Strange matter in the Universe

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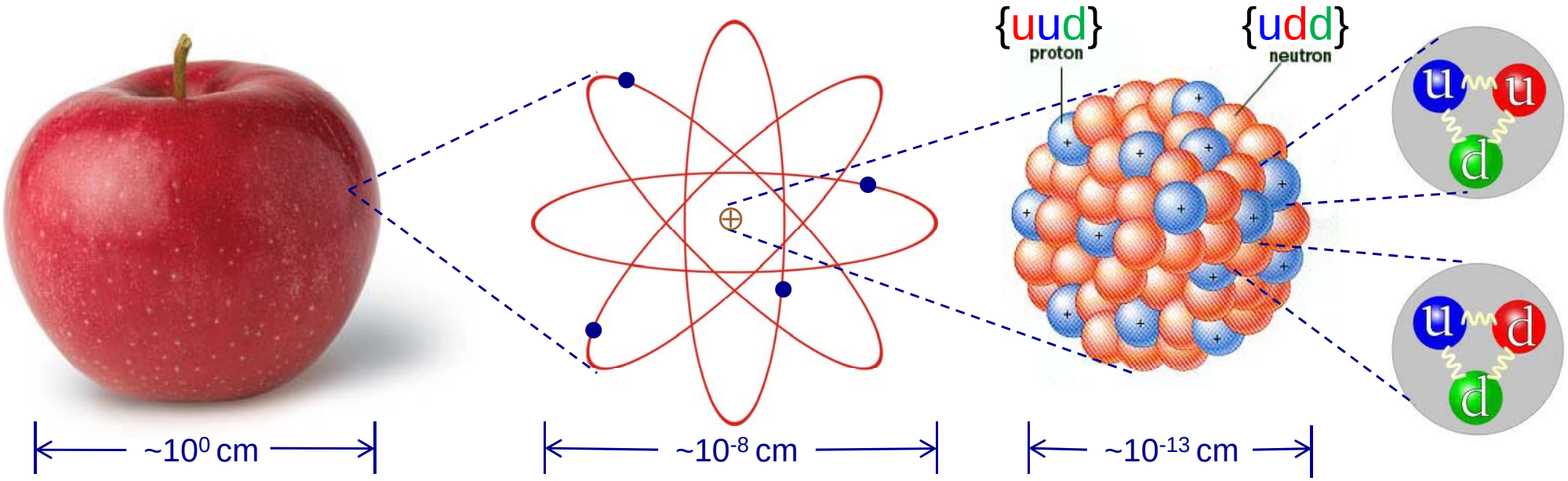
Summary

- Introduction: from NM to SM
- Why SM: bottom up and top down
- Hints from different manifestations?
- Conclusions

Introduction: *from NM to SM*



What does a little nucleus behave like?

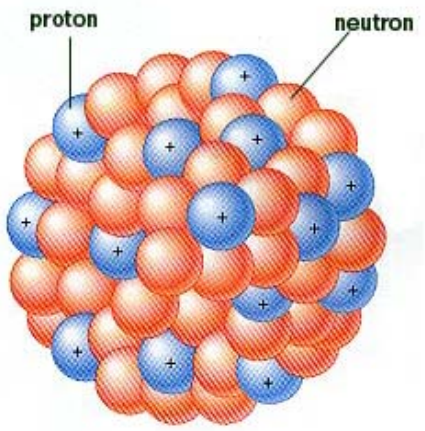
George Gamow (~1930): ***liquid*** drop!

(to treat the nucleus as a drop of incompressible nuclear fluid)

…then developed by Niels Bohr and John Archibald Wheeler

Can we have a kind of macroscopic matter composed by such liquid?

Introduction: *from NM to SM*



~10^{-13} cm

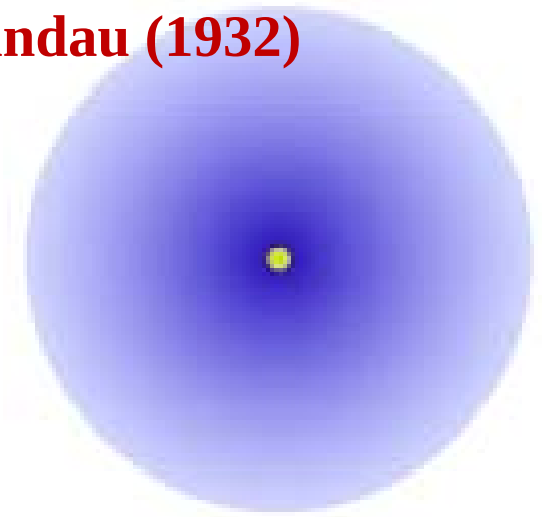
a little nucleus

after CC-SN

~$10^{0\sim6}$ cm?

a gigantic nucleus

Landau (1932)



~10^{11} cm

a gigantic nucleus in a star

What's ***difference*** between little and gigantic ones?

- **Large scale:** ***Electrons*** are included in gigantic nuclei but not in daily life nuclei
- **Gravity:** Matters at ***supra-nuclear density*** (a few nuclear saturation densities)

Questions relevant to the gigantic nuclei:

- Still only two ***flavors*** participated? → strangeness?
- Still only three ***quarks grouped***? → *n*-quark clusters?
- Still in Gamow's ***liquid drop*** state? → solid?

A gigantic nucleus made of

Strange Matter

of quark-clusters in solid state

Introduction: *from MN to SM*

A rubber
made of NM/SM

All of the
world's population

Summary

- Introduction: from NM to SM

✓ *Why SM: bottom up and top down*

- Hints from different manifestations?

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Why SM: *top down and bottom up*

- ***Approach from hadronic state***: bottom-up
  - From the asymmetry term to a ***u-d-s***-flavor symmetry

$$E_{\rm b}(Z,N) = a_{\rm v}A - a_{\rm s}A^{2/3} - \underbrace{a_4\frac{(N-Z)^2}{A}}_{\text{Symmetry Energy Term}} - a_{\rm c}\frac{Z(Z-1)}{A^{1/3}} + a_{\rm p}\frac{\Delta(N,Z)}{A^{1/2}}$$

symmetry energy term → isospin symmetry → (***u***p, ***d***own) symmetry → (***u***p, ***d***own, ***s***trange) symmetry???

  - From hadrons (e.g. Λ?) to quark-clusters (e.g. H, …?)

H-particles in lattice QCD:

Beane et al. [NPLQCD Collaboration], Phys. Rev. Lett. 106, 162001 (2011)
Inoue et al. [HAL QCD Collaboration], Phys. Rev. Lett. 106, 162002 (2011)

H-cluster stars? (Lai, Gao & Xu, arXiv:1107.0834)

Why SM: *top down* and *bottom up*

- ***Approach from free-quark state***: bottom-up

If *turning* ***off color*** *interaction*: AF $\rightarrow$ CS

$$\mu_{\mathrm{u}}^{\mathrm{NR}} = \mu_{\mathrm{d}}^{\mathrm{NR}} \sim \mu_{\mathrm{s}}^{\mathrm{NR}} \approx \frac{\hbar^2}{2m_{\mathrm{q}}}(3\pi^2)^{2/3}\cdot n_{\mathrm{u}}^{2/3} = 380\mathrm{MeV} >> T!$$

$$\left(\mu_{\mathrm{u}}^{\mathrm{ER}} = \hbar c(3\pi^2)^{1/3}\cdot n_{\mathrm{u}}^{1/3} = 480\mathrm{MeV} >> T\right)$$

If *turning* ***on color*** *interaction*: q-cluster?

$$l_{\mathrm{q}} \sim \frac{1}{\alpha_{\mathrm{s}}}\frac{\hbar c}{mc^2} \sim 1\mathrm{fm}/\alpha_{\mathrm{s}}, \quad E_{\mathrm{q}} \sim 300\alpha_{\mathrm{s}}^2\mathrm{MeV},$$

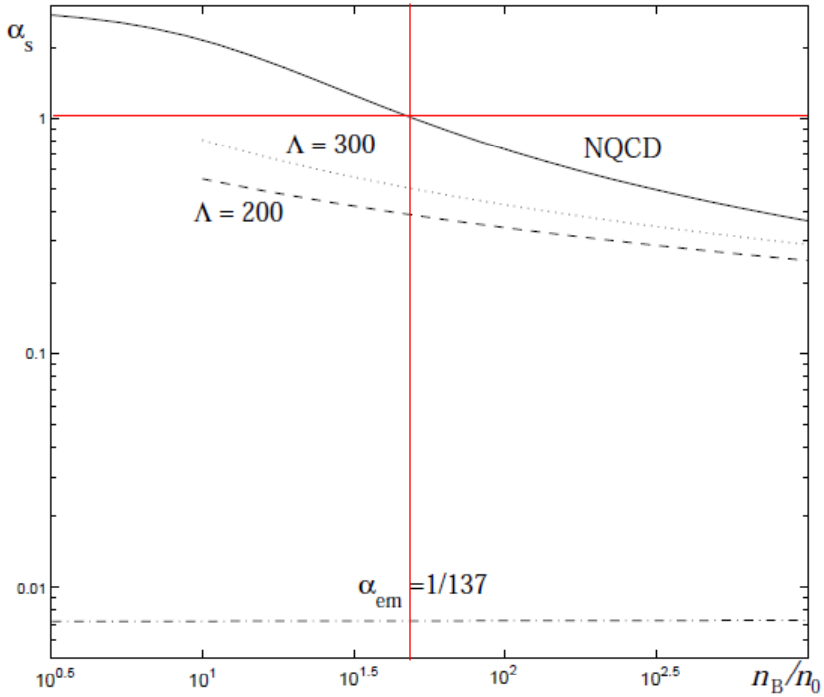
in case of dressed quarks, mass ~ 300MeV.

What about α_{s}?

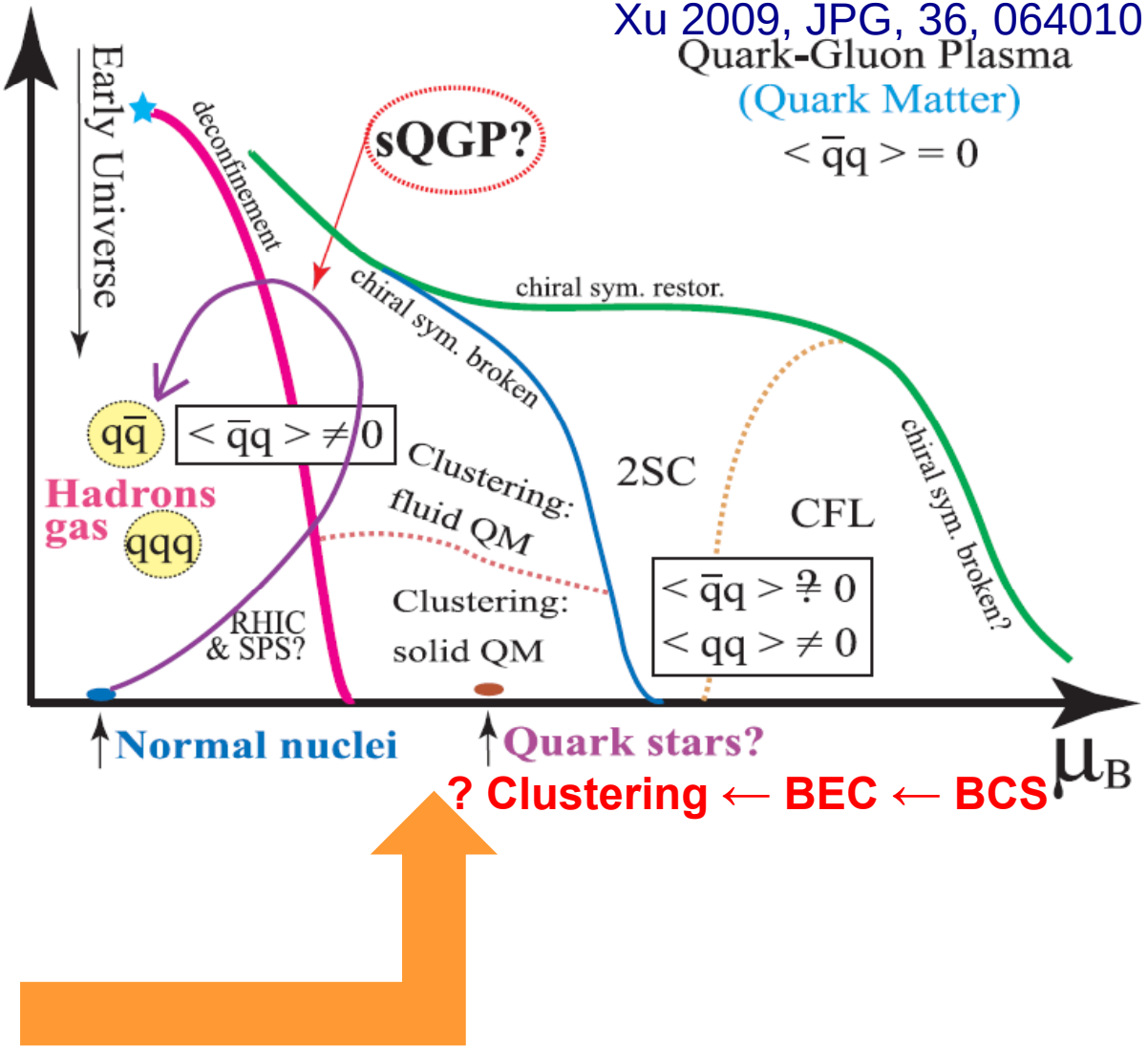
Why SM: *top down and bottom up*

coupling between quarks?

… DSE approach of NQCD



Xu 2009, JPG, 36, 064010



A quark ***clustering*** phase?

Why SM: *top down and bottom up*

- A quark-cluster star looks like a ***big*** metal ball

Metal ball ***V.S.*** **Quark-cluster star**

ions/nuclei ⟷ **quark clusters**

E-M interaction ⟷ **strong/color one**

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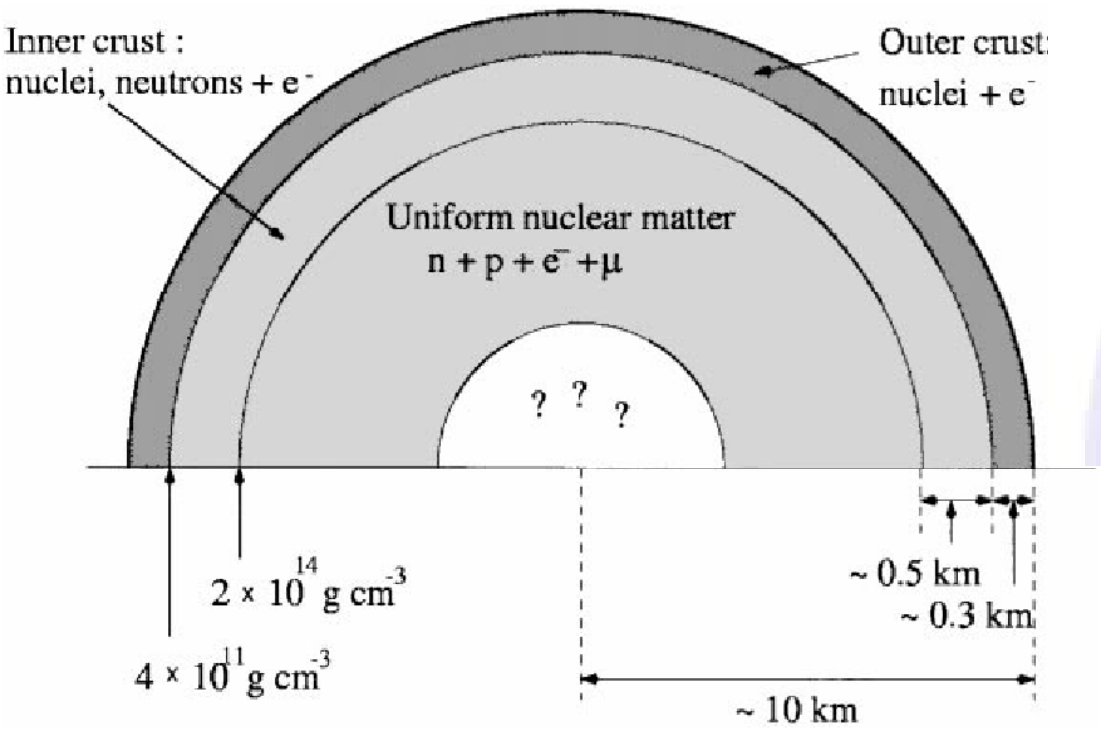
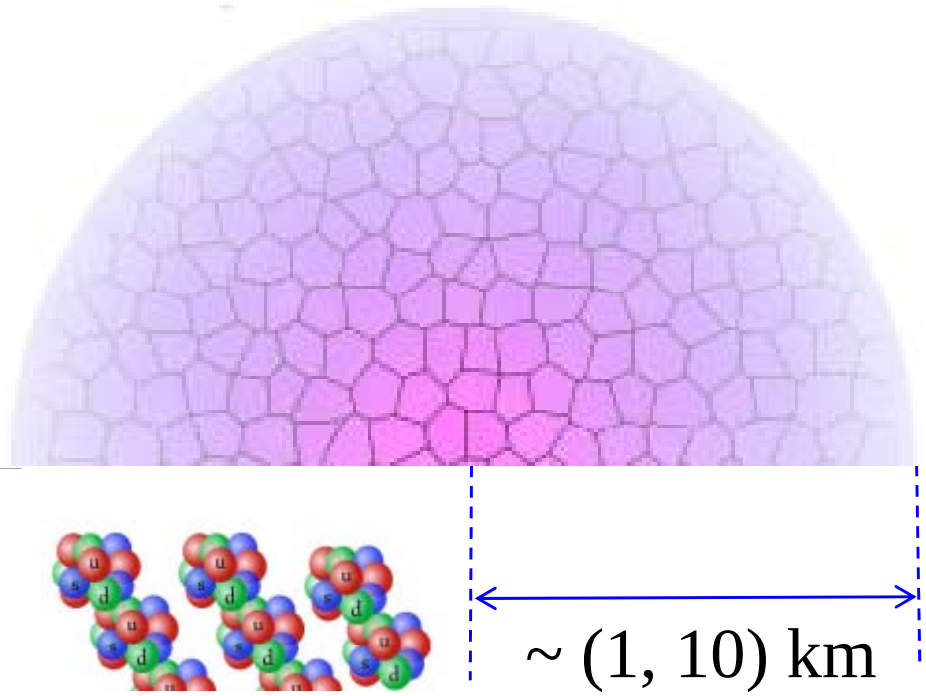
Hints from different manifestations?

- What is a ***quark-cluster star***? (Xu, ApJ, "*Solid quark stars?*" 2003)





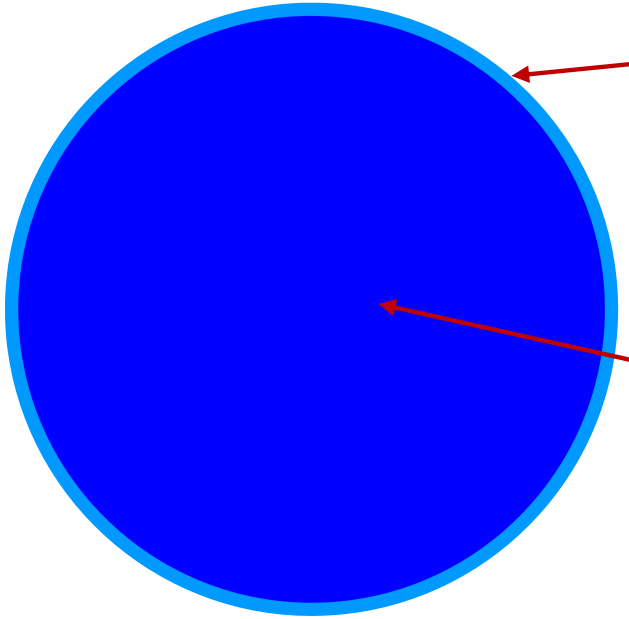
conventional neutron star (Heiselberg, 2000)

quark-cluster star (Xu, 2011)

- Gravity-bound (weak binding) ***vs.*** Self-bound (strong)
- Atmosphere ***vs.*** {q-clusters, electron sea}

Hints from different manifestations?

Any essential ***differences*** between NSs and QSs?



- ***Surface***:
  self- or gravity- ***confined***?
- ***Global***:
  complete or partial ***solid***?
  NR $\rightarrow$ stiff ***EoS***? (**ER**: soft!)

$E = (c^2p^2+m^2c^4)^{1/2} \sim p^2 \rightarrow P \sim \rho^{\gamma}$
($\gamma > 1$!)

idea gas:
$P = (1/3)\ \rho^1$

Hints from different manifestations?

- Non-thermal emission: bound strongly?
  - ***Subpulse drifting***: PSG or self-bound surface?
  - ***Bi-drifting***: strong self-bound quark surface?
- Thermal emission: featureless & clear?
  - ***Nonatomic spectra***: quark surface?
  - ***Clean fireball*** for SNE & GRB?

Surface

- Quark-cluster stars in a solid state?
  - ***Precessions*** of pulsars?
  - ***Quake***-induced free energy for AXP/SGRs?
- Test if stiff equation of state?

Global

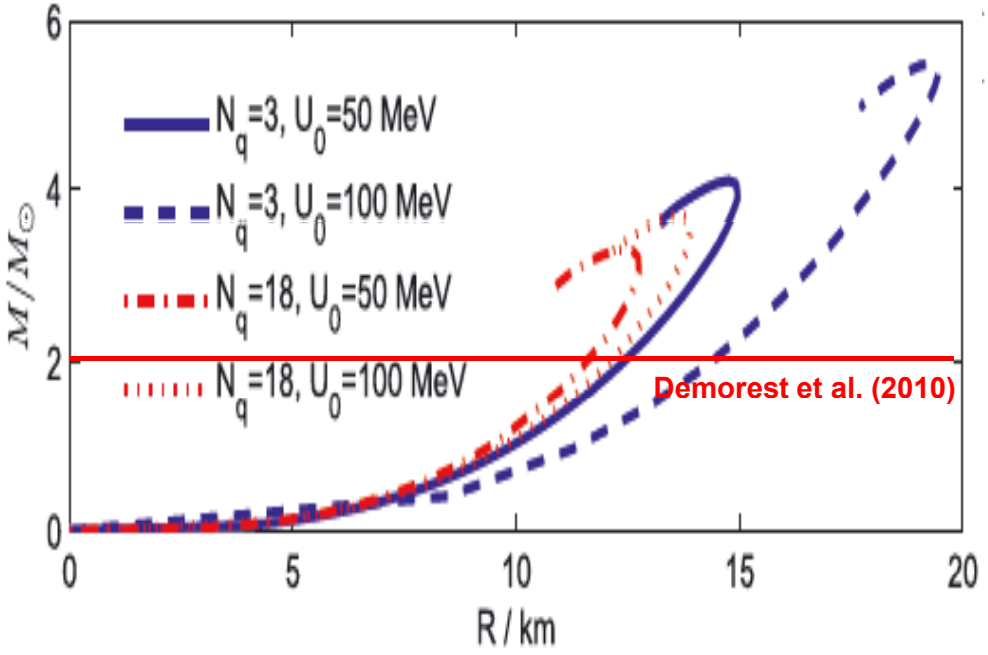
Quark-cluster star passes test of M/R ***measurements***

Lennard-Jones quark matter and massive quark stars

X. Y. Lai★ and R. X. Xu

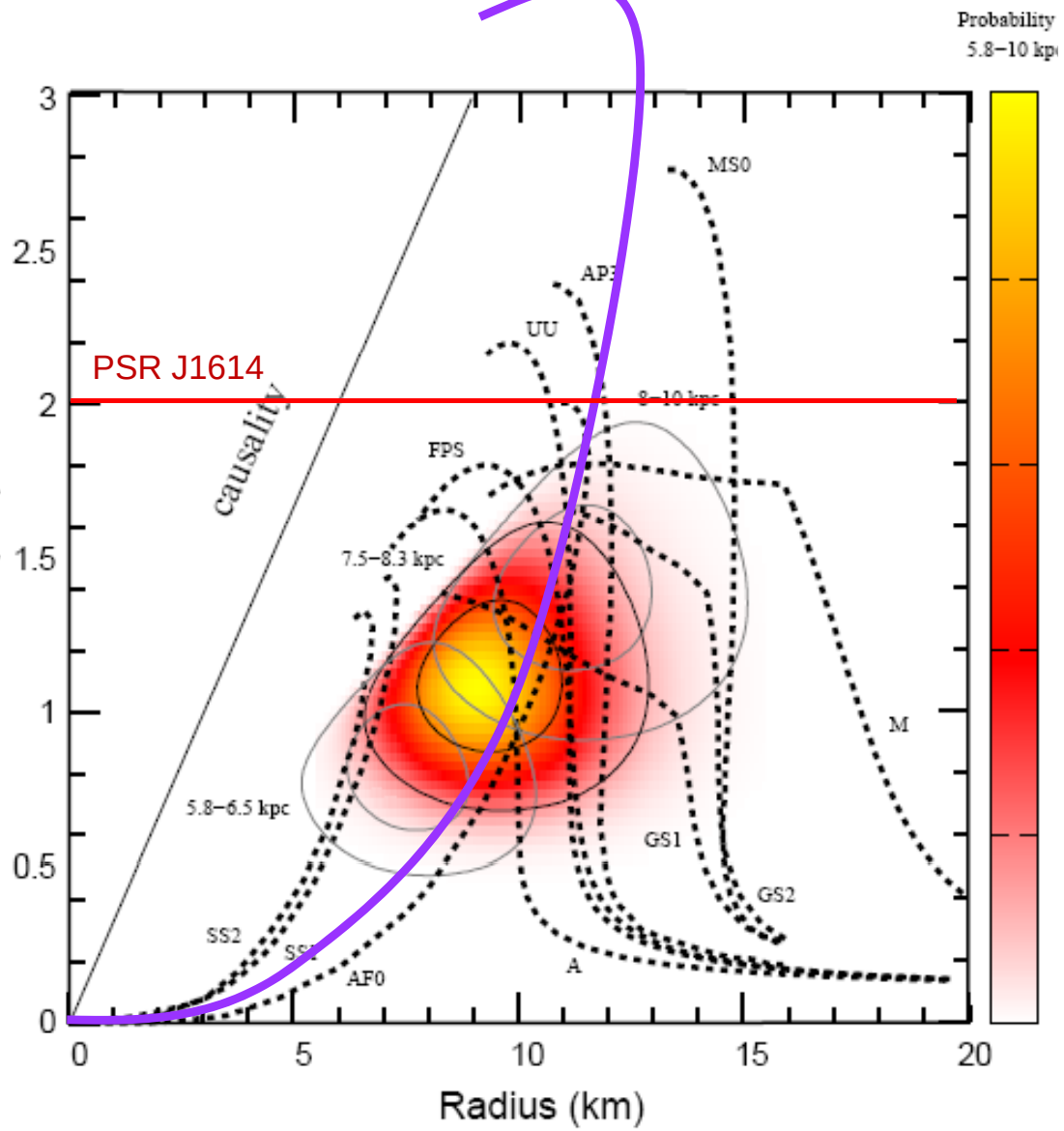
ABSTRACT

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.



(Lai & Xu 2009 MNRAS, 398, L31)

Lai & Xu (2009, N_q = 18, U_0 = 100 MeV)



(Sala et al. ApJ, arXiv:1204.3627)

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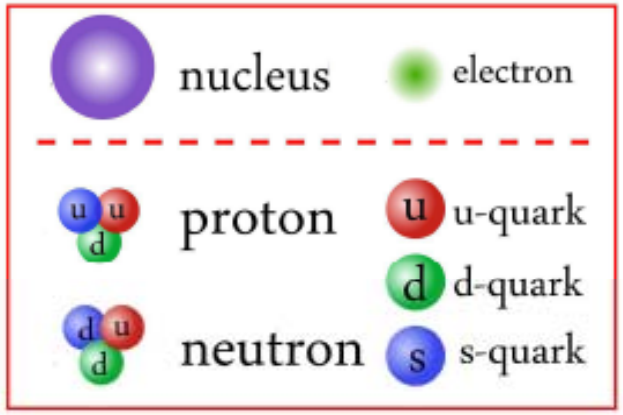
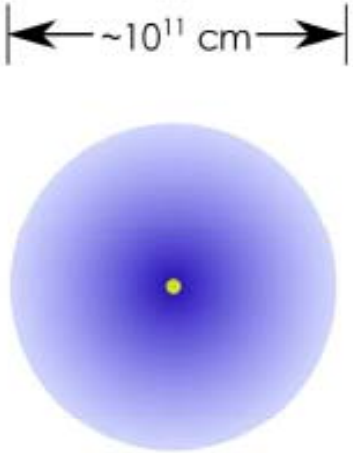
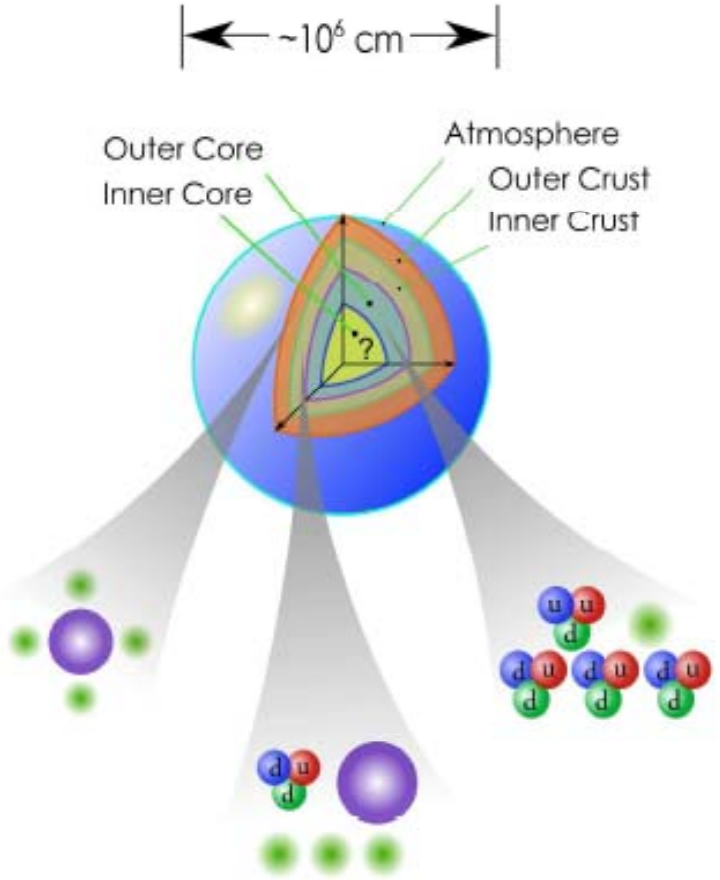
Conclusions

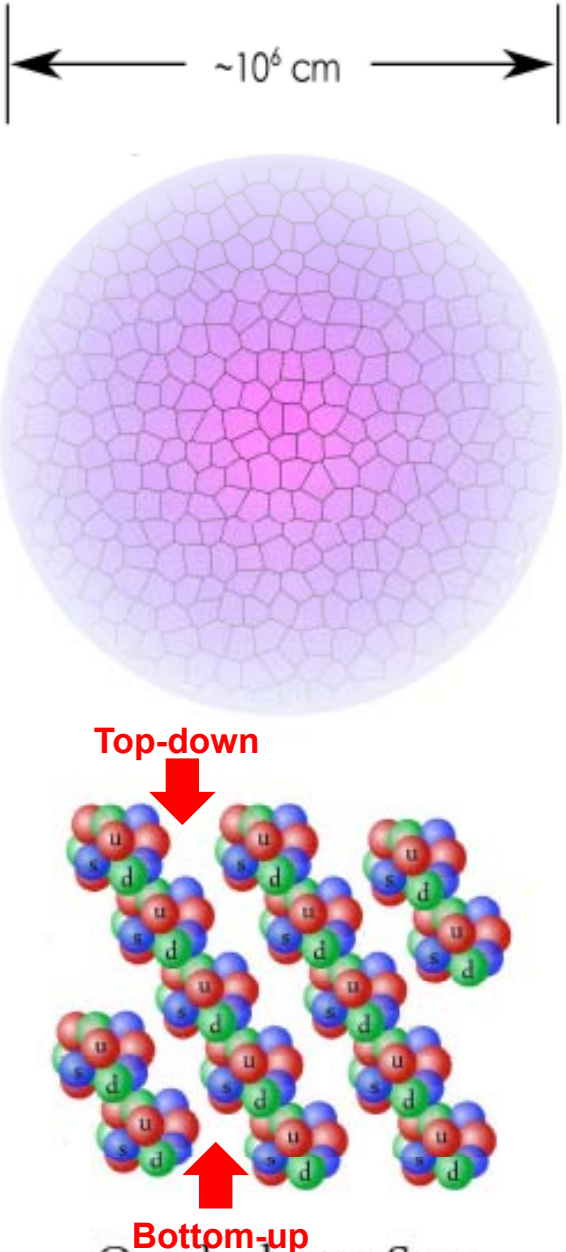




Landau's Gigantic Nucleus



Normal Neutron Star



Quark-cluster Star

Thank you!

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A short review:

Xu (2011) IJPME 20, 149 (arXiv:1109.0665)