THE ENIGMA OF THE PERFECT FLUID - QUARK GLUON PLASMA

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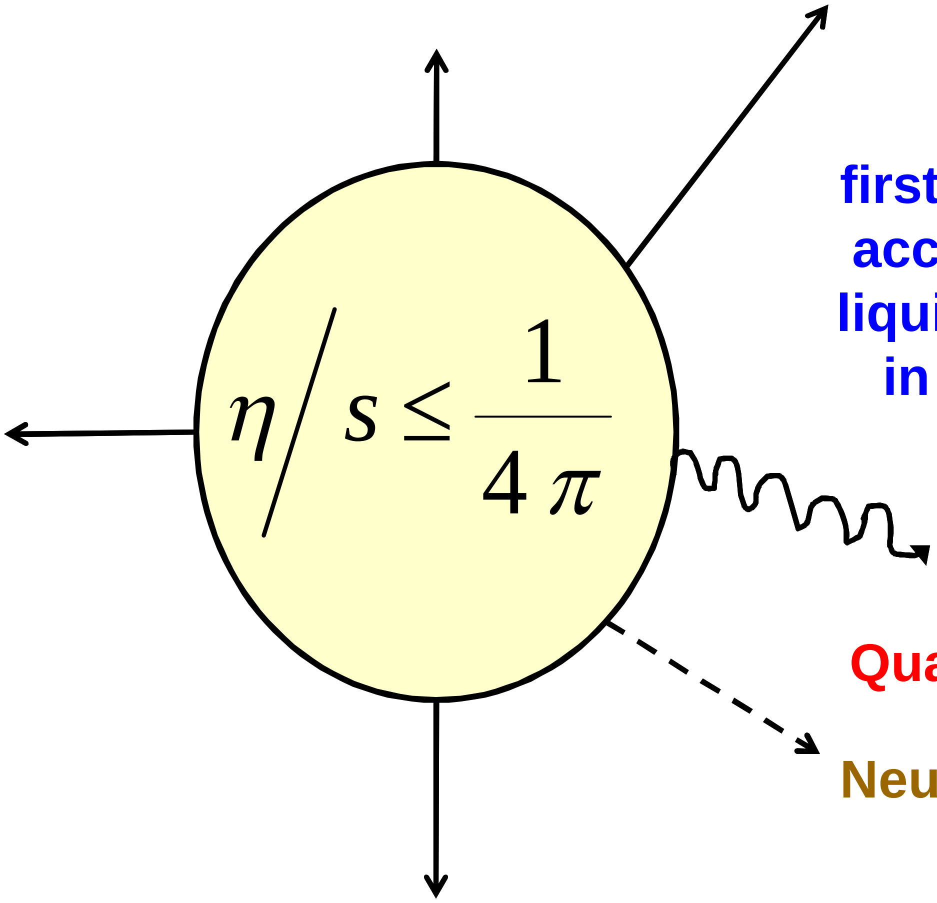
Moscow, May 28 –June 1, 2012

IMPORTANT DISCOVERY

Universality of $\eta / s = 1 / 4\pi$

Strong coupling behaviour of conformal gauge theories, Kovtun, Son and Starinetes (KSS bound)

η/s Saga



$$\eta/s \le \frac{1}{4\pi}$$

Ultra Cold
Quantum degenerate,
strongly interacting
Atomic Fermi Gas

RHIC, Flow, QGP
PERFECT Fluid

LHC ?

first experimentally accessible perfect liquid even isolated in the laboratory

Graphene

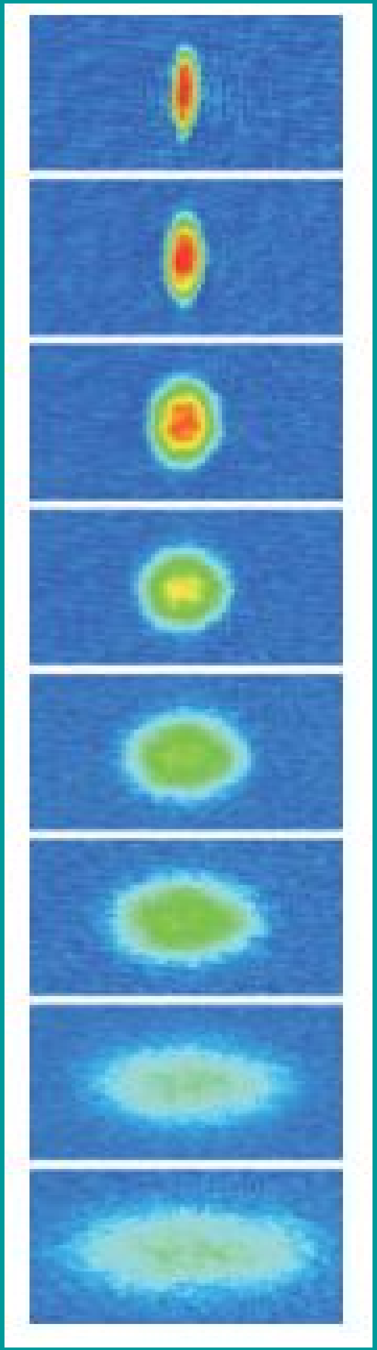
Quantum Criticality

Neutron Star ?

Microsecond Universe : QGP
String Theory
AdS / CFT

Finite Nuclei
Giant Resonances (Nuclear matter)

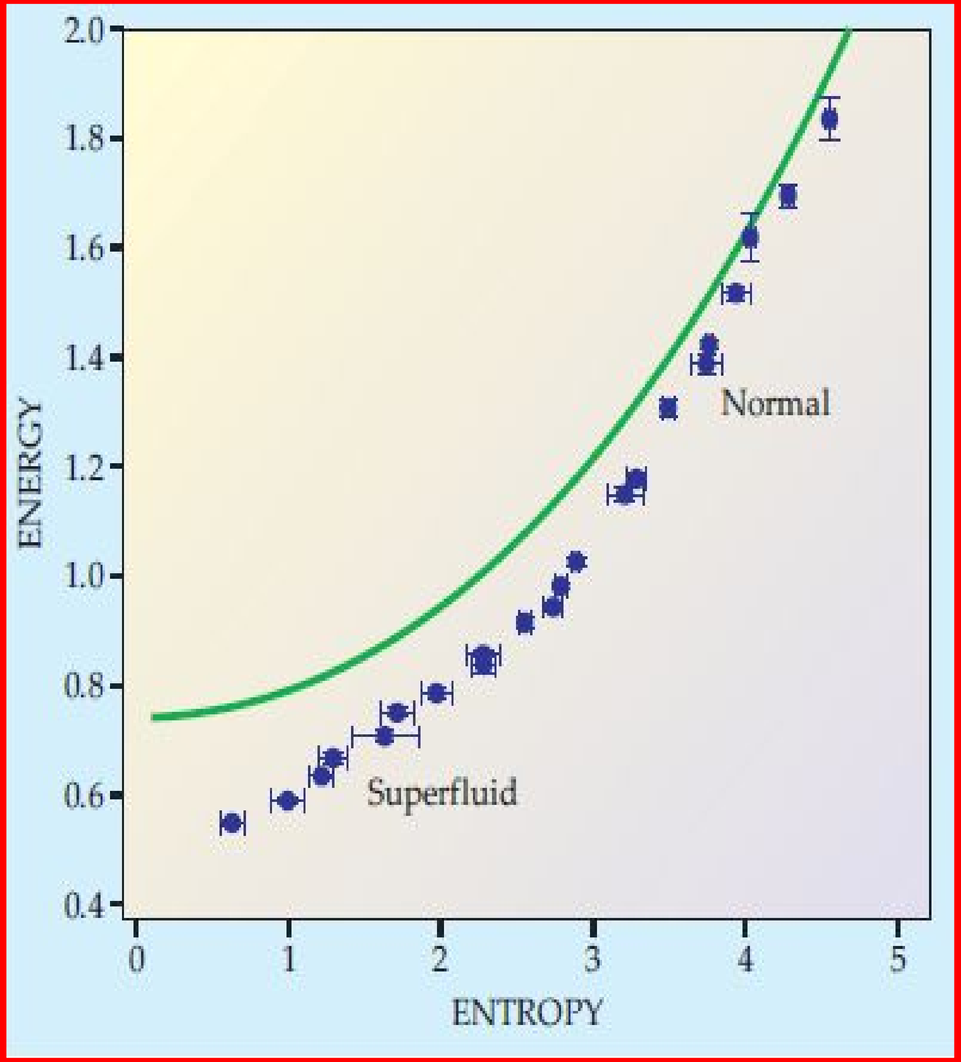
Strongly interacting System



John E. Thomas, Physics Today, 2010

Upon release from a cigar-shaped trap, a cloud of strongly interacting lithium-6 atoms experiences a pressure gradient that is larger in the transverse directions than in the longitudinal direction. As a result, it expands and changes in shape from cigar to ellipse. Such elliptic flow arises in a quark-gluon plasma as well, and it is a consequence of very low viscosity hydrodynamics characteristics of a nearly perfect fluid. The color scale indicates density, with red more dense and light blue less dense. Time increases from 0.1 ms after release (top image) to 2 ms (bottom image).

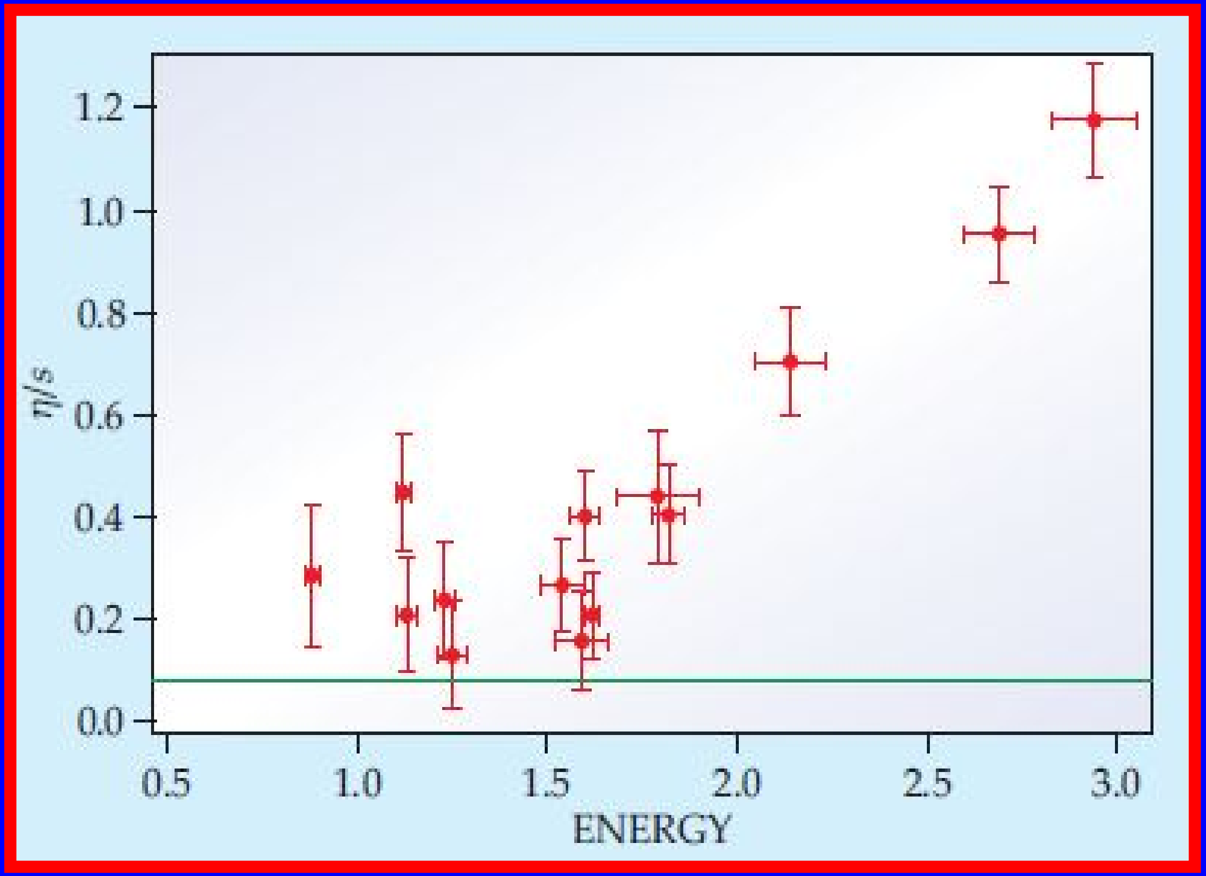
(K. M. O’Hara et al., Science, 2002)



John E. Thomas, Physics Today, 2010

The superfluid-to-normal- fluid transition for lithium-6, a strongly interacting Fermi gas, is signaled by a change in the scaling of energy with entropy. On this plot, the energy per particle is divided by the Fermi energy of an ideal Fermi gas at the trap center, and the entropy per particle is divided by Boltzmann's constant. The data indicate that the transition takes place at a normalized energy of about 0.8. For comparison, the green curve shows the energy-entropy plot for an ideal Fermi gas.

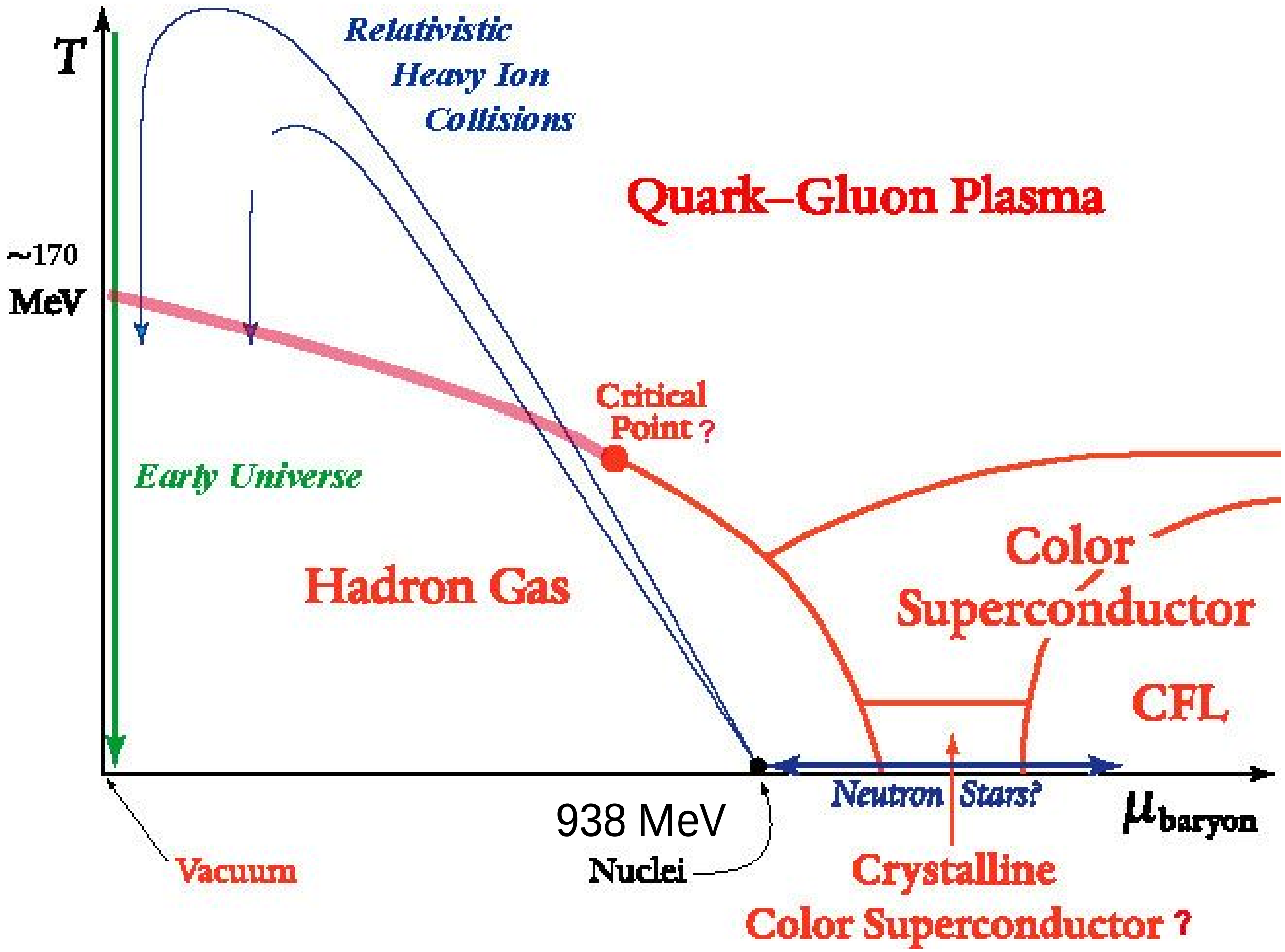
(Luo & Thomas, J. Low Temp. Phy., 154, 1, 2009)



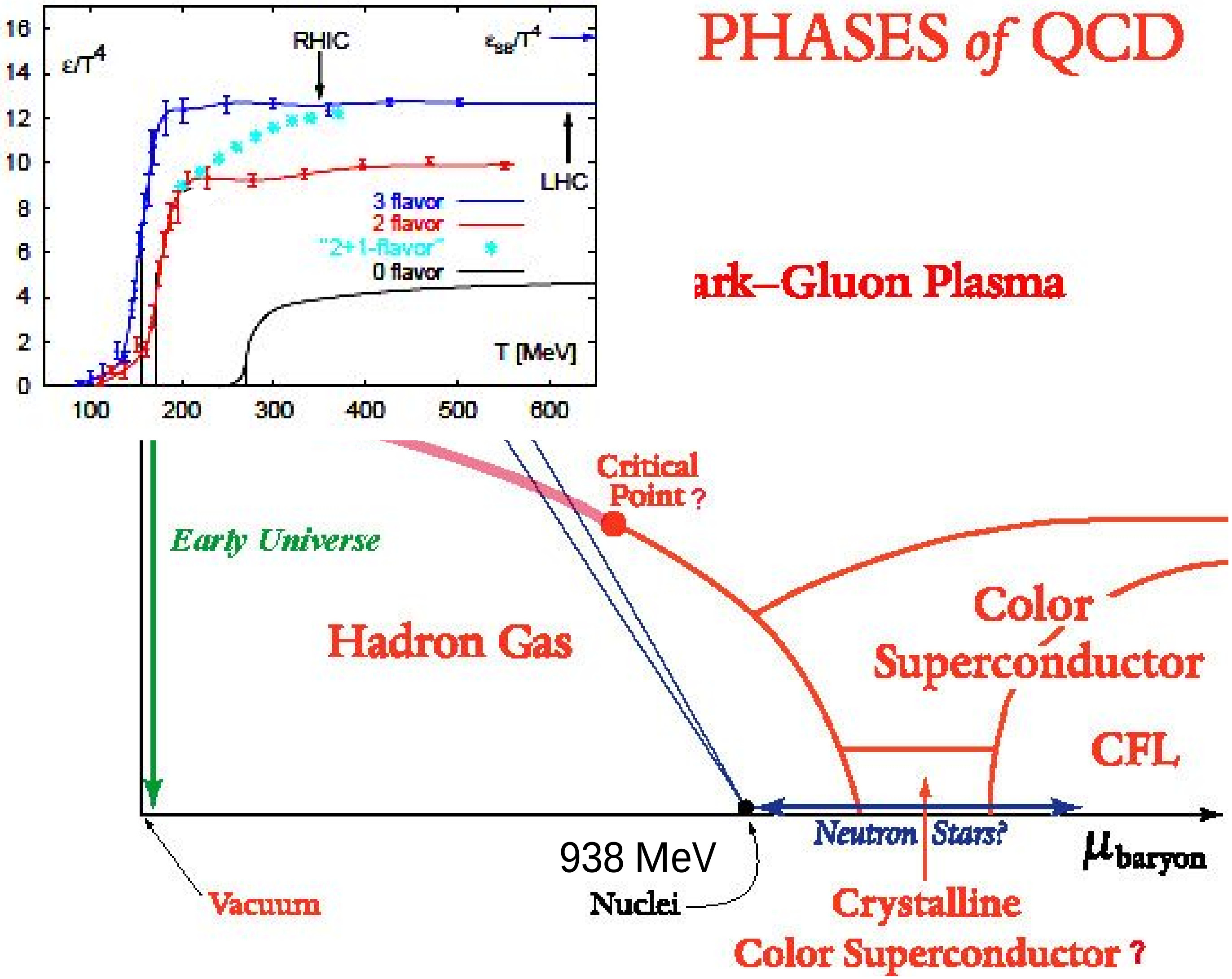
John E. Thomas, Physics Today, 2010

The experimentally determined ratio of shear viscosity to entropy density (η / *s*, red data points) for normal, strongly interacting lithium-6 is comparable to the conjectured lower bound inspired by string theory (green line). The energy per particle is normalized to the Fermi energy; in those units the superfluid-to-normal-fluid transition occurs at an energy of 0.8. The statistical error bars do not include possible systematic errors arising from the model used to estimate the viscosity.

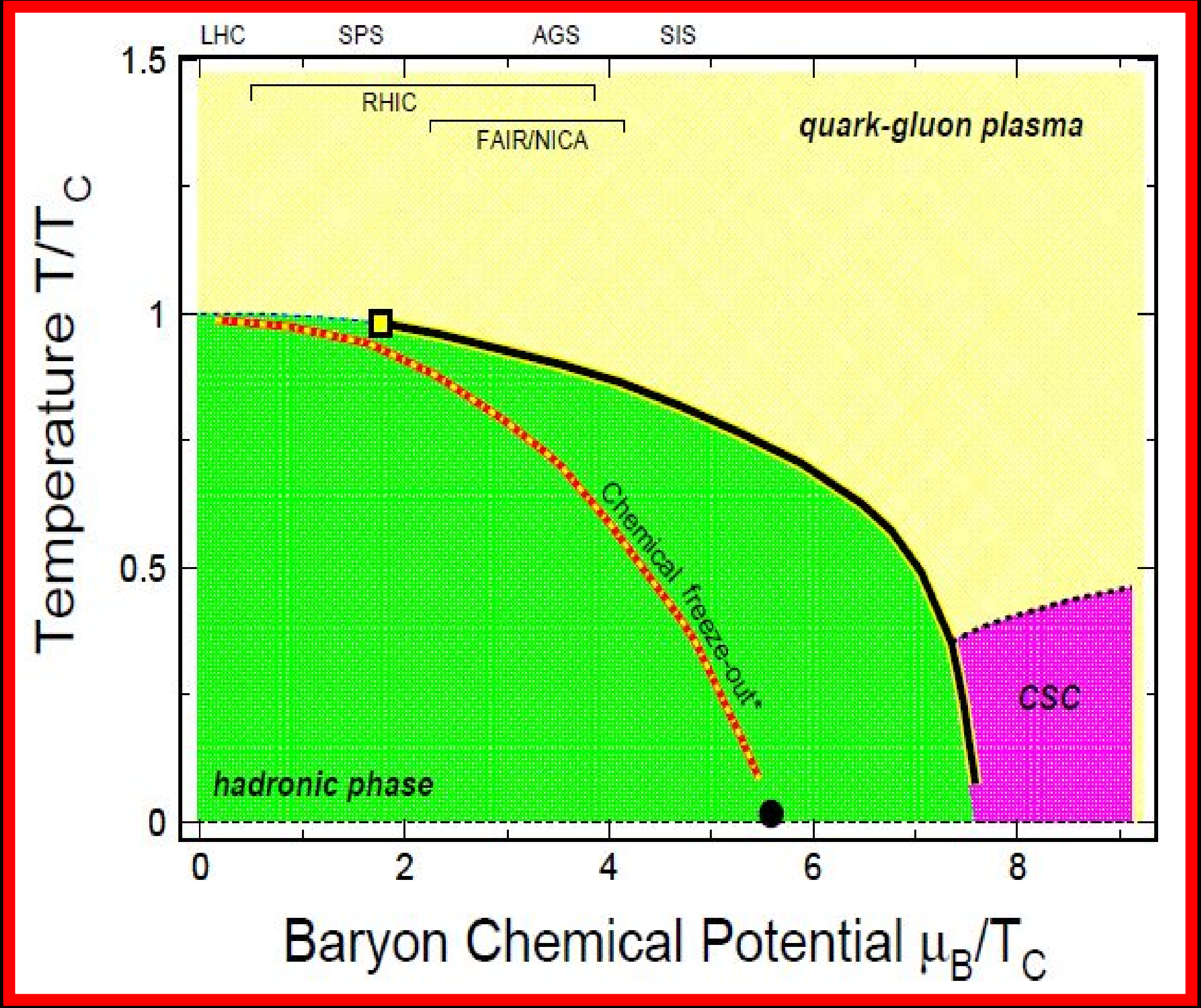
EXPLORING *the* PHASES *of* QCD



S.Gupta et al 1105.3934: T_c=175 MeV. [Paper selected as one of the top 10 breakthroughs in 2011 by Physics



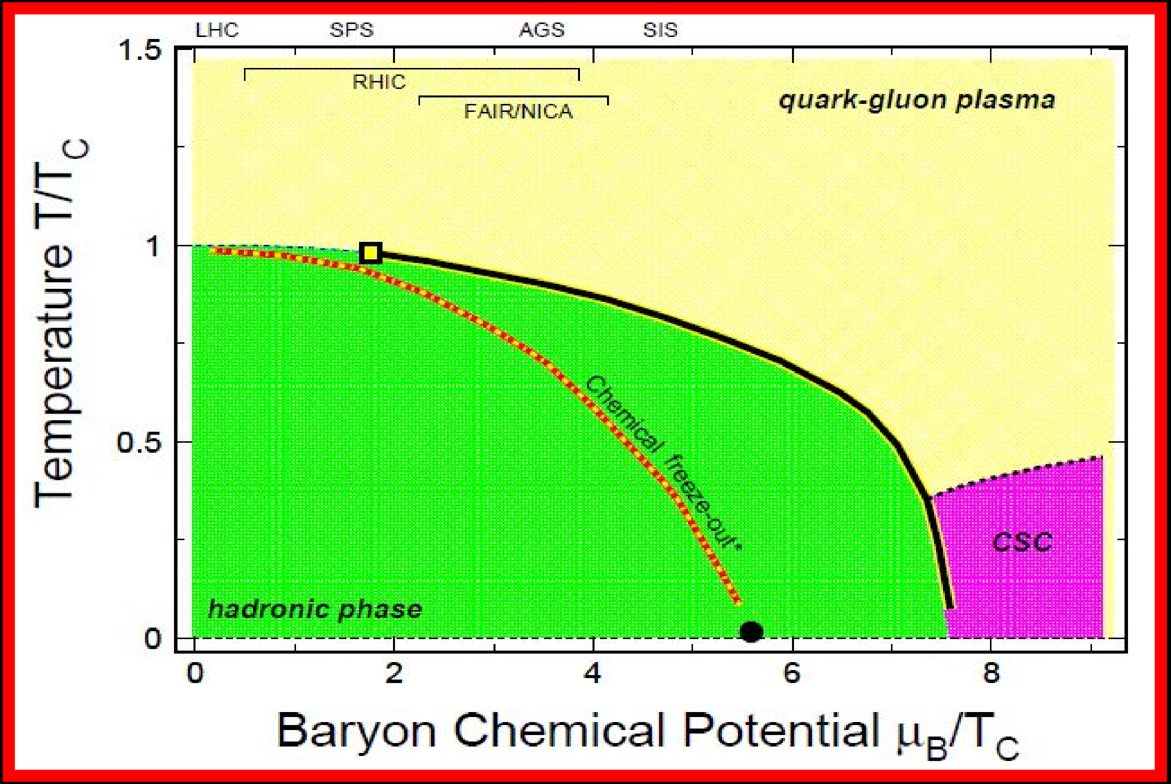
S.Gupta et al 1105.3934: T_c=175 MeV. [Paper selected as one of the top 10 breakthroughs in 2011 by Physics



S. Gupta et al., 2011
arXiv:1105.3934v1

Current conjectures for the QCD phase diagram. The phase boundary (solid line) between the normal low-temperature hadronic phase of bulk QCD matter and the high-temperature partonic phase is a line of first order phase transitions which begins at large μB and small T and curves towards smaller μB and larger T.

[M. G. Alford, K. Rajagopal and F. Wilczek, Phys. Lett.B 422, 247,1998].

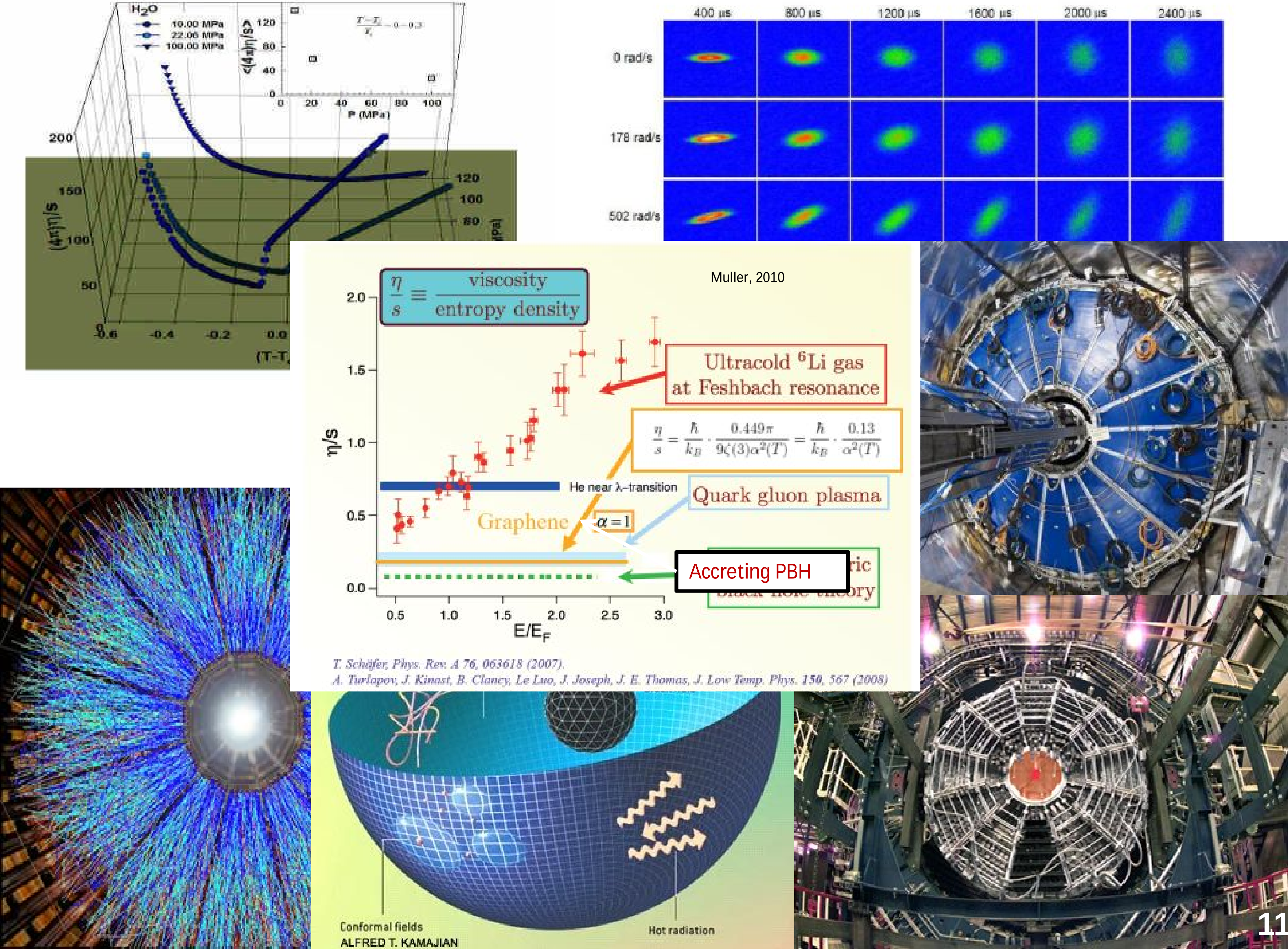


S. Gupta et al., 2011 arXiv:1105.3934v1

This line ends at the QCD critical point whose probable position, derived from lattice computations, is marked by a square. At even smaller μB there are no phase transitions, only a line of cross-overs (shown by a dashed line).

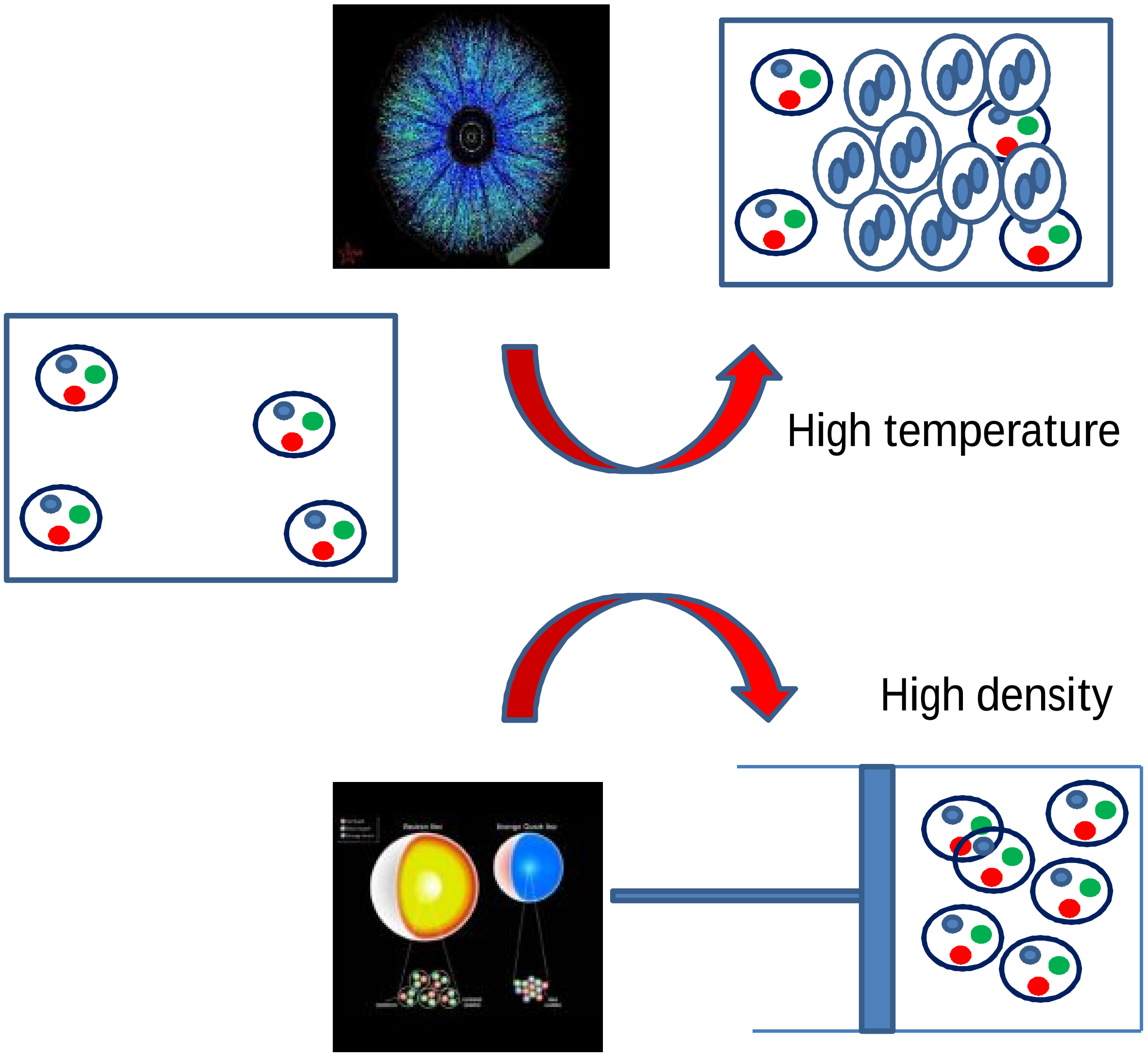
The red-yellow dotted line corresponds to the chemical freeze-out line from the evolution of the bulk QCD matter produced in high energy heavy-ion collisions. The solid point at T = 0 and μB = 938 MeV represents nuclear matter in the ground state. At large μB and low T is the color superconductor phase (CSC)

[M. G. Alford, K. Rajagopal and F. Wilczek, Phys. Lett.B 422, 247,1998].



T. Schäfer, Phys. Rev. A 76, 063618 (2007).
A. Turlapov, J. Kinast, B. Clancy, Le Luo, J. Joseph, J. E. Thomas, J. Low Temp. Phys. 150, 567 (2008)

Quark Gluon Plasma



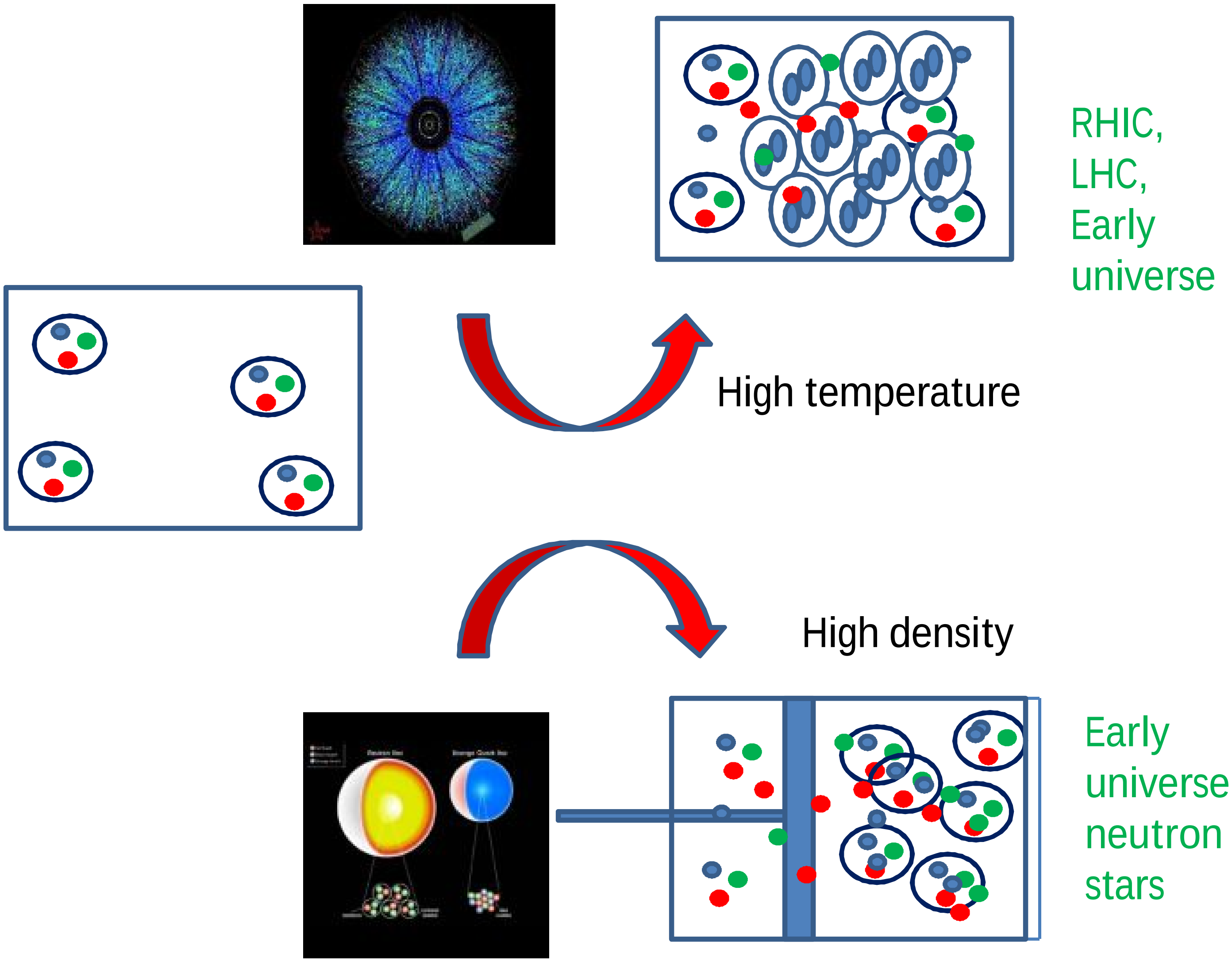
High temperature

RHIC,
LHC,
Early
universe

High density

Early
universe,
neutron
stars

Quark Gluon Plasma



RHIC,
LHC,
Early
universe

High temperature

High density

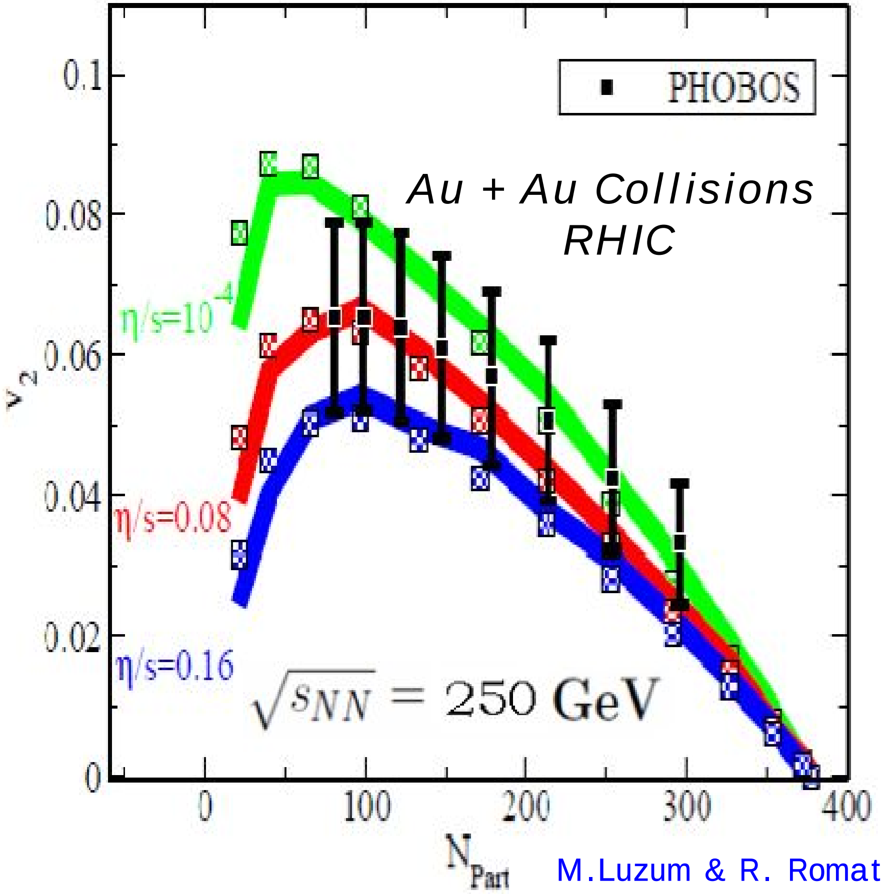
Early
universe,
neutron
stars

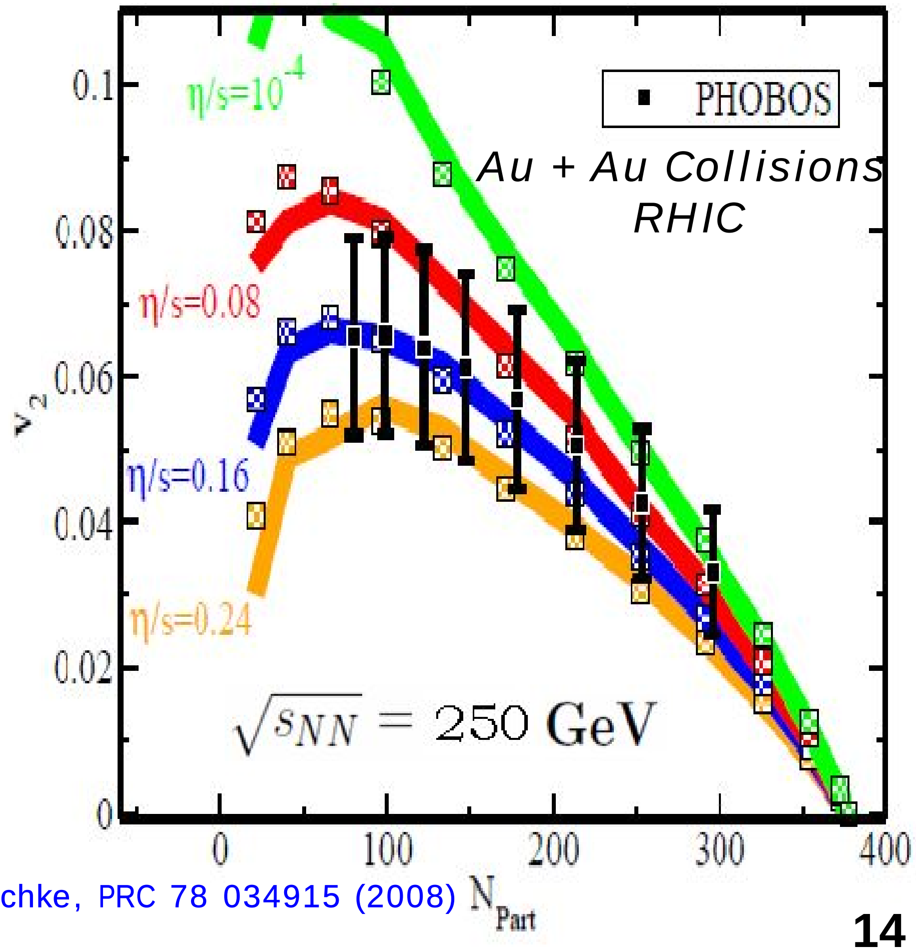
Hydrodynamic models to experimental data on charged hadron integrated elliptic flow by PHOBOS

Glauber

Elliptic Flow PHOBOS

CGC





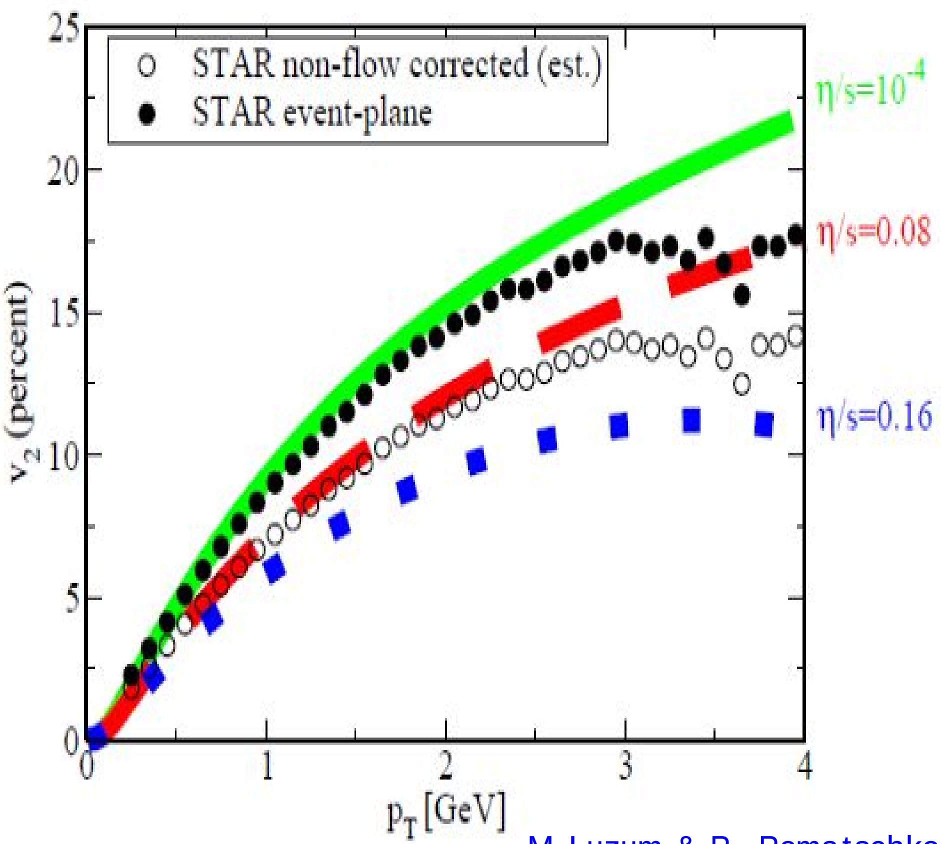
M.Luzum & R. Romatschke, PRC 78 034915 (2008)

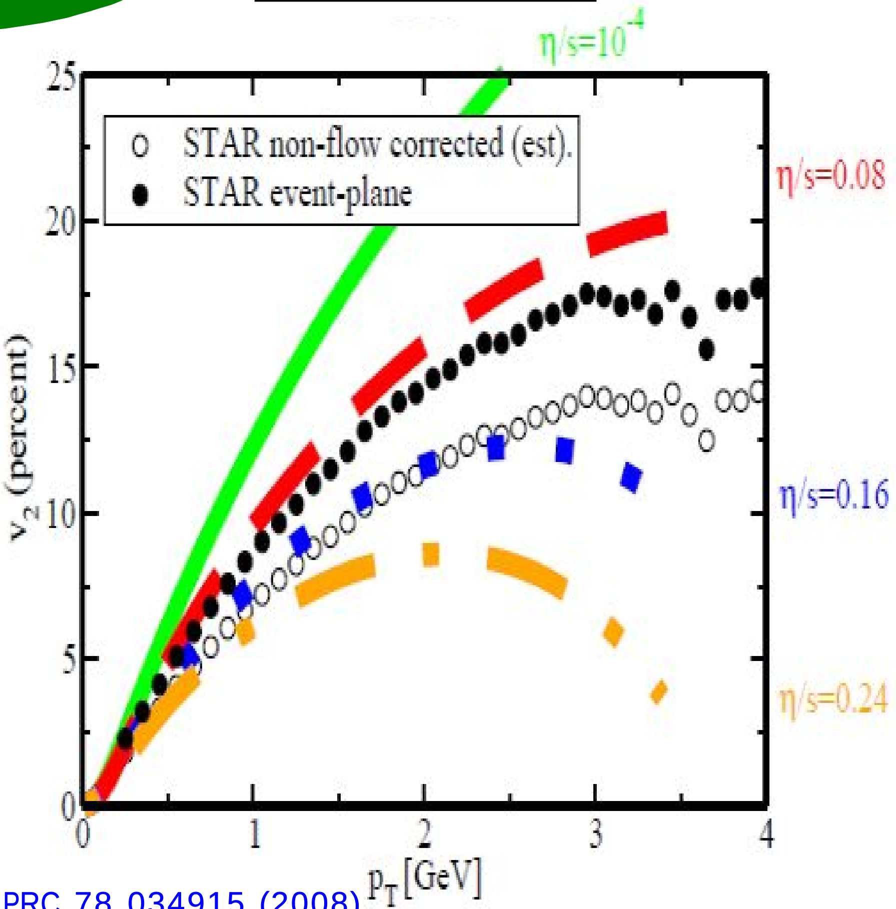
Hydrodynamic models to experimental data on charged hadron minimum bias elliptic flow by STAR

Glauber

Elliptic Flow STAR

CGC



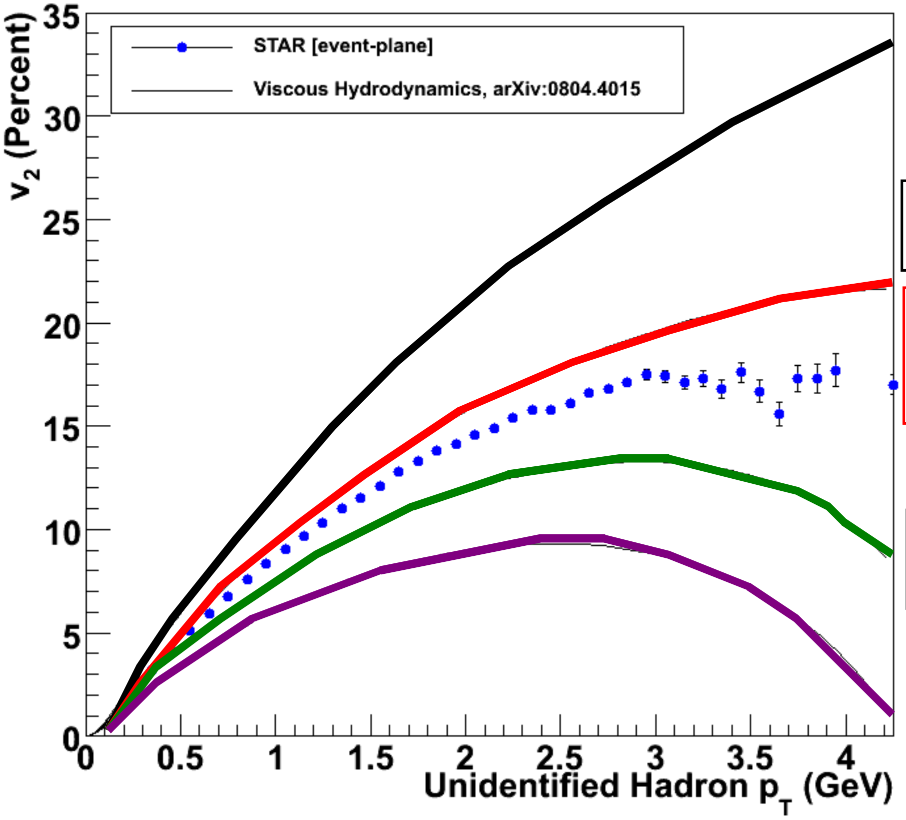


M.Luzum & R. Romatschke, PRC 78 034915 (2008)

Quark-Gluon Plasma: A Perfect Fluid

M.Luzum & R. Romatschke
PRC 78 034915 (2008)

Viscous Hydrodynamics



$\eta/s \sim 0$

$\eta/s = 1/4\pi$

Lowest Predicted Value (i.e. Perfect).

$\eta/s = 2 \times 1/4\pi$

$\eta/s = 3 \times 1/4\pi$

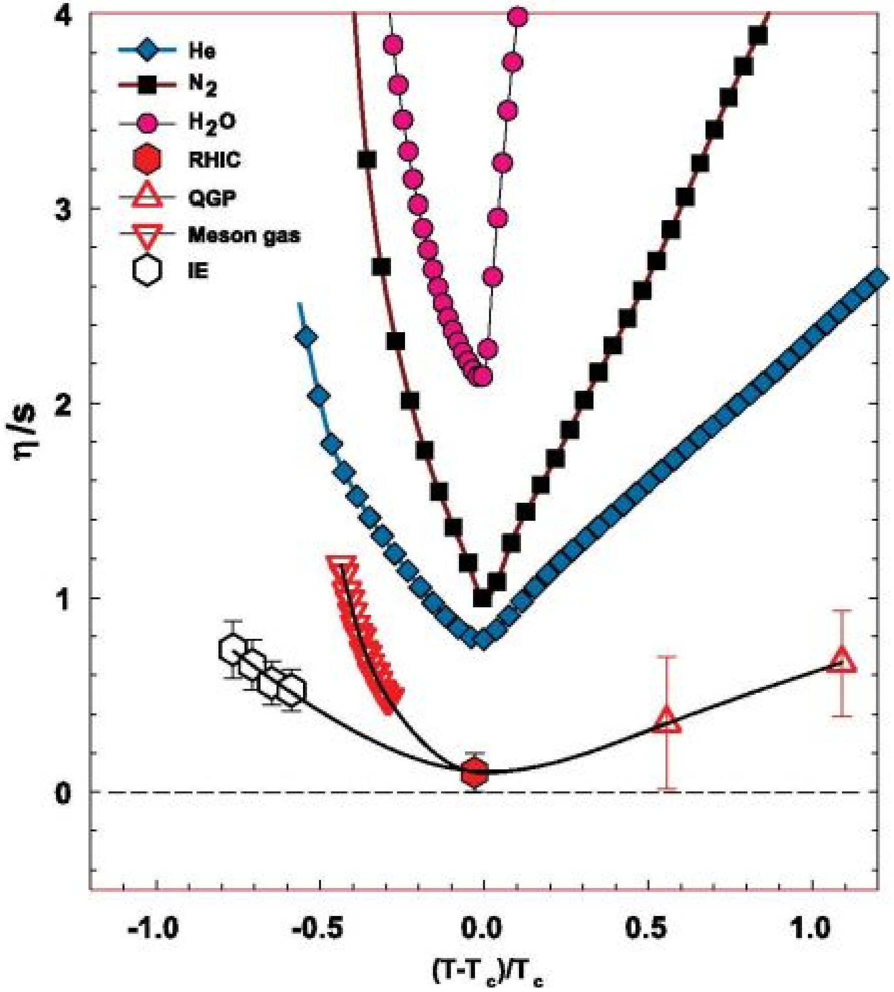
$\sqrt{s_{NN}} = 250\ \mathrm{GeV}$

Au + Au Collisions
RHIC

String Theory (AdS/CFT)
predicted η/s Bound

Roy A. Lacey et. al

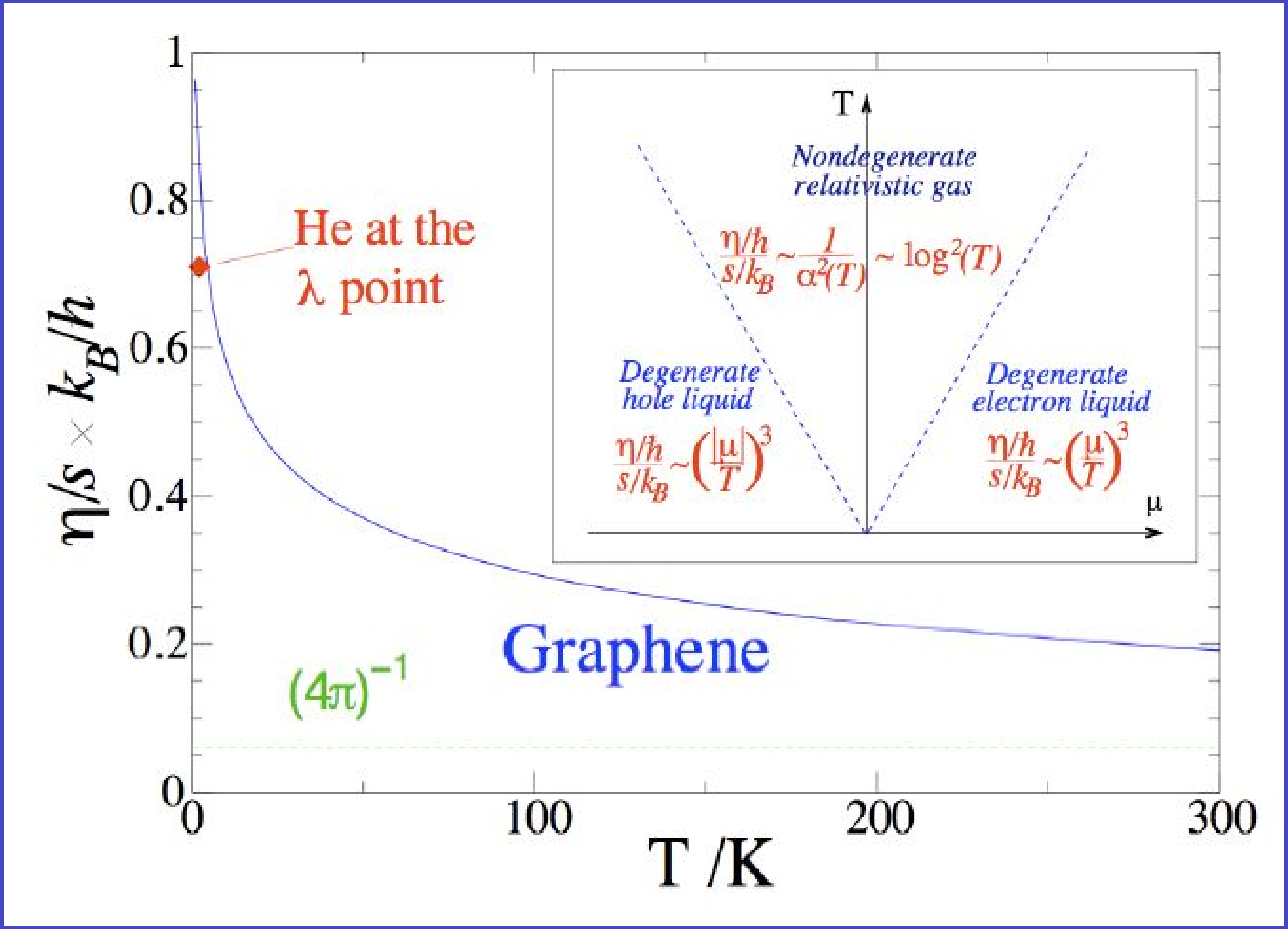
PRL 98, (2007)



$$\eta/s \sim T\lambda_f c_{s'}$$

η/s vs $(T - T_c)/T_c$ for several substances as indicated. The calculated values for the meson gas have an associated error of ~50% [46]. The lattice QCD value T_c = 170 MeV [48] is assumed for nuclear matter. The lines are drawn to guide the eye.

The ratio η/s of the shear viscosity η to the entropy density s is uniquely suited to determine how strongly the excitations in a quantum fluid interact. We determine η/s in <u>clean undoped graphene</u> using a quantum kinetic theory. As a result of the quantum criticality of this system the ratio is <u>smaller than</u> in many other correlated quantum liquids and, interestingly, comes close to a lower bound conjectured in the context of the quark gluon plasma.



M. Muller et. al arXiv:0903.4178v2 [cond-mat.mes-hall] 14 Jul 2009

Classical Nuclear Physics

Collective Phenomena

1. **Giant Resonances/proton & neutron fluids Hydro dynamical model => widths of resonances to the viscosity of the proton – neutron fluids**

2. Fission process

At high temp : $T \gg \hbar\omega$

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}\frac{16}{5\pi}\left(\left(\frac{\in_F}{T}\right)^2\frac{\alpha}{T}\right) \longrightarrow$$ **Neutron Star?**

$$T \approx {\in_F}/{2} \longrightarrow {\eta}/{s} \sim {\hbar}/{4\pi k_B}$$

Unusually similar to RHIC results

What about Giant dipole resonances on highly excited state $\longrightarrow {\eta}/{s}$

Auerbach & Shlomo, PRL, 103, 172501 (2009)

$$\left.\frac{\eta}{s}\right)_{QGP} = \frac{5.12}{16\pi^{2}\alpha_{s^{2}}\,\ln(2.42/\sqrt{4\pi\alpha_{s}})} \approx \frac{\hbar}{4\pi k_{B}}$$

$$\left.\frac{\eta}{s}\right)_{nm} = \frac{\hbar}{4\pi k_{B}}\,\frac{16}{5\pi}\in_{F}^{2}\,\frac{\alpha}{T}\,\frac{T^{2}+(\hbar\omega/2\pi)^{2}}{(\hbar\omega\alpha)^{2}+[T^{2}+(\hbar\omega/2\pi)^{2}]^{2}}$$

$$\Rightarrow \approx \frac{\hbar}{4\pi k_{B}}$$

$$T \ll \hbar\omega \quad \Rightarrow \quad \frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \frac{14}{5\pi^3} \in_F^2 \frac{1}{\alpha T} \approx 3 \text{ x } \frac{\hbar}{4\pi k_B}$$

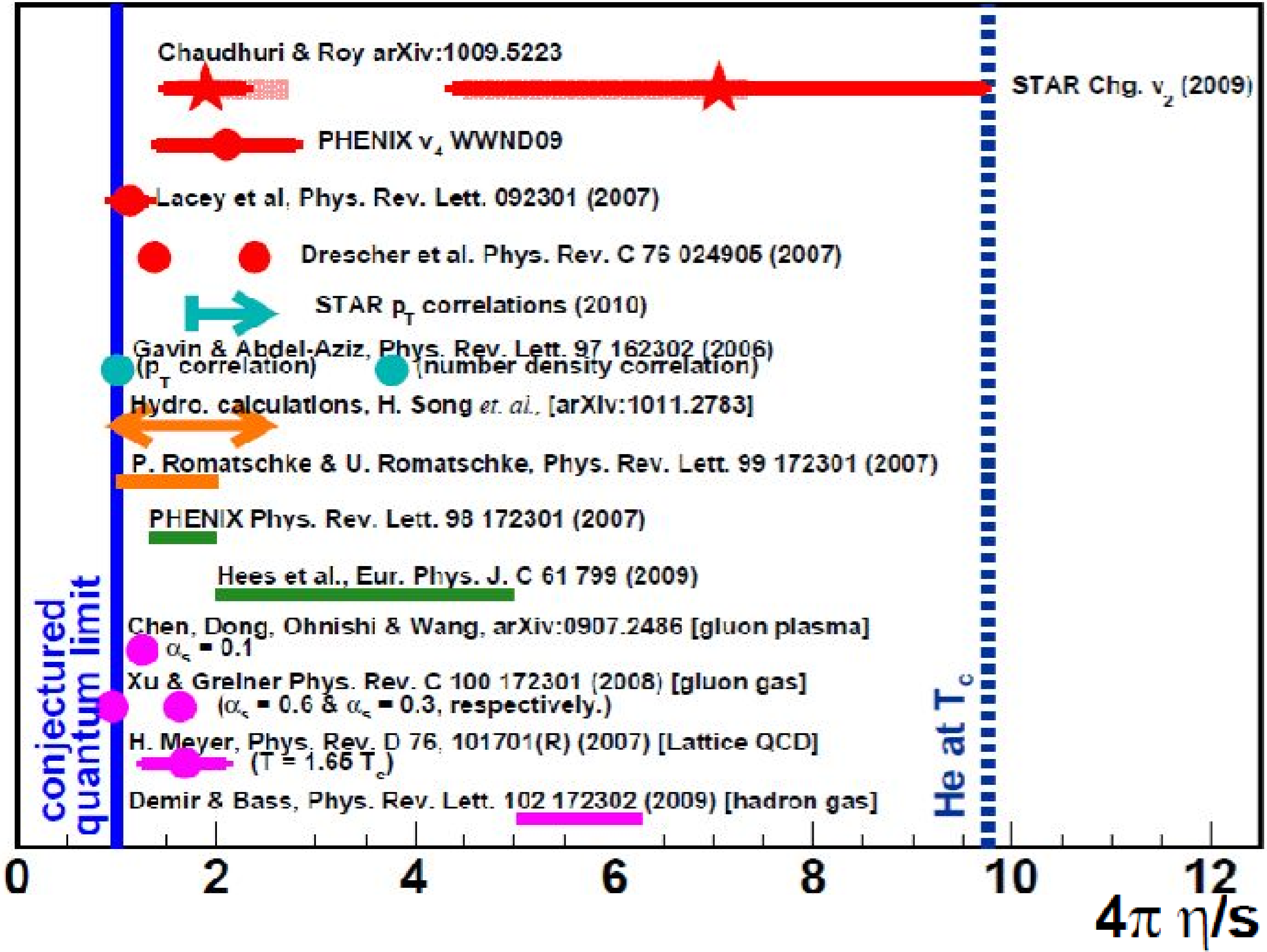
$$T \gg \hbar\omega \quad \Rightarrow \quad \frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \frac{16}{5\pi} \left(\frac{\in_F}{T}\right)^2 \frac{\alpha}{T} \quad \Rightarrow \quad \textbf{high } \boldsymbol{\rho}$$

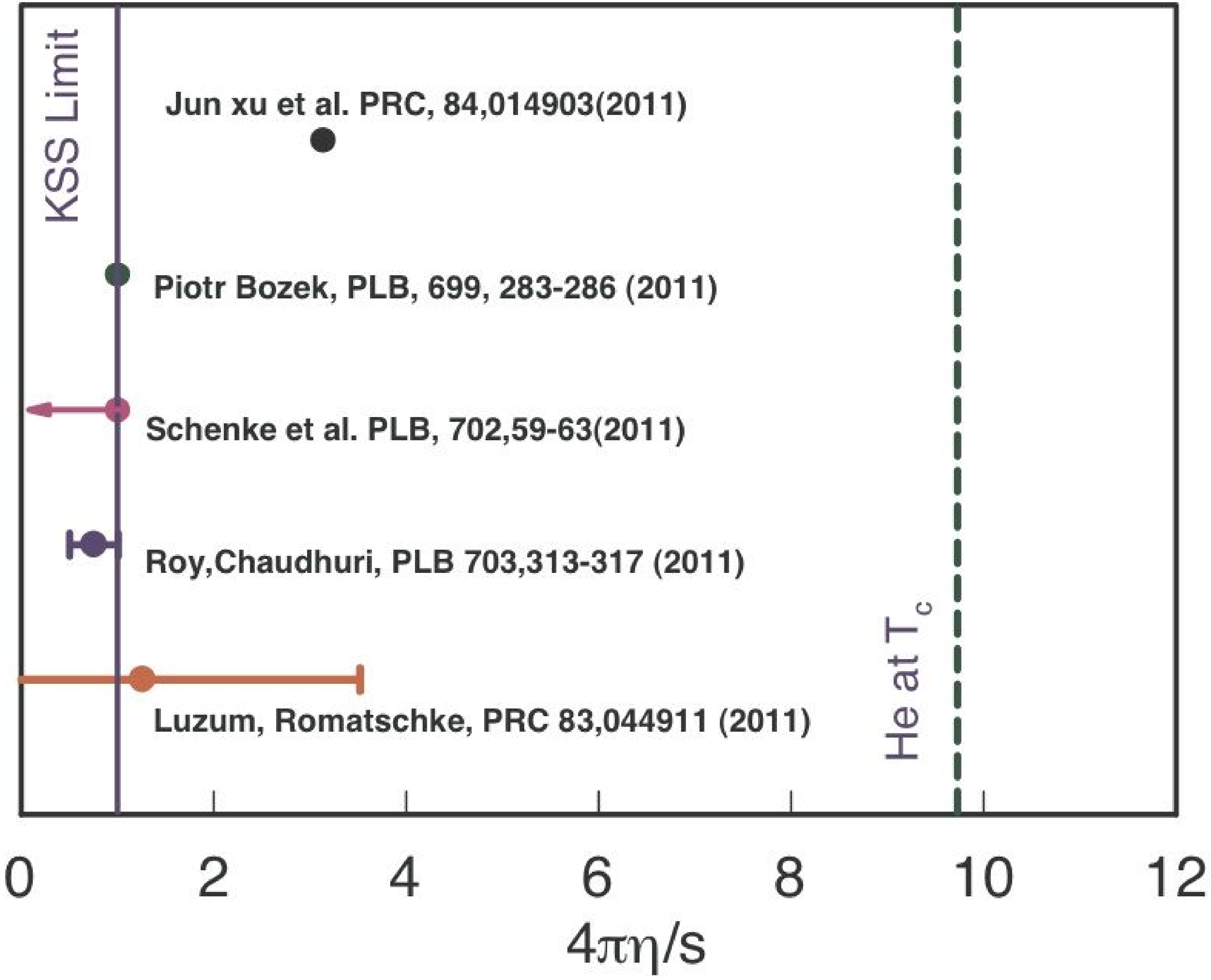
$\in_F$ = 100 MeV

$T \approx \in_F / 2$

$\eta / s \to \dfrac{\hbar}{4\pi k_B}$

STRONG CORRELATION


Chaudhuri & Roy arXiv:1009.5223
STAR Chg. v_2 (2009)
PHENIX v_4 WWND09
Lacey et al. Phys. Rev. Lett. 092301 (2007)
Drescher et al. Phys. Rev. C 76 024905 (2007)
STAR p_T correlations (2010)
Gavin & Abdel-Aziz, Phys. Rev. Lett. 97 162302 (2006)
(p_T correlation)
(number density correlation)
Hydro. calculations, H. Song et. al., [arXiv:1011.2783]
P. Romatschke & U. Romatschke, Phys. Rev. Lett. 99 172301 (2007)
PHENIX Phys. Rev. Lett. 98 172301 (2007)
Hees et al., Eur. Phys. J. C 61 799 (2009)
Chen, Dong, Ohnishi & Wang, arXiv:0907.2486 [gluon plasma]
$\alpha_s = 0.1$
Xu & Greiner Phys. Rev. C 100 172301 (2008) [gluon gas]
($\alpha_s = 0.6$ & $\alpha_s = 0.3$, respectively.)
H. Meyer, Phys. Rev. D 76, 101701(R) (2007) [Lattice QCD]
($T = 1.65\ T_c$)
Demir & Bass, Phys. Rev. Lett. 102 172302 (2009) [hadron gas]
conjectured quantum limit
He at T_c
0
2
4
6
8
10
12
$4\pi\ \eta/s$


KSS Limit
Jun xu et al. PRC, 84,014903(2011)
Piotr Bozek, PLB, 699, 283-286 (2011)
Schenke et al. PLB, 702,59-63(2011)
Roy,Chaudhuri, PLB 703,313-317 (2011)
Luzum, Romatschke, PRC 83,044911 (2011)
He at T_c
0
2
4
6
8
10
12
$4\pi\eta/s$

The strongly coupled plasma

By 2004, RHIC experiments determined and reported several key properties of the hot, dense matter. Its opacity to energetic quarks and gluons indicates extremely high density. Hydrodynamic descriptions reproduce the data and describe the collision from early times through expansion, cooling, and hadron formation, but only if η/s is taken to be very small. The system is therefore not the weakly coupled gas of almost freely moving quarks and gluons one would naively expect from asymptotic freedom. Instead, it is strongly coupled.

The strongly coupled plasma

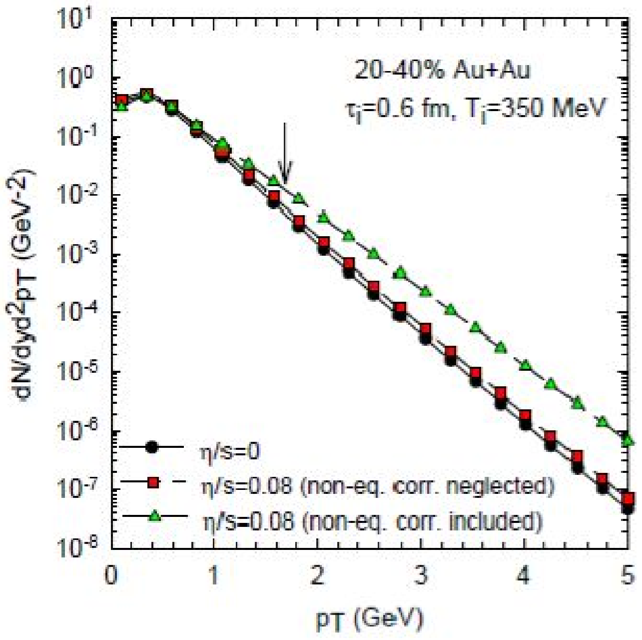
The strong coupling implies that some correlation among the quarks and gluons may survive within the plasma phase near T_c and produce multiplarticle interactions with near neighbors. Indeed, lattice QCD studies of energy-density correlations in a QGP at temperatures of 1-2 T_c show small correlation peaks. The correlation is similar to the short-range order observed in ordinary liquids near the liquid-gas phase transition.

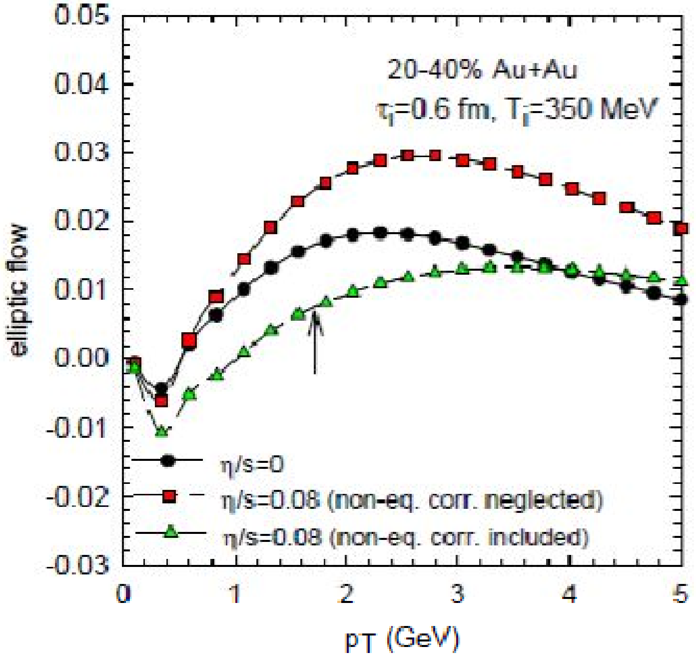
It is remarkable that both the coldest and the hottest matter on Earth exhibit very similar elliptic flow patterns, with η/s near the conjectured lower bound, Ad S / C F T.

What does the “FLOW” at LHC tell us about η/s

Intriguing, Interesting, Captivating !!!

Effect of viscosity on photon spectra and elliptic flow:





Validity of hydrodynamics require that non-equilibrium contribution to photon spectra is smaller than the equilibrium contribution. For AdS/CFT limit for viscosity to entropy ratio, $\eta/s=1/4\pi$, hydrodynamics is applicable only in a limited pT region (marked by the arrow).

It is important to have a consistent model, e.g. neglect of non-equilibrium correction to distribution function can lead to increased elliptic flow.

Space-time evolution of the fluid was obtained by solving Israel-Stewart's 2nd order hydrodynamics,

$$\begin{aligned}\partial_\mu T^{\mu\nu} &= 0; \text{(energy-momentum conservation equation)}\\ D\pi^{\mu\nu} &= -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\nabla^{<\mu}u^{\nu>}) - [u^\mu \pi^{\nu\lambda} + u^\nu \pi^{\nu\lambda}]Du_\lambda.\\ &\quad \text{(relaxation equation for shear stress tensor)}\end{aligned}$$

Hydrodynamic equations are closed with an equation of state (EOS). We use an EOS based on Wuppertal-Budapest lattice simulation.

With initial conditions appropriate for 200 GeV Au+Au collisions, the equations are solved with the code AZHYDRO-KOLKATA developed at the Cyclotron Centre, Kolkata.

viz : Chowdhury and Sinha as cited

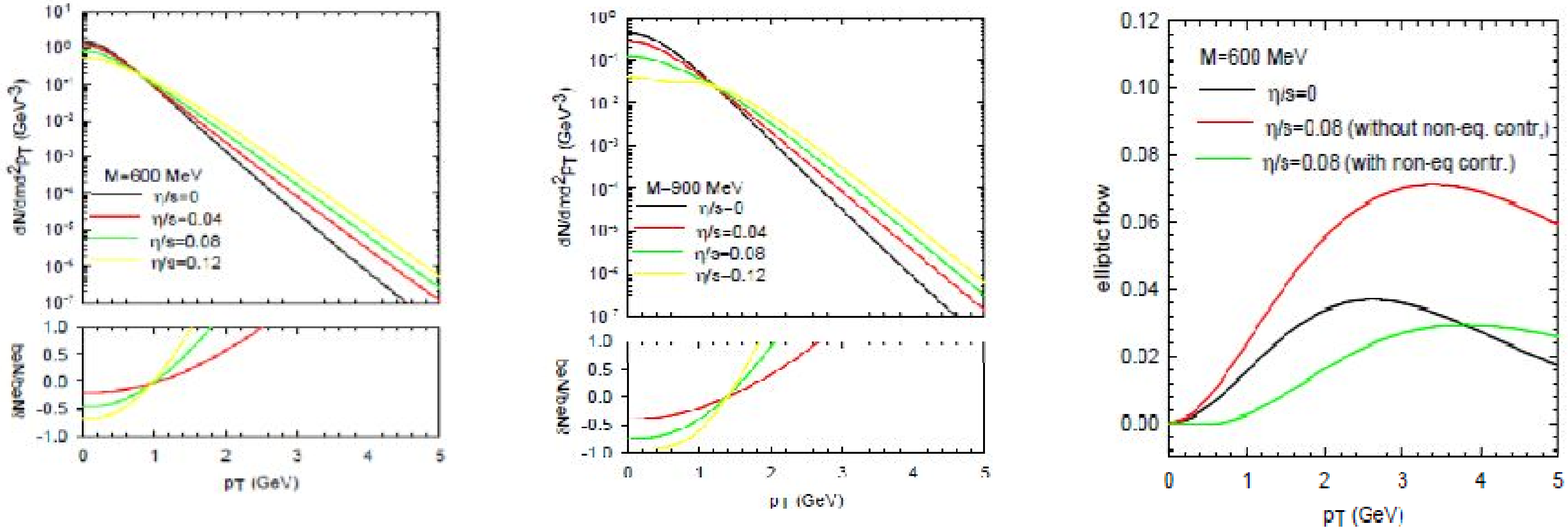
In a hydrodynamic model, invariant distribution of photon and dilepton are obtained by convoluting the photon/dilepton rate over the space-time evolution of the QGP fluid produced in the collisions. In the following we study viscous effects on photon and dileptons. Some of the details of the model can be found in [1].

[1] A. K. Chaudhuri and B. S., Phys. Rev. C83(2011)034905.

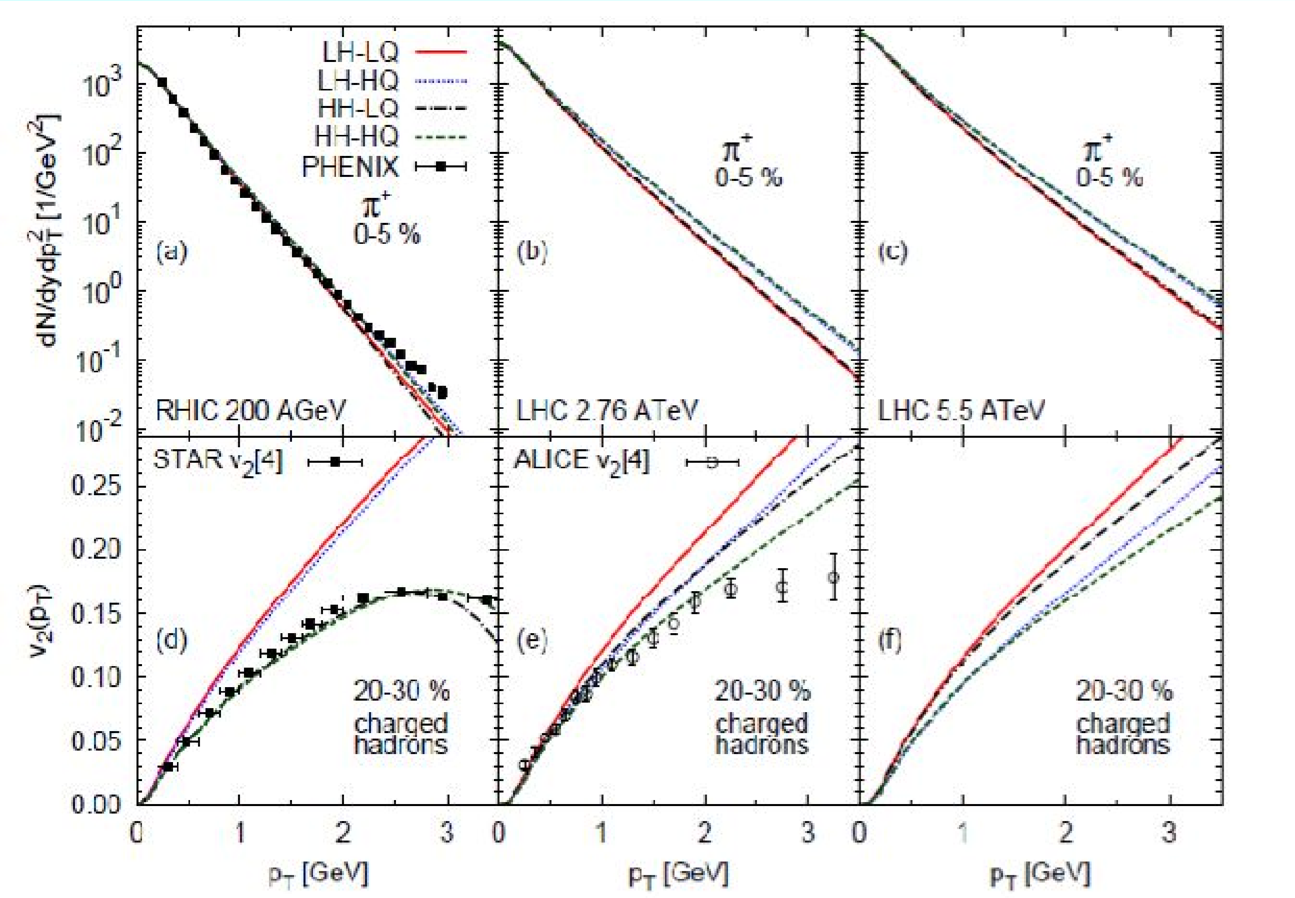
Viscous effect on dilepton production:

Production rate of dileptons of invariant mass M, from the QGP phase can be approximated as [**3**],

$$E\frac{dN}{dM^2d^3p} \approx \frac{\alpha^2}{8\pi^4}\sum e_q^2 f_{neq}(E)$$



similar to photons, viscous effects on dilepton production is also large.
pT spectra is hardened, elliptic flow is reduced.
Also, viscous hydrodynamics remain applicable only in a limited pT range.
Applicability range increase with invariant mass.



H. Niemi et al.
arXiv: 1101.24442v2
[nucl-th] 17 Jun 2011

(Color online) Transverse momentum spectra of positive pions in the 0–5% most central collisions and elliptic flow coefficients in the 20–30% centrality class at RHIC and LHC. Different curves correspond to the different parametrizations of the temperature dependence of η/s. Data in panel (a) are from [S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. C 69, 034909 (2004).] and in panels (d) and (e) from [K. Aamodt et al. (The ALICE Collaboration), Phys. Rev. Lett. 105, 252302 (2011)].

ALICE data for charged particles elliptic flow

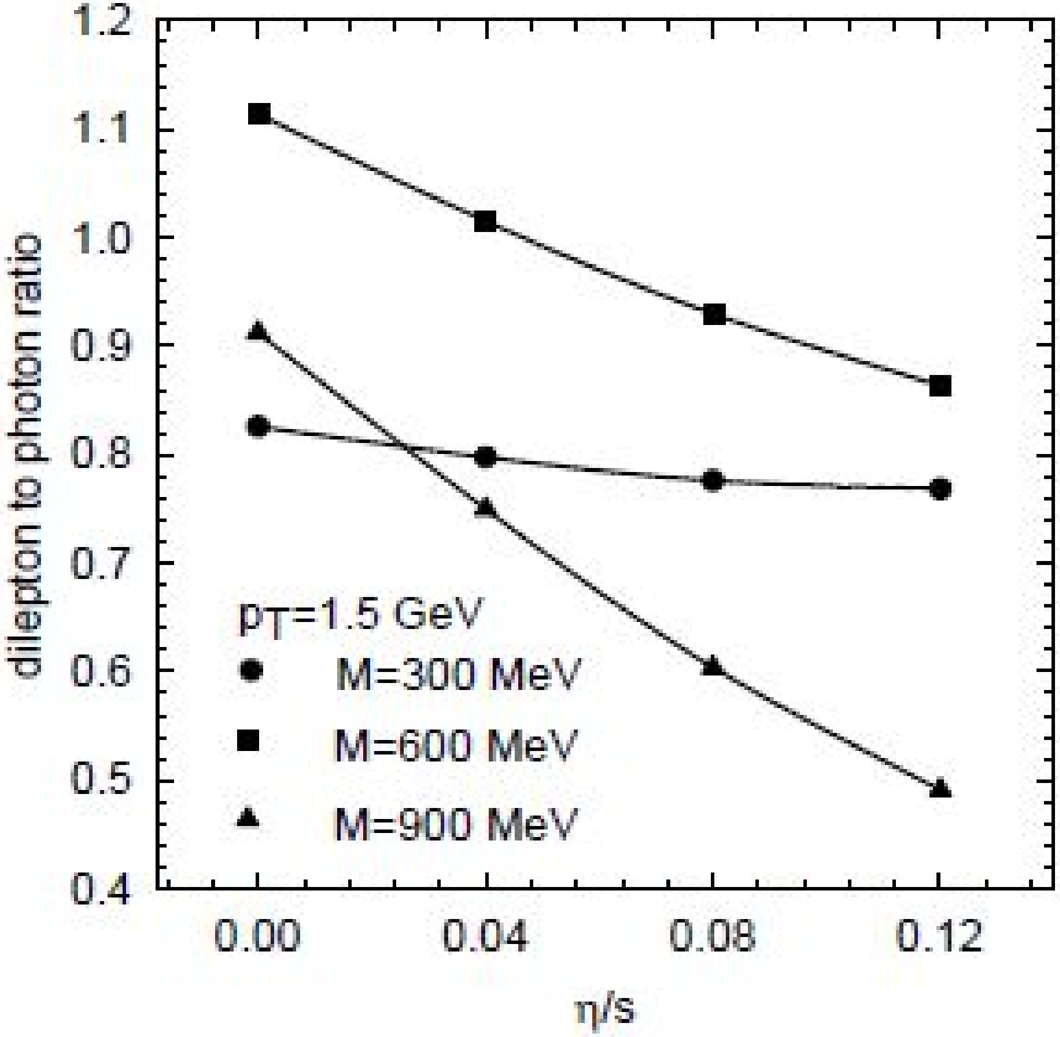
in 20-30%, 30-40% and 40-50% collision are

best explained for fluid viscosity η/s= 0.08.

In very central 10-20 % collisions however,

ALICE data prefer ideal fluid rather than

a viscous fluid.



Dileptons to photon ratio as a function of viscosity

Chowdhury & Sinha

To be published

The ratio is largely p$_T$ independent. The p$_T$ dependence of non-equilibrium correction largely cancels out. For low dilepton invariant mass M = 300 MeV, as expected, the ratio do not distinguish between viscosities, the curves are nearly identical for ${}^{n}\!/_{s} = 0 - 0.12$. For invariant mass M = 600 or 900 MeV on the other hand, the ratio depends on viscosity.

For dilepton mass M = 600 MeV, if the ratio is measured within 10 % accuracy, viscosity to entropy ratio can be estimated within an accuracy of ~ 5 %. The sensitivity is increased to ~ 2 % for invariant mass M = 900 MeV.

Our analysis indicates that the specific viscosity of the QGP produced in LHC collisions is similar to that for the strongly coupled QGP produced in RHIC collisions.

The temperature dependence of η/s is not yet discovered. I believe there is substantial hope to discover the temperature dependence of η/s and so, a more precise determination of the critical point (if it at all exists) as we reach the highest energy of LHC.

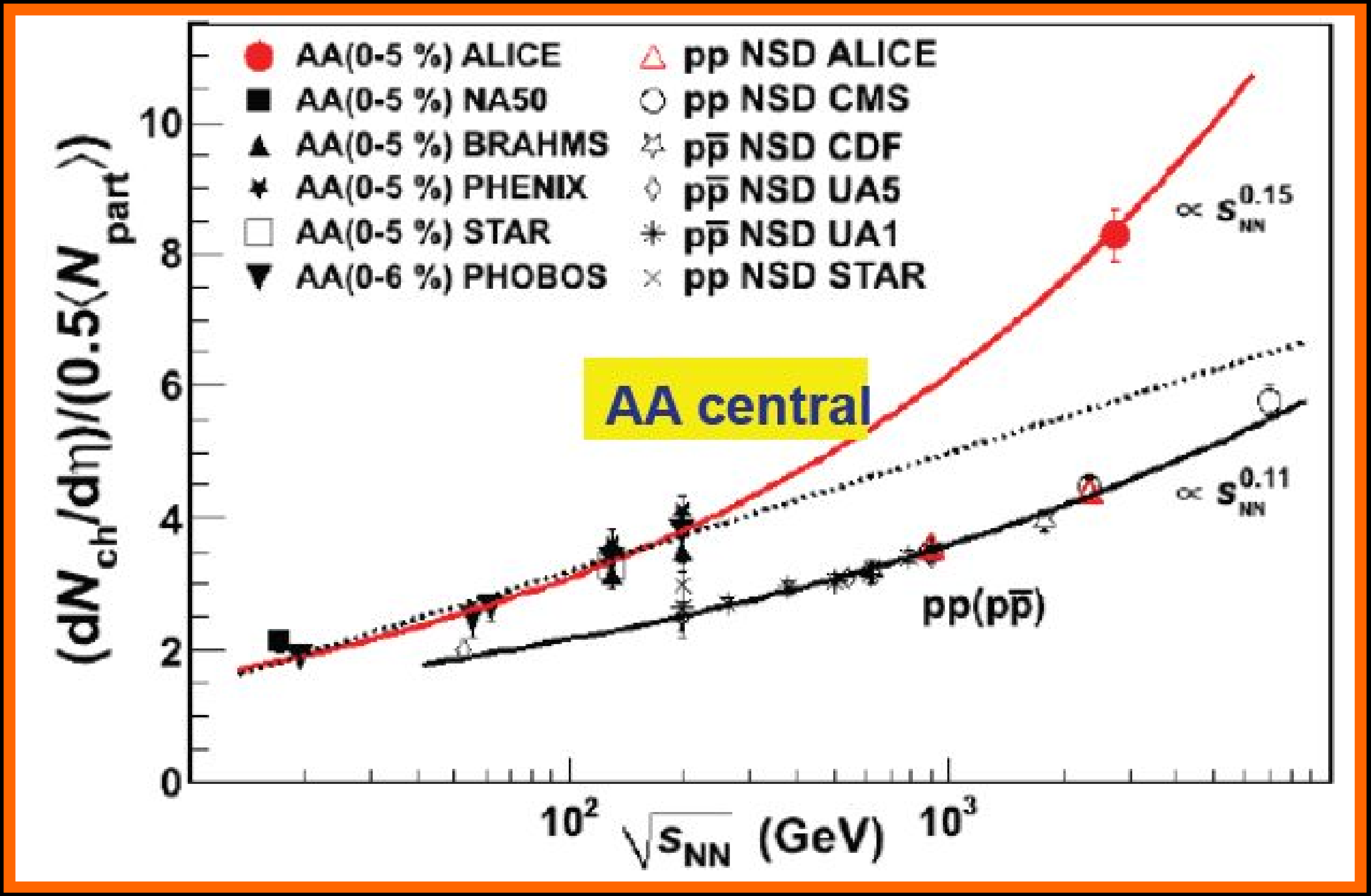
EPILOGUE

- Temperature dependence of η/s:

  The average elliptic flow

$$v_2 = [\int N(P_T) v_2(p_T) dp_T / \int N(p_T) dp_T]$$

in 20%-30% centrality increase by 25% from RHIC to LHC.

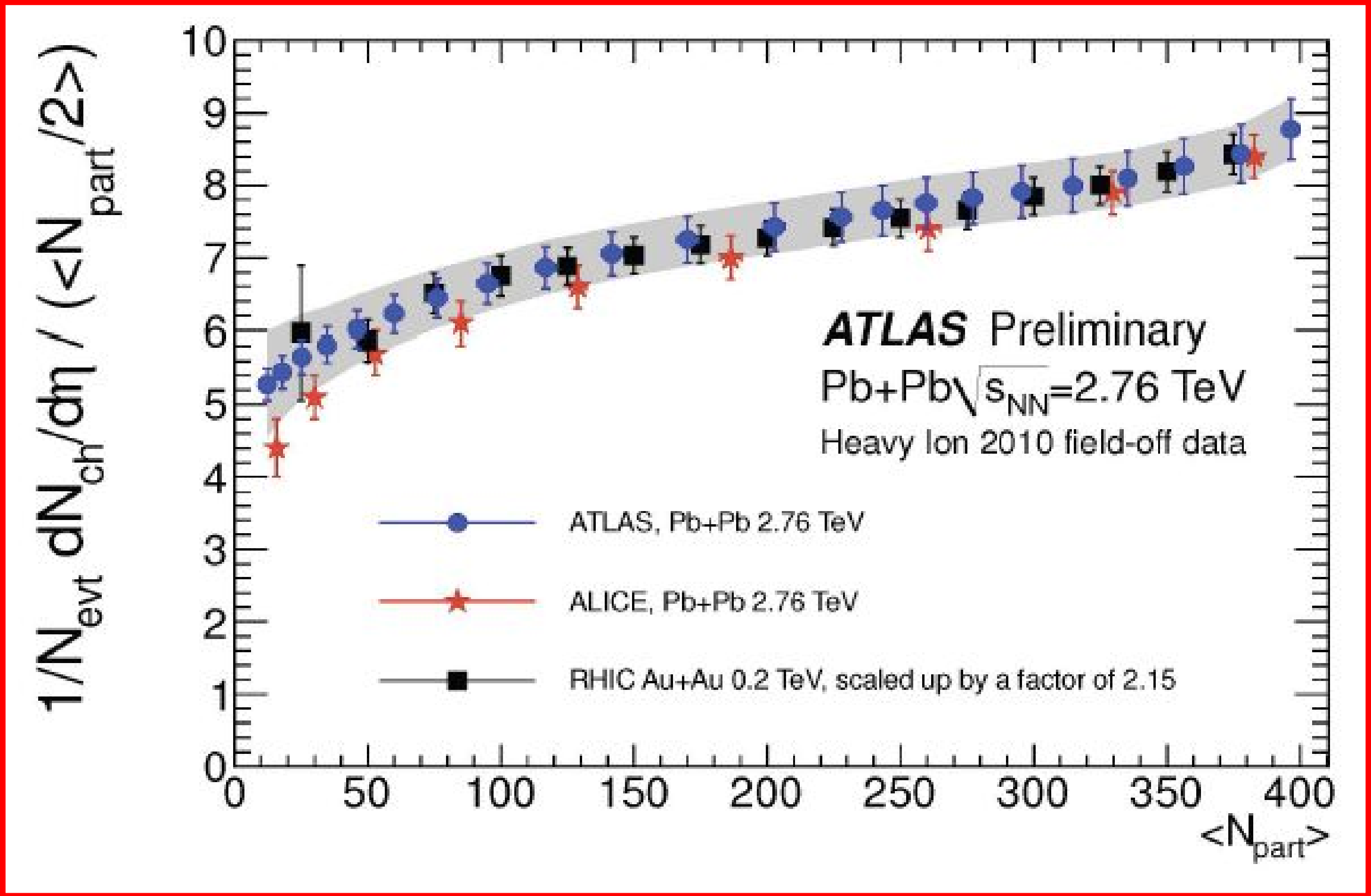


Energy dependence of the charged particle density at mid-rapidity per pair of participants in pp and central AA collisions

[K. Aamodt et al. (ALICE) Phys. Rev. Lett. 105, 252301 (2010)].

[I. Tserruya, arXiv:1110.4047v1, 2011]

Even this increase mainly reflects the observed increase in the average p_T rather than an increase of the differential elliptic flow $v_2(p_T)$. This latter changes very little from $\sqrt{S_{NN}}$ = 39 GeV upto the new LHC data point.

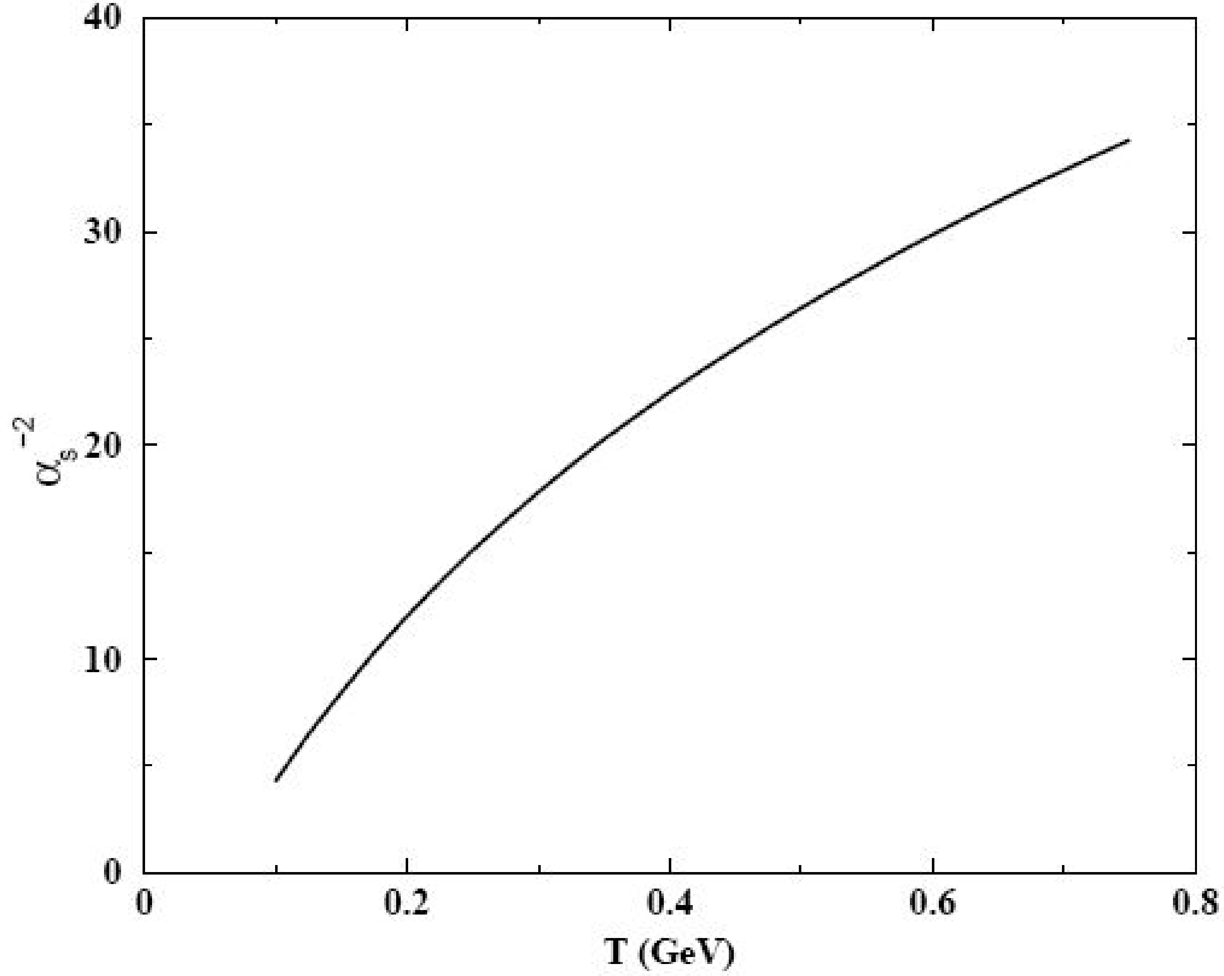


Centrality dependence of the charged particle density per pair of participants in AA collisions at LHC and RHIC [P. Steinberg, (ATLAS), arXiv:1107.2182]. The latter has been scaled up by a factor of 2.15 for a better shape comparison with the LHC data.

[I. Tserruya, arXiv:1110.4047v1, 2011]

This saturation of v_2 at around or below 39 GeV clearly indicates that the “perfect fluid” property of the QGP discovered at RHIC is valid for LHC energies to at least 2.76 TeV.

On a pedagogical level $\eta / s \tilde{\alpha} \; 1/\alpha_s^2$, it changes very little as one goes from RHIC → LHC. Even at the highest level of energy to be achieved at LHC 5.5 TeV, our prediction is η / s will not change perceptibly.



$$\eta/s \;\propto\; 1/\alpha_s^2$$

Clearly, seemingly unrelated systems lead to somewhat similar values of η / s - from the QGP of the perfect fluid produced at RHIC on to LHC, to Ultra Cold Quantum degenerate strongly interacting nearly Fermi gas, to the microsecond early universe to neutron star, Graphene to even Giant Resonances in finite nuclei.

The fundamental reason for that unexpected universality linking energy scales some 18 orders of magnitude can be traced to universality in few body physics.

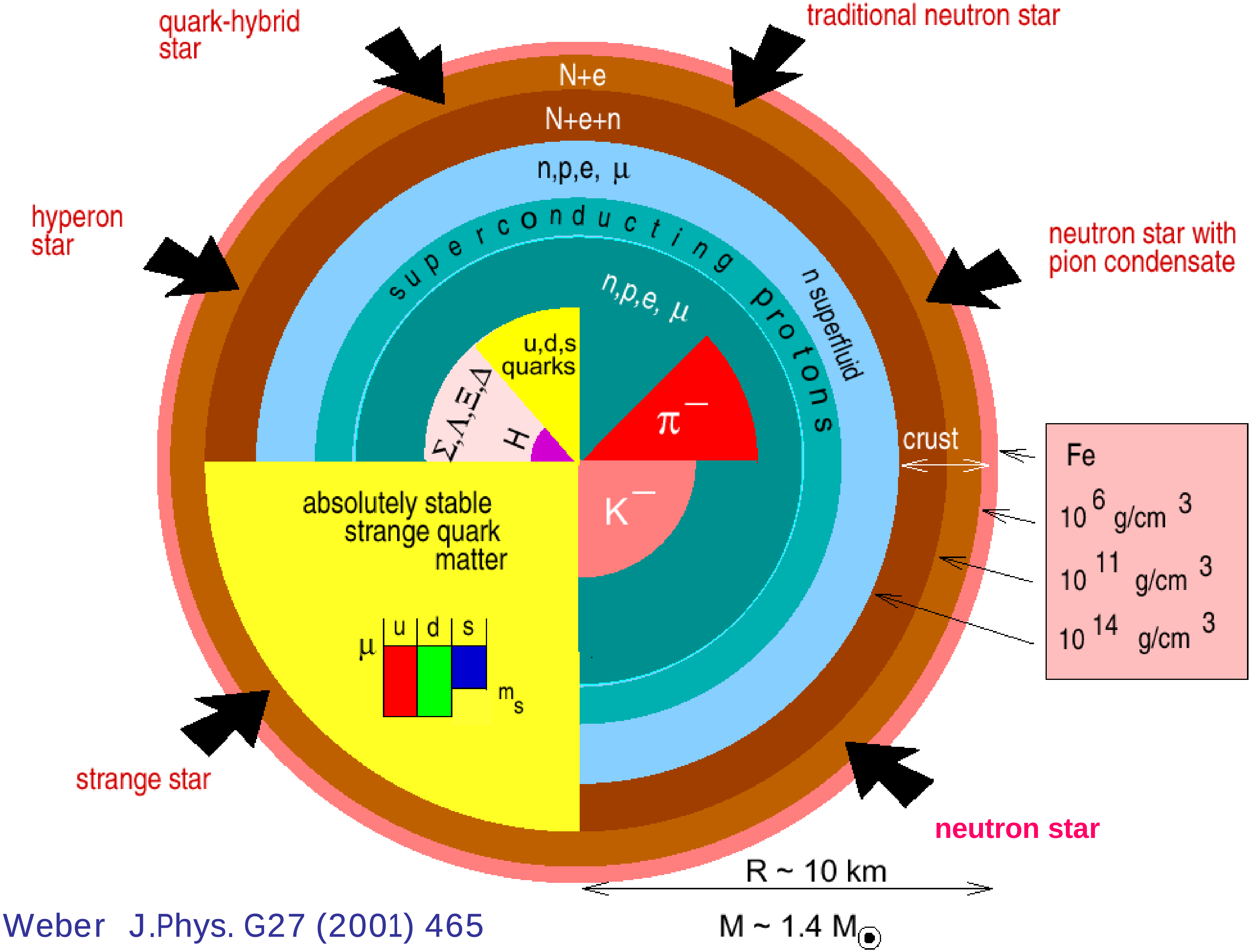
Efimov’s (PLB 33, 1970) astonishingly and counterintuitive prediction highlighted this years ago. This is manifest for Graphene, atomic nucleus and cold Fermi gas.

Indeed, in a different guise, the strong coupling at the phase transition point implies that some correlation among the quarks and gluons may indeed survive within the plasma near the critical temperature and go on to produce multi-particle interactions with immediate neighbours.

The correlation is rather similar to the short range observed in ordinary liquid near the phase transition to gas. It has all to do with the point of phase transition with strong correlation and nothing else! All we need is strongly interacting system of any system.

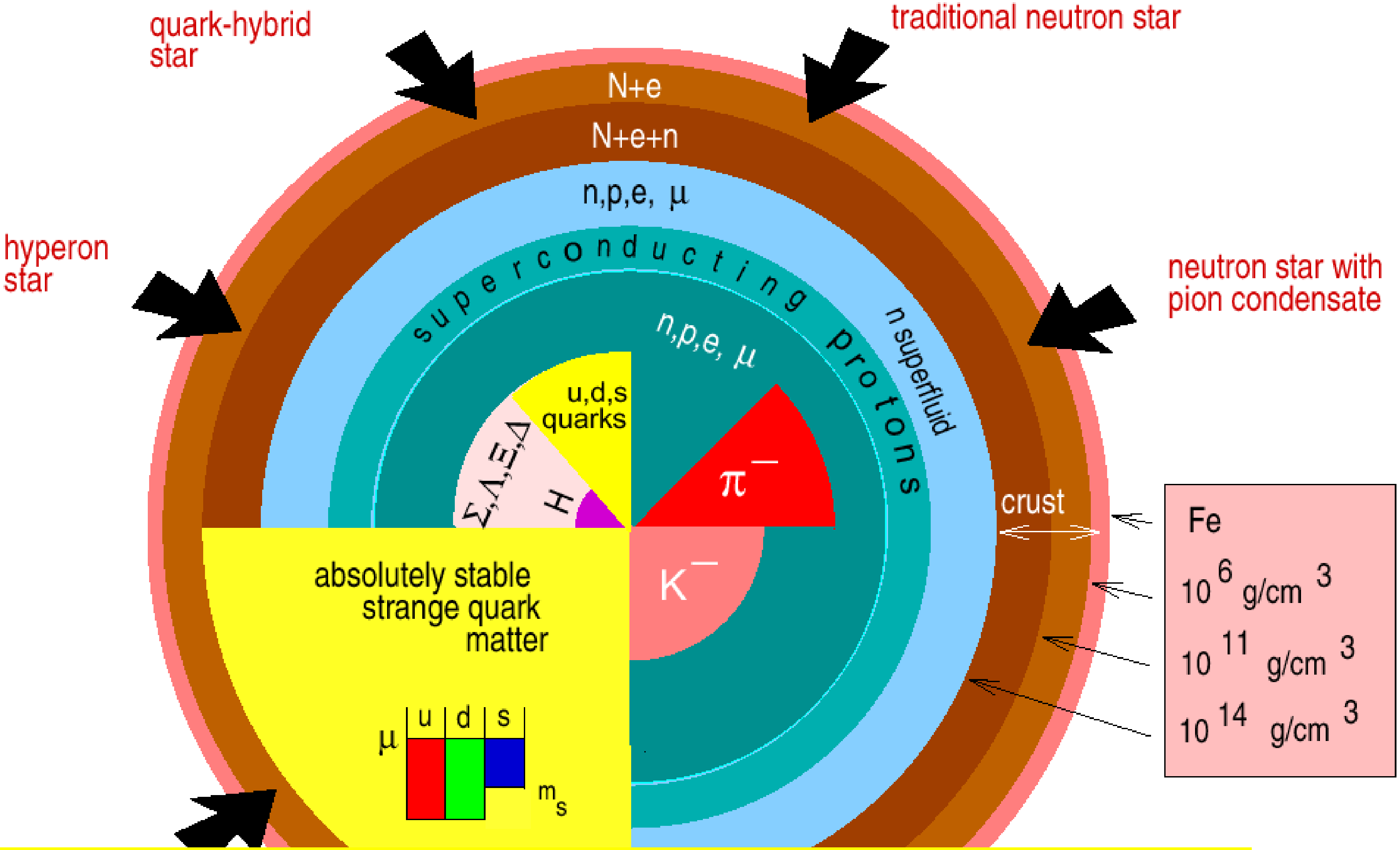
Now,
Neutron Star
&
The Early Universe (Micro second)

Strongly interacting matter in neutron stars

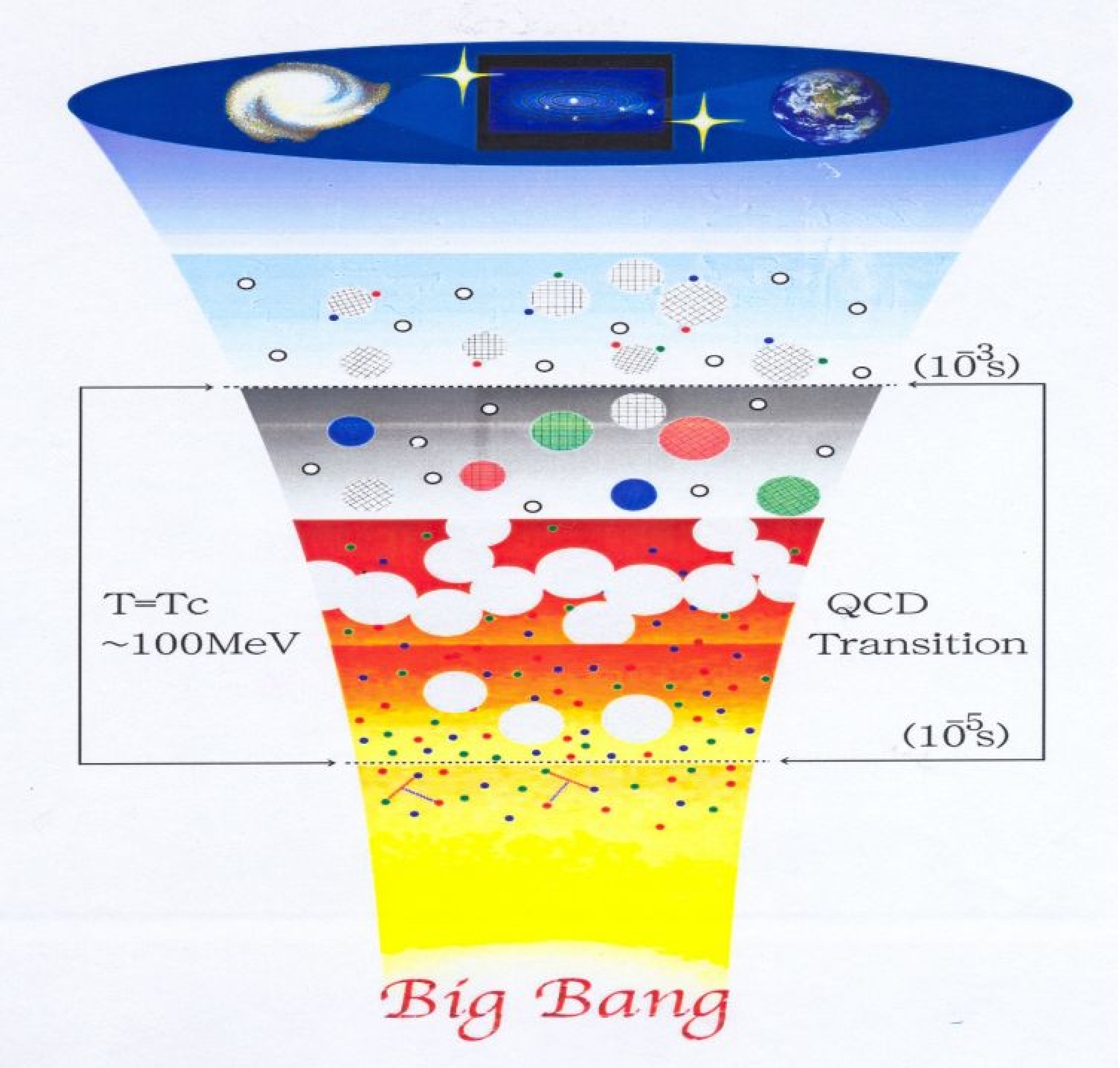


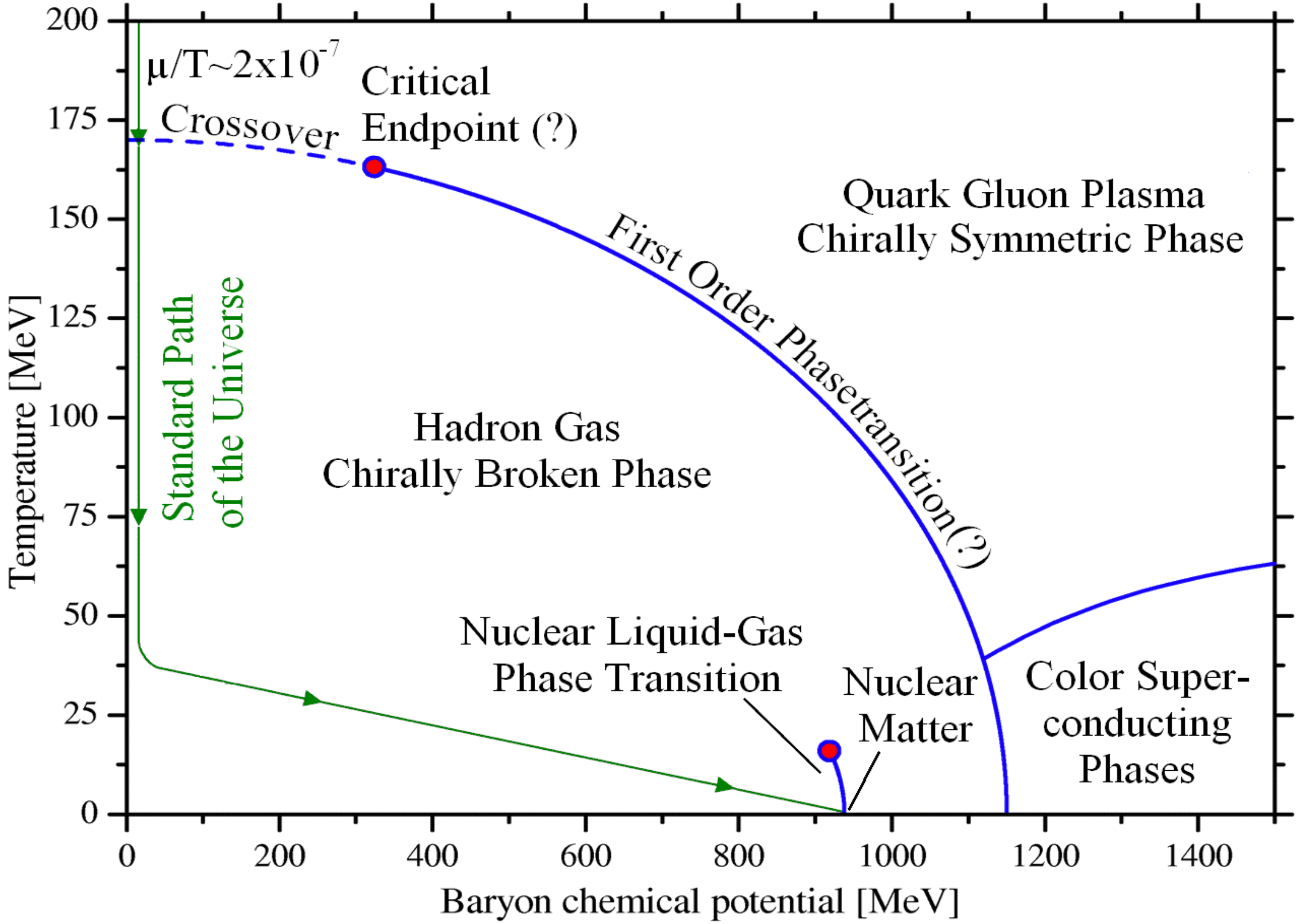
F. Weber J.Phys. G27 (2001) 465

Strongly interacting matter in neutron stars

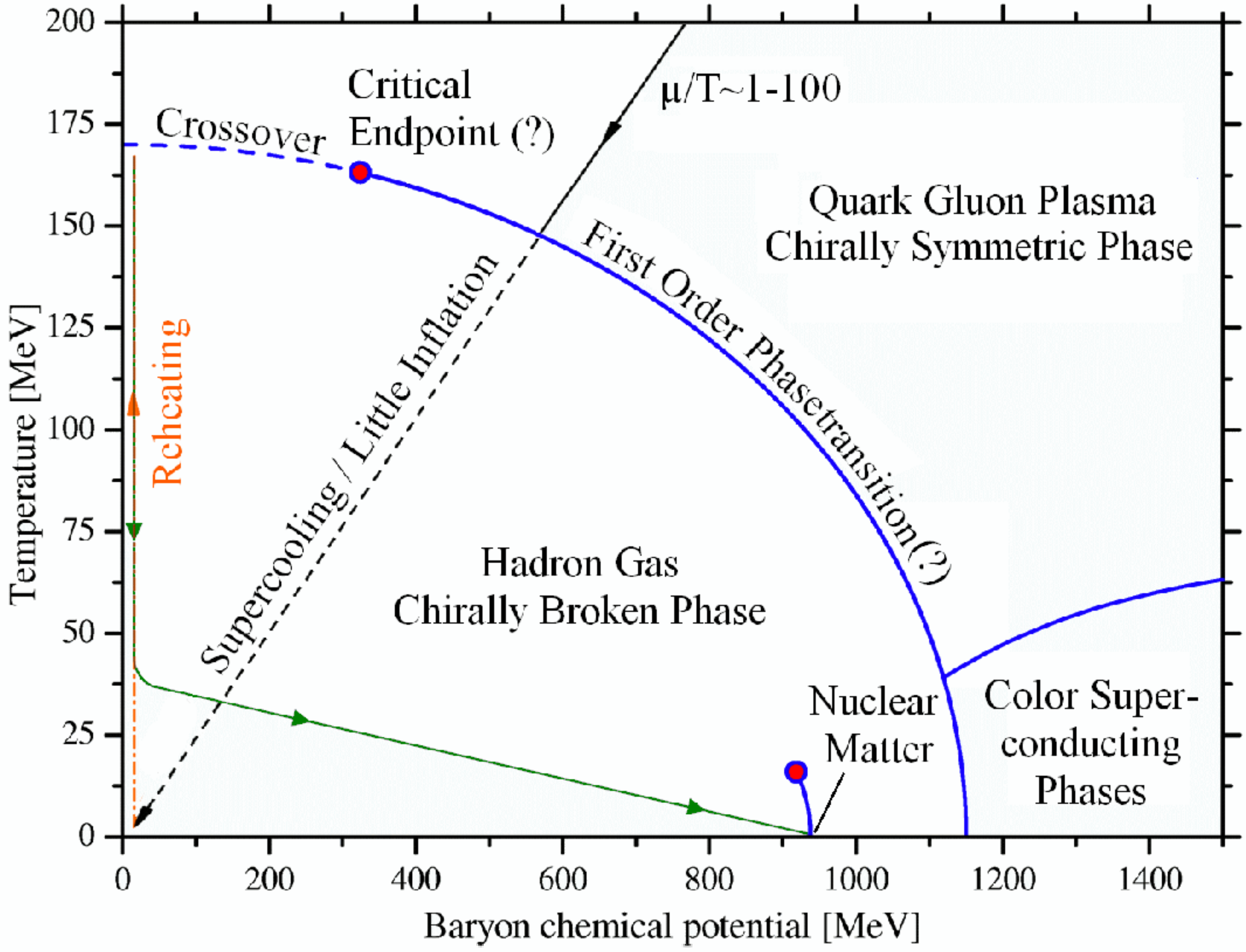


"Strangeness" of dense matter ?
In-medium properties of hadrons ?
Compressibility of nuclear matter?
Deconfinement at high baryon densities ?


(10^{-3}s)
T=Tc
~100MeV
QCD
Transition
(10^{-5}s)
Big Bang



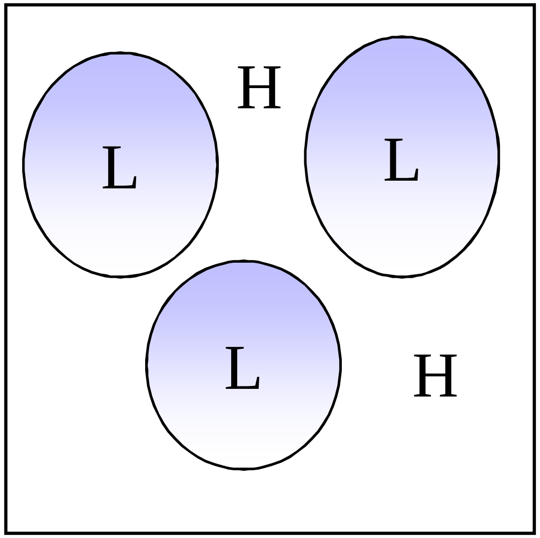
Sketch of a possible QCD-phase diagram with the commonly accepted standard evolution path of the universe as calculated e.g. in [Fromerth and Rafelski] depicted by the green path. [Source: Boeckel and Bielich, 2011, arXiv:1105.0832v2 [astro-ph.CO] and Fromerth and J. Rafelski, (2002), arXiv:astro-ph/0211346.



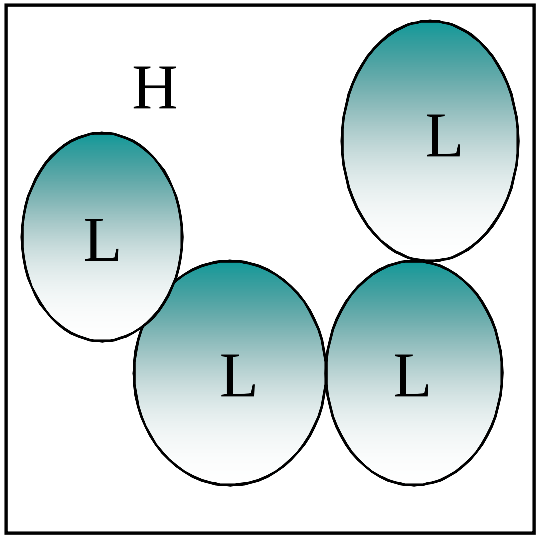
Sketch of a possible QCD-phase diagram with the evolution path of the universe in the little inflation scenario.

[Source: Boeckel and Bielich, 2011, arXiv:1105.0832v2 [astro-ph.CO]]

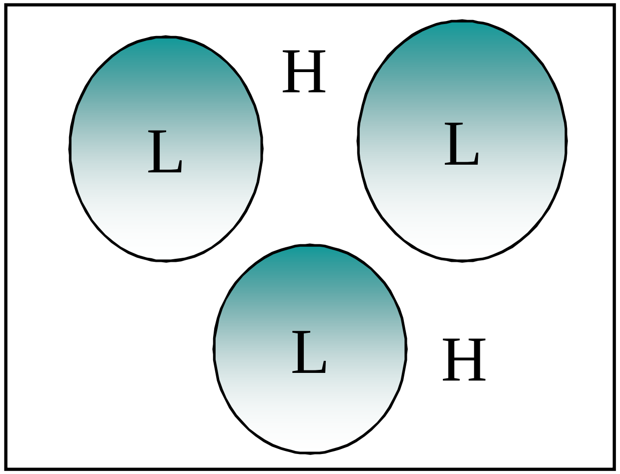
Strange quark nuggets (SQN)



Isolated expanding bubbles of low temp
In high temp phase



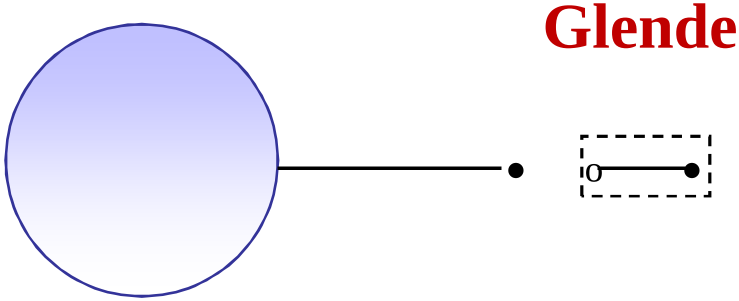
Expanding bubbles meet



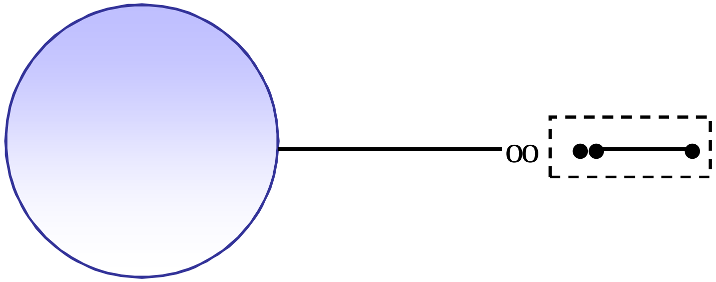
Isolated shrinking bubbles of High temp phase

CEFT MODEL

Glendenning & matsui -1983



meson evaporation



Sumiyoshi et al 1990

Baryon evaporation

Chromo electric Flux-tube fission

P. Bhattacharya
J. Alam
S. Raha
B.S. (PRD ’93)

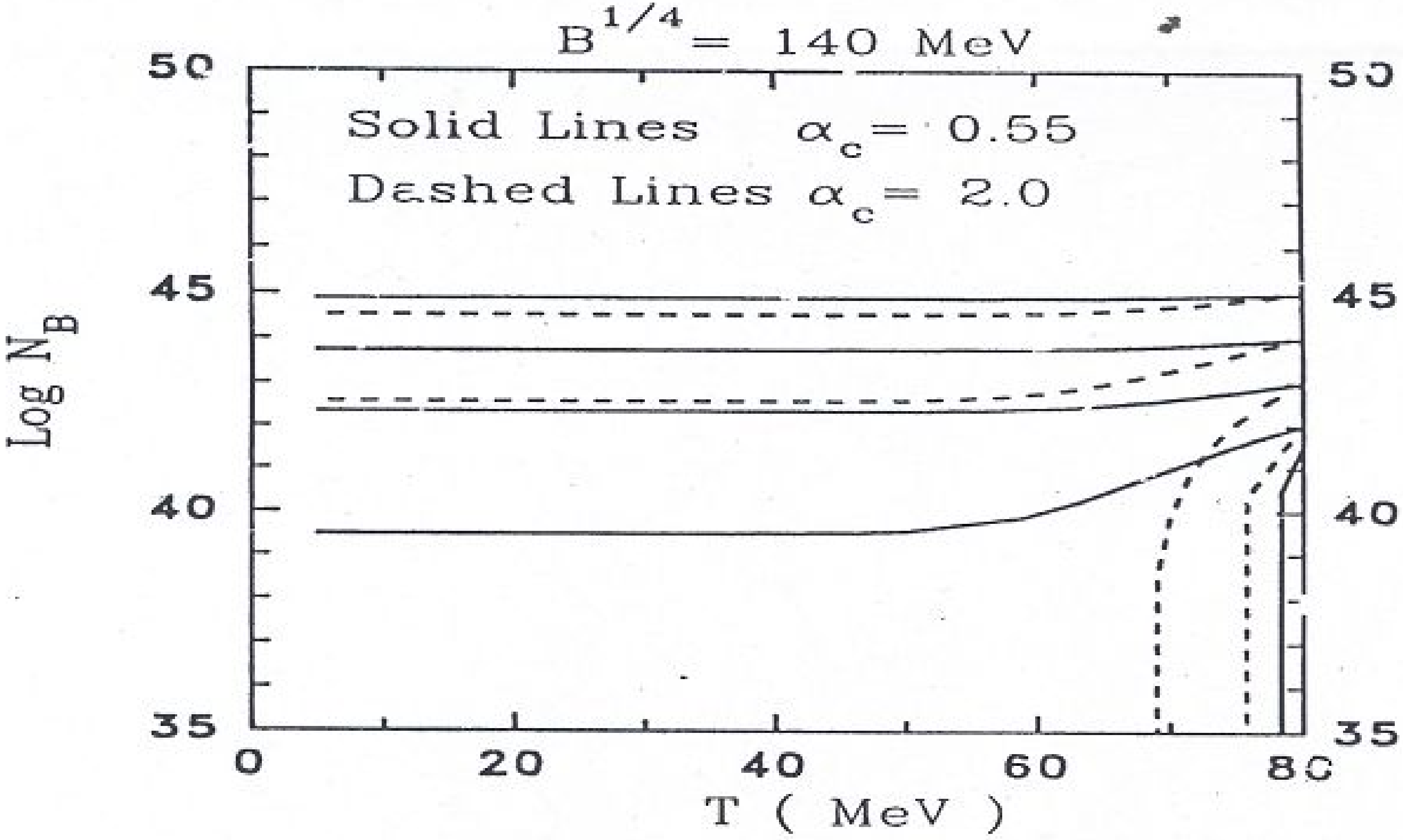
$$dN_B /dt = [dN_B/dt]_{ev} + [dN_B/dt]_{abs}$$

$$[dN_B/dt]_{abs} = -2\pi^2 [n_N \upsilon_N / m_N T^2] \exp [m_N - \mu_N^{\theta} / T] [dN_B / dt]_{ev}$$

Q N's with baryon number N_B at time t will stop evaporating (survive) if the time scale of evaporation

$$\tau_{ev}(N_B,t) \equiv \frac{N_B}{dN_B / dt}$$

$$\overset{\sim}{>>} \; H^{-1}(t) = 2t \text{ of the universe}$$


B$^{1/4}$ = 140 MeV
Solid Lines α_c = 0.55
Dashed Lines α_c = 2.0
Log N_B
T (MeV)
50
45
40
35
0
20
40
60
80

This fascinating universality,

it seems, has opened up

entirely new domain of physics.

THROUGH
THE LOOKING GLASS
Lewis Carroll

Alice in Quark Land

"The time has come," the Walrus said,
"To talk of many things:
Of shoes – and ships – and sealing-wax-
Of cabbages – and kings-
And why the sea is boiling hot –
And whether pigs have wings."