A 2M_sun pulsar: implications for quark matter

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Outline

- Strange quark matter and pulsars
- Models of quark stars

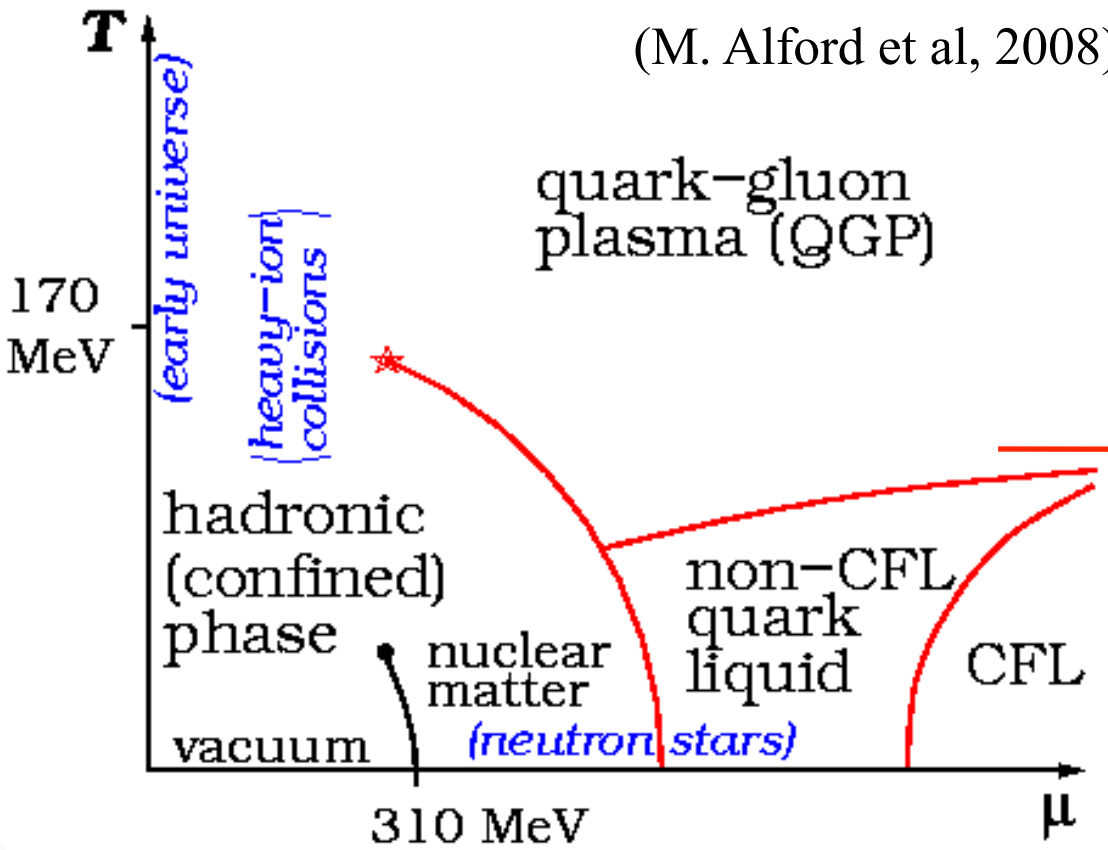
  → Maximum mass of quark stars: reach 2M_sun?

  → Implications for state of quark matter
- Conclusions

What is Strange Quark Matter

QCD phase diagram

(M. Alford et al, 2008)



Large baryon density leads to non-zero strange-number

Strange Quark Matter

(deconfined **u**, **d** and **s** quarks)

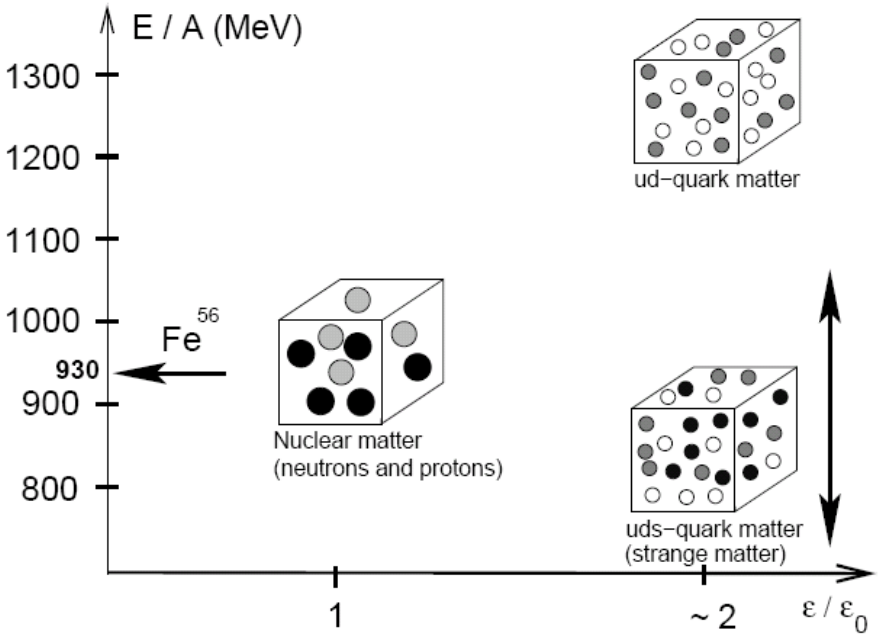
What is Strange Quark Matter

- SQM is composed of ***u***, ***d*** and ***s*** quarks (~ 10^{-5} ***e***/baryon).

- SQM could be more stable than ordinary matter

  (Bodmer 1971, Witten 1984).

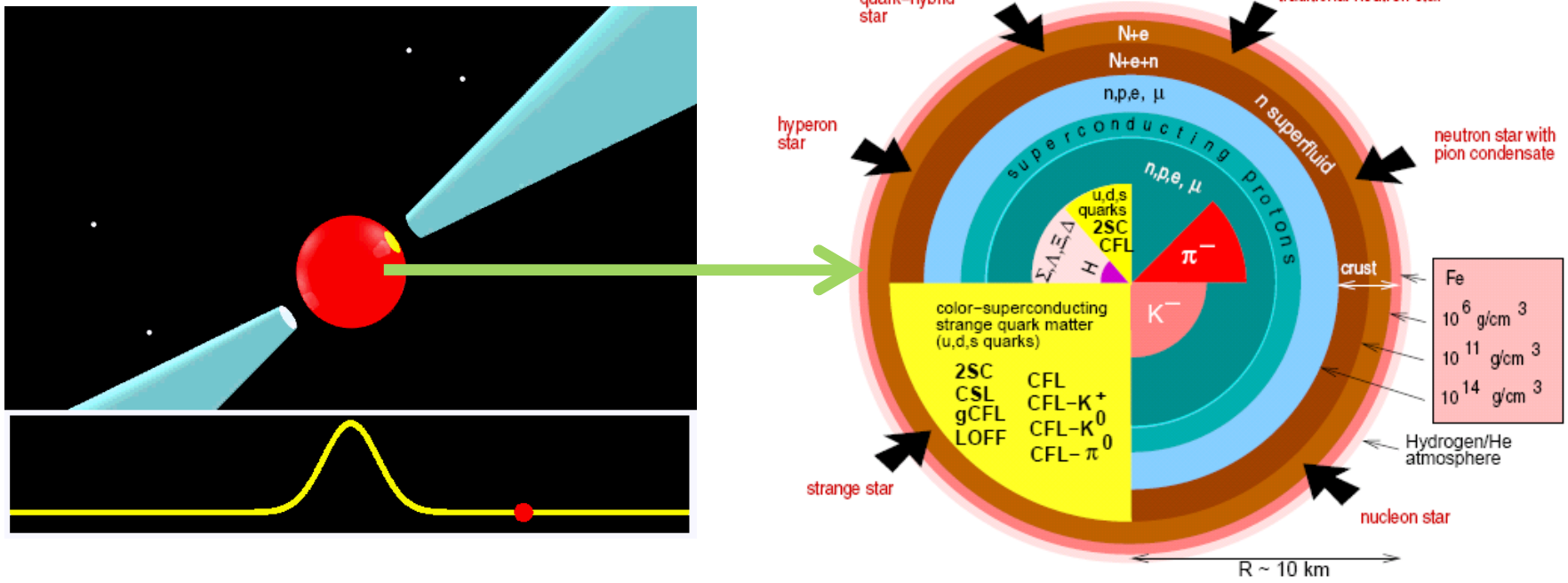
- Astrophysical implications of *Bodmer-Witten conjecture*?



(F. Weber, 2005)

Pulsars

pulsars = rotating "neutron stars"



(F. Weber 2005)

Average density $\bar{\rho} = \dfrac{1.4\ M_\odot}{4\pi(10\ \mathrm{km})^3/3} \simeq 2.4\ \rho_0$

⟶ Deconfinded quarks ⟶ Quark stars

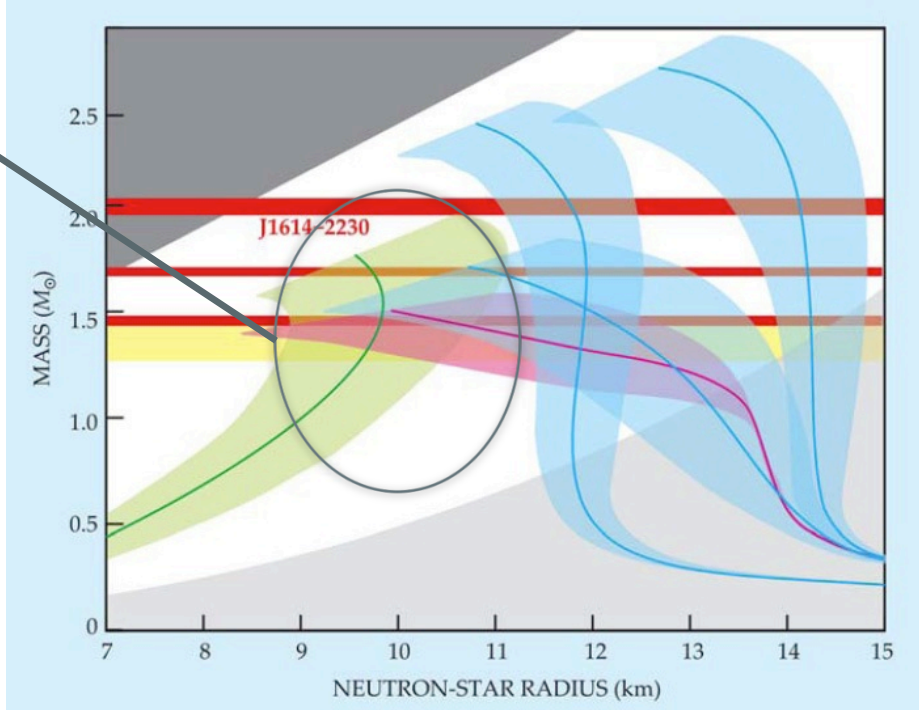
M_{max}: implications for quark matter

PSR J1614-2230 M=1.97±0.04 $M_\odot$

Quark stars are characterized by **soft equations of state**

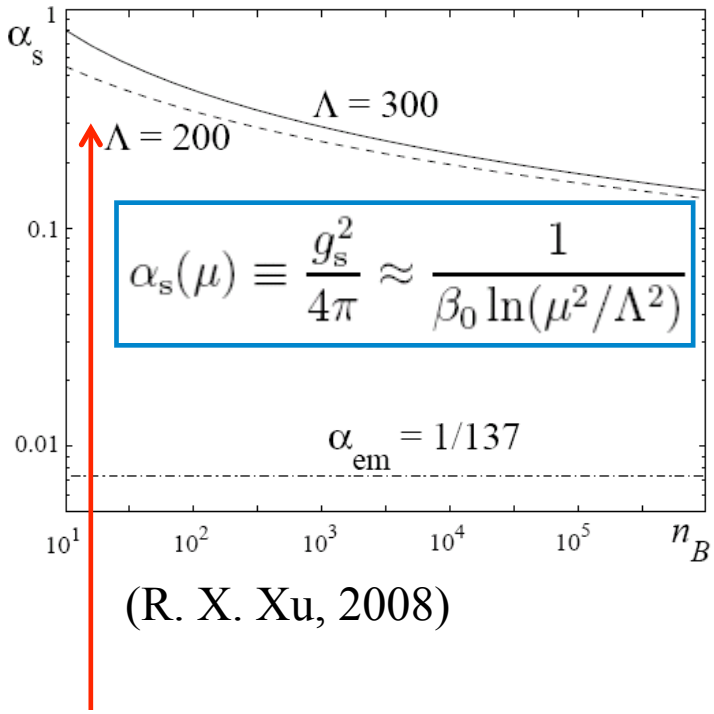
Quarks in SQM are treated as **relativistic** and **weak-interacing** particles

What is the state of SQM at realistic density of pulsars ?



(P. Demorest, et al, 2010)

Quark-clustering in cold quark matter



$$\alpha_s(\mu) \equiv \frac{g_s^2}{4\pi} \approx \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}$$

(R. X. Xu, 2008)

interior of quark stars

Astrophysical implications for **quark matter**

Quark-clusters ?

highly non-perturbative effect
(Energy scale ~ 0.4-0.8 GeV)

A polytropic model of quark stars

- Polytropic model is widely used in *main-sequent stars* and *hadronic phase of neutron stars*

$$P = K\rho_g{}^{\Gamma},$$

$$\rho = \rho_g c^2 + nP, \quad \Gamma = 1 + 1/n$$

- If quark stars are composed of quark clusters, their equation of state could be also the polytropic form

→ **a general framework**

- Equation of state

$$P = K\rho_g^{1+\frac{1}{n}} - \Lambda,$$

$$\rho = \rho_g c^2 + nK\rho_g^{1+\frac{1}{n}} + \Lambda.$$

QCD vacuum energy density

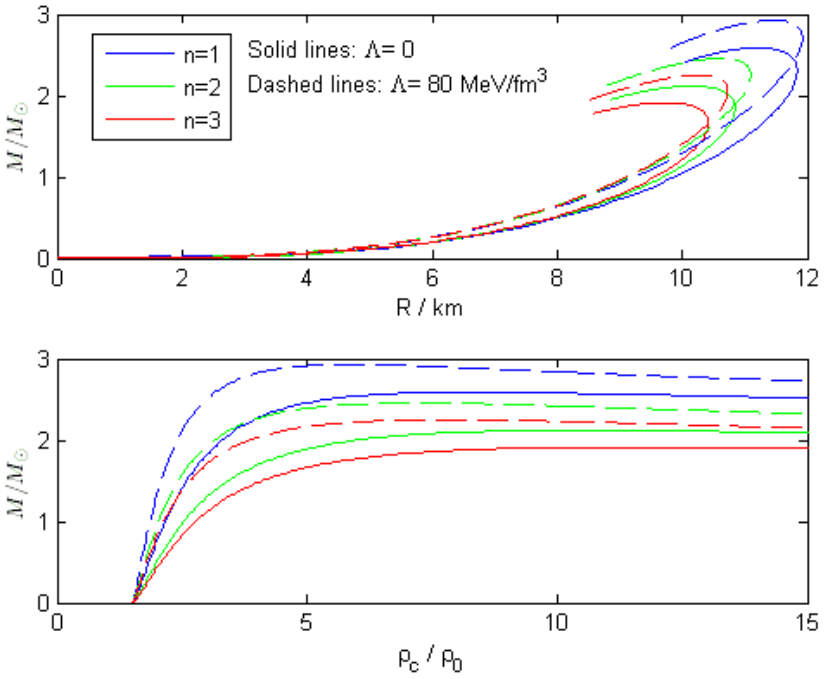
Quark star

$\Lambda \neq 0$

$\Lambda = 0$

What's ***new*** in our polytropes:

1. Non-zero surface density
2. Different vacuum energy density inside and outside of a quark star



(X. Y. Lai & R. X. Xu, 2009a)

Lennard-Jones quark matter

- ***Quantum*** kinetic energy of quark-clusters

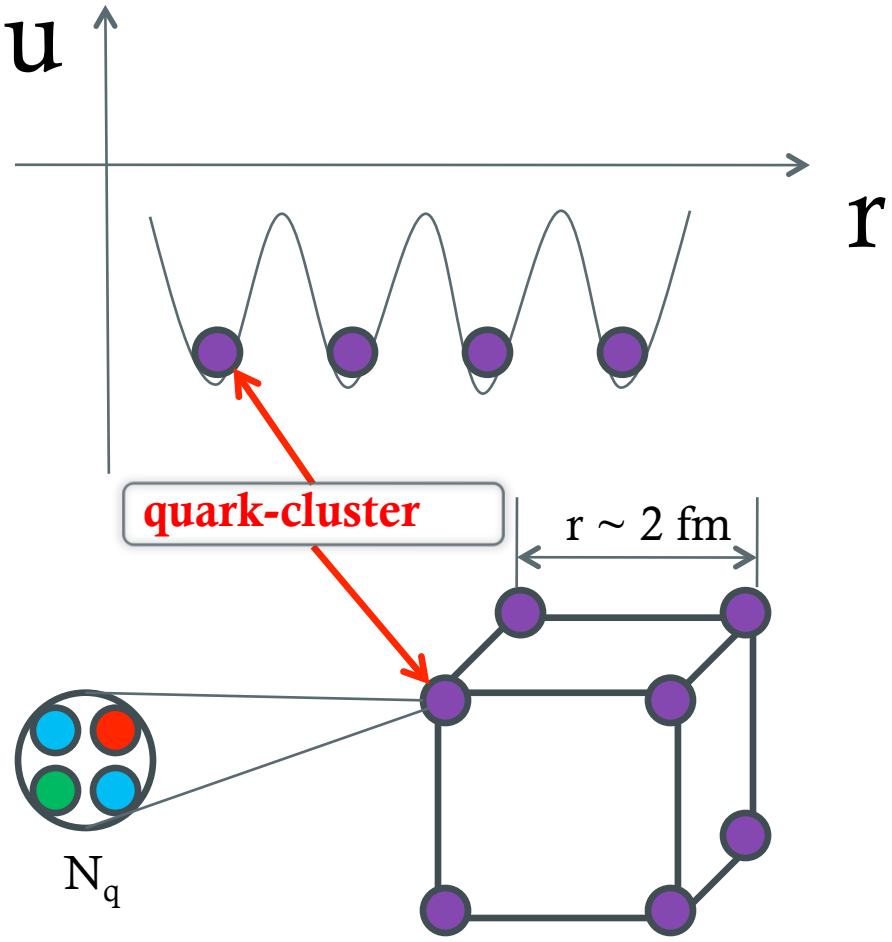
$$E_k \sim 1\ \mathrm{MeV}(\frac{\rho}{\rho_0})^{\frac{2}{3}}(\frac{N_q}{18})^{-\frac{5}{3}}$$

- If the inter-cluster potential well is deep enough (>>1 MeV), quark-clusters could crystallize

- Apply L-J model to describe inter-cluster potential:

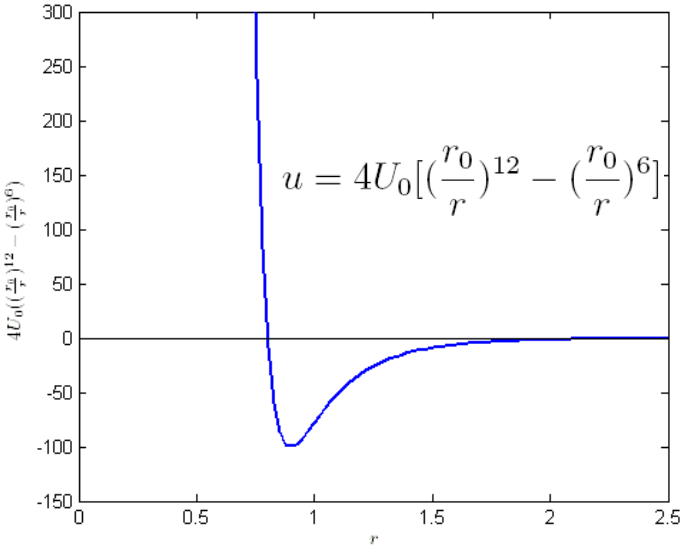
$$u = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6]$$

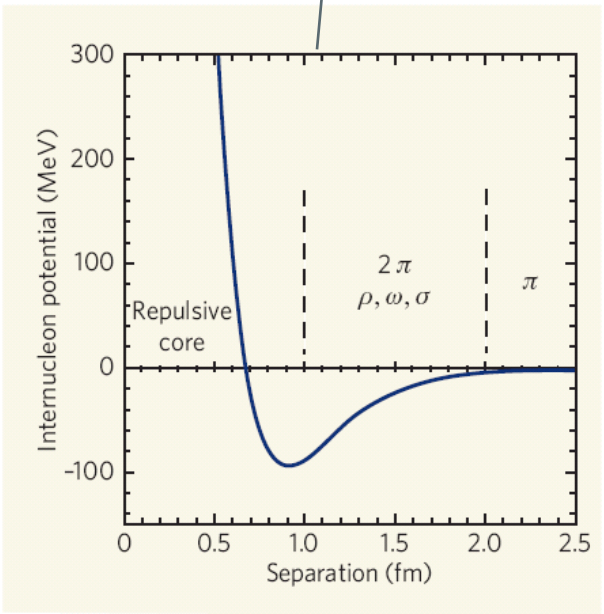
(similar to inert gas)

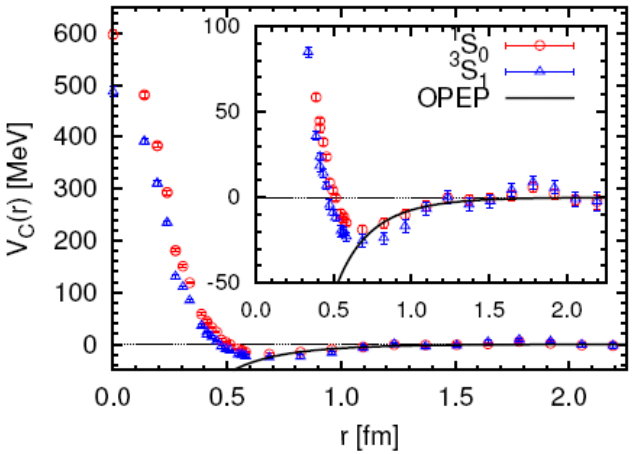


For the nucleon-nucleon potential

A strong repulsive core







Empirical form
(F. Wilczek, 2007)

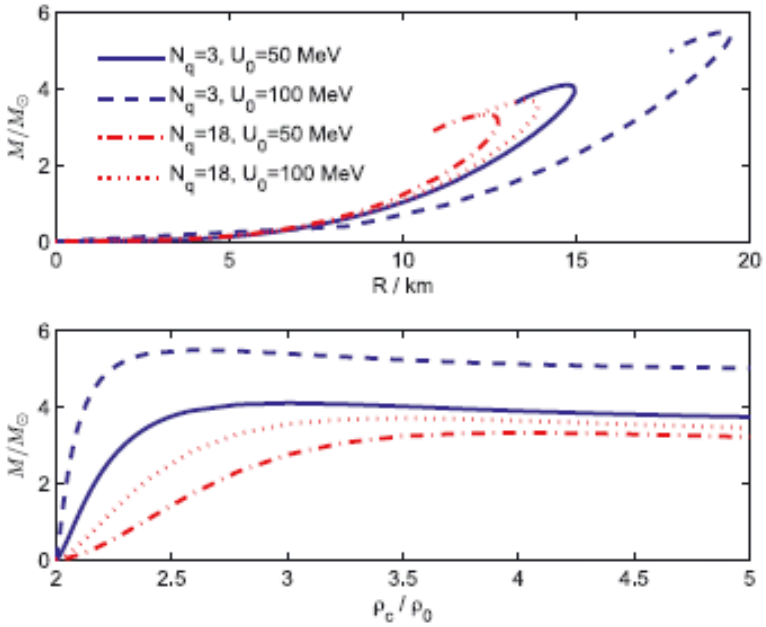
Results of Lattice QCD simulations
(N. Ishii et. al, 2007)

$$\epsilon_{\rm q} = \epsilon_{\rm p} + \epsilon_{\rm L} + nm_{\rm c}c^2$$
$$= 2U_0(A_{12}r_0^{12}n^5 - A_6 r_0^6 n^3) + \frac{9}{8}(6\pi^2)^{\frac{1}{3}}\hbar v n^{\frac{4}{3}} + nm_{\rm c}c^2,$$

$$P_{\rm q} = n^2\frac{d(\epsilon_{\rm q}/n)}{dn}$$
$$= 4U_0(2A_{12}r_0^{12}n^5 - A_6 r_0^6 n^3) + \frac{3}{8}(6\pi^2)^{\frac{1}{3}}\hbar v n^{\frac{4}{3}}.$$

$$P = P_{\rm q},$$
$$\rho = \epsilon_{\rm q}/c^2.$$

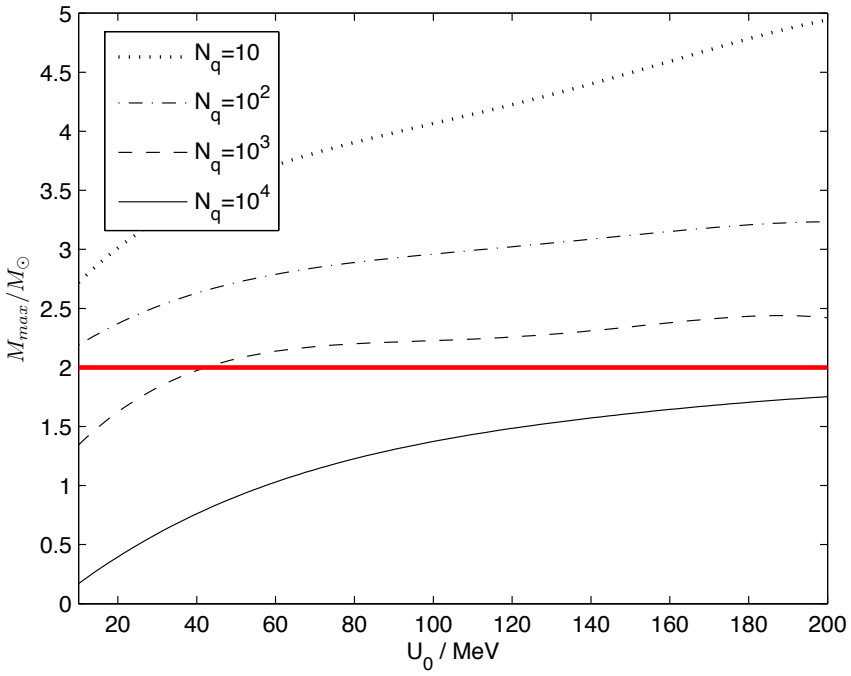
Mass-radius
&
Mass-central density
curves



Stiffer EoS ⟹ Larger maximum mass

(Lai & Xu 2009b)

$2M_\odot$ pulsar: constraint on N_q



→ $Nq \leq 10^3$

(X. Y. Lai & R. X. Xu, 2011)

Conclusions

- Quark stars with quark-clusters
  - stiff EoS $\longrightarrow$ $M_{max} > 2\ M_{\odot}$
- M_{max} could have implications on state of SQM
  - Number of quarks of each cluster: $Nq \leq 10^3$

Properties of low energy QCD
(energy scale ~ 0.4-0.8 GeV)

Thank you !