Compressed baryonic matter of astrophysics

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中科院理论物理研究所：2012年9月5日

All began from "MN **87** (1926) 114"

On Dense Matter. By R. H. Fowler, F.R.S.

§ 1. *Introductory.*—The accepted density of matter in stars such as the companion of Sirius is of the order of 10^5gm./c.c. This large density has already given rise to most interesting theoretical considerations, largely due to Eddington. We recognise now that matter can exist in such a dense state if it has sufficient *energy*, so that the electrons are not bound in their ordinary atomic orbits of atomic dimensions, but are in the main free—with sufficient energy to escape from any nucleus they may be near. The density of such "energetic" matter is then only limited *a priori* by the "sizes" of electrons and atomic nuclei. The "volumes" of these are perhaps 10^{-14} of the volume of the corresponding atoms, so that densities up to 10^{14} times that of terrestrial materials may not be impossible. Since the greatest stellar densities are of an altogether lower order of magnitude, the limitations imposed by the "sizes" of the nuclei and electrons can be ignored in discussions of stellar densities, and the structural particles of stellar matter can be treated as massive charged points.

Eddington has recently * pointed out a difficulty in the theory of such matter. Assuming it to behave more or less like a perfect gas,

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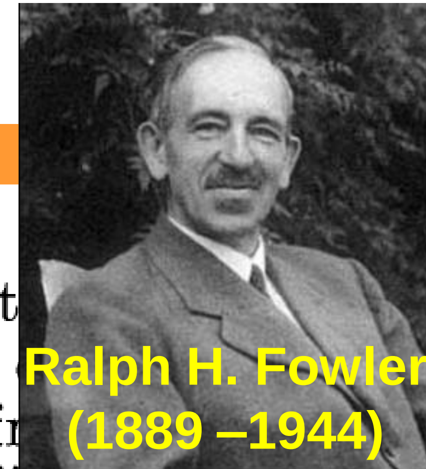
S. Chandrasekhar
Paul Dirac
Douglas R. Hartree
John Lennard-Jones


Ralph H. Fowler (1889 –1944)

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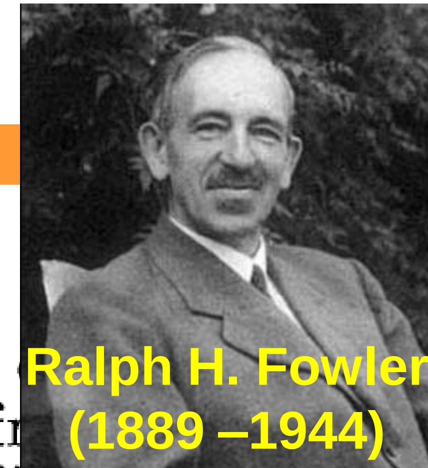

王竹溪（1911年6月7日生，1983年1月30日卒），湖北公安人。1933年进清华研究院，1935年Dirac推荐给Fowler，1938年获博士学位回国，任西南联合大学清华大学教授。1952年全国高等院校调整，王竹溪到北京大学任物理系教授、理论物理教研室主任。

王竹溪是我国热力学统计物理研究的开拓者。在表面吸附、超点阵统计理论、植物细胞的吸水等方面做过基础性工作。撰写了《热力学》、《统计物理学导论》等教材。发明汉字新部首检字法，独立编纂《新部首大字典》。

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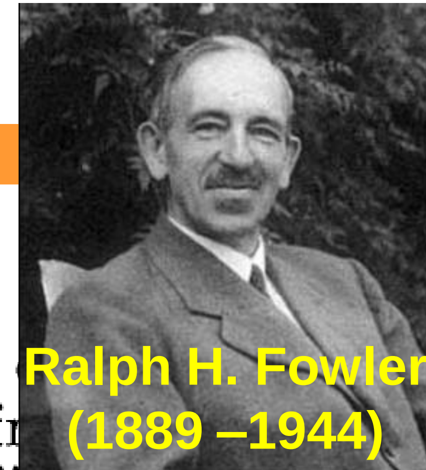
张宗燧



张宗燧（1915年6月1日生，1969年6月30日卒），浙江杭州人。1938年获剑桥大学博士学位。1940-1945年担任国立中央大学物理系教授。1948年回国任北京大学教授，1952年任北京师范大学教授。1956年任中国科学院数学研究所研究员及理论物理研究室主任兼中国科技大学教授等职。1957年受聘为中国科学院数理化部学部委员。1969年6月30日，因受极左路线的迫害而死，仅54岁。

2005年出版《张宗燧论文选集》，并召开学术会议以纪念张宗燧先生80周年诞辰。

Summary

- Introduction: What's compressed BM?
- An old answer proposed by Landau
- A new answer: quark-cluster matter?
- Hints from different manifestations
- Conclusions

Introduction: what's compressed BM?

- What is ***baryon***: the standard model of particle physics

48

Baryon (a quark) = 1/3

	Leptons		Quarks£¨mass£©	
color number	1	1	3	3
electricity	0	−1	+2/3	-1/3
1st generation	νe	e	u(2-8MeV)	d(5-15MeV)
2nd generation	νμ	μ	c(~1GeV)	s(~200MeV)
3rd generation	ντ	τ	t(~100GeV)	b(~4GeV)

	Strong	electro-magn.	Weak	gravity
Gauge Boson	gluon	photon	W, Z	graviton
Spin	1	1	1	2
number	8	1	3	1

13

Higgs Boson 1

Totally: 62

4 July 2012 Last updated at 07:35 GMT

Higgs boson-like particle discovery claimed at LHC

COMMENTS (1232)

By Paul Rincon
Science editor, BBC News website, Geneva

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The moment when Cern director Rolf Heuer confirmed the Higgs results

Cern scientists reporting from the Large Hadron Collider (LHC) have claimed the discovery of a new particle consistent with the Higgs boson.

The particle has been the subject of a 45-year hunt to explain how matter attains its mass.

5σ!

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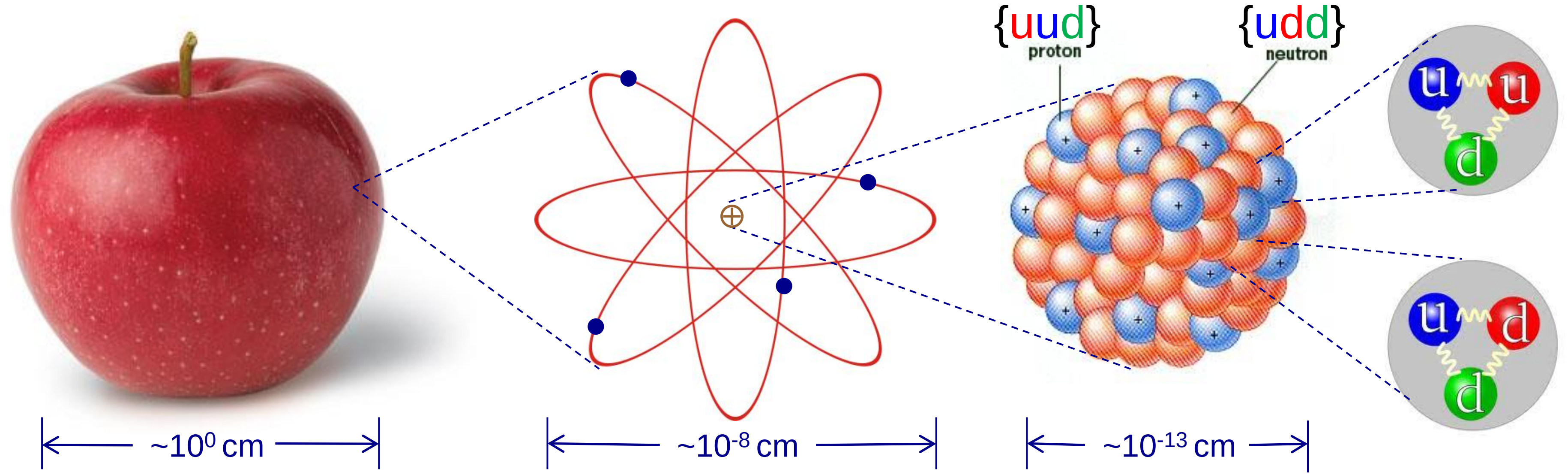
Introduction: what's compressed BM?



There is plenty of ***empty vacuum*** between atoms…

- What if the vacuum is squeezed out? —— density extremely high, ∞?
- How can one squeeze? —— gravity!
- Where would such matter exist? —— in the heaven!

Supernovae creates compressed baryonic matter

Introduction: what's compressed BM?

Introduction: what's compressed BM?

- ***Three*** reasons to study compressed BM now...

✓ to understand the fundamental strong interaction between quarks at low-energy scale (***non-perturbative QCD***) through extreme events of astrophysics (different manifestations of compact stars, stellar evolution, SN, GRB, …).

➢ to use pulsars as ***tools*** for fundamental (naro-Hertz GWs, ephemeris, ISM) and applicable (time standard, navigation) reasons.

➢ to do at least science at FangLZ's 2nd level because of advanced facilities in China (***FAST***, ***HXMT***, ...).

Millennium Prize Problems - Mozilla Firefox

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First Clay Mathematics Institute Millennium Prize Announced

Prize for Resolution of the Poincaré Conjecture Awarded to Dr. Grigoriy Perelman

March 18, 2010. The Clay Mathematics Institute (CMI) announces today that Dr. Grigoriy Perelman of St. Petersburg, Russia, is the recipient of the Millennium Prize for resolution of the Poincaré conjecture. The citation for the award reads:

The Clay Mathematics Institute hereby awards the Millennium Prize for resolution of the Poincaré conjecture to Grigoriy Perelman.

More ...

The Millennium Prize Problems

In order to celebrate mathematics in the new millennium, The Clay Mathematics Institute of Cambridge, Massachusetts (CMI) established seven *Prize Problems*. The Prizes were conceived to record some of the most difficult problems with which mathematicians were grappling at the turn of the second millennium; to elevate in the consciousness of the general public the fact that in mathematics, the frontier is still open and abounds in important unsolved problems; to emphasize the importance of working towards a solution of the deepest, most difficult problems; and to recognize achievement in mathematics of historical magnitude.

The prizes were announced at a meeting in Paris, held on May 24, 2000 at the Collège de France. Three lectures were presented: Timothy Gowers spoke on *The Importance of Mathematics*; Michael Atiyah and John Tate spoke on the problems themselves.

- Birch and Swinnerton-Dyer Conjecture
- Hodge Conjecture
- Navier-Stokes Equations
- P vs NP
- Poincaré Conjecture
- Riemann Hypothesis
- Yang-Mills Theory

- Rules
- Millennium Meeting Videos

Poincaré: 1904
a proof in 2002-2003,2006

Dr. Grigoriy Perelman
(1966.6.13-)

数学困难引发的物理难题

- 之一、NSE与湍流：经典物理中最后一个难题！
- 之二、Yang-Mills理论：当代物理重大难题！

$$L_{\text{QCD}} = \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - gG^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- 两个“问题”对比：NS方程 vs. Yang-Mills理论

	数学问题	物理现象
NS方程	非线性	层流 vs. 湍流
QCD	非微扰	高能 vs. 低能

- Compressed baryonic matter is ***astro-lab for NQCD***!

Introduction: what's compressed BM?

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你是做理论还是观测？我是不择手段做脉冲星的！理论、观测、外星人打电话…都可以。

Summary

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- ✓ An old answer proposed by Landau
- A new answer: quark-cluster matter?
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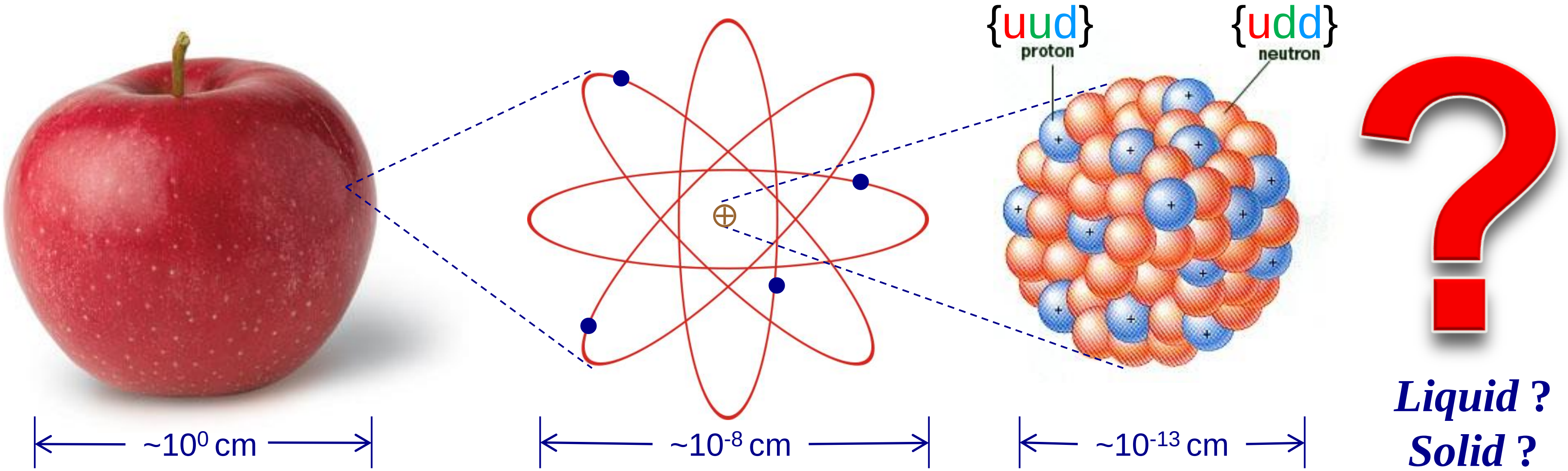
An old answer proposed by Landau



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

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

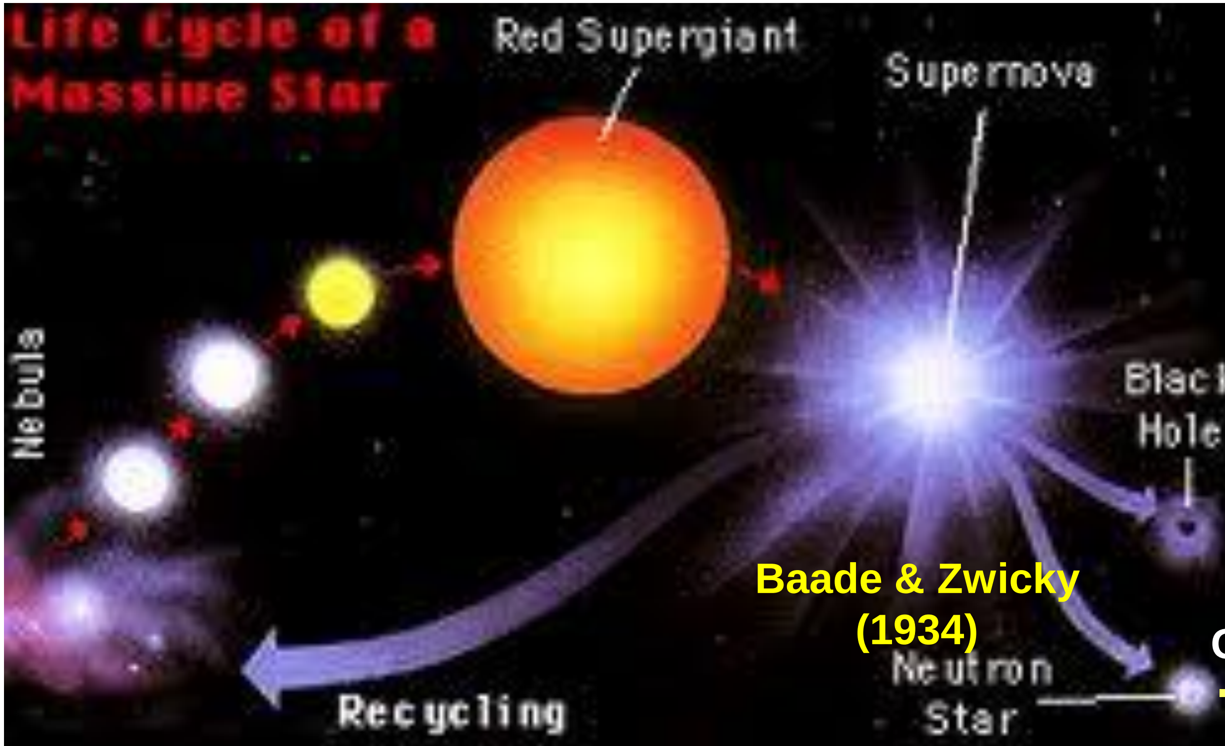
…then developed by Niels Bohr and John Archibald Wheeler

Weizsaecker formula (1935): $E_b \sim A - A^{2/3} - A^{-1/3} - (A-2Z)/A + \delta$

G. F. Bertsch (1974): ***solid*** nucleus?

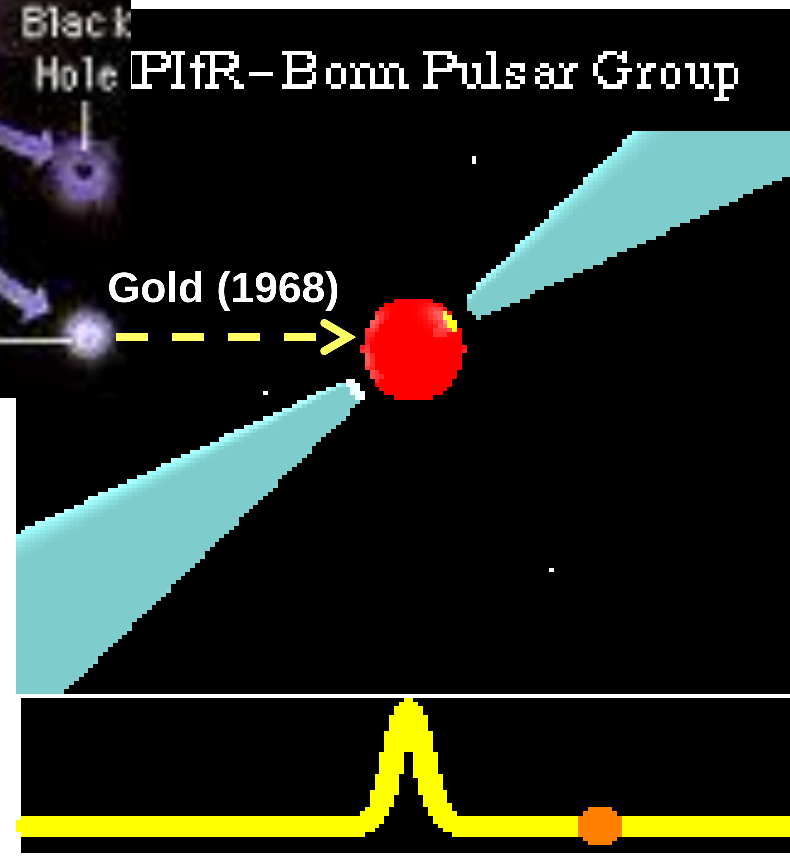
(giant resonance resembles the vibration of an elastic solid?)

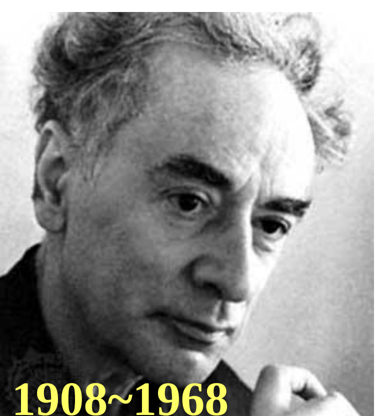
An old answer proposed by Landau



Hewish, Bell et al. discovered pulsars in 1967.

Gold: PSR = $NS_{spinning}$





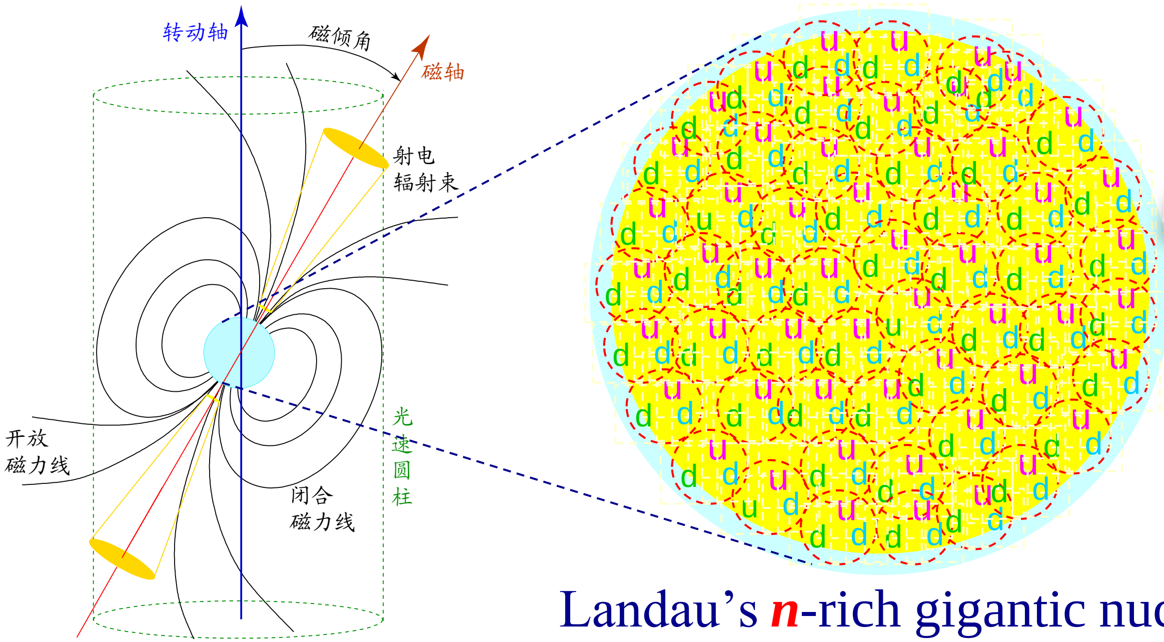
L. D. Landau ***speculated*** in 1931/1932:

matter $\sim\rho_{nucl}$ in star for energy

$\rightarrow$**gigantic nucleus**

$e \rightarrow$ **GN = NS**

An old answer proposed by Landau



Landau's *n*-rich gigantic nucleus

- Liquid? ***Solid***?
- Still only ***three*** quarks grouped?
- ***Quark***-degree still negligible?
- More flavors? (***strange*** flavor)

What's the ***difference*** between daily life nuclei and the "gigantic" one?

- ***Electrons*** are included in gigantic nuclei but not in normal nuclei due to **large scale**
- NSs at ***supra-nuclear density*** (a few nuclear saturation densities) due to **gravity**

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?

My gigantic nuclei:
solid quark (clustering) stars!

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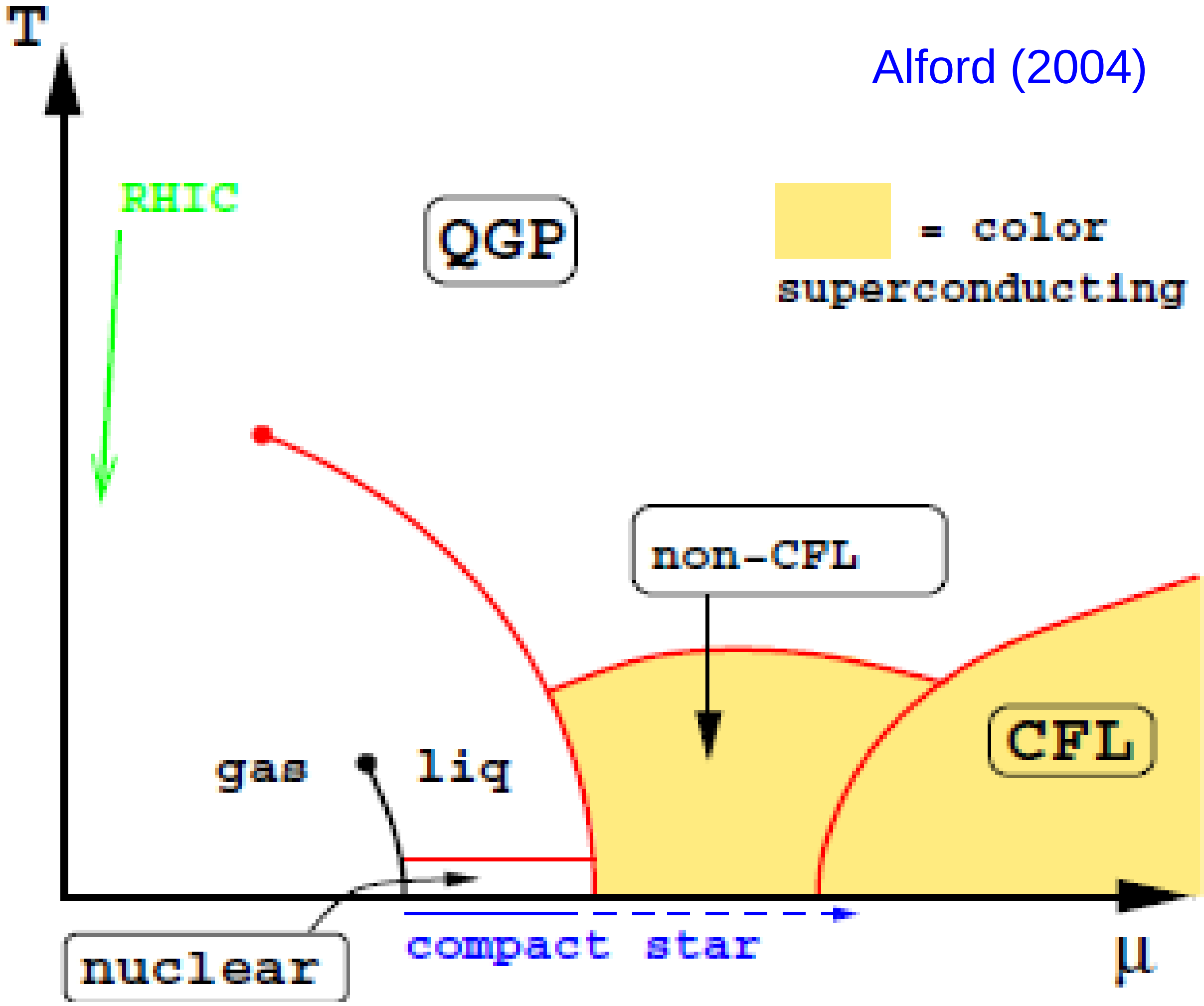
A new answer: quark-cluster matter?

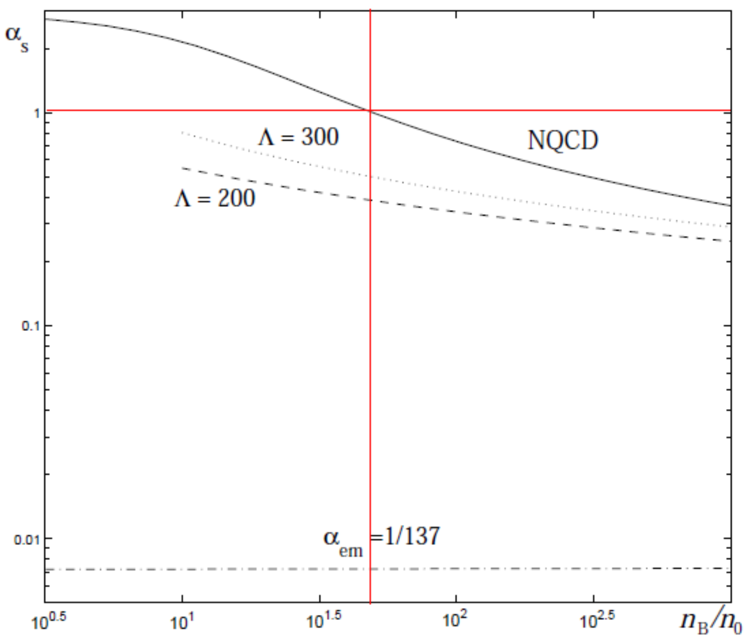
- EoS of compressed BM: the mainstream …



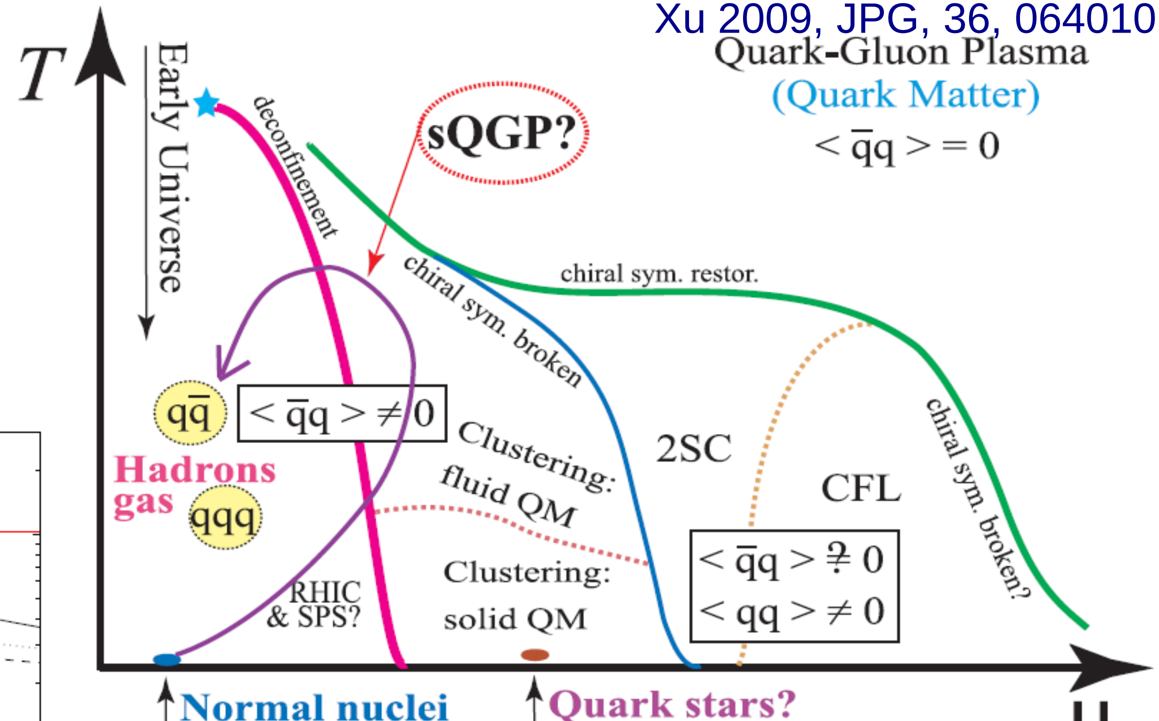
A new answer: quark-cluster matter?

coupling between quarks?

… DSE approach of NQCD



Xu 2009, JPG, 36, 064010

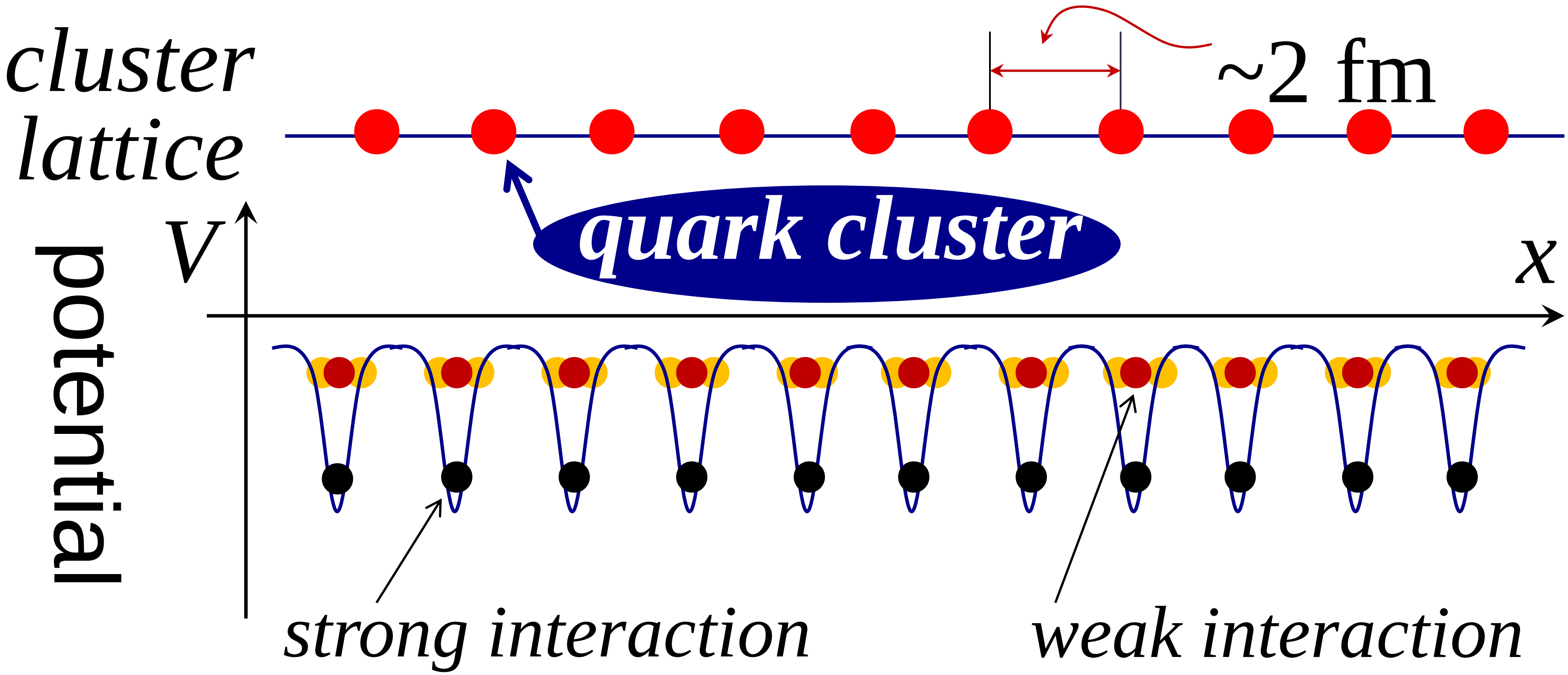


? Clustering ← BEC ← BCS

A quark ***clustering*** phase?

A new answer: quark-cluster matter?

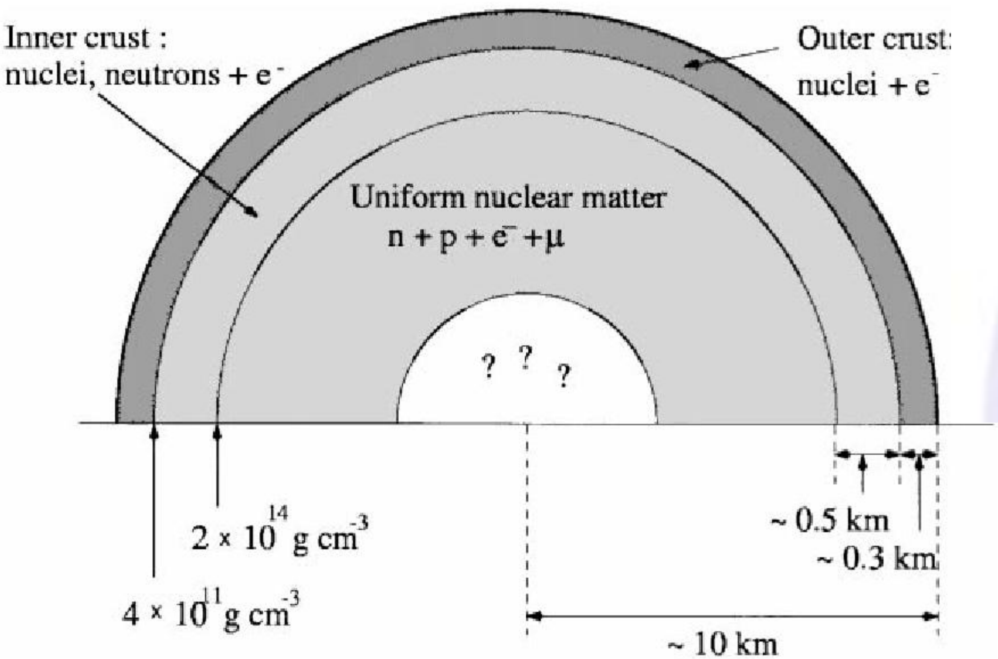
- The ***state*** of QcM: ***solid*?**



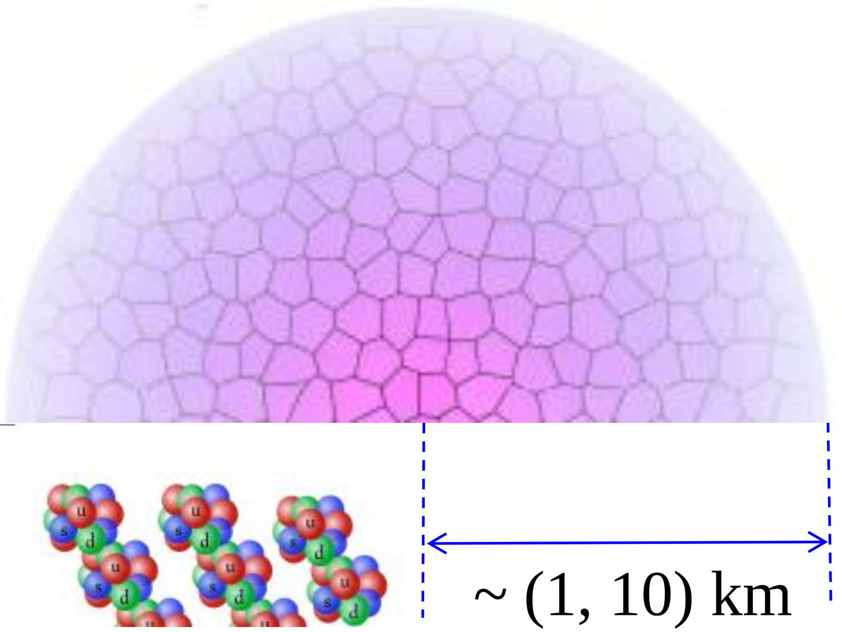
- *Classical solid*: barrier penetration *negligible*
- *Quantum solid*: penetration *significant*

A new answer: quark-cluster matter?

- Differences between NS & ***quark-cluster star***?



conventional neutron star
(Heiselberg, 2000)



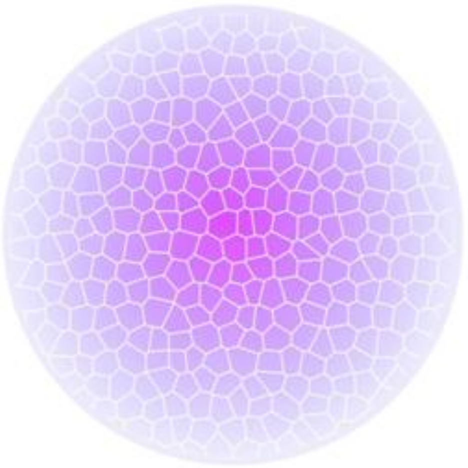
quark-cluster star
(Xu, 2011)

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

A new answer: quark-cluster matter?

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

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

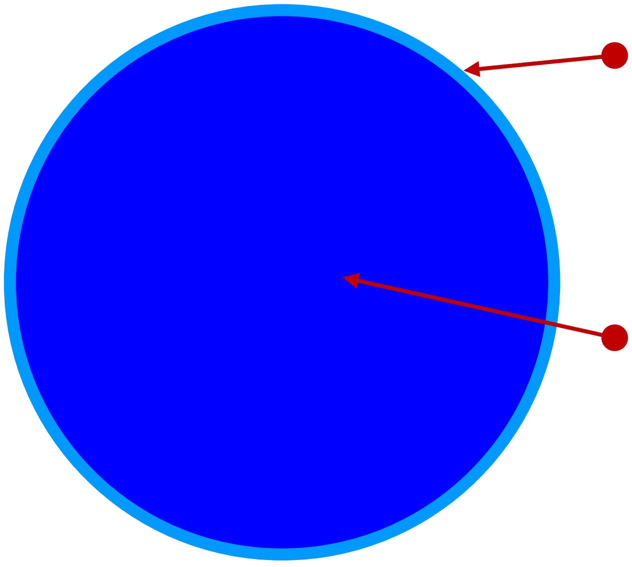


ions/nuclei ⟷ **quark clusters**

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

A new answer: quark-cluster matter?

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



- ***Surface***:

  self- or gravity- ***confined***?

- ***Global***:

  complete or partial ***solid***?

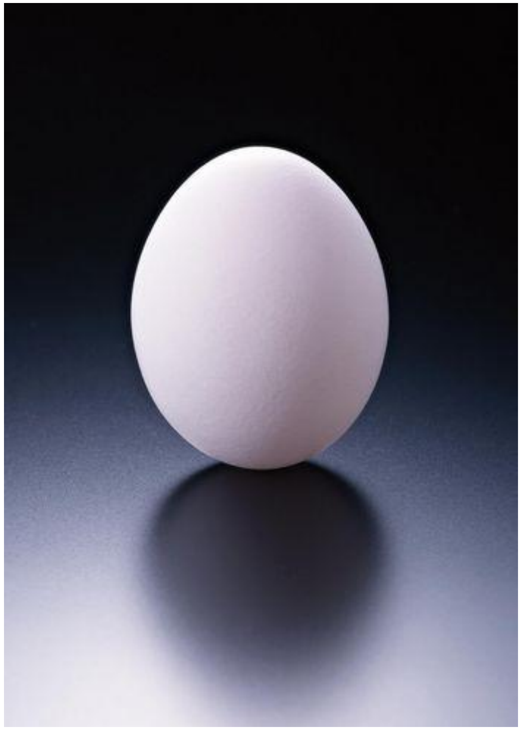
  NR $\rightarrow$ stiff ***EoS***? (**ER**: soft!)

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

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

A new answer: quark-cluster matter?

- To distinguish: an easy ***example*** …



Pulsars B1821-11: *precession* or even *free precession*?
(Stairs, Lyne & Shemar, 2000, Nature, 406, 484)

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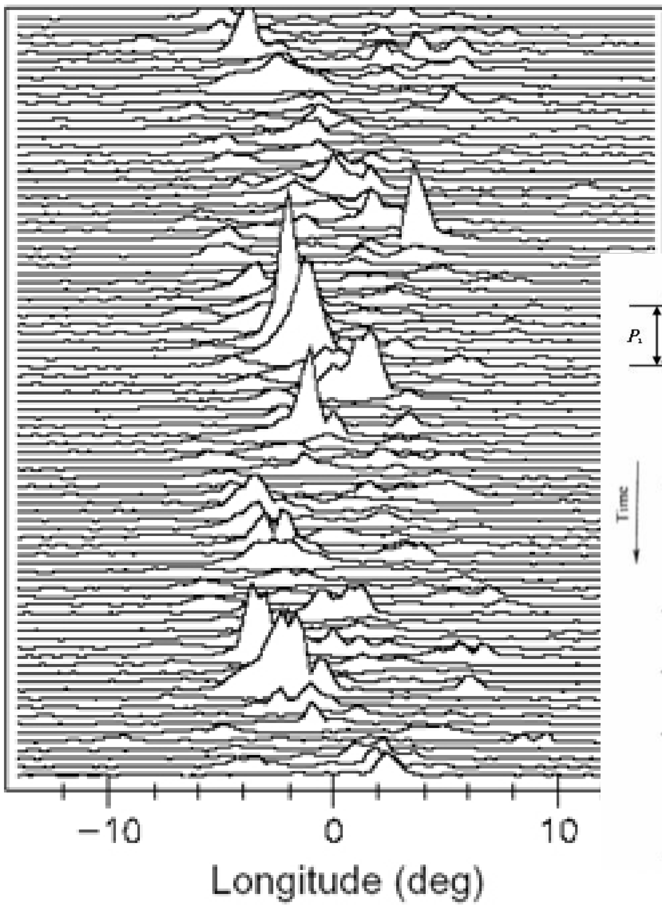
Hints from different manifestations

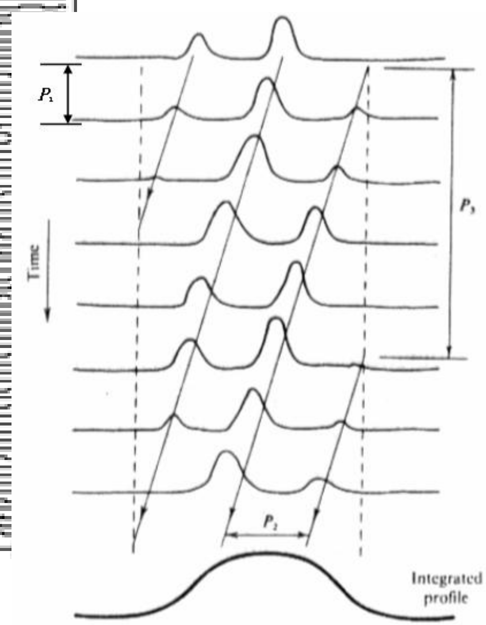
Xu et al. (1999) ApJ; Yu & Xu (2011) MN

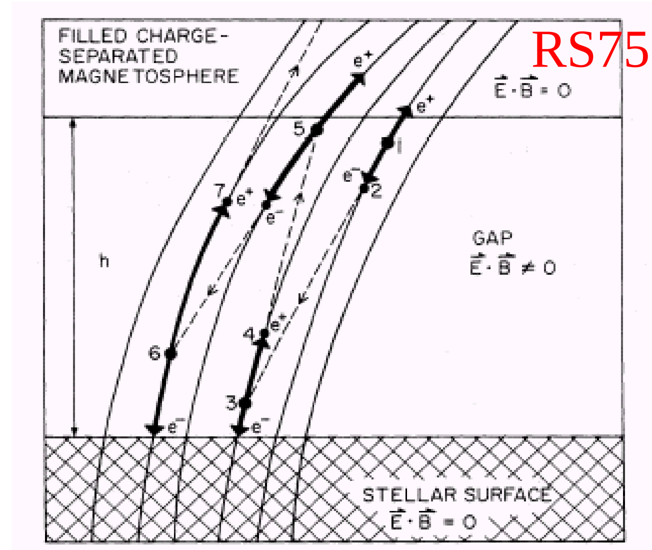
•*Subpulse drifting*: quark-c surface?



Drifting subpulses

PSR B0943+10
Gil & Sendyk(2000)



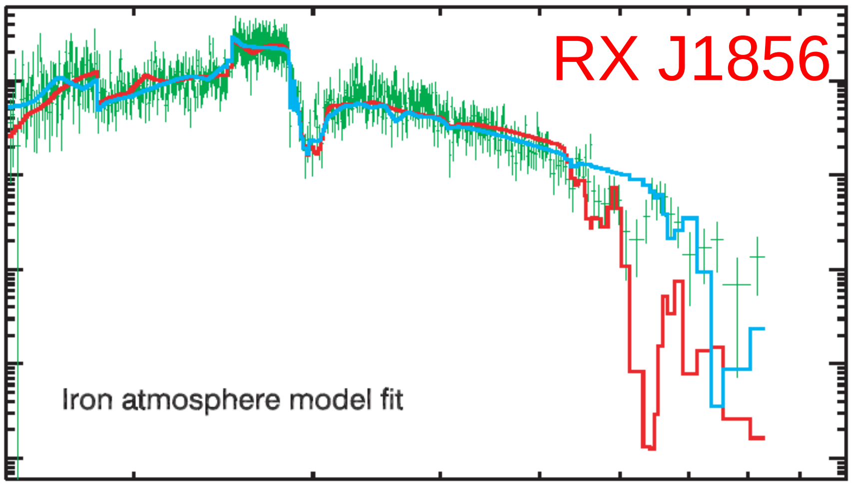


In RS75, NSs as pulsars bear a severe problem, *binding energy problem*: particles flow freely.

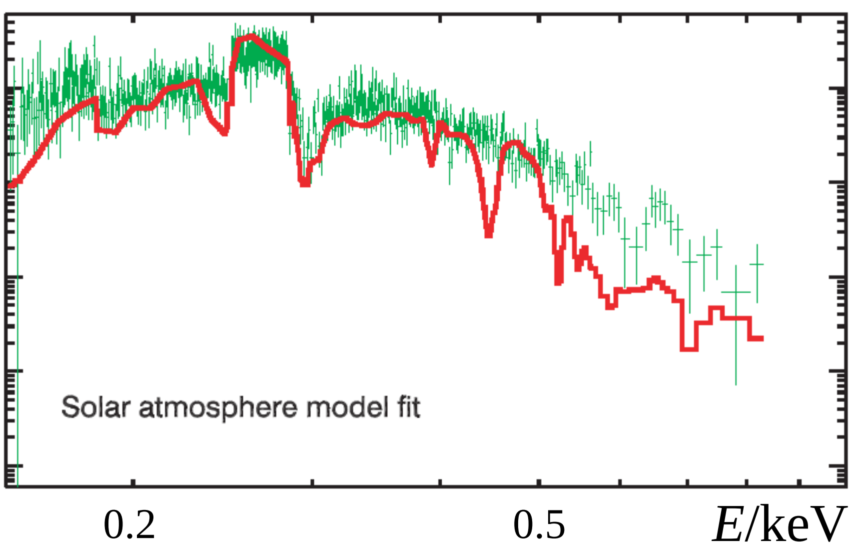
Hints from different manifestations

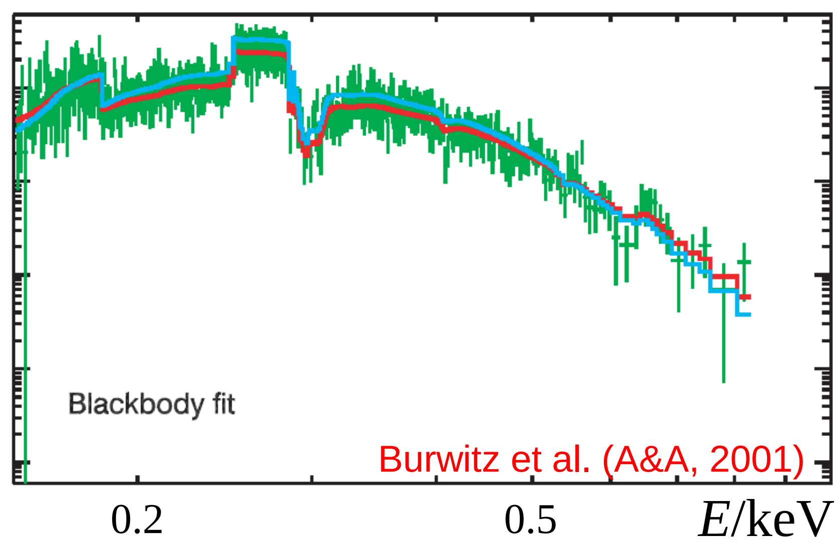
Xu (2002) ApJ; Xu (2006) ASR

- *Nonatomic spectra*: quark-c surface?



NSs: atomic atmosphere
Obs: no such feature
detected with certainty!
Ex.: RX J1856, a DTN

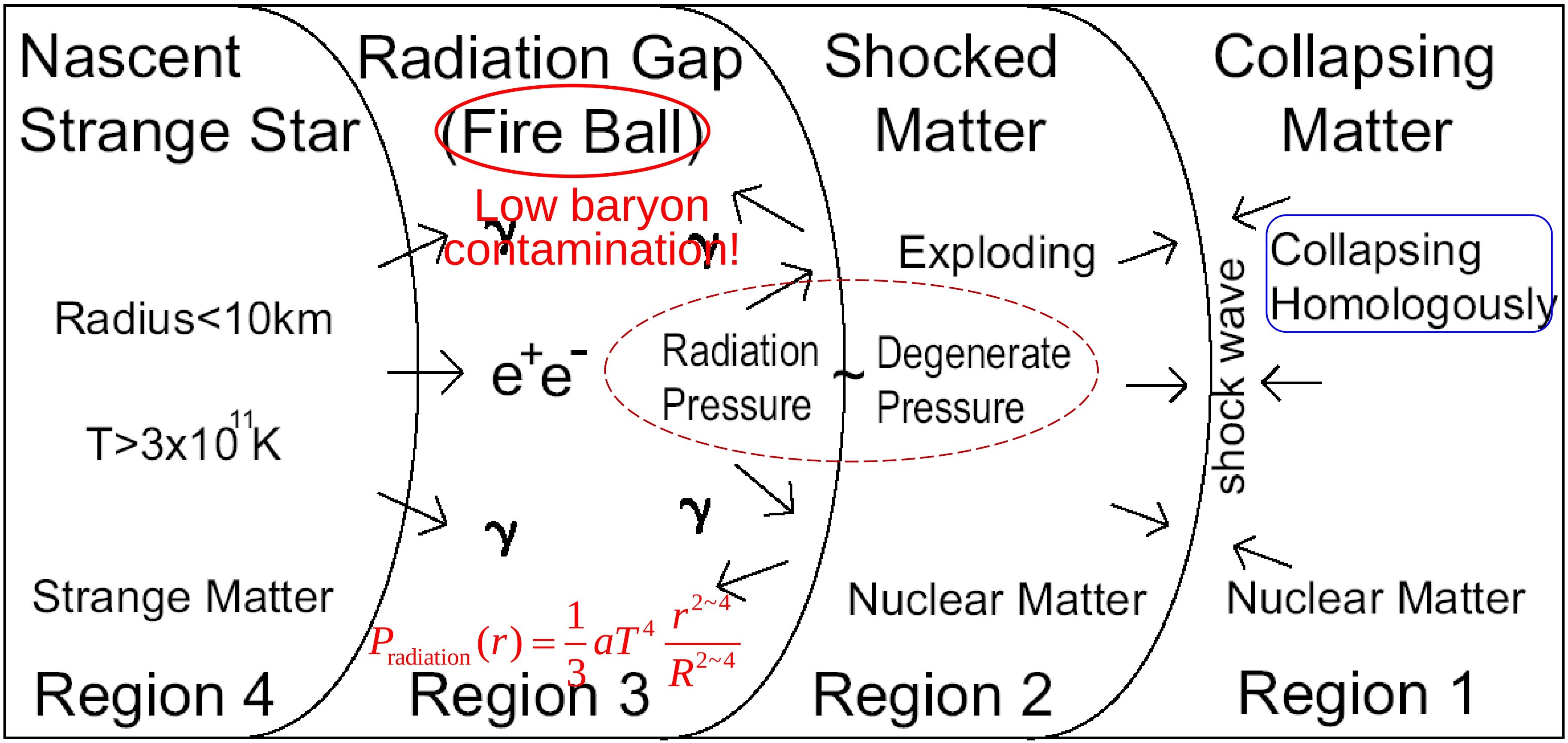




Hints from different manifestations

Xu (2005) MN; Chen, Yu & Xu (2007) ApJ; Cui, Xu & Wei (2011)

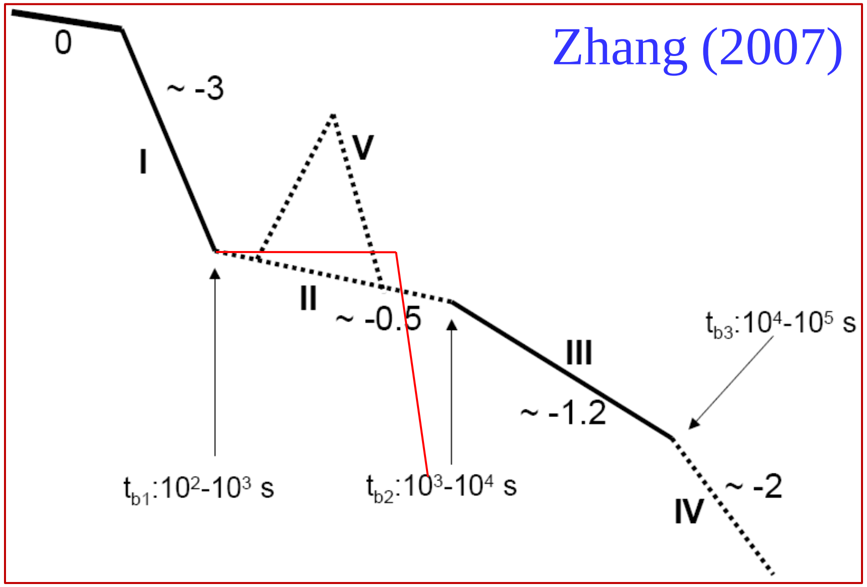
- *Clean fireball* for SNE & GRB?

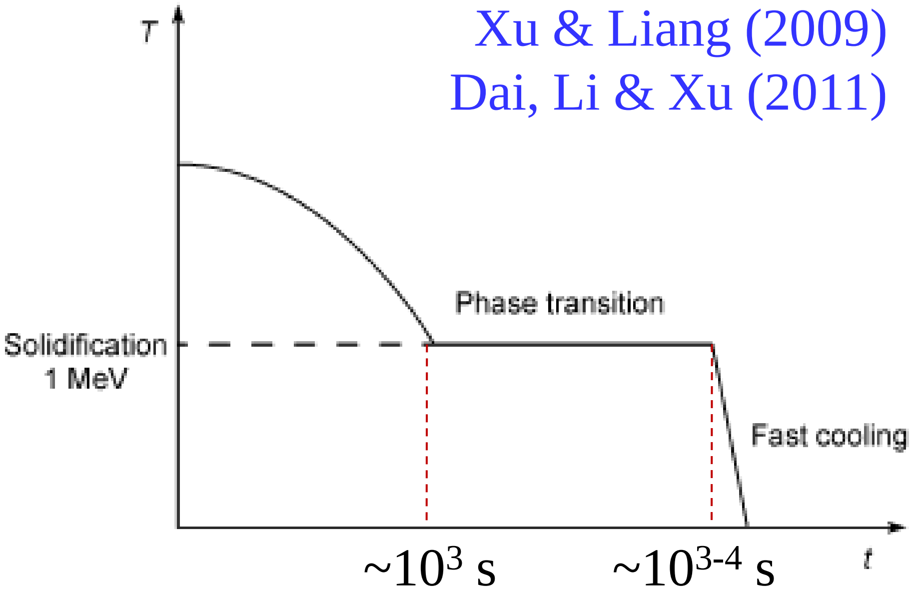


SNE: ν-driven *or* γ-driven?

Hints from different manifestations

- GRB abrupt falloff and X-ray flare





1. ***Platform-like behavior***: solidification of newborn quark cluster stars with latent heat released as energy injection to the GRB afterglow.
2. ***Central engine X-ray flares***: magnetic energy ejection before and quake-induced release after solidification.

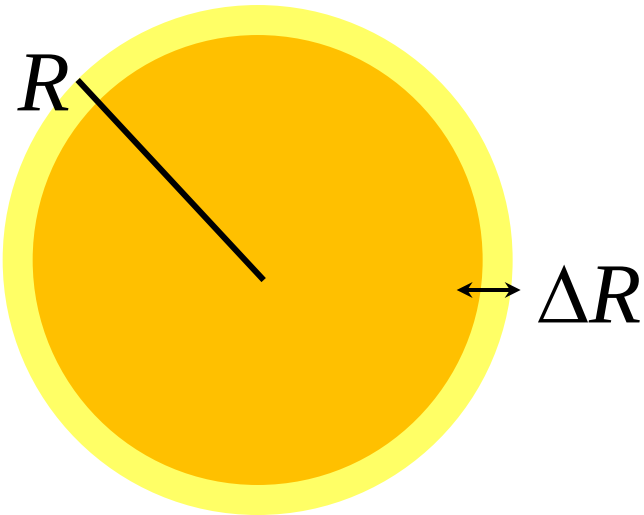
Hints from different manifestations

- Advantages of central engines related to QcSs

(Dai & Lu, Zhang, …)

1. A very clean fireball: *less baryon contamination*
2. GRB-SNE connection
3. Restart of the engines
4. Quake-induced energy release: same for sGRBs & SGR?

IceCube



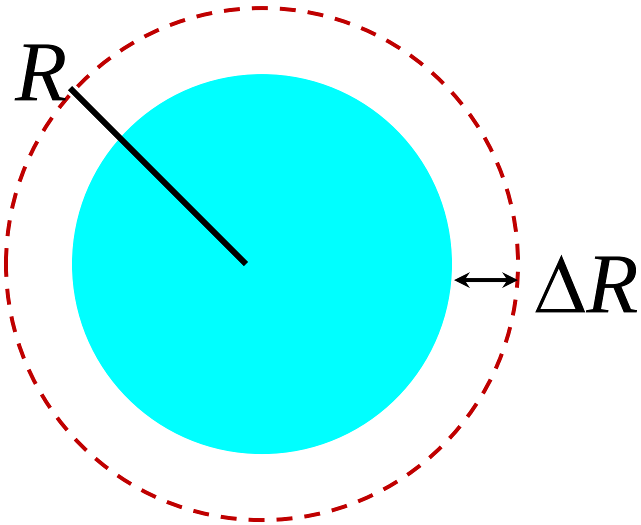
$$E_{\rm stored} \approx \frac{GM^2}{R} \sim 10^{53} \frac{\Delta R}{R} \text{ ergs}$$

for $M \sim M_\odot$

Hints from different manifestations

Xu et al. (2006) MNRAS; Xu (2007) ASR; Xu & Liang (2009) Sci. China G.; Dai, Li & Xu (2011)

- Gravitational & elastic ***free*** energy



$$E_{\rm stored} \approx \frac{GM^2}{R} \sim 10^{53} \frac{\Delta R}{R} \ {\rm ergs}$$

$$\text{for } M \sim M_\odot$$

⇒ ***quake***-induced fireballs for AXP/SGR/sGRB?

***Quark-star* vs. *Magnetar* …**

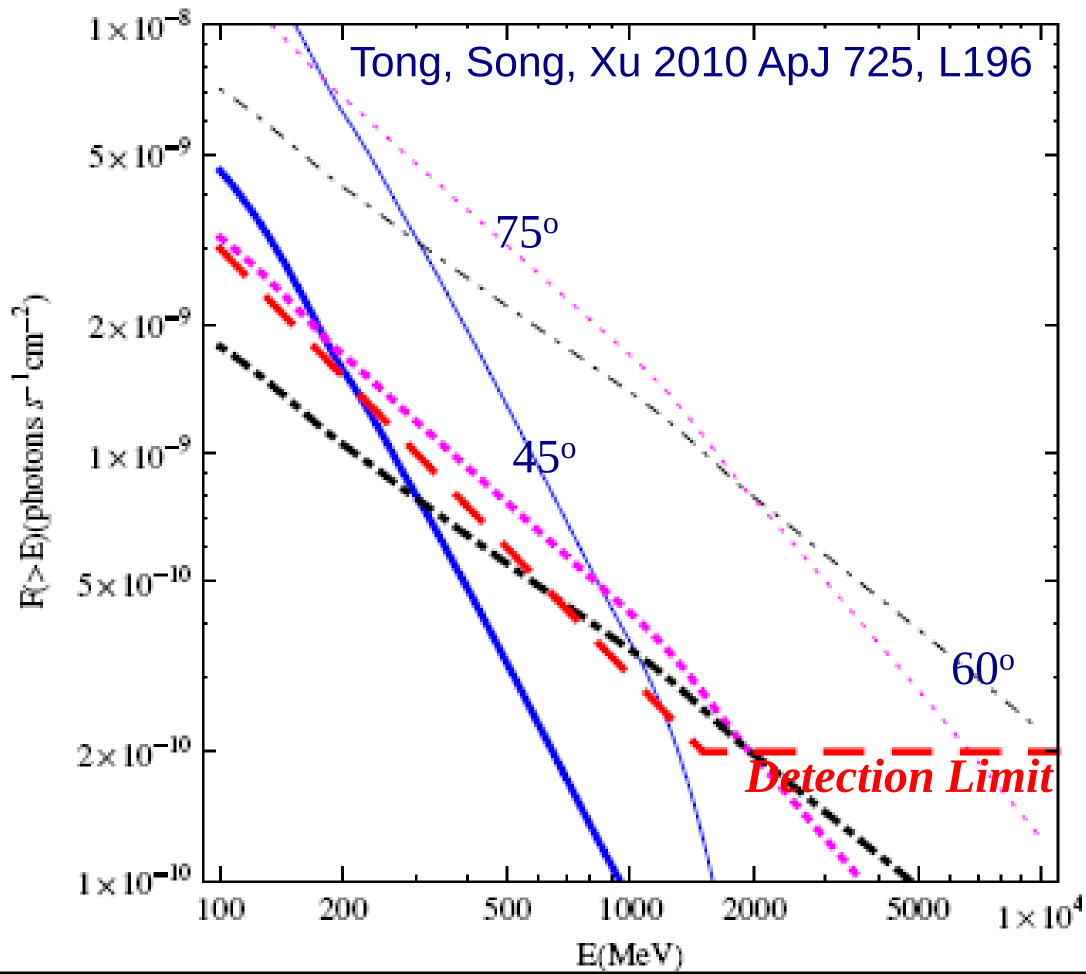
Hints from different manifestations

• ***Non-detection*** of AXP in *Fermi*/LAT

➢ Magnetospheric activity:

$$L_\gamma (P, B)$$

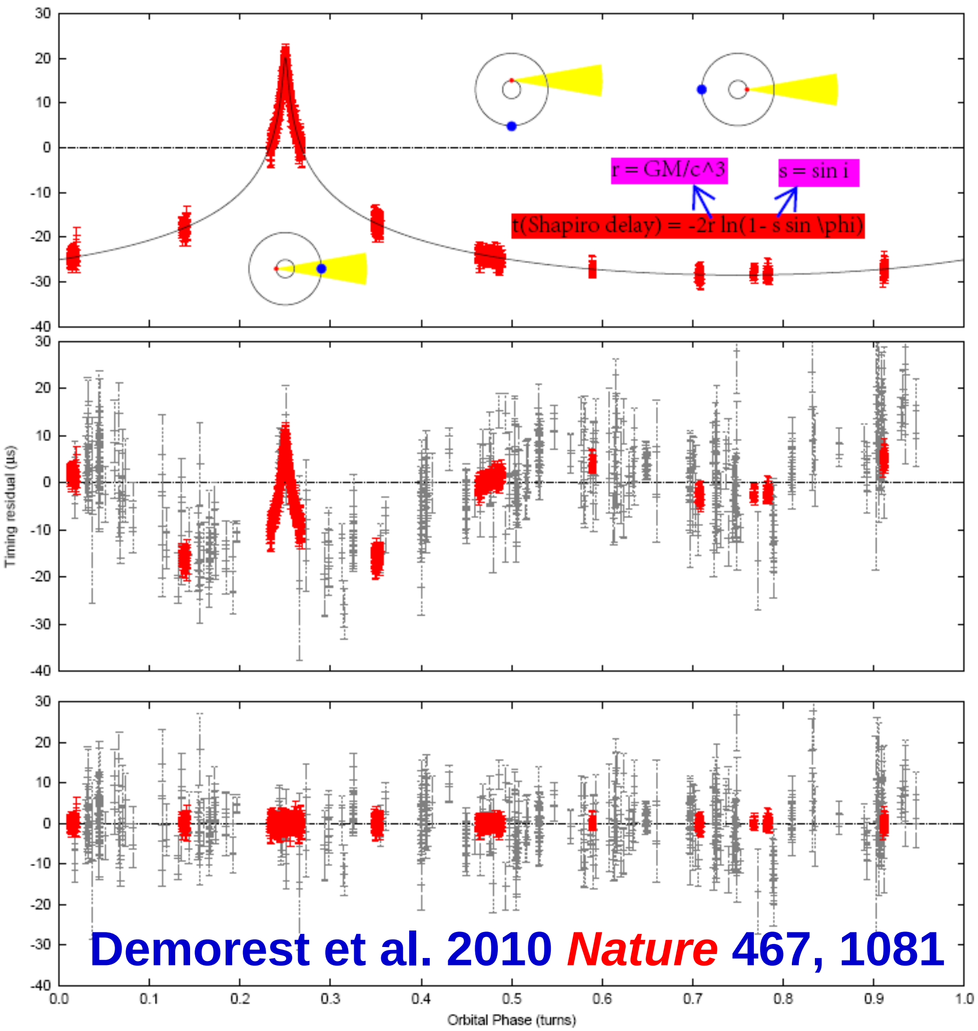
➢ A L_γ calculation in the outer gap model is higher than the detection limit of *Fermi*/LAT!



Hints from different manifestations

Lai & Xu (2009) Astropart. Phys., (2009) MN, (2011) RAA; Na & Xu (2011) CPC

- A ***stiffer*** equation of state …



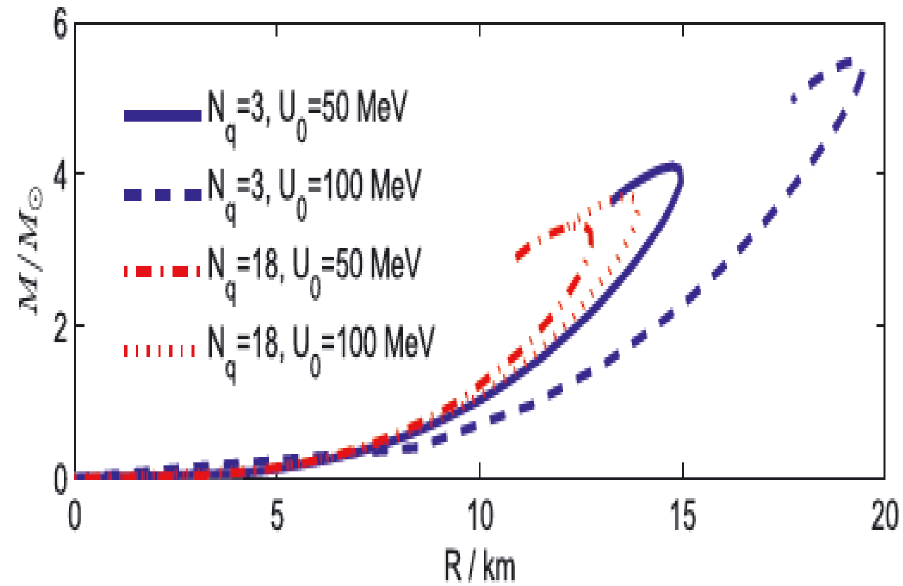
Demorest et al. 2010 *Nature* 467, 1081

Lennard-Jones quark matter and massive quark stars

X. Y. Lai★ and R. X. Xu **MNRAS 2009, 398, L31**

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.



Hints from different manifestations

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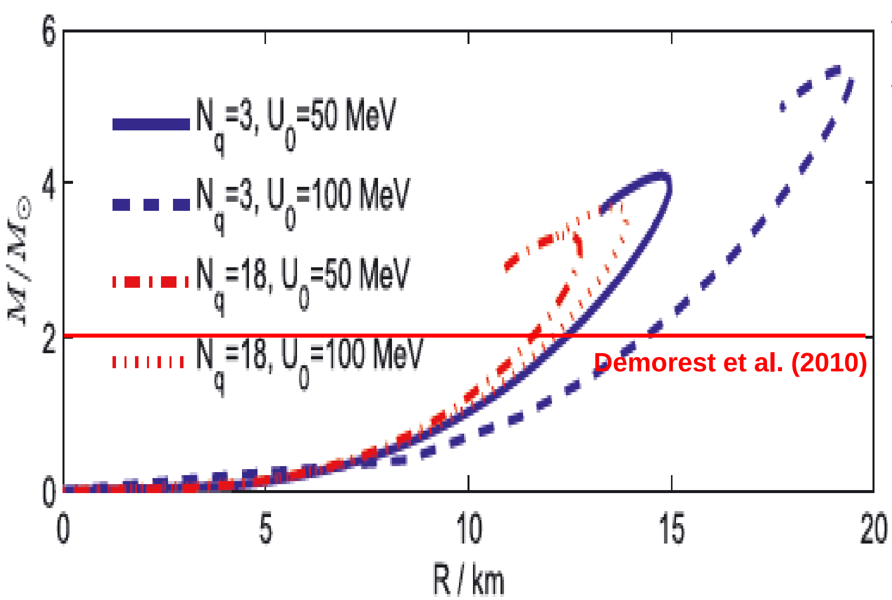
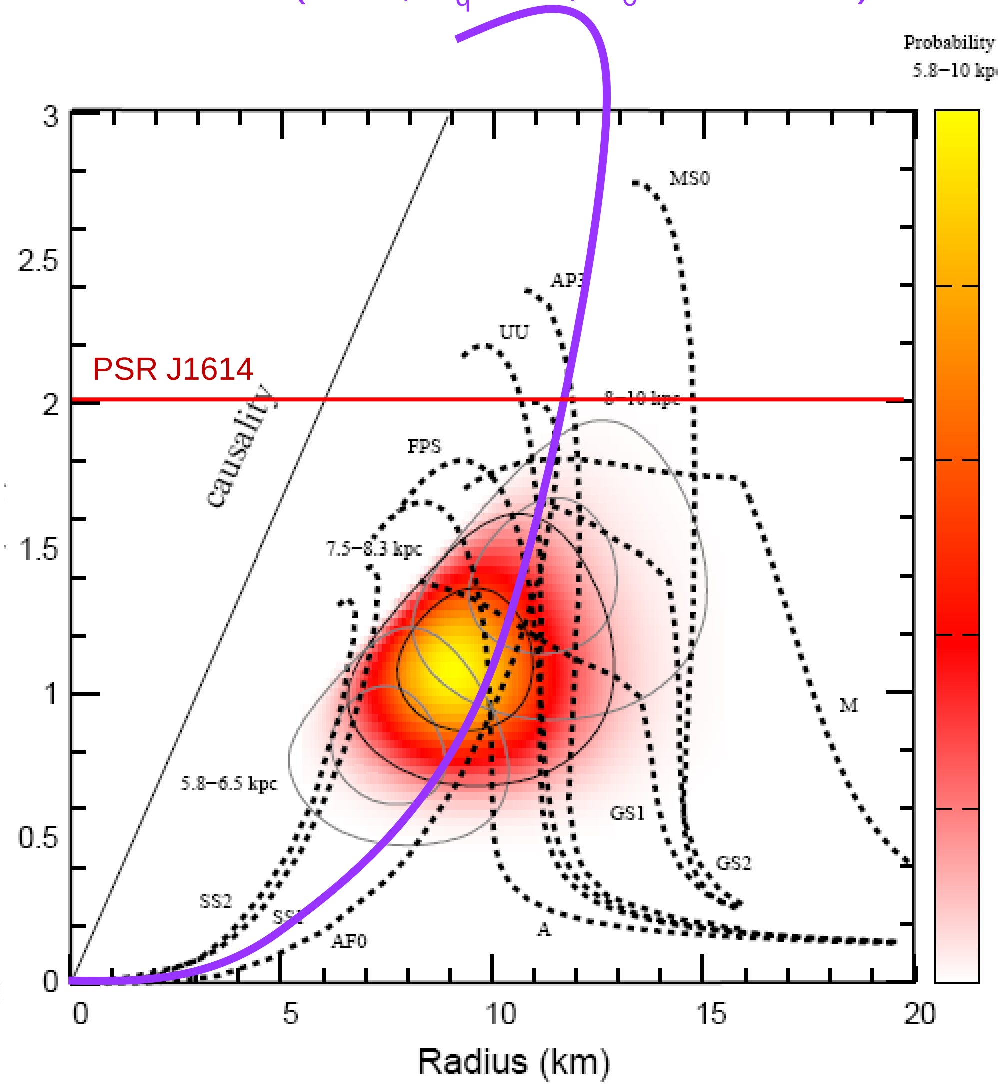


(Lai & Xu 2009 MNRAS, 398, L31)

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



(Sala et al. ApJ, arXiv:1204.3627)

Summary

- Introduction: What's compressed BM?
- An old answer proposed by Landau
- A new answer: quark-cluster matter?
- Hints from different manifestations

✓ Conclusions

Conclusions