Quark star RX J1856.5-3754 and its mass

Kazunori Kohri
(郡　和範)
RESCEU, Univ. of Tokyo

K. Kohri, K. Iida and Katsuhiko Sato,
Prog. Thor. Phys. 105 (2002) in press

Contents

Introduction

Recent deep Chandra LETG+HRC-S observations of RX J1856.5-3754 reports,

Drake et al., ApJ. 572 (2002) 996-1001

Black body of

$$T = 61.2 \pm 1.0 \text{ eV},$$

X-ray luminosity,

$$L_X = 6 \times 10^{31} (D/140\text{pc})^2 \text{ erg s}^{-1}$$

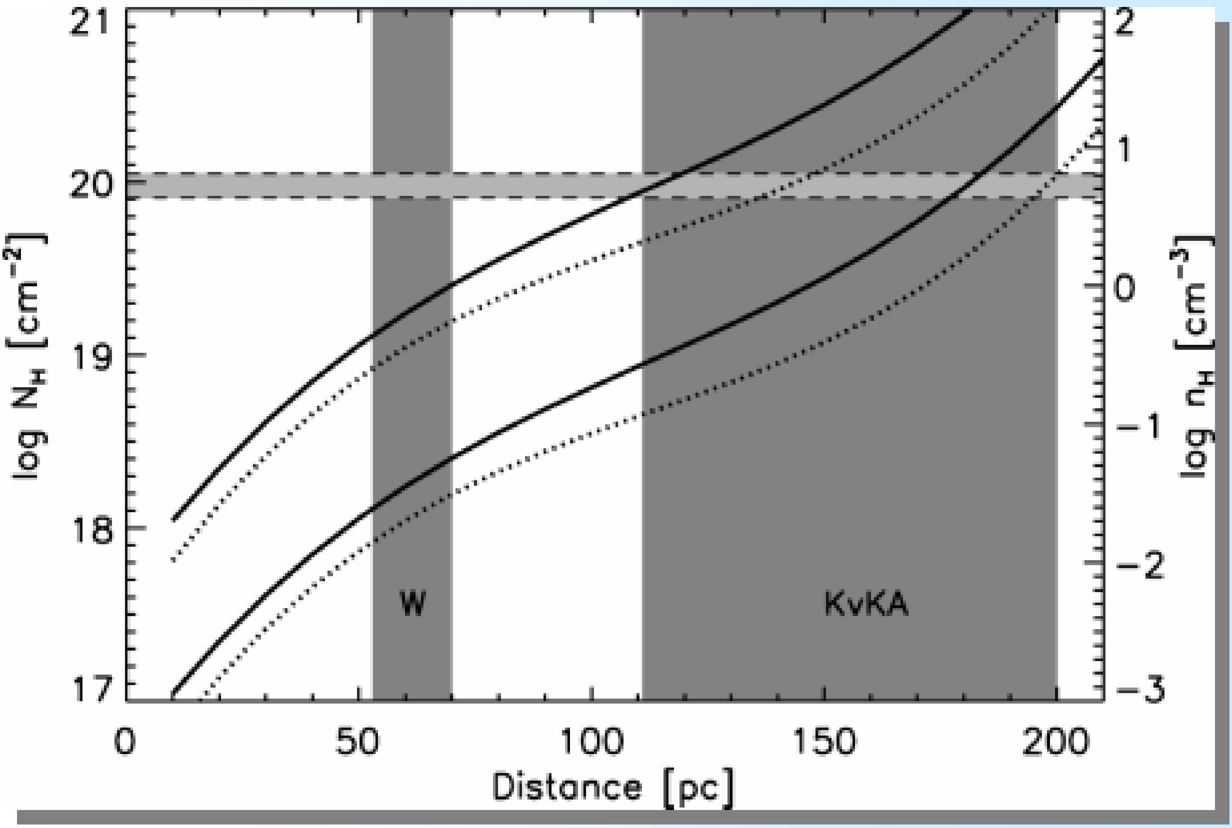
$$\left(= 4\pi {R_\infty}^2 \left(\pi^2/60\right) T^4\right)$$

$$\text{where, } D = 110 - 170\text{pc}$$

Radiation radius

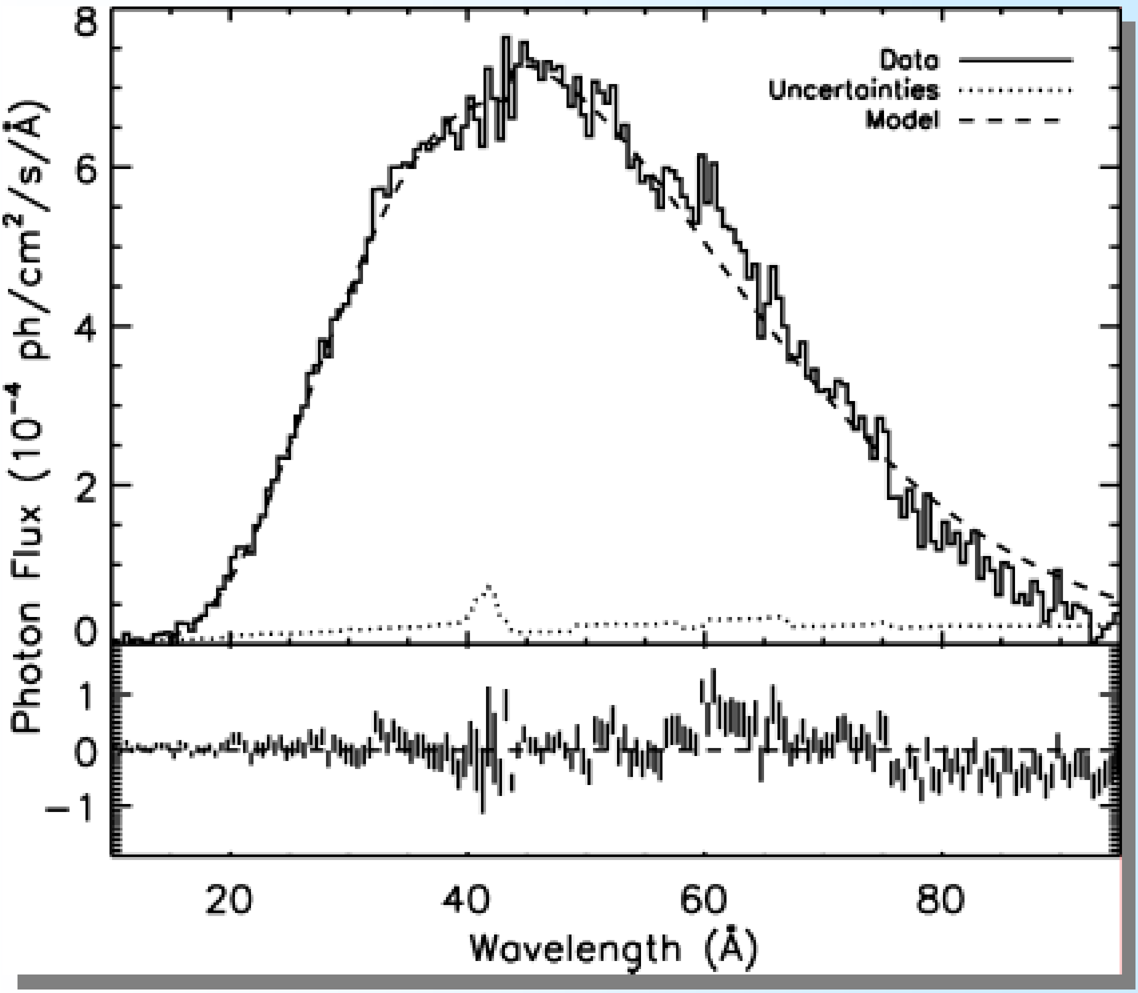
$$R_\infty = 3.8 - 8.2\text{km}$$

Distance toward RX J1856.5-3754



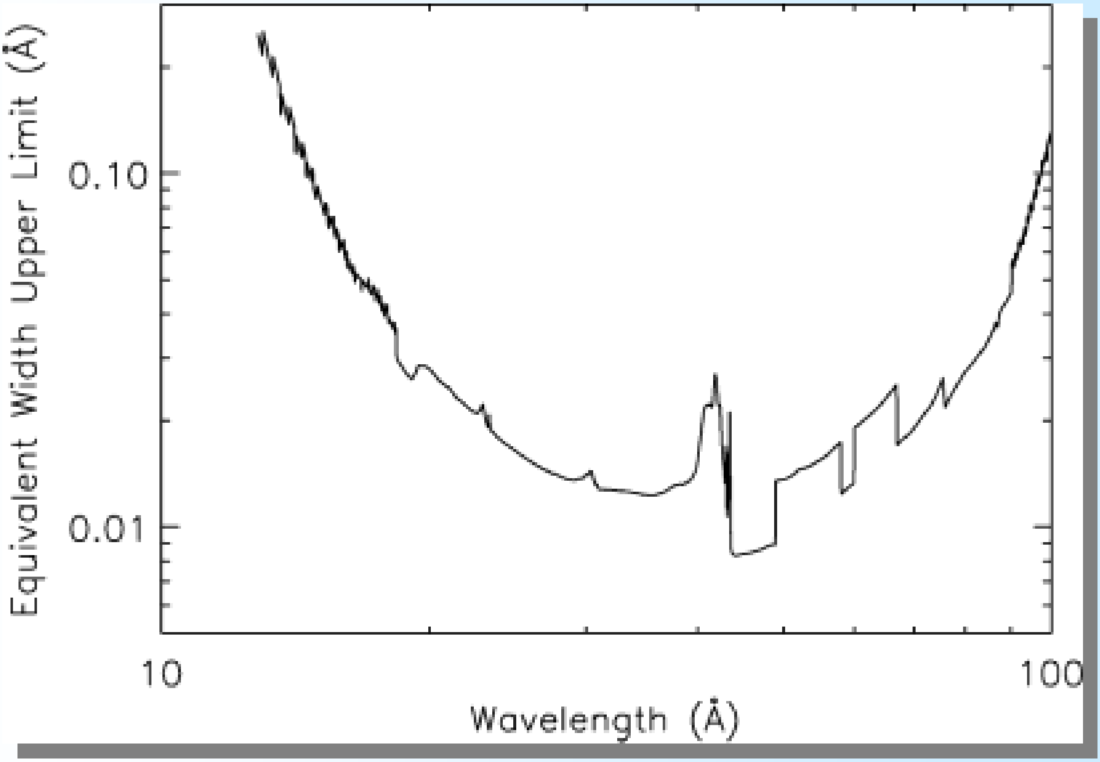
Drake et al., ApJ. 572 (2002) 996-1001

Spectra of RX J1856.6-3754



Drake et al., ApJ. 572 (2002) 996-1001

The 3σ equivalent width upper limit to line features

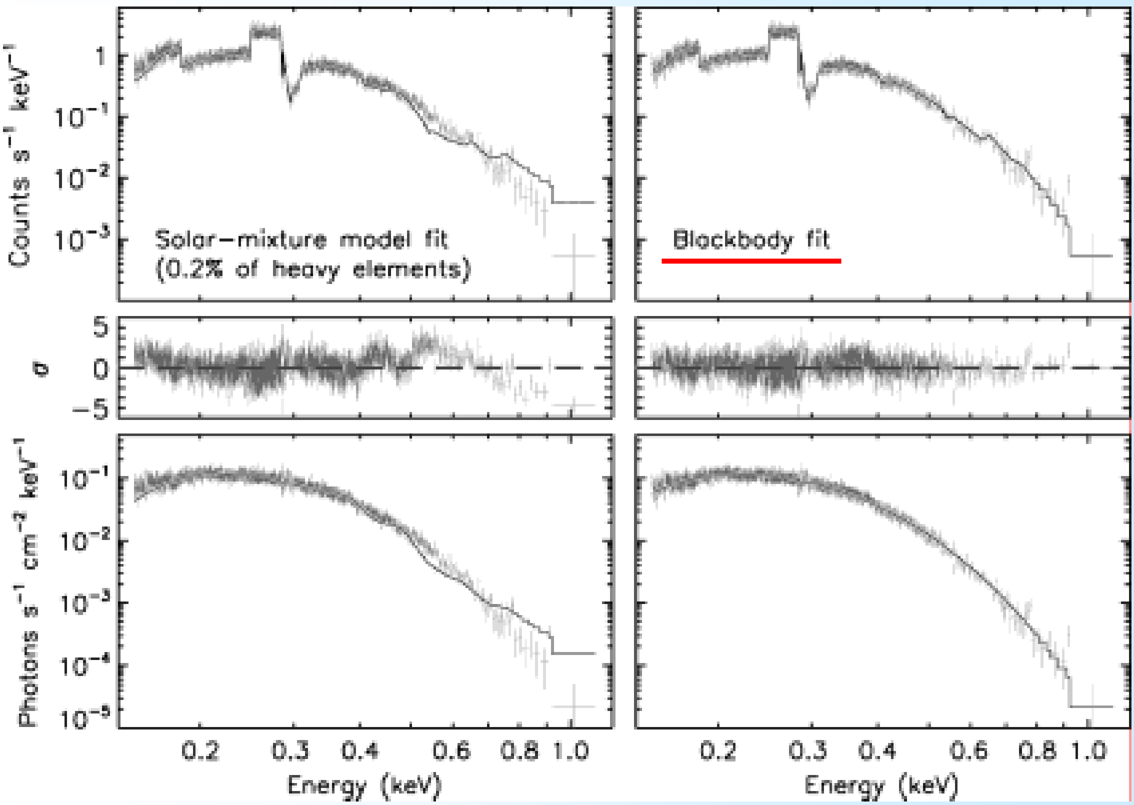


Drake et al., ApJ. 572 (2002) 996-1001

The upper limit on the periodic variation is 2.6 % at 99 % C.L. from 10^{-4} to 100 Hz frequency range

XMM-Newton observation

V. Burwitz et al, astro-ph/0211536



The upper limit on the periodic variation is

1.3 % at 99 % C.L.

from 10^{-3} to 50 Hz frequency range

RX J1856.5-3754 is quark star?

i) No pulsation

ii) No spectral features

iii) Small radiation radius

$$R_\infty = 3.8 - 8.2\mathrm{km}$$

$$\left(= R/\sqrt{1 - 2GM/R}\right)$$

Mass-radius relation of compact star

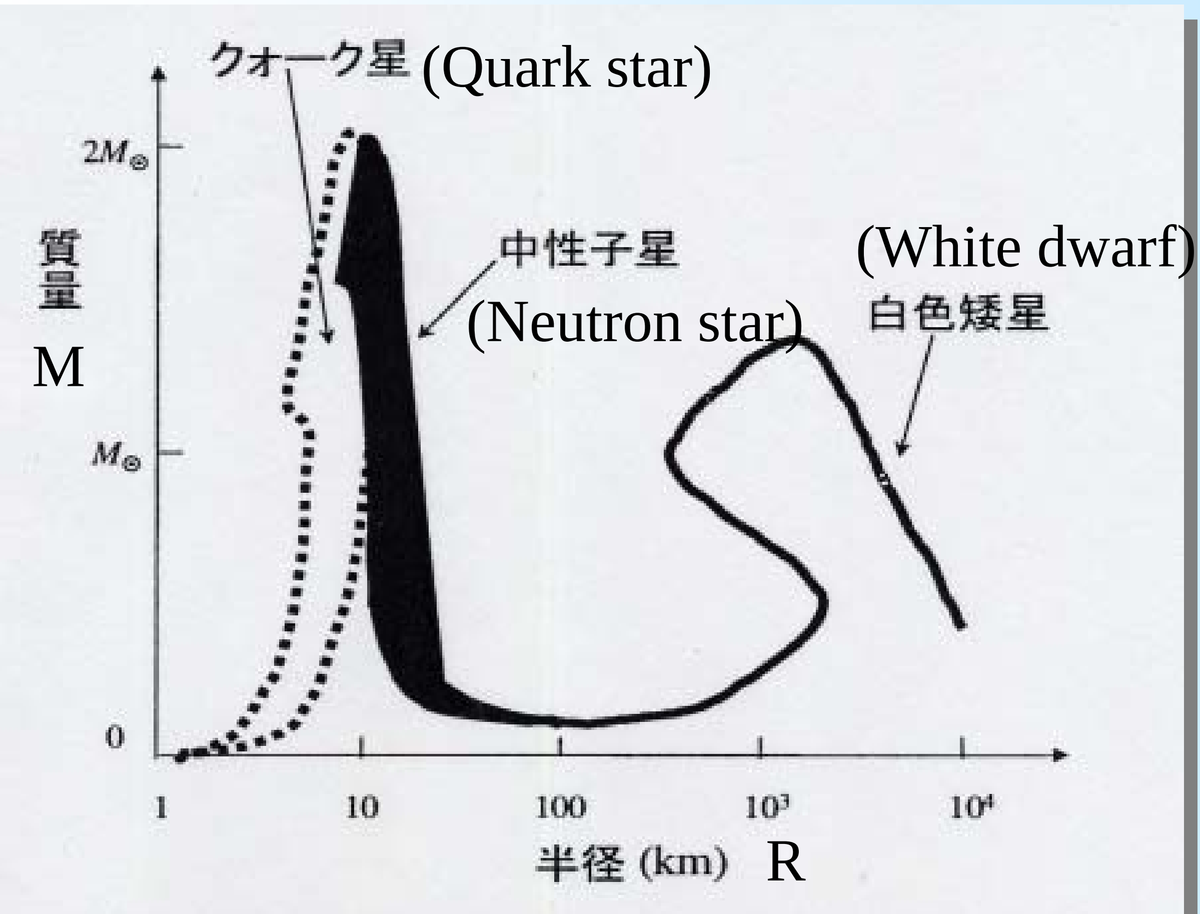


図1 高密度天体の質量・半径の概略 (幅は状態方程式の不定性による)

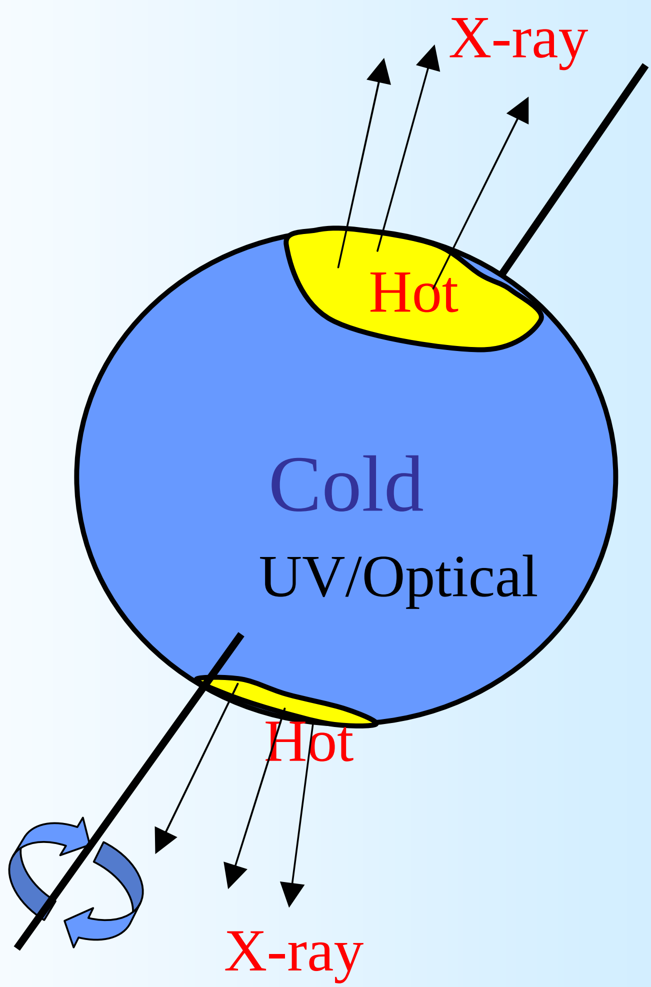
Courtesy of K. Iida

Two temperature model

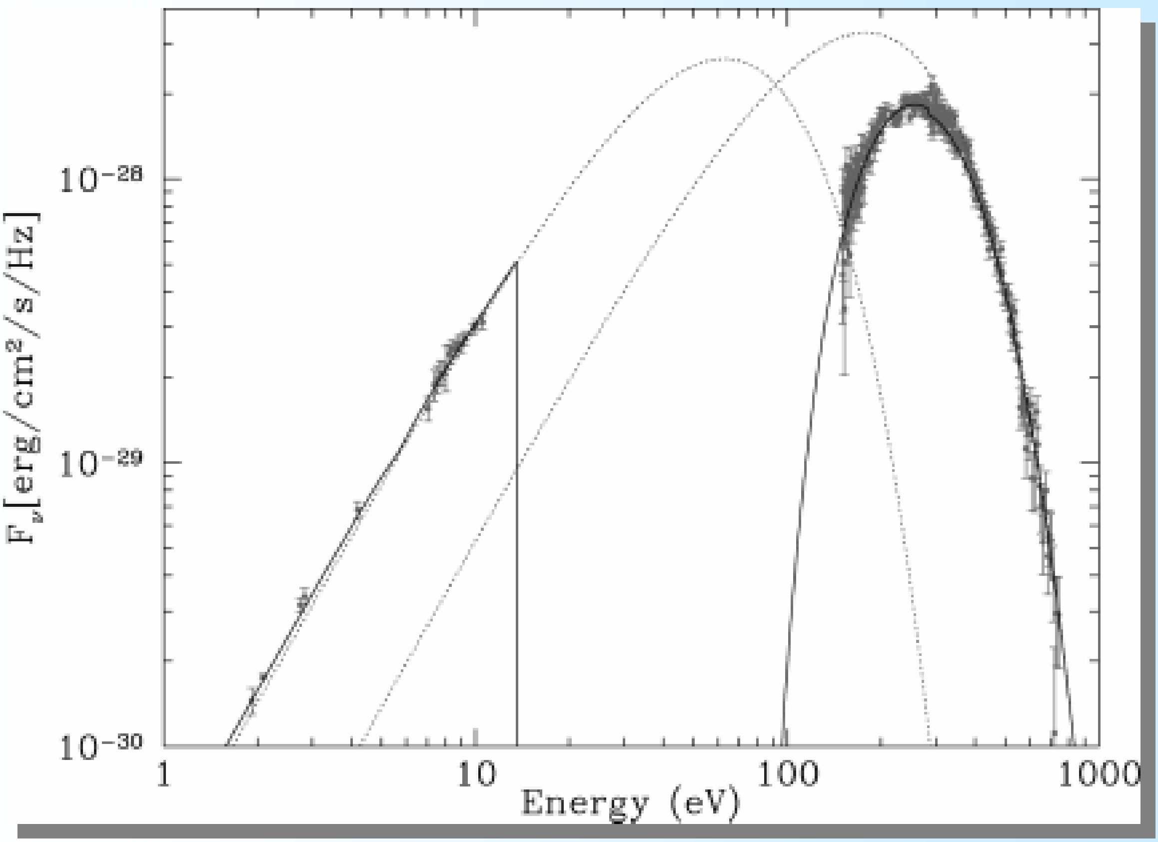
with heavy-element atmosphere

F.Walter and J.Lattimer, ApJ (2002)

T.M. Braje and R.W. Romani, ApJ (2002)



Broad band spectral fit in two-temperature blackbody



T. Braje and R.W. Romani, ApJ (2002)

Quark matter

(zero-temperature uds quark matter)

Thermodynamic potential

$$\Omega_u = -\frac{{\mu_u}^4}{4\pi}\left(1-\frac{2\alpha_c}{\pi}\right),$$

$$\Omega_d = -\frac{{\mu_d}^4}{4\pi}\left(1-\frac{2\alpha_c}{\pi}\right),$$

α_c QCD coupling constant

$$\Omega_s = -\frac{m_s^4}{4\pi^2}\left\{x_s\eta_s^3-\frac{3}{2}F(x_s)\right.$$

$$\left.-\frac{2\alpha_c}{\pi}\left[3F(x_s)\left(F(x_s)+2\ln x_s\right)-2\eta_s^4+6\left(\ln\frac{\Lambda}{\mu_s}\right)F(x_s)\right]\right\},$$

$$\Omega_e = -\frac{{\mu_e}^4}{12\pi^2}$$

where

$$F(x_s) = x_s\eta_s - \ln\left(x_s+\eta_s\right)$$

$$x_s \equiv \mu_s/m_s, \quad \eta_s = \sqrt{x_s^2-1}$$

Strange quark mass m_s

Energy density

$$\rho = \sum_{i=u,d,s,e}\left(\Omega_i+\mu_i n_i\right)+B$$

Bag constant

Quark matter-2

Number density

$$n_i = -\frac{\partial \Omega_i}{\partial \mu_i}$$

Pressure

$$p = -\sum_{i=u,d,s,e} \Omega_i - B \quad \left(= -\frac{\partial(\rho/n_{\mathrm{B}})}{\partial(1/n_{\mathrm{B}})}\right)$$

Baryon number

$$n_B \equiv \frac{1}{3}(n_u + n_d + n_s)$$

Conditions

In equilibrium through weak interactions

$$\mu_u = \mu_d - \mu_e$$

$$\mu_d = \mu_s,$$

Charge neutrality

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s = n_e$$

Bag model parameters fitted to hadron mass spectra

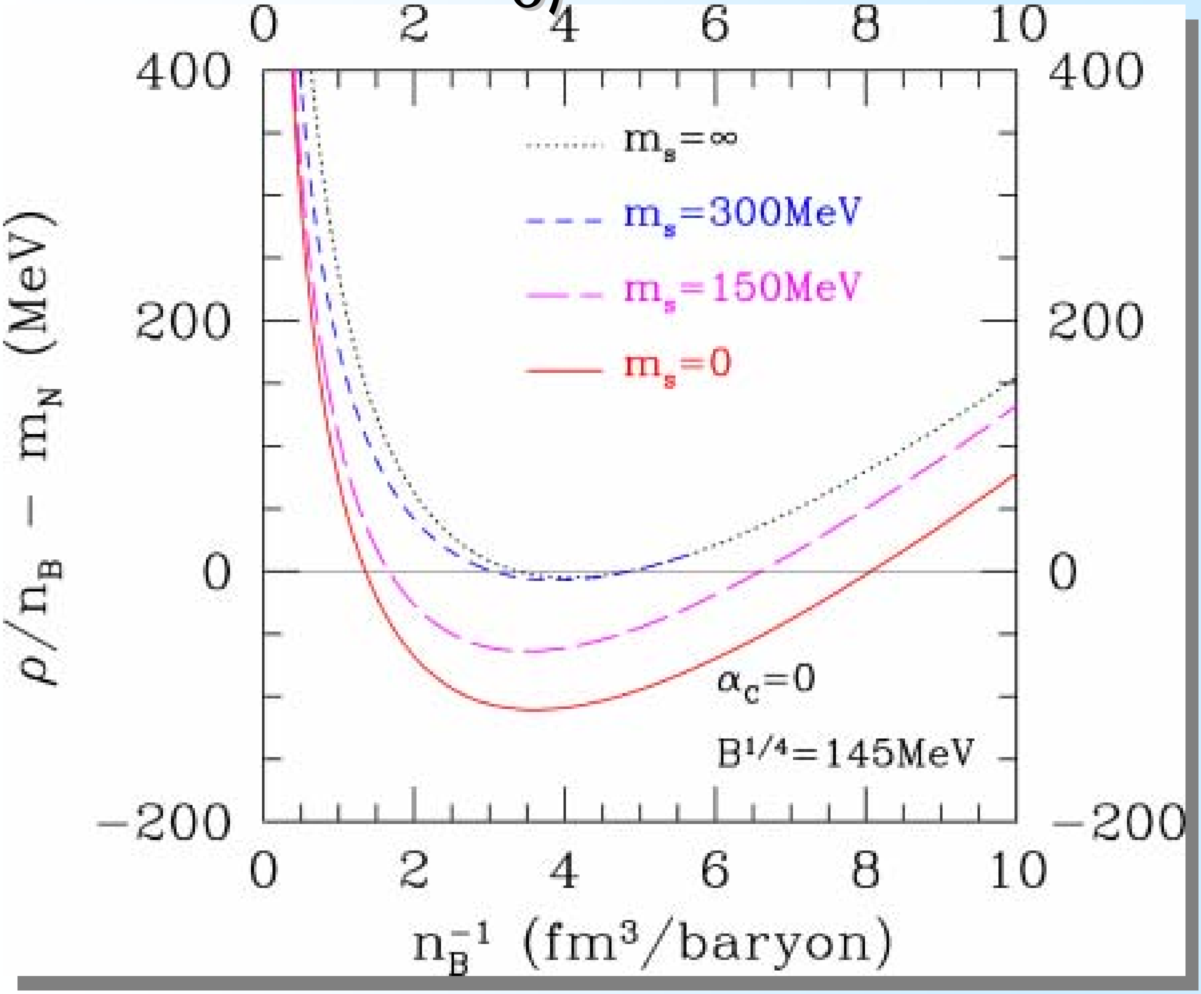
Table I. Bag-model parameters fitted to hadron mass spectra.

$B^{1/4}$(MeV)	m_s (MeV)	α_c	Reference
145	279	2.2	T. DeGrand et al. (1975) [32)]
200–220	288	0.8–0.9	C.E. Carlson et al. (1983) [33)]
149	283	2.0	J. Bartelski et al. (1984) [34)]

Kohri, Iida and Sato, arXiv:astro-ph/0210259

Energy per baryon

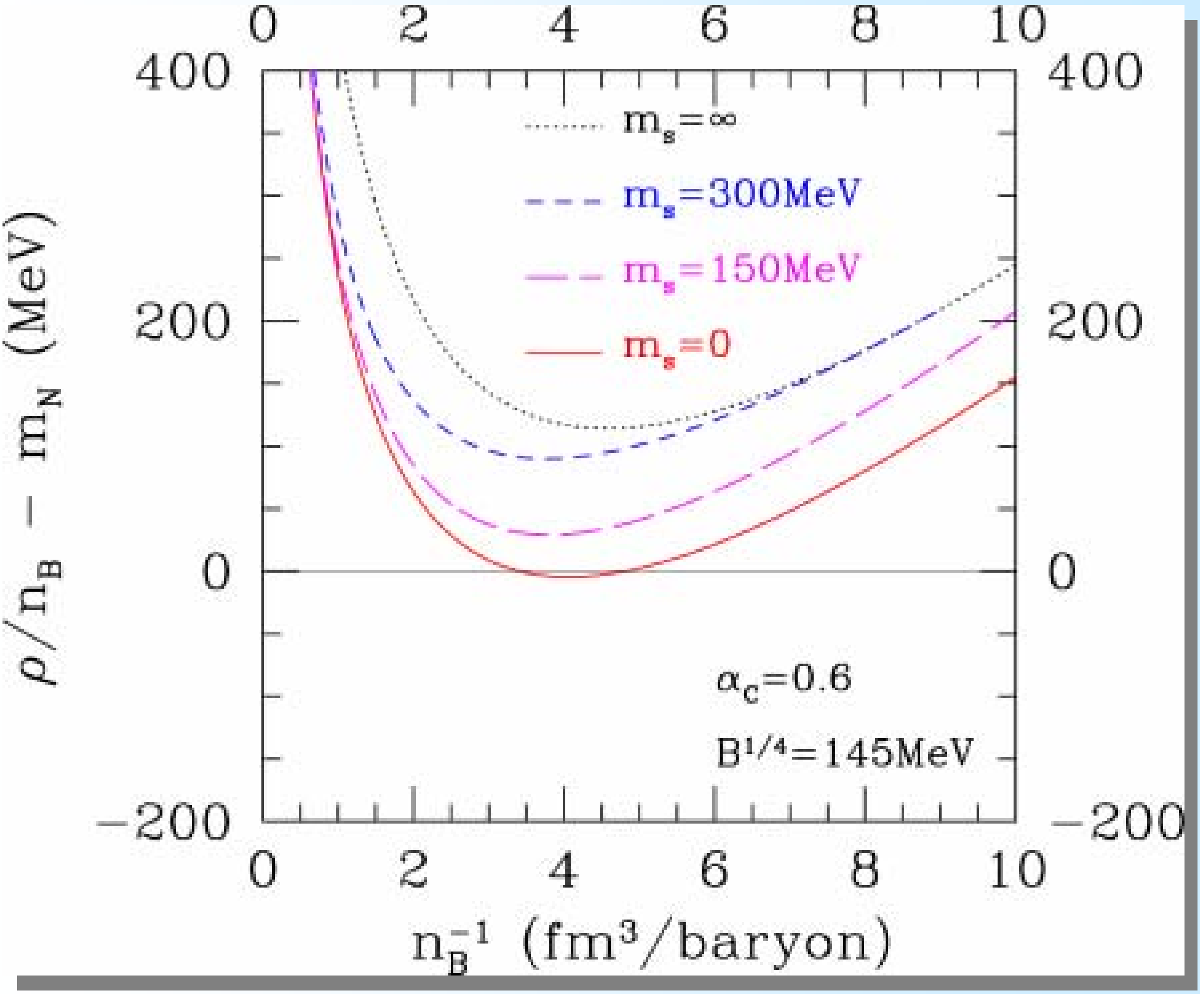
($\alpha_c =$ 0)



$$E_s = \mu_s = \sqrt{k_F^2 + m_s^2}$$

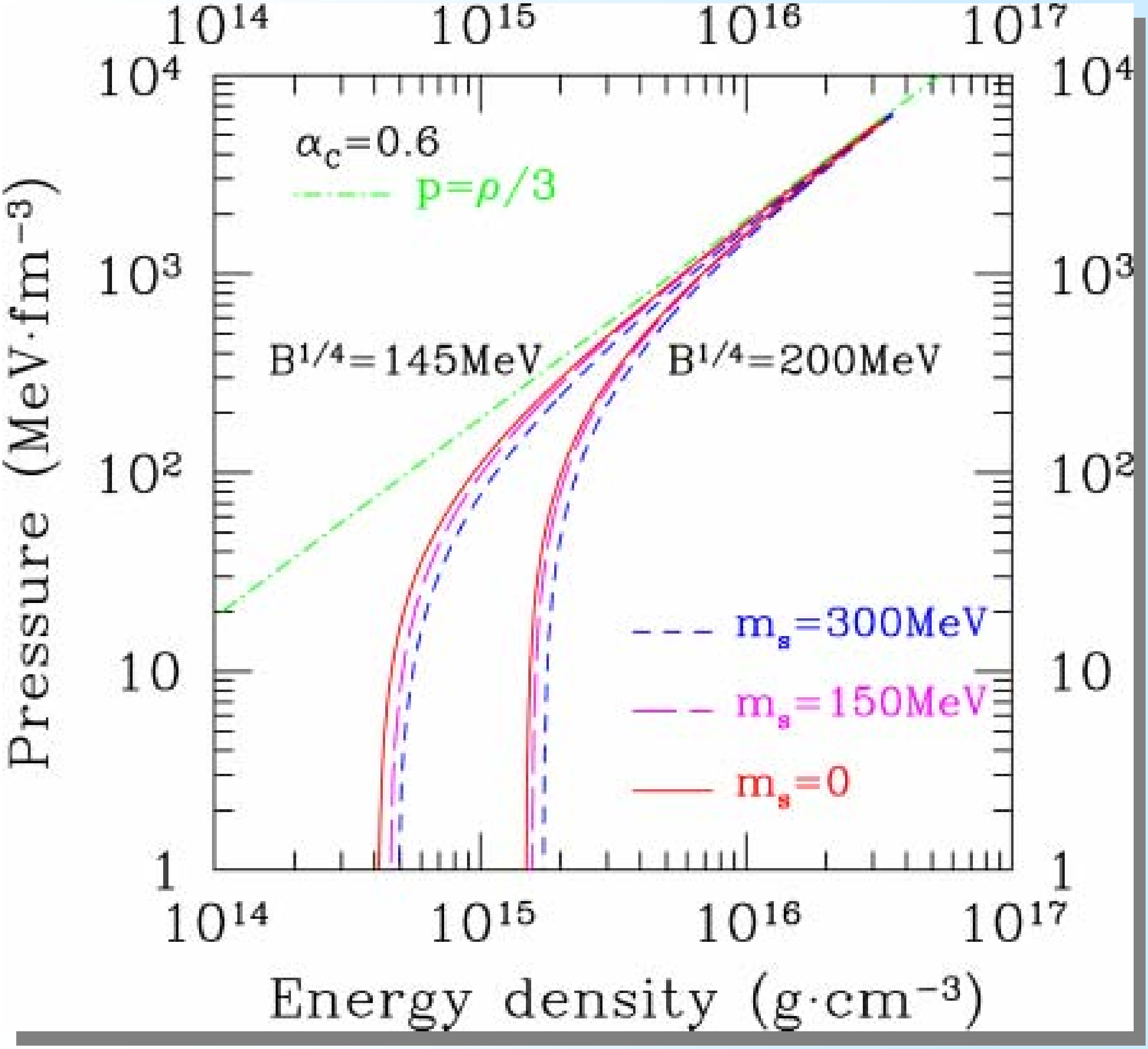
Energy per baryon

(α_c = 0.6)



$$\rho_i/n_B \simeq \left[\pi n_i (1 + 2\frac{\alpha_c}{\pi})\right]^{1/3}$$

Equation of state



Quark star

Equation of hydrostatic equilibrium

(Tolman-Oppenheimer-Volkoff (TOV) equation)

$$\frac{dp(r)}{dr} = -G\frac{[\rho(r)+p(r)]\left[M(r)+4\pi r^3 p(r)\right]}{r^2\left[1-\frac{2GM(r)}{r}\right]}$$

Equation of mass conservation

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)$$

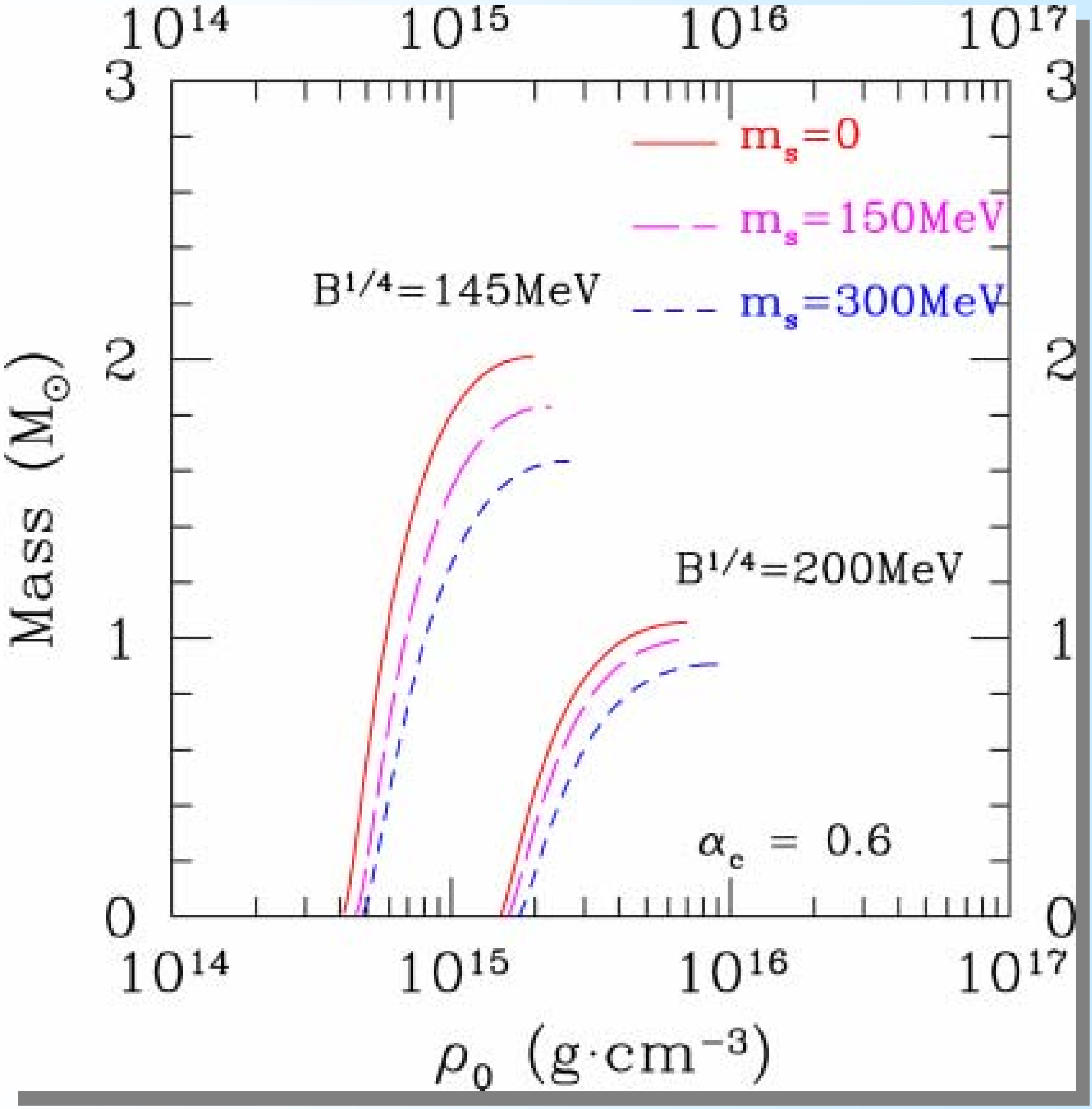
Then, the radius is determined by

$$p(r=R)=0$$

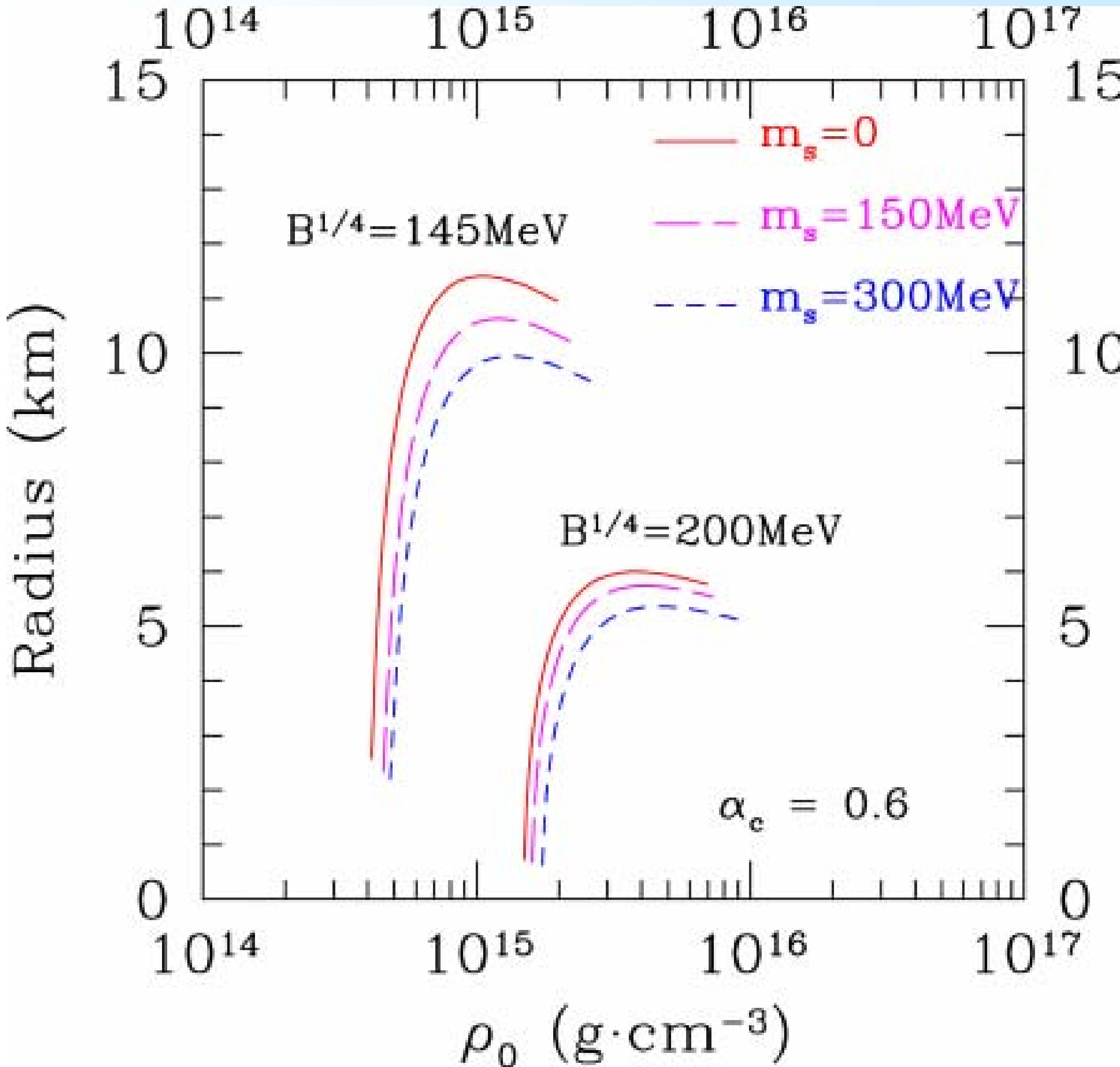
The mass is

$$M \equiv M(R)$$

Mass of quark star

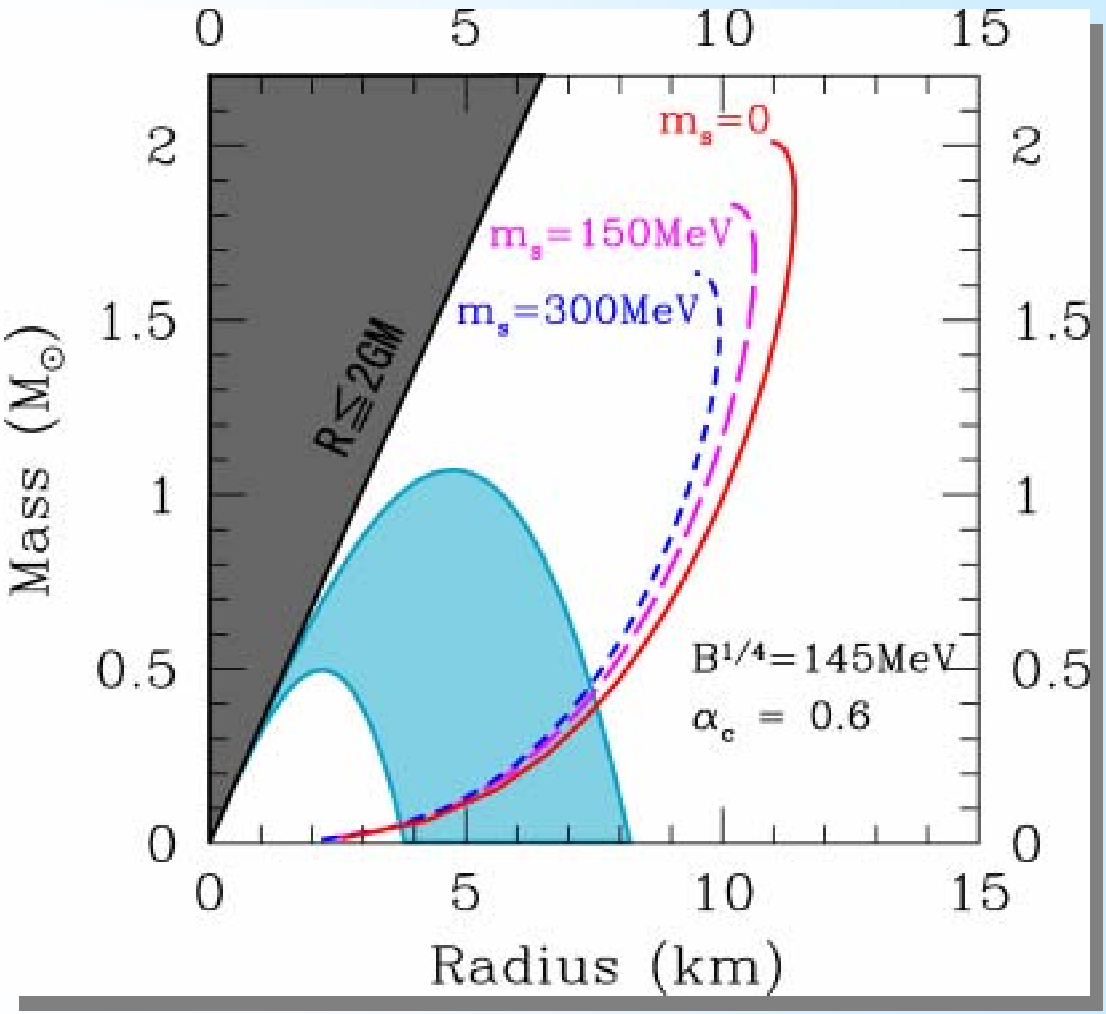


Radius of quark star



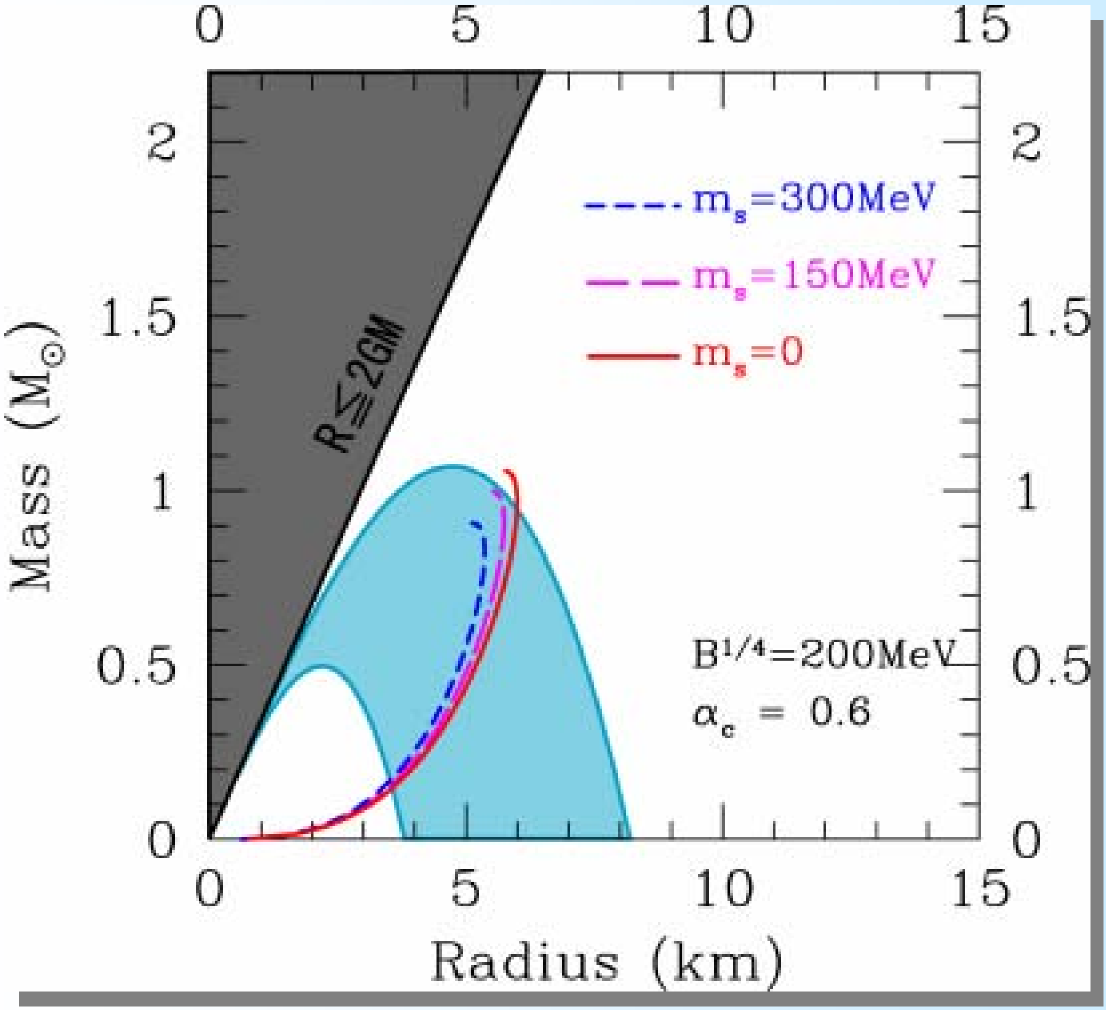
Mass-radius relation

$B^{1/4} = 145$ MeV



Mass-radius relation

$B^{1/4} = 200$ MeV



Observed X-ray luminosity

Bondi accretion rate

$$\dot{M} = 4\pi\lambda \left(\frac{GM}{v^2}\right)^2 \rho_H v$$

where,

$$\rho_H = m_N N_H / R_H$$

$$\lambda \sim \mathcal{O}(1)$$

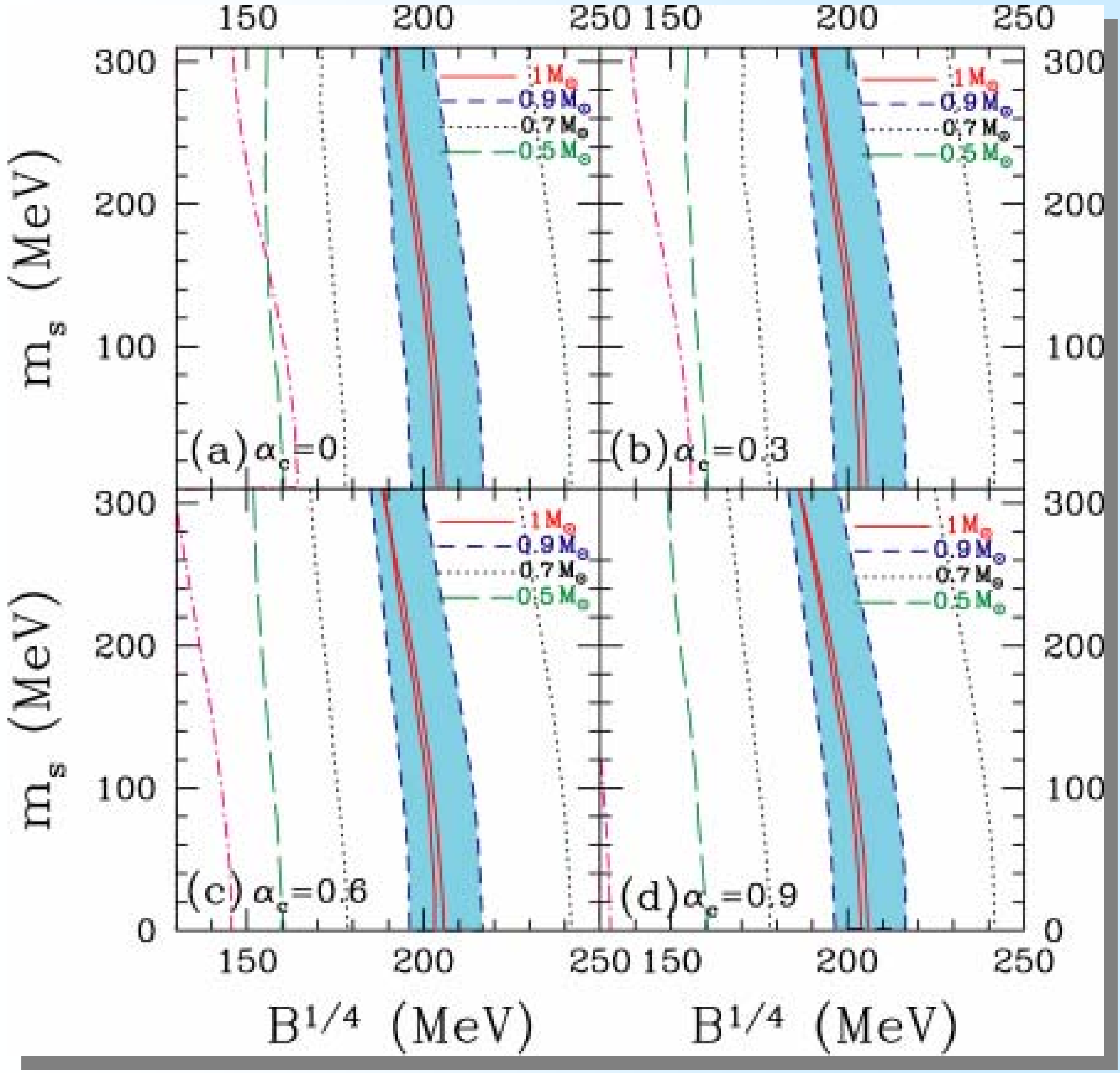
$$v = 200 \text{km s}^{-1} (D/140\text{pc})$$

$$L_X = 6 \times 10^{31} (D/140\text{pc})^2 \text{erg s}^{-1}$$
$$\gtrsim GM\dot{M}/R$$

Then,

$$M \lesssim 0.4 M_\odot \left(\frac{v}{200 \text{ km}}\right) \left(\frac{D}{140 \text{ pc}}\right)^{5/3} \left(\frac{N_H}{10^{20} \text{ cm}^{-2}}\right)^{-1/3} \left(\frac{R_H}{100 \text{ AU}}\right)^{1/3} \left(\frac{R}{5 \text{ km}}\right)^{1/3}$$

Contours of upper limit of mass



Effects of the pressure-dependent bag constant

Generally, we can parameterize the EOS as

$$p = \frac{1}{A}(\rho - 4B)$$

$$(\text{for } m_s = 0, \alpha_c = 0)$$

A ~ 3 -- 4, for Lattice data , Peshier,Kampfer,Soff (2001).

A ~ 2, for Relativistic Mean Field, Dey et al. (1998) etc.

Then, we transform it into

$$p = \frac{1}{3}(\rho - 4B_{\text{eff}}),$$

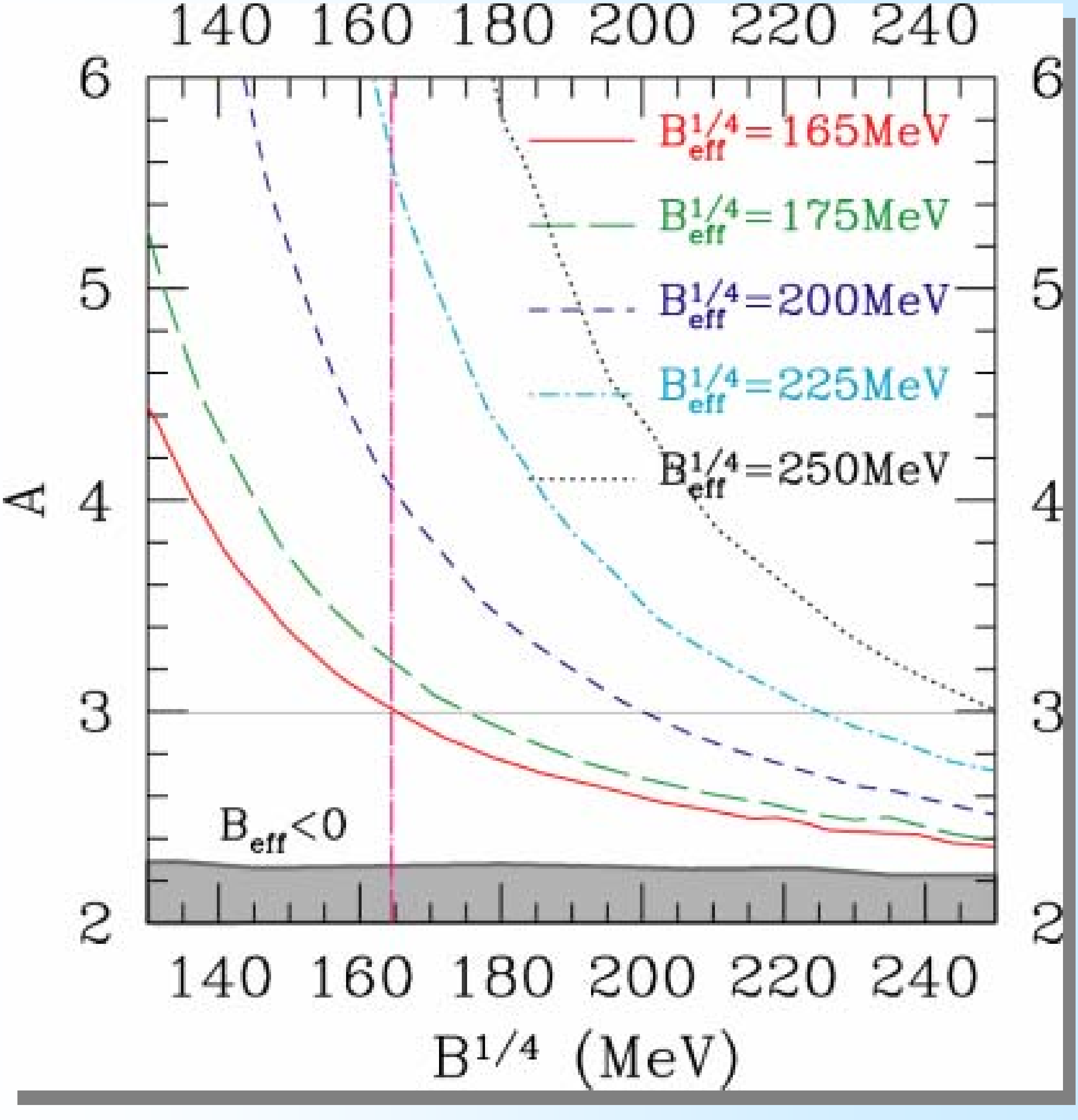
where

$$B_{\text{eff}} = \frac{1}{4}(A-3)p + B,$$

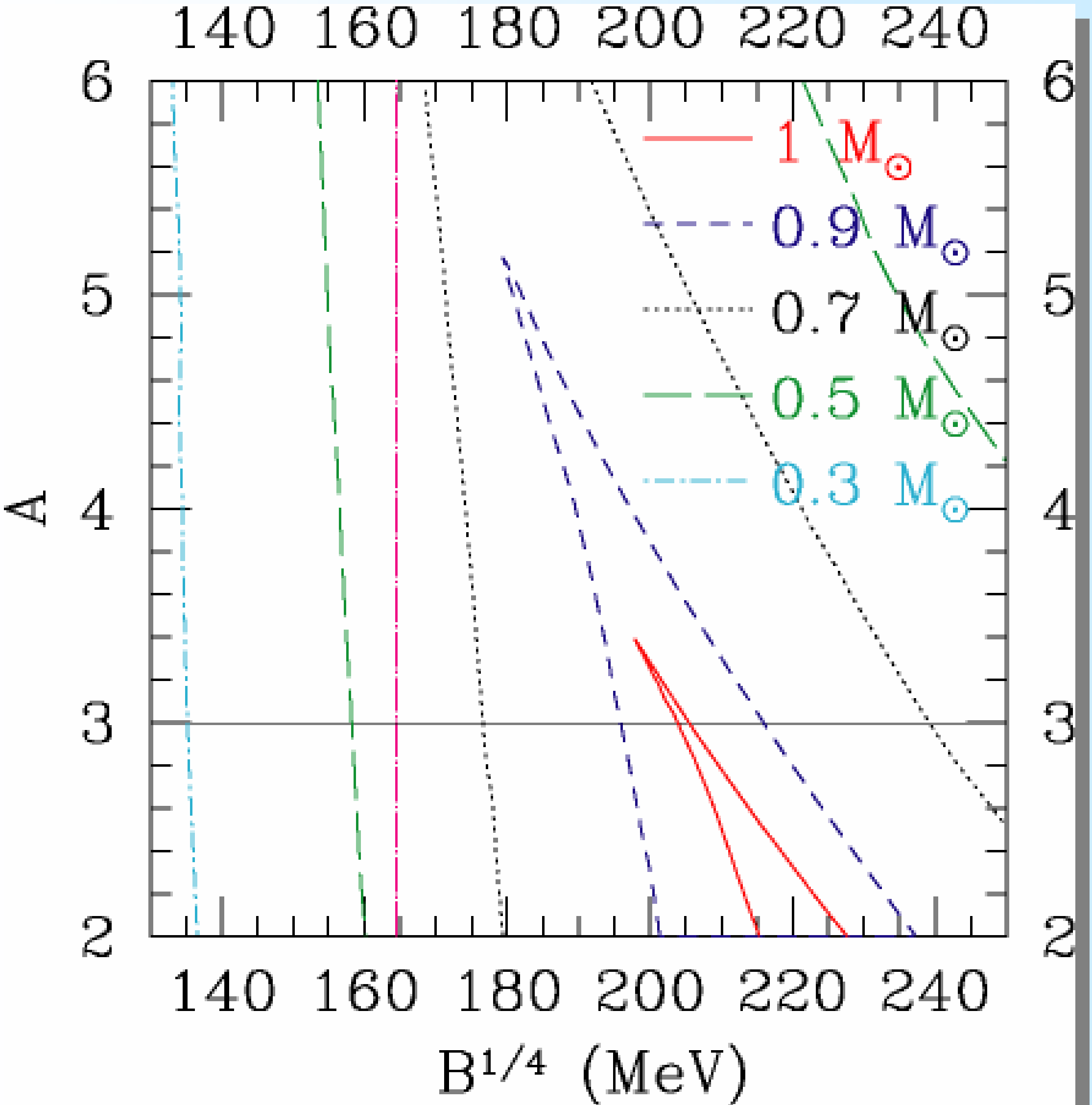
$$= \frac{1}{4}\left(1 - \frac{3}{A}\right)\rho + \left(\frac{3}{A}\right)B.$$

Namely, inside the star the bag constant effectively becomes large!

Contour of the effective bag constant



Contours of the upper limint of the mass



Conclusion

- We have systematically computed mass-radius relation of quark star within the bag model.
- Assuming that RX J1856.5--3754 is a pure quark star, we have derived an upper limit on its mass.
- We find the upper limit can amount to 1 $M_\odot$ around

$B \sim (200\text{MeV})^4$.