Classifying the phases of gauge theories by spectral density of probing chiral quarks

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Refs: arXiv:1502.07732, 1405.2968, 1409.7094

Credits: M. Sun

Data Credits: A. Hasenfratz, D. Schaich, Z. Fodor, S. Borsanyi

The Plan:

- Phase and the Phase Structure
- Probing ("valence") Quarks
- The Result
- Lattice Input

  - Existence of anomalous phase in pure-glue system
  - Anomalous phase of heated quark-gluon matter (RHIC, LHC) !!!
  - Anomalous phase without thermal effects (many flavors)

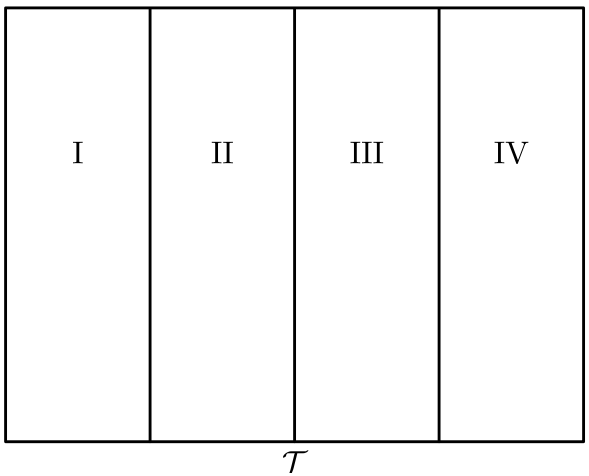
- Generalization and One Consequence

  - Anomalous phase in massless quark dynamics?

- Summary

Phase: region of parameter space with particular dynamical feature(s)

Phase Structure: associated partition of the parameter space



$\mathcal{T}$: SU(3) theories w fundamental quarks
arbitrary number of flavors
arbitrary masses
arbitrary temperature

- phase boundaries present by definition
- transitions mark well-defined change of dynamics but not necessarily associated with singularities
- Which dynamical features are useful to focus on?

[<u>non-Pearson correlations</u> provide one option: arXiv:1009.4451, 1210.7849, 1405.2968]

Probing Quarks (aka valence quarks)

Let "good" external quarks live on the <u>gauge vacua</u> from $\mathcal{T}$ and analyze their response!

pure glue (N_f=0)	generic element of $\mathcal{T}$
⇩	⬇
infinitely heavy quark probe	very light quark probe
⇩	⬇
Wilson loops [extended gauge objects] identifies confinement	Dirac spectral density [extended gauge object] identifies confinement???

"good" external quarks = chirally clean = defined by overlap Dirac matrix

Why Dirac spectral density?

- Dirac operator D=D[A] defines dynamics of probing quarks $\bar{\eta}\,(D + m_v)\,\eta$
- Naturally incorporates scale $D\psi_\lambda = i\,\lambda\,\psi_\lambda$
- Reduce D[A] to the simplest gauge invariant object incorporating scale:

$$\sigma(\lambda, m_f, V) \equiv \frac{1}{V}\,\langle \sum_{0\le\lambda_k<\lambda} 1 \,\rangle_{m_f,V}$$

cumulative density

$$\rho(\lambda, m_f, V) \equiv \frac{\partial}{\partial\lambda}\,\sigma(\lambda, m_f, V)$$

spectral density

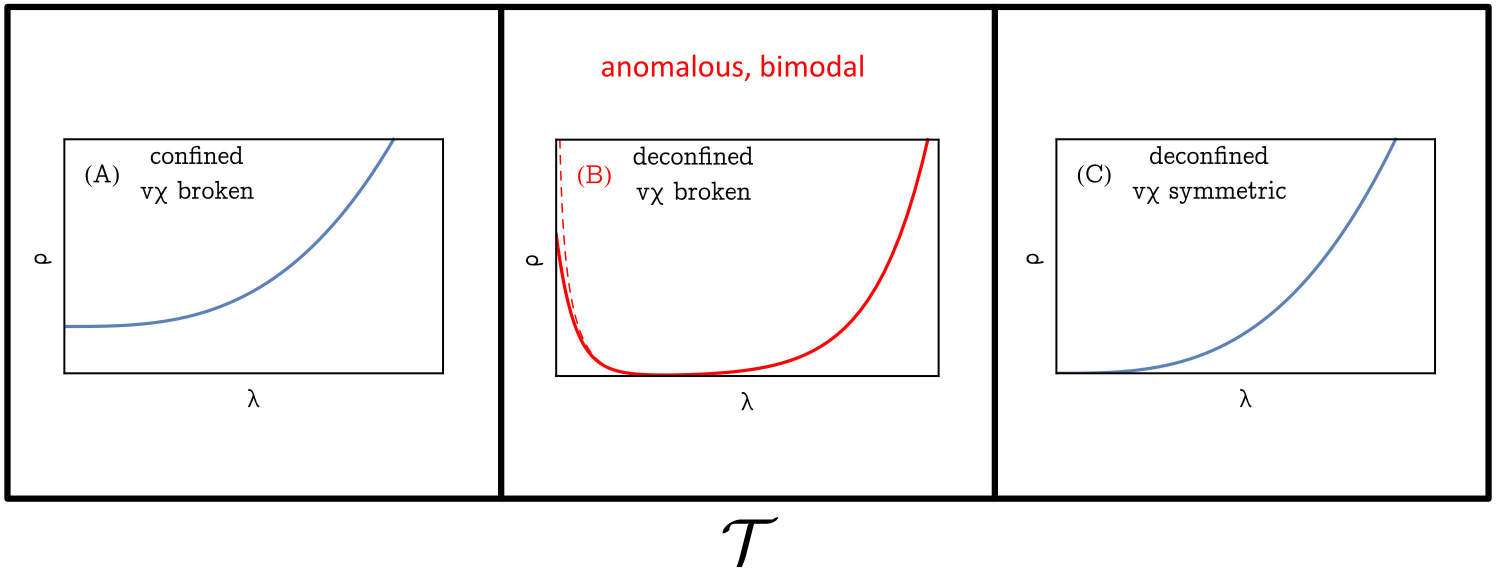
View Dirac spectral density as a vacuum object assigned to each theory in $\mathcal{T}$!

- ρ(λ=0) > 0 indicates breakdown of probing/valence chiral symmetry via Banks-Casher relation

The Result:

arXiv:1502.07732

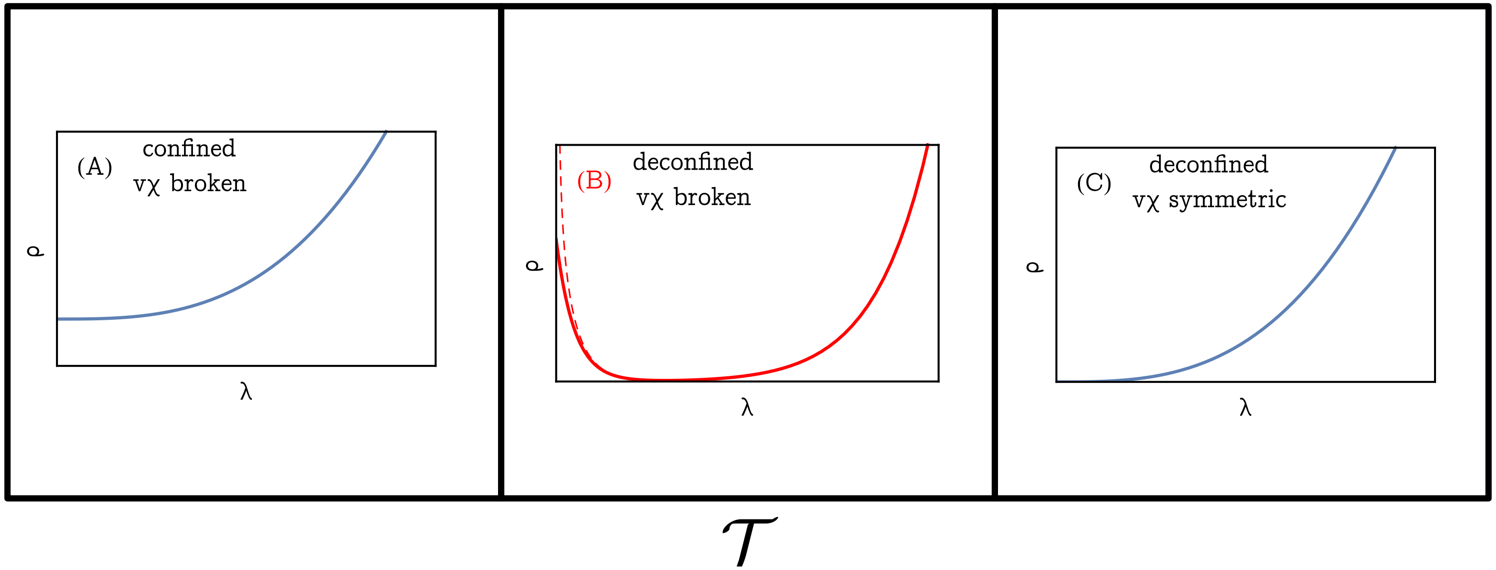
vχ symmetry = valence chiral symmetry



- The relevant feature of (B) is infrared-ultraviolet bimodality (separation)
- Two types of vχ broken phases: standard (A) and anomalous (B)
- One type of confined phase : (A) identifies confinement in $\mathcal{T}$
- No confined and vχ symmetric phase: agree with Casher
- Anomalous phase generic when crossing between (A) and (C)

The Result… comments

- Probing quarks always defined by overlap
- Possible divergence of valence condensate due to mixed nature NOT RELEVANT
  - shape (bimodality) matters, divergence at fixed cutoff may in fact be crucial
    EXAMINING THE VACUUM RATHER THAN CALCULATE PHYSICAL OBSERVABLE!
- Other aspects also well distinguish the anomalous phase
  - non-Pearson correlation (for chiral polarization) arXiv: 1405.2968
  - spatial inhomogeneity of modes (not discussed here)



Lattice Input

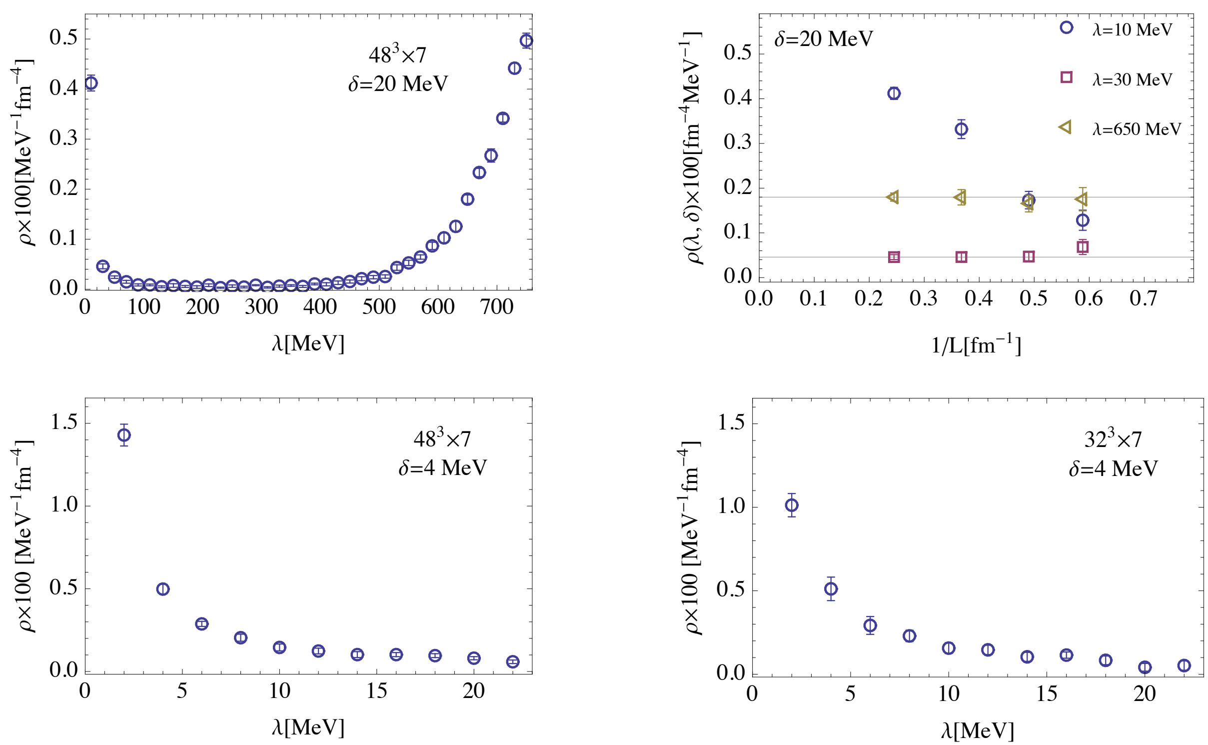
i. Show that theory with anomalous spectral density exists anywhere in $\mathcal{T}$

Do this carefully in thermal N_f=0!

anomalous peak first seen by
Edwards, Heller, Kiskis, Narayanan, 1999

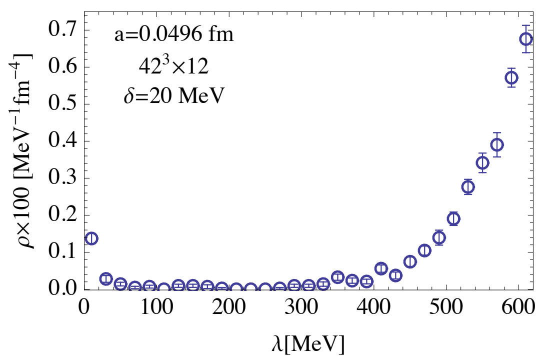
Fix T/T_c and check stability in both infrared and ultraviolet cutoffs

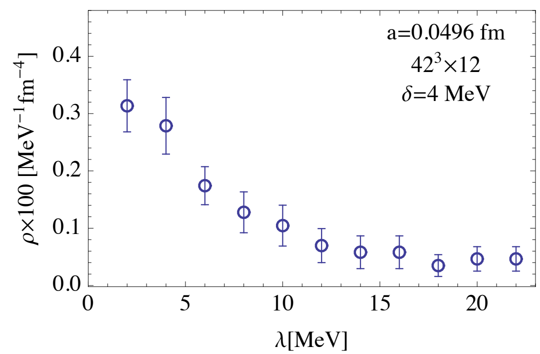
Wilson action , a=0.085 fm , T = 1.12 T_c , N^3 x 7 , N = 16,20,24,32,48

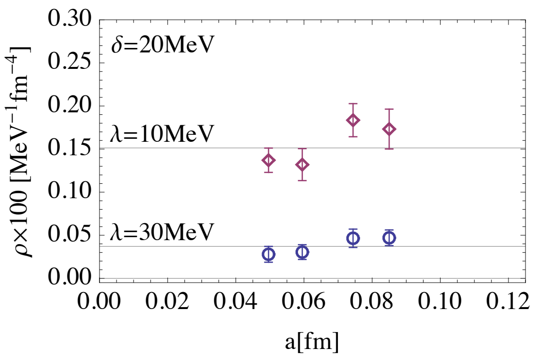


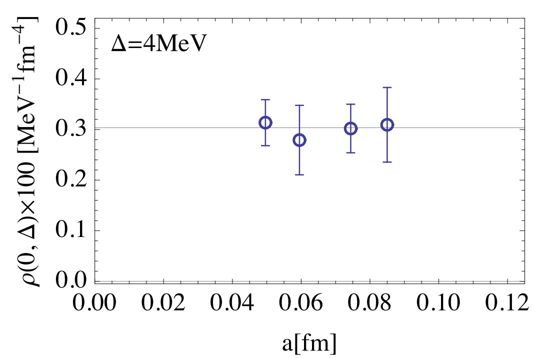
Lattice Input… Thermal $N_f=0$: ultraviolet cutoff

Wilson action , $T = 1.12\, T_c$ fixed , Volume fixed: L=2 fm , range of lattice spacings







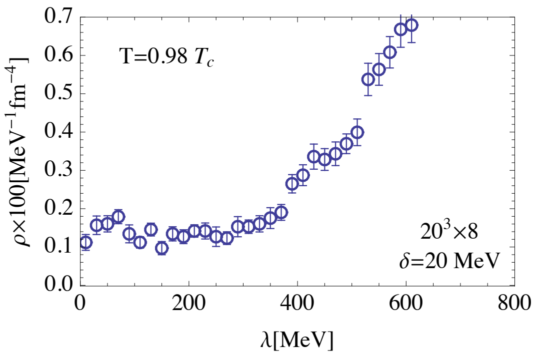


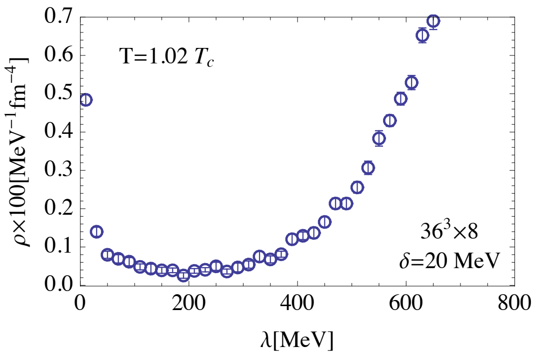
Anomalous spectral density, deconfinement and chiral symmetry breaking simultaneously exist in the continuum theory!

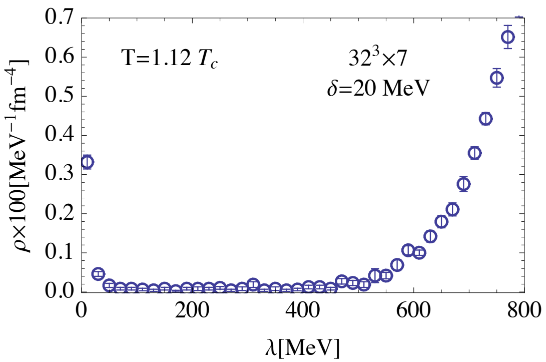
Lattice Input…

ii. Show that thermal N_f=0 follows the proposed behavior wrt deconfinement

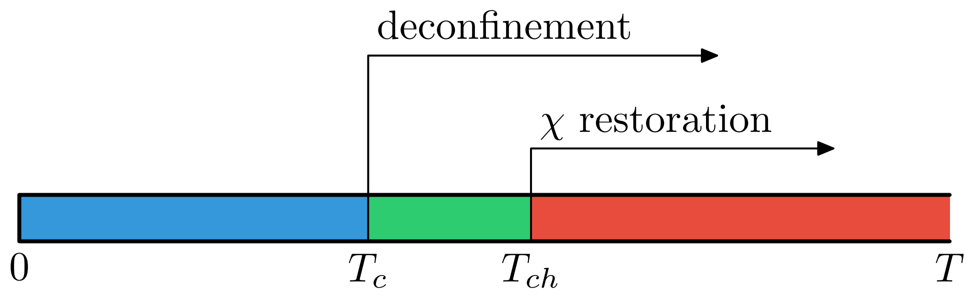
Tune temperatures to “hug” Z_3 transition:







Deconfinement transition and transition to anomalous density coincide!



ANOMALOUS PHASE EXISTS!

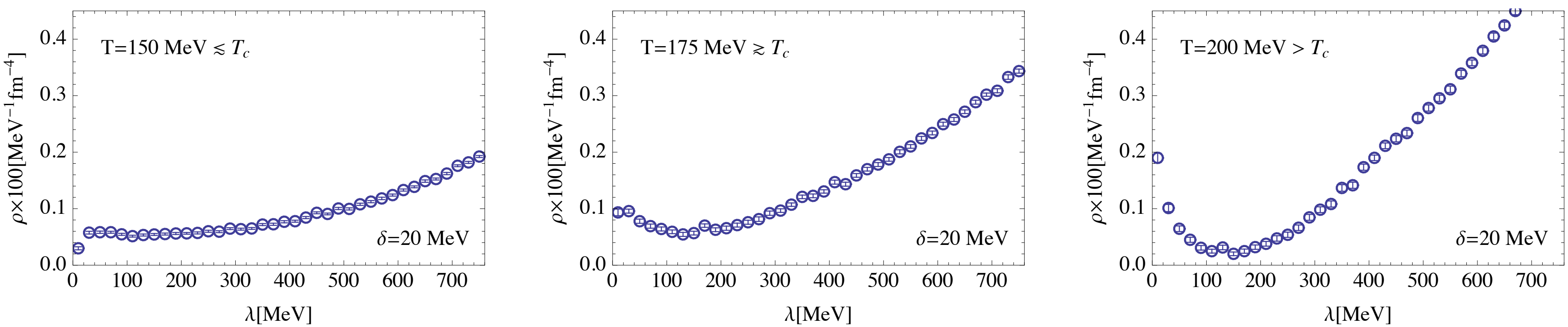
Lattice Input…

iii. Show that thermal effects generically lead to anomalous phase

N_f=2+1 at physical point: "real world" QCD

Ensembles from Borsanyi et al, 2010 : 32x8 staggered, checked carefully for artifacts
used for determination of crossover temperatures

They report: T_c (Polyakov line) = 170 MeV T_c(quark condensate) = 155 MeV



(1) Anomalous phase in "real world" quark-gluon matter! (see also Dick et al 1502.06190)

(2) Onset coincides with inflection point in L ("deconfinement") to available precision!

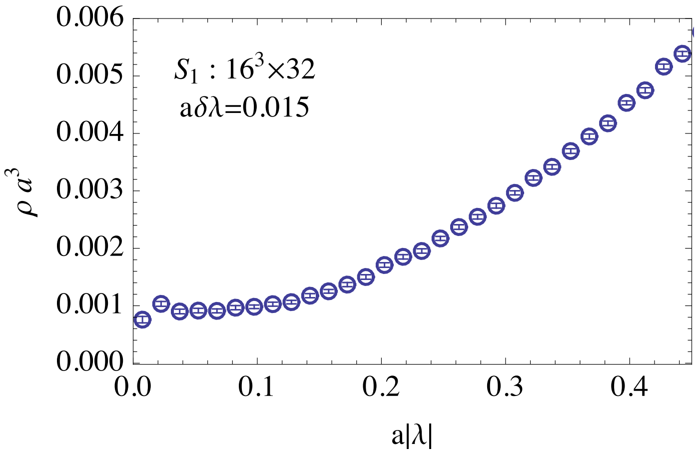
(3) Dirac density defines its own T_c

Lattice Input…

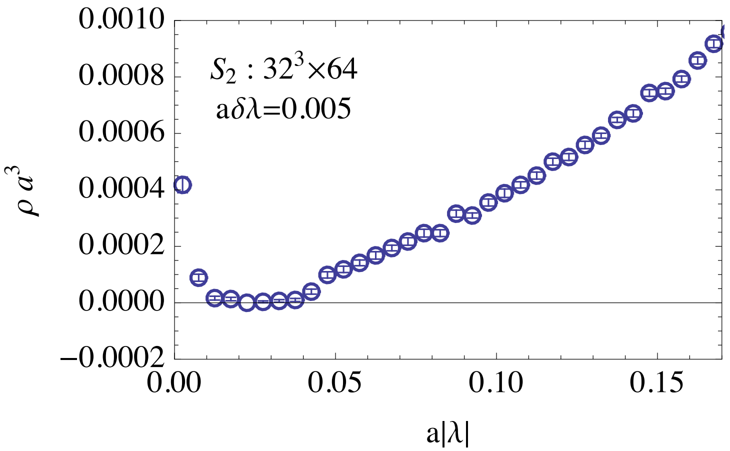
iv. Show that light-quark effects alone also lead to anomalous phase

N_f=12, T=0   Ensembles: A. Hasenfratz et al, arXiv:1207.7162   staggered with nHYP, β_F=2.8, β_A/β_F=-0.25

am=0.02



am=0.0025



Light quarks generate anomalous phase without the help of temperature!

Anomalous range: $0 \leq m_{ch} < m < m_c$

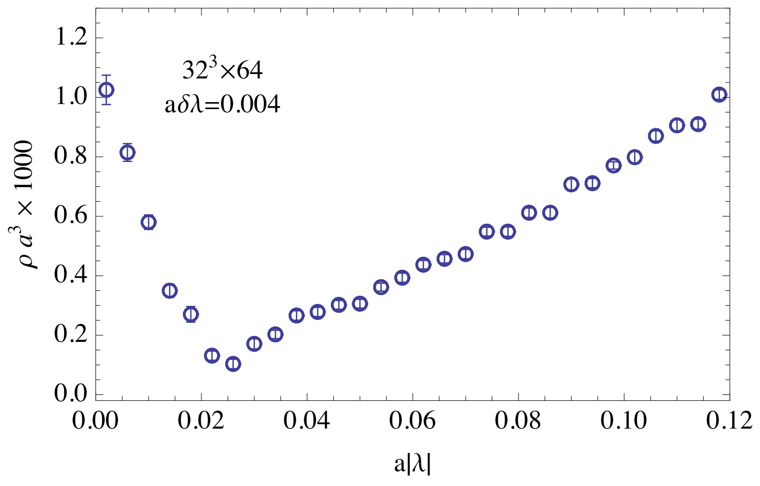
Conformality at m=0 only if m_{ch}>0! Restoration hasn't been seen!

Lattice Input…

iv. Show that light-quark effects alone also lead to anomalous phase…

N_f=8, T=0 Ensemble: A. Hasenfratz, D. Schaich staggered with nHYP, β_F=4.8, β_A/β_F=-0.25

am=0.0



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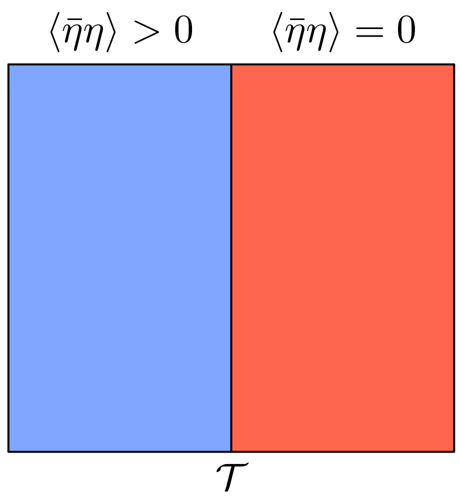
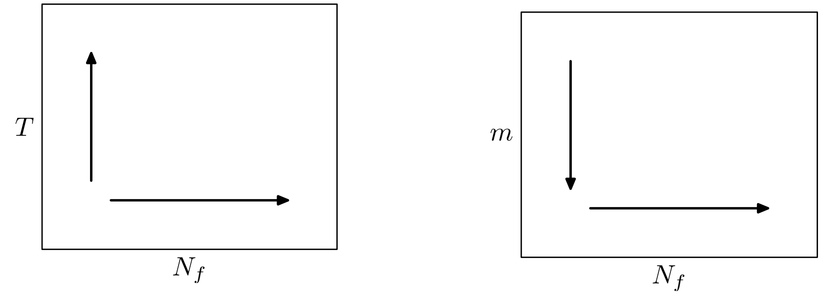
Anomalous phase present at N_f=8!

Generalization





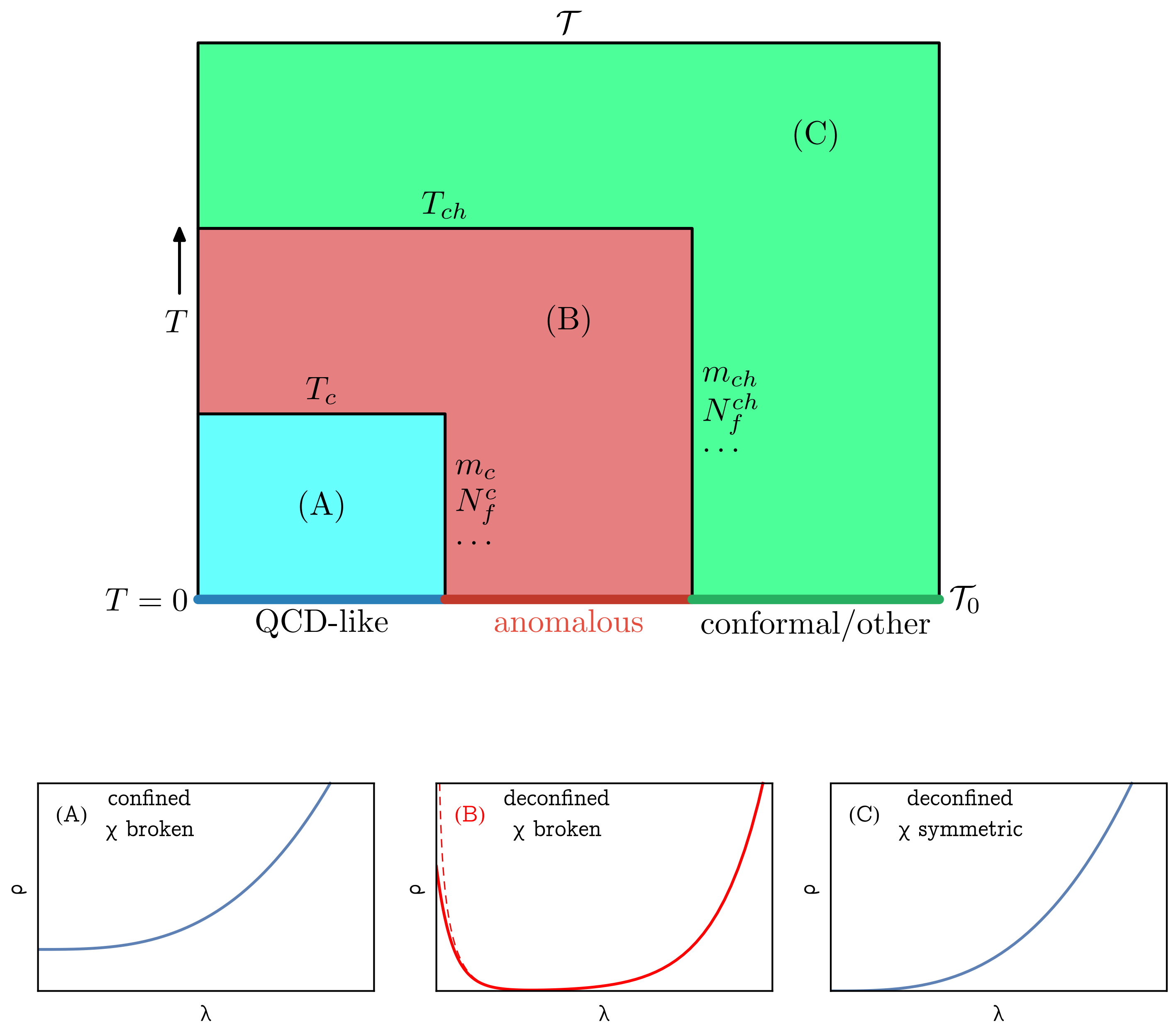
Direction of weakening condensate!

(1) Temperature and dynamical quark effects the only mechanisms

(2) Both generate anomalous phase

We conclude this happens on generic paths connecting broken and symmetric vacua in $\mathcal{T}$.

Generalization...



Interesting Consequence

$T_c < T < T_{ch}$ thermal anomalous phase

$m_{ch} < m < m_c$ mass anomalous phase

$N_f^c < N_f < N_f^{ch}$ (m=0) anomalous window???

Here deconfinement precedes the onset of conformal window with massless flavors!

Data is consistent with this possibility so far!

Summary

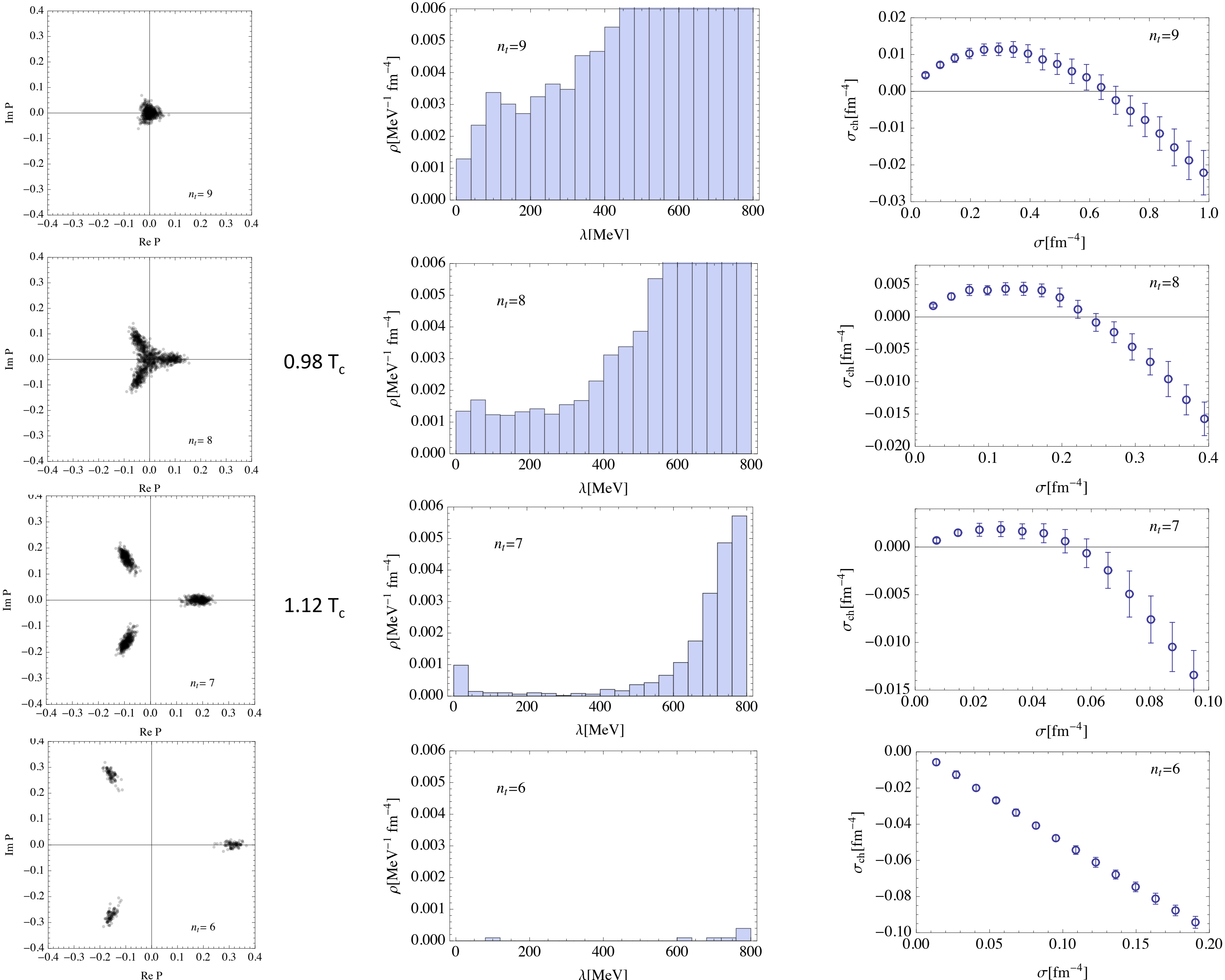
1. Anomalous phase in $\mathcal{T}$ exists and is generic!

2. We propose that it is a <u>deconfined phase</u>

3. Most likely a property of real-world thermal quarks and gluons (plasma state)

4. Changes global landscape of SU(3) theories with fundamentals

5. Its nature needs to be investigated in detail


Im P
Re P
n_t= 9
n_t= 8
n_t= 7
n_t= 6
0.98 T$_c$
1.12 T$_c$
ρ[MeV^{-1} fm^{-4}]
λ[MeV]
n_t=9
n_t=8
n_t=7
n_t=6
σ_{ch}[fm^{-4}]
σ[fm^{-4}]