Welcome to Astronomy @ PKU

- DoA (Dept. of Astronomy, School of Physics)

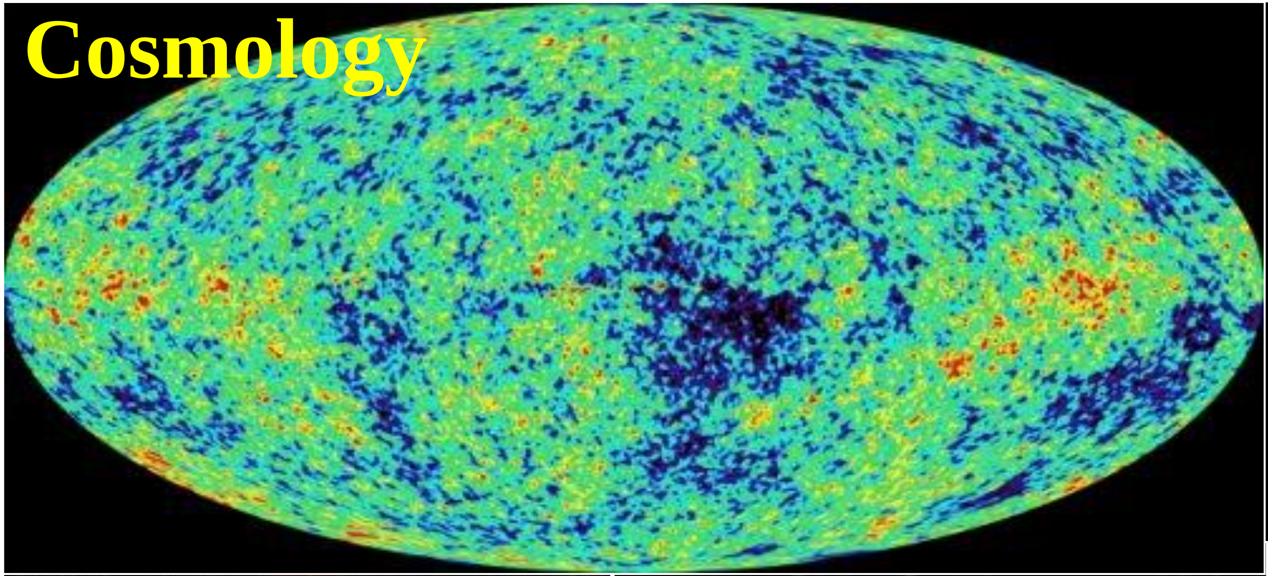
DoA

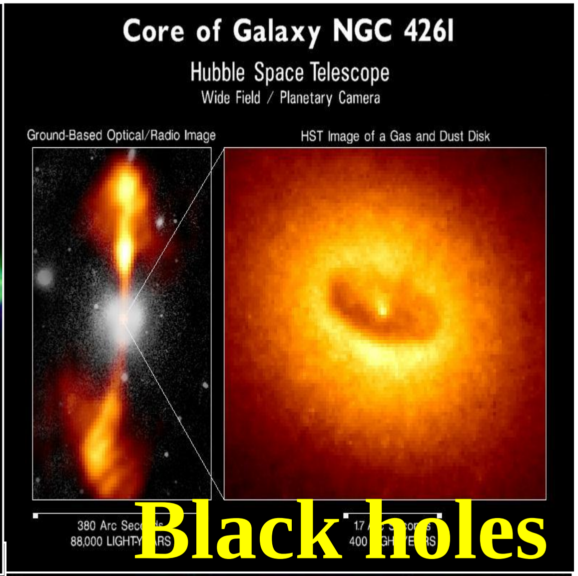
KIAA

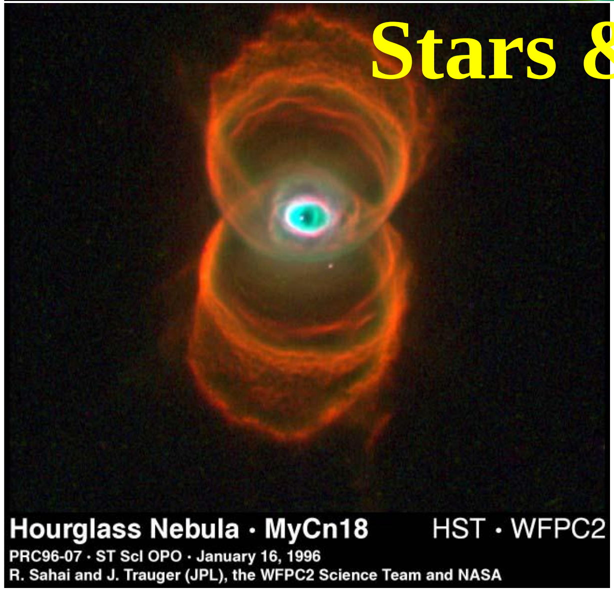
- KIAA (Kavli Inst. for Astro. & Astrophys. at PKU)

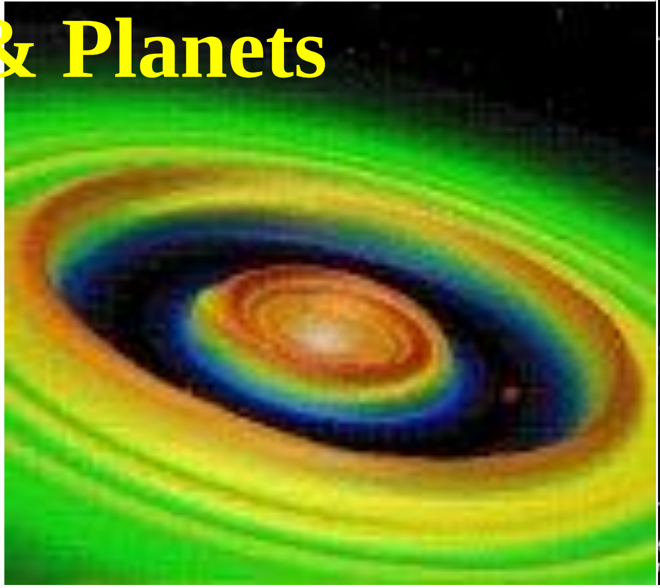
  An *international platform* for research of A&A

Astro-programs @ Peking Univ.









A strangeness barrier
on strange star surface

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PKU-CUSTIPEN Nuclear Reaction Workshop

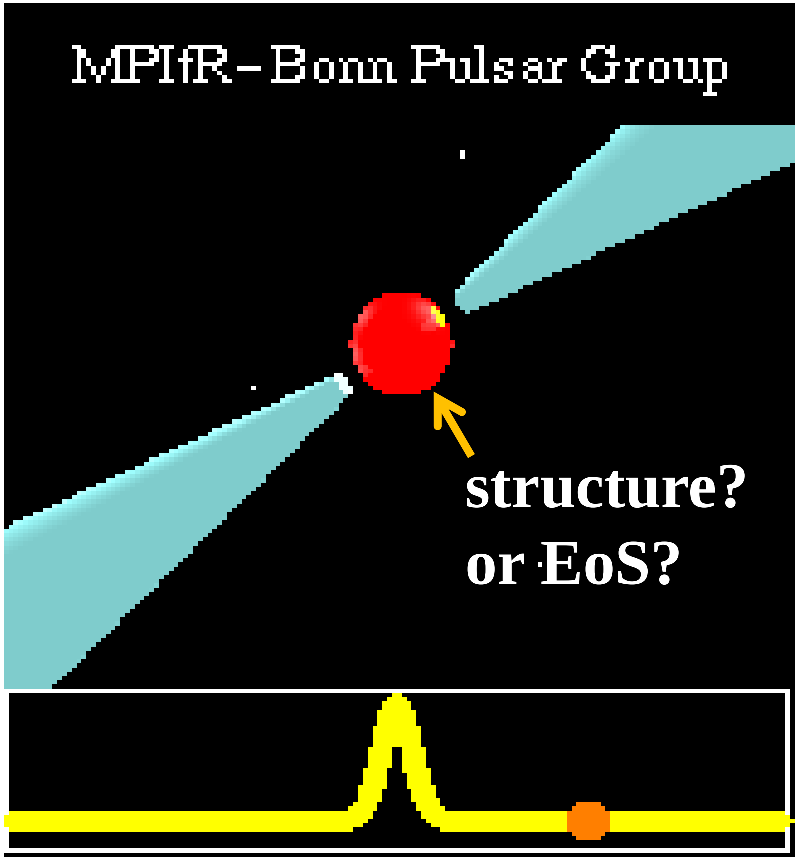
Aug. 14, 2014; PKU, Beijing

Summary

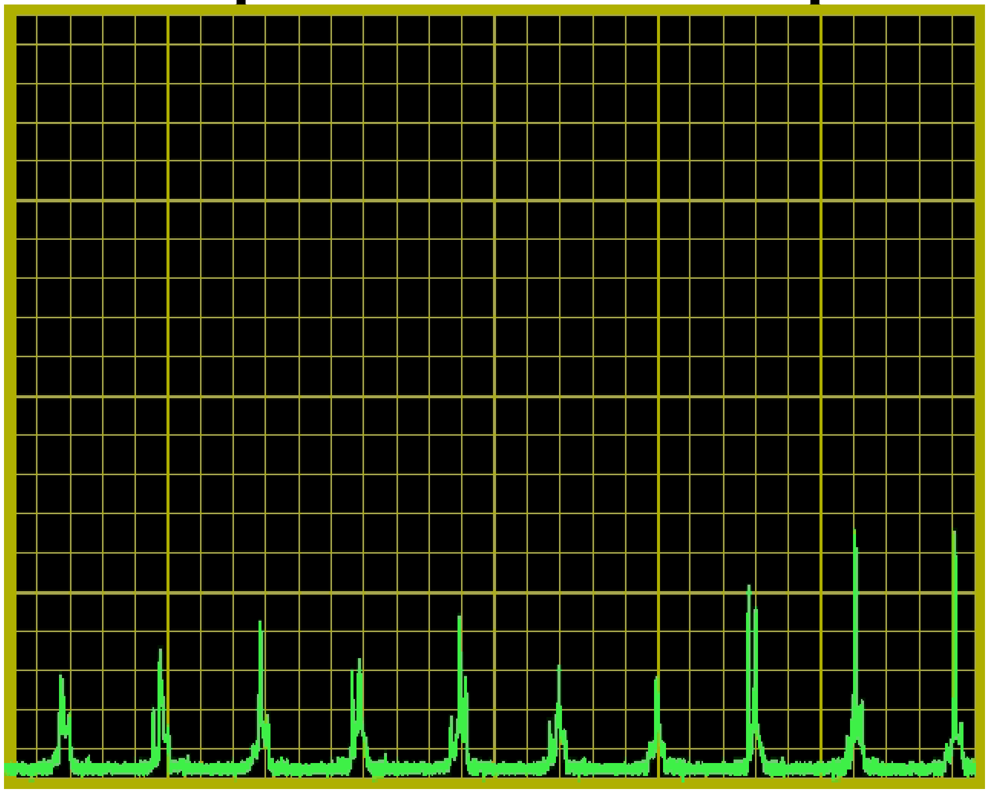
- Introduction: What is a pulsar?
- Pulsars: Strange stars?
- Strange star: a strangeness barrier?
- An observational hint?
- Conclusions

What is a Pulsar?

- Pulsar: *cosmological lighthouse*...



Pulse sequences from a radio pulsar



EoS of pulsar is meaningful for both

- QCD at low-energy scale: non-perturbative features of fundamental strong interaction
- Understanding cosmic events: SNE, GRB, bursts of AXPs/SGRs, timing behavior ...


Millennium Problems | C ×

www.claymath.org/millennium-problems

CMI

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Millennium Problems

Yang–Mills and Mass Gap

Experiment and computer simulations suggest the existence of a "mass gap" in the solution to the quantum versions of the Yang-Mills equations. But no proof of this property is known.

Riemann Hypothesis

The prime number theorem determines the average distribution of the primes. The Riemann hypothesis tells us about the deviation from the average. Formulated in Riemann's 1859 paper, it asserts that all the 'non-obvious' zeros of the zeta function are complex numbers with real part 1/2.

P vs NP Problem

If it is easy to check that a solution to a problem is correct, is it also easy to solve the problem? This is the essence of the P vs NP question. Typical of the NP problems is that of the Hamiltonian Path Problem: given N cities to visit, how can one do this without visiting a city twice? If you give me a solution, I can easily check that it is correct. But I cannot so easily find a solution.

Navier–Stokes Equation

This is the equation which governs the flow of fluids such as water and air. However, there is no proof for the most basic questions one can ask: do solutions exist, and are they unique? Why ask for a proof? Because a proof gives not only certitude, but also understanding.

Hodge Conjecture

The answer to this conjecture determines how much of the topology of the solution set of a system of algebraic equations can be defined in terms of further algebraic equations. The Hodge conjecture is known in certain special cases, e.g., when the solution set has dimension less than four. But in dimension four it is unknown.

Poincaré Conjecture

In 1904 the French mathematician Henri Poincaré asked if the three dimensional sphere is characterized as the unique simply connected three manifold. This question, the Poincaré conjecture, was a special case of Thurston's geometrization conjecture. Perelman's proof tells us that every three manifold is built from a set of standard pieces, each with one of eight well-understood geometries.

Birch and Swinnerton-Dyer Conjecture

Supported by much experimental evidence, this conjecture relates the number of points on an elliptic curve mod p to the rank of the group of rational points. Elliptic curves, defined by cubic equations in two variables, are fundamental mathematical objects that arise in many areas: Wiles' proof of the Fermat Conjecture, factorization of numbers into primes, and cryptography, to name three.

However, non-perturbative QCD is ***challenging*** us, being related to one of the Millennium Problems.

"… The successful use of ***Yang-Mills theory*** to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "***mass gap***": the quantum particles have positive masses, even though the classical waves travel at the speed of light. …"

The undoable problems in mathematics could be solved by ways of sciences, e.g. physics, chemistry, biology, geology, …

- As in the case of *Navier-Stokes Equation*, we do have a framework for strong interaction, the QCD Lagrangian:

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

- QCD has asymptotic freedom in high-energy limit, but is strongly ***non***-perturbative in low-energy scale.
- *N*QCD not only is necessary to understand pulsar inner structure, but is meaningful to know broad nature, e.g., the origin of mass, the QCD phase transition in the early University, and even ultra-high energy cosmic rays.

Summary

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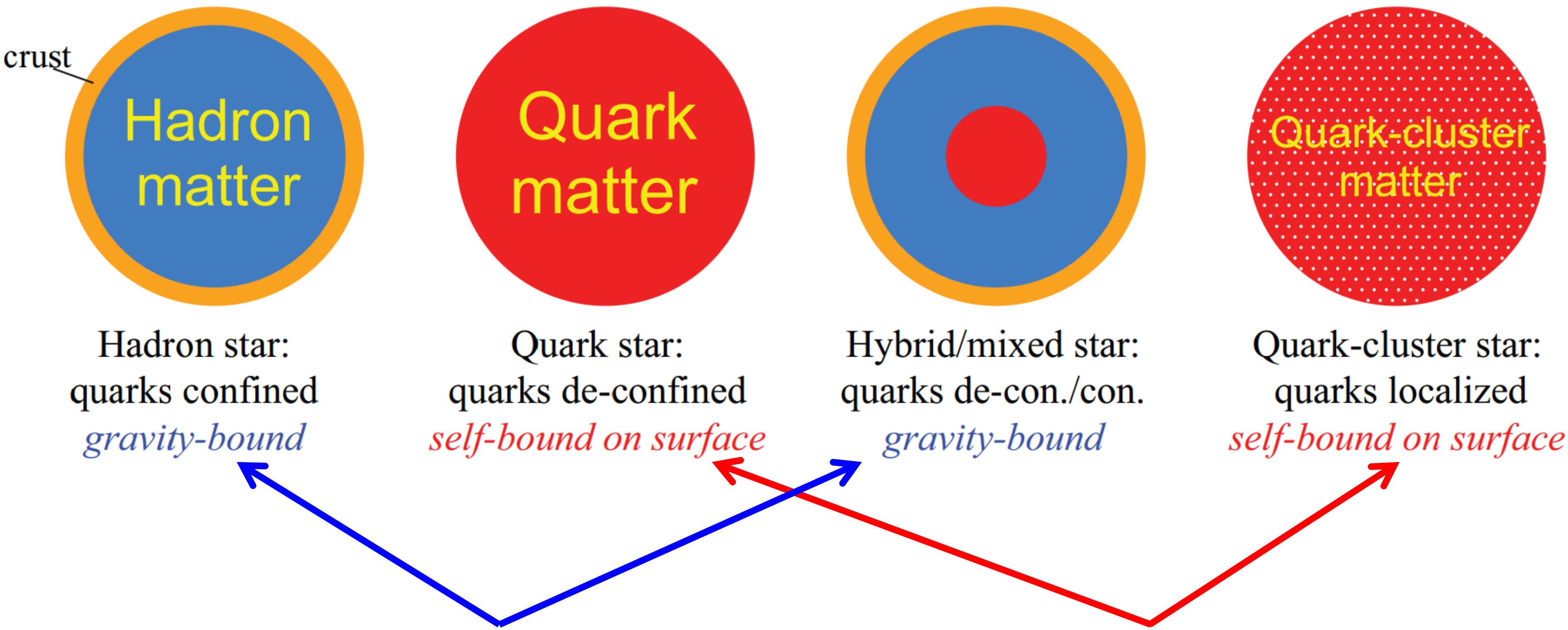
Pulsars: Strange Stars?

- Different models of pulsar inner structure…



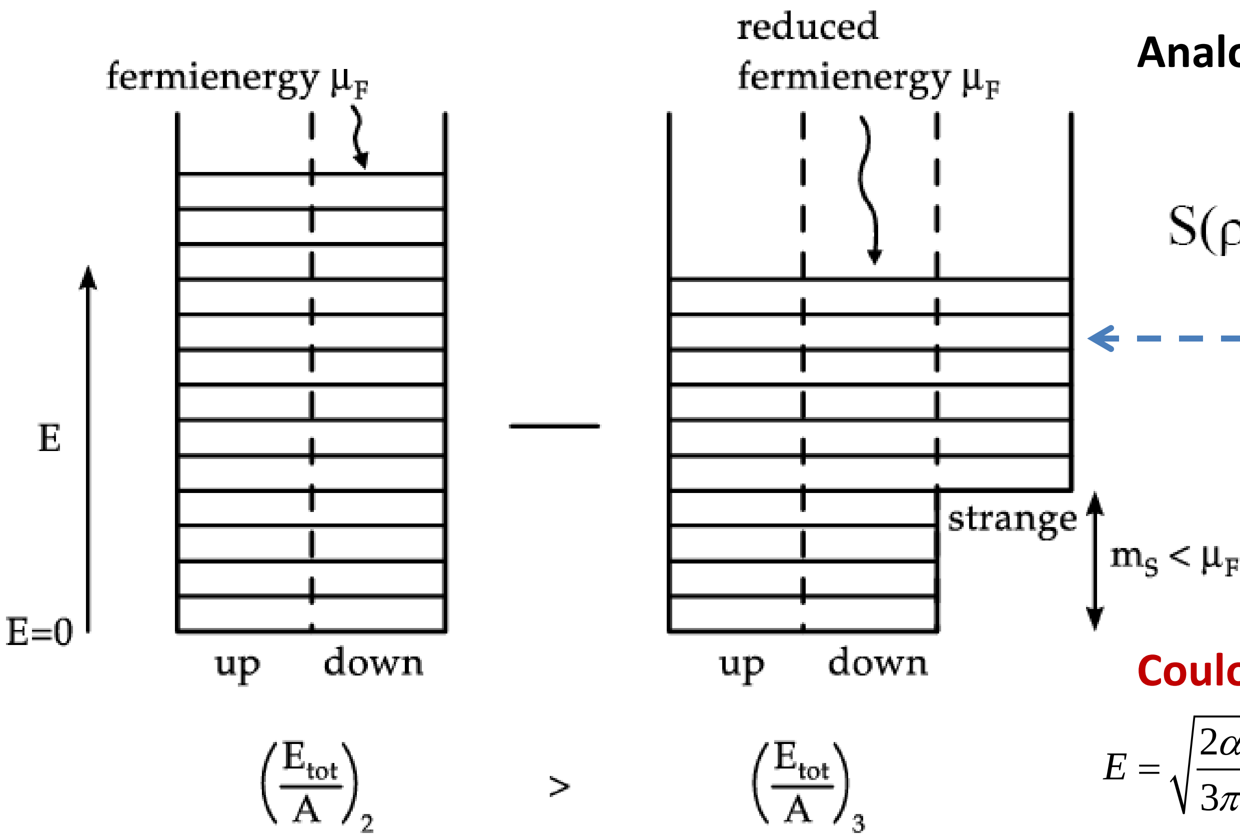
conventional
Neutron Star

light flavour symmetry:
Strange Star

Pulsars: Strange Stars?

- Strange (***quark***) stars

Witten's (1984) conjecture: for quark matter {***u***, ***d***, ***s***, (***e***)}



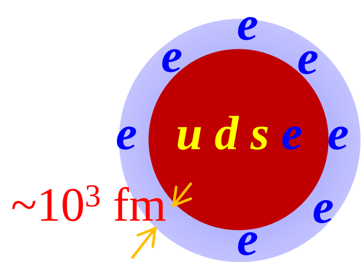
Greiner et al. (1998)

Analogy of Nuclear Symmetry Energy:

From Baoan's talk yesterday

$$S(\rho)=\frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3}+\frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

Kinetic Potential



Coulomb barrier on surface: ~10 MeV

$$E=\sqrt{\frac{2\alpha}{3\pi}}\frac{9V_q^2}{\left(\sqrt{\frac{6\alpha}{\pi}}V_q z+4\right)^2}\sim\frac{7.2\times10^{18}}{(1.2z_{11}+4)^2}\ \text{V/cm}$$

Xu & Qiao (1999)

Pulsars: Strange Stars?

• Strange (***quark-cluster***) stars

Clustering? pressure-free → in "low ρ" regime

Interaction? DSE approach of NQCD…

• Fermi gas at a few ρ_0:

$\mu \approx (3\pi^2)^{1/3}\, \hbar c n^{1/3} \sim 0.4\,\text{GeV} < 1\,\text{GeV}$

• Fischer & Alkofer (2002)

$$\alpha(x) = \frac{\alpha(0)}{\ln(e + a_1 x^{a_2} + b_1 x^{b_2})}$$

~ 2 at even $10\rho_0$!

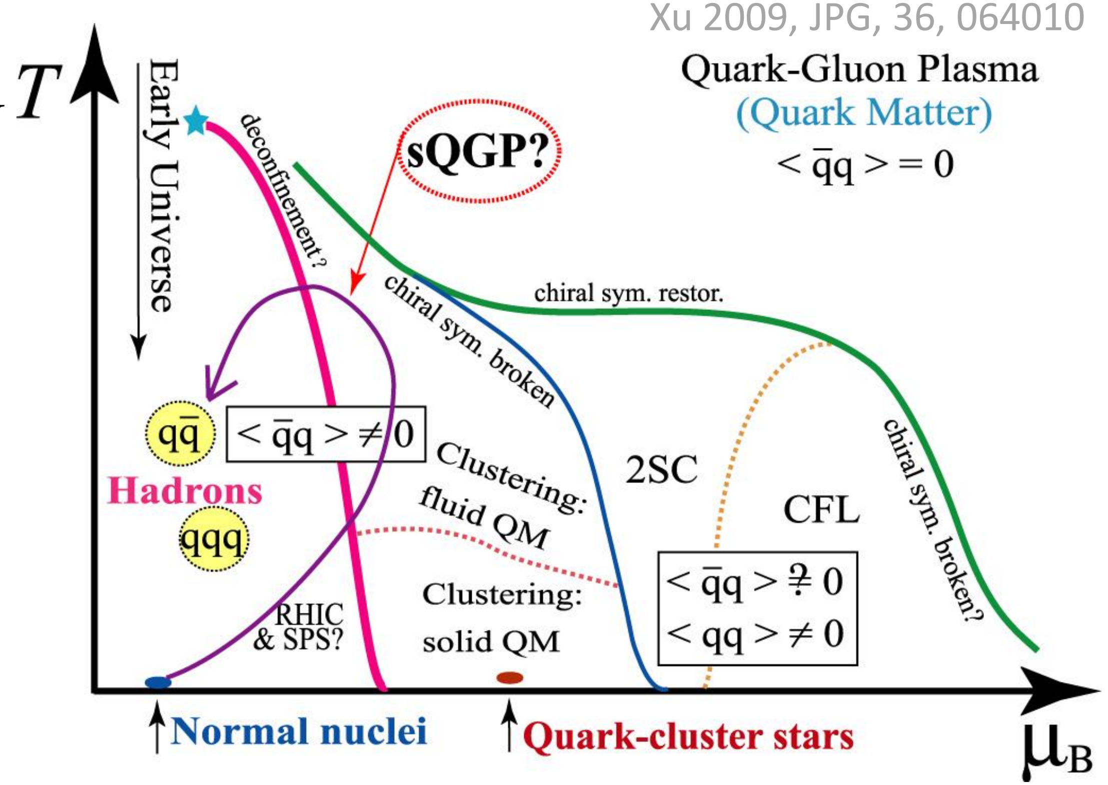
• If Coulomb-like color interaction

$E_q \sim \alpha_s^2 m_q c^2 \simeq 300\alpha_s^2\ \text{MeV} > \mu$

⇒ Fermi gas is dangerous?

• A quark-cluster state expected …

Xu 2009, JPG, 36, 064010

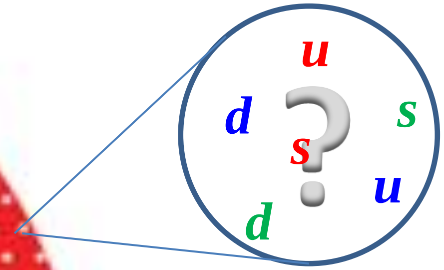


? Clustering ← BEC ← BCS

Pulsars: Strange Stars?

- Strange (***quark-cluster***) stars

Witten conjecture ***extended***: for quark/quark-cluster matter



Each quark-cluster could have N_q quarks with almost equal numbers of ***u***, ***d***, and ***s***.

An extension of the Witten conjecture:
it does not matter whether three flavours of quarks are free or bound.

strange matter = **cold dense matter with light flavour symmetry**

Certainly ~10 MeV Coulomb barrier still exist in case of quark-cluster stars!

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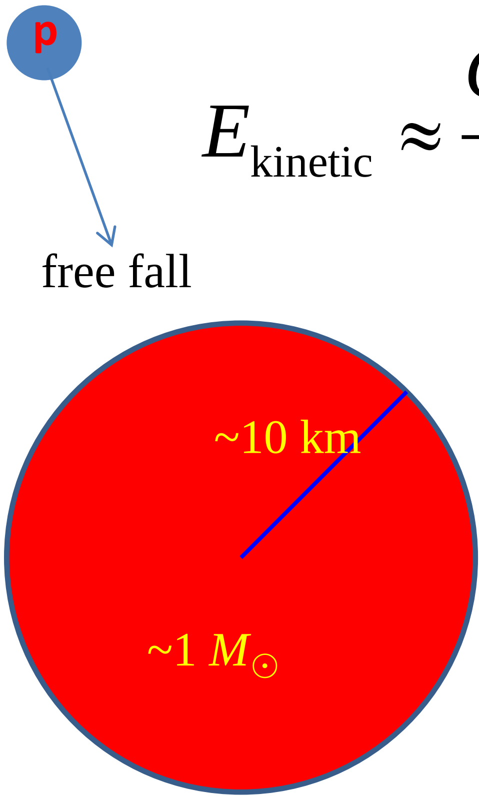
Strange Star: a strangeness barrier?

- Accreted matter ***easily*** penetrate Coulomb barr.



$$E_{\text{kinetic}} \approx \frac{GMm_{\text{p}}}{R} \sim 100\ \text{MeV} \gg V_{\text{Coulomb}} \sim 10\ \text{MeV}$$

Accreted ions (with kinetic energy ~ 100 MeV) could easily penetrate the Coulomb barrier: ***de-confine first*** into 2-flavour quark matter by fast strong force (~10^{-24}s) and then change to 3-flavour quark matter by slow weak force (~10^{-7}s).

A strange quark star should keep bare even during a phase of accretion!

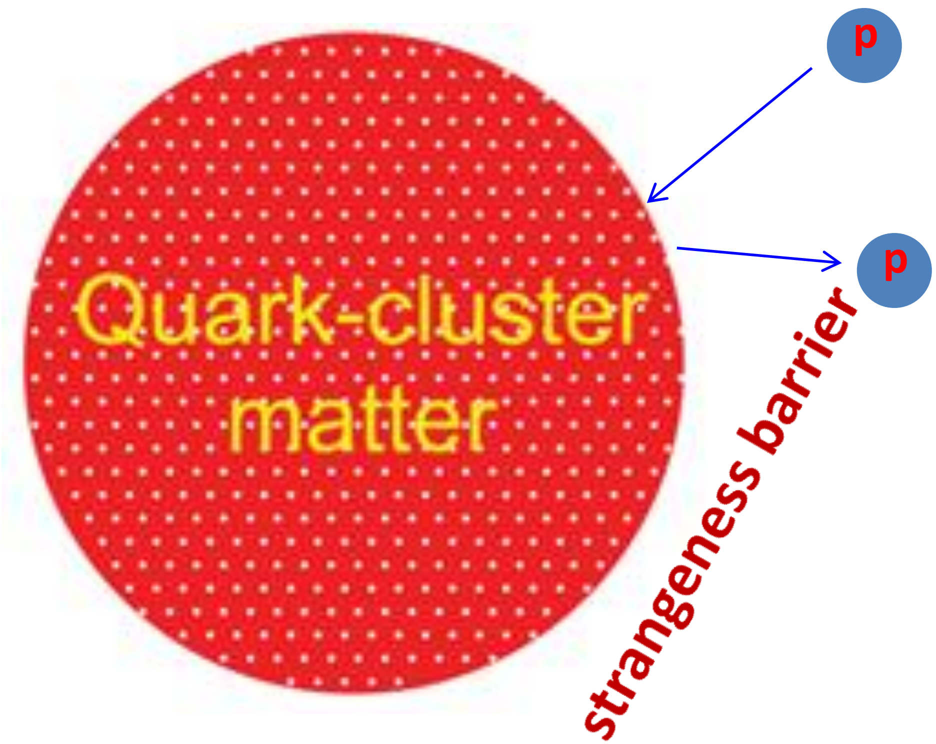
Strange Star: a strangeness barrier?

- Weak interaction ***first*** for quark-cluster star!

pp reaction as an analogy: $p + p \rightarrow d + e^+ + \nu_e$

Two steps: barrier penetration ($\sim 10^{-10}$), flavor-changed weak interaction ($\sim 10^{-20}$)

For comparison: $^{12}C(p, \gamma)^{13}N$, cross-section > 10^{20} times higher



Though ion kinematic energy could be higher than the barrier, $V_{coulomb}$

But it is difficult to produce strangeness from u and d

A corona composed by ions and electrons forms above a strange quark-cluster star!

Strange Star: a strangeness barrier?

- A very ***simple*** corona model: $\rho(h)$

Because of mass conservation, we have

$$\xi 4\pi R^2 v_{\rm s} \rho_{\rm b} = \dot{M}$$

or the bottom density of the corona above strange star surface

$$\rho_{\rm b} = \frac{7.24\times 10^{-8}}{1+8.05\times 10^2 \eta \cdot {R_1}^{-2}} \cdot L_{31} \cdot {T_1}^{-\frac{1}{2}} \cdot {R_1}^{-4} \cdot A^{\frac{1}{2}} \cdot \xi^{-1} \quad {\rm g/cm^3}$$

Then we could have a very simple model for the corona:

$$\rho(h) = \rho_{\rm b} \exp(-h/kT) \quad {\rm g/cm^3}$$

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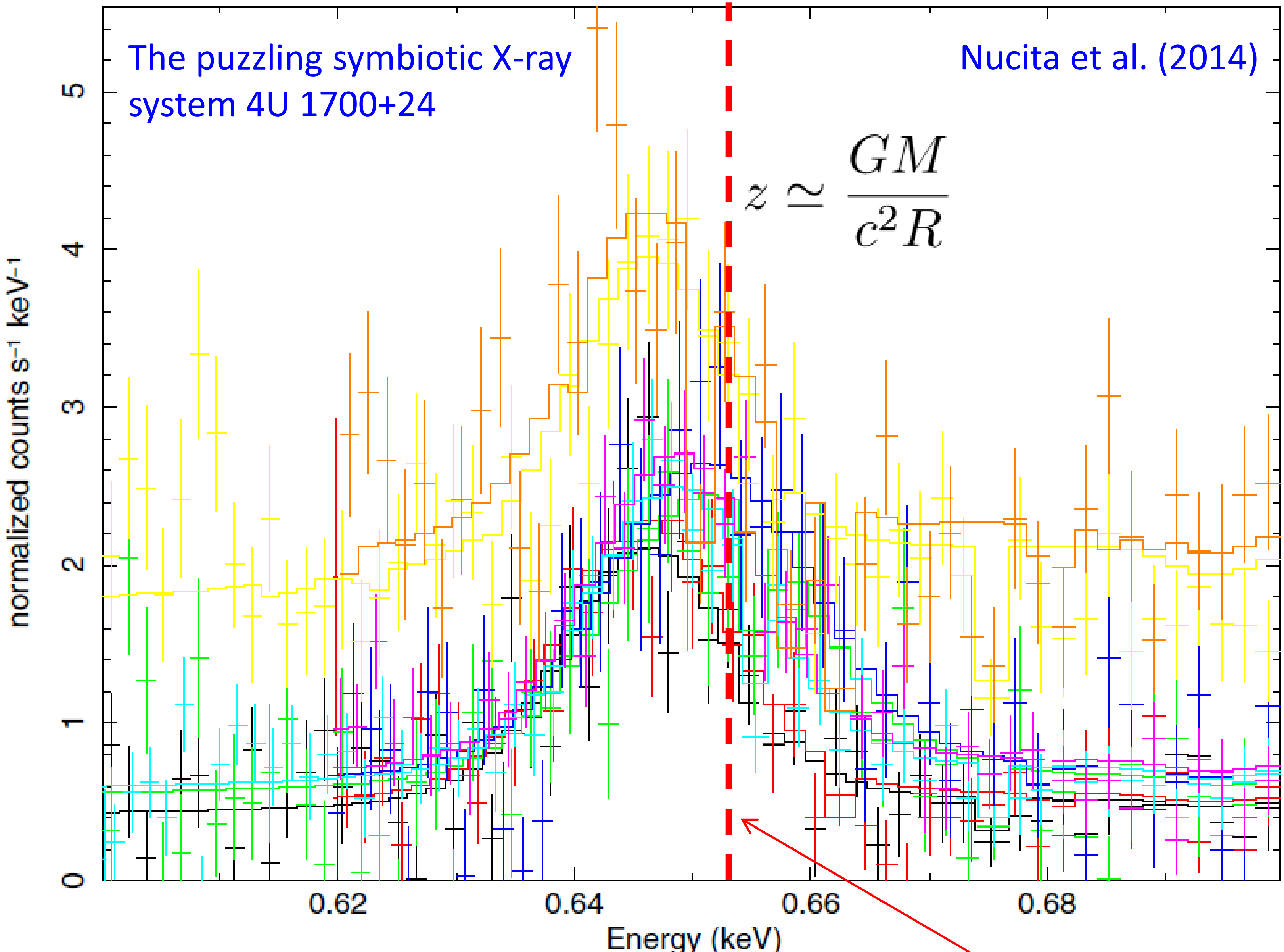
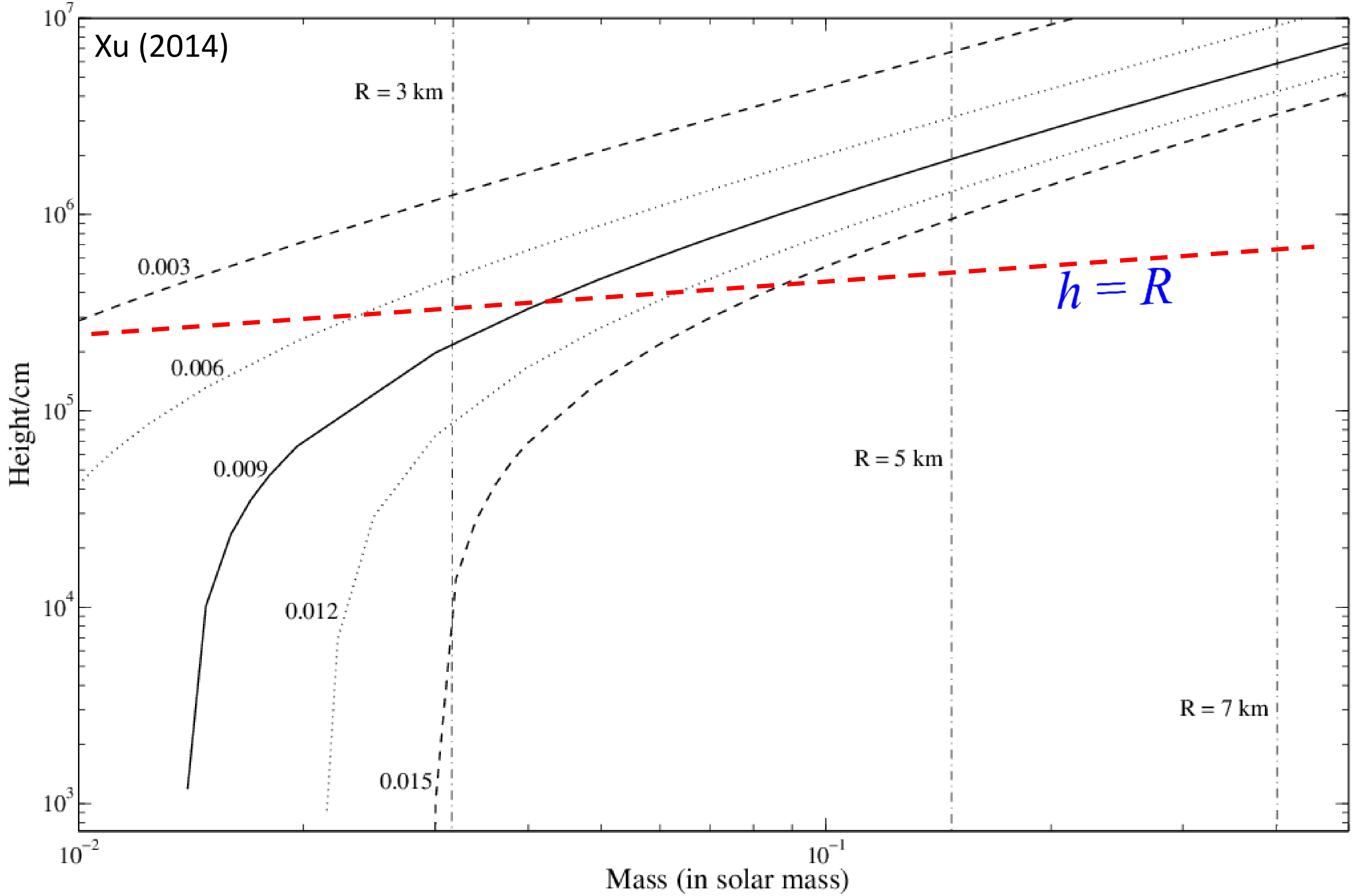


H-like Ly-α Lines at E/eV: {10.2, 40.8, 91.8, 163.2, 255, 367.2, 500, **652.8**, 826.2, 1020, 1234.2, 1468.8, 1723.8, 1999.2, 2295, 2611.2, 2947.8, 3304.8, 3682.2, 4080, ...}

A solution of the puzzling symbiotic X-ray system 4U 1700+24?

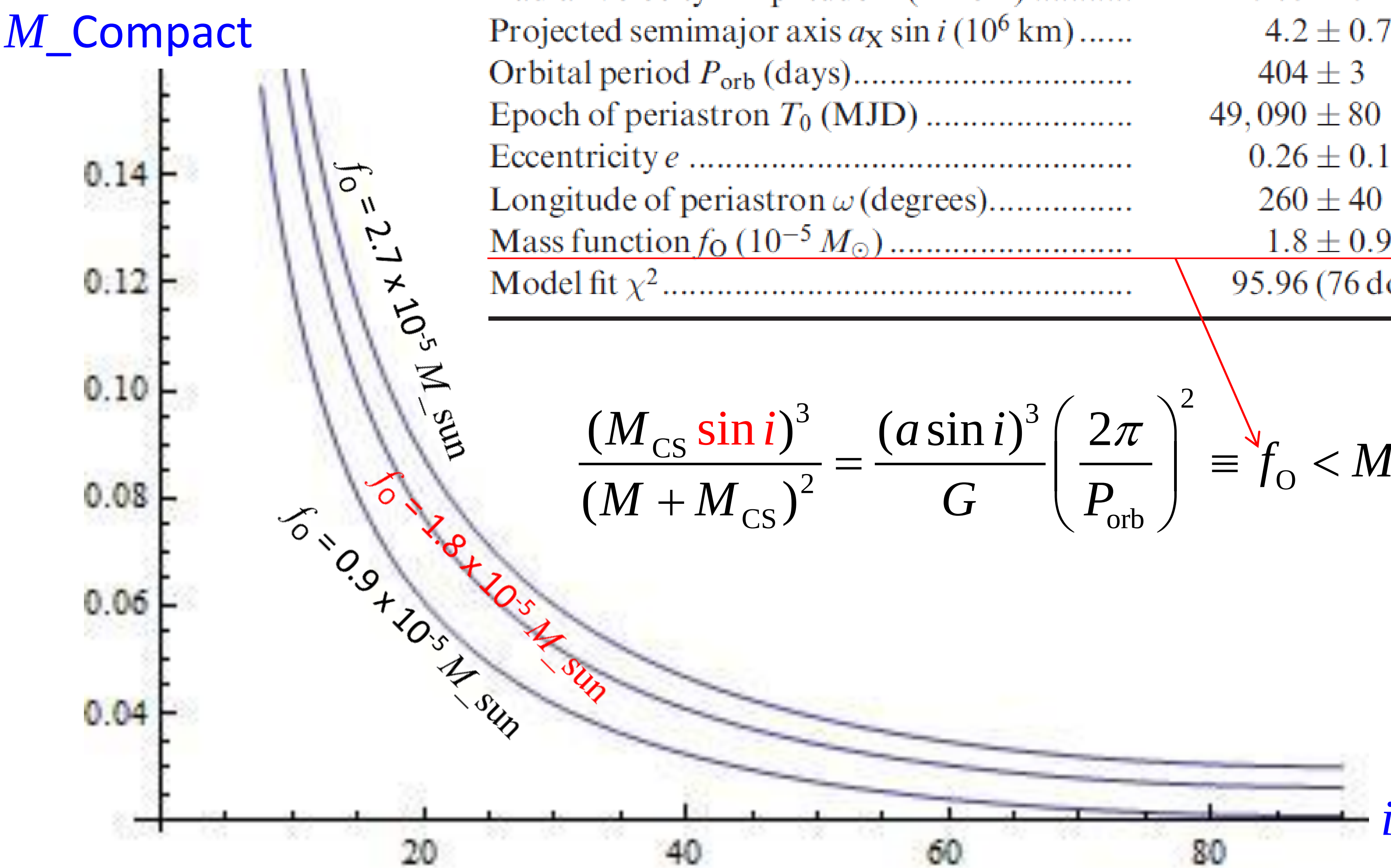


Galloway+ (2002)

ORBITAL PARAMETERS FOR HD 154791

Parameter	Value
Radial Velocity Amplitude K (km s^{-1})	0.75 ± 0.12
Projected semimajor axis $a_X \sin i$ (10^6 km)	4.2 ± 0.7
Orbital period P_{orb} (days).............................	404 ± 3
Epoch of periastron T_0 (MJD)	$49,090 \pm 80$
Eccentricity e	0.26 ± 0.15
Longitude of periastron ω (degrees)................	260 ± 40
Mass function f_O (10^{-5} $M_\odot$)	1.8 ± 0.9
Model fit χ^2	95.96 (76 dof)

$$\frac{(M_{CS} \sin i)^3}{(M + M_{CS})^2} = \frac{(a \sin i)^3}{G}\left(\frac{2\pi}{P_{orb}}\right)^2 \equiv f_O < M_{CS}$$



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Conclusions

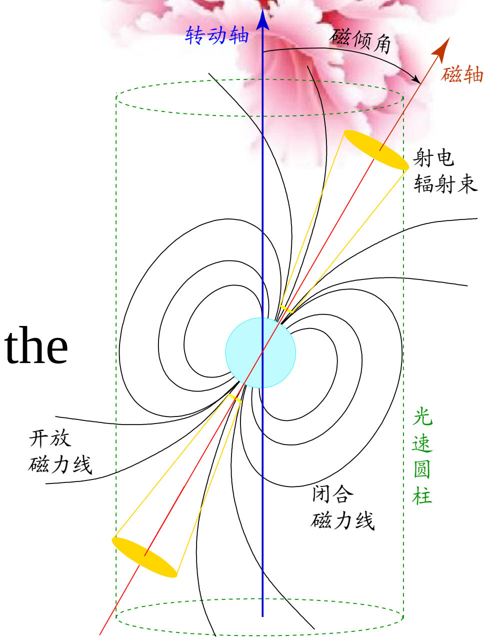
- Compact stars are sending us message being essential for us to know non-perturbative QCD.

- A ***strangeness barrier*** is suggested to exist on a strange quark-cluster star surface.

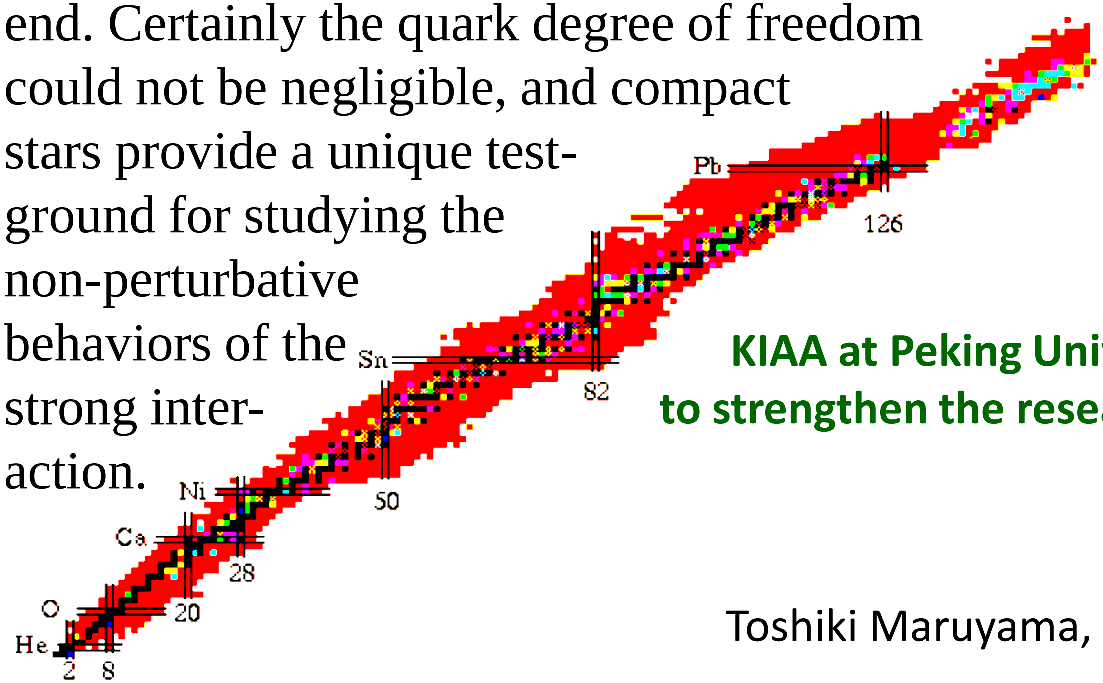
- Beside observations (stiff EoS, two types of glitches and extra free energy for bursts), the quark-cluster model is also **good** to understand the detected $\boldsymbol{z}$ and $\boldsymbol{f_{\mathrm{O}}}$ of 4U 1700+24, $\sim 10^{-2} M_{\odot}$!

Quarks and Compact Stars

KIAA at Peking University, Beijing; Oct. 20-22, 2014



Though the standard model of particle physics is proved to be successfully perfect as the discovery of Higgs boson, the nature of strong interaction at low energy scale, which is essential for us to understand atomic nuclei and compact stars as well as the early Universe, is still far from the end. Certainly the quark degree of freedom could not be negligible, and compact stars provide a unique test-ground for studying the non-perturbative behaviors of the strong inter-action.



KIAA at Peking University hosts a bilateral meeting to strengthen the researches and foster collaborations between China and Japan.

Organizers:

Toshiki Maruyama, Toshitaka Tatsumi and Renxin Xu

http://kiaa.pku.edu.cn/qcs2014