“RHIC Serves a Near-Perfect Fluid”--- a Paradigm Shift

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National Taiwan U.

QCD Phase Diagram

2 *M. Stephanov*

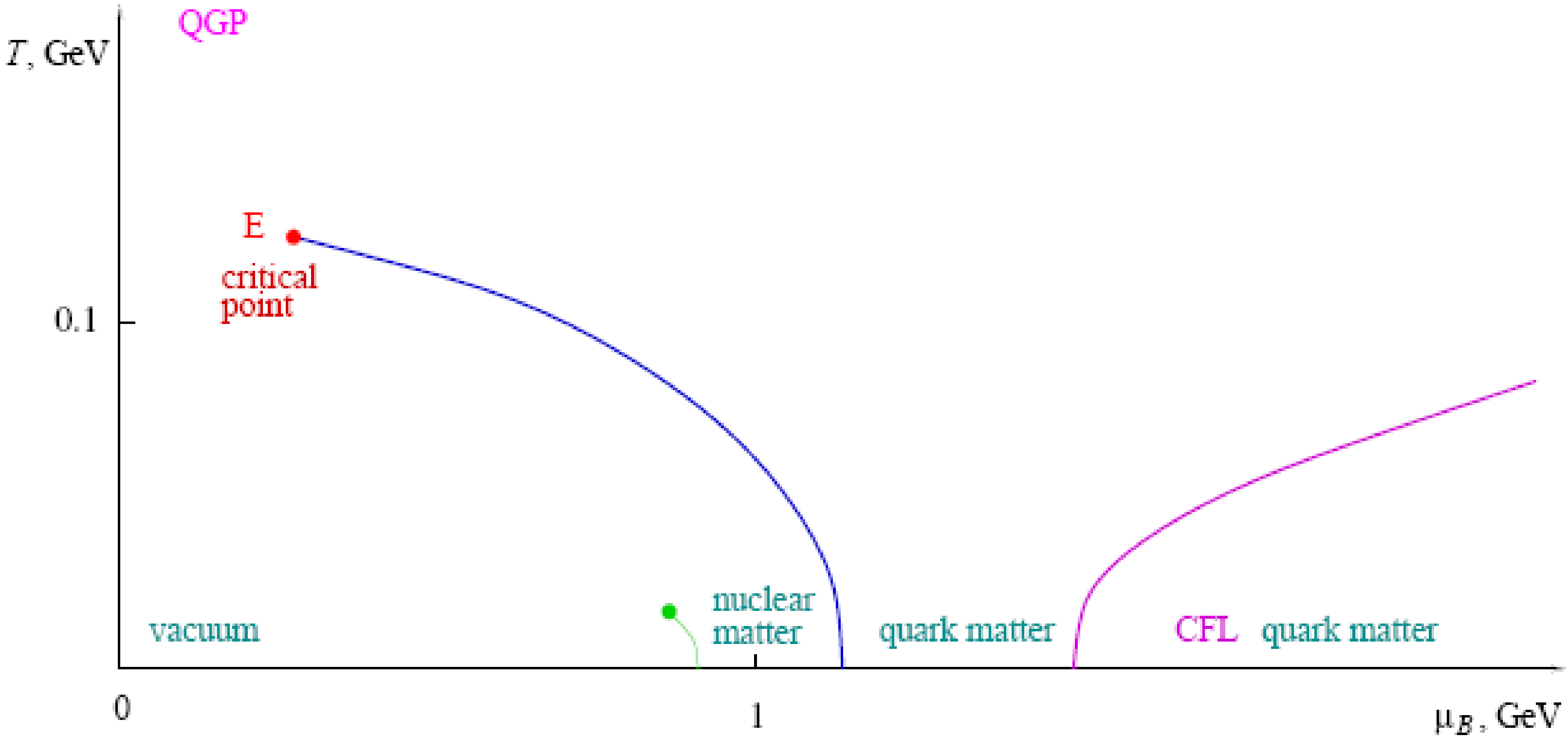
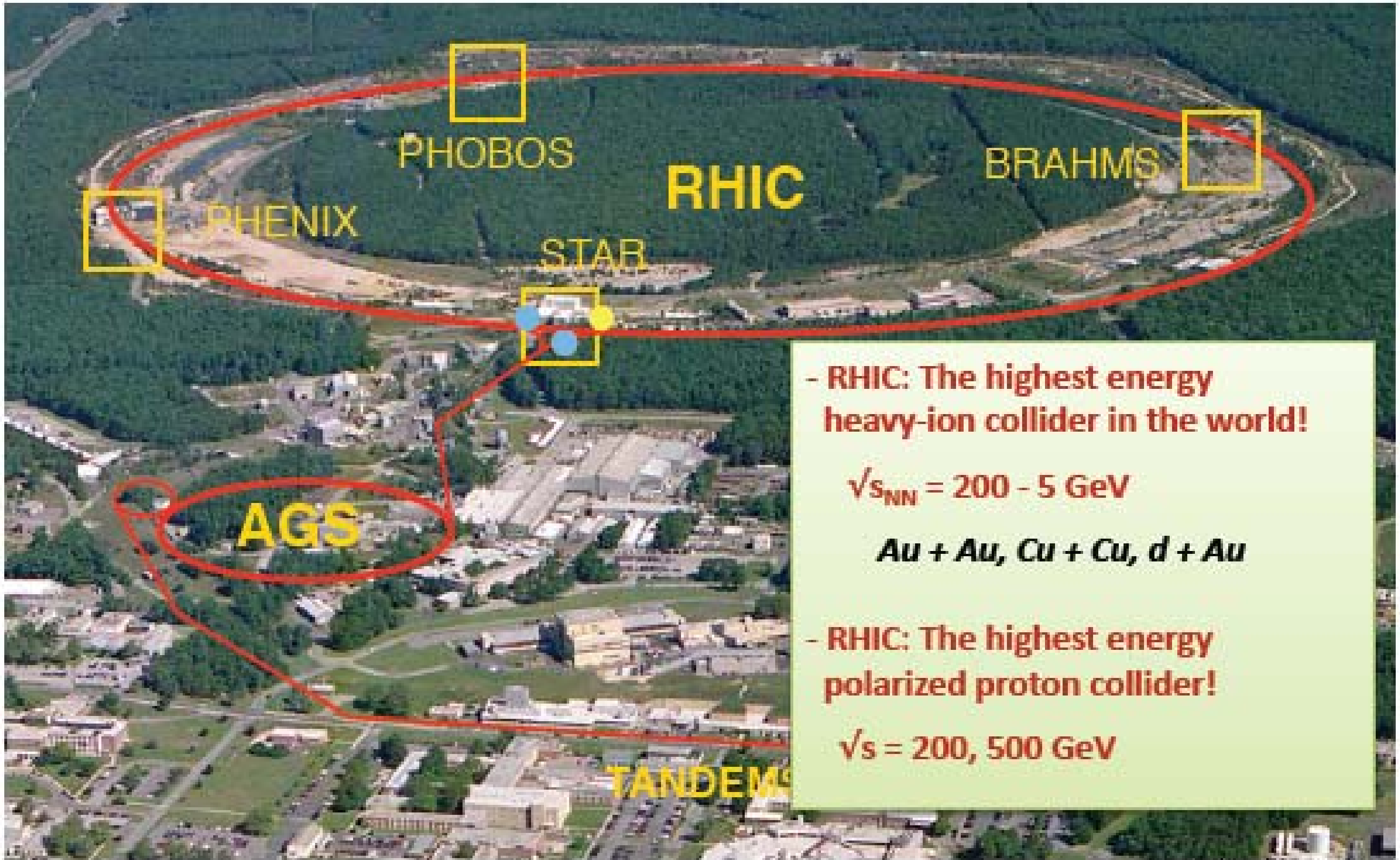


Fig. 1. QCD phase diagram

Relativistic **H**eavy **I**on **C**ollider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The highest energy heavy-ion collider in the world!

  $\sqrt{s_{NN}}$ = 200 - 5 GeV

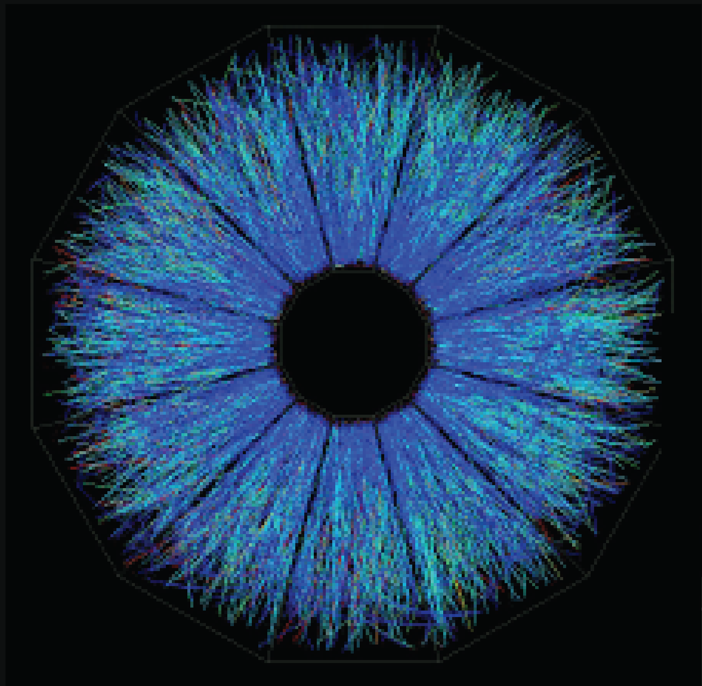
  Au + Au, Cu + Cu, d + Au

- RHIC: The highest energy polarized proton collider!

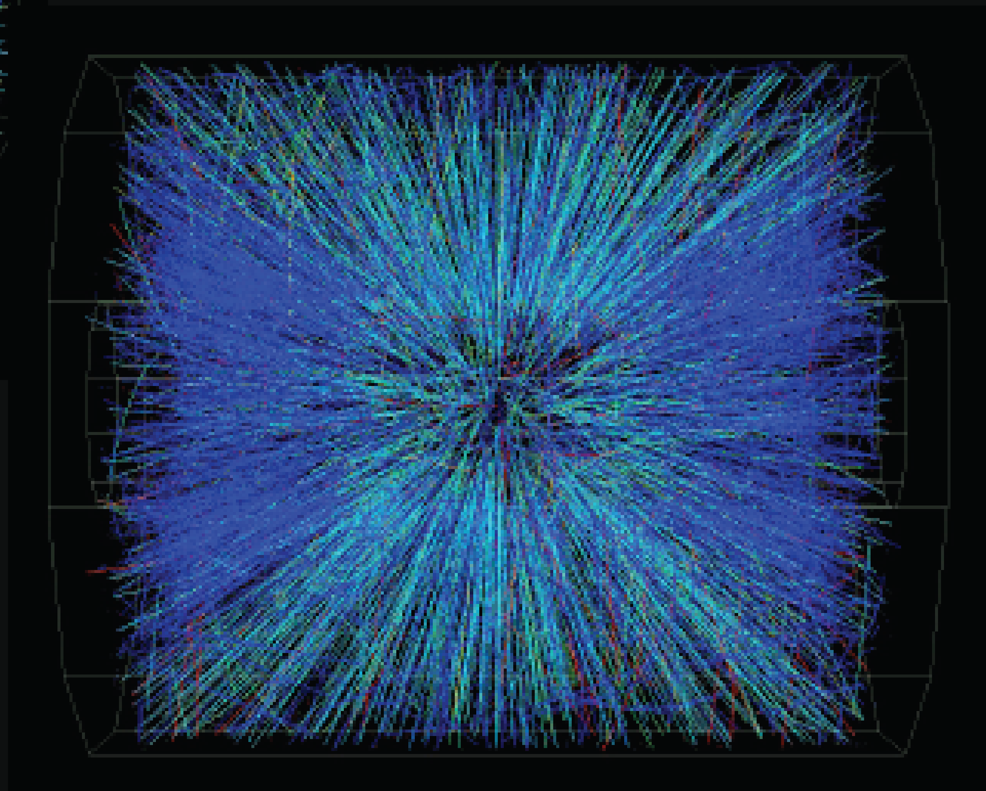
  $\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

Au + Au Collisions at RHIC



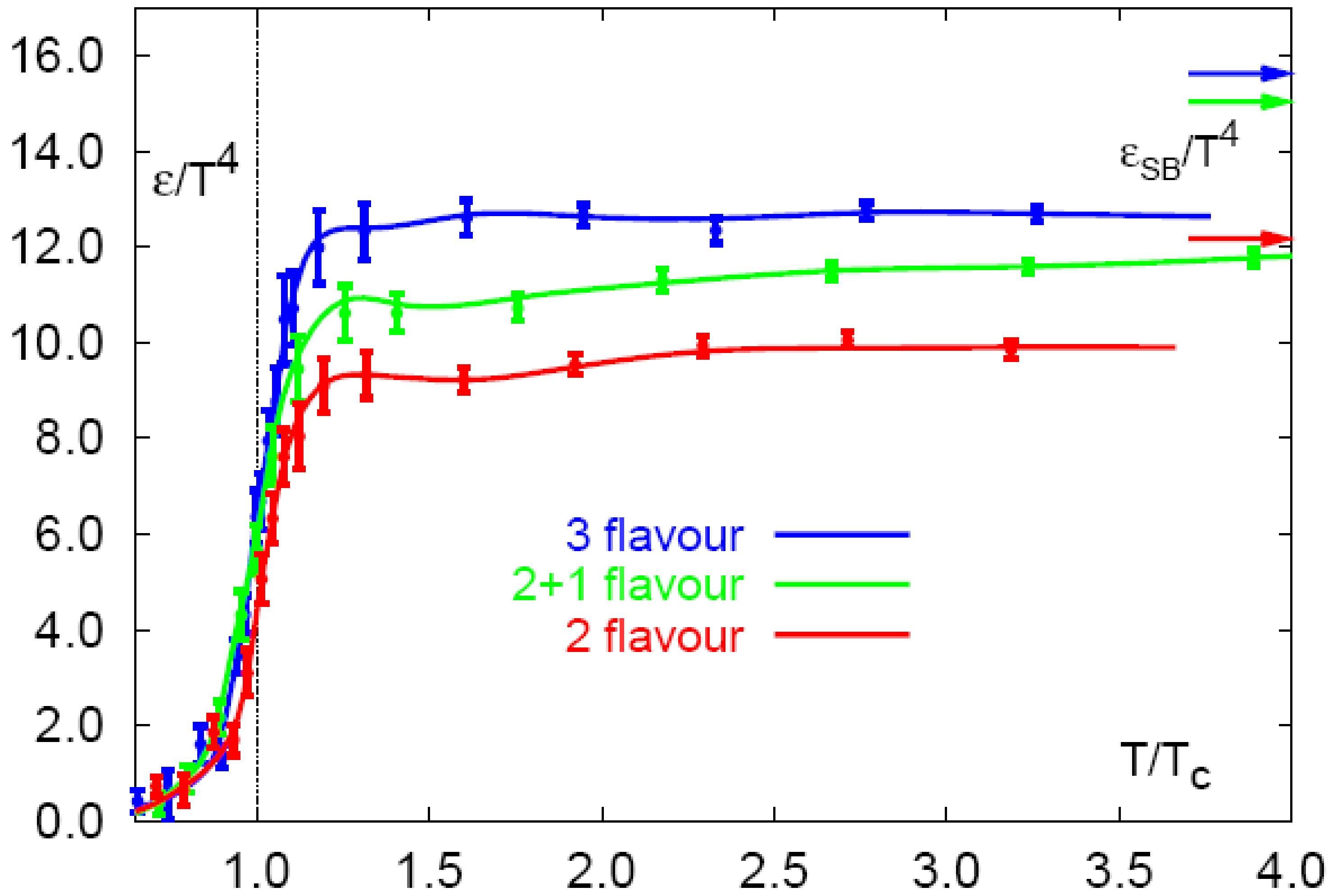
Central Event



STAR

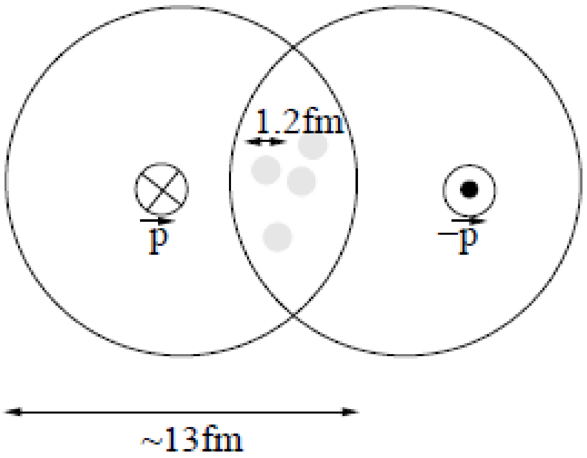
(real-time Level 3)

QGP EOS (LQCD) ~ an ideal gas



Karsch hep-lat/0106019

Elliptic Flow: QGP ~ a perfect fluid



$$\frac{\eta}{s} = 0.1 \pm 0.1(\mathrm{th}) \pm 0.08(\mathrm{exp})$$

Luzum, Romatschke, 2008

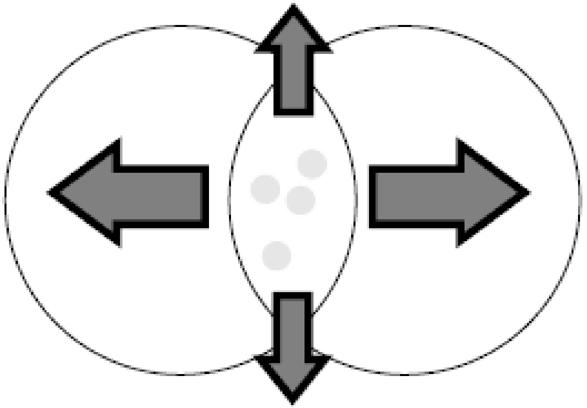
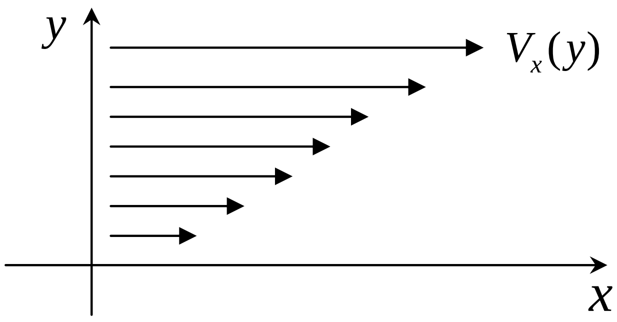


Figure: H. Meyer

A Paradigm shift!

- Shear viscosity



Frictional force

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

Shear viscosity measures

how “perfect” a fluid is!

- Kovtun, Son, and Starinets ('05)

  Conjecture: Shear viscosity / entropy density

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

- Motivated by AdS/CFT

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

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

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

- "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

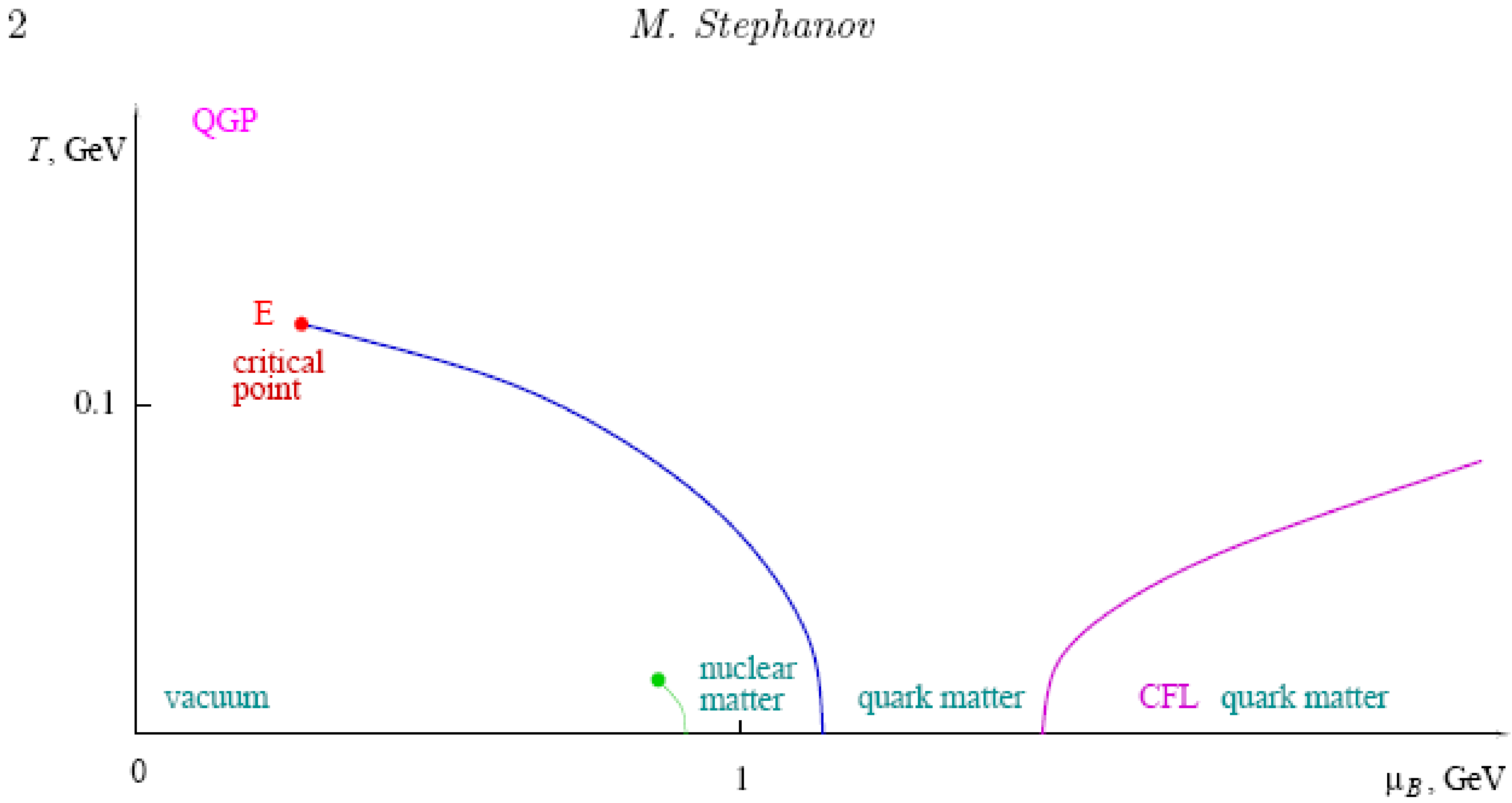


Fig. 1. QCD phase diagram

η/s of QCD below T_c

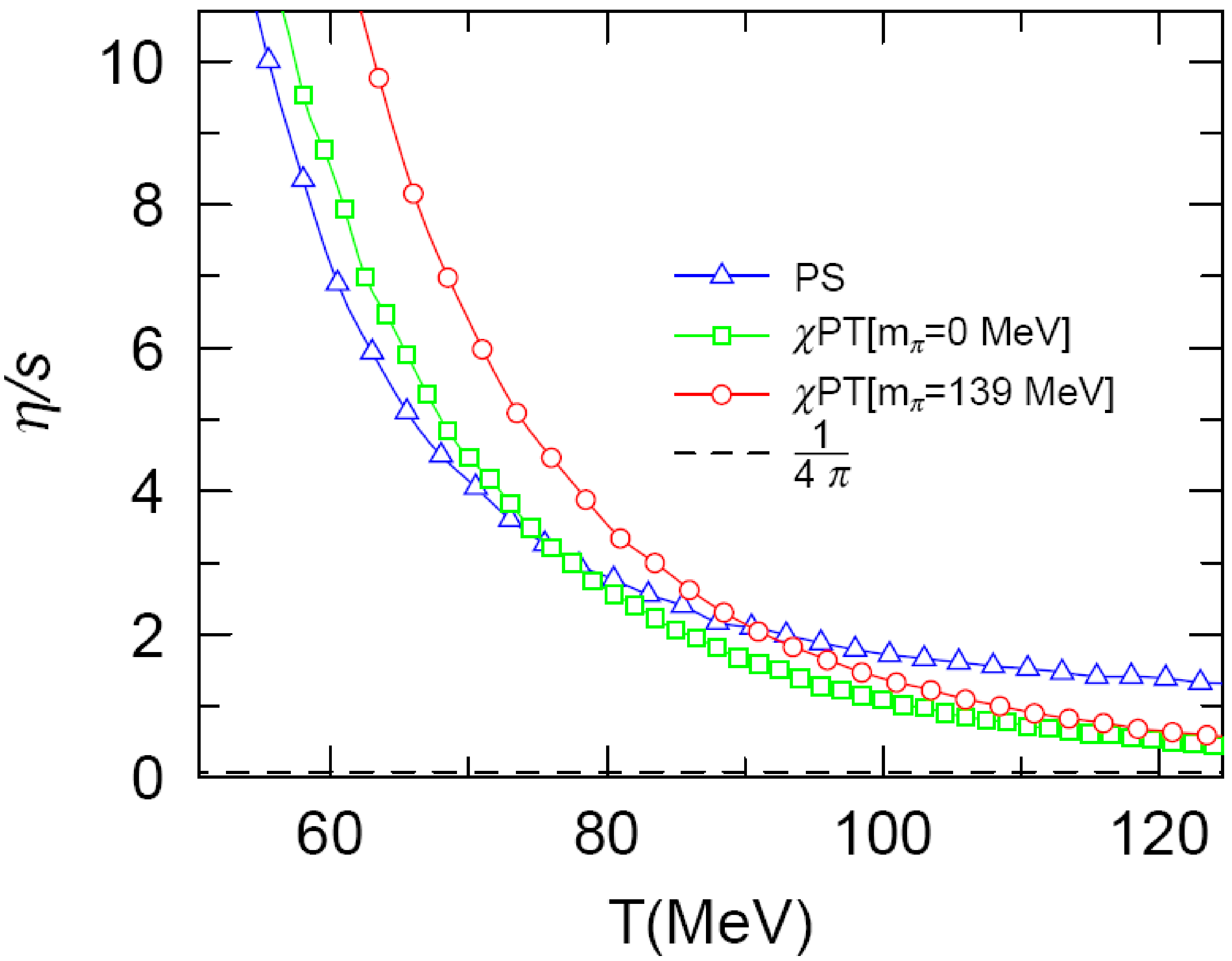
- Pion gas ⟹ ChPT (chiral perturbation theory)
- Non-perturbative in coupling

  ⟹ 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

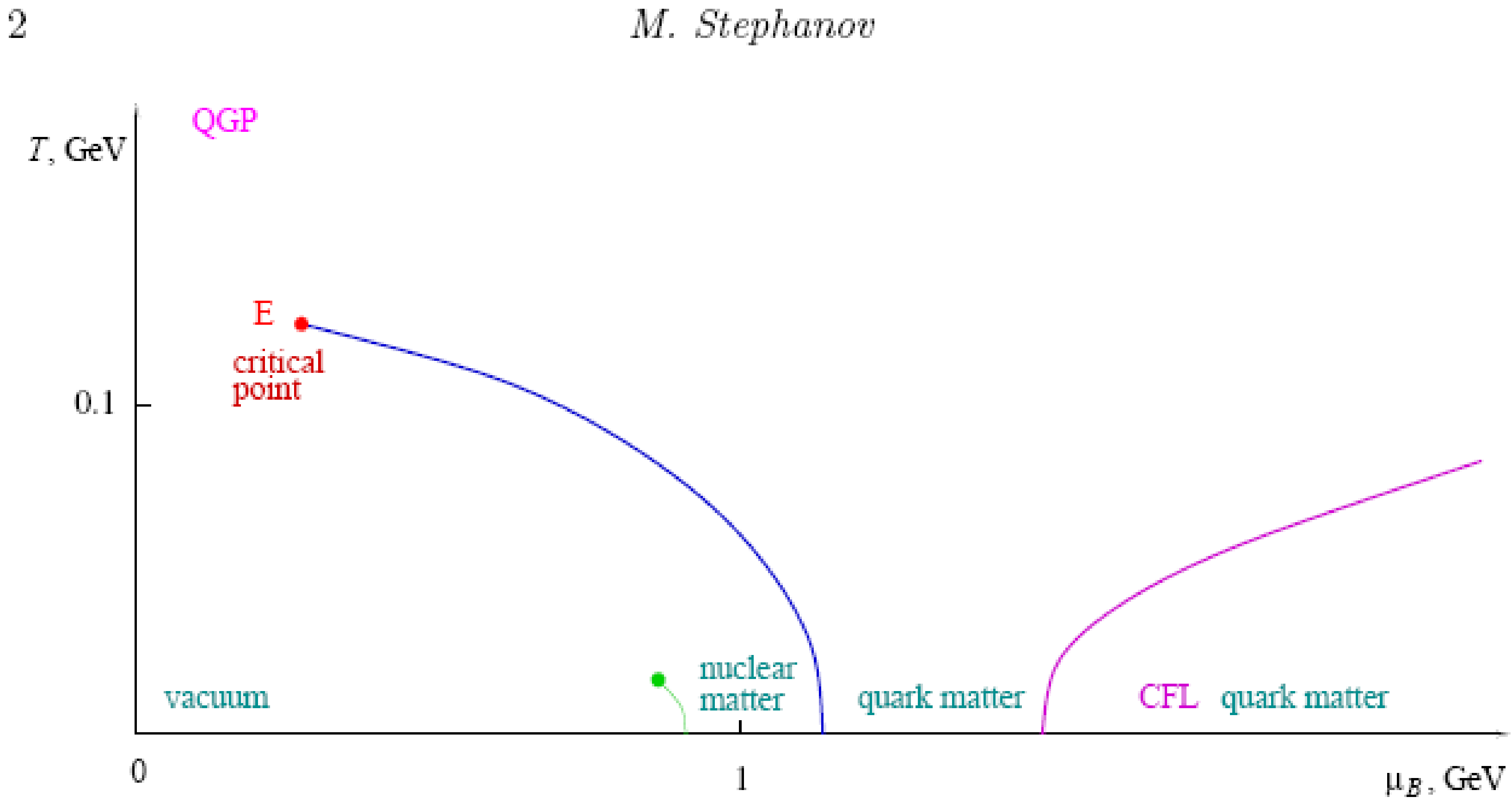
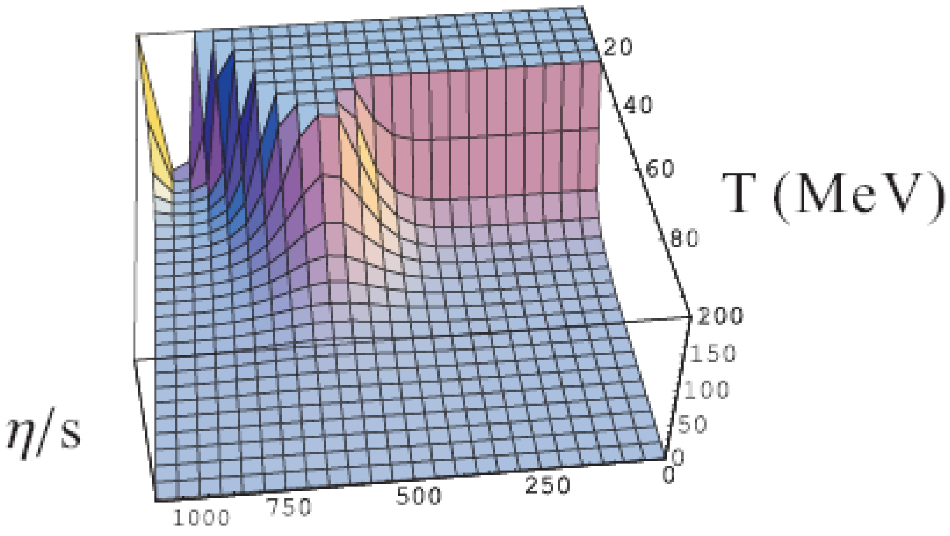
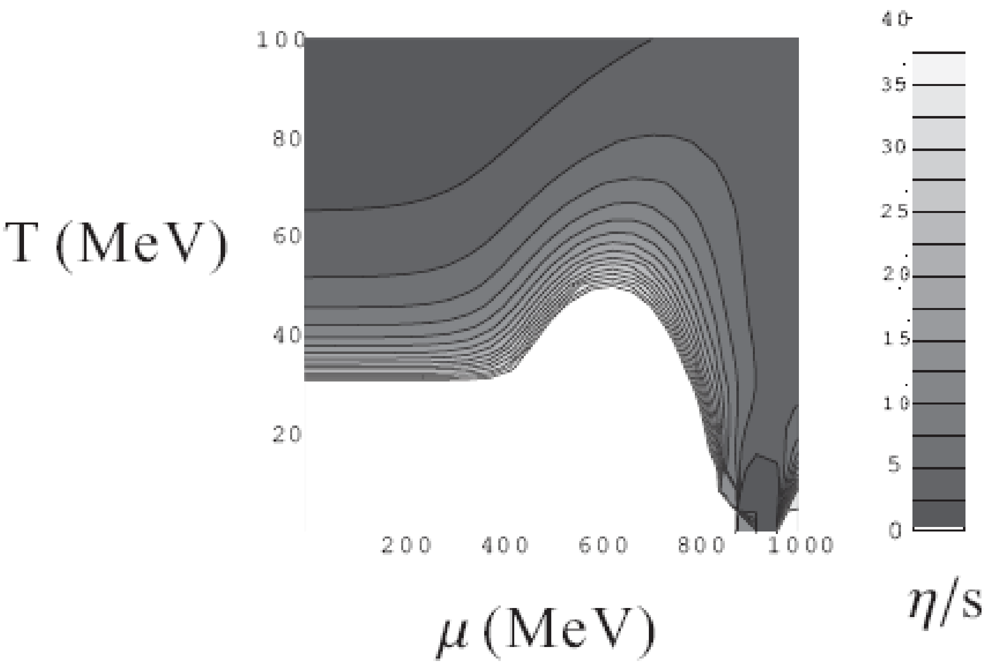


Fig. 1. QCD phase diagram

The η/s "Landscape"

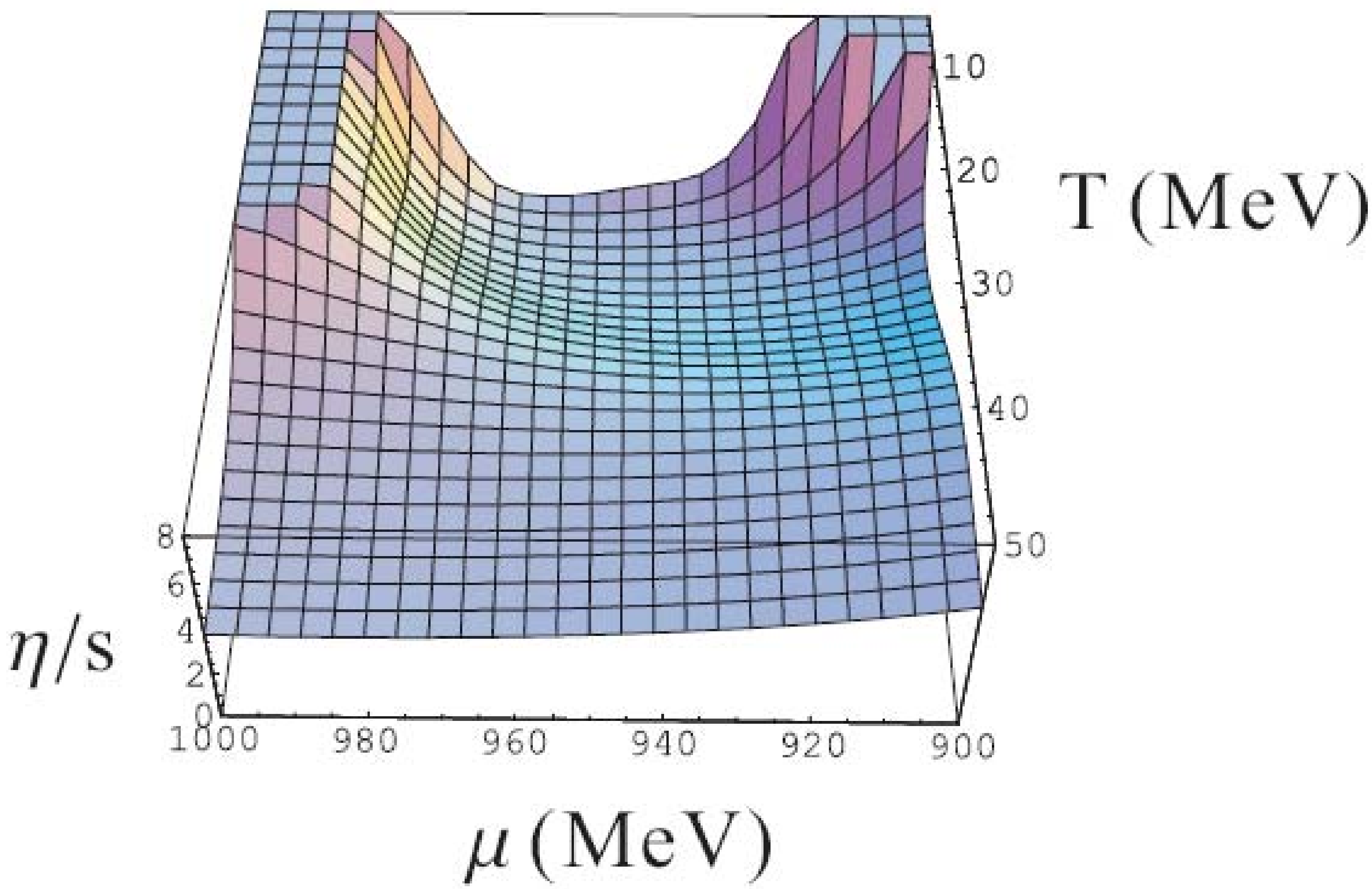


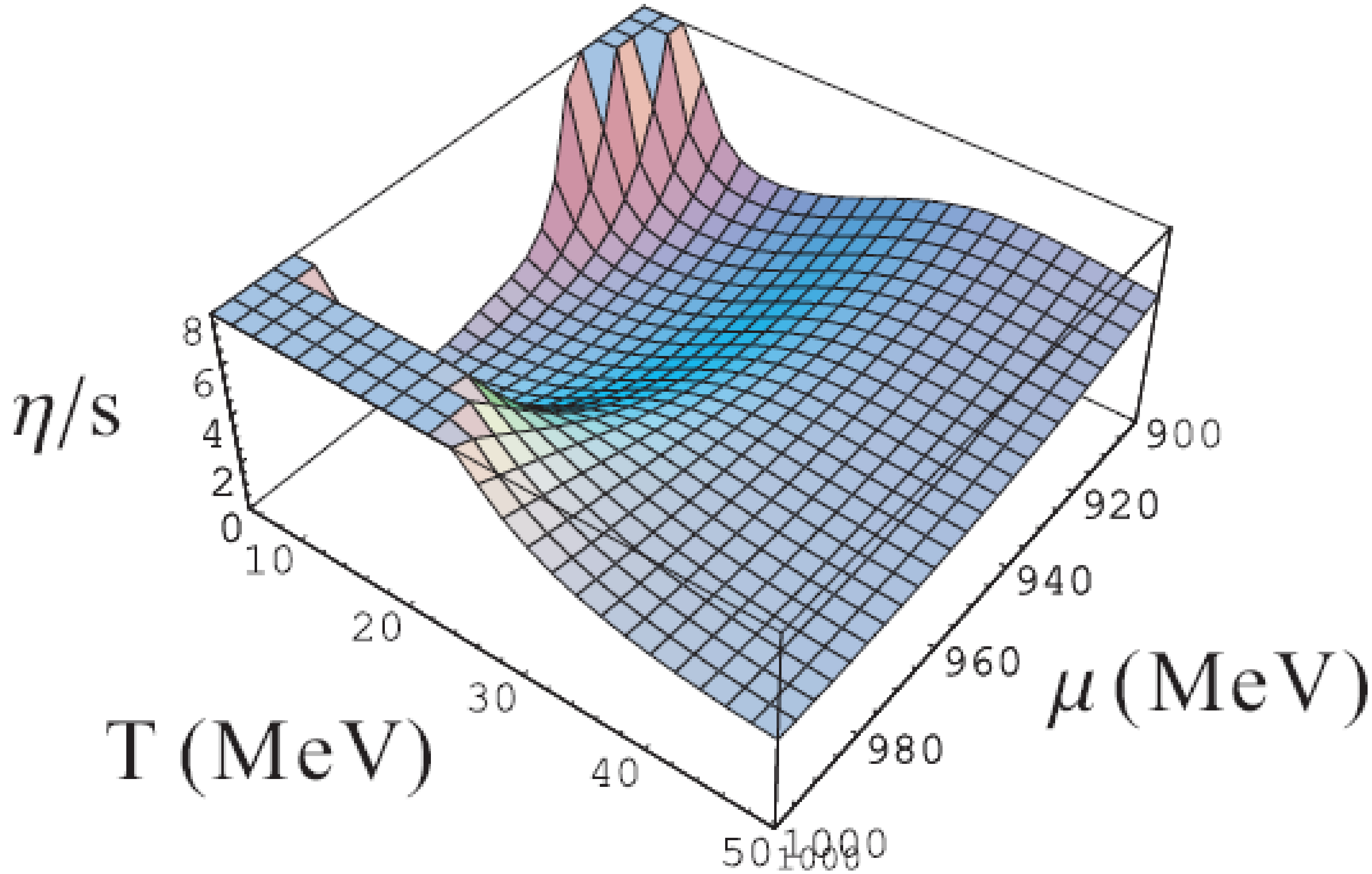
JWC, Li, Liu, Nakano; Itakura , Morimatsu, Otomo



The η/s "Landscape"

JWC, Li, Liu, Nakano





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

QCD Phase Diagram

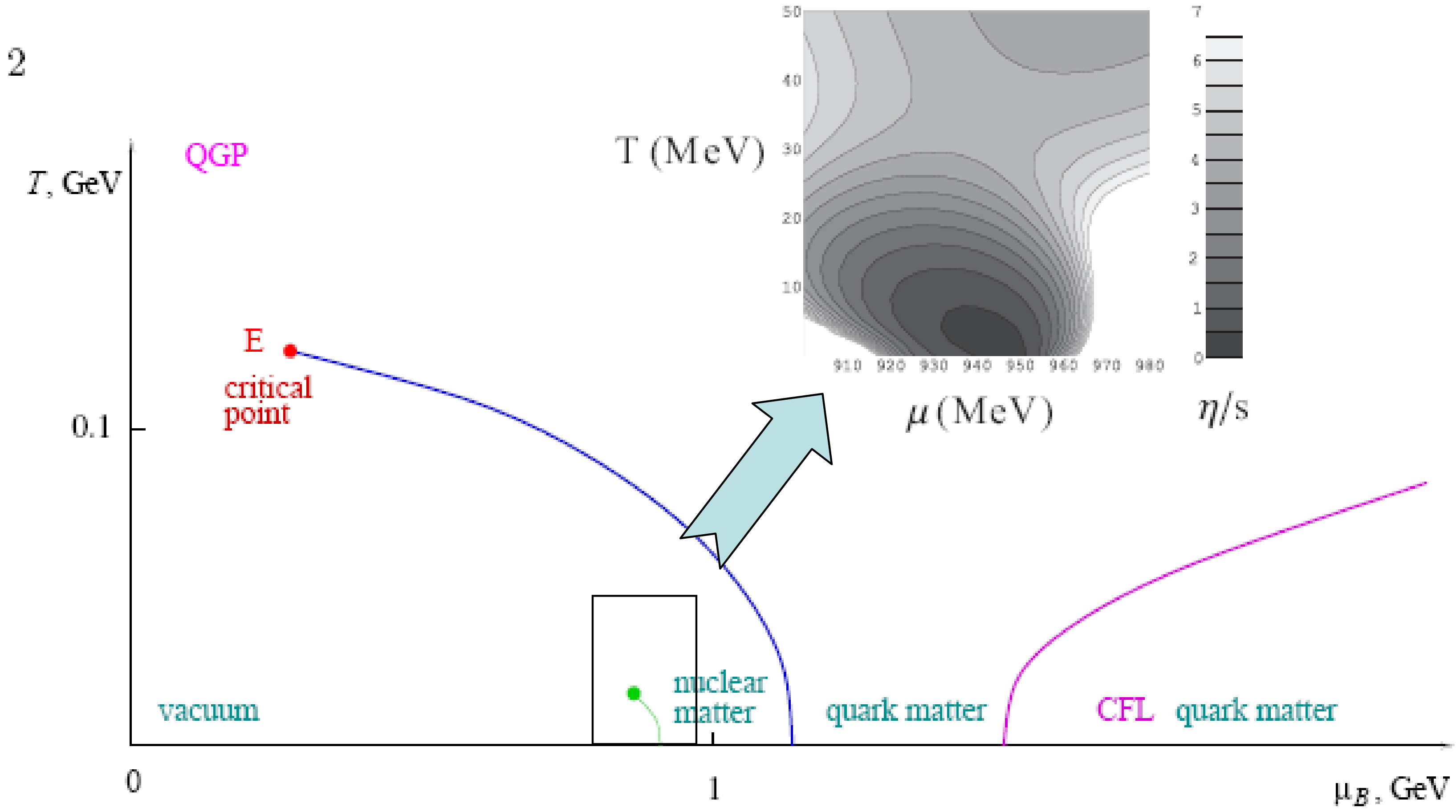
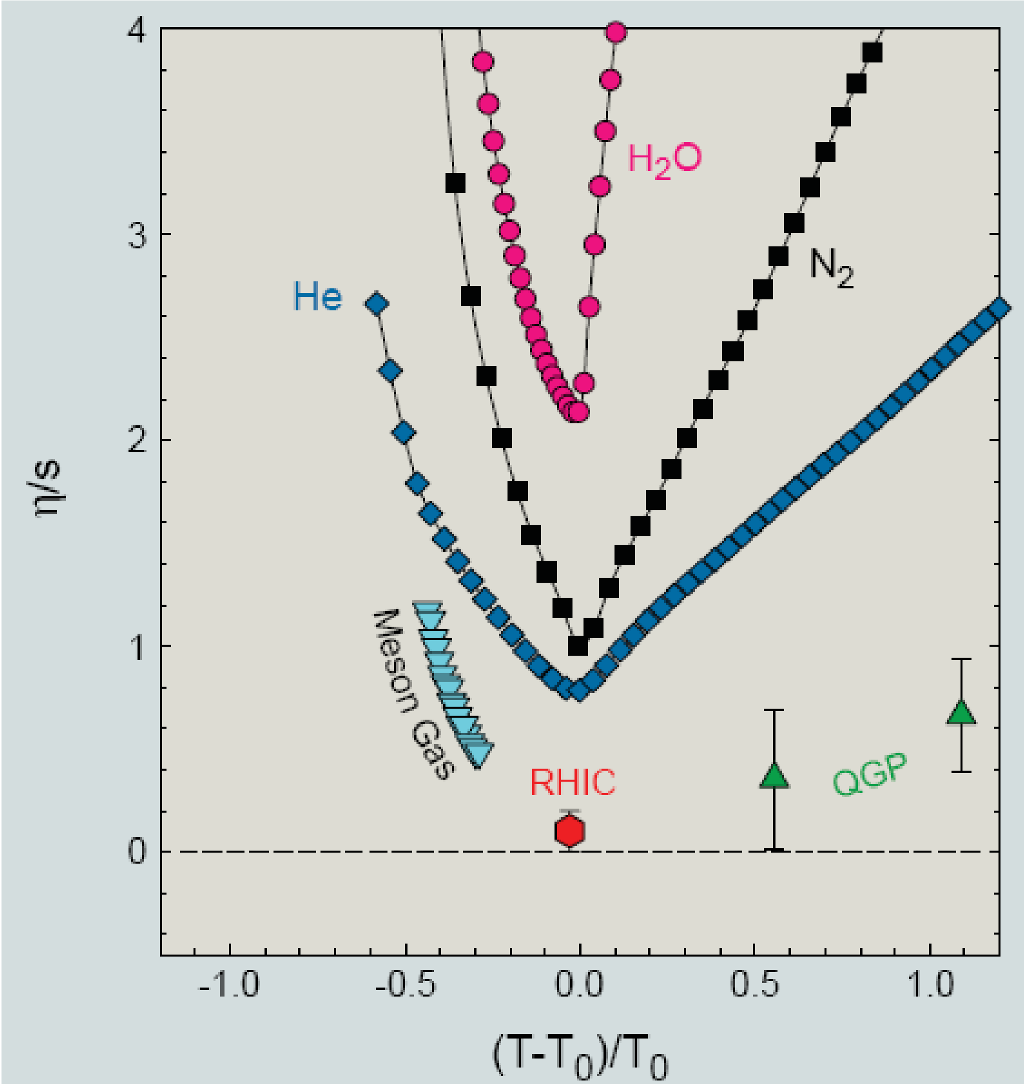


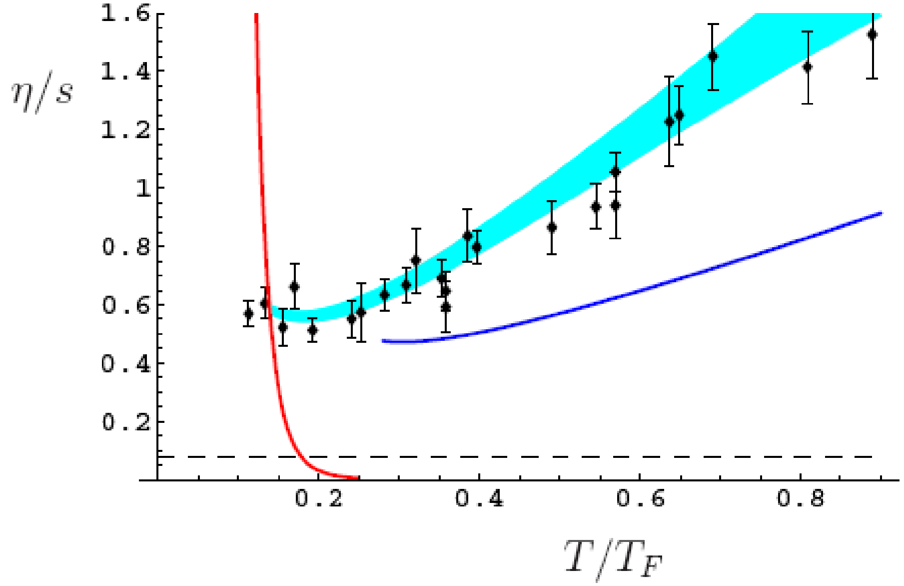
Fig. 1. QCD phase diagram

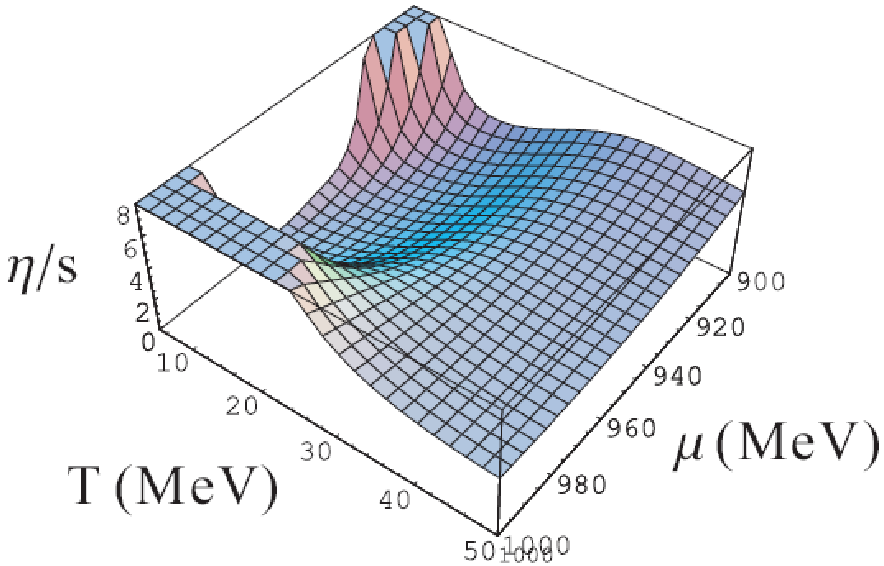


Lacey et al., PRL 98:092301,2007; 2007 US Nuclear Science Long Range Plan

Cold Unitary Atoms

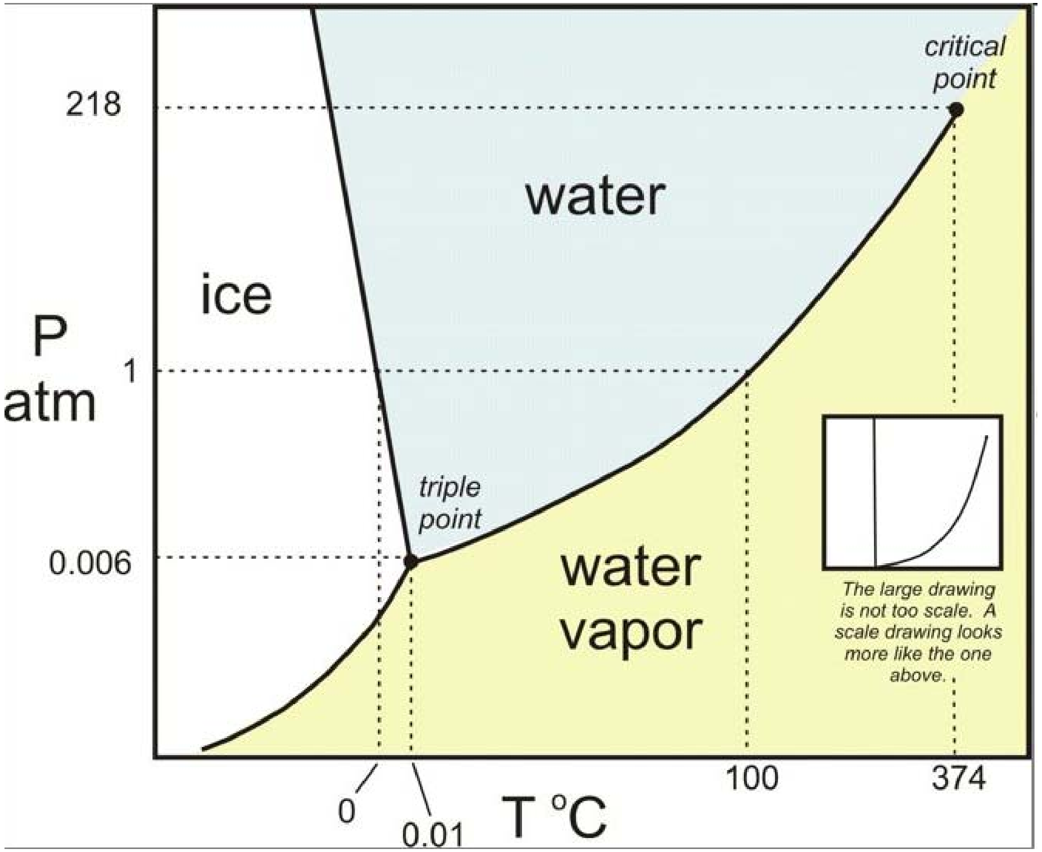
Rupak & Schafer 2007

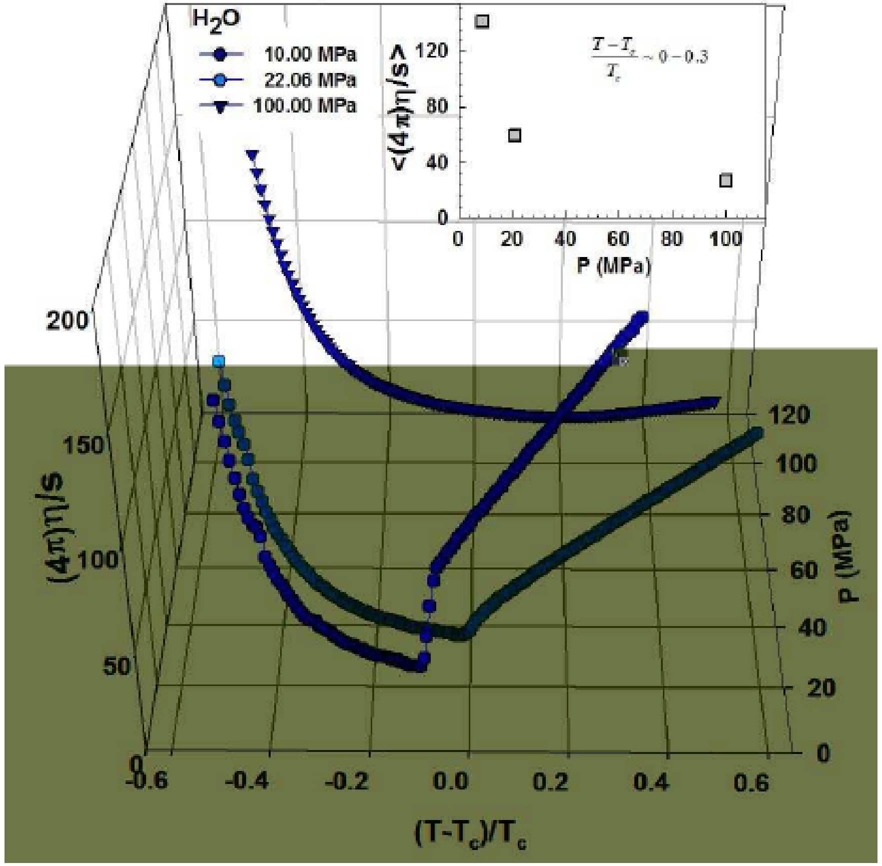




Water P-T Phase Diagram

η/s of Water

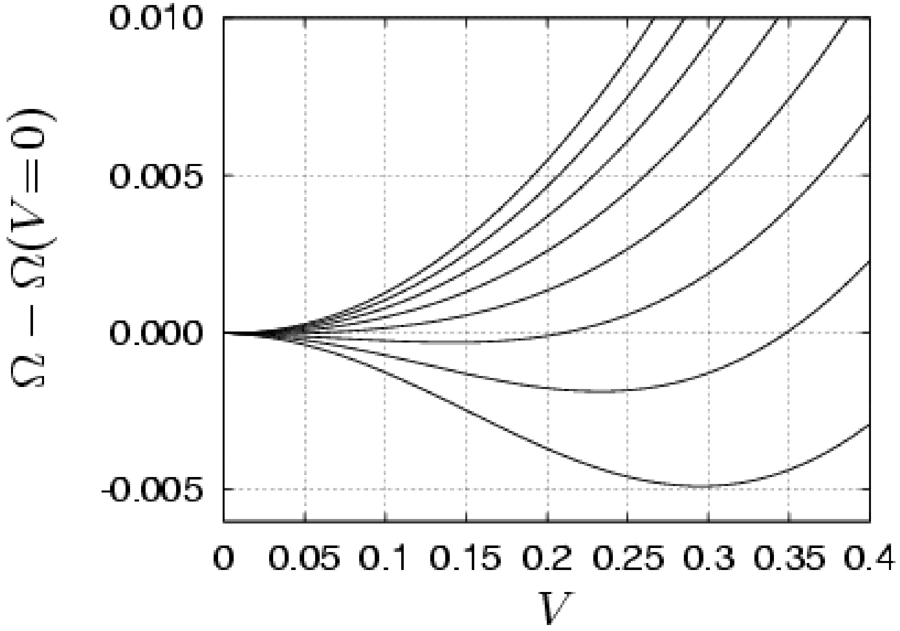


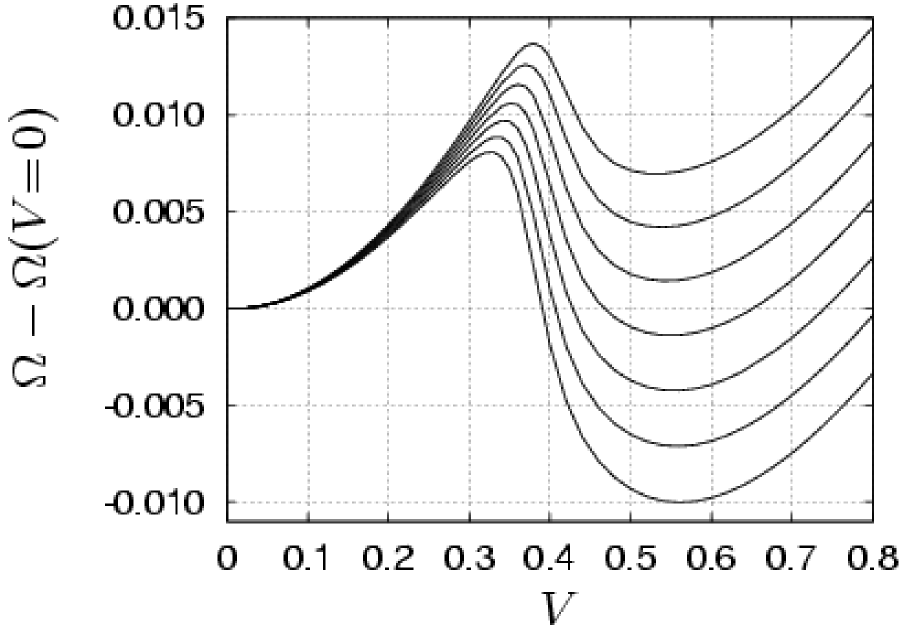


(Lacey et al.)

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

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



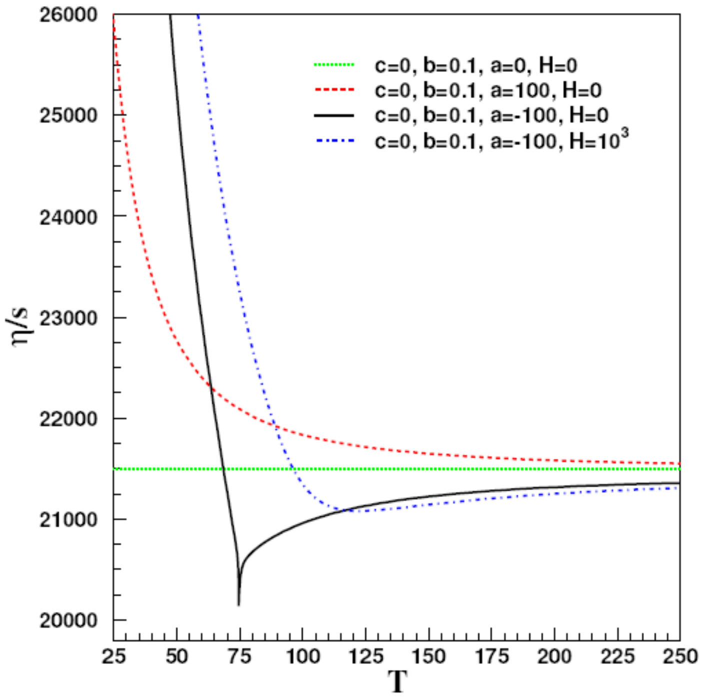


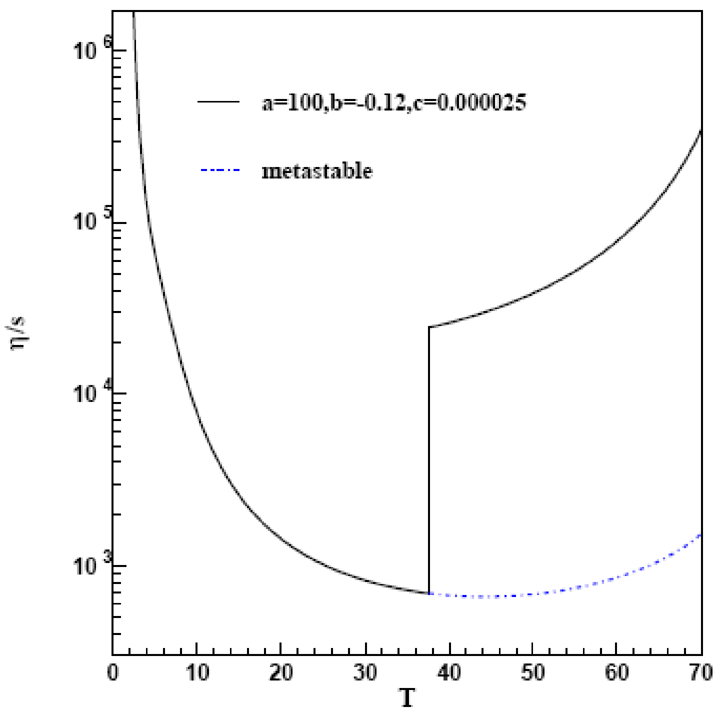
2nd-order p.t.:
a < 0, b > 0, c = 0
crossover: + $\delta\mathcal{L} = H\phi$
No p.t.: a > 0, b > 0, c = 0

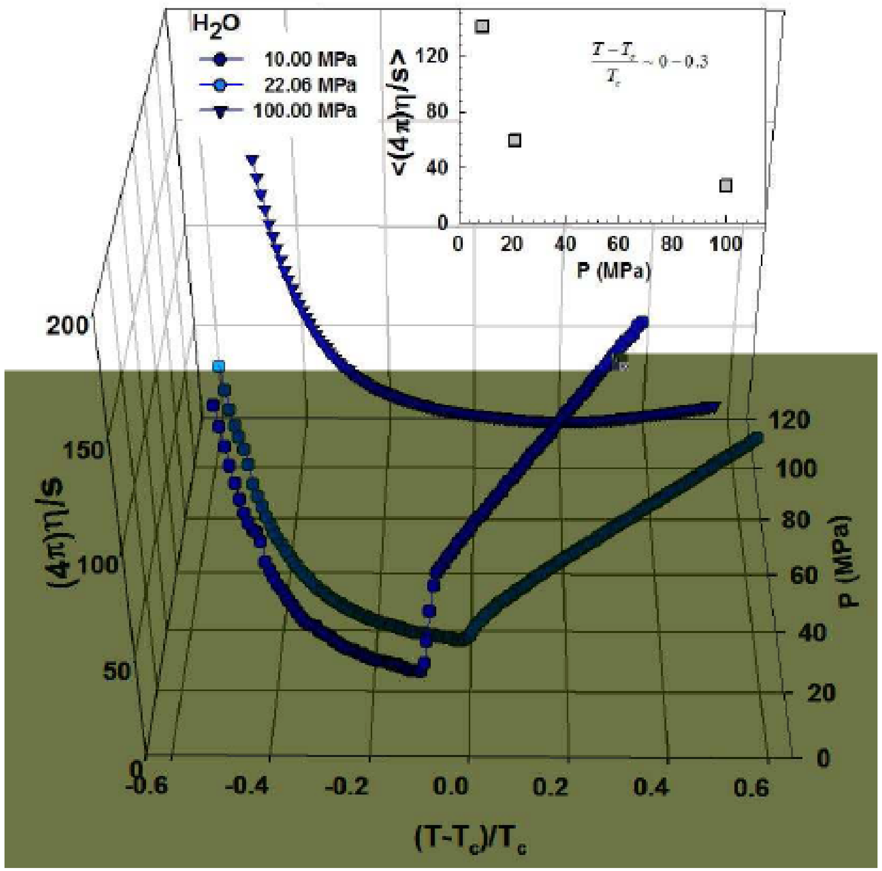
1st-order phase transition
a > 0, b < 0, c > 0

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

η/s of Water



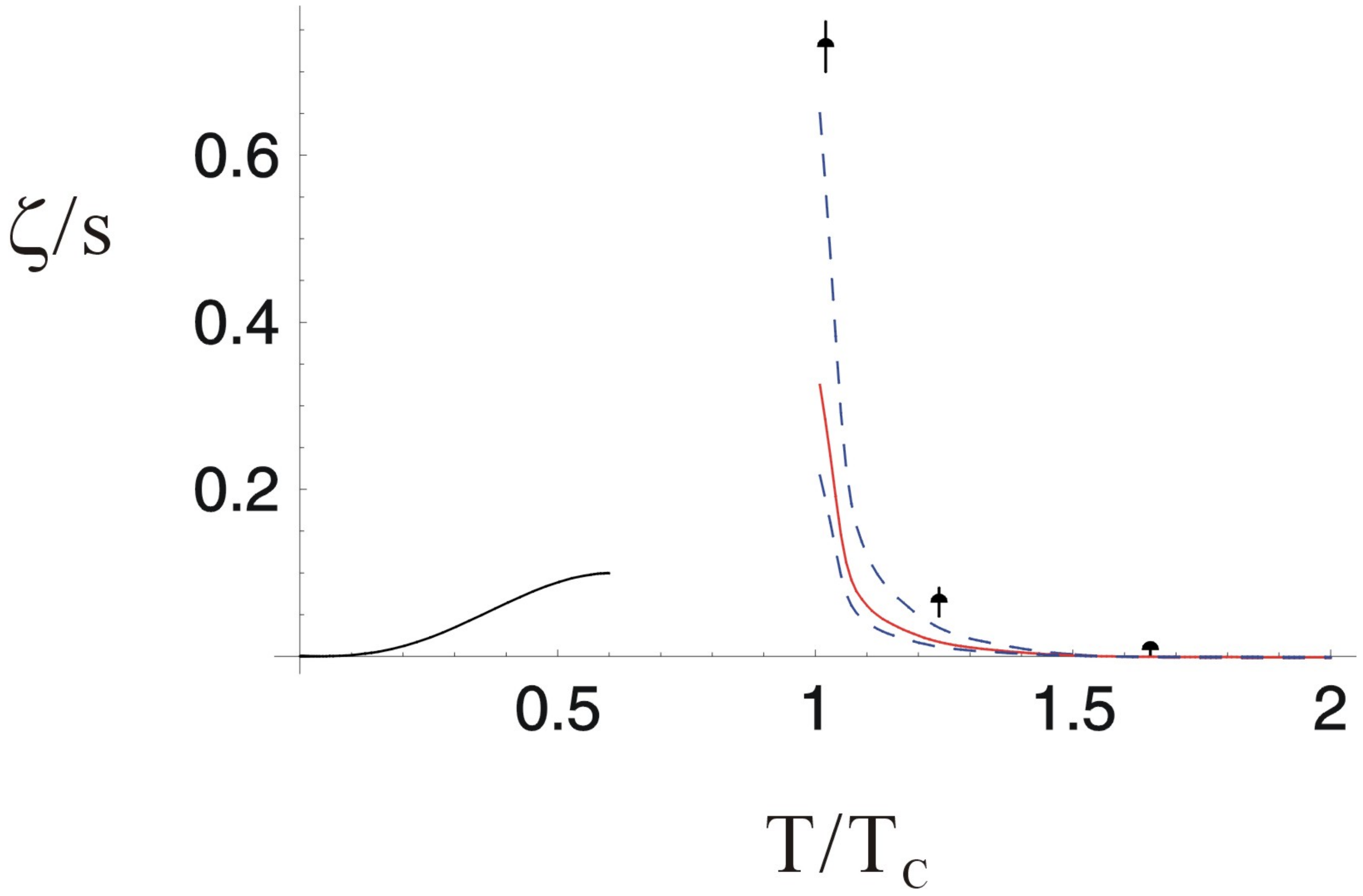




(Lacey et al.)

QCD Bulk Viscosity (Chiral Limit)

Karsch, Kharzeev, Tuchin;
Meyer; JWC, Wang



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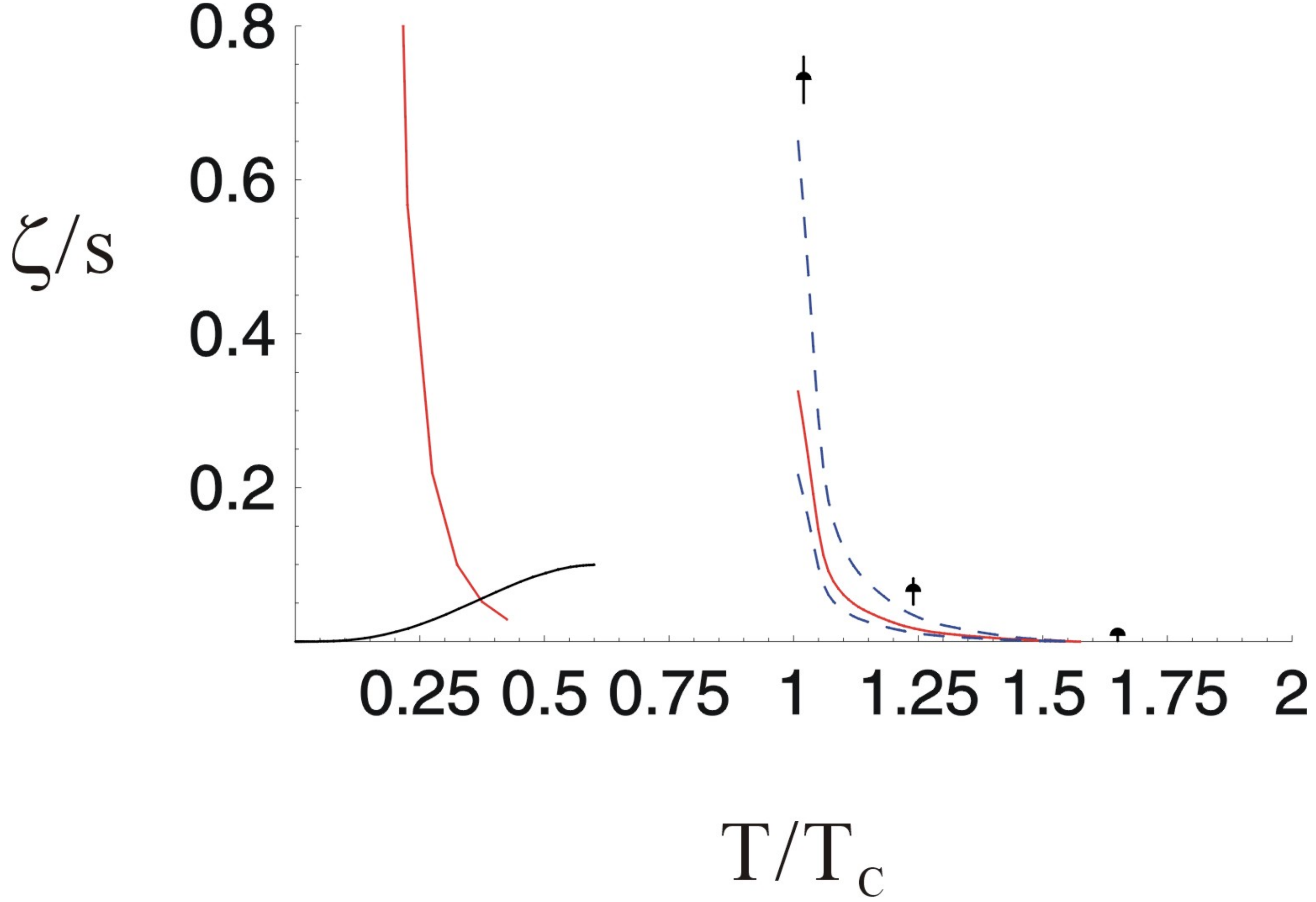
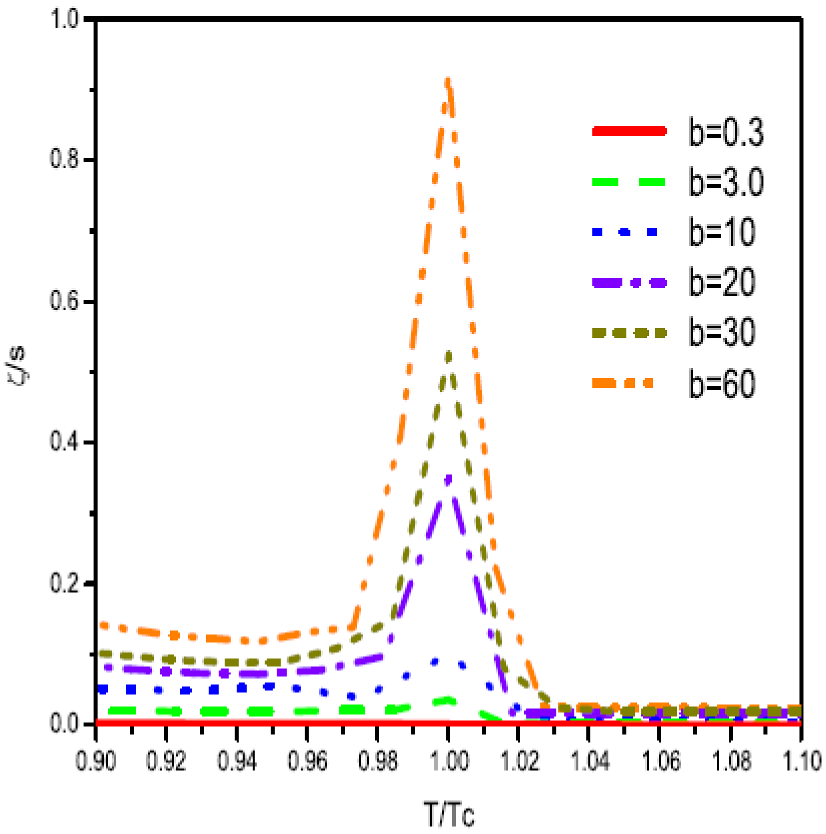
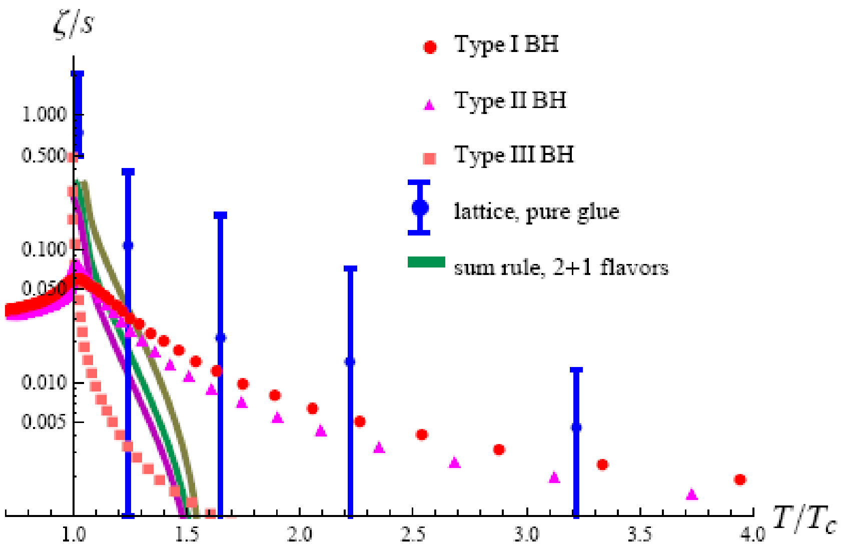


Bulk Viscosity





Gubser, Nellore, Pufu, Rocha

Li, Huang

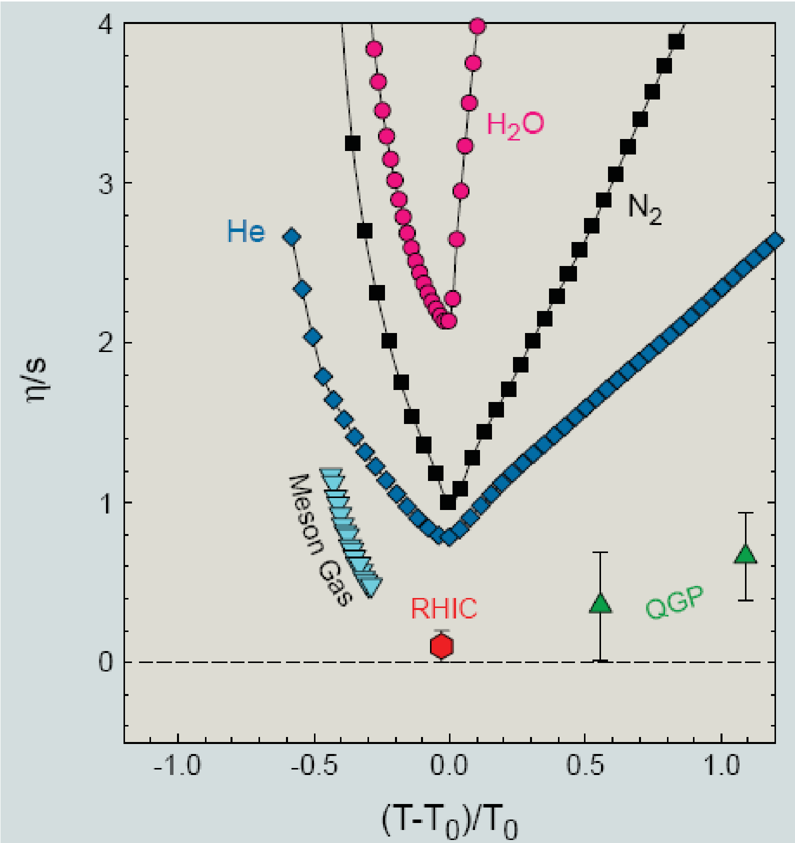
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

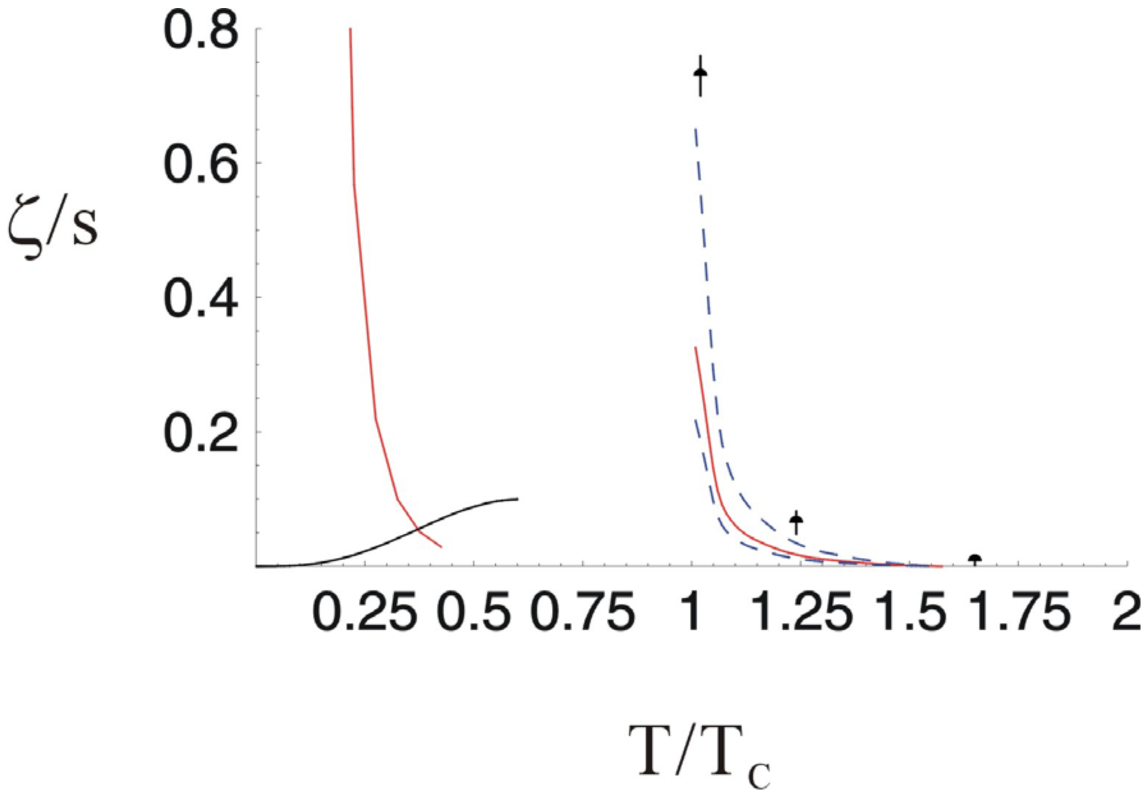
Outlook I: Universality?

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 ?

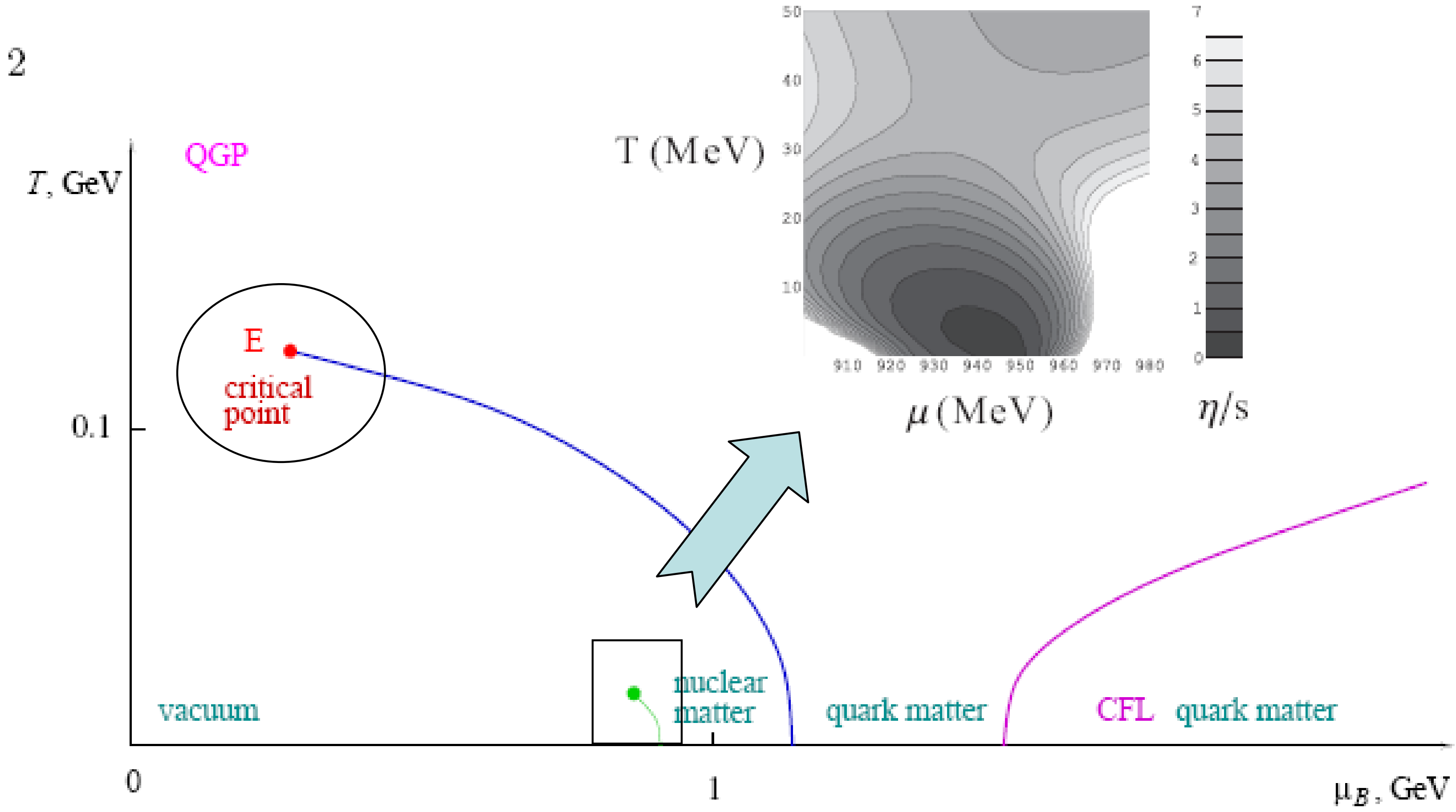


Fig. 1. QCD phase diagram

Locating critical end point (Lacey)

Outlook II: Invading the Bound

Go metastable (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

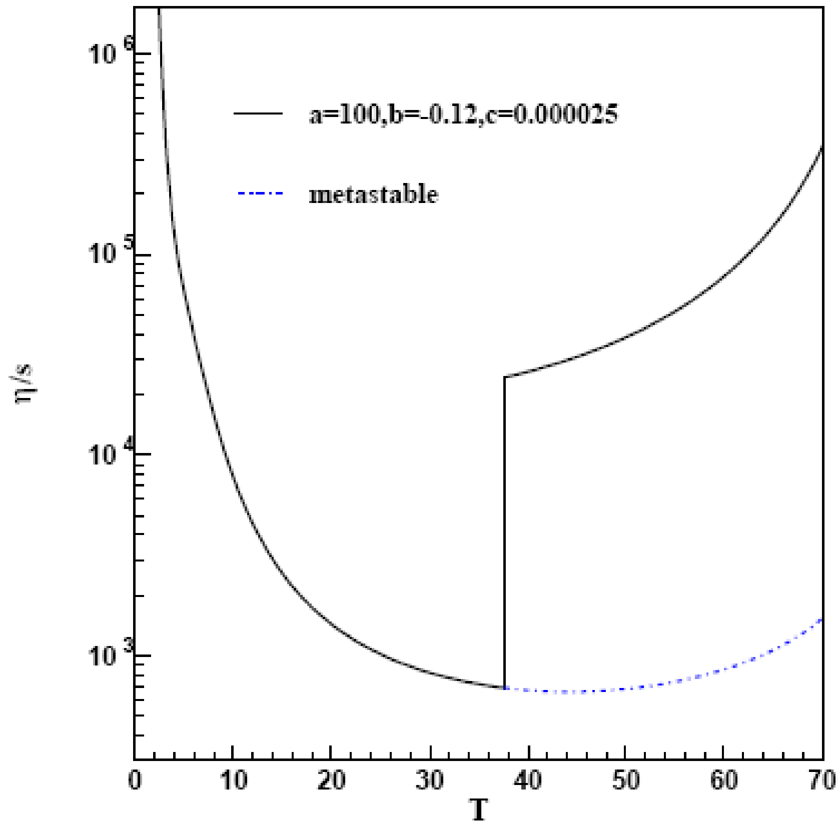
Invading the bound

$Q\overline{q}$

N_Q

m_Q

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



UV complete but metastable

Go Finite N

- 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 III: Cold Atoms

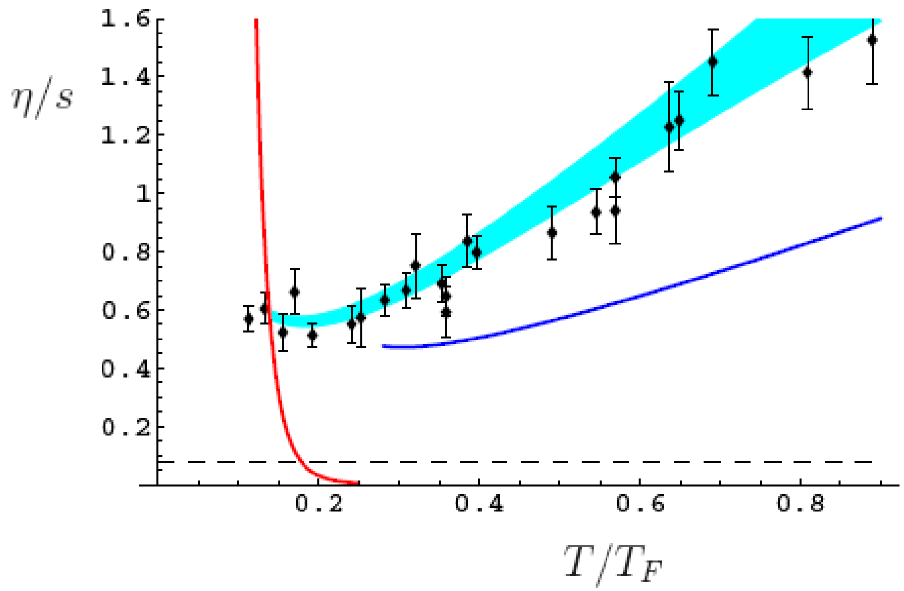
- NR AdS/CFT

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

d = 2 + 1

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

Cold Unitary Atoms



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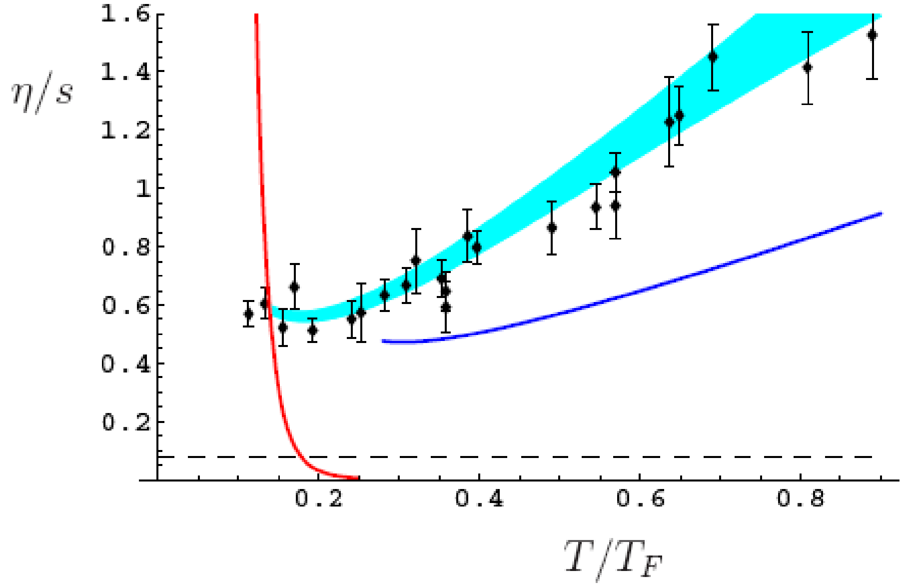
Cold Unitary Atoms



Not for cold atoms at 2+1 d,

where unitary fermi gas is a free gas JWC, Wen, 08

- 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)
- Gluon Plasma (w/ Kazuaki Ohnishi, Hui Dong, Qun Wang) Anion (w/ Shu-Ping Lee)

How do we distinguish different phases?

- thermodynamics: different equations of state
  - but often qualitatively different phases have numerically close equations of state. Examples:
  - strongly coupled and weakly coupled $\mathcal{N} = 4$ SYM: $s_{\lambda=\infty}/s_{\lambda=0} = 3/4$ (AdS/CFT methods)
  - large baryon density: nuclear matter and quark matter can have similar EoS

- transport coefficients: perturb the system slightly, let it relax to equilibrium
  - viscosity, heat conductivity, diffusion constants
  - in $\mathcal{N} = 4$ SYM, $(\eta/s)_{\lambda=\infty} = 1/4\pi$ vs. $(\eta/s)_{\lambda=0} = \infty$
  - $(\eta/s)_{CFL} \ll (\eta/s)_{nucl.\ matt.}$