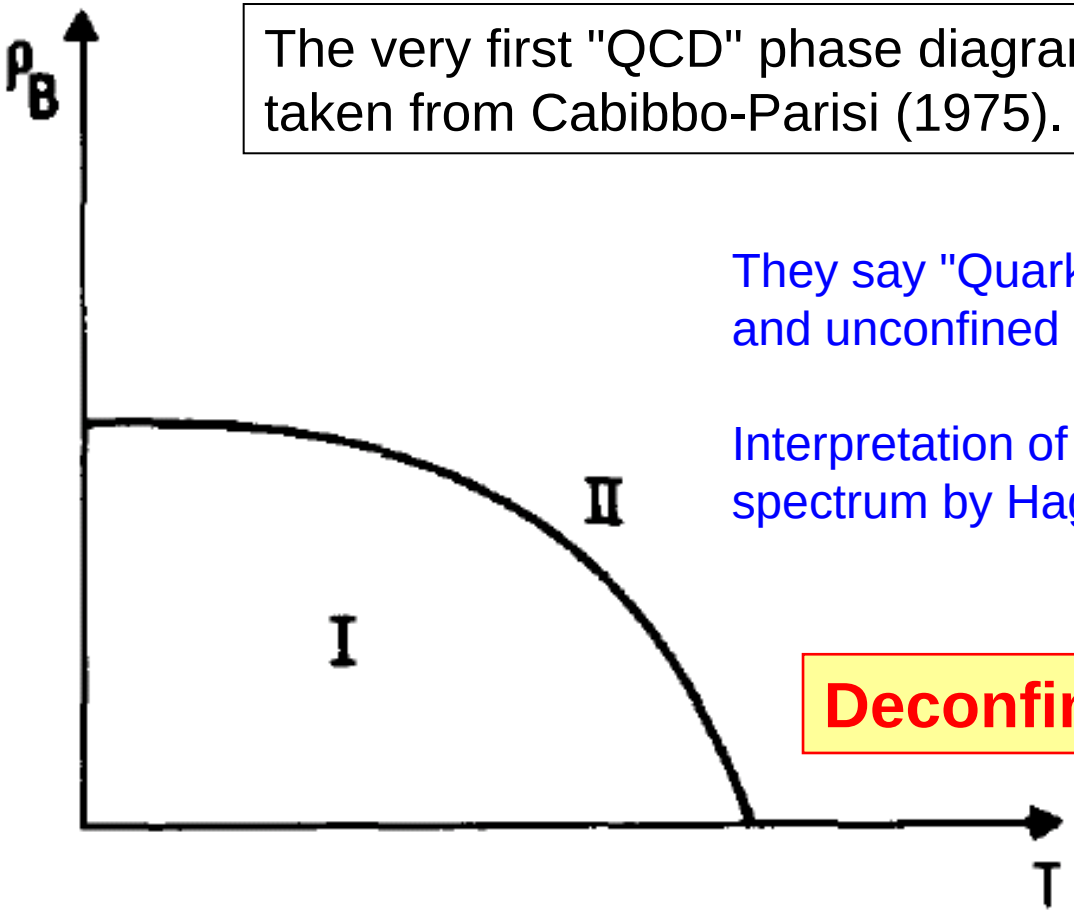
How much do we really know in theory?

Agenda

- **QCD phase diagram is really established ?**
  - What is robust and what is not ?
  - How to draw the phase diagram ?
- **Lattice does not work at finite μ . . .**
  - What is to be described by the model ?
  - QCD critical point

History of the Phase Diagram

The very first "QCD" phase diagram taken from Cabibbo-Parisi (1975).



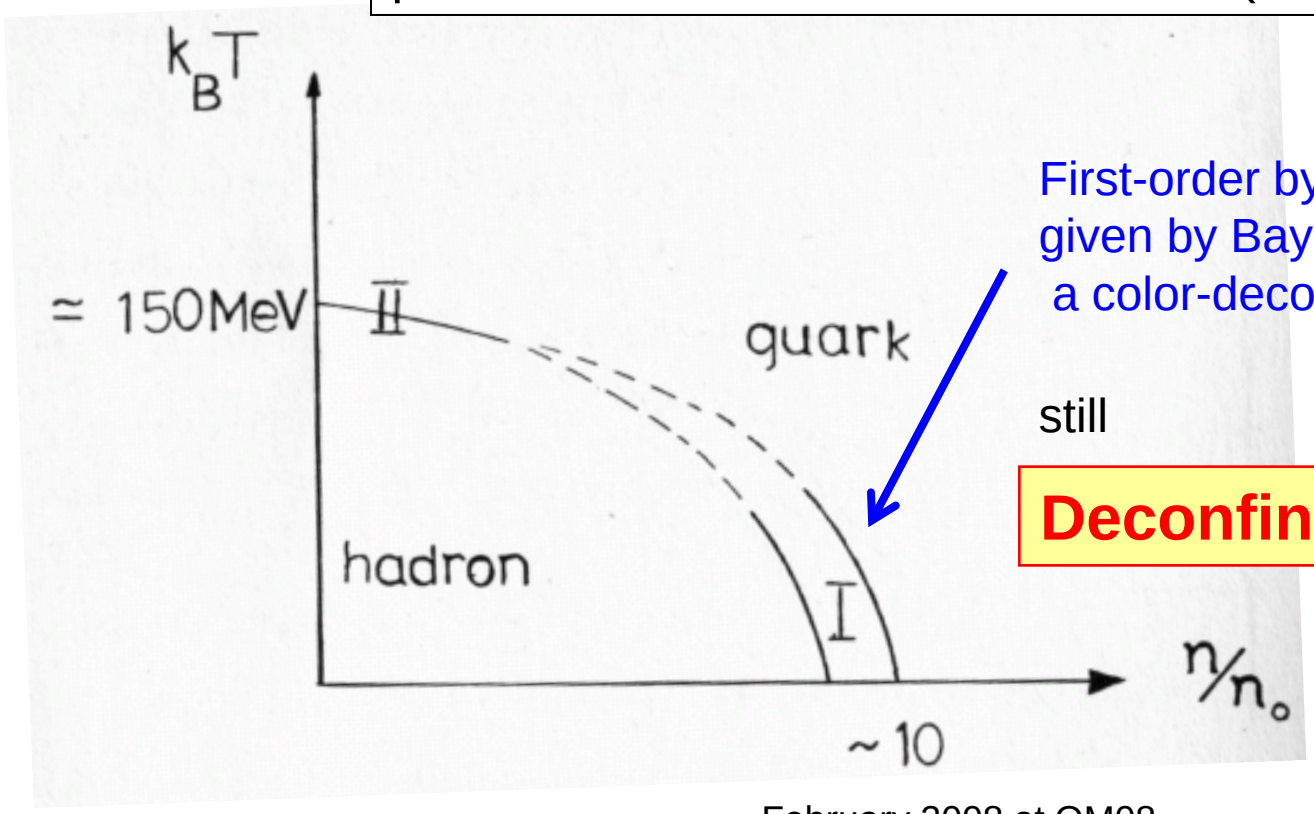
They say "Quarks are confined in phase I and unconfined in phase II".

Interpretation of the exponentially increasing spectrum by Hagedorn.

Deconfinement Transition

Bielefeld Proceedings in 1980

The very first phase diagram with both the continuous and discontinuous phase transitions taken from Kallen (1980)



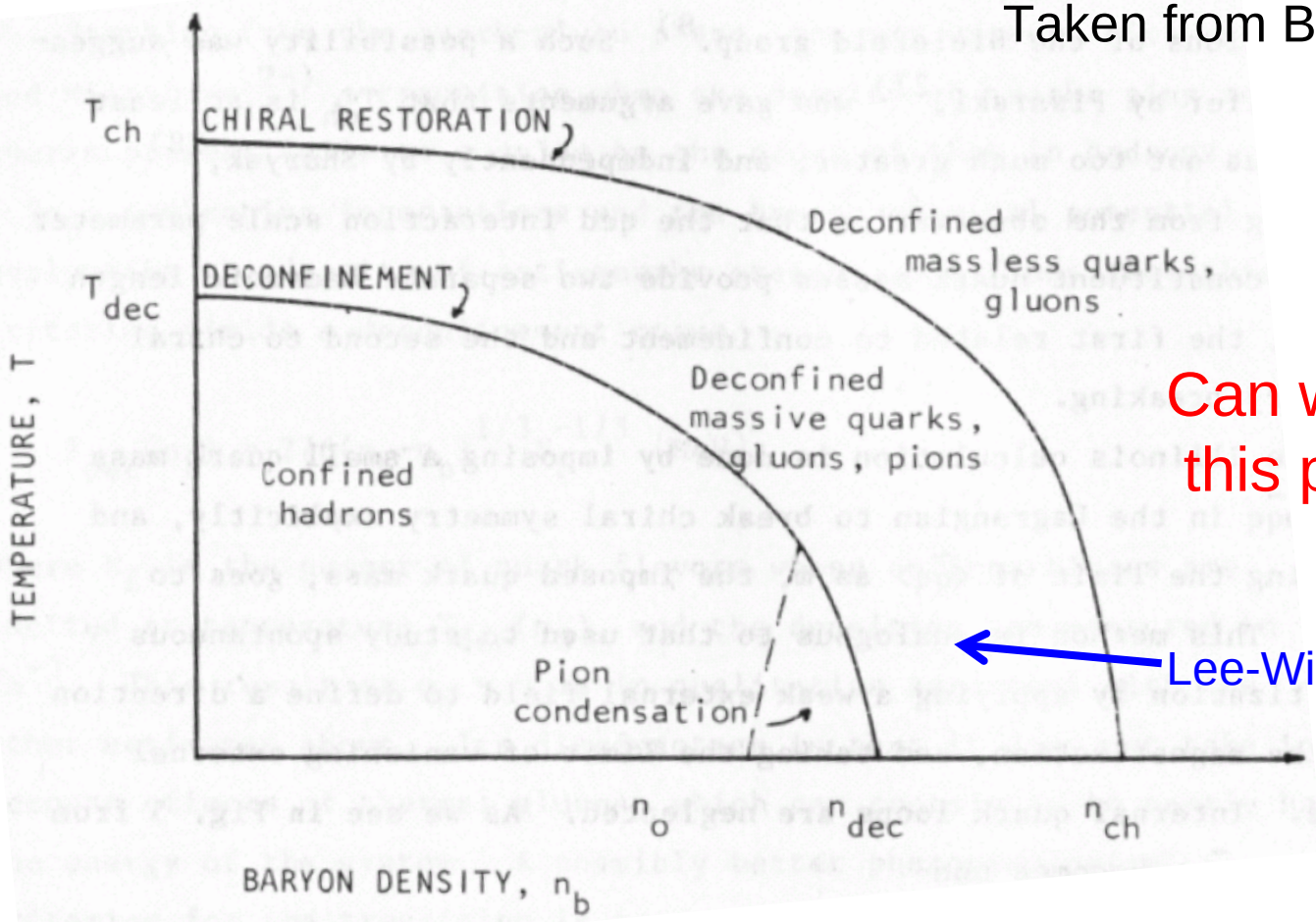
First-order by the argument given by Baym based on a color-deconfinement picture.

still

Deconfinement Transition

Bielefeld Proceedings in 1982

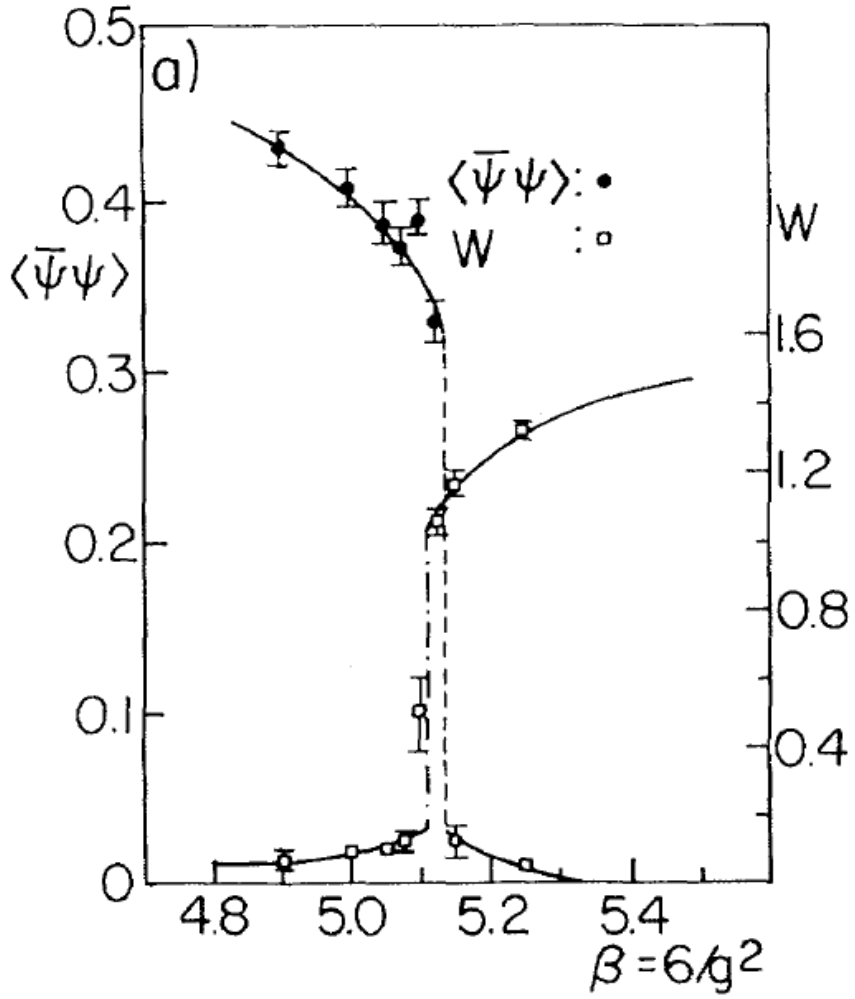
Taken from Baym (1982)



Can we exclude this possibility ???

Lee-Wick abnormal matter

Lattice QCD



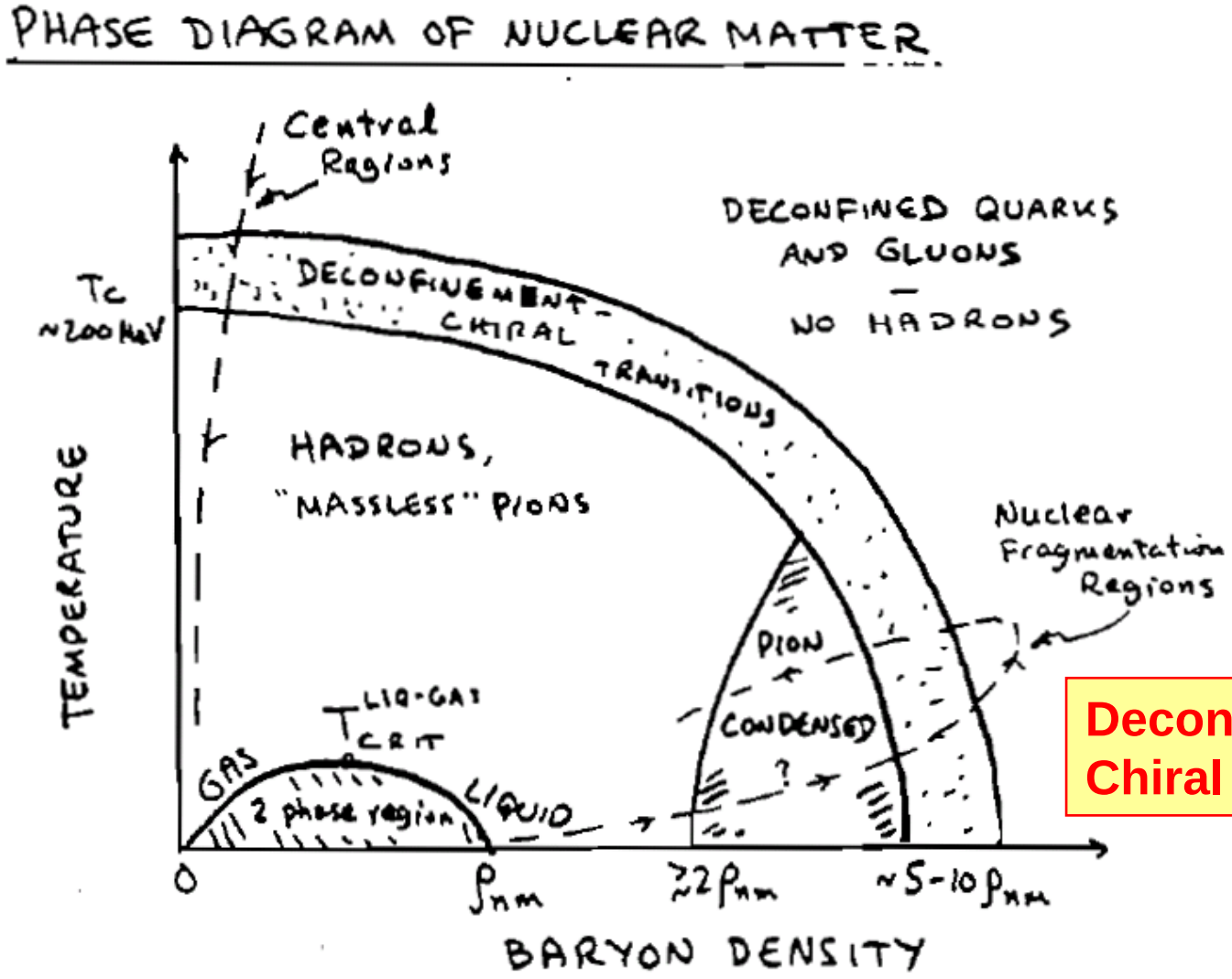
Taken from
Kogut, Stone, Wyld, Gibbs,
Shigemitsu, Shenker, Sinclair (1983)

$\langle\bar{\psi}\psi\rangle$ Chiral Condensate

$W \sim \exp[-f_q/T]$ Polyakov Loop

Chiral Restoration
occurs simultaneously
with **Deconfinement** !

Long Range Plan in 1983

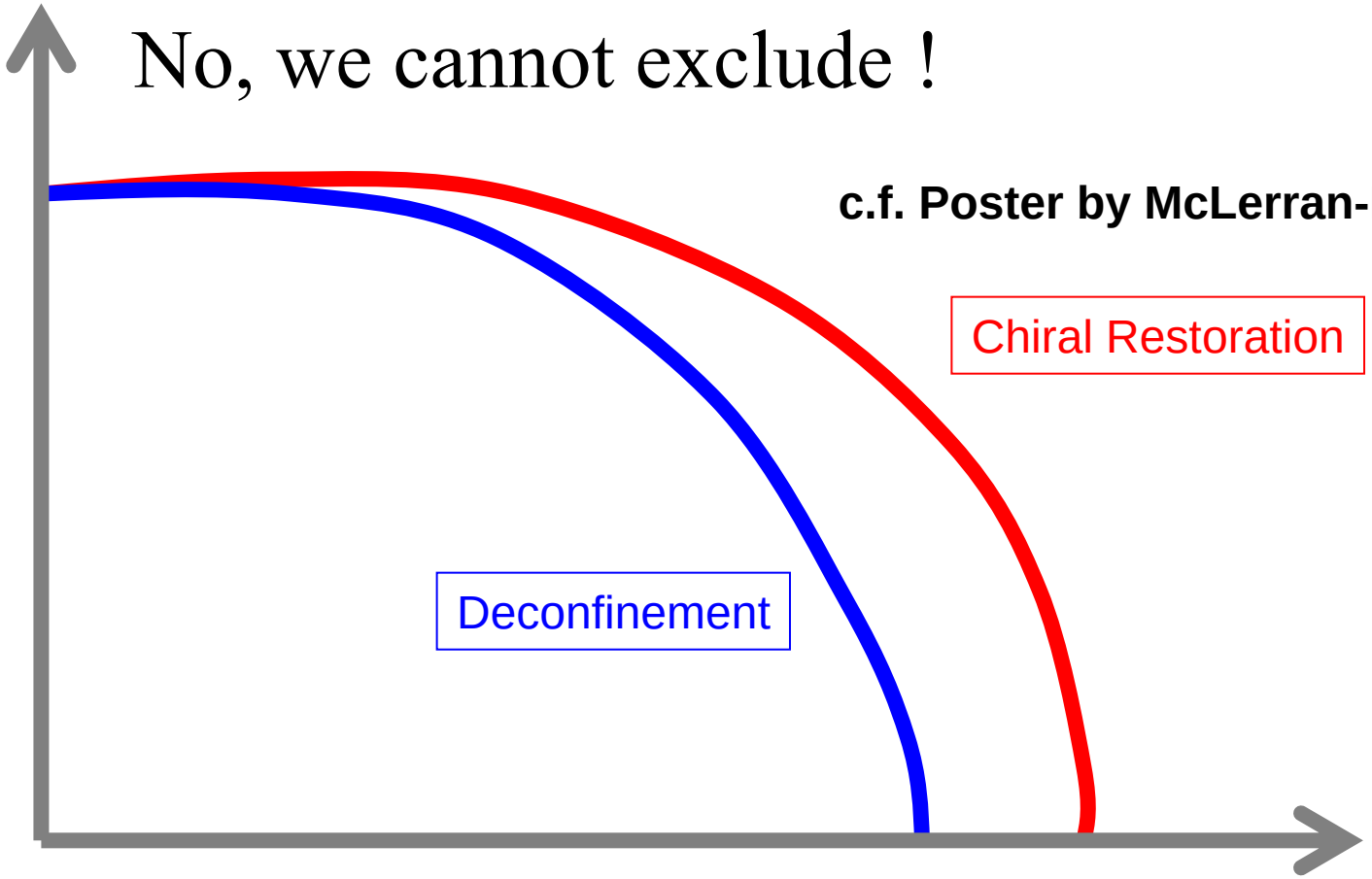


Deconfinement and Chiral Transitions

Why not?

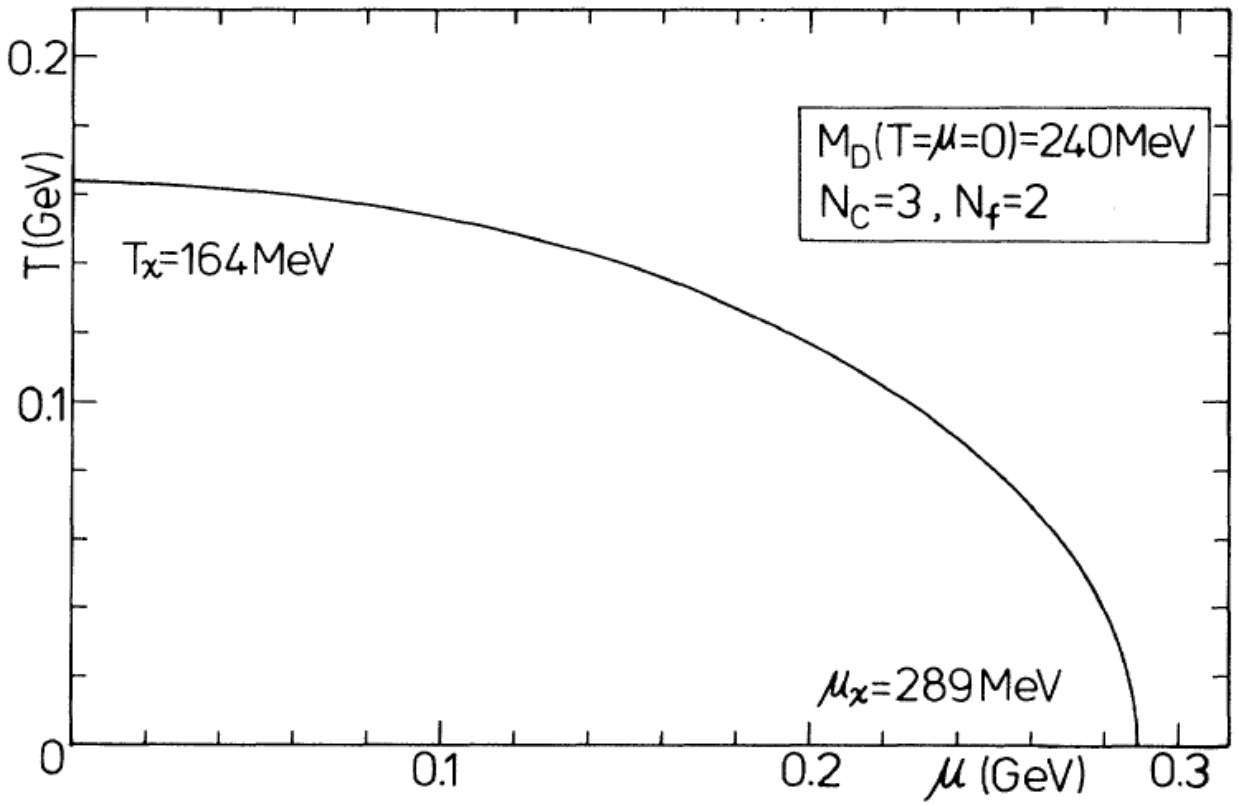
How can we exclude a possibility like...

No, we cannot exclude !



c.f. Poster by McLerran-Pisarski

Low-Energy Chiral Model



No confinement

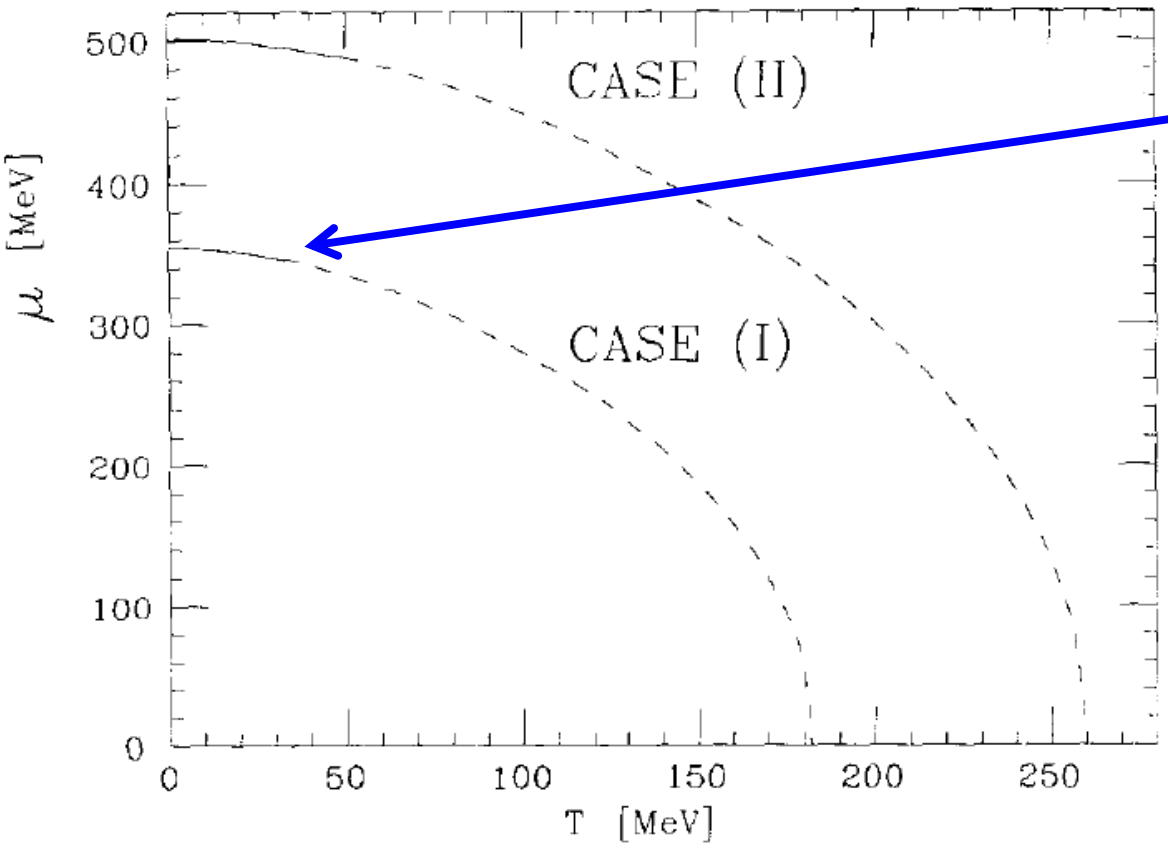
only chiral dynamics

though looks similar

Chiral Transition

Taken from Hatsuda-Kunihiro (1985)

Critical End-Point (QCD Critical Point)



First-order Transition but has nothing to do with Baym's argument

Chiral Transition

Taken from Asakawa-Yazaki (1986)

Theory tells us...

- Much about Chiral Phase Transition — Phase Diagram
  - Effective models based on chiral symmetry
  - Well-defined order parameter in $m \to 0$ limit

The phase structure can be clarified without confinement or deconfinement unless two transitions are distinct.

Confirmed only at $\mu=0$

- Little about Deconfinement Transition
  - Effective models based on center symmetry
  - Well-defined order parameter in $1/m \to 0$ limit

Lattice QCD simulations cannot draw the phase diagram yet...

→ Talks at Session XI
Posters

Entanglement of Two Dynamics

- **Ideas**
  Pisarski (1982) Shuryak (1981)
  Digal-Satz (2001) Mocsy-Sunnino-Tuominen (2003)
  Hatta-Fukushima (2003)

- **QCD**
  Gocksch-Ogilvie (1985)
  Fukushima (2002)
  Strong coupling expansion

- **Model**
  Fukushima (2003)
  NJL model with the Polyakov loop
  (Partial) confinement below T_c
  Simultaneous transitions

- **Consistency with Lattice**
  Ratti-Thaler-Weise (2004)
  Named PNJL model

→ **Posters on PNJL**
by Hansen-Alberico-Costa,
Ghosh-Mukhejee-Mustafa-Ray

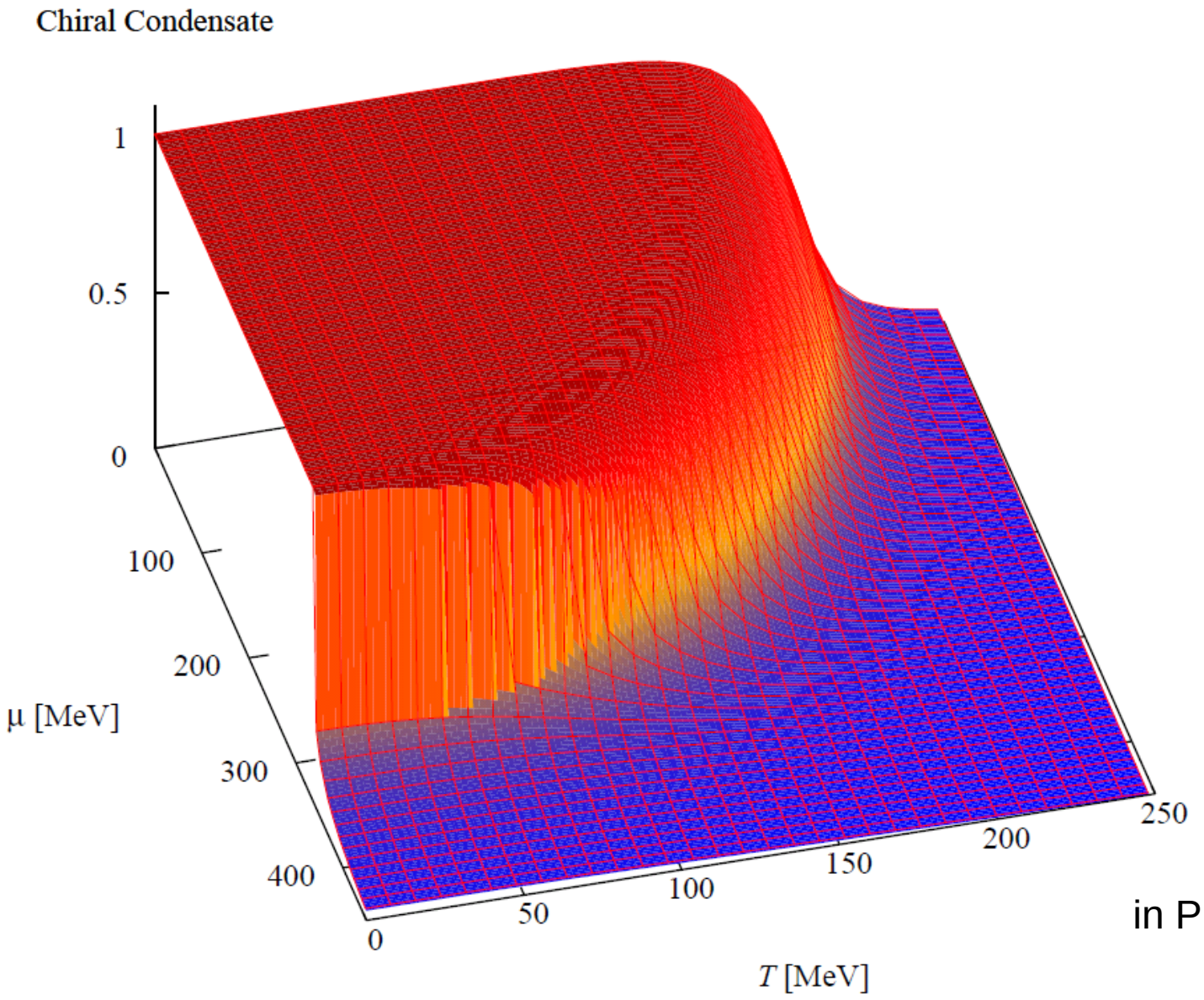
Idea

$$\langle \mathrm{tr} L \rangle \sim \exp\left[- f_q / T \right] \sim 0 \quad \text{in the confinement phase}$$

Only $L \cdot L^{+}$ and $L \cdot L \cdot L$ nonvanishing

meson-like **baryon-like**

Chiral Condensate

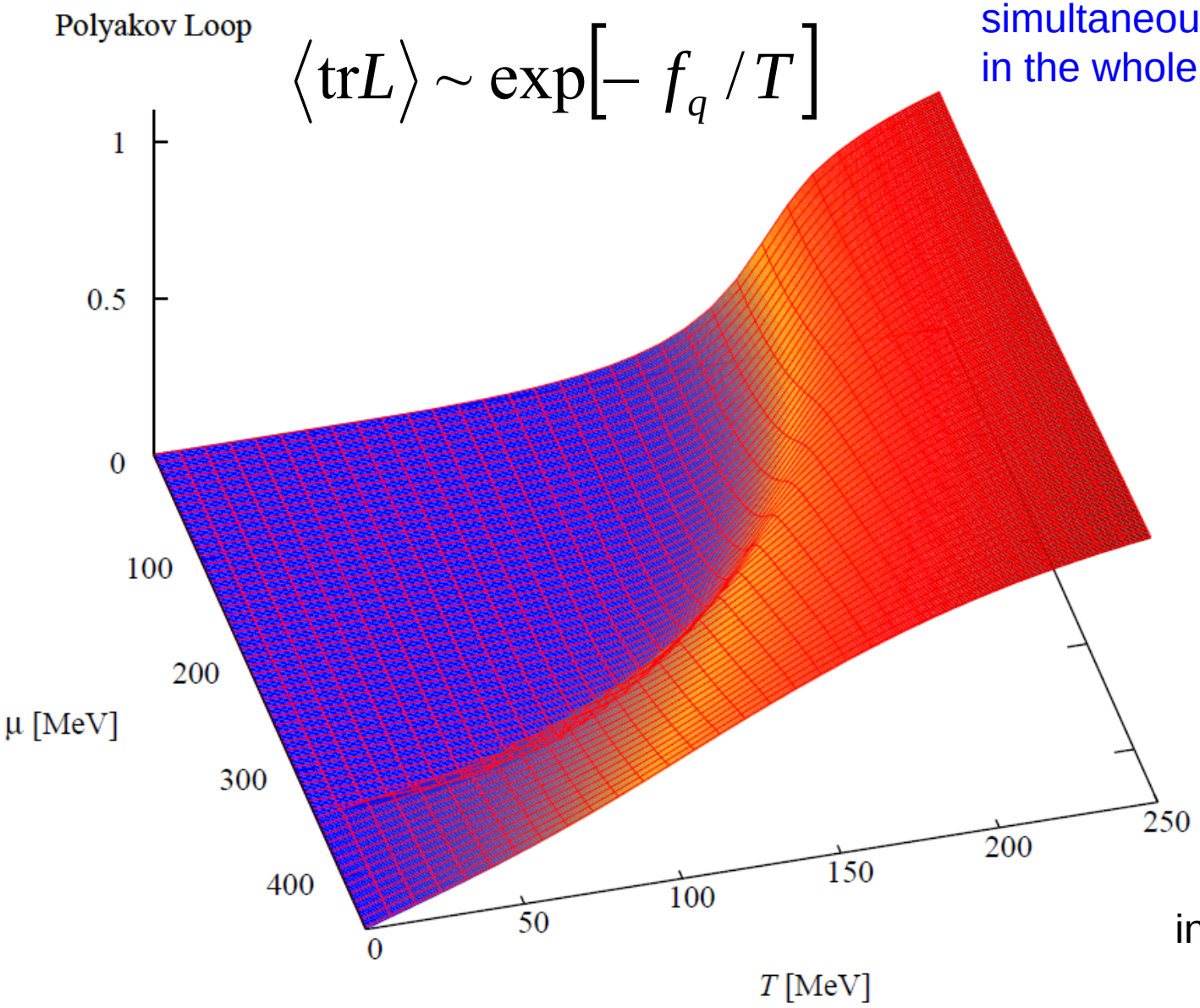


in PNJL

Polyakov Loop

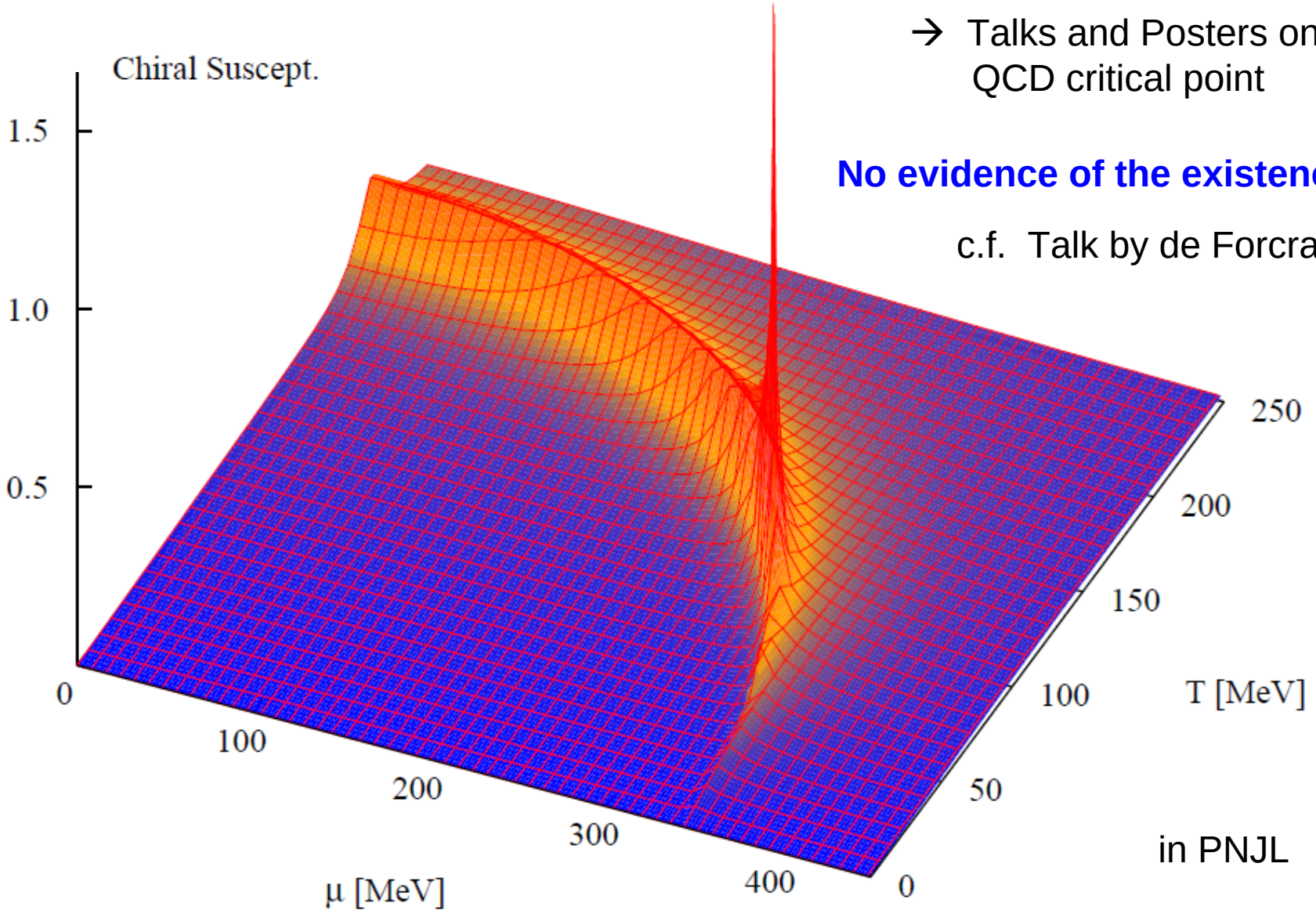
Model indication of simultaneous crossover in the whole region

$$\langle \mathrm{tr} L \rangle \sim \exp\left[- f_q / T \right]$$



in PNJL

Chiral Susceptibility



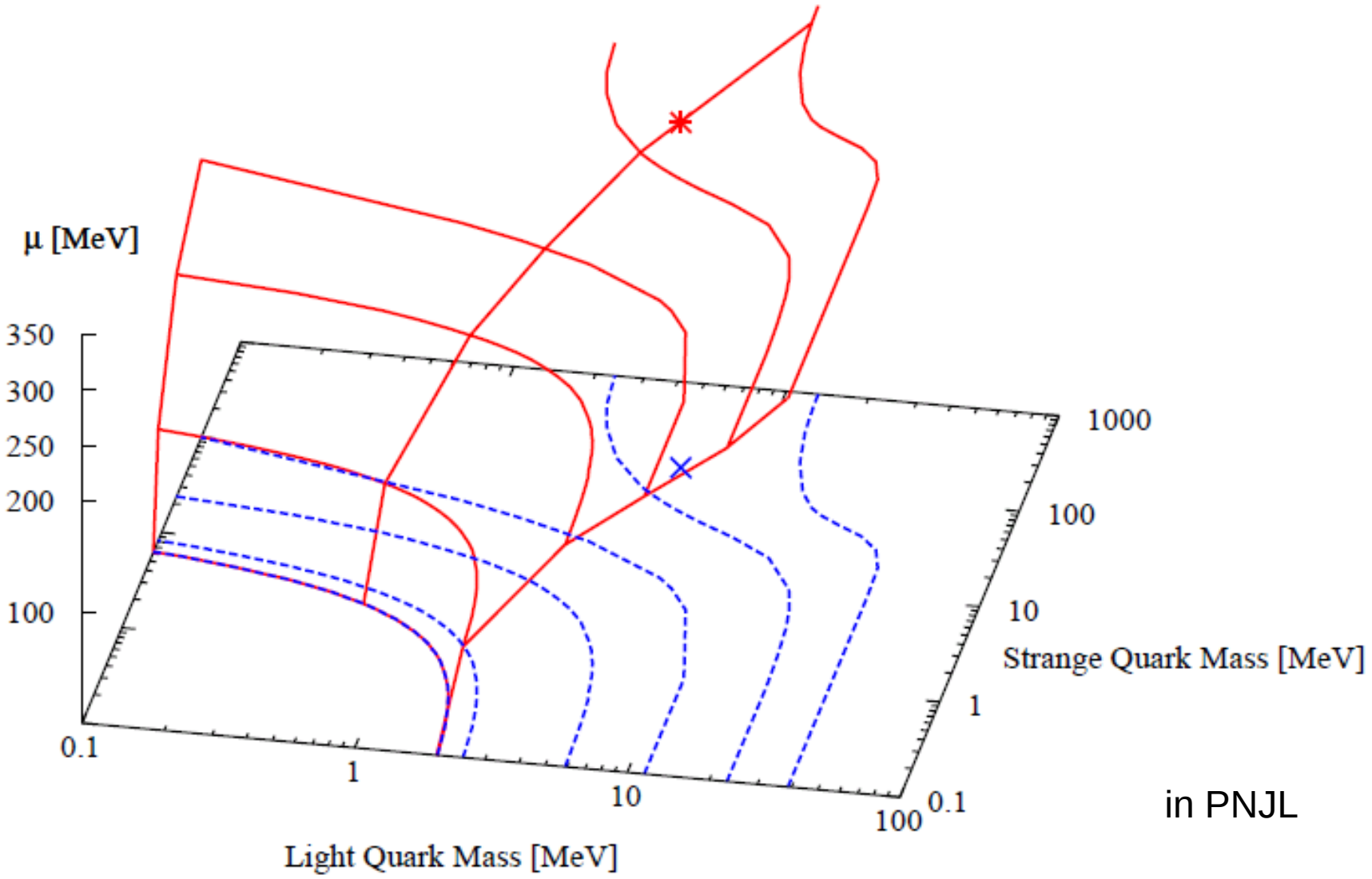
→ Talks and Posters on QCD critical point

No evidence of the existence

c.f. Talk by de Forcrand

in PNJL

From a different view point



in PNJL

No critical point ?

Is it possible for the chiral model studies to lead to **NO** critical point ?

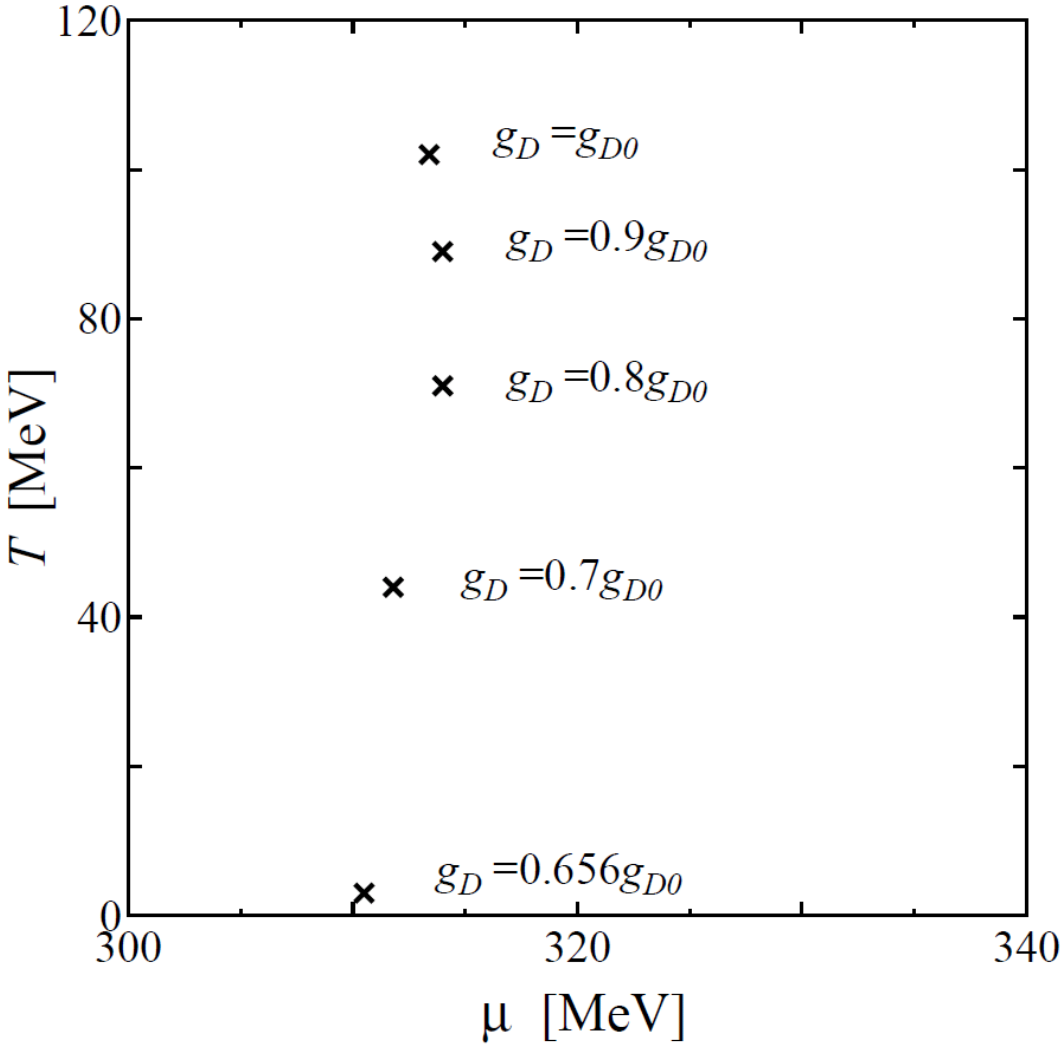
Yes... but the reason is rather technical...

$U_A(1)$ breaking term → Flavor Mixing

→ First-order Transition

could be reduced at high density

't Hooft interaction dependence



35% reduction of the six-point flavor mixing interaction leads to NO critical point on the QCD phase diagram.

Remarks

- Deconfinement
  - Thermodynamics (Equation of State)

    (QCD critical point is an exception.)

    Talk by Nonaka
- Chiral Restoration
  - Reduction of decay constants

    ~30% reduction of f_π in nuclei
  - Collective excitations (indirect)
    - ♦ Mass shift and/or width broadening of mesons

      ρ meson from dilepton
    - ♦ Quark spectral functions
  - Fluctuation (only near T_c)

Not work for the critical point
Poster by Fujii-Tanji

Summary

- We should keep in mind that deconfinement and chiral restoration are different phenomena.
- It could be still possible to have modification on the (nearly established) QCD phase diagram.
- The critical-point search is a big challenge for theory and experiment.