The Phases of Thermal QCD

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A.A , I.H. 1906.08047 : BRINGING A.A , I.H. 1502.07732 TO FRUITION

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No communication for 3 days! Excommunicated?

arXiv:1906.08047v1 [hep-lat] 17 Jun 2019

A Possible New Phase of Thermal QCD

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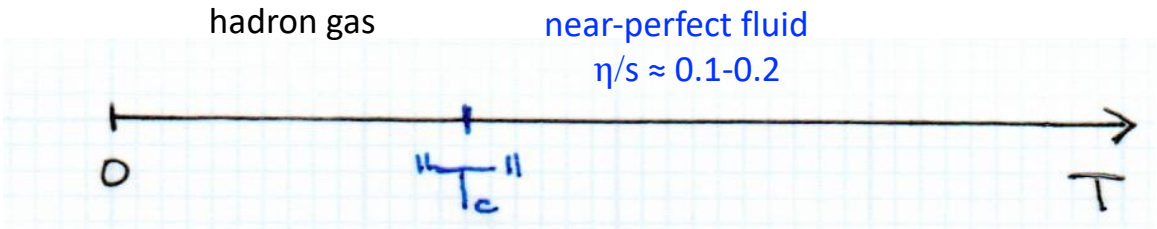
Using lattice simulations, we show that there is a phase of thermal QCD, where the spectral density $\rho(\lambda)$ of Dirac operator changes as $1/\lambda$ for infrared eigenvalues $\lambda < T$. This behavior persists over the entire low energy band we can resolve accurately, over three orders of magnitude on our largest volumes. We propose that in this "IR phase", the well-known non-interacting scale invariance at very short distances (UV, $\lambda \to \infty$, asymptotic freedom), coexists with very different interacting type of scale invariance at long distances (IR, $\lambda < T$). Such dynamics may be responsible for the unusual fluidity properties of the medium observed at RHIC and LHC. We point out its connection to the physics of Banks-Zaks fixed point, leading to the possibility of massless glueballs in the fluid. Our results lead to the classification of thermal QCD phases in terms of IR scale invariance. The ensuing picture naturally subsumes the standard chiral crossover feature at "T_c" ≈ 155 MeV. Its crucial new aspect is the existence of temperature $T_{\rm IR}$ (200 MeV $< T_{\rm IR} <$ 250 MeV) marking the onset of IR phase and possibly a true phase transition.

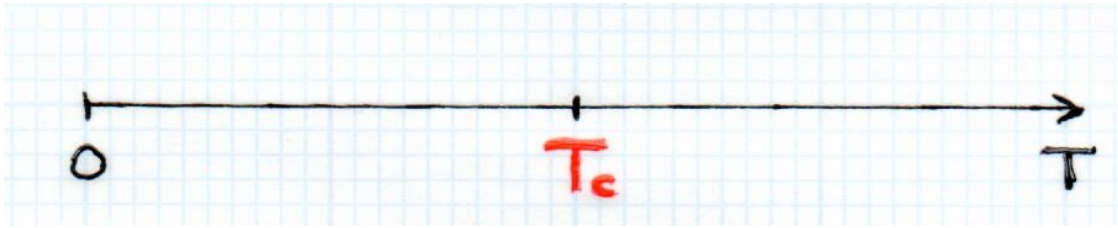
I. The Question

QCD



μ=0
LHC, universe

pgQCD
(pure glue)



Can this account for the change from hadron gas to intriguing near-perfect fluid???

II. The Strategy: PROBE THE GLUE

- usually about quarks (chiral symmetry, confinement of quarks)
- Polyakov line in pgQCD??? glue object but for confinement of external quarks
- glue is common to all SU(N) theories of interest
  [here: asymptotically free SU(3) theories with fundamental quarks]
- glue rough → probe by spectral response of the Dirac operator D=D[A]
  - D=D[A] naturally incorporates the scale via its spectrum $D\psi_\lambda = i\,\lambda\,\psi_\lambda$
  - reduce D[A] to simplest gauge invariant object featuring scale dependence

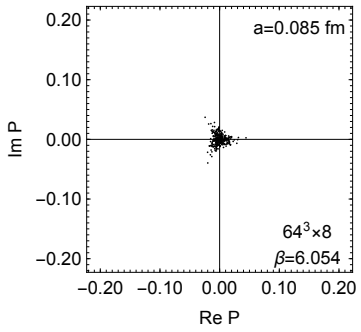
$$\sigma(\lambda, m_f, V) \equiv \frac{1}{V} \langle \sum_{0 \le \lambda_k < \lambda} 1 \rangle_{m_f, V}$$

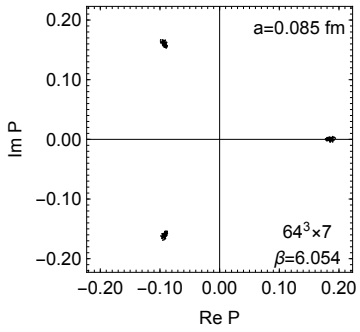
cumulative density

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

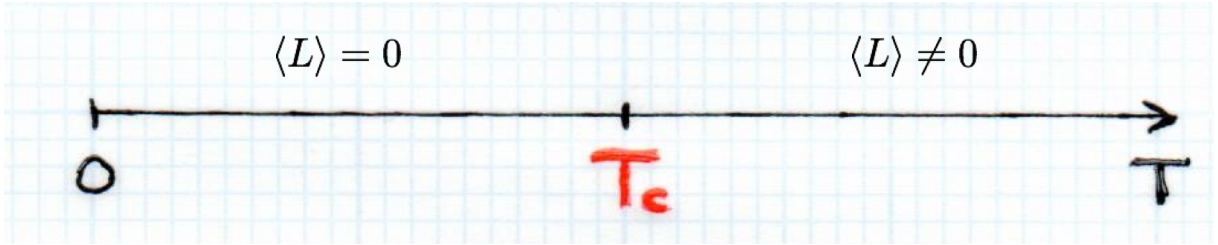
spectral density

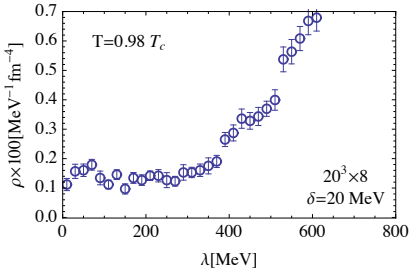
III. Pure Glue

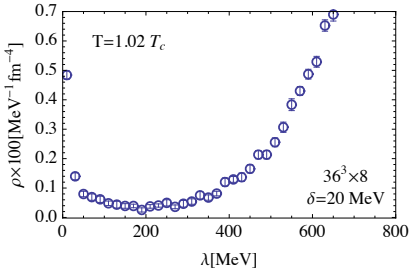




$$|\langle L\rangle| \propto \exp(-F/T)$$





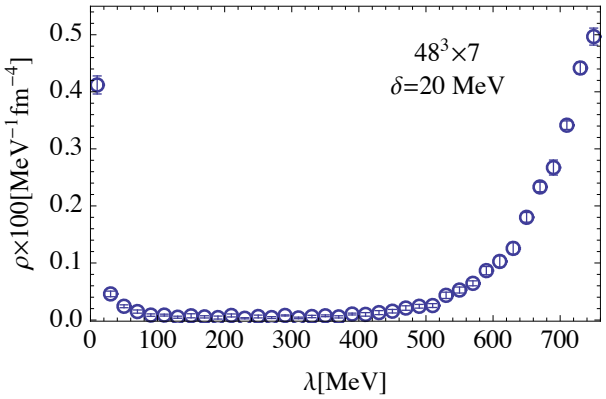


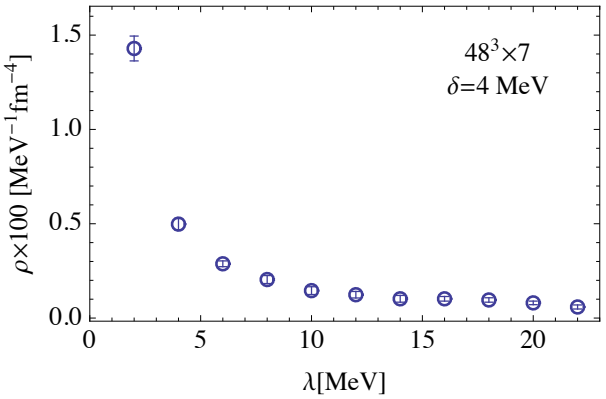
A.A , I.H. 1502.07732

Was interpreted as TRANSITION TO BIMODALITY. But what is the interpretation here?

T=1.12 T_c

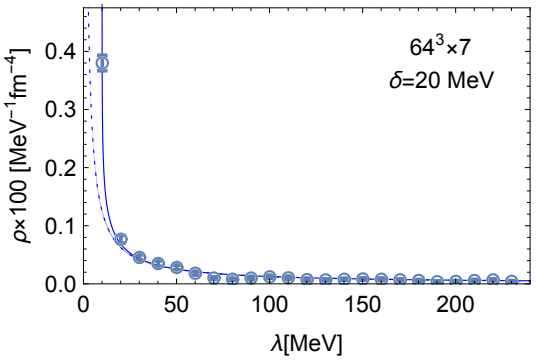
A.A , I.H. 1502.07732

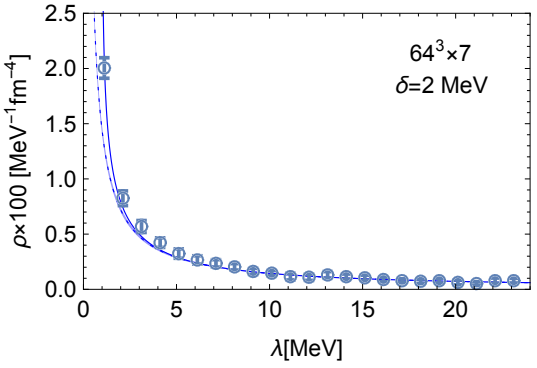


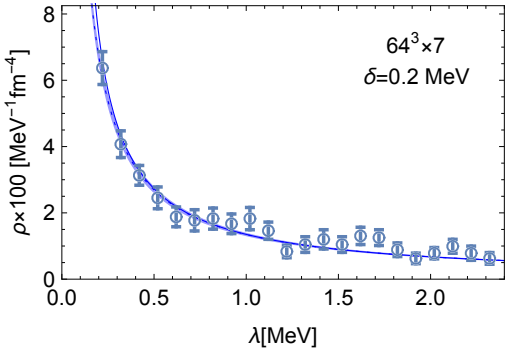


- bimodality pronounced (two separate regimes)
- infrared mode just too orderly & inviting to study details
- modified eigenmode techniques required for larger lattices

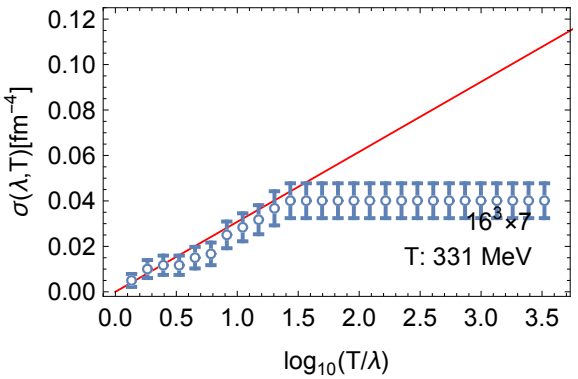
fits to $1/\lambda$

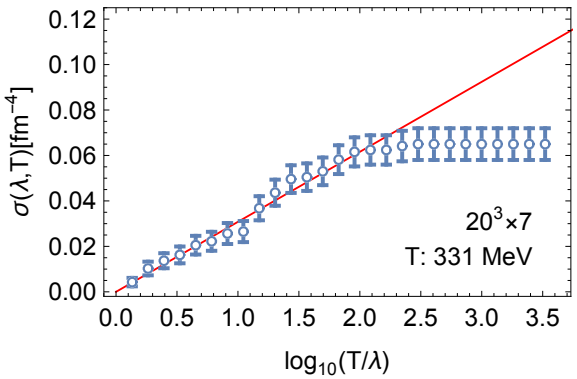


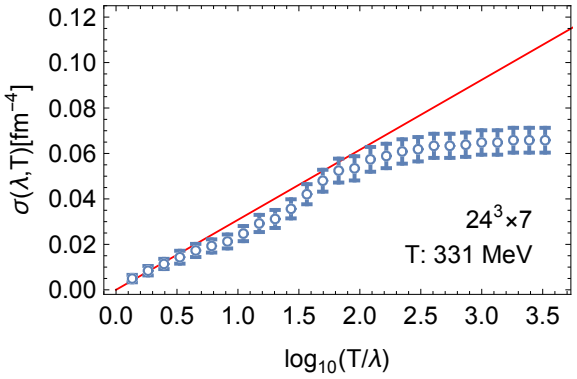


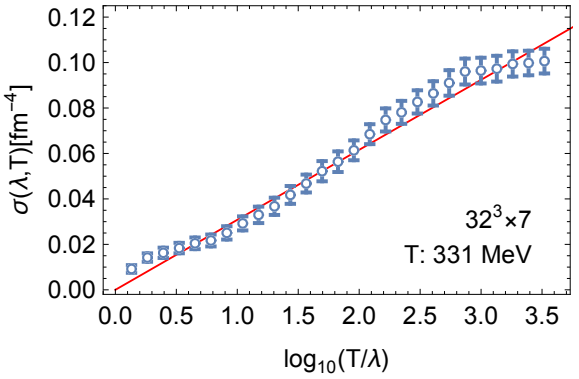


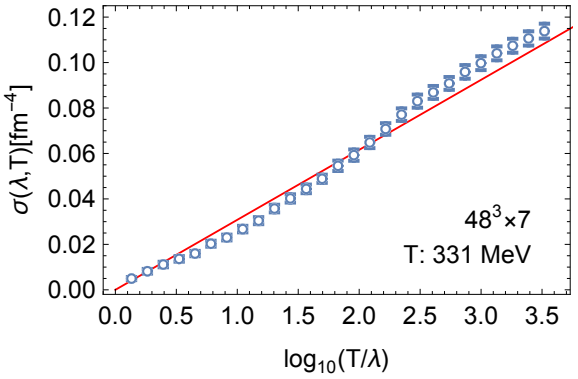
Check this further & better… $\sigma(\lambda_1,\lambda_2) \equiv \int_{\lambda_1}^{\lambda_2} d\lambda\, \rho(\lambda)$ $\rho(\lambda) = c/\lambda \longrightarrow \sigma(\lambda,T) = c\,\ln(T/\lambda)$

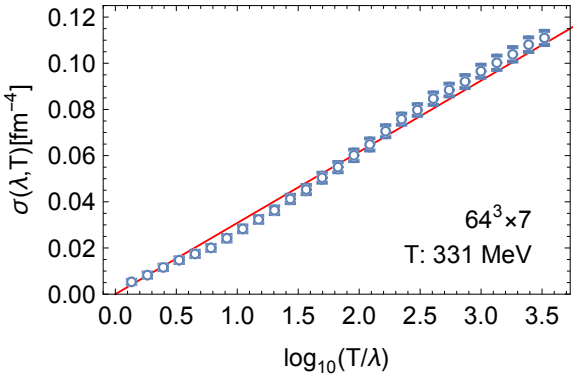












POINT 1: In pgQCD $1/\lambda$ spectral density over at least 3.5 orders of magnitude!

Is this thermal transition to low energy scale invariance?

Remember: we probe the gauge field! $D(A)\,\psi_\lambda(x) = \lambda\,\psi_\lambda(x)$

$A_s(x) \equiv sA(sx)$ $\quad (\,A, \lambda, \psi_\lambda(x)\,)$ $\quad (\,A_s, s\lambda, \psi_\lambda(sx)\,)$ simultaneous eigentriples

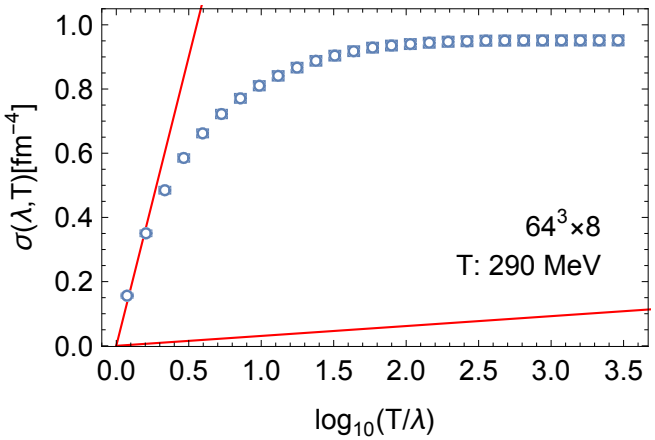
if $A_s(x) = A(x)$ and $x_\mu \in (\epsilon, \infty)$

$$\int_{\lambda_1}^{\lambda_2} d\lambda\,\rho(\lambda,\epsilon) \;=\; \frac{1}{s^3}\int_{s\lambda_1}^{s\lambda_2} d\lambda\,\rho(\lambda,\epsilon/s) \qquad \Rightarrow \qquad \rho(\lambda) = \lambda^3 f(\lambda\epsilon)$$

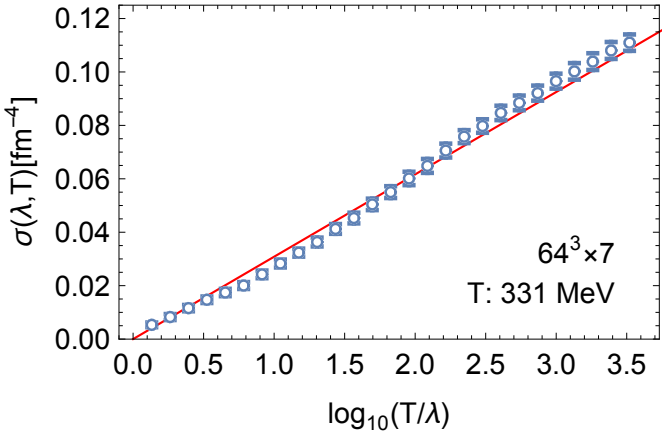
For thermalized configuration: $\epsilon \;\to\; \Lambda_{\rm IR}(T) \;<\; T$ $\qquad \rho(\lambda) \;\propto\; \dfrac{\Lambda_{\rm IR}^4}{\lambda}$

POINT 2: $1/\lambda$ conveys statistical self-similarity (scale invariance) of glue in IR

Look at the Polyakov line transition with eyes scale invariance:



T=0.98 T_C



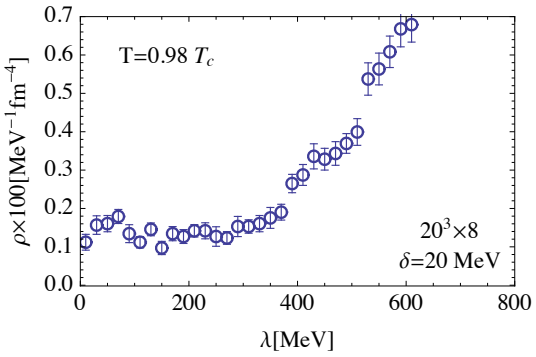
T=1.12 T_C

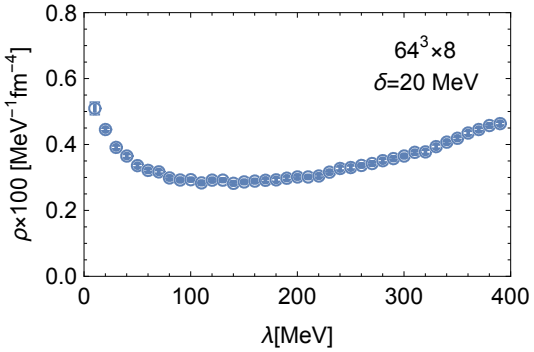
POINT 3: Polyakov line phase transition = restoration of scale invariance at long distances

$$T_c \equiv T_{\rm IR}$$

Another twist...

T = 0.98 T_c

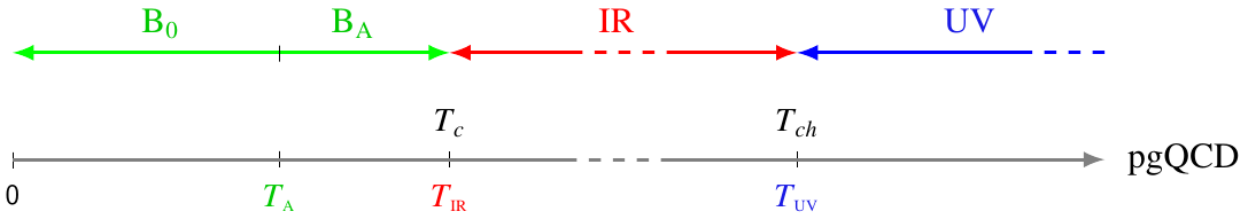




There is bimodality but no IR scale invariance for $T \lesssim T_{IR}$ but not seen for $T \gtrsim 0$!

POINT 4 [prediction]:

pgQCD has crossover at temperature $T_A < T_{IR}$ (crossover toward scale invariance restoration)



1. Scale invariance in deep UV (asymptotic freedom) present at all temperatures

2. We are classifying phases of thermal QCD based solely on scale invariance

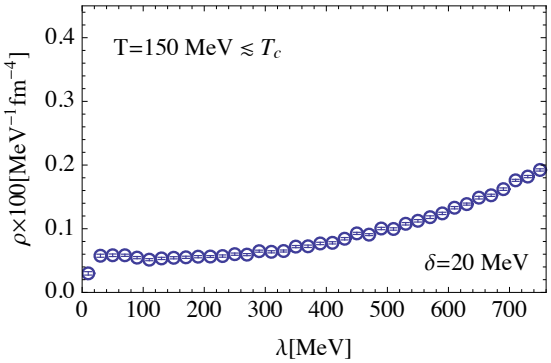
IV. QCD

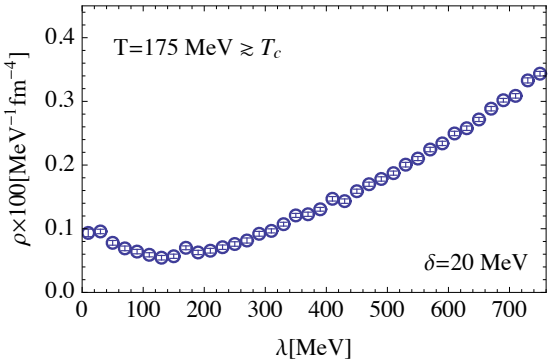
Is the story here similar or entirely different? Is there a crossover?

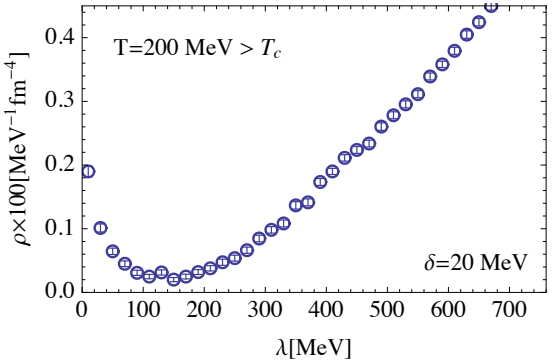
N_f=2+1 at physical point: ensembles from Borsanyi et al, 2010

They report: ``$T_c$'' (Polyakov line) = 170 MeV ``T_c''(chiral) = 155 MeV

A.A , I.H. 1502.07732



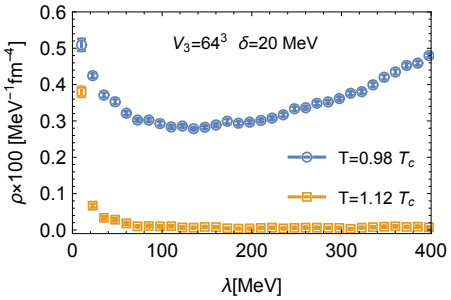


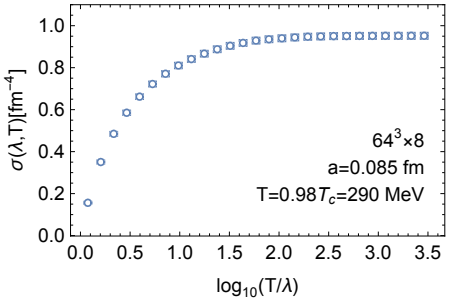


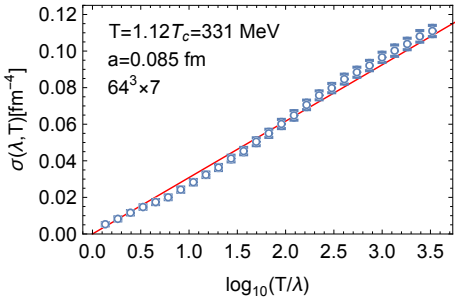
POINT 5: chiral crossover = IR scale invariance crossover $\quad$ "T_c" $\approx$ $T_{\rm A}$

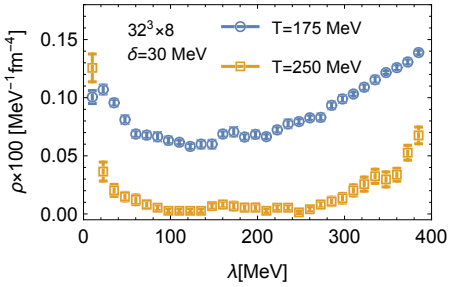
Note: OUR PROPOSAL NATURALLY INCORPORATES THE STANDARD SCENARIO!

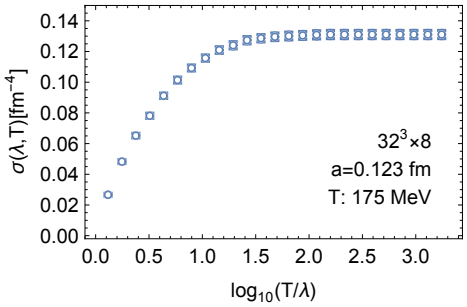
Is there an IR phase?

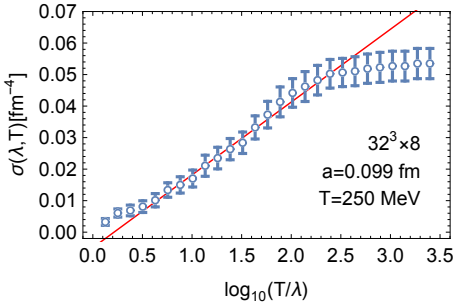


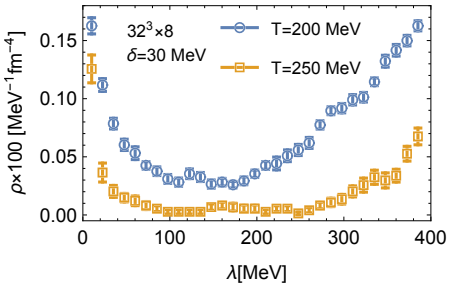


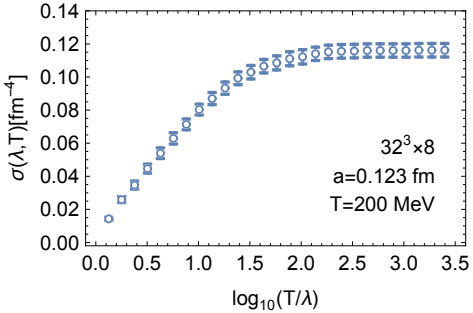


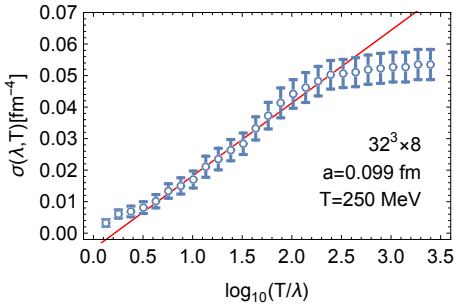






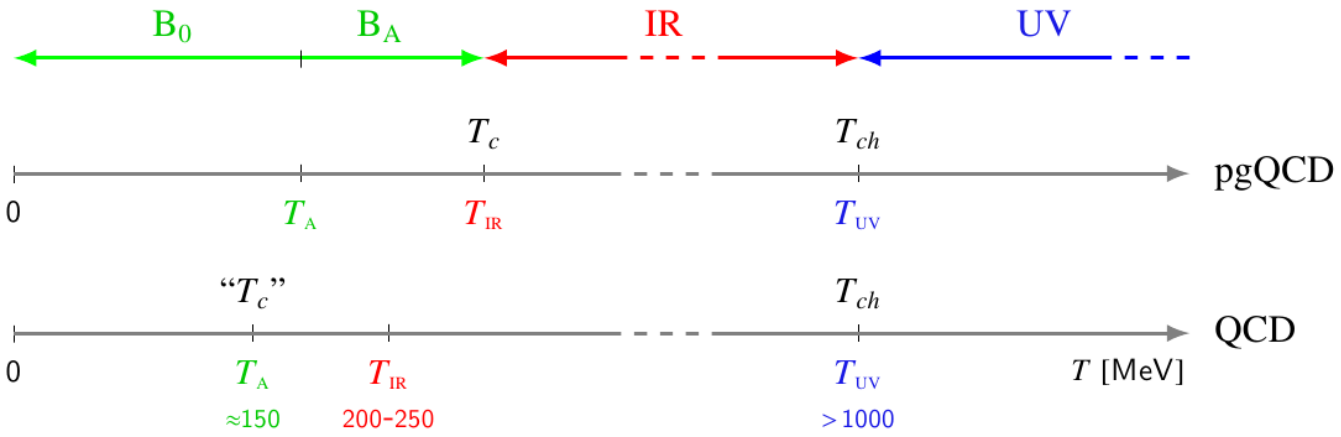






POINT 6: [proposition] QCD has an IR phase $200\,\mathrm{MeV} < T_{\mathrm{IR}} < 250\,\mathrm{MeV}$

PHASE STRUCTURE OF QCD AND pgQCD IN TERMS OF SCALE INVARIANCE



STRONGLY COUPLED	LESS STRONGLY COUPLED	PERTURBATIVE
IR-BROKEN	IR-SYMMETRIC	IR-DEPLETED
UV-SYMMETRIC	UV-SYMMETRIC	UV-SYMMETRIC
p = 0	p $\gtrapprox$ -1	p > 0

P = leading IR power in $\rho(\lambda)$

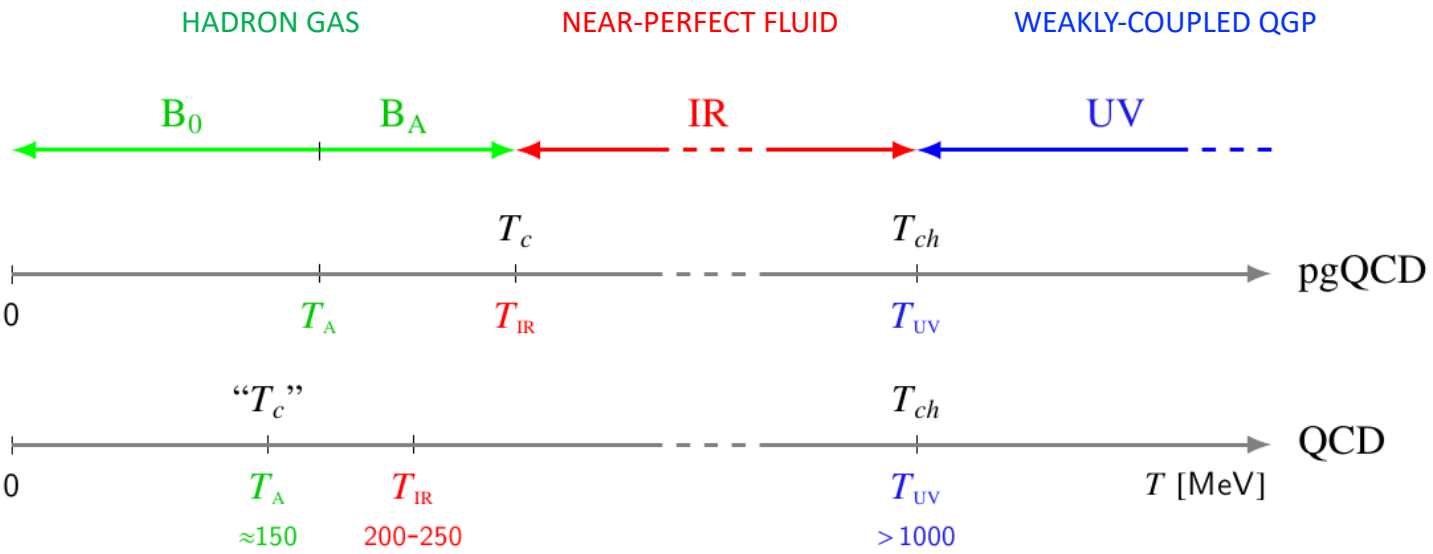
V. ACCOMMODATING NEAR-PERFECT FLUID

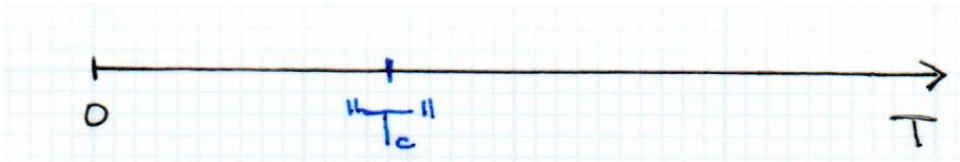
- highly symmetric, large N, strongly coupled theories accommodate η/s

Policastro,Son, Starinets, 2001

- scale invariance will play role in understanding fluidity

POINT 6: We propose that near-perfect fluid is realized by IR phase!





Look what we started from!

VI. IR PHASE, BANKS-ZAKS & CONSEQUENCES

1) What is the nature of IR scale invariance in thermal IR phase?
How does it come about?

2) What are its consequences for near-perfect fluid?

Look at it in larger context: SU(3) with fundamentals

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

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

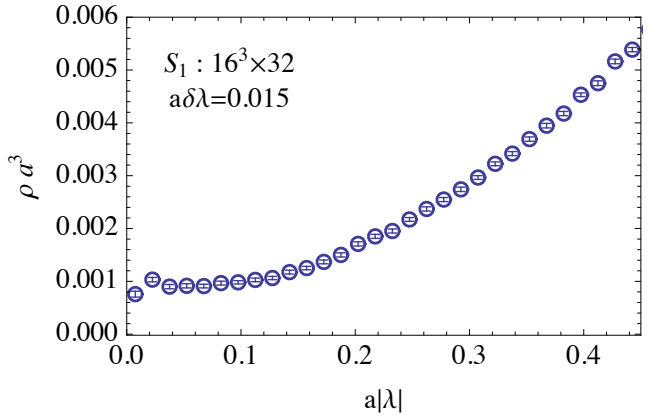
$$D\chi \equiv \gamma_\mu(\partial_\mu + A_\mu)\chi \qquad \chi \in C^{12}$$

Space parametrized by (T, m_f, N_f)

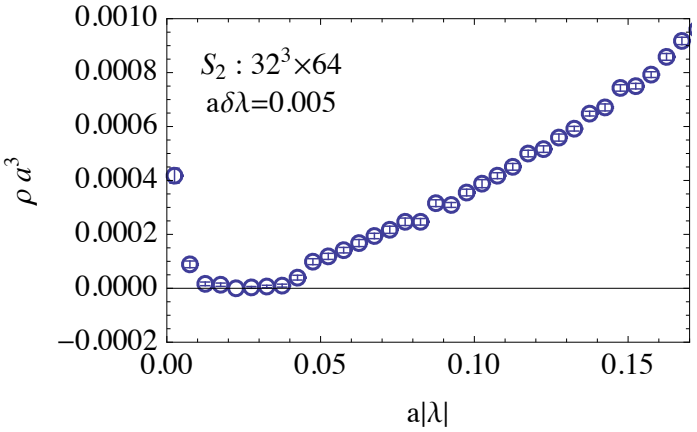
Bimodality due to lowering quarks mass:

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

am=0.02



am=0.0025



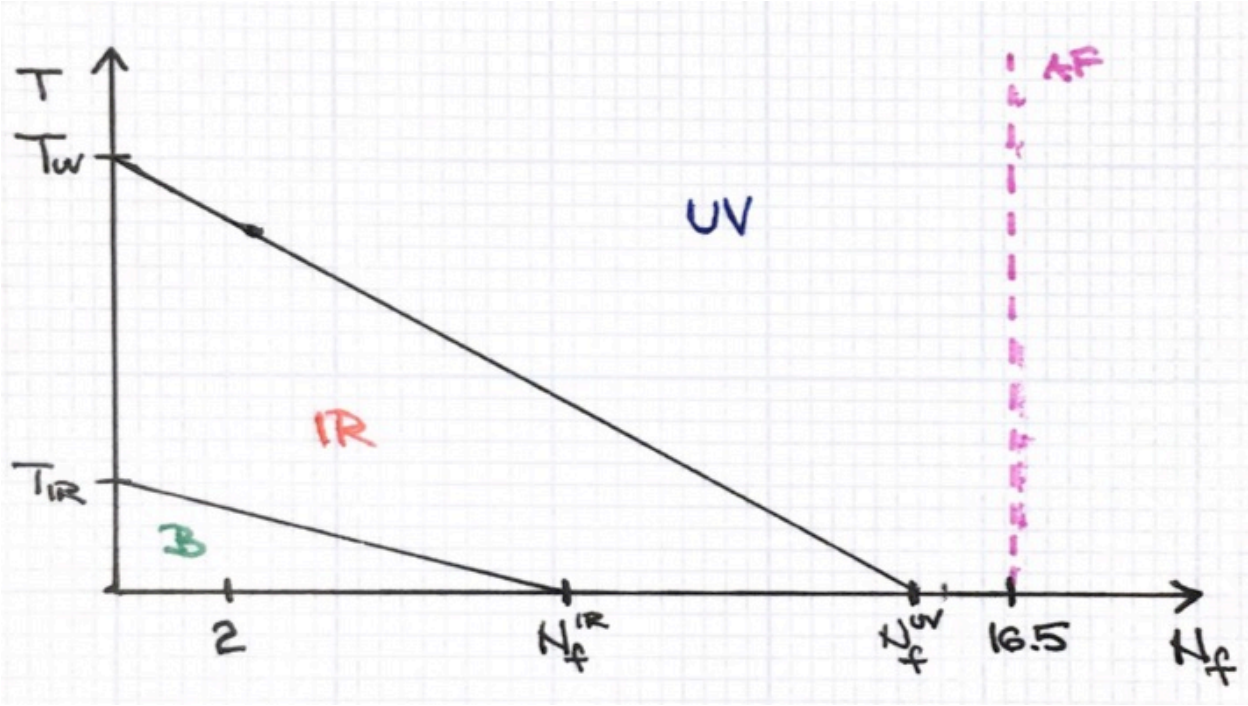
A.A, I.H. 1405.2968, 1411.1777

- Light quarks generate bimodality without temperature!
- Since near conformal window, it is expected $\rho(\lambda) \propto \lambda^p$ but then p<0!

POINT 7: Conformal window has a strongly coupled part with p < 0

$$N_f^c \equiv N_f^{\rm IR} < N_f < N_f^{\rm UV} \leq 16.5$$

Trends found in A.A , I.H. 1502.07732 : IR-UV separation increases with: increasing T, decreasing m, increasing N



POINT 8: There is a contiguous IR phase ($p < 0$) in space of SU(3) gauge theories with fundamentals containing both strongly coupled part of conformal window and (T_{IR} , T_{UV}) of thermal QCD.

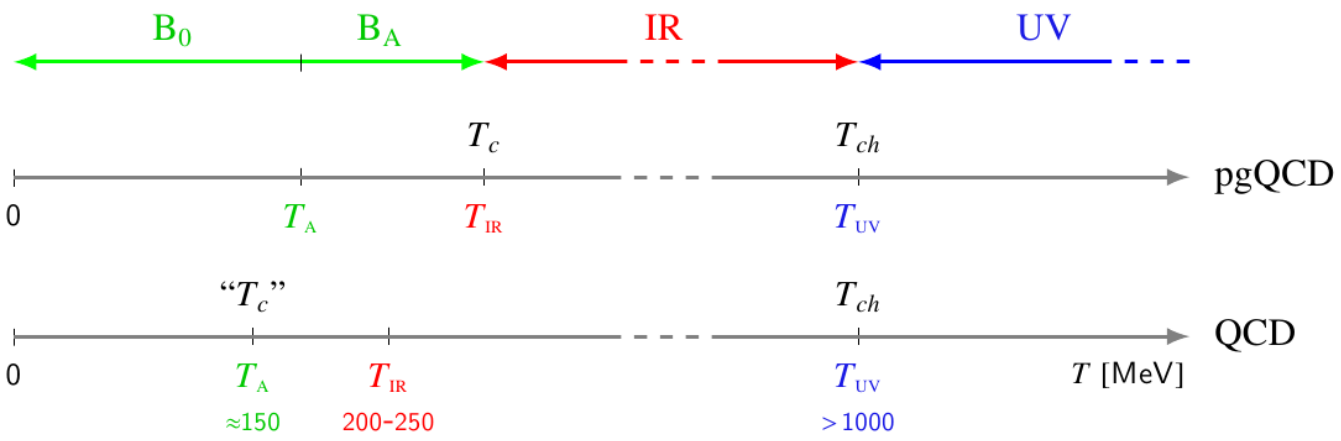
POINT 9: The near-perfect fluid of QCD is characterized by the lowest glueball ``screening masses" and lowest ``pseudoparticle masses" being zero, and lowest meson/baryon masses light. There is gap (IR-UV separation) of order T in the spectrum of excitations.

SUMMARY

MASSLESS GLUEBALLS

& IR-UV SEPARATION

HADRON GAS | NEAR-PERFECT FLUID | WEAKLY-COUPLED QGP



STRONGLY COUPLED | LESS STRONGLY COUPLED | PERTURBATIVE

IR-BROKEN | IR-SYMMETRIC | IR-DEPLETED

UV-SYMMETRIC | UV-SYMMETRIC | UV-SYMMETRIC

$p = 0$ | $p \gtrapprox -1$ | $p > 0$