The Astrophysics of Strange Matter

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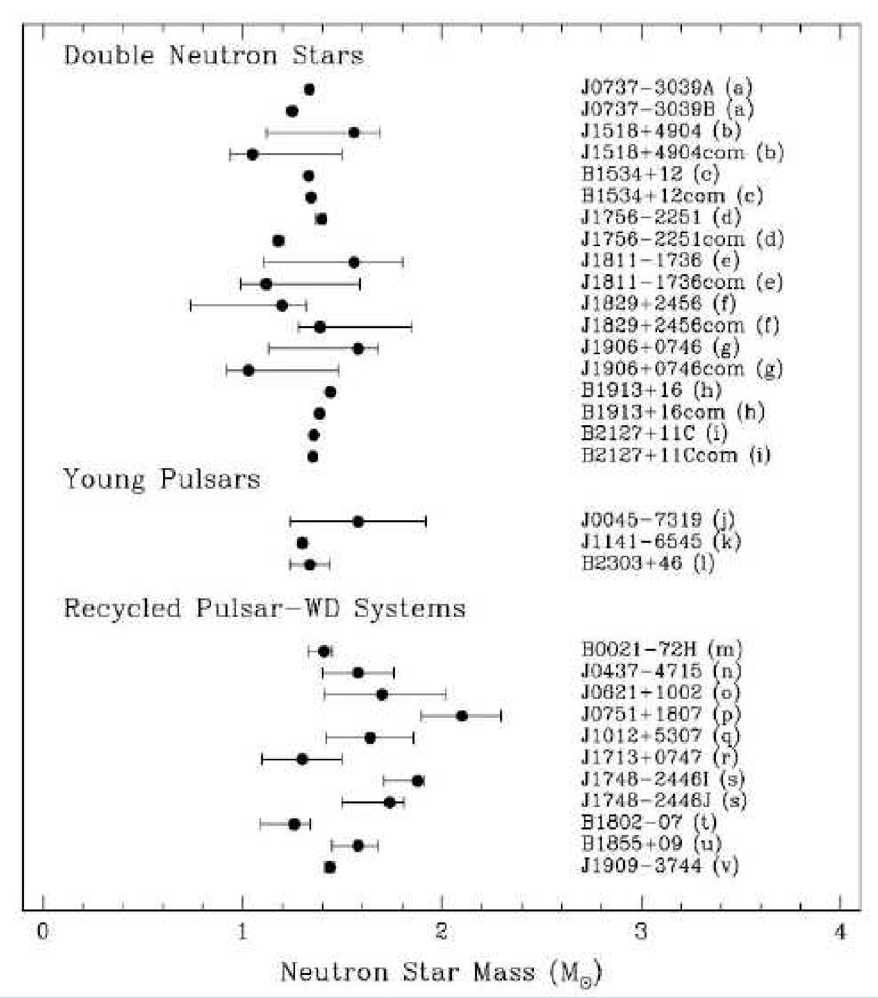
Quark Matter

$T >> \mu$

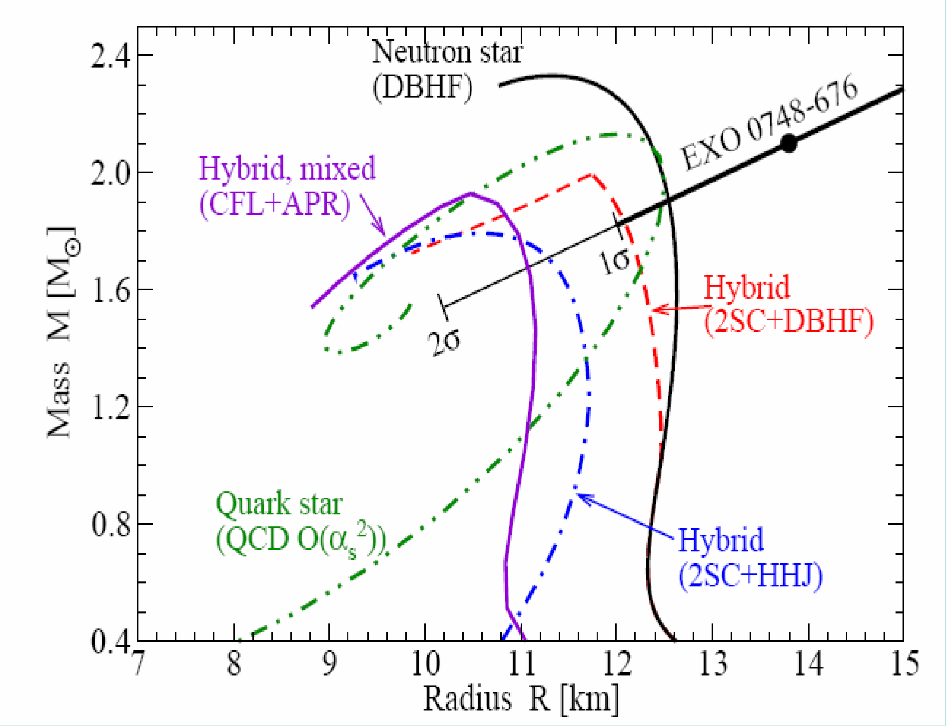
- Quark-gluon plasma phase
- filled the universe after microsecond of big bang
- created in the laboratory in relativistic heavy ion collisions

$T << \mu$

- rich variety of symmetry breaking
- might exist in the interior of compact objects like neutron stars
- time enough for weak interaction – strangeness production



I.H. Stairs, J.Phys G 32, S259 (2006)



M. Alford et al., Nature 445, E7 (2006)

Quark Matter and neutron stars

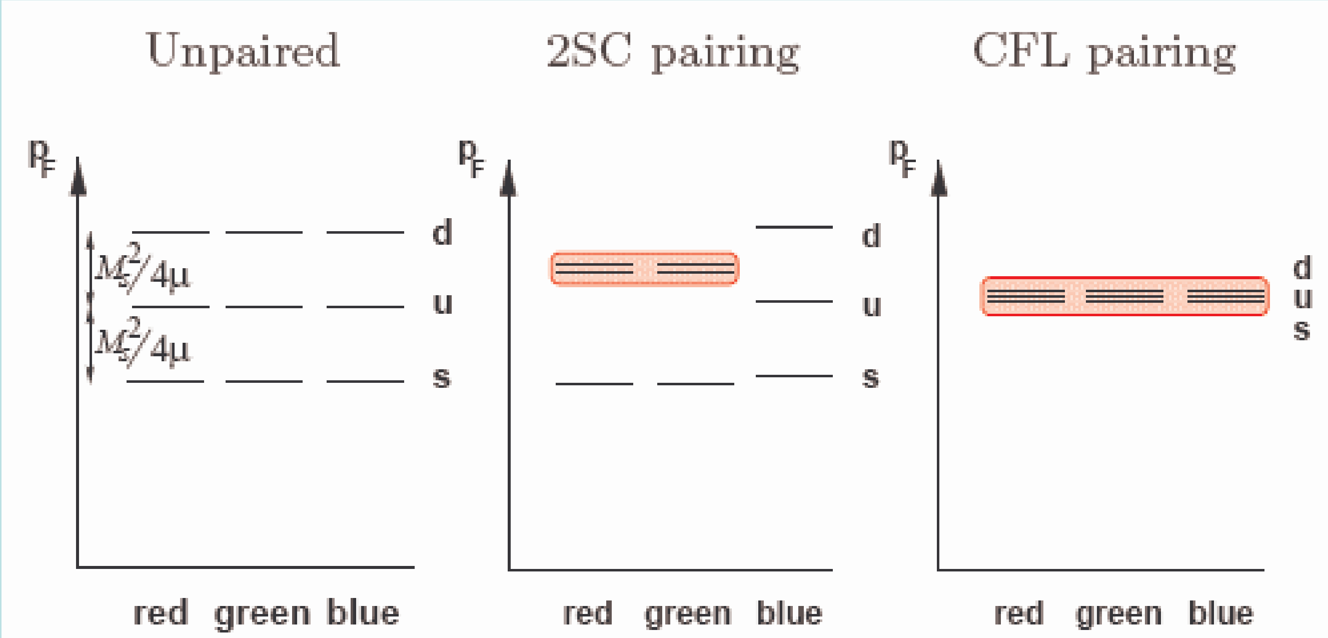
- Different facets:

(a) Symmetry structures at high density systems

(b) Consequences of a quark matter phase
for example : gravitational waves
GRB connection

(c) Mechanism of the phase transition itself

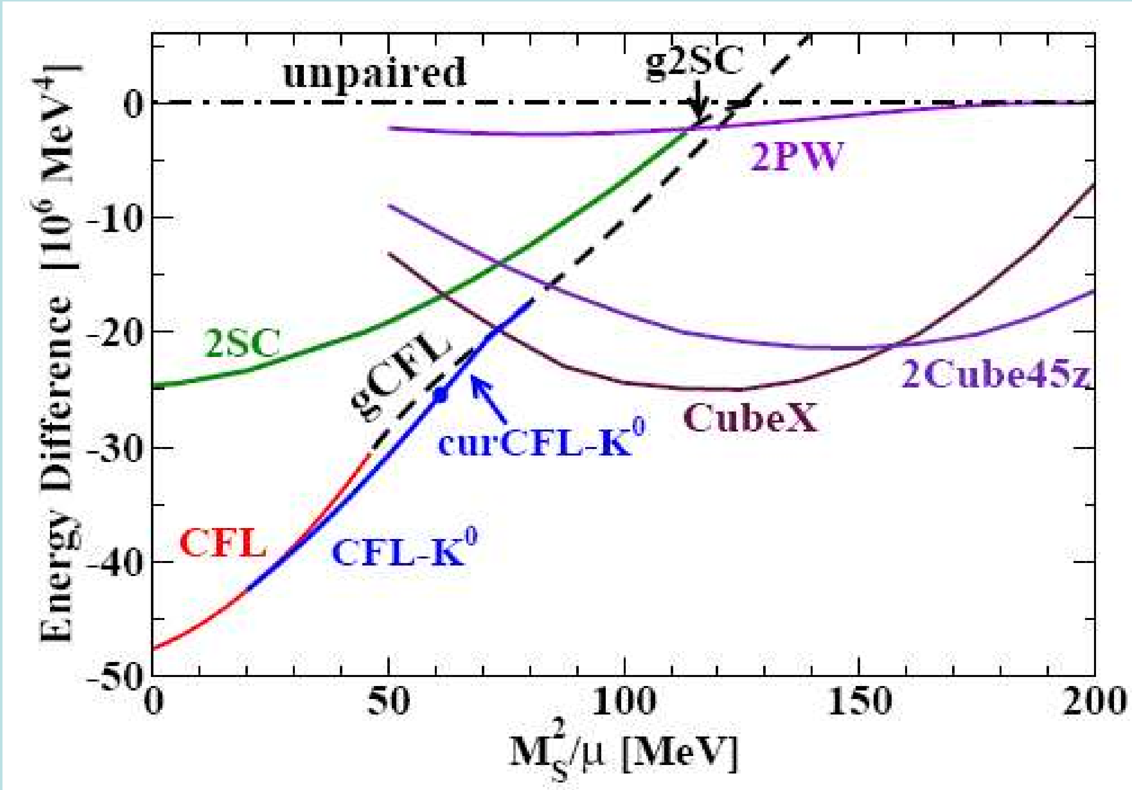
Symmetries



Alford et al.

hep-ph/0709.4635

Rev. Mod. Phys.



Phase Transition : Consequences

- Cooling

1. Direct URCA
   Relativistic NM, Unpaired QM,
   pion and kaon condensates
   single flavour pairing

$$\left.\begin{array}{l} n \to p + e^- + \bar{\nu}_e \\ d \to u + e^- + \bar{\nu}_e \end{array}\right\} \quad \varepsilon_\nu \propto T^6$$

Iwamoto, Ann. Phys. 141 (1982)

Ghosh et al. MPLA9 (1994), IJMPE5 (1996)

2. Modified URCA
   NM at lower density
   (proton fraction < 0.1)

$$\left. n + X \to p + X + e^- + \bar{\nu}_e \right\} \quad \varepsilon_\nu \propto T^8$$

3. CFL phase

$$\left.\begin{array}{l} \pi^\pm, K^\pm \to e^\pm + \bar{\nu}_e \\ \pi^0 \to \nu_e + \bar{\nu}_e \end{array}\right\} \text{suppressed by } \exp(-E/T)$$

$$\left. \varphi + \varphi \to \varphi + \nu_e + \bar{\nu}_e \right\} \quad \varepsilon_\nu \propto T^{15}$$

Jaikumar et al. PRD66 (2002)

Reddy et al. NPA714 (2003)

Gravitational Waves

- Ripples in space-time curvature propagating through space at the speed of light

- because of their compactness, oscillating neutron star could be interesting astrophysical source of gravitational wave

- maybe detected by new generation of gravitational wave detectors

Consequences

- r – Mode instability

  - bulk flow known as Rossby modes or r (rotational) mode

  - coriolis force effect

  - radiates away the energy and angular momentum in form of gravitational wave

  - so above a critical frequency spin slow down

  - critical frequency depends on the sources of damping e.g shear and bulk viscosity – larger damping implies larger critical frequency

  - strange stars have larger viscosity so will be affected immediately i.e. strange stars may have higher frequency

  - r-mode rules out CFL quark stars

  - may provide signature of hybrid stars

Madsen PRL85, Andersson et al. IJMPD10, 381 (2001)

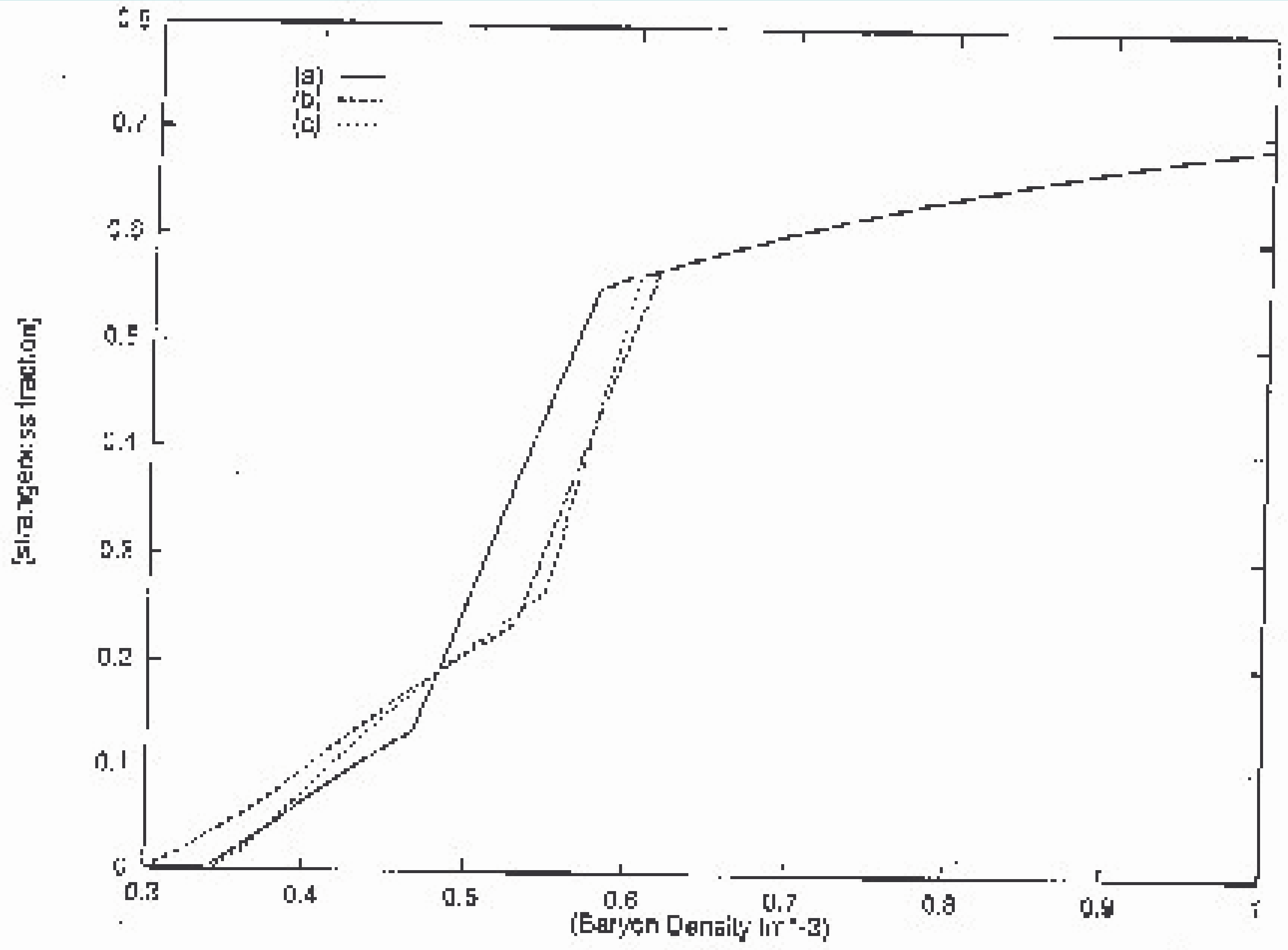
Andersson et al. MNRAS337, 1224 (2002), Drago et al. Astron. Astrophys. 445, 053 (2006)

(For boson condensation picture see Chatterjee et al. PRD75 (2007))

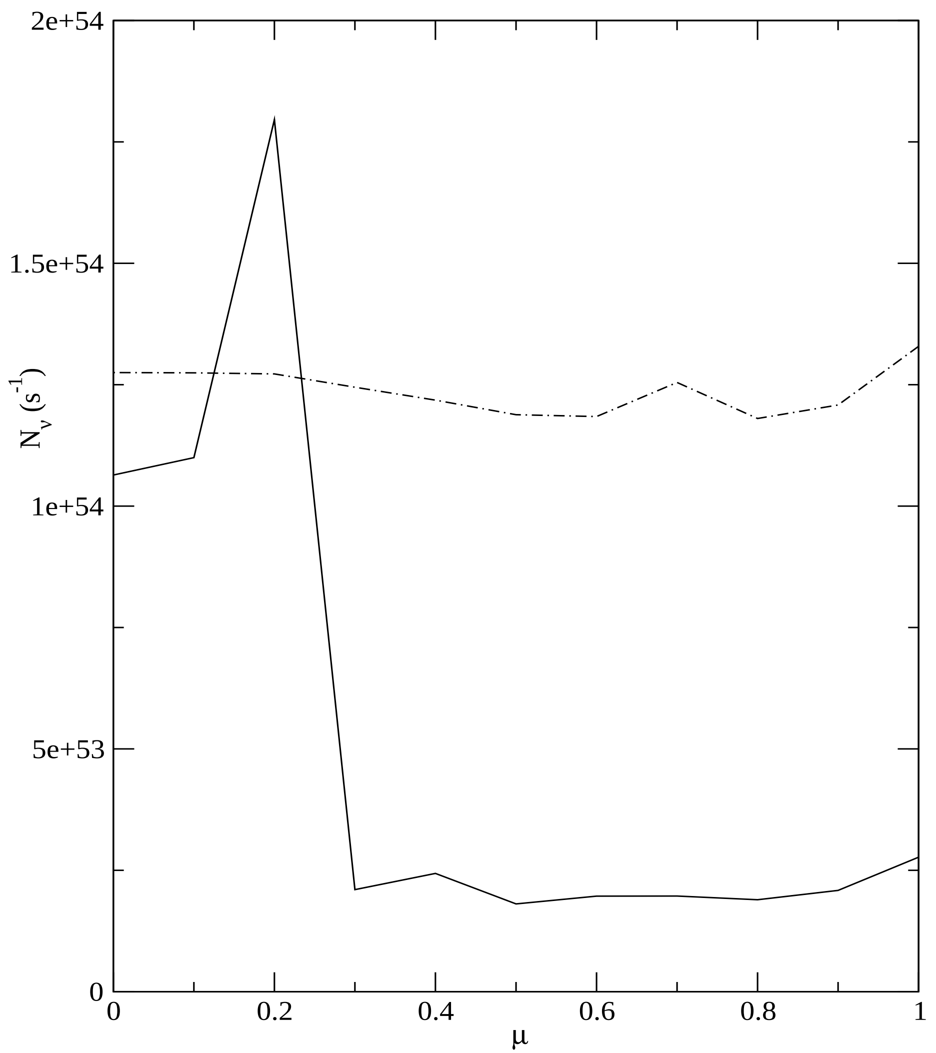
Hadron-quark phase transition – GRB connection

What happens in phase transition ?

1. Hadronic sector : small no. of strange baryons, small strangeness fraction (strange baryon density/total baryon density)
2. Quark sector : Strangeness fraction ~ 1

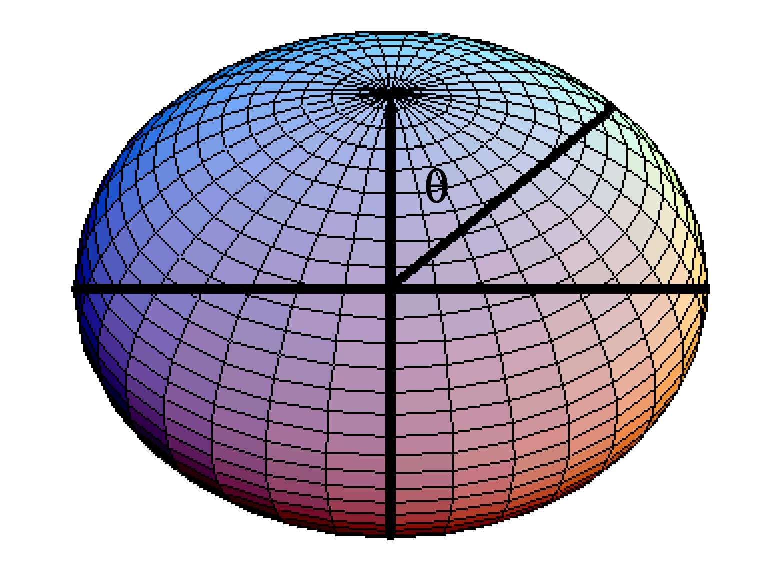


Ghosh et al.
Zphys C1995



$\mu = \cos\theta$

θ → polar angle



Sharp peak - μ = 0.1 and 0.24

θ ≈ 12 degrees

Ghosh et al. PLB635 (2006)

GRB connection ….

- Time scale $10^{-3} - 10^{-1}$ seconds

$$\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$$

✸ Normally small energy deposition

✸ The high gravity environment might enhance the deposition (Salmonson & Wilson *APJ, 517 (1999) 859*

Result of two effects

1. **Path bending of neutrinos**
2. **Gravitational red shift**

⇨ **10% energy deposit**

Effect of rotation and gravitation
Bhattacharyya et al. astro-ph/0707.2475 (see Poster for details)

GRB connection……

- Magnetized star in CFL phase

(a) High initial temperature - 30 – 60 MeV

(b) High surface magnetic field - $10^{15} - 10^{17}$ G

- collimated neutrino emission
- time scale 0.001 sec.

Berdermann et al. Prog. Part. Nucl. Phys. 57, 334 (2006)

Mechanism of phase transition

- **Two step process**

  (a) hadronic matter to two flavour matter

  - deconfinement
  - t ~ milliseconds

  (b) two flavour to three flavour matter

  - generation of strange quark via weak process
  - t ~ 100 seconds

  Presence of two fronts ?

  Bhattacharyya et al. PRC74, 065804 (2006)

- **General relativistic effects**

  Bhattacharyya et al. PRC76, 052801(R) (2007)

(see poster for details)

Early Universe

- Contents of the Universe:

  5% Atoms, 25% Cold Dark Matter, 70% Dark Energy

Different Epochs :

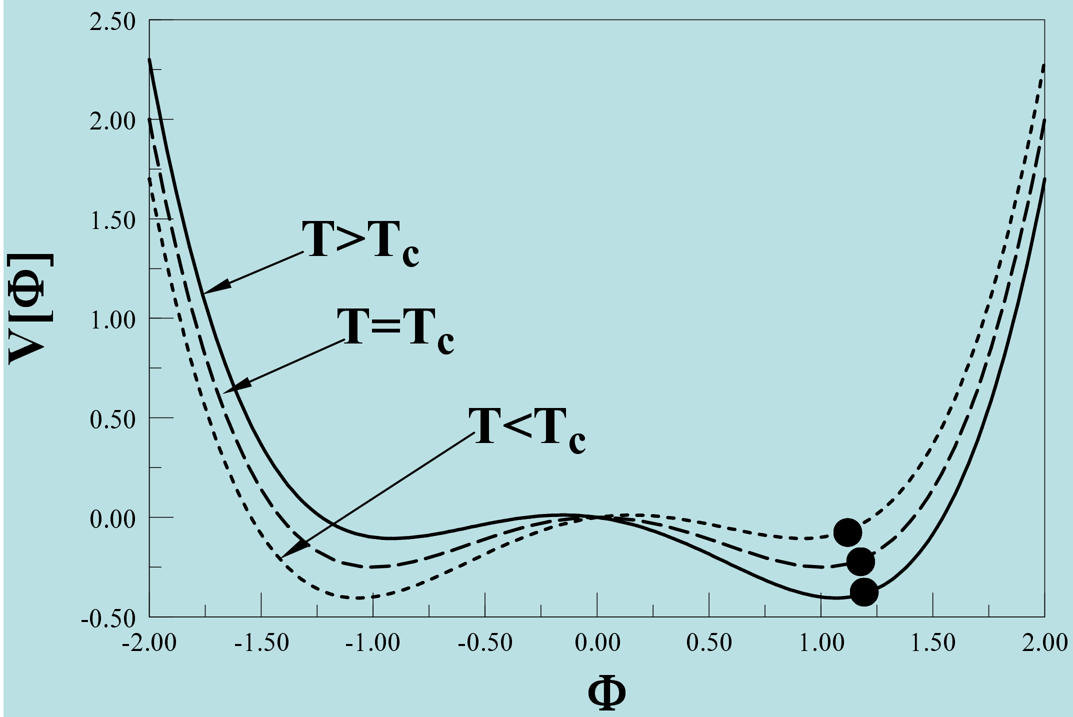
Planck Scale	E ~ 10^{19} GeV
GUT	E ~ 10^{16} GeV
Electroweak	E ~ 100 GeV
QCD	E ~ 100 MeV
Nucleosynthesis (Nuclear Physics)	E ~ 2 MeV
Recombination (Atomic Physics)	E ~ 10 eV

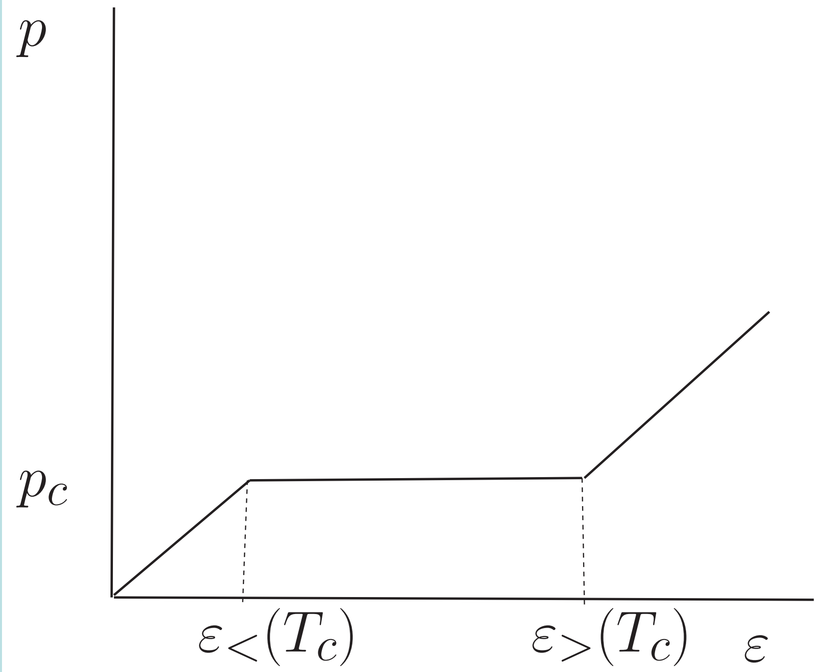
QCD :

(a) Initial conditions for nucleosynthesis

(b) Relics of transition may obseved today

QCD phase transition



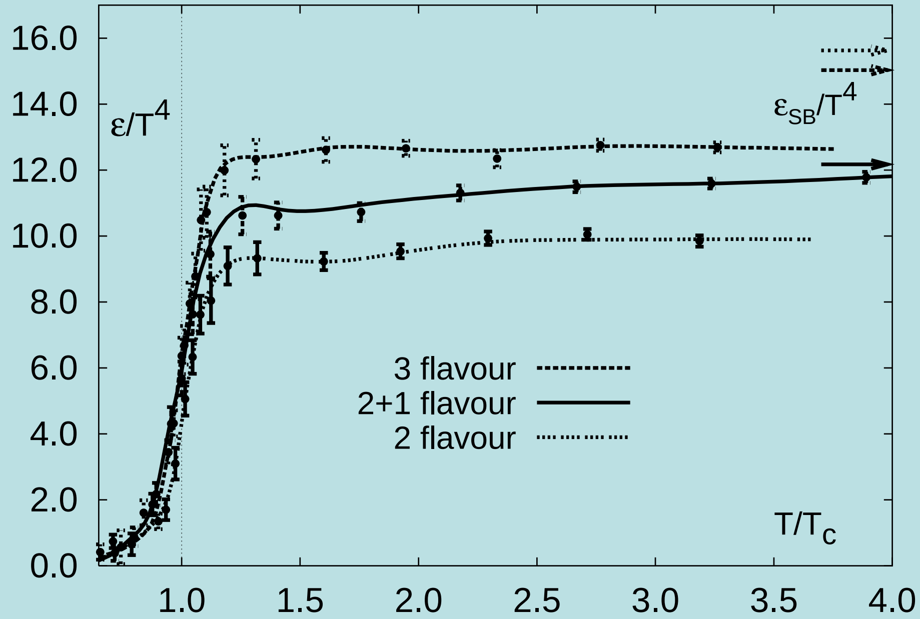


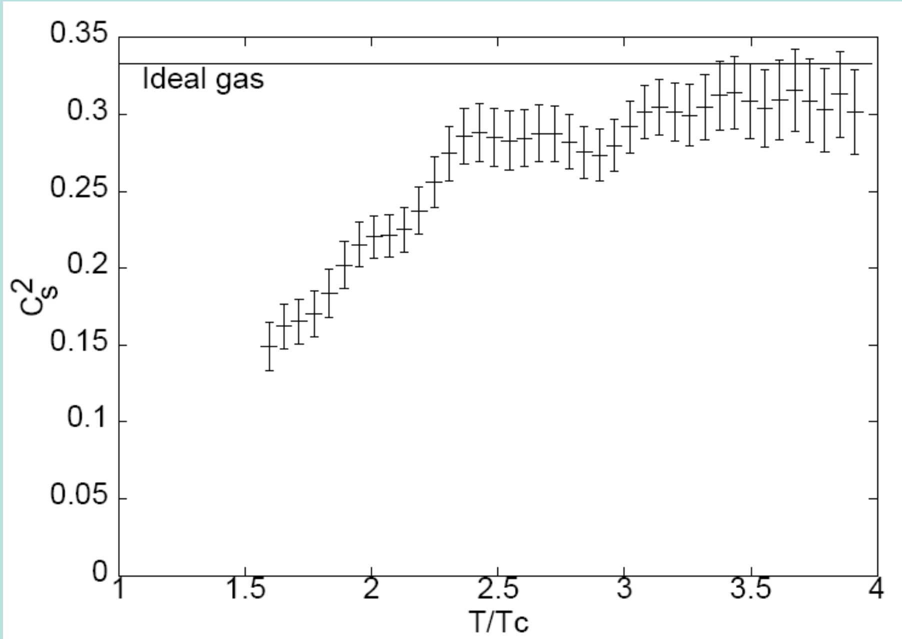
1st Order :

- Position of the minimum of free energy jumps discontinuously
- free energy difference gives latent heat
- speed of sound is zero in mixed phase

QCD Phase Transition

- Lattice results





- Sharp change in energy density
- Sharp drop in speed of sound

Karsch et al. PLB478, 447 (2000), Bernard et al. PRD55, 6861 (1997)

Gupta S. Pramana 61, 877 (2003), S. Raha(1983)

Debye Length and QGP

- colour charges neutralised within Debye length d ~ 1/gT
- d < hadronic radius (R) ⇨no bound state of coloured charges

- life time of QGP ≡ temperature at which d >R

- Universe >>d ⇨Overall colour neutral
- need for sufficient no.of colour charge inside debye volume

- upto Tc d~ fm, total colour charge inside inside debye volume ~ 10
- Baryon number is carried by quarks
- ⇨ net quark no. – multiple of 3

- Net quark no. within Debye volume ~ 10^{-9}

  ⇨ Need for long range correlation for colour neutrality and integer baryon number

  ⇨ ***Quantum Entanglement***

Role of colour Charge

Assumption : Many body system

$\Downarrow$

Colour is averaged

$\Downarrow$

Only statistical degeneracy

Too Simplified ?????

- Before P.T. ➔ Universe singlet

$\Downarrow$

Wave functions of coloured objects entangled

$\Downarrow$

Universe characterized by perturbative vacuum

$\Downarrow$

During P.T. local colour neutral hadrons

$\Downarrow$

Gradual decoherence of entangled wave functions

$\Downarrow$

Proportionate reduction of vacuum energy

★ In Quantum mechanical sense

completion of quark-hadron P.T.

$\Downarrow$

Complete decoherence of colour wave function

$\Downarrow$

Entire vacuum energy disappear

$\Downarrow$

Perturbative vacuum is replaced by non-perturbative one

Does that really happen ????

Colour neutral

$\Downarrow$

All have integer baryon number

$\Downarrow$

At the moment of formation quark number multiples of 3

$\Downarrow$

Statistical system ➔ some residual colour

$\Downarrow$

For colour neutrality : one or two residual quarks

✹ End of cosmic quark-hadron phase transition

➷ few coloured quarks separated in space

$\Downarrow$

Colour wave functions are still entangled

$\Downarrow$

Incomplete decoherence

$\Downarrow$

Residual perturbative vacuum energy

Dark Energy ~ 10^{-48} GeV^4 (Ω_{DE} ~ 0.7)

✯ DE ➔ Constant

✯ Matter density ➔ decreases as R^{-3}

DE is dominant at late times *Banerjee et al. PLB611 (2005)*

Another Picture: *Oaknin et al. PRD71(2005)*

CS matter nugget – antinugget

separation of charges

Baryogenesis after QCD Phase transition

Summary

- High density physics has interesting posssibilities
- Early universe may still be a interesting place in this crossover era

The End