# Confinement, Dirac spectral density and phases of SU(3) gauge theories with fundamentals

Ivan Horváth

University of Kentucky, Lexington, KY

in collaboration with

Andrei Alexandru

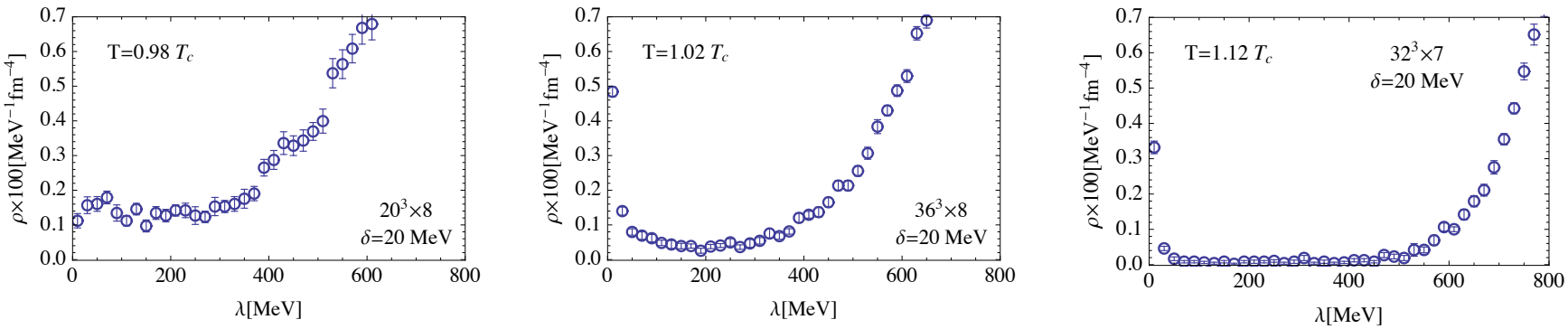
George Washington University, Washington, DC

Refs: arXiv:1502.07732, 1405.2968, 1409.7094

Credits: M. Sun

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

The goal of this talk is to show you some data…




…and argue that it is consequential!

# The Plan

- Motivation and Setup
  - SU(3) with fundamentals and physics
  - "phases"
  - probing (valence) quarks
  - valence chiral symmetry
- The Proposal
- 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

## Motivation… SU(3) with fundamentals

$$S = -\frac{1}{2g^2}\,\mathrm{tr}\,F_{\mu\nu}F_{\mu\nu} + \sum_{f=1}^{N_f}\bar{\psi}_f(D+m_f)\psi_f$$

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu + [A_\mu, A_\nu] \qquad A_\mu \in su(3)$$

$$D\chi \equiv \gamma_\mu(\partial_\mu + A_\mu)\chi \qquad \chi \in C^{12}$$

Zero temperature: set $\mathcal{T}_0$ Arbitrary temperature: set $\mathcal{T}$

---

Why $\mathcal{T}$?

(1) Description of nature's quarks and gluons – RHIC/LHC heavy ion physics

(2) BSM technicolor-like scenarios – LHC physics???

(3) Playground for understanding infrared conformality in 4d

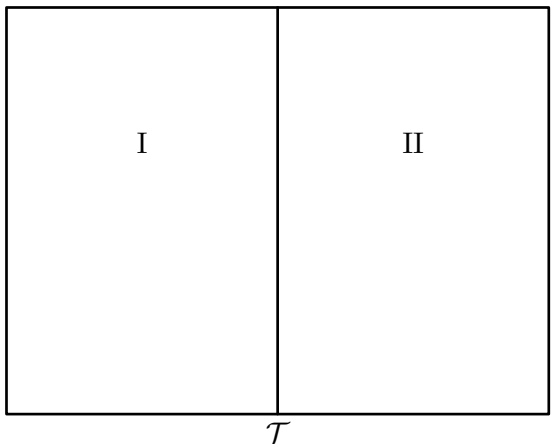
(4) Space for deforming real-world QCD to get information on vacuum structure

# Motivation… "phases"

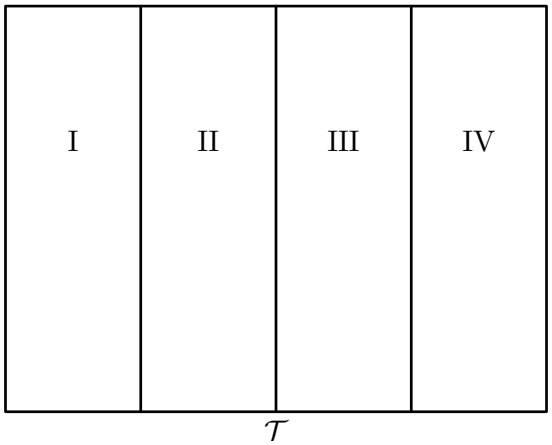
**Phase:** region of parameter space with particular dynamical feature(s)

**Phase Structure:** associated partition of the parameter/theory space

1 property:




2 properties:




More properties: will characterize the vacuum/thermal state of any theory in $\mathcal{T}$ in ever increasing level of detail!

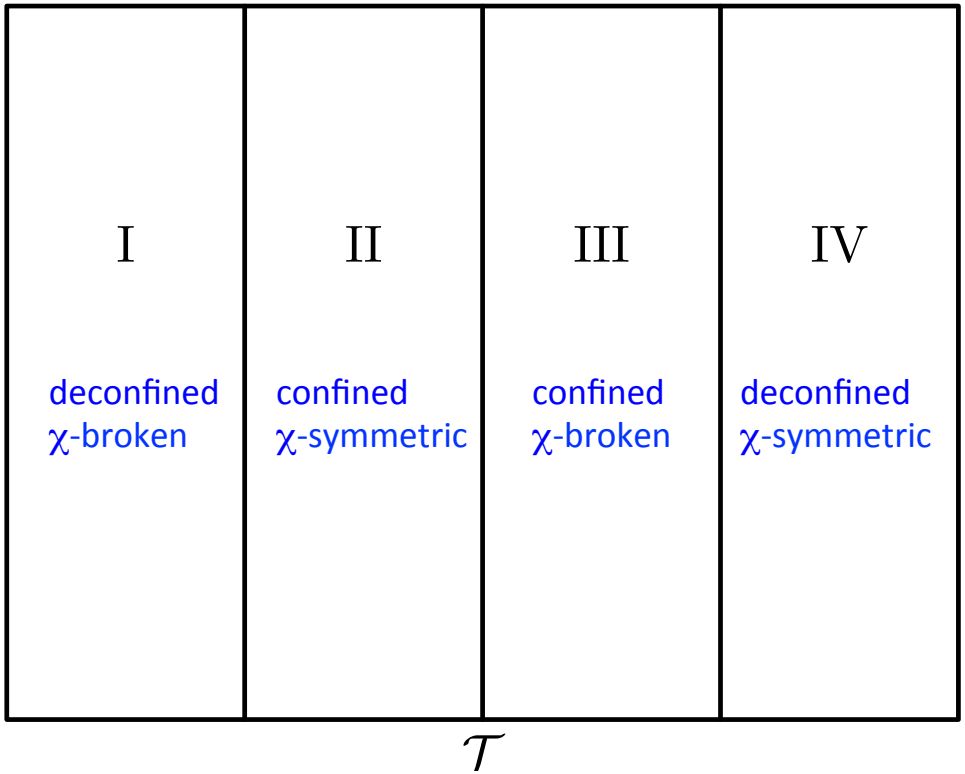
---

COMMERCIAL BREAK: non-Pearson correlations provide a systematic framework for this!

1009.4451 – prototype of such correlation

# Motivation… "phases"…

Why don't we just apply this to chiral symmetry breaking and confinement???




Because there are problems with their definition/meaning over $\mathcal{T}$ !

# Motivation… "phases"…

Z(3) symmetry: confinement easy $\langle L \rangle = 0$

$N_f$=0 (infinite masses)

$\mathcal{T}$

<u>identifying confinement unclear</u>

<u>SChSB not well-defined</u>

multiple massless flavors

chiral symmetry: SChSB meaningful $\langle \bar{\psi}\psi \rangle > 0$

There is no point in $\mathcal{T}$ where both confinement and SChSB are good!

So how does one do phases in this case???

# Probing Quarks (aka valence quarks)

Let "good" external quarks live on gauge vacua 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 <u>gauge invariant</u> object still 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 <u>vacuum object</u> assigned to each theory in $\mathcal{T}$ !

But how exactly does one use it for what we need???

# Motivation... valence (probing) chiral symmetry

$$S' = S + \sum_{i=1}^{2} \bar{\eta}_i \left( D + m_v^i \right) \eta_i + \sum_{i=1}^{2} \phi_i^\dagger \left( D + m_v^i \right) \phi_i$$

Morel, 1987

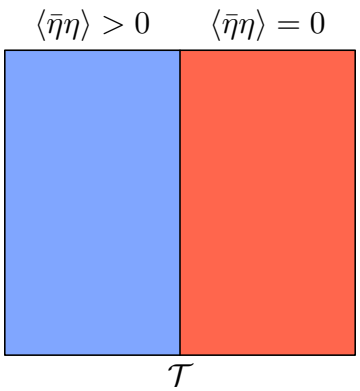
$$m_v = 0 \implies \text{valence chiral symmetry}$$

"probing chiral symmetry"

- vacuum respects it or not
- massless valence pions if broken

Valence Chiral Symmetry Breaking (vSChSB) meaningful for all theories in $\mathcal{T}$

- order parameter is the valence quark condensate $\langle \bar{\eta}\eta \rangle$
- probes long-range correlations of <u>gauge vacuum</u>
- vSChSB reduces to SChSB when dynamical quarks are massless
- partitions $\mathcal{T}$ (phase boundary)




CONVENIENT BONUS:

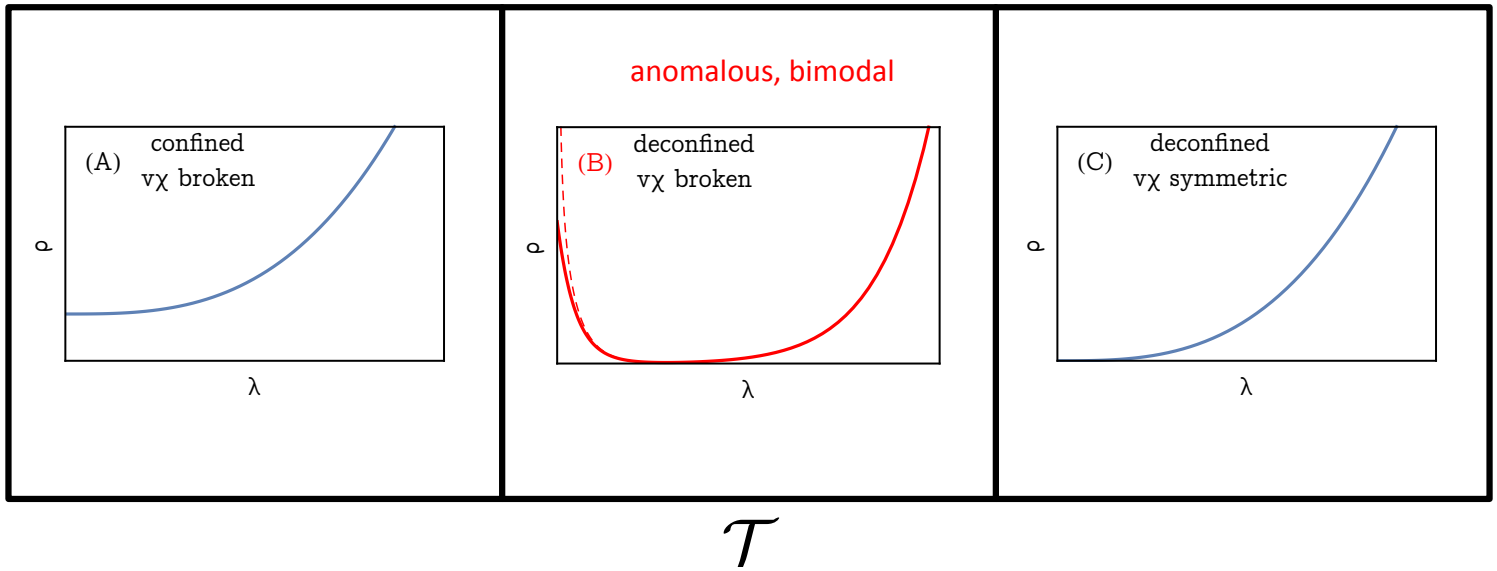
$$\lim_{m_v \to 0} \lim_{V \to \infty} \langle \bar{\eta}\eta \rangle_{m_f, V} > 0 \iff \lim_{\lambda \to 0} \lim_{V \to \infty} \rho(\lambda, m_f, V) > 0$$

$$\text{vSChSB} \iff \text{mode condensation}$$

Banks, Casher, 1980

The Proposal: 1502.07732

vχ symmetry = <u>valence</u> chiral symmetry




(1) existence deconfined and vχ broken phase (B) – the anomalous phase

(2) absence of confined and vχ symmetric phase – agree with Casher

(3) relevant aspect in (B) is infrared—ultraviolet bimodality (separation)

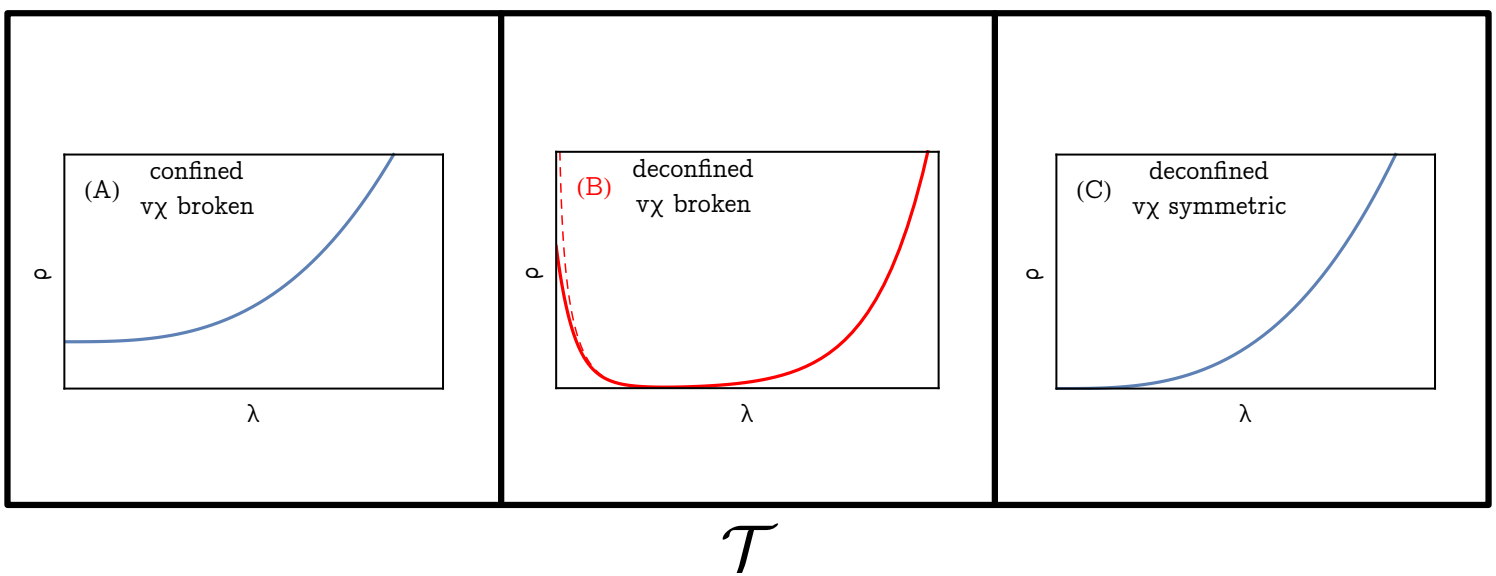
(4) (B) is robustly abundant in $\mathcal{T}$

# The Proposal… technical comments

- Probing quarks always defined by overlap

- Possible divergence of valence condensate NOT RELEVANT
  - shape (bimodality) matters, divergence at fixed cutoff may in fact be crucial
  PROBE THE VACUUM RATHER THAN CALCULATE PHYSICAL OBSERVABLE!

- Other aspects also well distinguish the anomalous phase
  - non-Pearson correlation (for chiral polarization) 1405.2968
  - spatial inhomogeneity of modes (not discussed here)



# Lattice Input… The Plan

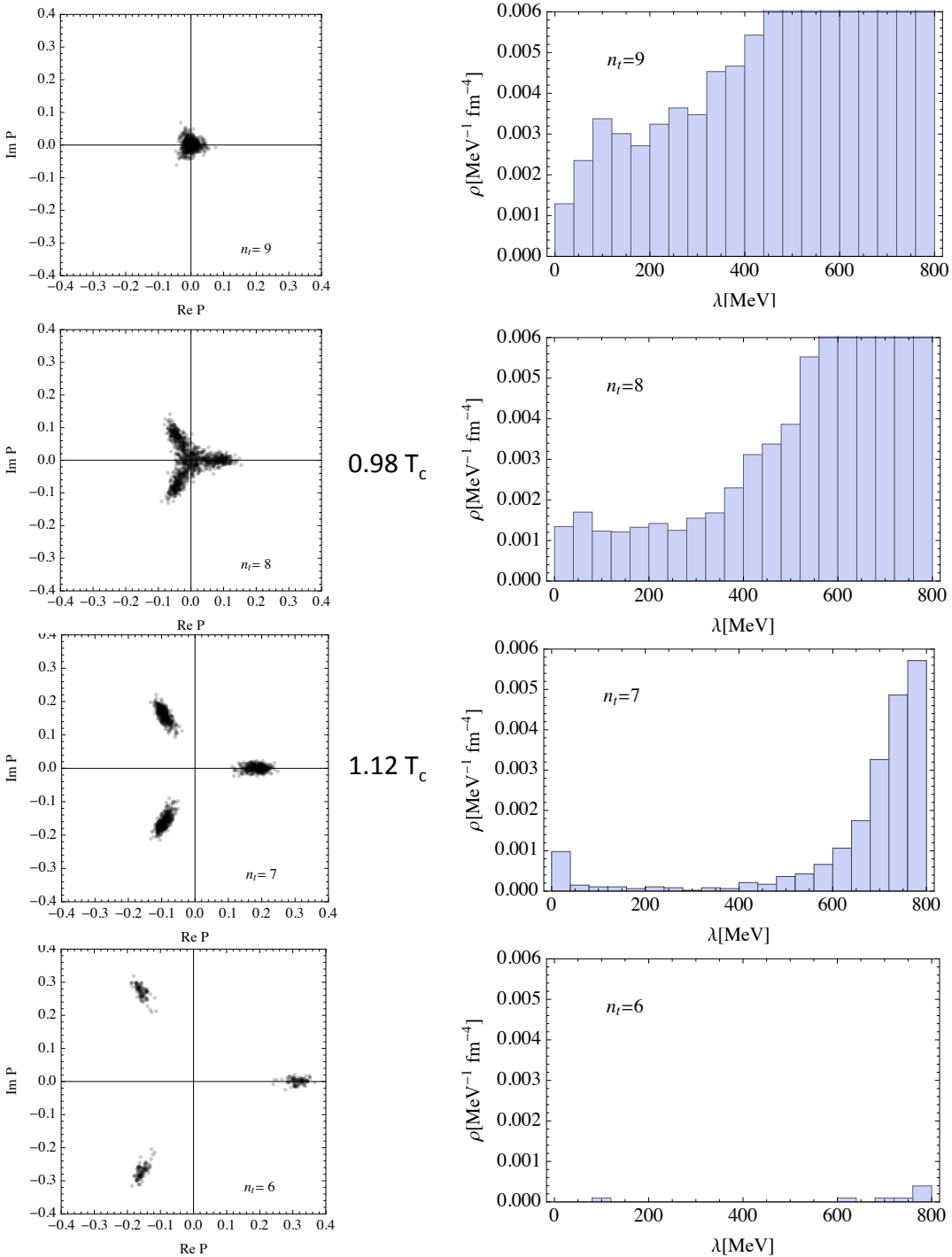
i. Show that theory with anomalous spectral density exists anywhere in $\mathcal{T}$

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

iii. Show that thermal effects generically lead to anomalous phase

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

# Lattice Input… prologue




0.98 $T_c$

1.12 $T_c$

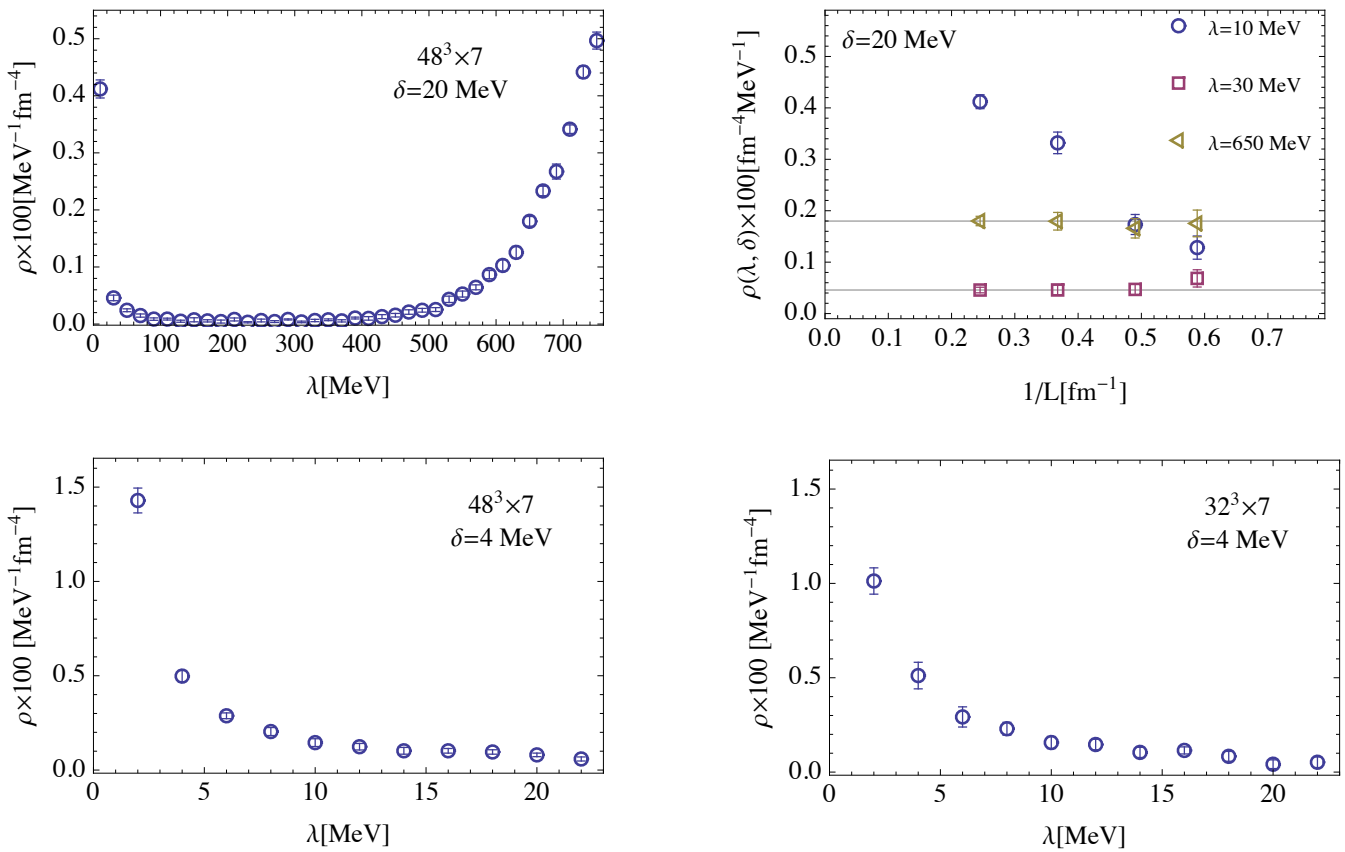
- We found this in thermal $N_f$=0, surprised, in 2012. Different reasons.
- Peak first seen by Edwards, Heller, Kiskis, Narayanan, 1999
- Overlap artifact? Buividovich, Luschevskaya, Polikarpov, 2008
- Not taken seriously and no systematics until 1405.2968

# Lattice Input … i. existence

Do this carefully in thermal $N_f$=0!

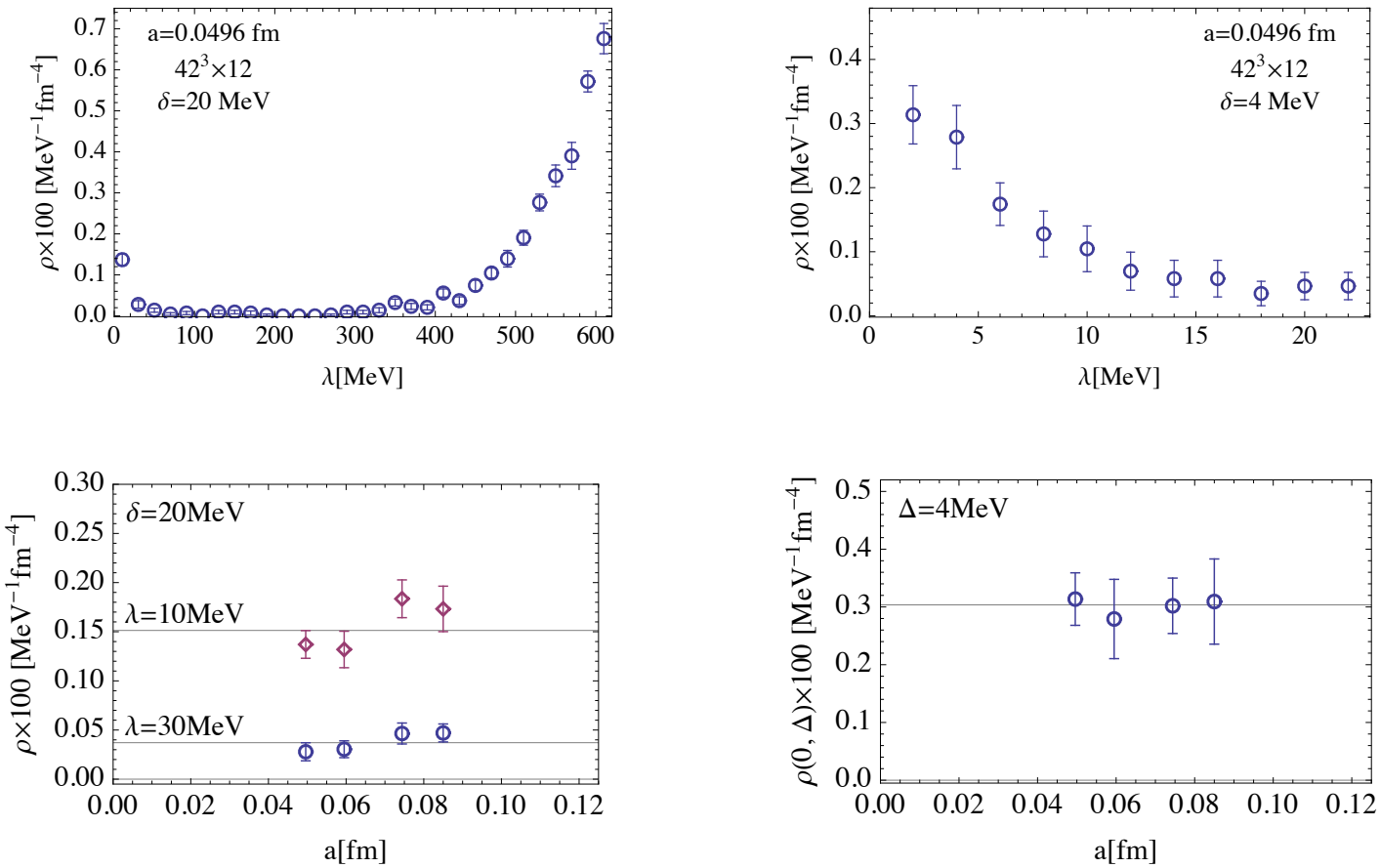
Fix $T/T_c$ and check stability in both infrared and ultraviolet cutoffs

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



# Lattice Input … i. existence …ultraviolet cutoff

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

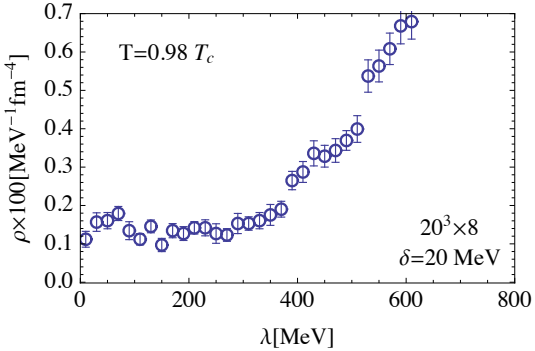


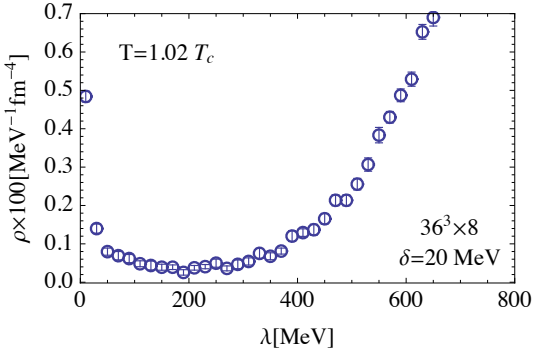

Anomalous spectral density, deconfinement and chiral symmetry breaking simultaneously exist in the continuum theory!

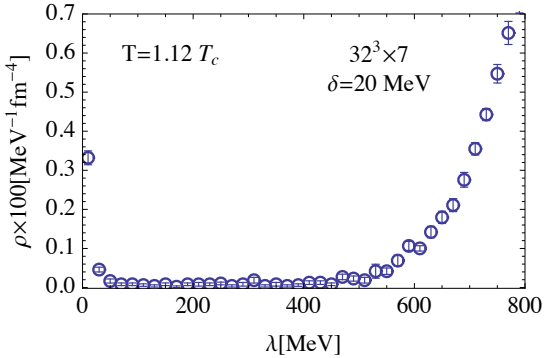
# Lattice Input…

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

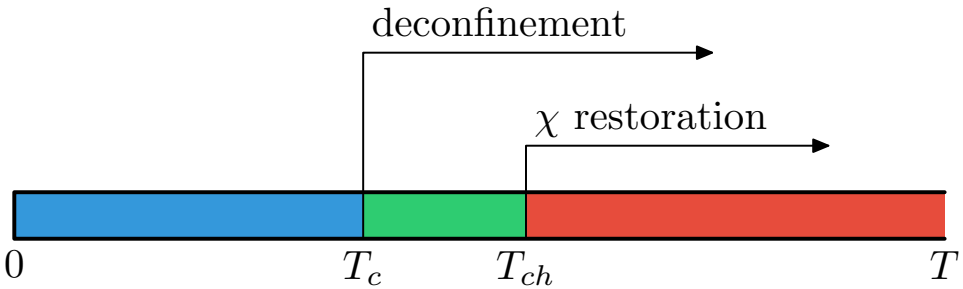
Tune temperatures to "hug" $Z_3$ transition:



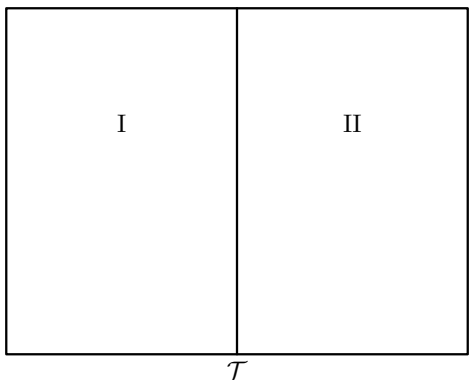




Deconfinement transition and transition to anomalous density coincide!



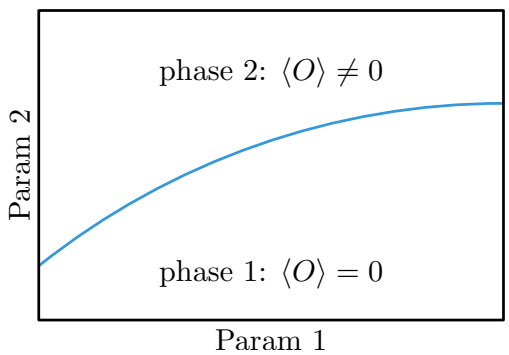

ANOMALOUS PHASE EXISTS!

# Dynamical Phases vs Phases of Matter



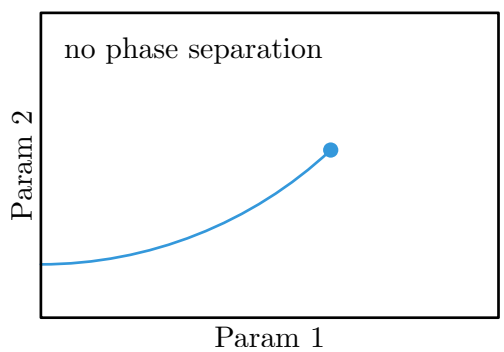

Dynamical phases:

- singularity not required
- phase separation automatic
- if singularity, dynamical phase must follow, not vice-versa



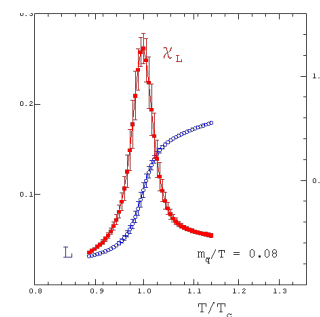

Phases of matter:

- singularity required
- phase separation not automatic
- one loves those with phase separation




Real-world QCD was concluded to be of this type!

Aoki et al, 2007



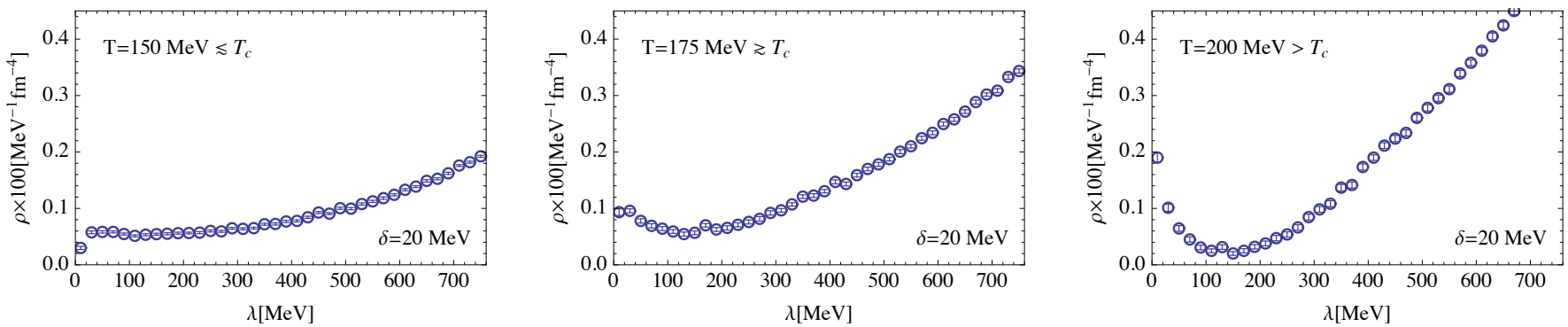
# Lattice Input…

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 <u>crossover temperatures</u>

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!

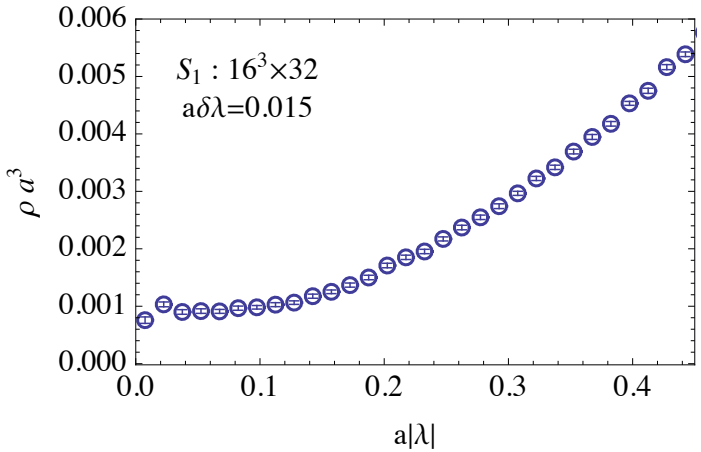
(3) Dirac density defines its own $T_c$

# Lattice Input…

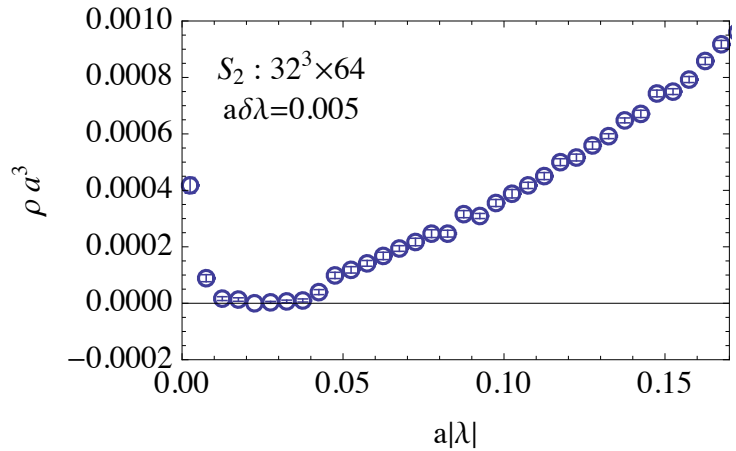
## iv. Show that light-quark effects alone also lead to anomalous phase

$N_f$=12, T=0 Ensembles: A. Hasenfratz et al, arXiv:1207.7162 staggered with nHYP, $\beta_F$=2.8, $\beta_A/\beta_F$=-0.25

am=0.02




am=0.0025




Light quarks generate anomalous phase without the help of temperature!

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

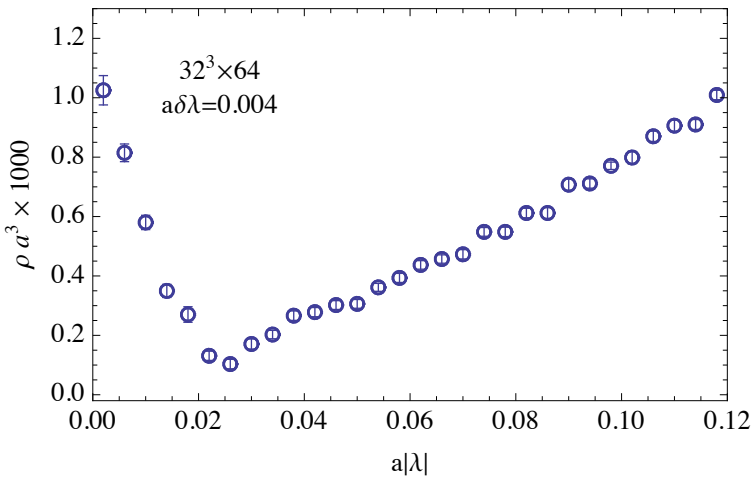
Conformality at m=0 only if $m_{ch}$>0! Restoration hasn't been seen!

# 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, $\beta_F$=4.8, $\beta_A/\beta_F$=-0.25

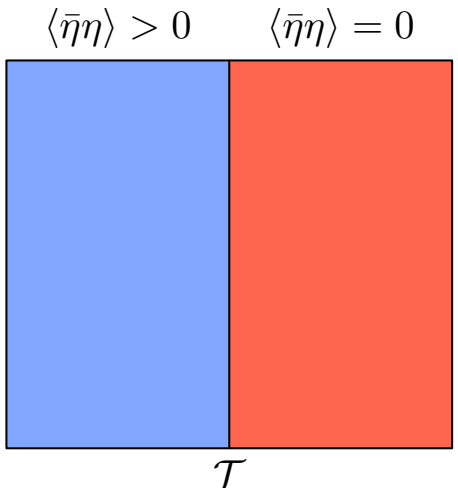
am=0.0

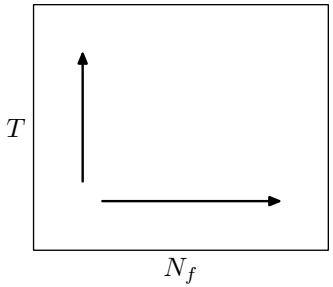


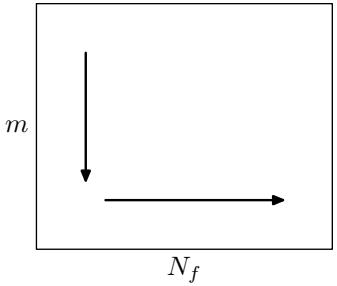

unpublished

Anomalous phase present at $N_f$=8?

# Generalization



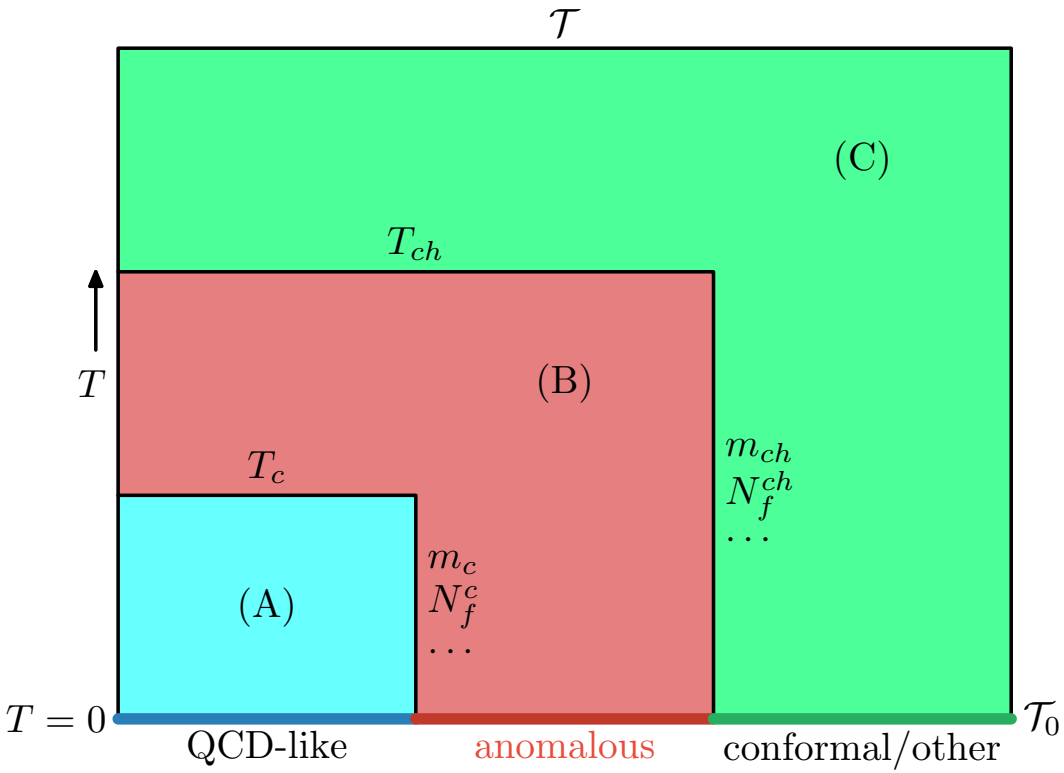

Direction of weakening condensate!

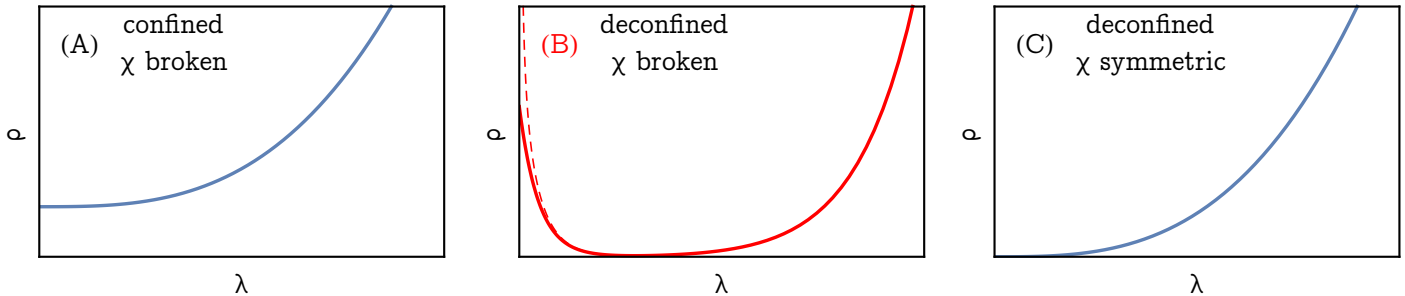
(1) Temperature and dynamical quark effects the only mechanisms

(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!

<u>Data is consistent with this possibility so far!</u>

# Summary

1. Anomalous phase in $\mathcal{T}$ exists and is generic!
2. We propose that it is a deconfined phase
3. Property of real-world thermal quarks and gluons (plasma state)
4. Changes global landscape of SU(3) theories with fundamentals
5. Its detailed nature interesting for many reasons