From quark stars to H-cluster stars

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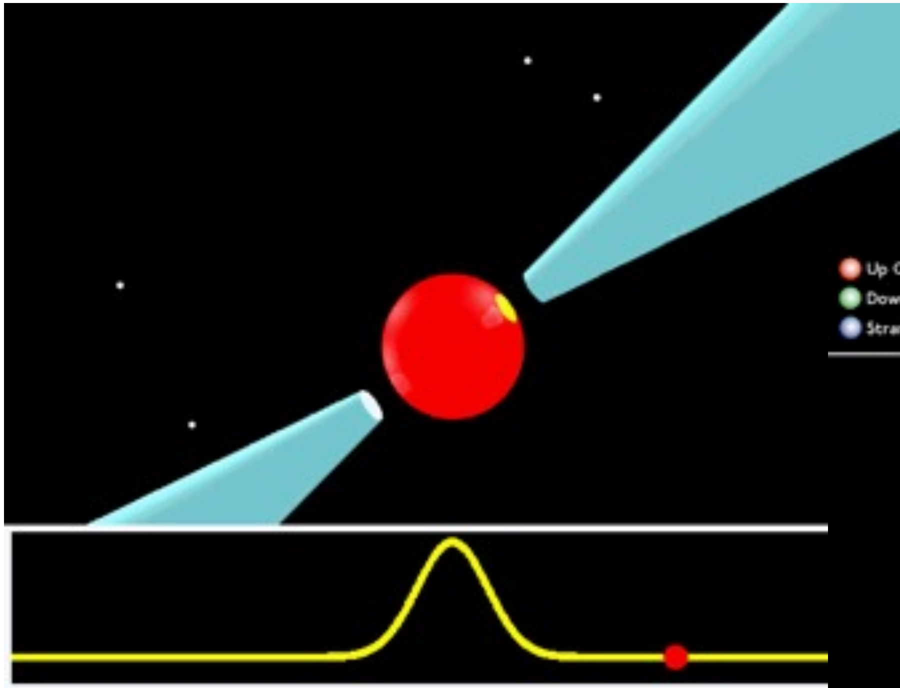
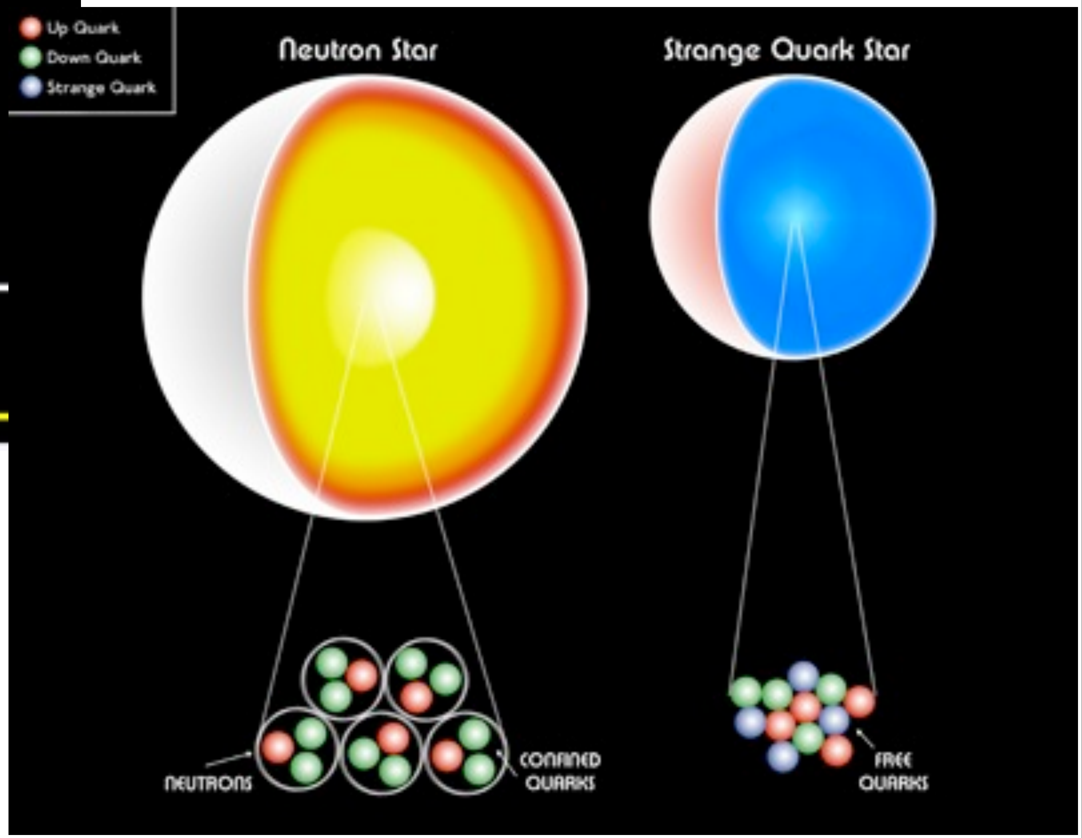
Outline

- Pulsars: neutron stars *vs* quark stars
- Quark stars: quark-clustering phase?
- H-cluster stars
  - H-dibaryons: a possible kind of quark-clusters
- Summary and discussions

Pulsars: neutron stars or quark stars?





Possible evidence for quark stars?

- Drifting subpulses
  - Binding energy of baryons on the surface is very high
- A clean fireball for both supernova and γ-ray bursts
  - No baryon contamination
- Non-atomic thermal spectra

These problems could be solved naturally
if pulsars are **bare quark stars**

Quark Stars = Strange Quark Stars

Strangeness !

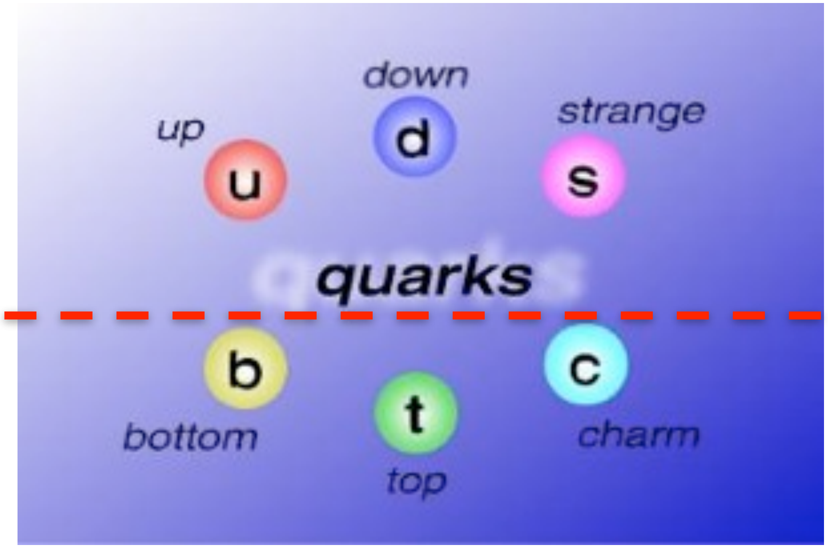
- Typical average density of pulsars > $2\rho_0$
- Energy scale inside pulsars ($2\rho_0 < \rho < 10\ \rho_0$): 400 MeV < E < 800 MeV

Strange Quark Matter (SQM, or Strange Matter)

- u + d + s

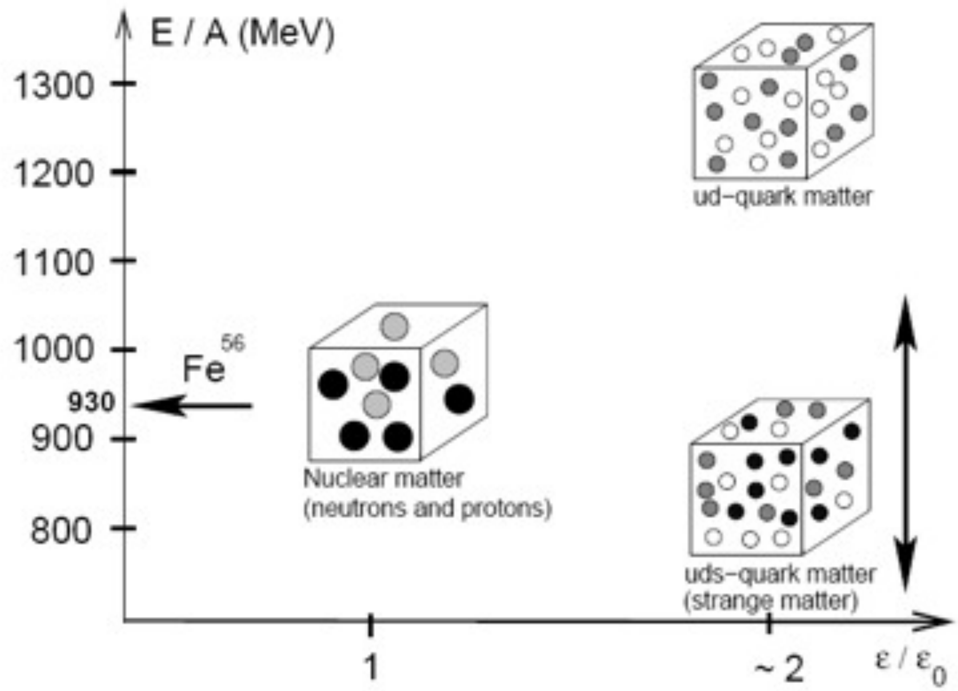
light quarks

heavy quarks (M > 1 GeV)



Strange Quark Stars

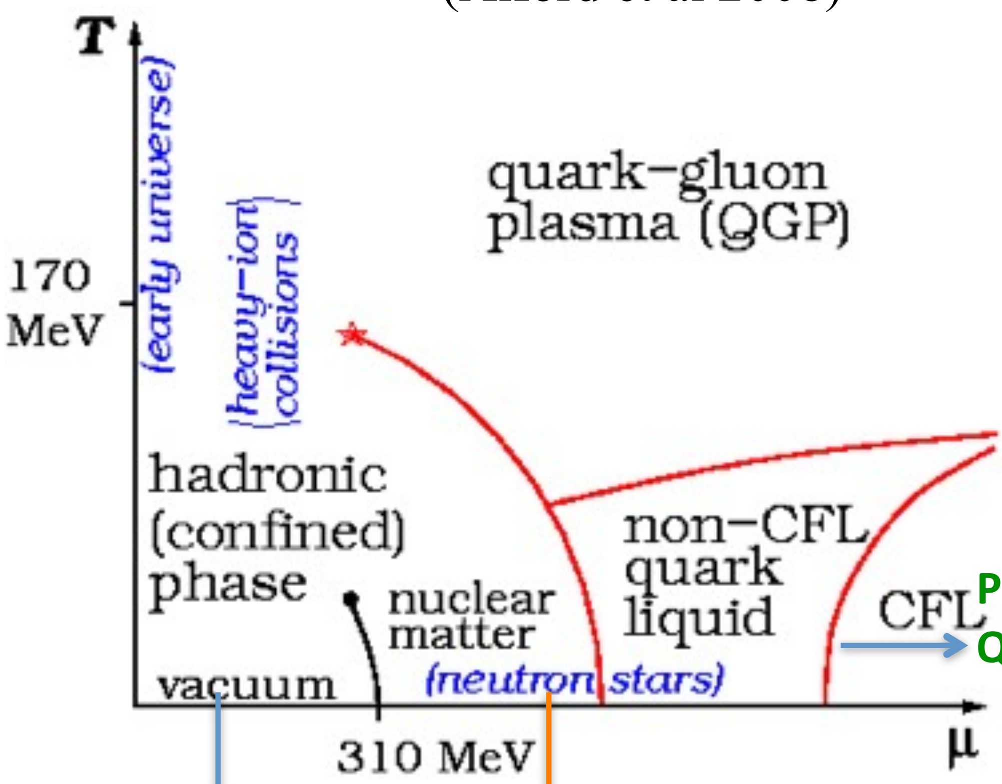
- Theoretically
  - Quark-deconfinement at high densities
  - Stability: Bodmer-Witten conjecture
- Observationally
  - Quark stars cannot be ruled out



(Weber 2005)

QCD phase diagram

(Alford et al 2008)



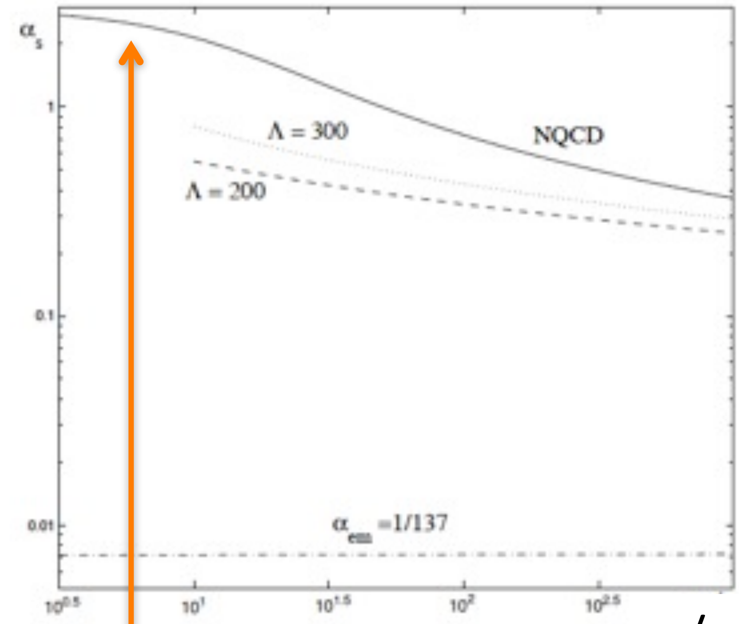
Perturbative QCD

Hadrons:
MIT bag model

Interior of compact stars

(Xu 2009)

α_s

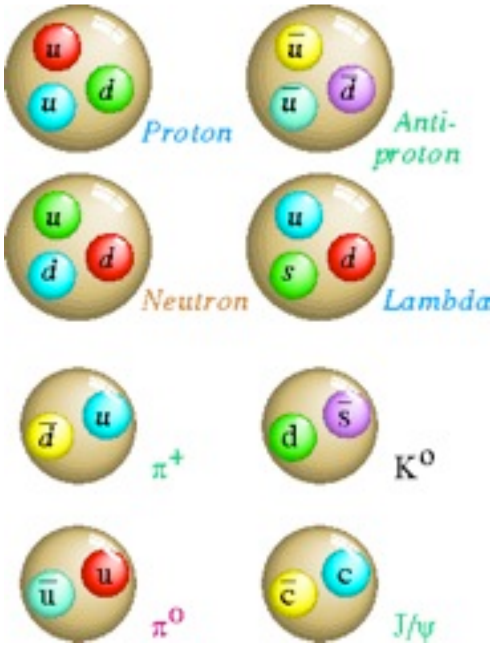


n_B/n_0

highly non-perturbative effect

Quark-clusters ?

hadrons: "quark-clusters"



quark-clustering in compact stars: **quark-cluster stars**

quark-cluster

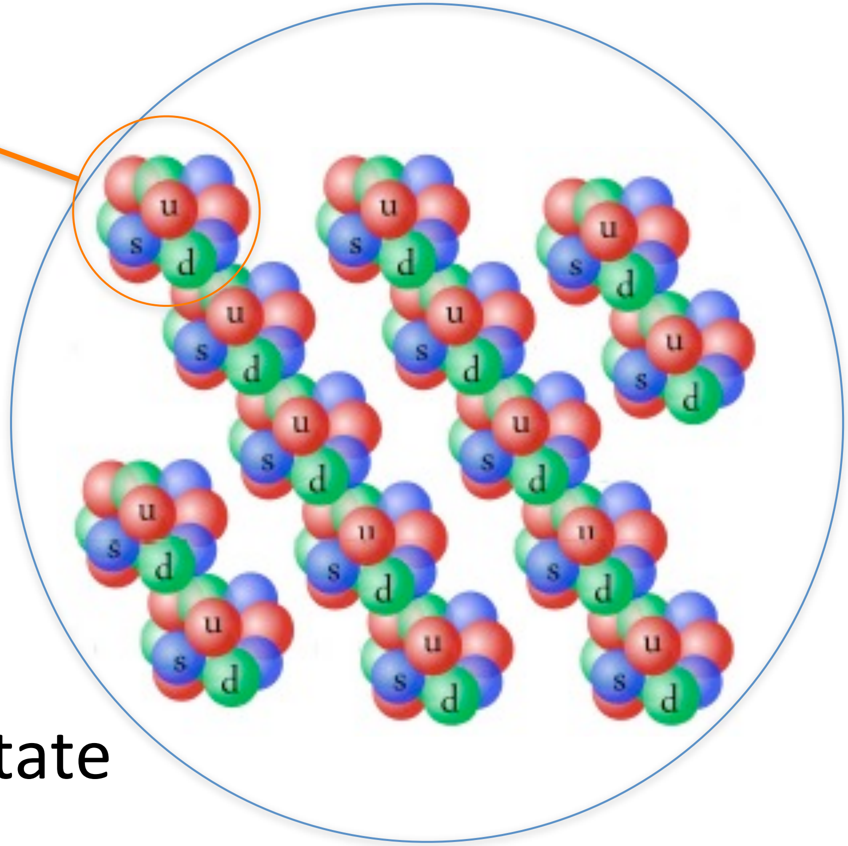
u, d & s

$N_q \geq 3$

non-relativistic & strongly interacting

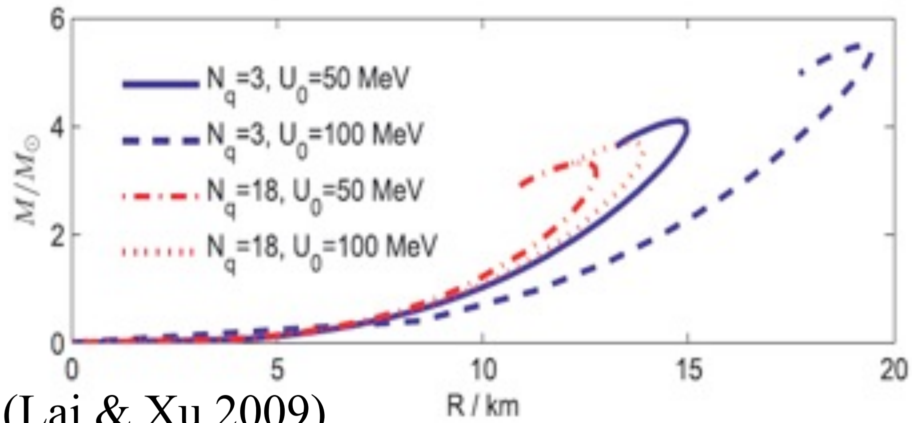
stiff equation of state

high maximum mass

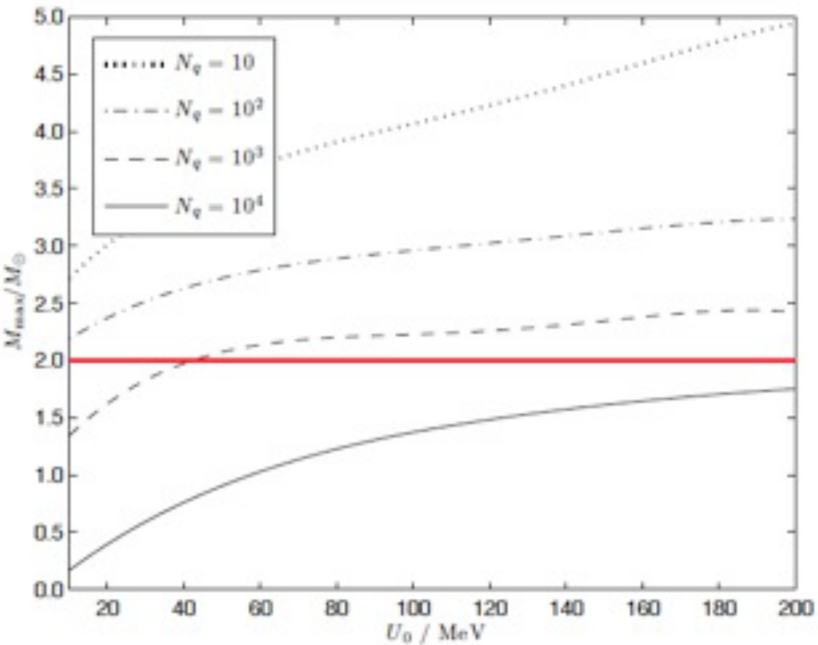


Quark stars with quark-clusters: high M_{max}

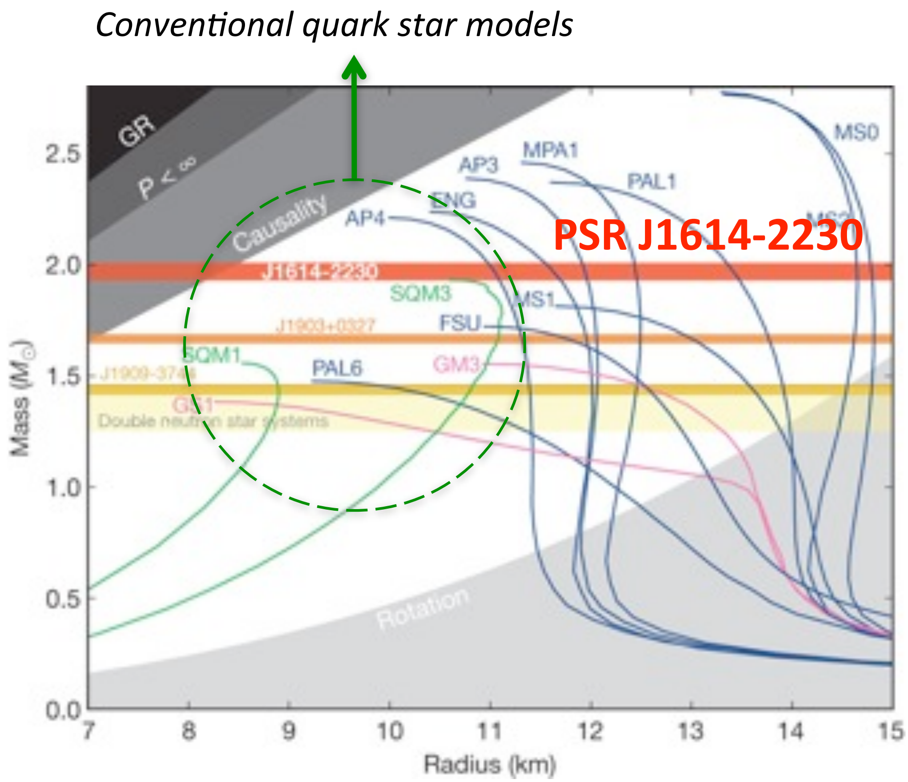
Lennard-Jones potential $u = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6]$



(Lai & Xu 2009)



(Lai & Xu 2011a)



(Demorest et al 2010)

What are quark-clusters ?

H-clusters: a kind of quark-clusters

- H-dibaryons:

  Λ-Λ bound states

- Theoretical prediction

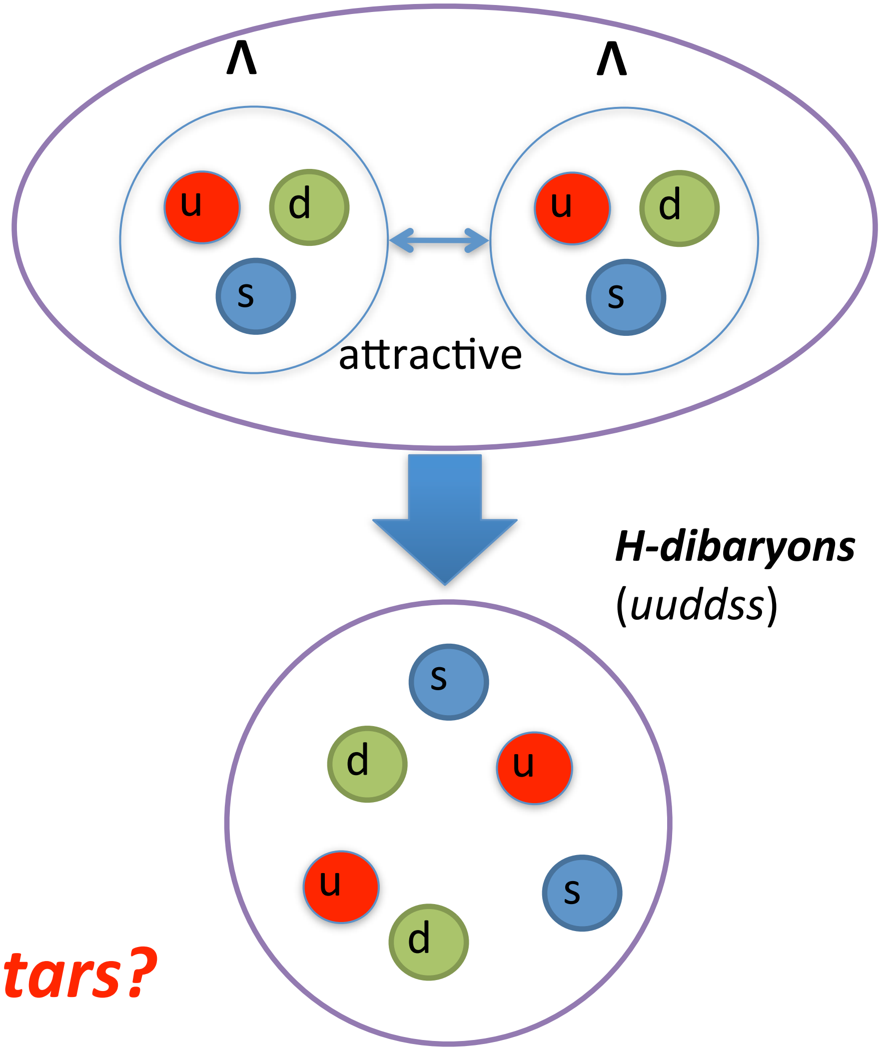
  (Jaffe 1977)

- Lattice QCD simulations

  (NPLQCD Collaboration 2011;
  HALQCD Collaboration 2011)

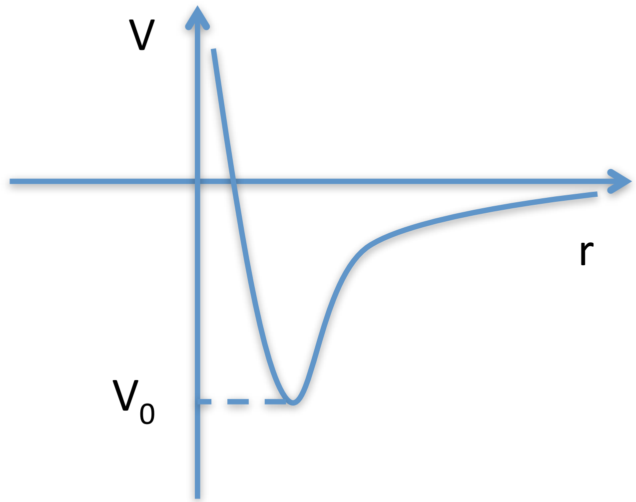
Quark-clusters with light flavor symmetry could be ***H-dibaryons***

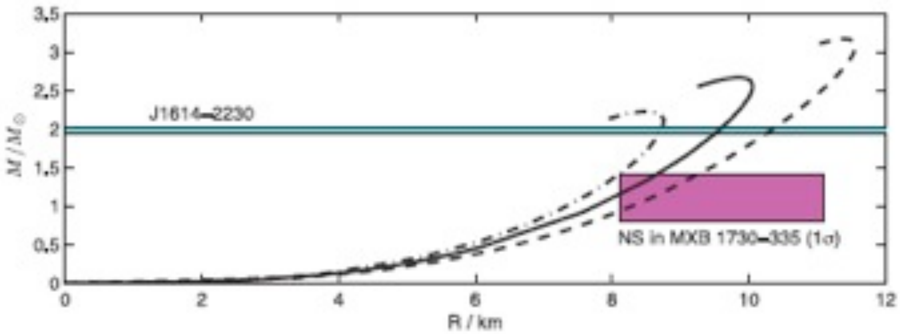
Quark-cluster stars: H-cluster stars?



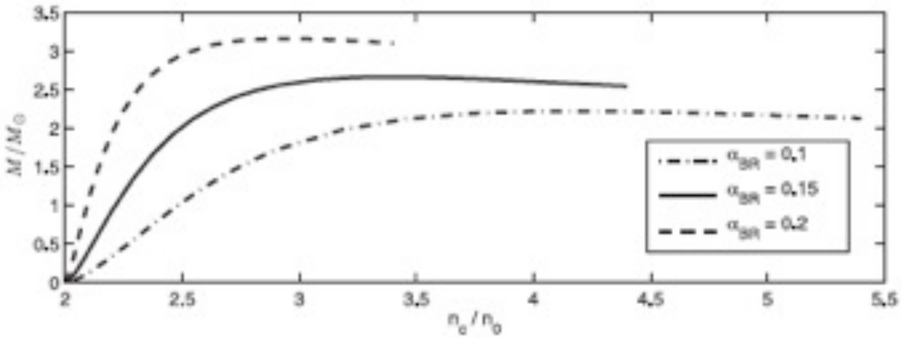
H-H interaction:
(Faessler et al. 1997)

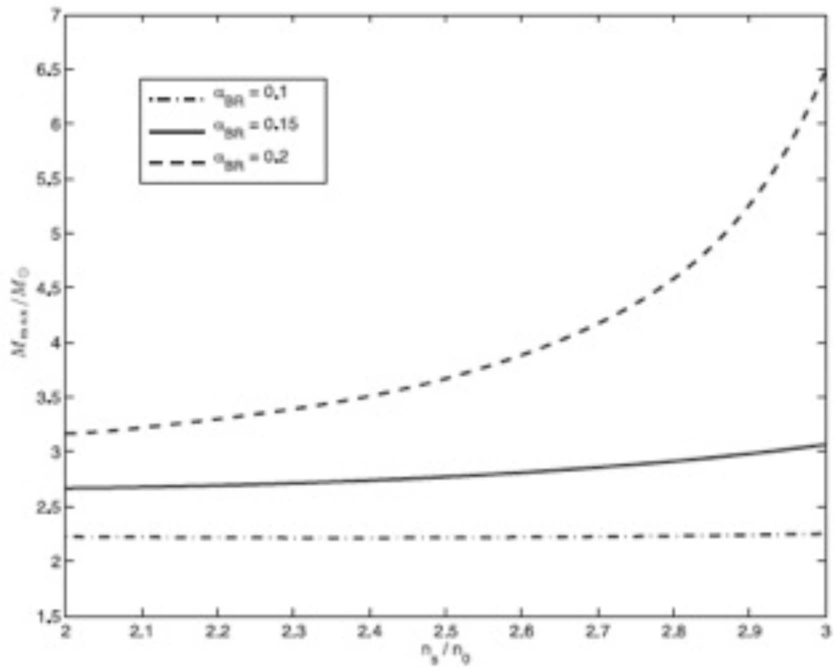
$$V(r) = \frac{g_{\omega H}^2}{4\pi}\frac{e^{-m_\omega r}}{r} - \frac{g_{\sigma H}^2}{4\pi}\frac{e^{-m_\sigma r}}{r}$$





mass-radius curves &
mass-central density curves





Dependence of M_{max} on α_{BR} and surface density

(Lai et al. 2013)

Summary

Quark-cluster stars

- quark-clustering phase
- strongly interacting
- non-relativistic

H-dibaryons: a specific kind of quark clusters

H-cluster stars

- Strongly interacting H-dibaryons in a dense medium

- **self-bound**
- **non-perturbative system**
- **stiff EoS**
- **high maximum mass**

Charge of u = +⅔ e
Charge of d = -⅓ e
Charge of s = -⅓ e

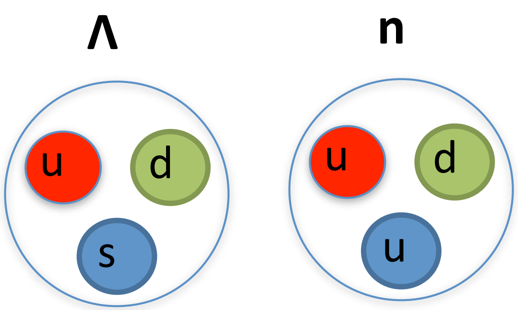
Discussion I
- *Stability of clustering SQM*

In nucleon matter [u+d]:

Isospin symmetry ($n_u=n_d$) + electrons, $E_s=0$, $E_F\neq0$

Isospin asymmetry ($n_d=2n_u$, no electron), $E_s\neq0$, $E_F=0$

In SQM [u+d+s]: Light flavor symmetry ($n_u=n_d=n_s$, no electron), $E_s=0$, $E_F=0$



In free space
- $m_s >> m_u \approx m_d$
- $m_\Lambda > m_n$
- Λ is unstable, Λ → n

In dense medium
- $m_s \approx m_u \approx m_d$
- $E_\Lambda < E_n$?
- $E_{u=d=s}/A < E_{u+d(+e)}/A$?

e.g. H-cluster matter
- In-medium effect: $m_N^* < m_N$, $m_M^* < m_M$ (Brown & Rho 1991)
- H-cluster matter could be more stable: $E_{H\text{-matter}}/A < E_{\text{nucleon matter}}/A$

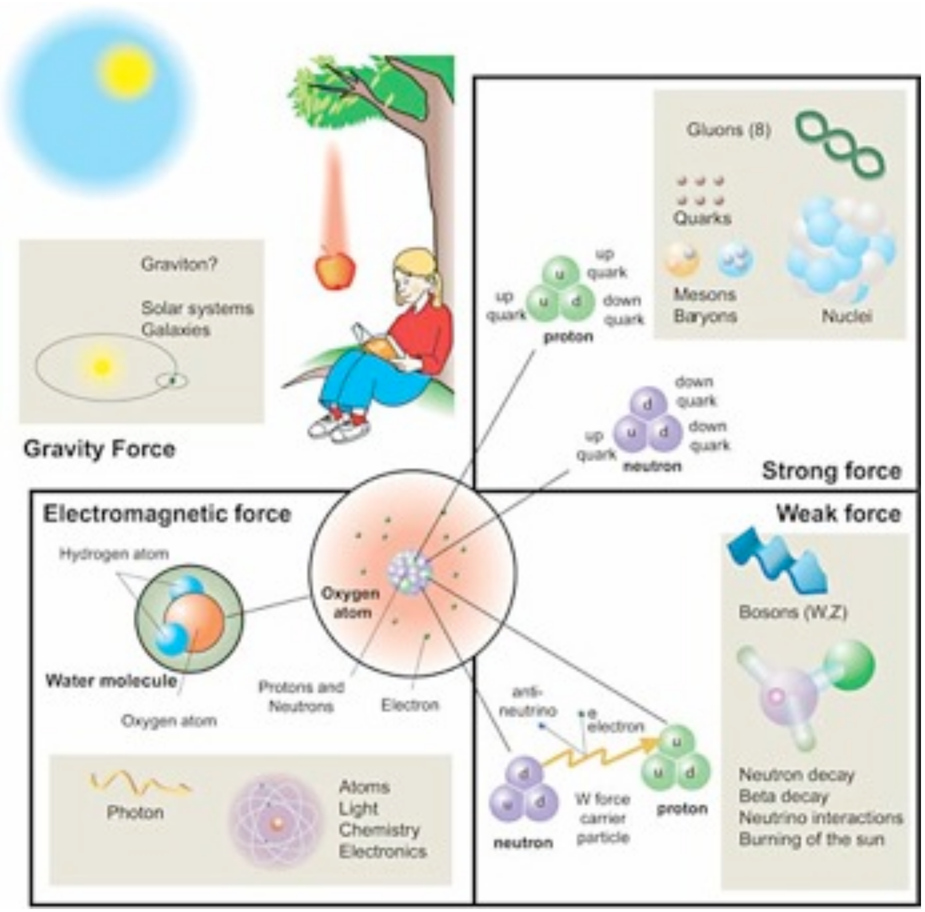
Discussion II
– *Astrophysical implications*

- 2 $M_\odot$ pulsar: implications for quark matter
  (PSR J1614-2230)
  - Quark matter
    - conventially soft EoS ✗
    - more realistic stiff EoS ✓
- Quark-cluster stars
  - very low mass & very high mass

    ↓

    *The **mass gap** between most massive pulsars (~ $2M_\odot$) and least massive black holes (~ $4.5M_\odot$)*
- To constrain quark matter
  - properties of cold matter at supra-nuclear densities

Thank you !



Gravity Force
Graviton?
Solar systems
Galaxies
Strong force
Gluons (8)
Quarks
Mesons
Baryons
Nuclei
up quark
up quark
down quark
proton
down quark
down quark
up quark
neutron
Electromagnetic force
Hydrogen atom
Water molecule
Oxygen atom
Oxygen atom
Protons and Neutrons
Electron
Photon
Atoms
Light
Chemistry
Electronics
Weak force
Bosons (W,Z)
anti-neutrino
electron
neutron
W force carrier particle
proton
Neutron decay
Beta decay
Neutrino interactions
Burning of the sun

S. Harris
Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them.

Quark, quark!