Quarks in Strange Matter: Localized or Not?

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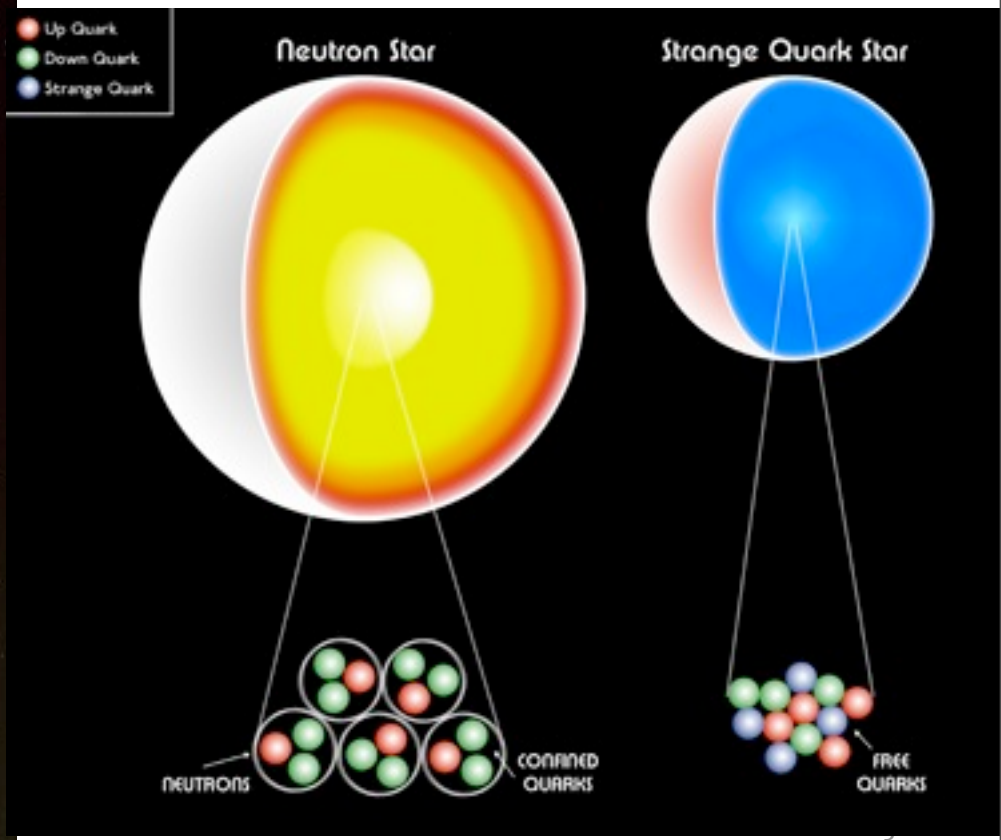
Outline

- ***Introduction: Deconfinement and Strangeness***
- Quarks in Compact Stars: Localized?
- Summary

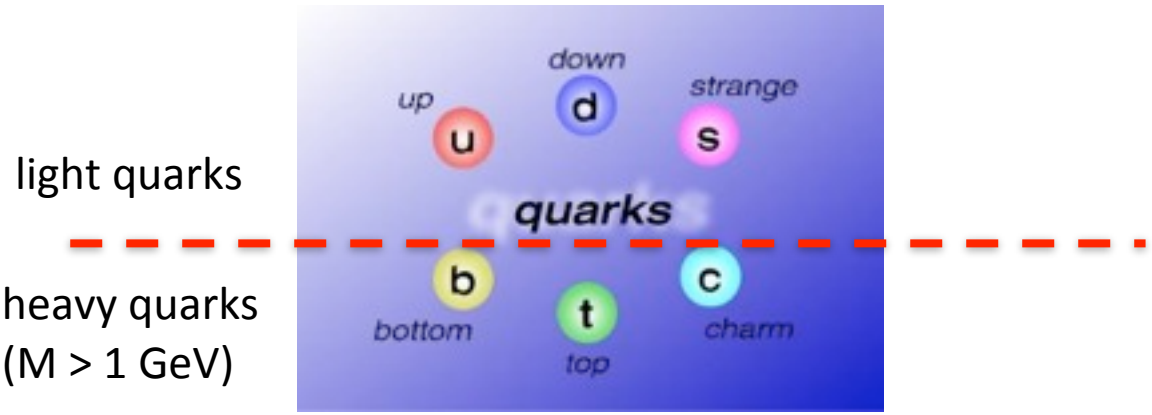
- **Neutron stars**
  - Speculated by Landau (1932)
  - Produced in supernova explosions (Baade & Zwicky 1934)
  - Identified as **pulsars** (since 1968)

- **Questions**
  - De-confined quarks in the inner-cores ?
  - Quark stars ?
  - The state of quark matter ?



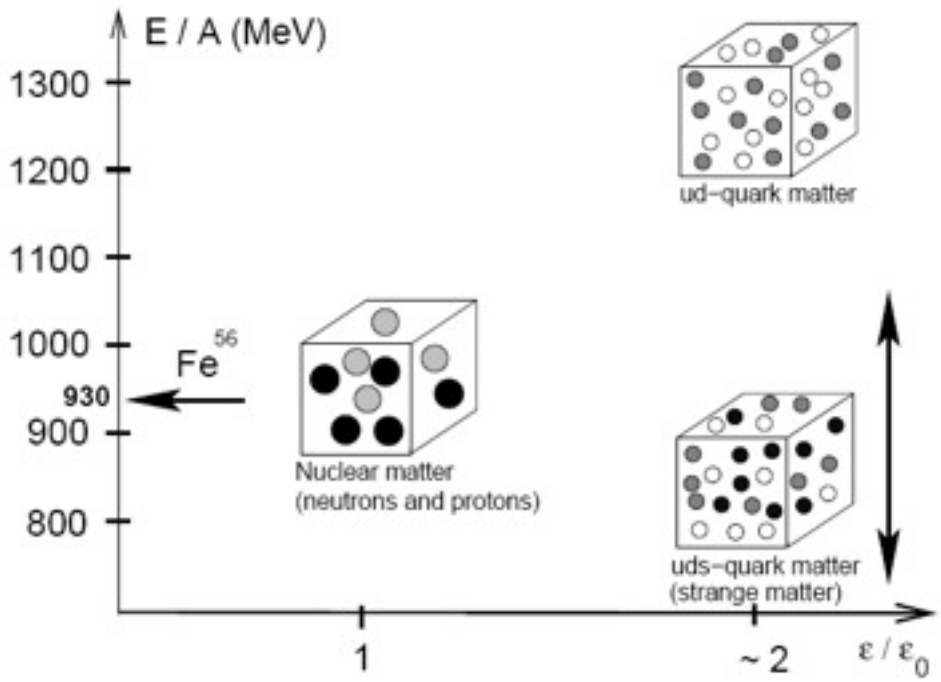
Quark-deconfinement + Strangeness at high densities

→ **Strange Quark Matter** (SQM, or Strange Matter)



Weber, 2005

- **A simple estimation on stability** →
  - Bodmer-Witten conjecture



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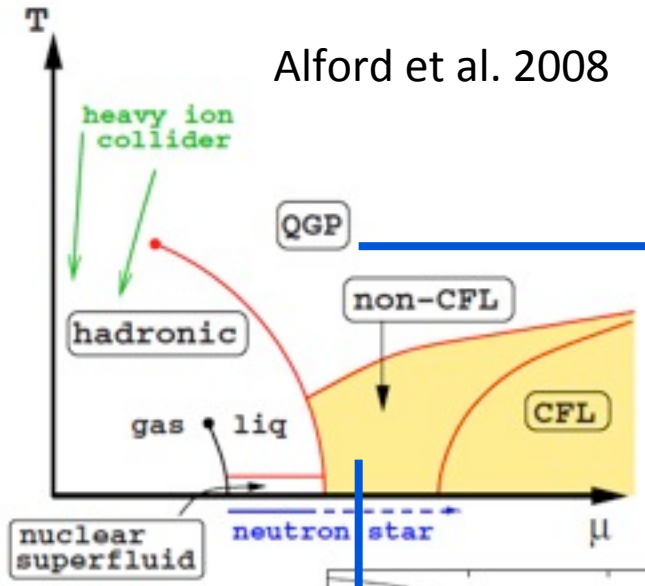
Quarks in Compact stars: **Free** *or* **Localized**

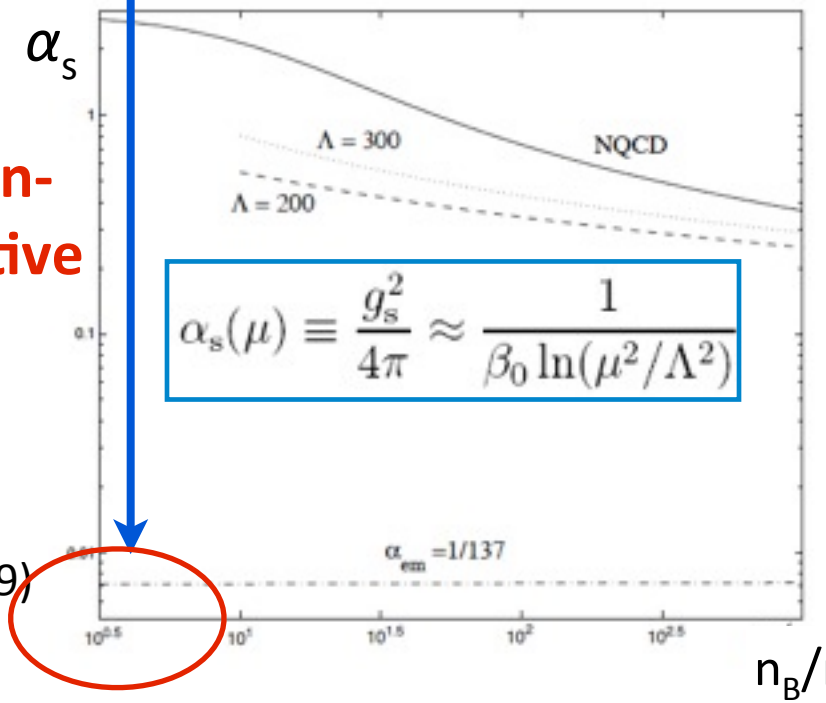


Alford et al. 2008

Asymptotic freedom

– weakly coupled quarks

Appliable to compact stars?



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

Highly non-perturbative

(Xu, 2009)

quarks

localized into

?

quark-clusters

hadrons: “quark-clusters”

Quark composition of a proton and a neutron (diagrams from Wikipedia)

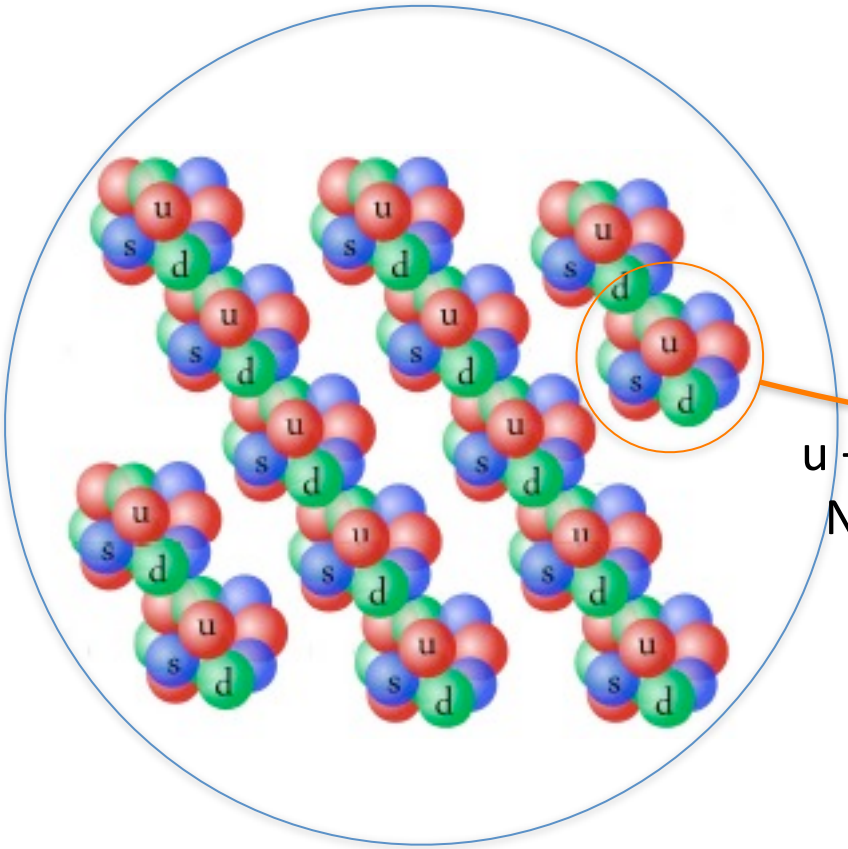
$$E_{\rm int} = \frac{\alpha_s}{l_{\rm cluster}} \simeq 300\alpha_s^2 \ {\rm MeV}$$

$$E_{\rm int} > E_{\rm Fermi} \sim 400 \ {\rm MeV}, \ {\rm if} \ \alpha_s > 1$$

The system could not be treated as Fermi gas

?

quark-clustering in compact stars



u + d + s

$N_q \geq 3$

Quarks are localized into quark-clusters

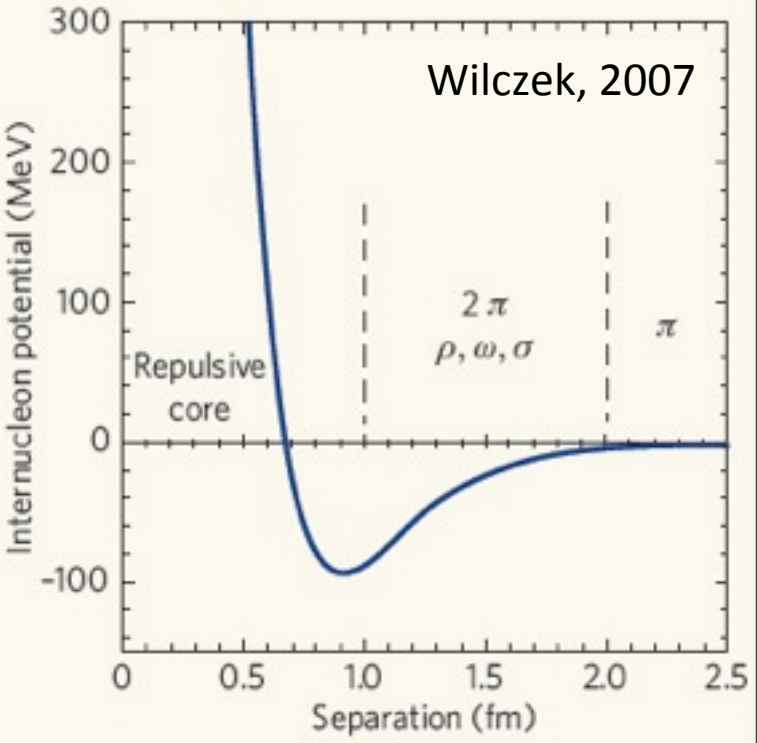
How to describe the state of clustered quark matter?

Lennard-Jones quark-cluster matter

Lai & Xu, MNRAS, 398, L31 (2009)

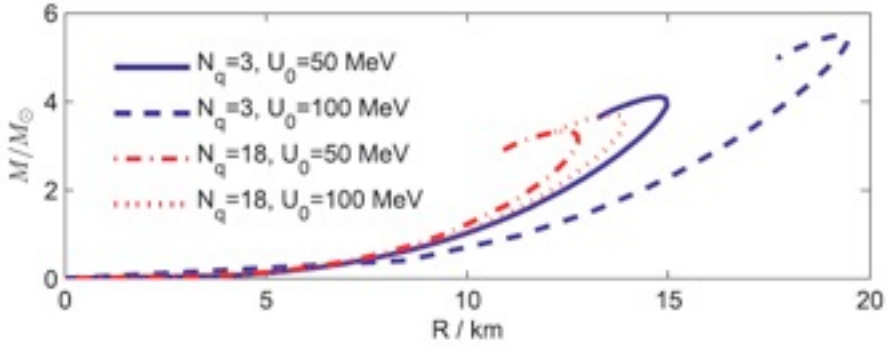
cluster-cluster potential:
(similar to inert gas)

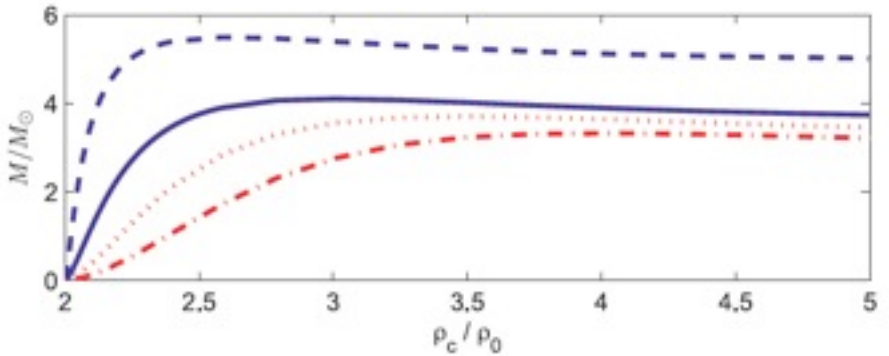
$$u = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6]$$

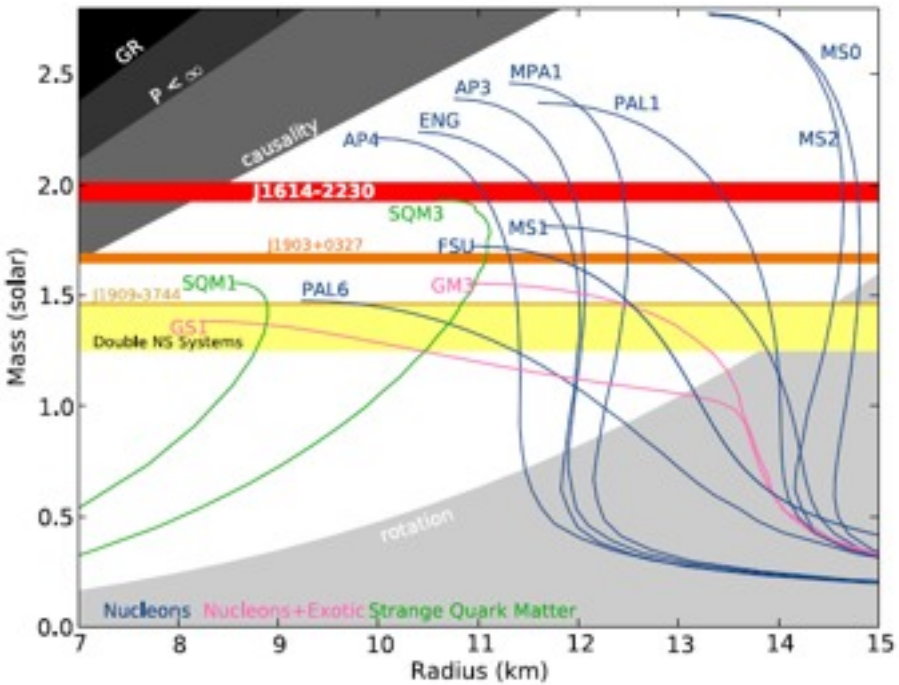


ABSTRACT

Quark clustering could occur in cold quark matter because of the strong coupling between quarks at realistic baryon densities of compact stars. Although one may still not be able to calculate this conjectured matter from the first principles, the intercluster interaction might be analogized to the interaction between inert molecules. Cold quark matter would then crystallize in a solid state if the intercluster potential is deep enough to trap the clusters in the wells. We apply the Lennard-Jones potential to describe the intercluster potential and derive the equations of state, which are stiffer than those derived in conventional models (e.g. MIT bag model). If quark stars are composed of the Lennard-Jones matter, they could have high maximum masses ($>2\,M_\odot$) as well as very low masses ($<10^{-3}\,M_\odot$). These features could be tested by observations.







Stiff equation of state

↓

High maximum masses

We *predicted* massive quark stars (M≳2M_sun)

Lai & Xu (MNRAS 2009)

Massive pulsars are found :

Demorest et al. (Nature 2010):
M=1.97+/-0.04 M_sun

Antoniadis et al. (Science 2013):
M=2.01+/-.04 M_sun

H-cluster stars

Lai, Gao & Xu, MNRAS, 431, 3282 (2013)

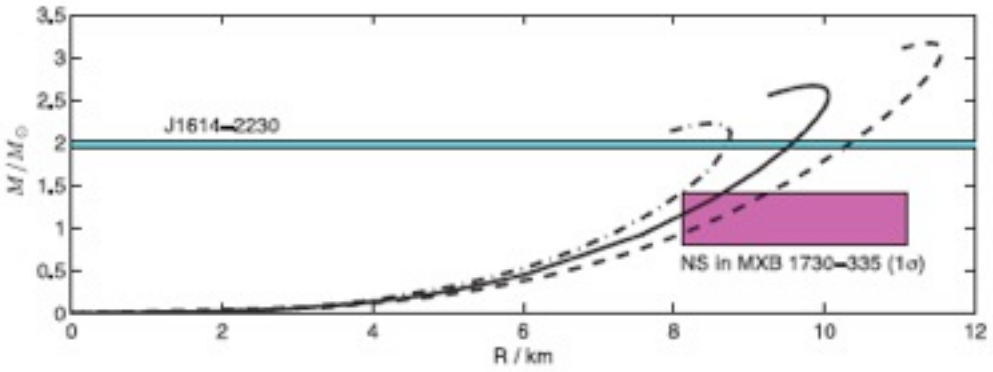
H-dibaryons (Λ-Λ bound states, uuddss): specific quark-clusters

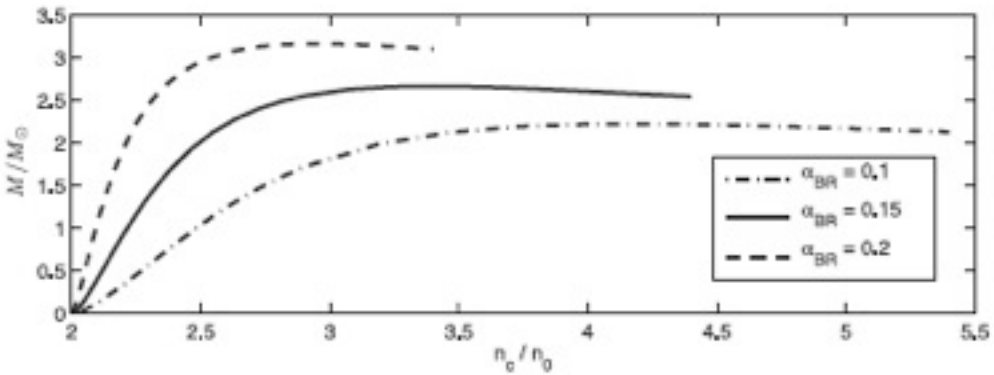
H-H interaction:

$$V(r) = \frac{g_{\omega H}^2}{4\pi}\frac{e^{-m_\omega^* r}}{r} - \frac{g_{\sigma H}^2}{4\pi}\frac{e^{-m_\sigma^* r}}{r}$$

Brown-Rho scaling for both mesons and H-dibaryons:

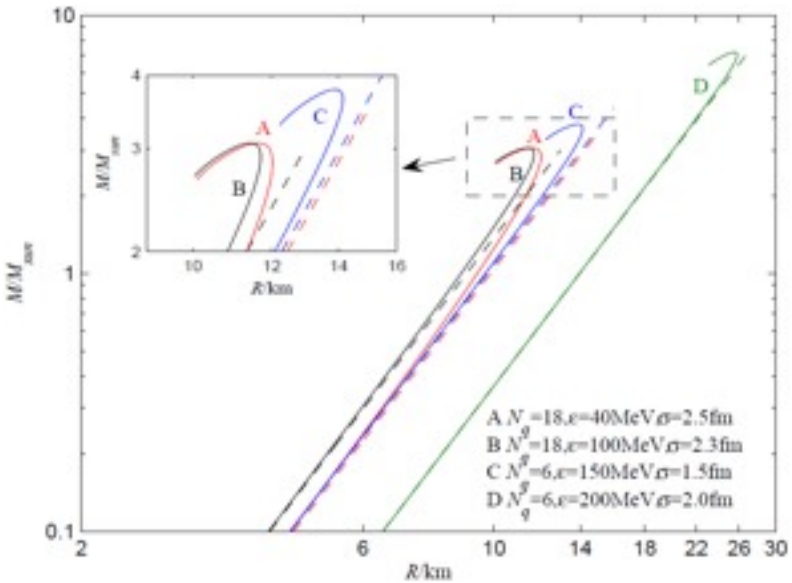
$$m^*/m = 1 - \alpha_{\rm BR}\frac{n}{n_0}$$





A corresponding-state approach to quark-cluster matter

Guo, Lai & Xu et al. 2013



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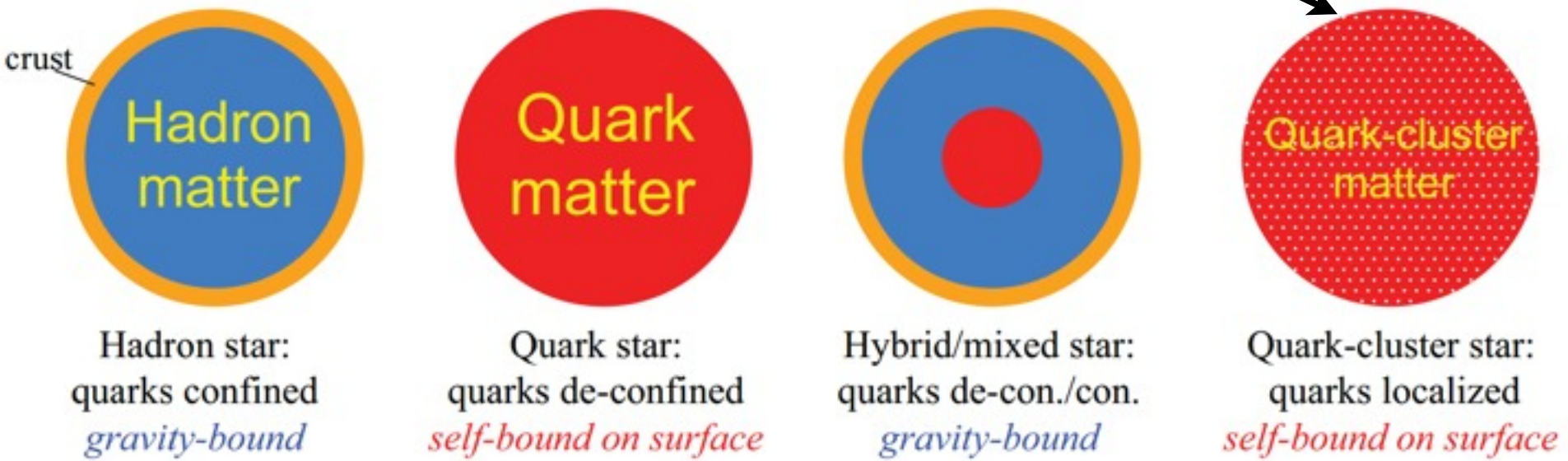
Summary

The nature of pulsar-like compact stars

My answer



Thank you!

comments and suggestions are welcome