Phase Transitions and the Perfectness of Fluids

Jiunn-Wei Chen

National Taiwan U.

Shear viscosity measures how “perfect” a fluid is!

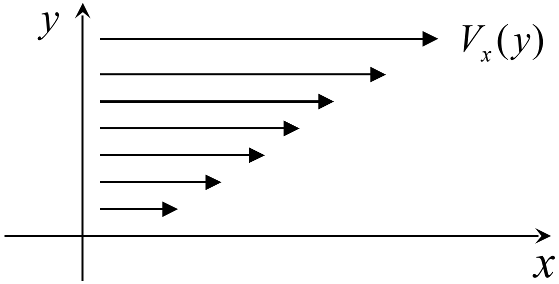
- Review: shear viscosity minimum bound conjecture
- QCD shear viscosity in the hadronic phase:

  (a) zero density (w/ Eiji Nakano)

  (b) nuclear L-G phase transition

  (w/ Yen-Fu Liu, Yen-Han Li, Eiji Nakano)
- Scalar field theory (w/ Mei Huang, Yen-Han Li, Eiji Nakano, Di-Lun Yang)
- Bulk Viscosity (w/ Juven Wang)

- Shear viscosity



Frictional force

$$T_{ij} = -\eta\left(\frac{\nabla_i V_j(x) + \nabla_j V_i(x)}{2} - \frac{1}{3}\delta_{ij}\nabla\cdot V(x)\right).$$

Kubo Formula

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t, \mathbf{x}),\, T_{xy}(0, \mathbf{0})] \rangle$$

- Kovtun, Son, and Starinets ('05)

  Conjecture: Shear viscosity / entropy density

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

- Motivated by AdS/CFT

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t, \mathbf{x}),\ T_{xy}(0, \mathbf{0})] \rangle$$

$$\eta = \frac{\sigma_{\rm abs}(0)}{16\pi G}$$

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

- QGP (quark gluon plasma) almost saturates the bound @ just above Tc (Teaney; Romatschke, Romatschke; Song, Heinz)
- LQCD, gluon pasma (Karsch, Wyld; Nakamura, Sakai; Meyer)

⇨ QGP near Tc, a perfect fluid, SQGP

- PQGP: Asakawa, Bass, Müller; Xu, Greiner

QCD Phase Diagram

2 *M. Stephanov*

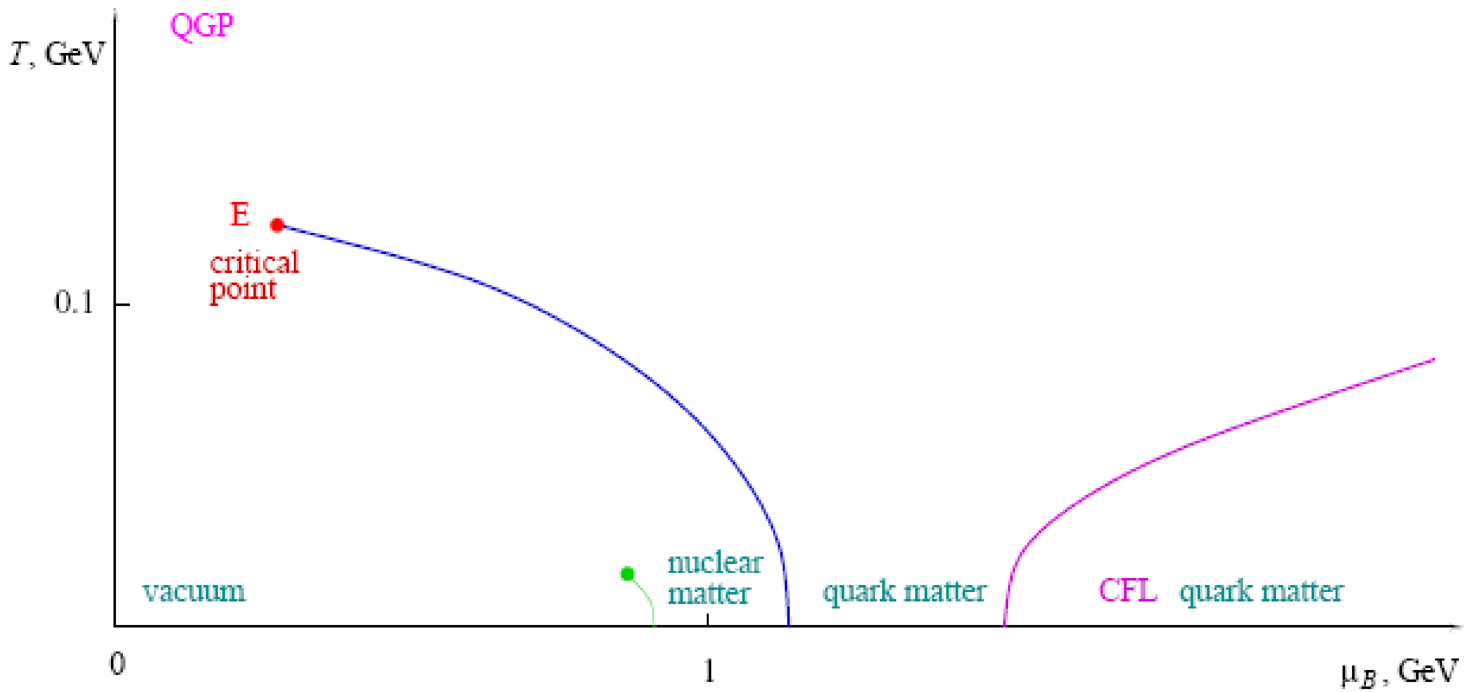


Fig. 1. QCD phase diagram

- What happens below T_c?

η/s of QCD below T_c

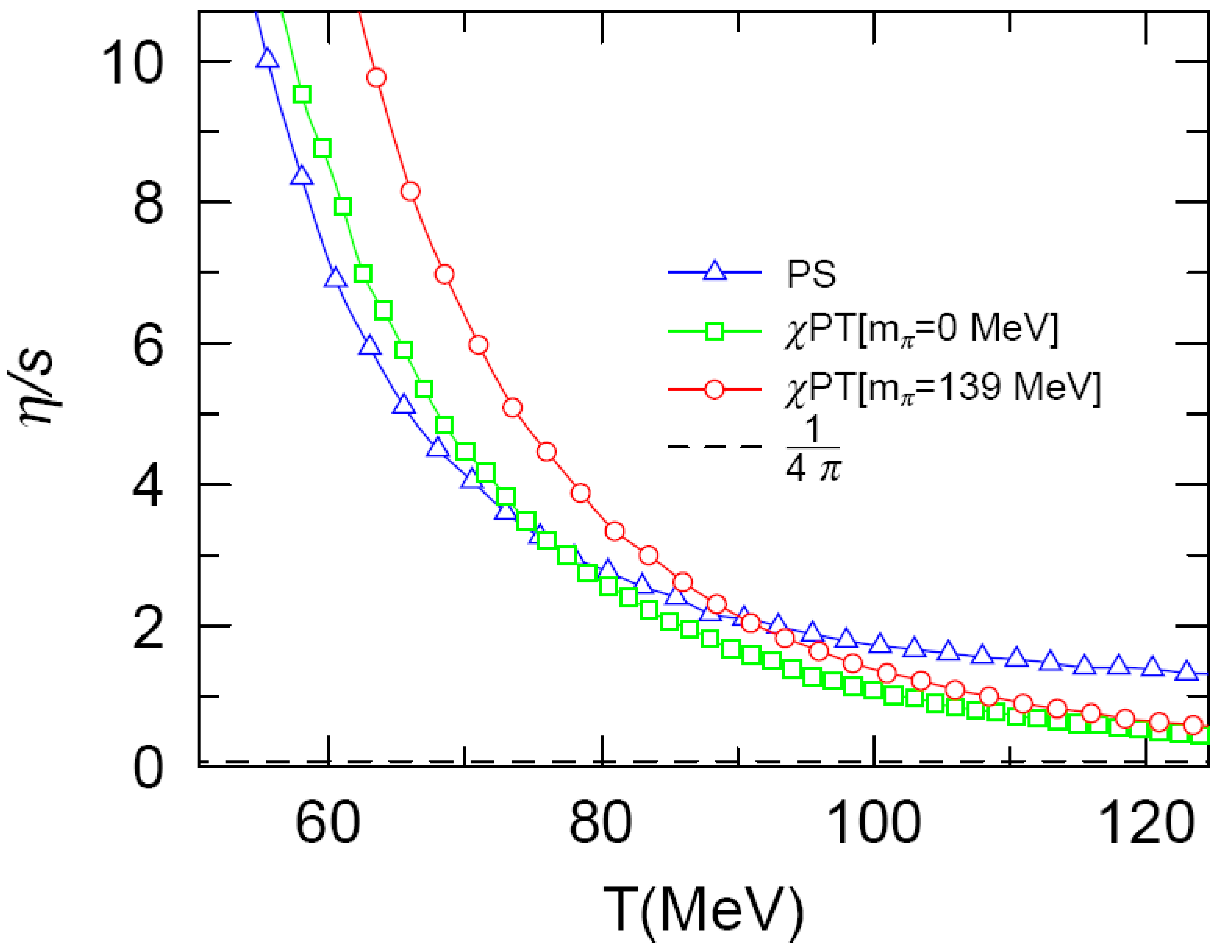
- Pion gas ⟹ ChPT (chiral perturbation theory)
- Non-perturbative in coupling

  ⟹ Boltzman equation

Earlier work: Prakash, Prakash, Venugopalan, Welke;

Dobado, Llanes-Estrada; Csernai, Kapusta , McLerran

η/s of QCD below T_c



JWC, Nakano

QCD Phase Diagram

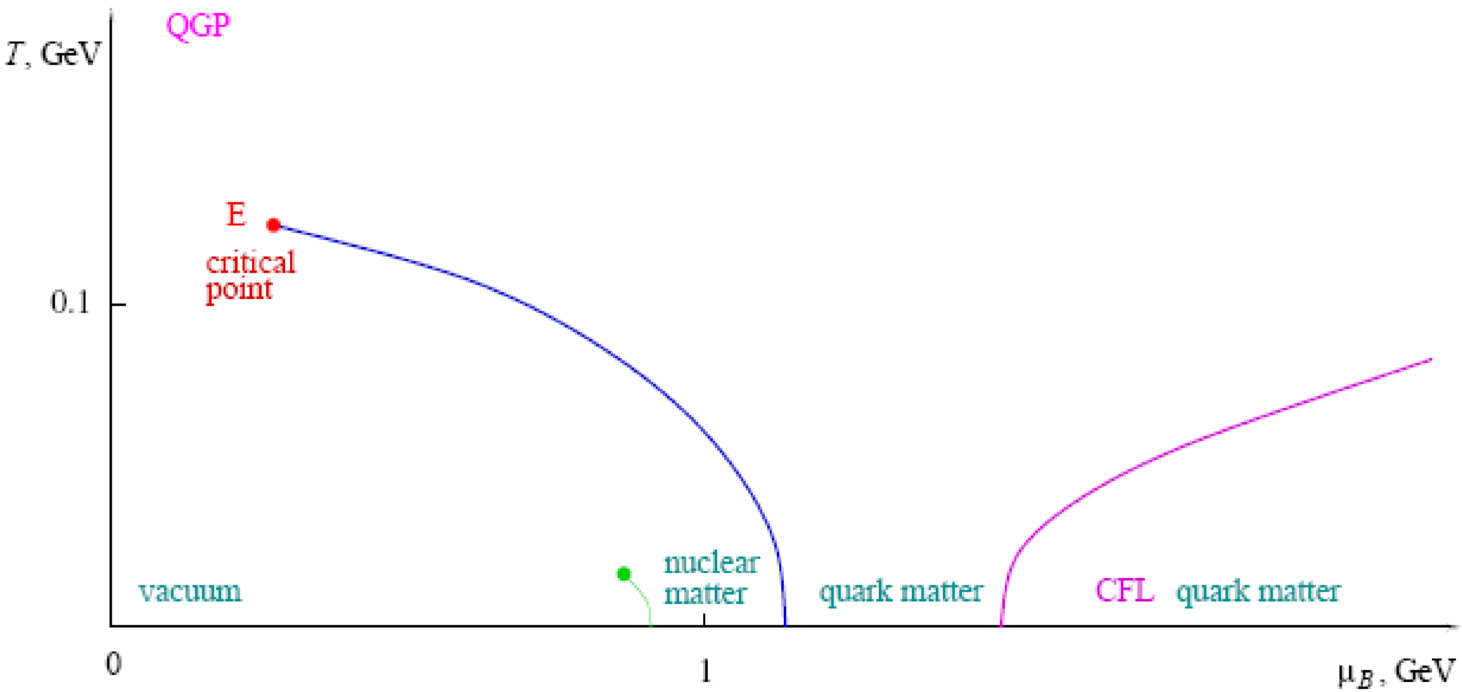
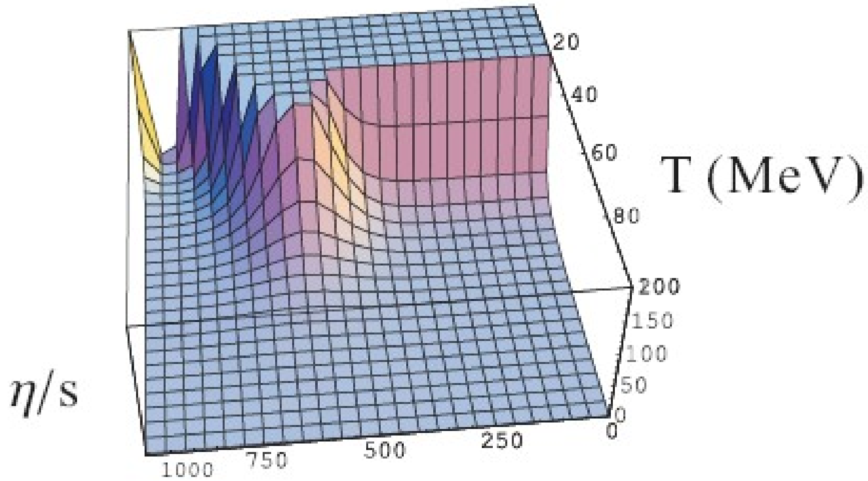
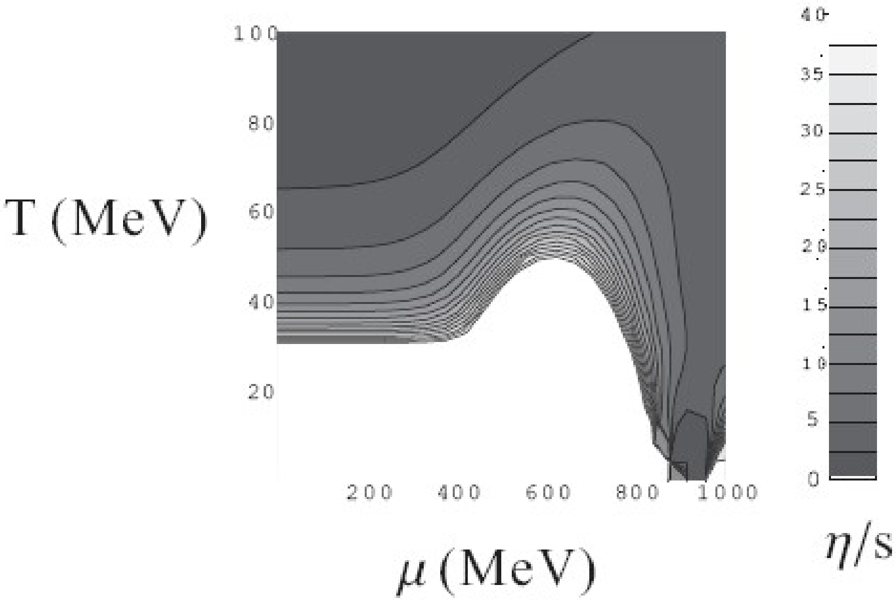


Fig. 1. QCD phase diagram

The η/s "Landscape"

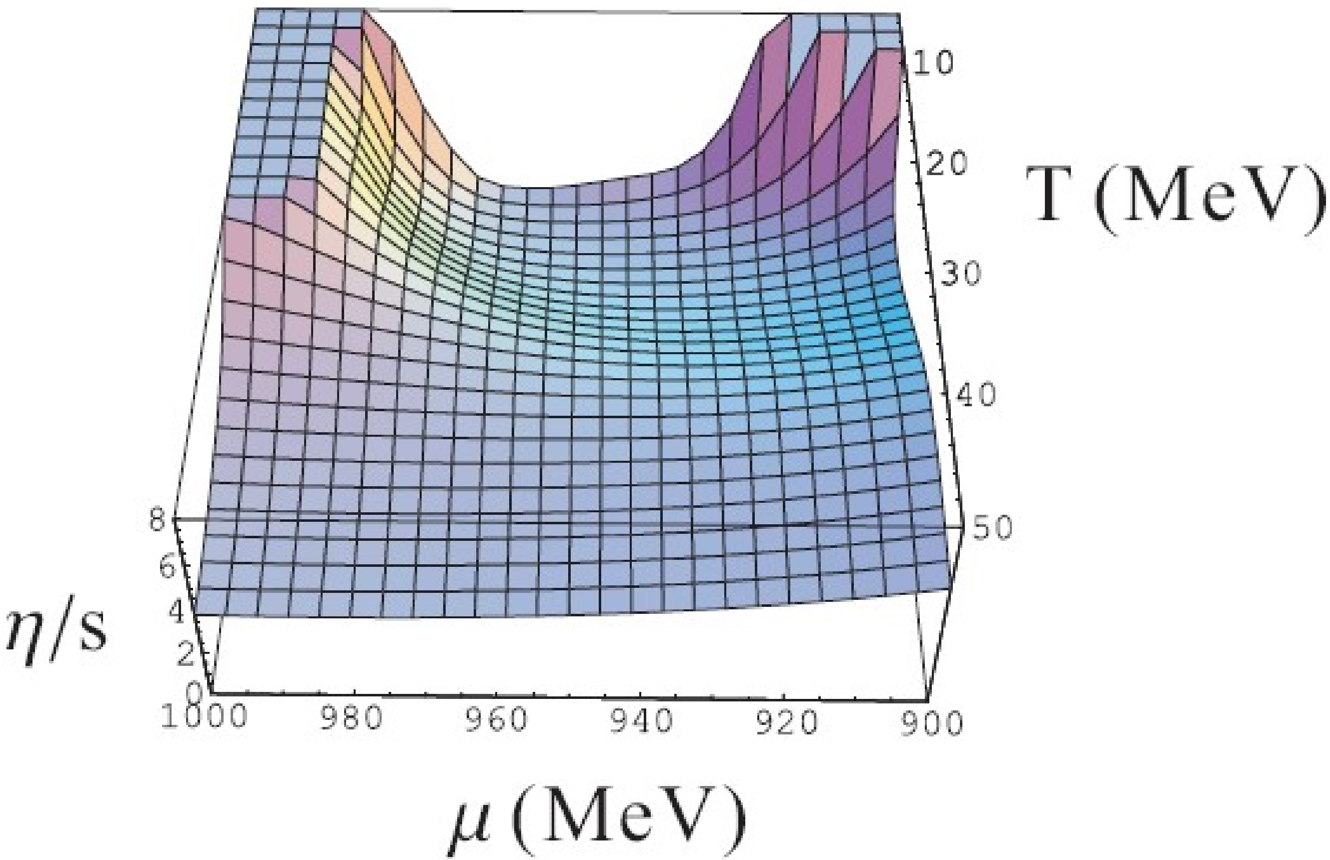


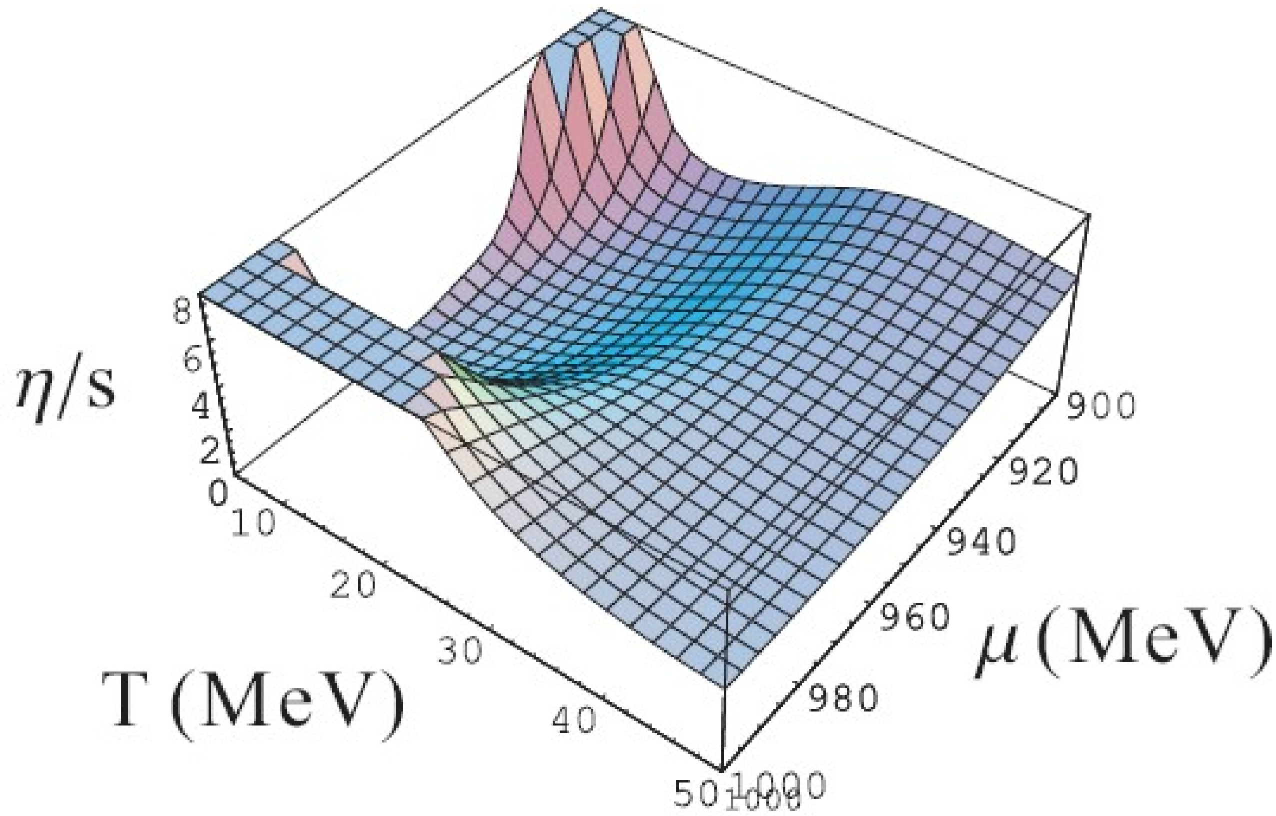
JWC, Li, Liu, Nakano; Itakura , Morimatsu, Otomo



The η/s "Landscape"

JWC, Li, Liu, Nakano





8
6
4
2
0
η/s
10
20
30
40
50
T (MeV)
900
920
940
960
980
1000
μ (MeV)

QCD Phase Diagram

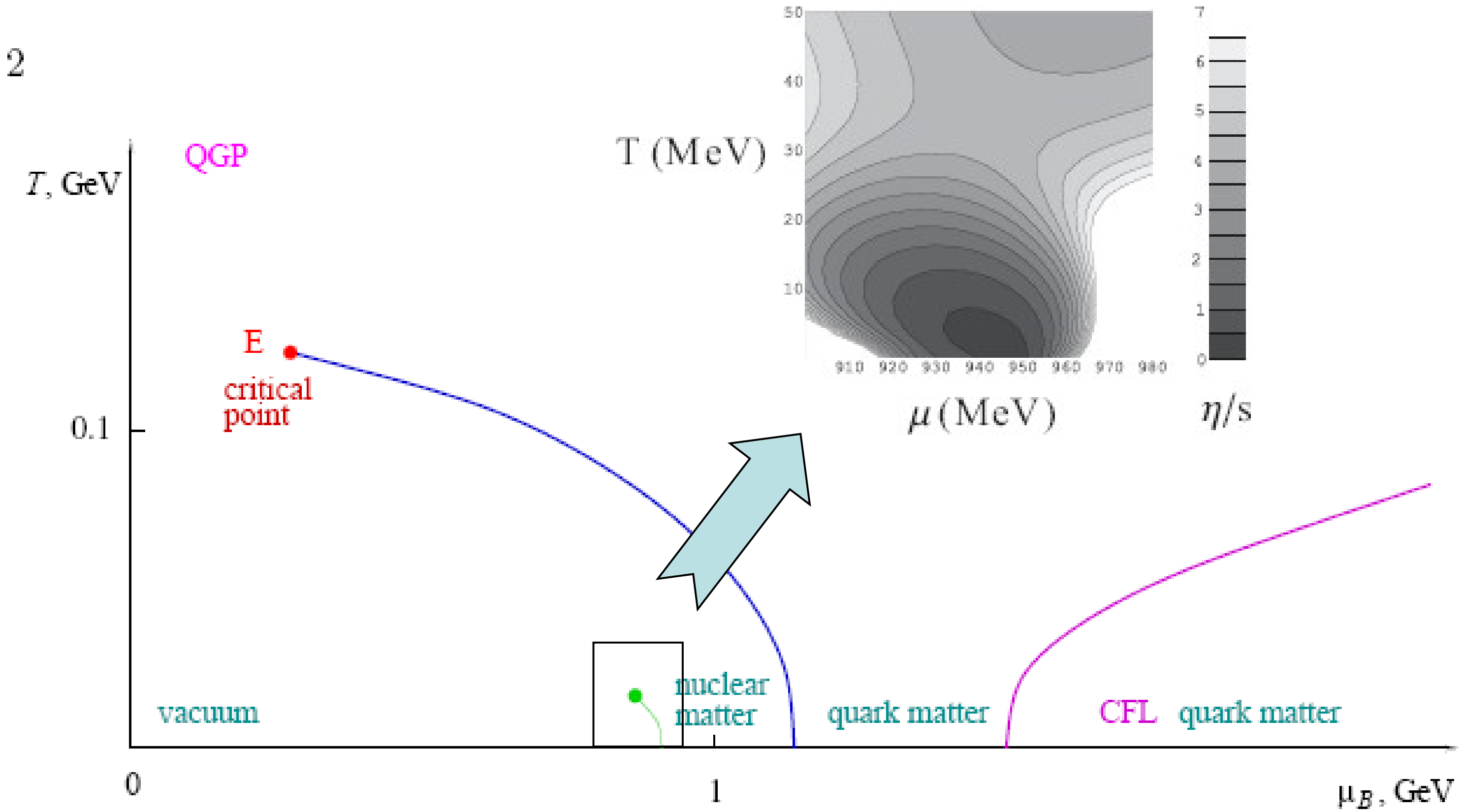
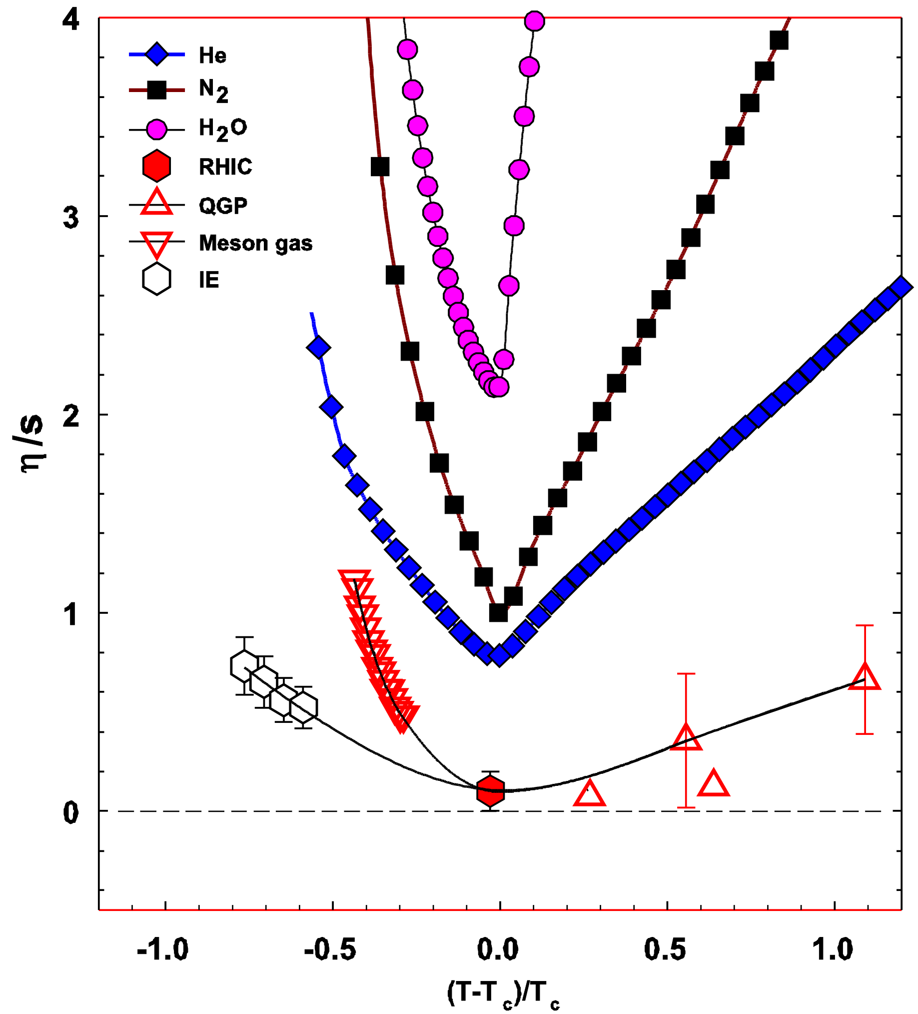


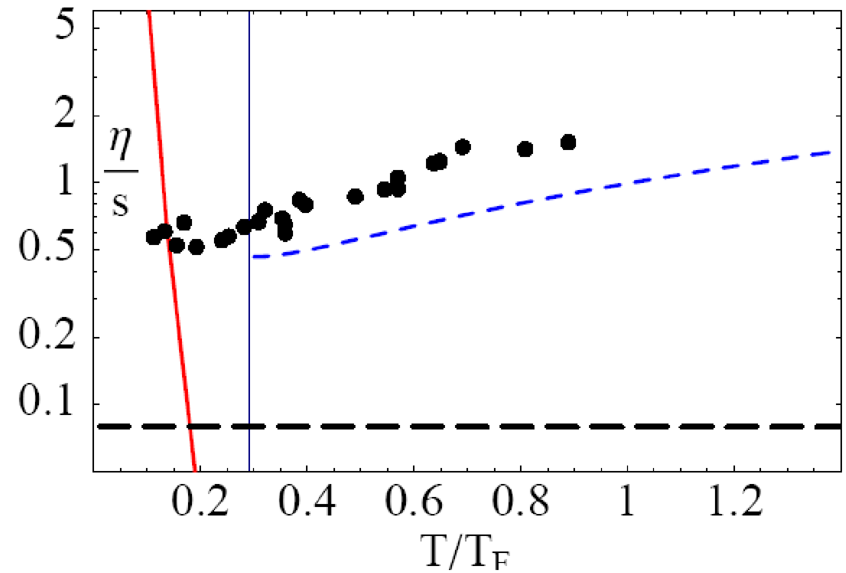
Fig. 1. QCD phase diagram

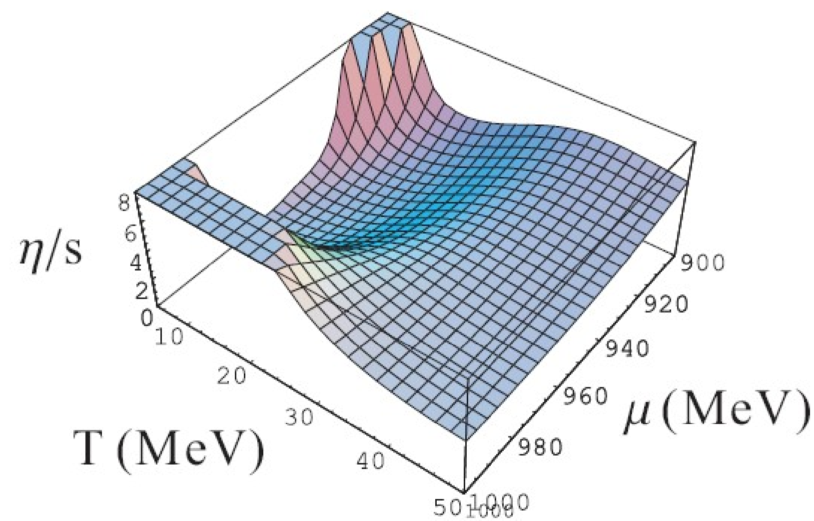


Lacey et al., PRL 98:092301,2007

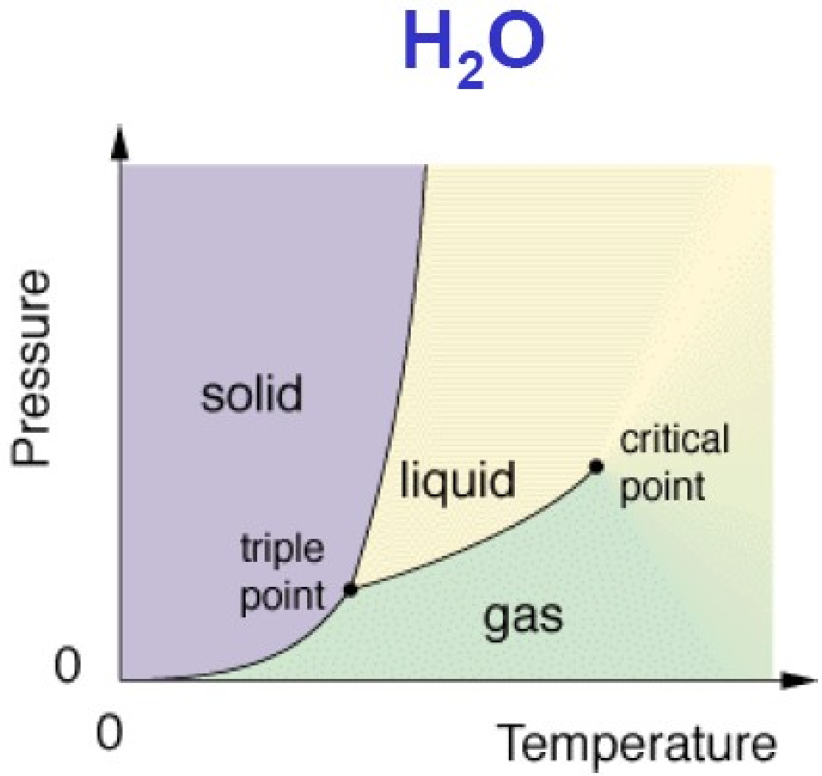
Cold Unitary Atoms

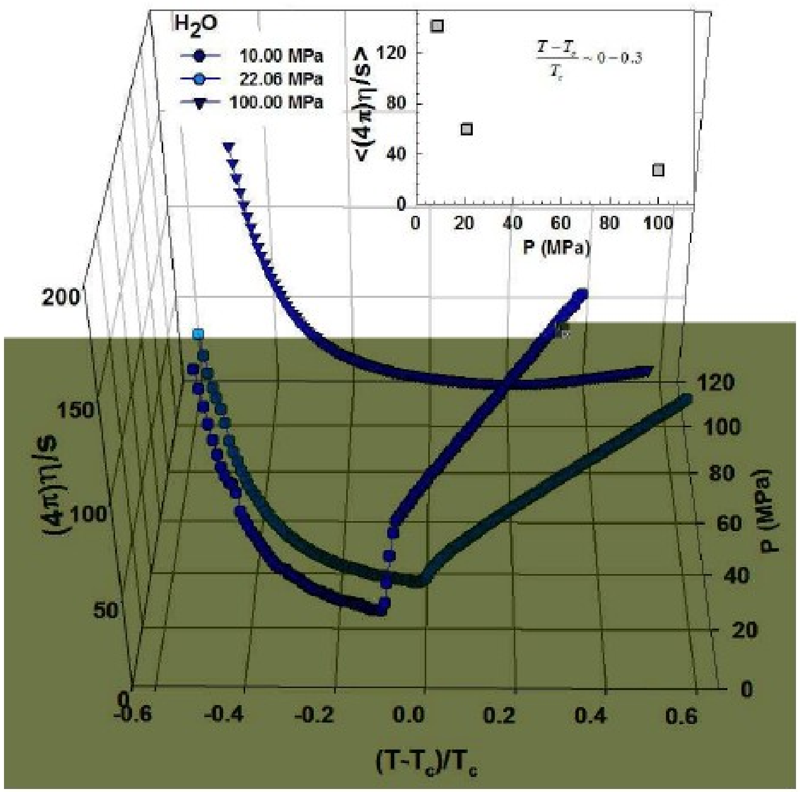
Rupak & Schafer 2007; NRCFT 2008





η/s of Water

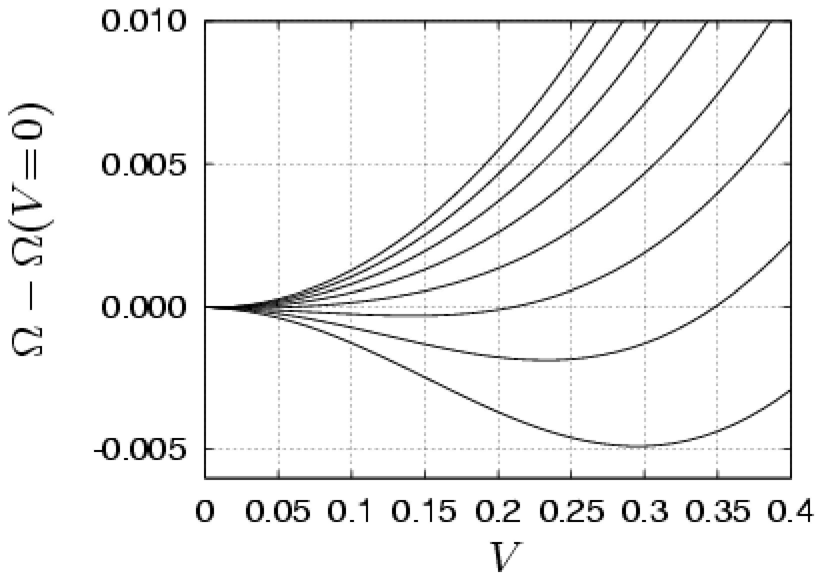


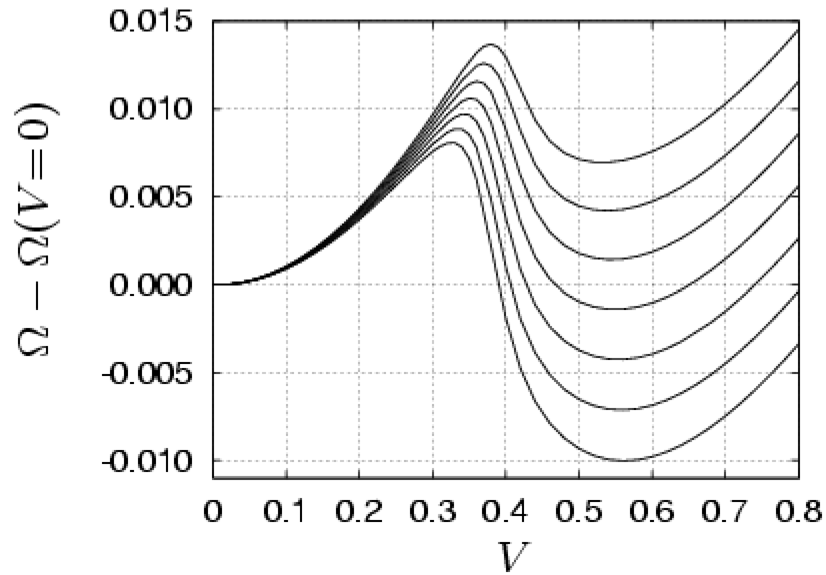


(Lacey et al.)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}a\phi^2 - \frac{1}{4}b\phi^4 - \frac{1}{6}c\phi^6$$

(JWC, M. Huang, Y.H. Li, E. Nakana, D.L. Yang)

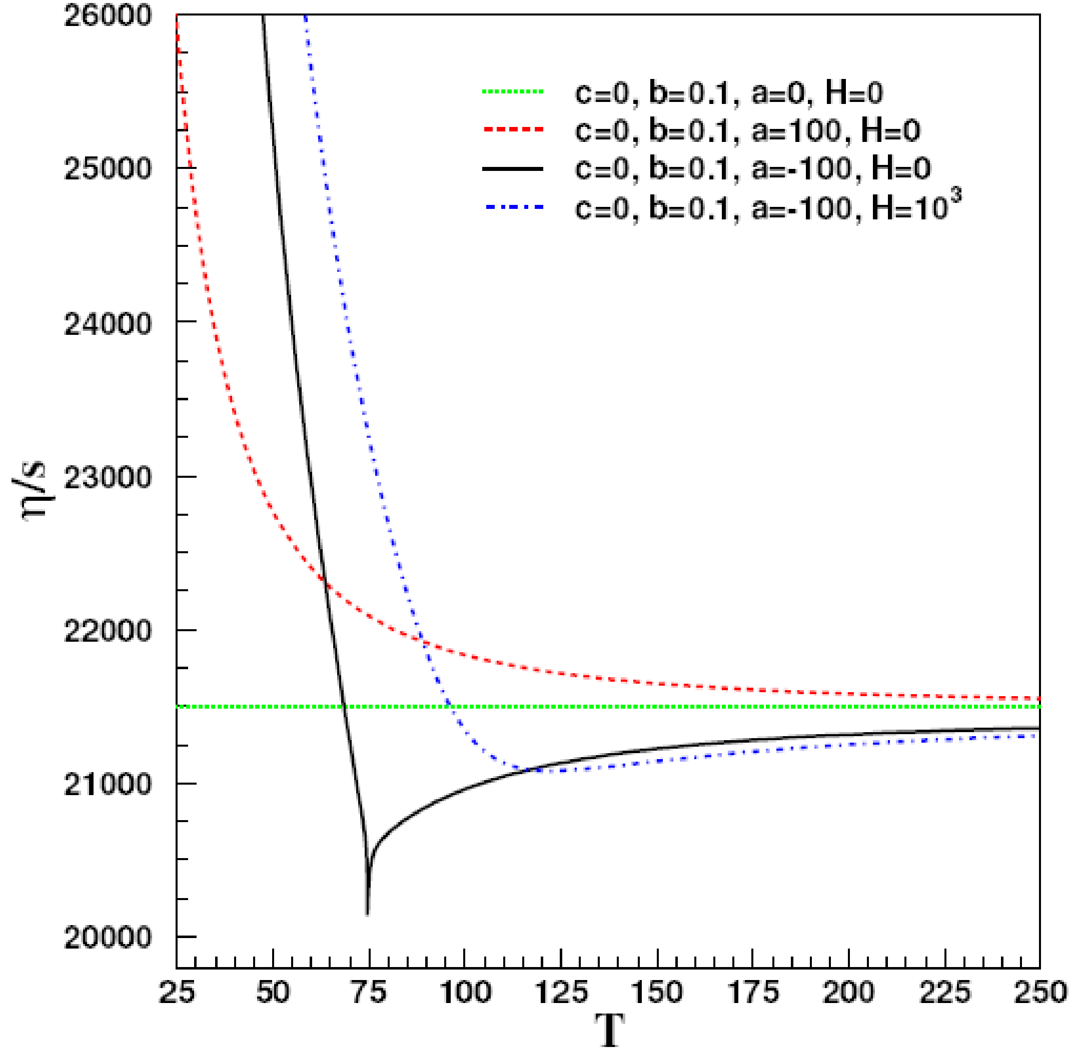




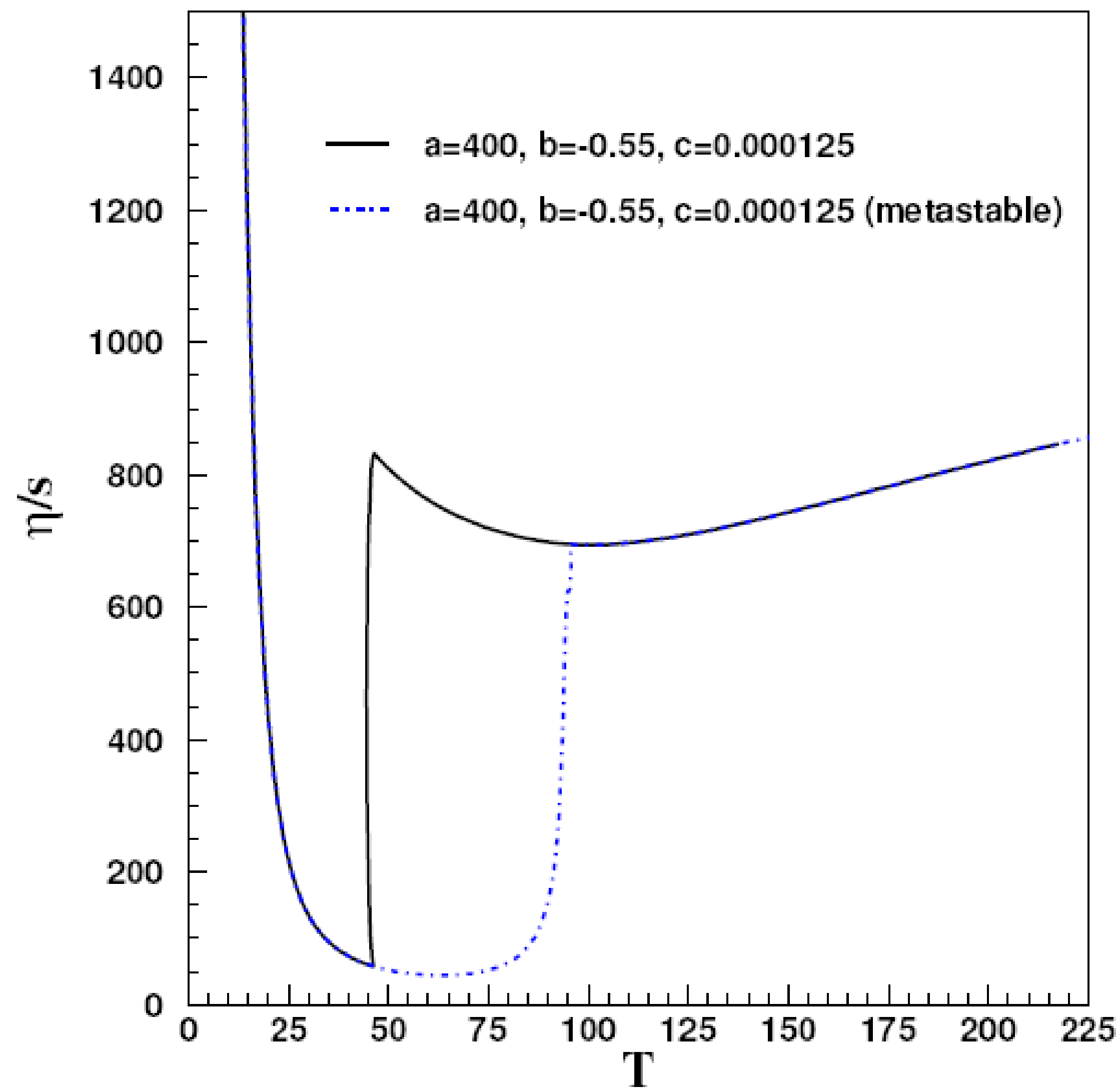
2nd-order p.t.:
a < 0, b > 0, c = 0
crossover: + $\delta\mathcal{L} = H\phi$
No p.t.: a > 0, b > 0, c = 0

1st-order phase transition
a > 0, b < 0, c > 0

- Weak coupling
- Mean field calculation
- CJT formulism (Cornwall, Jackiw, Tomboulis)
- Boltzmann eq.



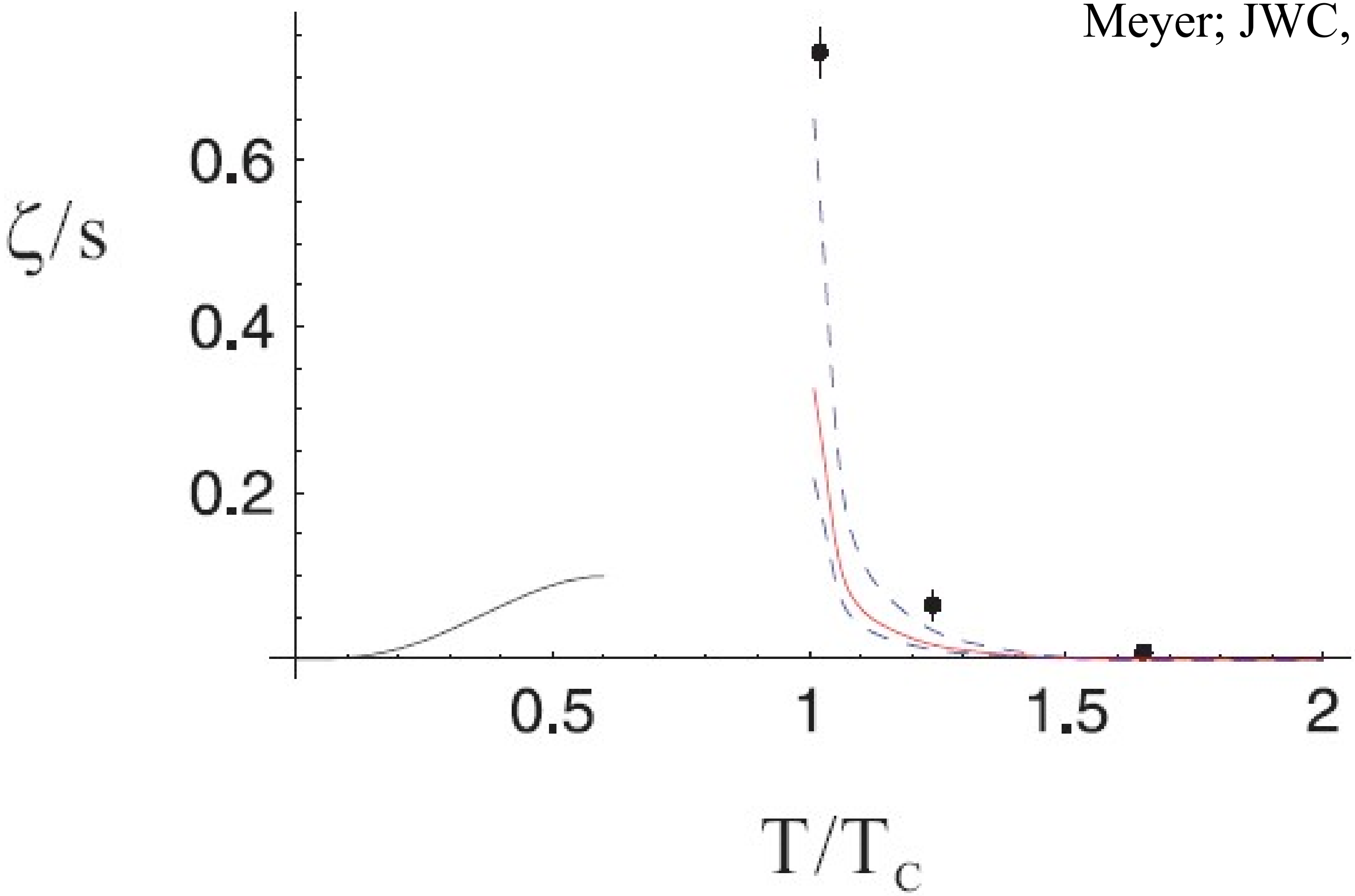
c=0, b=0.1, a=0, H=0
c=0, b=0.1, a=100, H=0
c=0, b=0.1, a=-100, H=0
c=0, b=0.1, a=-100, H=10^3
η/s
26000
25000
24000
23000
22000
21000
20000
T
25
50
75
100
125
150
175
200
225
250



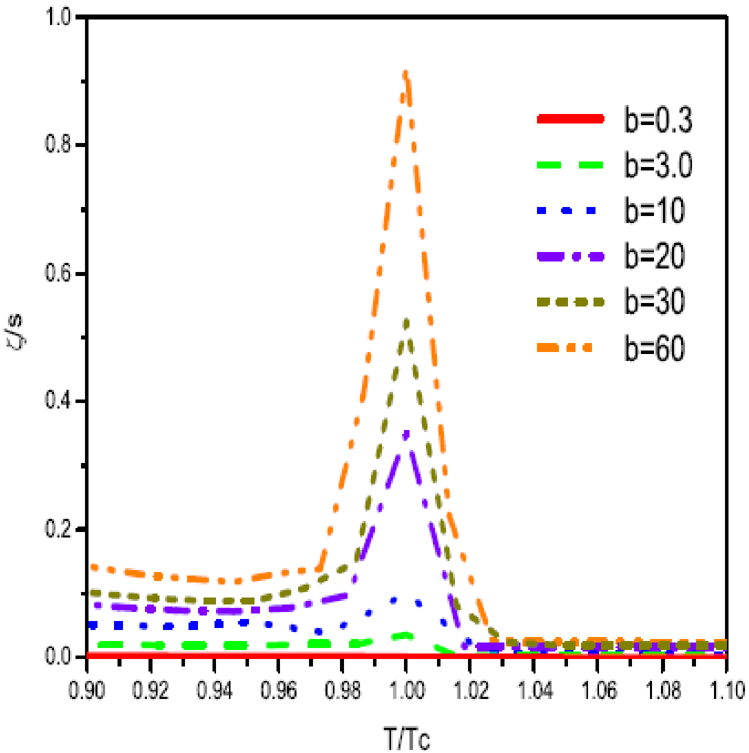
a=400, b=-0.55, c=0.000125
a=400, b=-0.55, c=0.000125 (metastable)
η/s
T
0
200
400
600
800
1000
1200
1400
0
25
50
75
100
125
150
175
200
225

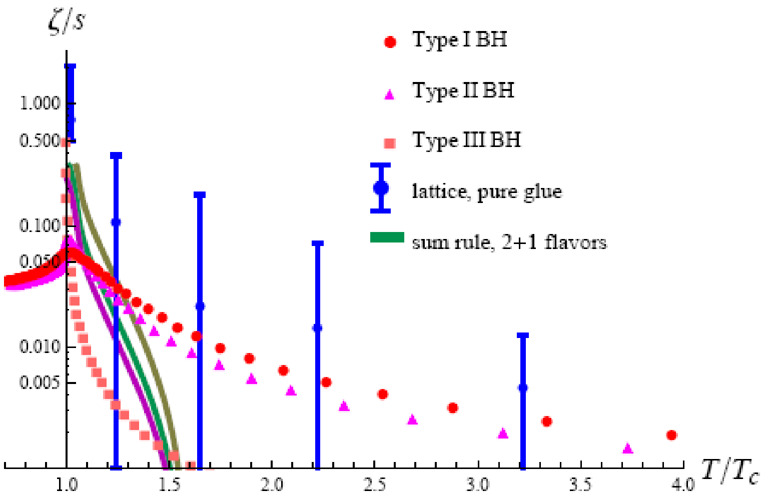
QCD Bulk Viscosity

Karsch, Kharzeev, Tuchin;
Meyer; JWC, Wang



Bulk Viscosity





Gubser, Nellore, Pufu, Rocha

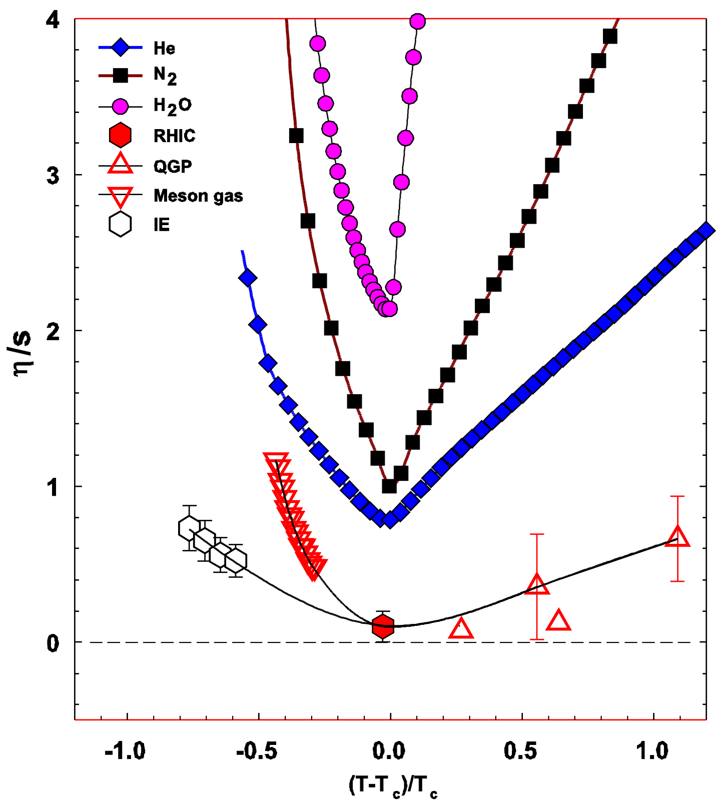
Li, Huang

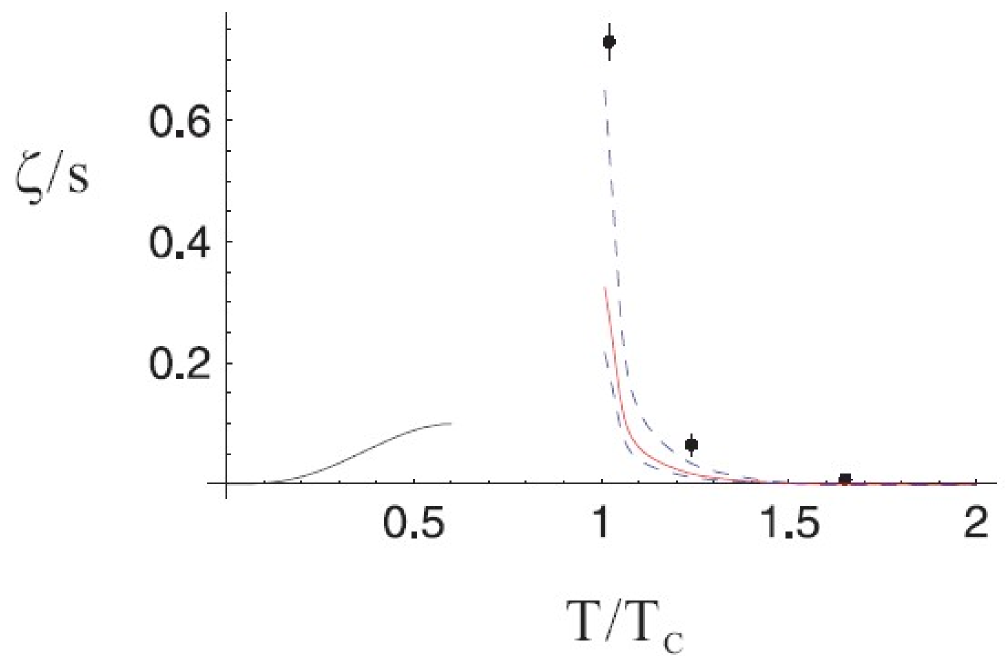
Outlook

Universal η/s and ζ/s behaviors?

(η/s reaches local minimum near p.t.

ζ/s reaches local maximum near p.t.)





Mapping QCD phase diagram by η/s ?

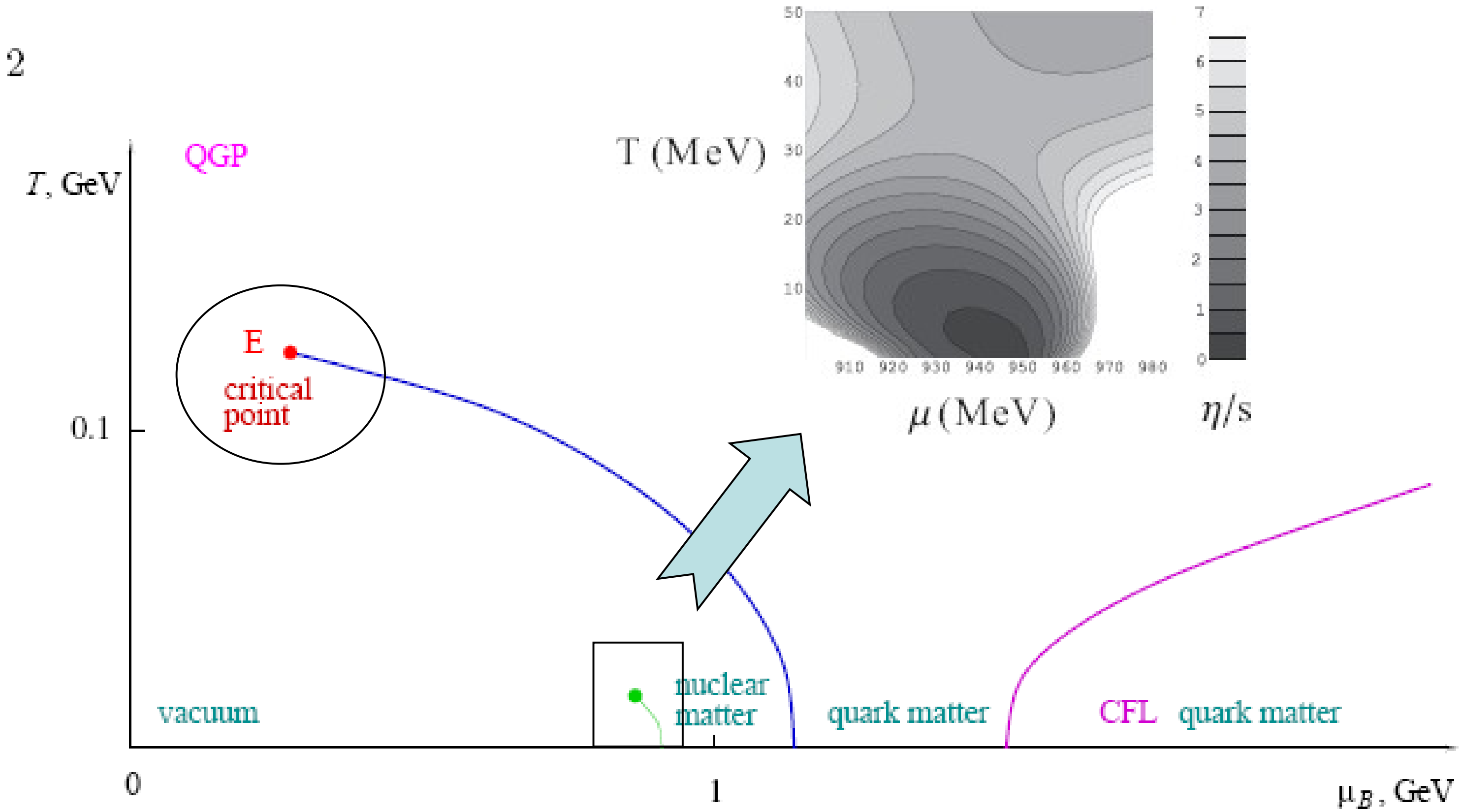


Fig. 1. QCD phase diagram

Locating critical end point (Lacey)

Outlook

Invading the bound (T. Cohen)

$$Q\overline{q}$$

$$\begin{aligned} N_Q &= N, \; N_{\overline{q}} = 1 \\ m_Q &\propto N, \; N_c \propto N \end{aligned}$$

$$\eta/s \propto 1/\ln N$$

UV complete but metastable

Outlook

- O(1/N) effect, Higher derivative gravity, (Brigante, Liu, Myers, Shenker, Yaida; Kats, Petrov)

$$\frac{\eta}{s} \geq \frac{16}{25}\left(\frac{1}{4\pi}\right)$$

Outlook

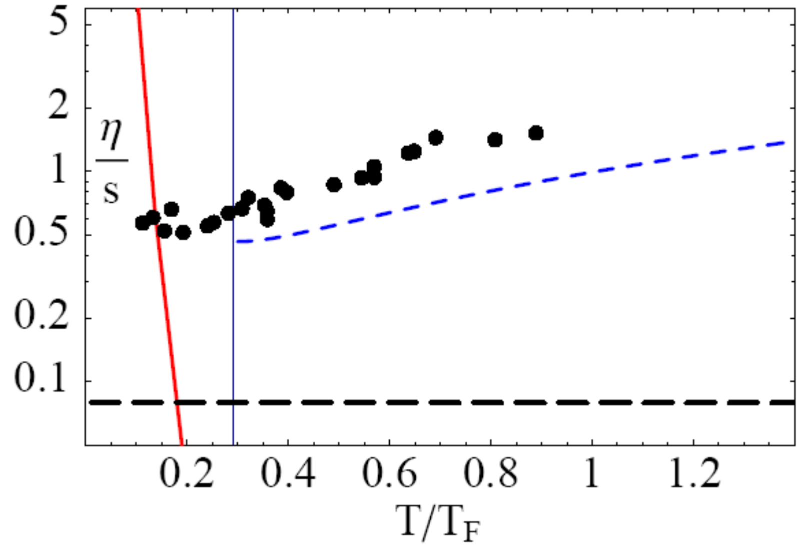
- NR AdS/CFT

Adams, Balasubramanian, McGreevy;
Maldacena, Martelli, Tachikawa;
Herzog, Rangamani, Ross, 2008

d = 2 + 1

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Cold Unitary Atoms



Outlook

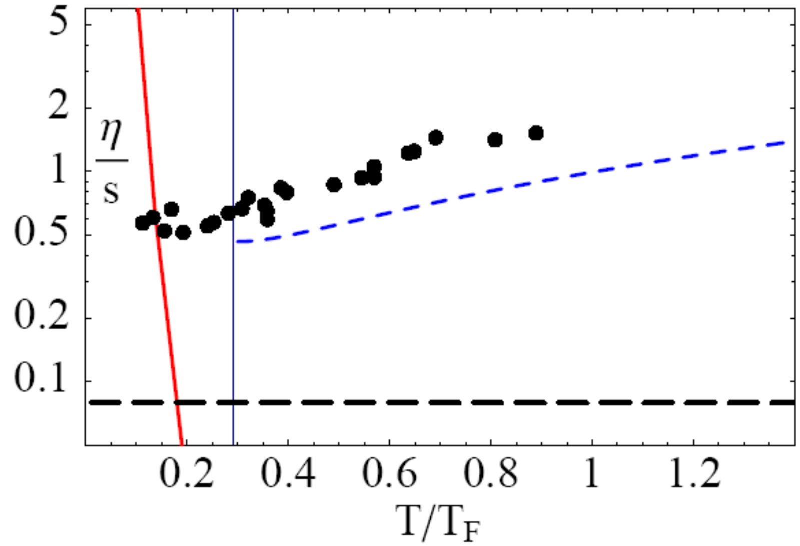
- NR AdS/CFT

Adams, Balasubramanian, McGreevy;
Maldacena, Martelli, Tachikawa;
Herzog, Rangamani, Ross, 2008

d = 2 + 1

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

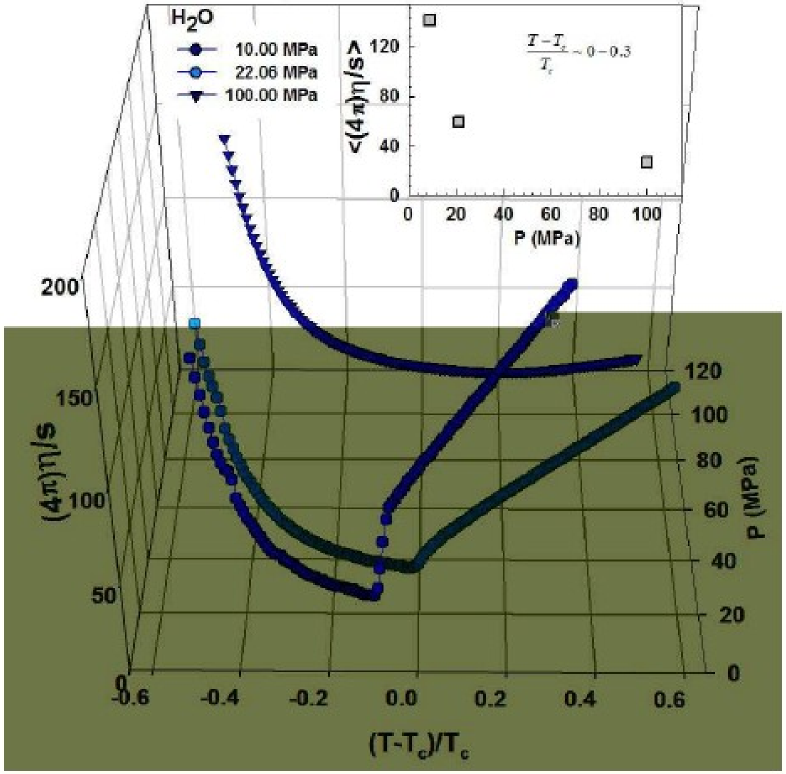
Cold Unitary Atoms



Not for cold atoms at 2+1 d,
where unitary fermi gas is a free gas JWC, Wen, 08

Outlook

η/s just below Tc for YM



$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}a\phi^2 - \frac{1}{4}b\phi^4$$

$$\frac{\eta}{s} \propto e^{\frac{m}{T}}, \; T \to 0$$

$$\frac{\eta}{s} \simeq \frac{k}{b^2}\left(1 + \#\frac{a}{T^2} + \cdots\right), \; T \to \infty$$

$$\# > 0$$

Just one minimum ($a < 0$)?

O(N) model?   Large b?

Invading the bound (I)

$$\mathcal{O}(N)$$

$a = c = 0$ $\eta/s \propto 1/(Nb^2)$

expansion parameter (Nb)

$b \propto 1/N$ $\eta/s \propto N$

w/o flavor changing $\eta/s \propto 1/\ln N$

(KSS; Cohen; Cherman, Cohen, Hohler)