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Quark Matter in Astrophysics and Cosmology

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Abstract

We discuss the role of quark matter in astrophysics and cosmology. The implications of the dynamics of the quark-hadron phase transition in the early universe for the element abundances from big bang nucleosynthesis and the composition of the dark matter in the universe are addressed. We discuss the possibility of deciding on an equation of state for high density matter by observing the cooling of a neutron star remnant of SN1987A. Quark matter models for the Centauros events, Cygnus X-3 cosmic ray events, high energy gamma-ray bursts and the solar neutrino problem are described.

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1. Introduction. Theories of matter at high density play an important role in understanding a variety of phenomena in cosmology and astrophysics. In particular, recent ideas about the nature of quark matter may shed light on the nature of the quark-hadron phase transition in the early universe, the structure of neutron stars and the possibility of exotic forms of matter.

On february 23rd, 1987 we were fortunate enough to observe the death of a blue supergiant in the nearby Large Magellanic Cloud ($\sim$ 55 kpc away). The supernova SN1987A provides a unique oppurtunity for testing models of stellar collapse, type II supernova explosions, and the formation of remnants (neutron stars or black holes.) Underground neutrino detectors (Kamiokande II and IMB)[1] confirmed the nearly model independent prediction that in a type II supernova, $\sim 10^{53}$ ergs is radiated in neutrinos of a few MeV average energy, within a few seconds. If we keep being fortunate, we might be able to observe the early cooling stages of a young neutron star remnant of SN1987A. Neutron star cooling curves differ significantly for different equations of state. Depending on the existence of such a remnant and the availability of X-ray telescopes when the envelope becomes transparent, an astronomical measurement might tell us how very dense matter behaves.

In what follows we discuss different topics in astrophysics and cosmology, where the understanding of quark matter is important. First, two scenarios for the quark-hadron phase transition in the early universe will be discussed. Next, we describe different neutron star models and their observational consequences. Finally, a few other astrophysical models based on quark matter theories will be mentioned.

2. The Quark-Hadron Phase Transition.

A phase transition from an unconfined quark-gluon plasma to a confined hadronic phase is believed to have taken place at 10^{-5} sec after the big bang, when the universe reached a critical temperature, $T_c \sim 100-200$ MeV. Some scenarios for the dynamics of the phase transition can substantially alter predictions for the element abundances from big bang nucleosynthesis and for the composition of the dark matter in the universe.

An interesting possibility is a scenario of a first-order phase transition[2] that gives rise to a cosmic separation of phases.[3] When the temperature drops below T_c, as the universe expands, bubbles of the confined phase can nucleate. These hadronic bubbles release latent heat (the difference between the energy densities of the two phases), reheating the universe to T_c. At T_c further nucleation is inhibited and the two phases can coexist in pressure equilibrium. As the universe expands, the temperature is kept at T_c by the growth of the hadronic phase at the expense of the quark-gluon phase. The universe may evolve into a completely hadronic phase[4], but it is possible that the shrinking bubbles of the unconfined phase cool and stabilize, surviving this epoch as quark matter nuggets.[3] These nuggets can be absolutely stable if their energy per baryon number is less than 930 MeV. The presence of strange quarks in this quark matter phase is crucial for stability since it increases the fermion degeneracy, lowering the energy of the system. Detailed studies[5] show that, within the uncertainties of strong interaction calculations, three-flavor quark matter can be less energetic than hadronic matter and, therefore, absolutely stable. Stable three-flavor quark matter is called "strange matter".

During this phase transition, up to 95% of the tiny baryon excess is likely to be concentrated in the unconfined phase. The strange matter nuggets would then carry most of the net baryon number at this early time, and, if they survive to the present, they would be a good candidate for the dark matter in the universe. A distribution of these nuggets in lumps larger than ~ 1 cm closes the universe without ever encountering the Earth.[6] However, even if such nuggets are formed, they might not survive the later stages of evolution of the universe, but may evaporate completely.[7]

Independently of the strange matter scenario, this baryon asymmetry will lead to large scale baryon number density fluctuations that may survive until the time of nucleosynthesis.[8] After the phase transition, neutrons diffuse out of the baryon dense regions faster than protons, changing the initial conditions for nucleosynthesis. Detailed treatments[9] of these isothermal baryon density fluctuations can reproduce the primordial abundances of ^2H, ^3He, and, ^4He, with a universe closed by baryons only. (^7Li is overprodoced as compared to the observed abundances.) These scenarios illustrate how one might be able to constrain the physics of the quark-hadron phase transition by analysing its astrophysical consequences.

3. Neutron Stars

Today the universe reaches quark matter densities during stellar collapse. The observation of supernovae and neutron stars will lead to a better understanding of high density matter.

The extremely complex dynamics of stellar collapse has been studied numerically with different equations of state.[10] Comparison of SN1987A, with these simulations might be able to decide on an equation of state.[11]

The remnant of SN1987A may tell us what neutron stars are made of. There are a number of possible equations of state for the composition of neutron stars. These are the more standard nuclear matter models (- see Ref.[12] for a review): Baym-Bethe-Pethick (BBP), Reid (R), Bethe-Johnson (BJ), tensor-interaction (TI), three-nucleon interaction (TNI), Mean Field (MF), and, relativistic mean field (RMF); and, the more exotic phases: quark matter (Q), pion condensate (π), kaon condensate (K),[13] and strange matter (SM).[14,15]

These models differ mostly in the highest density regions of the star, except for the strange matter possibility. If strange matter is stable, the density profile of a strange star is very different from a neutron star's profile. Strange stars can consist of bare strange matter up to the surface, with an almost constant density $\sim 4 \times 10^{14} g/cm^3$ There is no minimum mass for strange stars, unlike neutron stars. As Fig. 1 shows, the mass-radius relation for the different equations of state provide means of differentiating the models. Mass estimates from the observations of binaries lie around 1.4 $M_\odot$, where the models roughly agree. If a small, light compact object is found, it could be a strange star.

We might be able to measure the cooling curve of a young neutron star remnant of SN1987A. The core temperature as a function of time is plotted in Fig.2 for different equations of state. The temperature of the core is regulated by the loss of neutrinos which do not interact with the crust of the neutron star. The thermal structure of the crust and the core evolve essentially independently for roughly 10^4 yr. The core is approximately isothermal, while the crust acts as a thin insulating envelope containing almost all of the temperature gradient. The temperature gradient occurs where electrons become nondegenerate, which corresponds to the outermost layer of a neutron star. The temperature drops between two and three orders of magnitude in this small region.[17] Strange stars can either be bare or have a thin crust (comparable to the thin outer crust of normal neutron stars.[15]) Therefore, the surface temperatures of strange stars can vary by up to two orders of magnitude for a given core temperature (depending on the thickness of the crust), unlike neutron stars. Fig. 3 shows the acceptable ranges of surface temperature versus time for different models. (In this plot we exagerate theoretical uncertainties; a more detailed analysis can yield stronger bounds.) Neutron stars with a quark matter core cool like strange stars with a maximal crust. Pion and kaon condensates cool faster than other models, covering non-overlapping regions in this plot; they can be unambigously confirmed or ruled out. Hopefully, we shall see!

4. A few other 'strange' models

It has been suggested that the Centauros event[18] was caused by either a quark matter glob[19] or a strange matter nugget.[3] This cosmic ray event is very unconventional; the primary fragmented into hundreds of baryons deep in our atmosphere, with zero π^0 and e multiplicities. It presents serious obstacles to standard cosmic-ray models. More Centauros-like events have been reported recently.[20]

Other unconventional high-energy cosmic-ray events have been observed, arriving from Cygnus X-3.[21] The primary for such events might be a metastable low baryon number hadron, with multiple strangeness. originating from a strange star.[22]

Very high energy, short rise time γ-ray bursts can also be better explained with models based on strange stars. Since strange stars are held together by the strong force instead of gravity, they can radiate at super-Eddington luminosities without being disrupted. The burst can have the observed short rise time, since tidal forces will not destroy a strange matter lump that hits a strange star. A model based on these features was proposed for the March 5th, 1979 gamma-ray burst.[23]

A seed of strange matter in a neutron star will convert the star into a strange star. This conversion can be detected as a release of $\sim 10^{58}$ MeV of energy. Depending on the temperature of the original neutron star this energy release can be seen as a gamma-ray burst and as a "super-glitch" in pulsar frequencies.[24]

Finally, it has been recently suggested that the solar neutrino problem may be solved if there is a tiny concentration of strange matter in the sun.[25] Even at extremely low abundances, these strangelets can participate in nucleosynthesis and contribute substantially to stellar energy generation. This additional source of energy lowers the temperature of the Sun's core by a few tenths of a million degrees, reducing the detection rate for the ^{37}Cl detector.

The relevance of quark matter to astrophysics and cosmology is an extensive topic. We hope this attempt to illustrate some aspects of this relationship has been successful. We refer the reader to the references for more detailed disscussions.

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Figure Caption

Fig. 1.- Mass ($M/M_\odot$) versus radius (R) relation for strange stars (dotted line), as in Ref.[15], and neutron stars with different equations of state (solid lines) as in Ref.[12].

Fig. 2.- Core temperature (T_c) as a function of time (t) for different cooling mechanisms: (1) photon emission, (2) modified Urca, (3) crust bremsstrahlung, (4) kaon condensate, (5) pion condensate, and strange matter with strange quark mass, $m_s =$ 100 MeV, and strong coupling $\alpha_c = 0.1$ (a), and $\alpha_c = 0.6$ (b), and $m_s = 300$ MeV, $\alpha_c =$ 0.1 (c), and $\alpha_c = 0.6$ (d). (See Ref.[12] for (1)-(3), and (5); Ref.[16] for (4); and, Ref.[15] for (a)-(d).)

Fig. 3.- Surface temperature (T_s) versus time (t) ranges for different core compositions: standard nuclear equations of state, quark matter core, kaon condensate, pion condensates, and strange stars.

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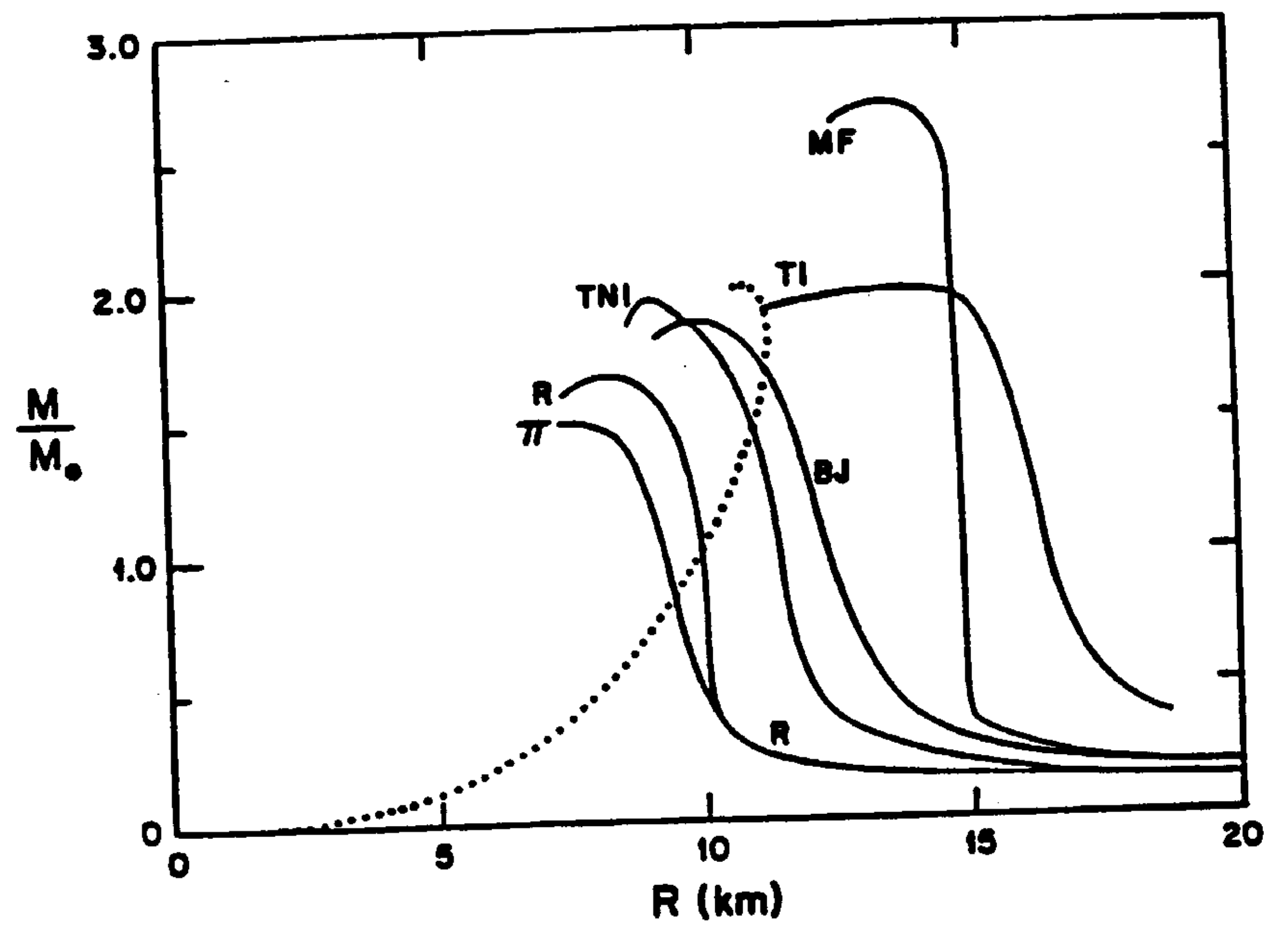
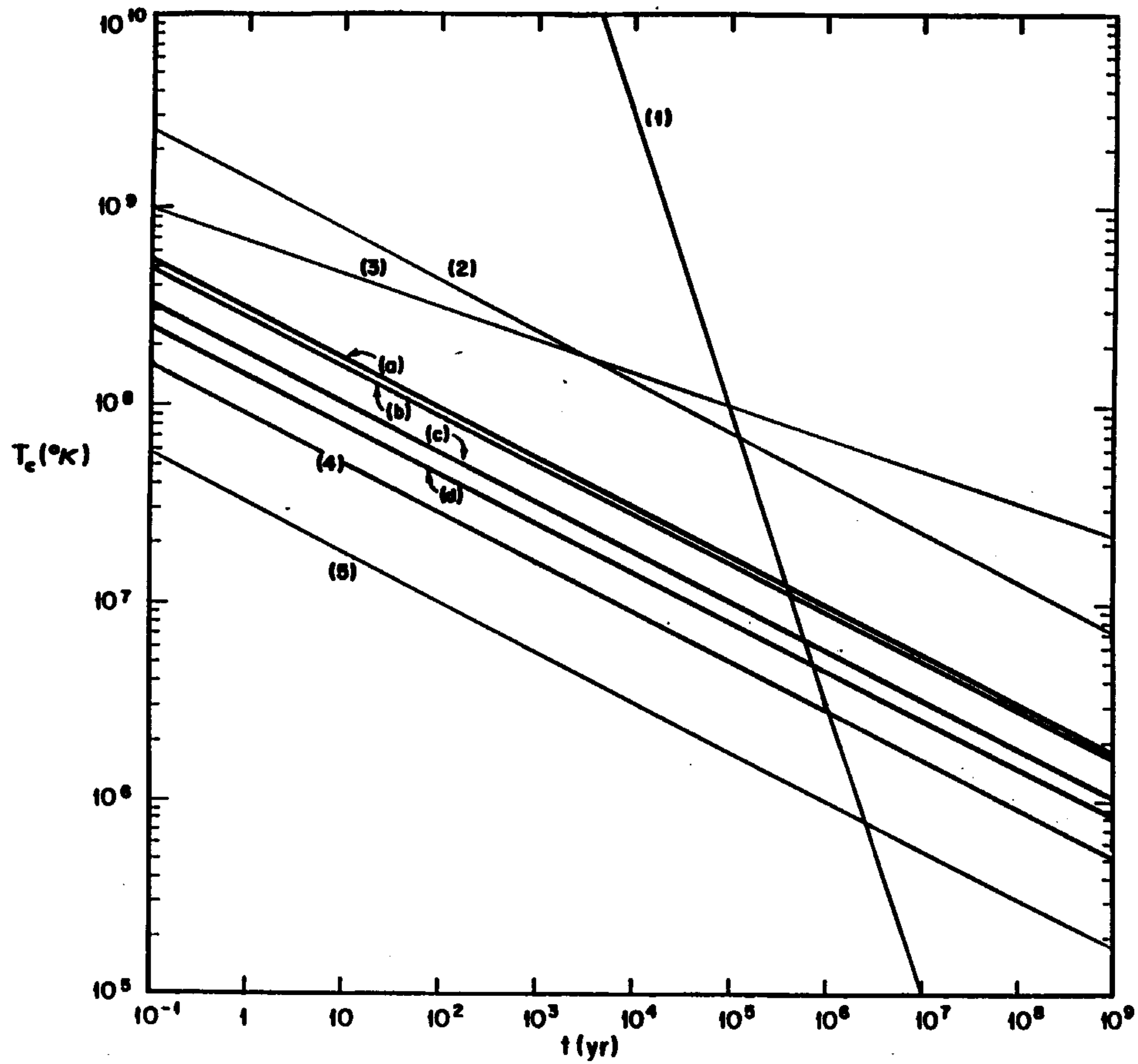


Fig 1



T_c(°K)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
t (yr)
(1)
(2)
(3)
(4)
(5)
(a)
(b)
(c)
(d)

Fig 2

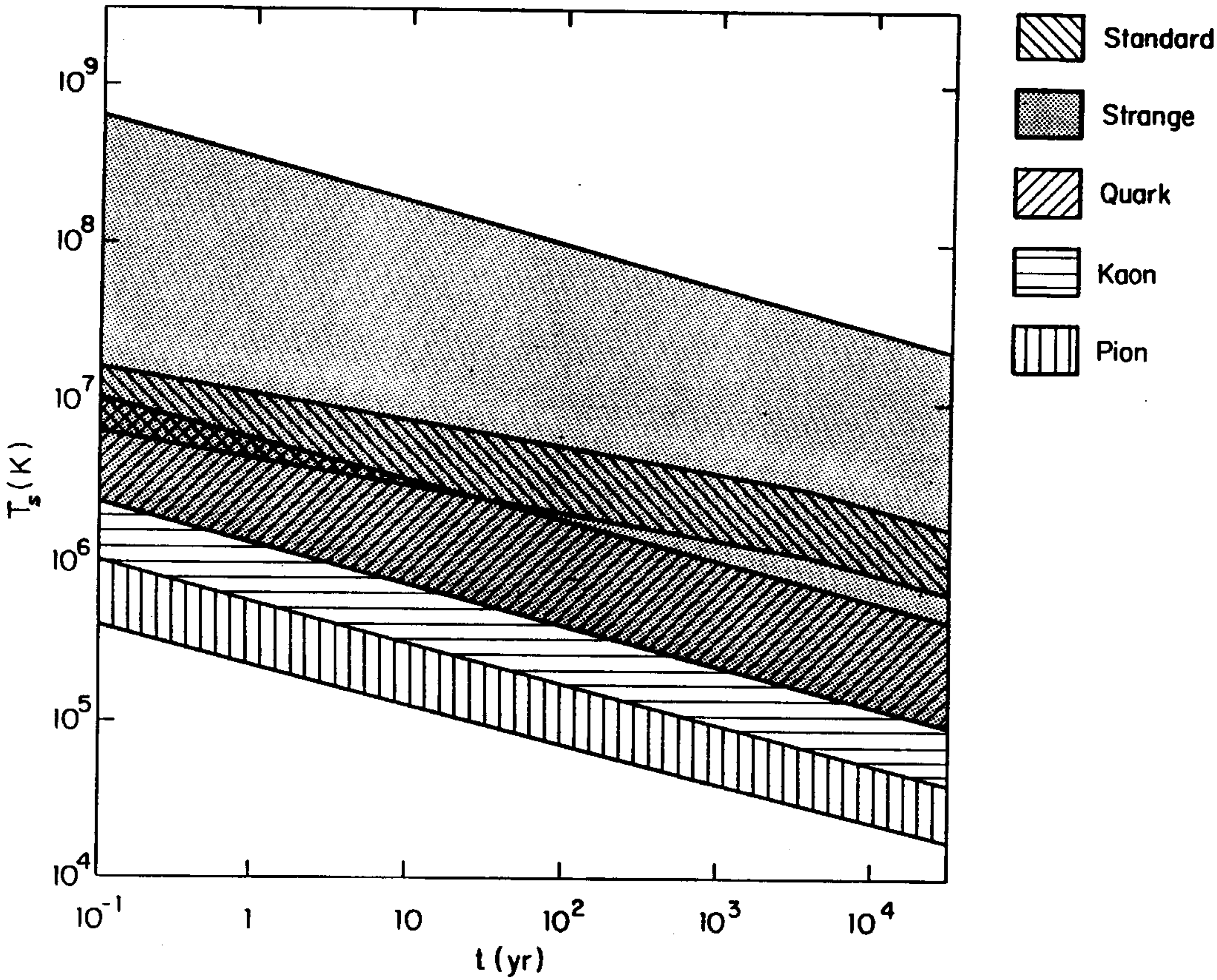

Standard
Strange
Quark
Kaon
Pion
T_s (K)
10^4
10^5
10^6
10^7
10^8
10^9
10^{-1}
1
10
10^2
10^3
10^4
t (yr)

Fig 3