香港科技大學
THE HONG KONG
UNIVERSITY OF SCIENCE
AND TECHNOLOGY

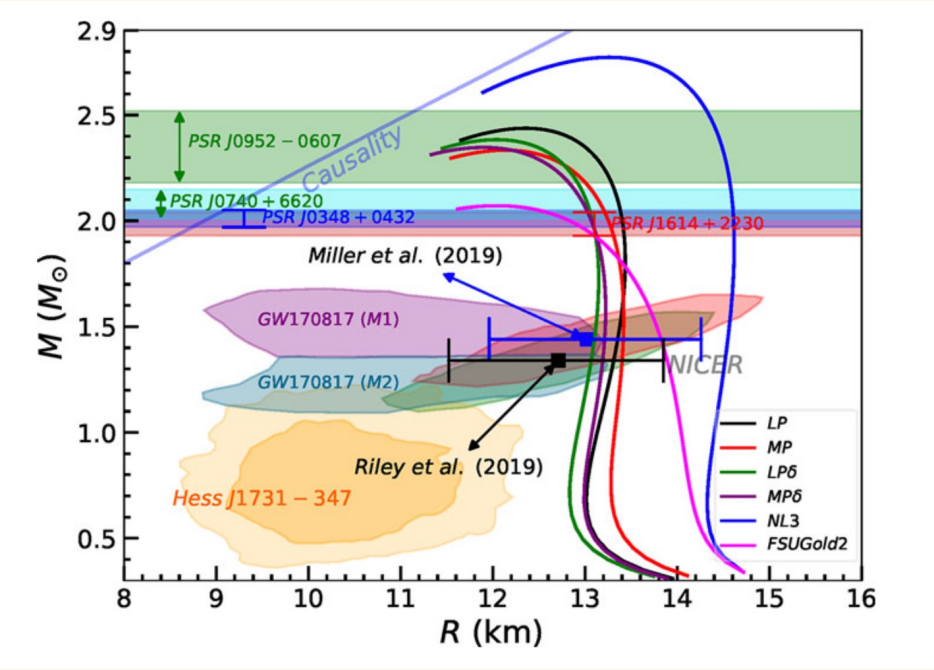
Slow Stable Self-bound Hybrid Stars Can Relieve All Tensions

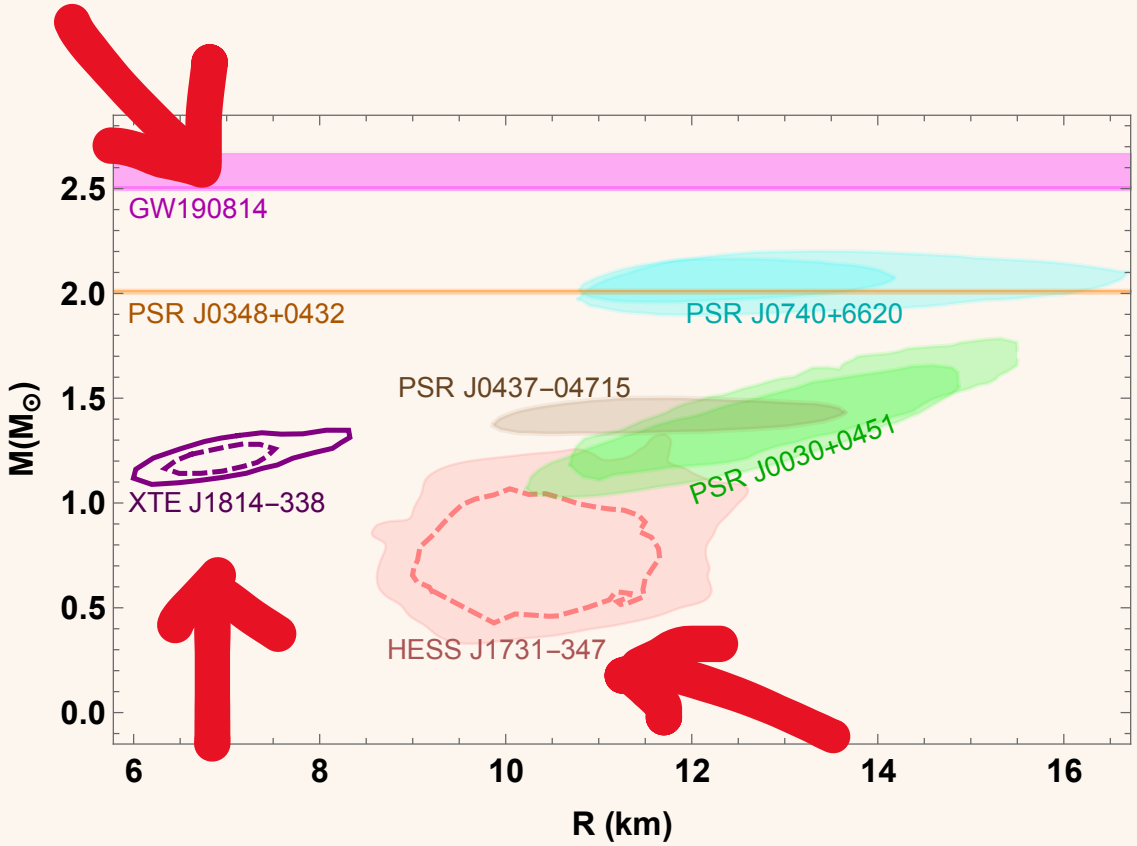
Chen **Z**hang (张晨)
IAS, HKUST

FPS14, Qingdao

Based on
arXiv:2507.01371 ;
Collaborator: Juan M. Z. Pretel, Renxin Xu
arXiv:2507.00776
Collaborator: ZongCan Yang, TianxiongZeng, Yan Yan, Wenli Yuan, Enping Zhou

Neutron Stars: Challenges





.Hypereon Puzzle

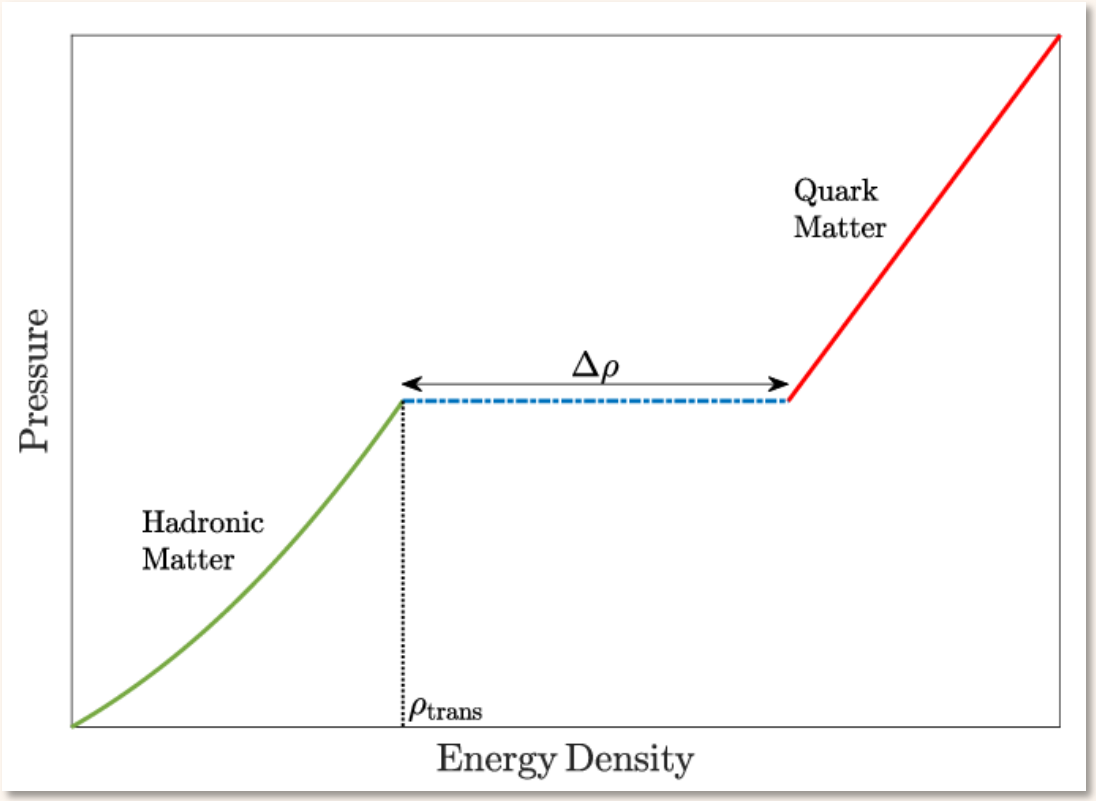
. HESS &XTE

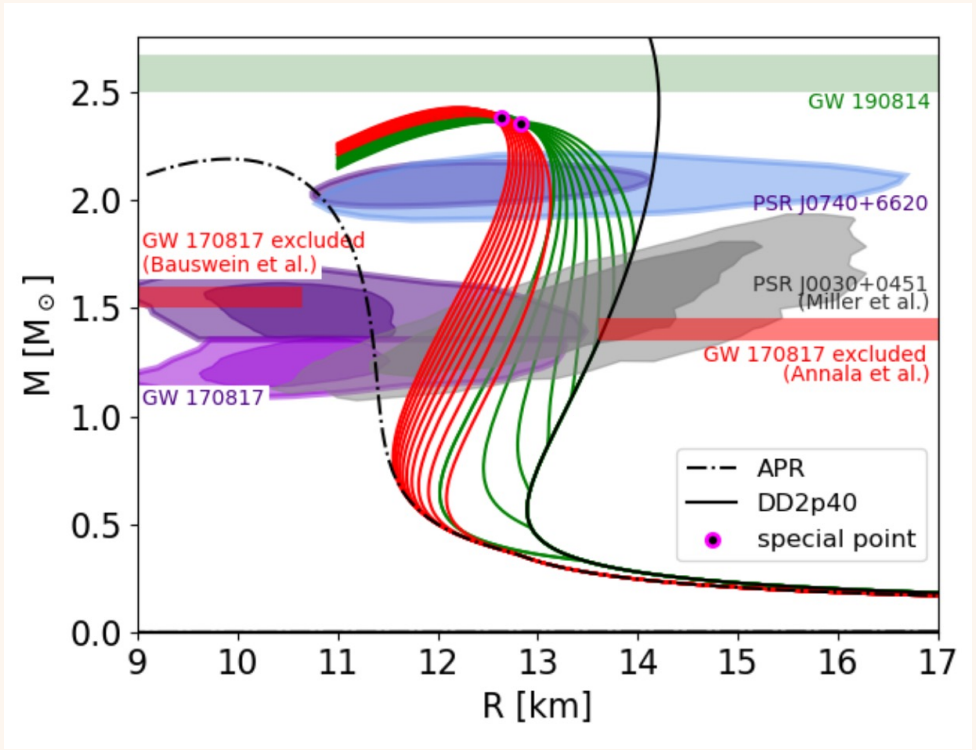
.GW190814 ($2.6M_{solar}$)

Hadron-Quark Phase transitions

Basic picture: at high pressure, hadrons deconfine into quark matter

→ Hybrid star: neutron star with a quark matter core





Graph from Cierniak et al. ***2106.06986***

Absolutely Stable Quark Matter

Strange Quark Matter (SQM) hypothesis

[1984 E. Witten]

QM with nearly equal number of u,d,s quarks, **may be the most stable form of matter** even at zero temperature and zero pressure

However, assumed that

1. QCD vacuum is flavor-independent (a universal bag const)

2. stable u,d quark matter (udQM) can not exist, considering we don't see proton&neutron being converted to udQM.

PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

Up-down Quark Matter (udQM) hypothesis

[B. Holdom, J. Ren, C. Z, Phys.Rev.Lett. 120 (2018) , 222001]

u,d quark matter could **be more stable than** SQM and ordinary nuclear matter at a sufficiently large baryon number A_{min}**>300**

Derived from an extended SU(3) chiral quark-meson model with the flavor dependence of the QCD vacuum naturally accounted and fits well with all the mass spectrum and decay widths of light scalar and pseudoscalar mesons.

PHYSICAL REVIEW LETTERS **120,** 222001 (2018)

Quark Matter May Not Be Strange

Bob Holdom,* Jing Ren,† and Chen Zhang‡
Department of Physics, University of Toronto, Toronto, Ontario M5S1A7, Canada

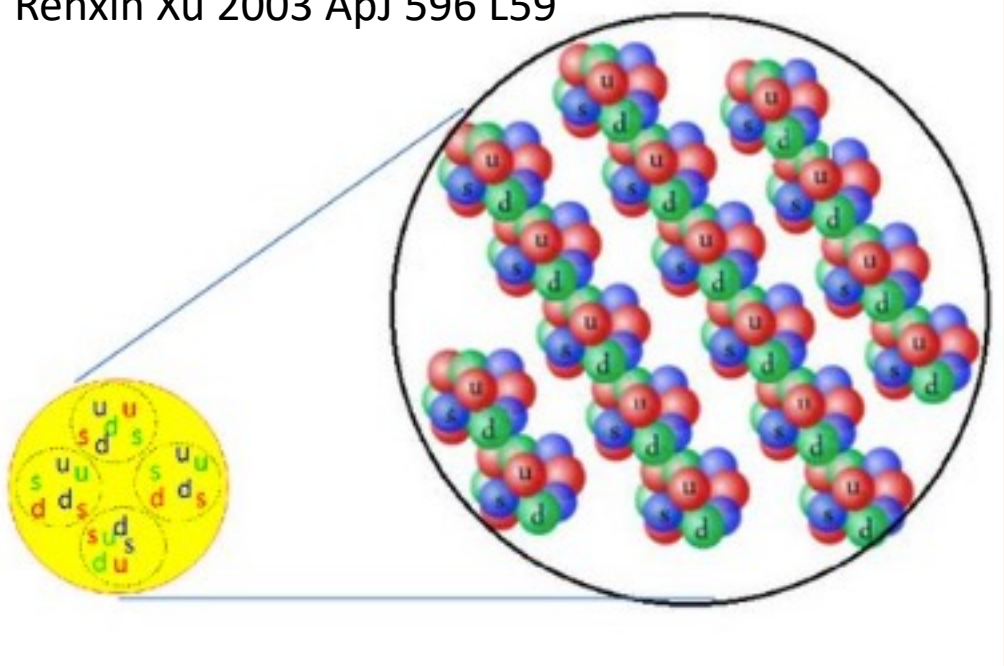
(Received 30 July 2017; revised manuscript received 23 October 2017; published 31 May 2018)

If quark matter is energetically favored over nuclear matter at zero temperature and pressure, then it has long been expected to take the form of strange quark matter (SQM), with comparable amounts of u, d, and s quarks. The possibility of quark matter with only u and d quarks (udQM) is usually dismissed because of the observed stability of ordinary nuclei. However, we find that udQM generally has lower bulk energy per baryon than normal nuclei and SQM. This emerges in a phenomenological model that describes the spectra of the lightest pseudoscalar and scalar meson nonets. Taking into account the finite size effects, udQM can be the ground state of baryonic matter only for baryon number $A > A_{\min}$ with $A_{\min} \gtrsim 300$. This ensures the stability of ordinary nuclei and points to a new form of stable matter just beyond the periodic table.

DOI: 10.1103/PhysRevLett.120.222001

Strangeon Matter

Renxin Xu 2003 ApJ 596 L59



Strangeon
(strange+nucleon)

Graph adapted from Xiaoyu Lai "Strangeon matter in kilonova"

$$V_{\rm LJ} = 4\epsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$

$$\rho = 2\epsilon\left(A_{12}\sigma^{12}n^5 - A_6\sigma^6 n^3\right) + nN_{\rm q}m_{\rm q}\,,$$
$$p = n^2\frac{{\rm d}(\rho/n)}{{\rm d}n} = 4\epsilon\left(2A_{12}\sigma^{12}n^5 - A_6\sigma^6 n^3\right)$$

X. Y. Lai , R. X. Xu, Monthly Notices of the Royal Astronomical Society: Letters, Volume 398, Issue 1, September 2009

$$\frac{\rho}{n_s} = \frac{a}{9}\tilde{\epsilon}\left(\frac{1}{18}\bar{n}^5 - \bar{n}^3\right) + m_q\bar{n},$$
$$\frac{P}{n_s} = \frac{2\,a}{9}\tilde{\epsilon}\left(\frac{1}{9}\bar{n}^5 - \bar{n}^3\right),$$
$$\Rightarrow \left(\frac{E}{A}\right)_{\rm strangeon} = 3m_q - \frac{3a}{2}\tilde{\epsilon}$$

where $a = A_6^2/A_{12} = 8.4^2/6.2 \approx 11.38$, $\tilde{\epsilon} = \epsilon/N_q$ and $\bar{n} = N_q\,n/n_s$. Note that $\bar{n} = 3$ at star surface where $P = 0$.

C.Zhang, Y.Gao, CJ Xia, RX Xu ***Phys.Rev.D*** **108 (2023) 6, 063002**

Self-bound Hybrid Star



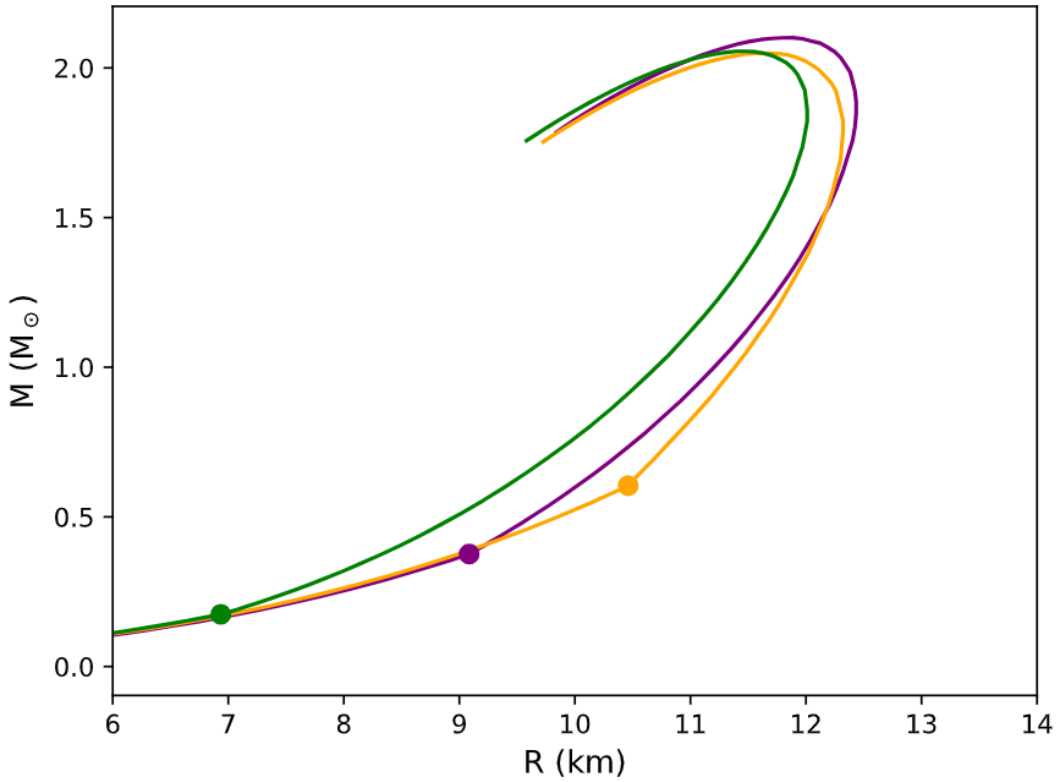
High density surface

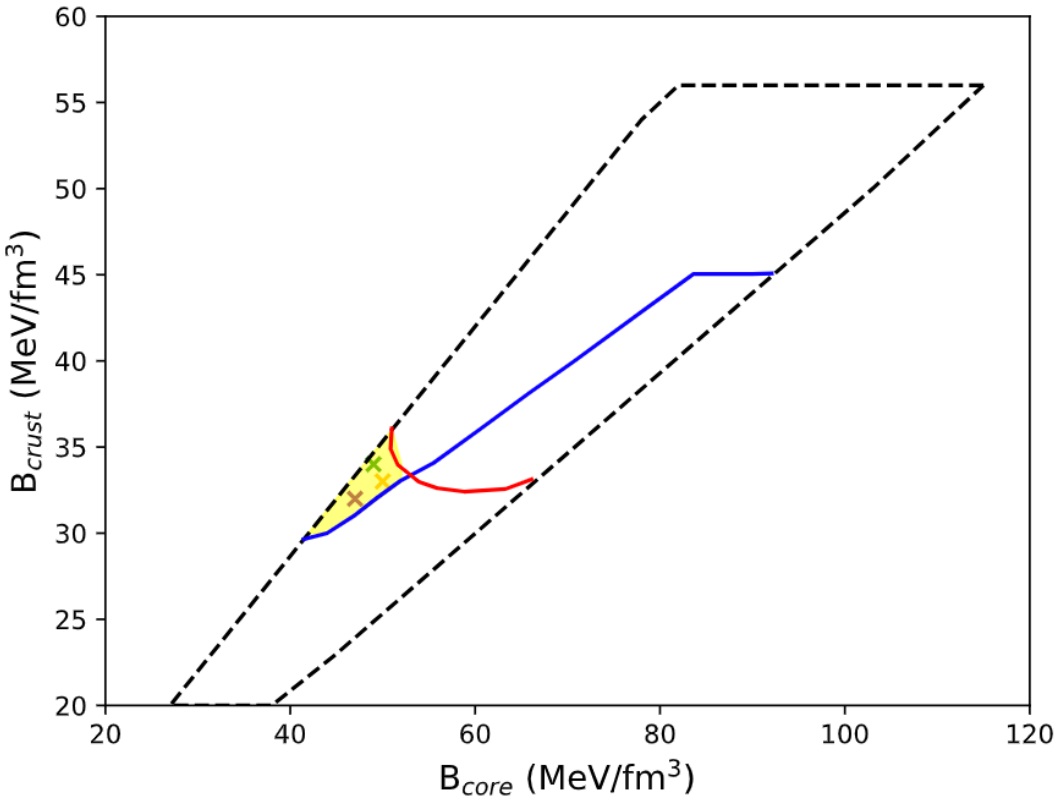
	Crust (Outer Layer)	Core (Inner core)
Hybrid Quark Star (HybQS)	Quark Matter	Quark Matter
Inverted Hybrid Star (IHS)	Quark Matter	Hadronic Matter
Hybrid Strangeon Star (HSS)	Strangeon Matter	Quark Matter

Hybrid Quark Star (HybQS)

ZC. Yang, TX. Zeng, Y. Yan, WL. Yuan, C. Zhang*, and EP. Zhou* arXiv:2507.00776 [astro-ph.HE]

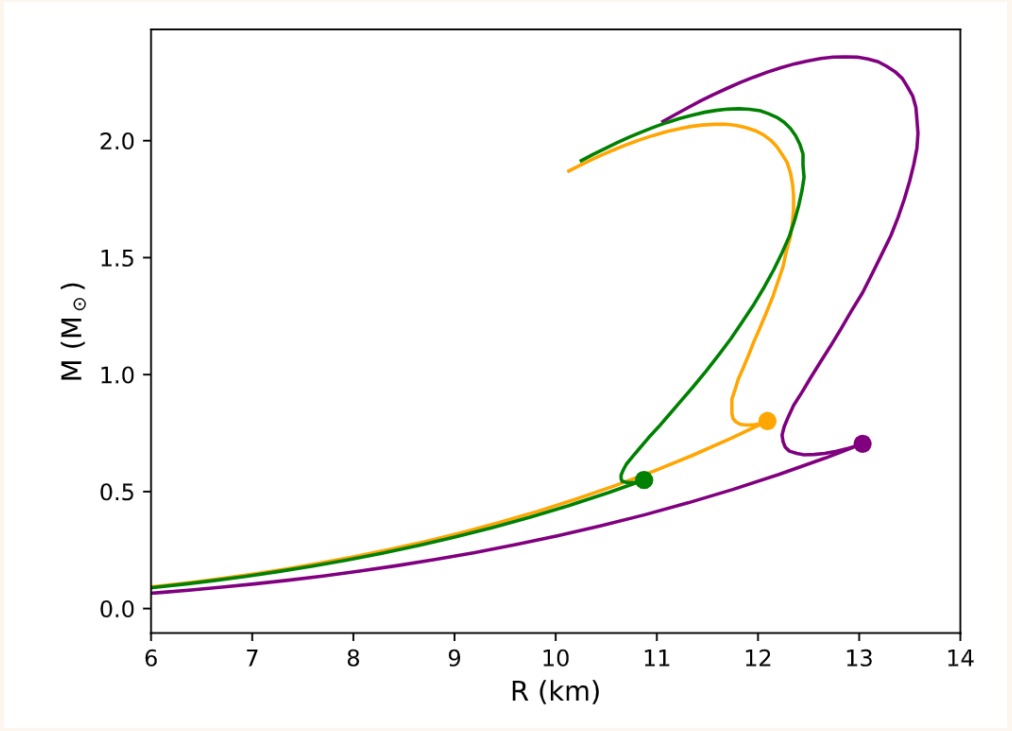
unpaired 2f to unpaired 3f phase transition

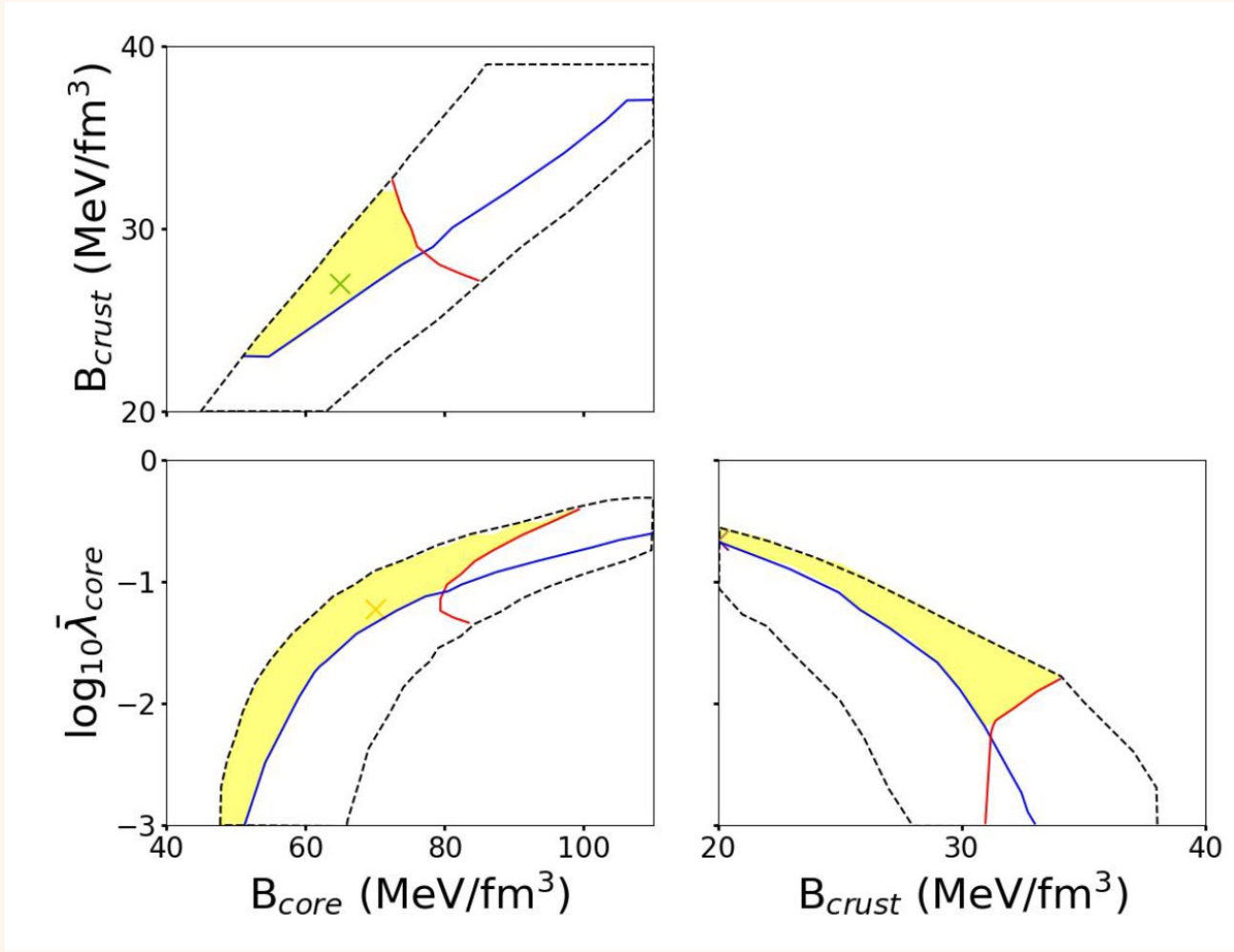




Hybrid Quark Star (HybQS)

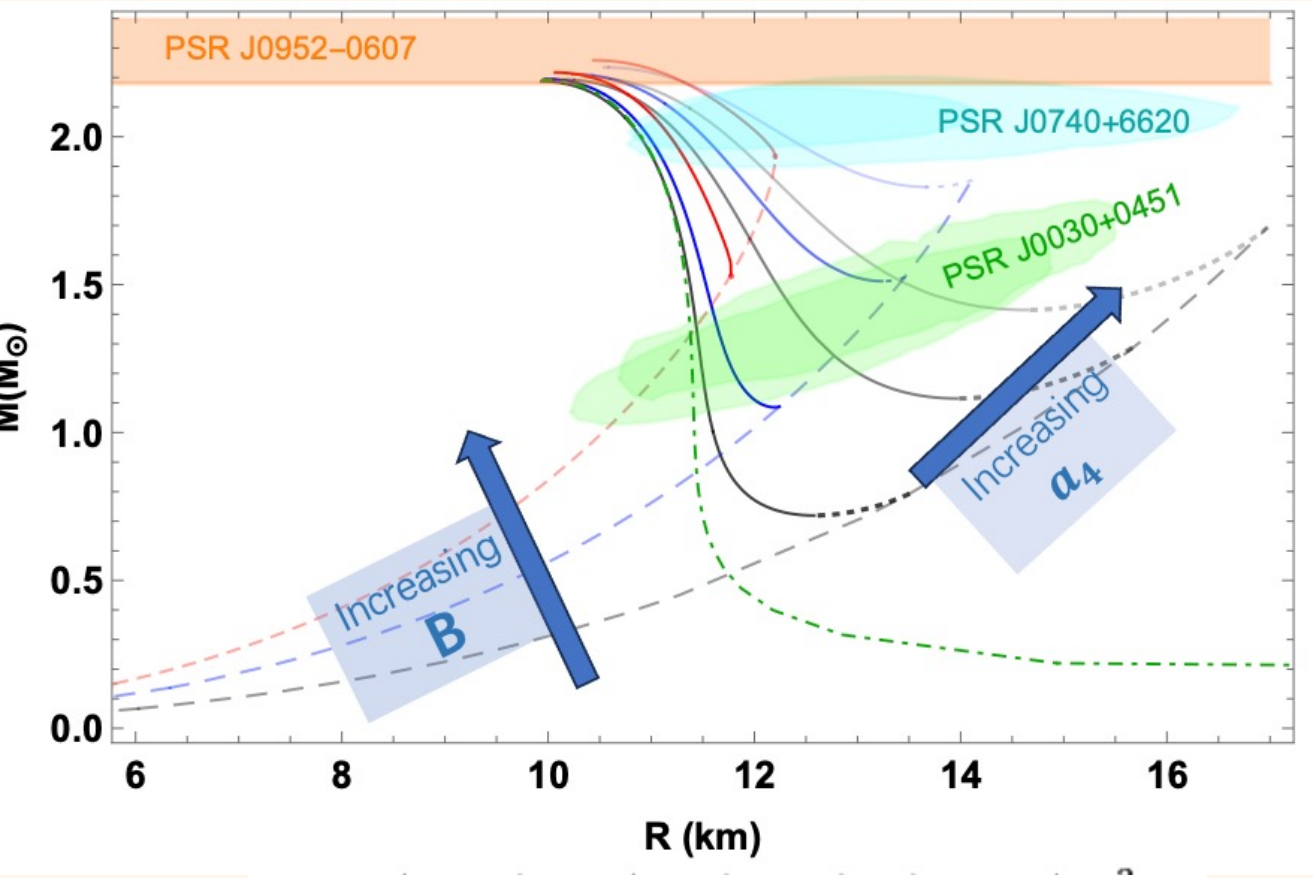
unpaired 2f to CFL phase transition

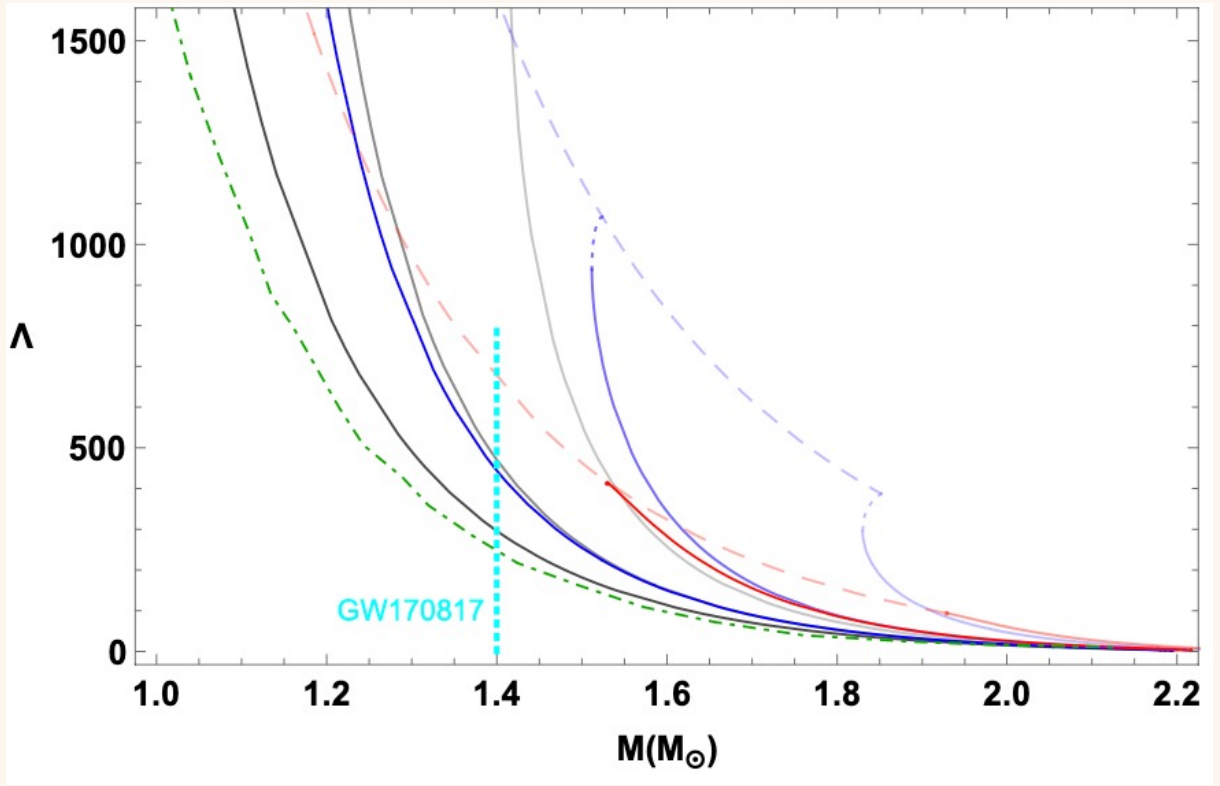




Inverted Hybrid Star (IHS)

C.Zhang, J. Ren, Phys. Rev. D 108, 063012 (2023)



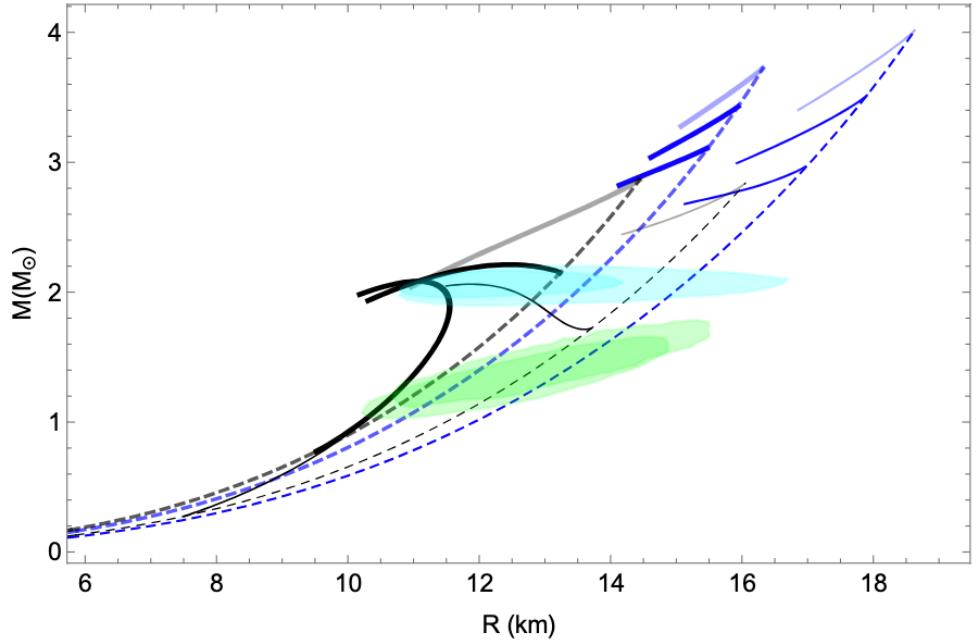


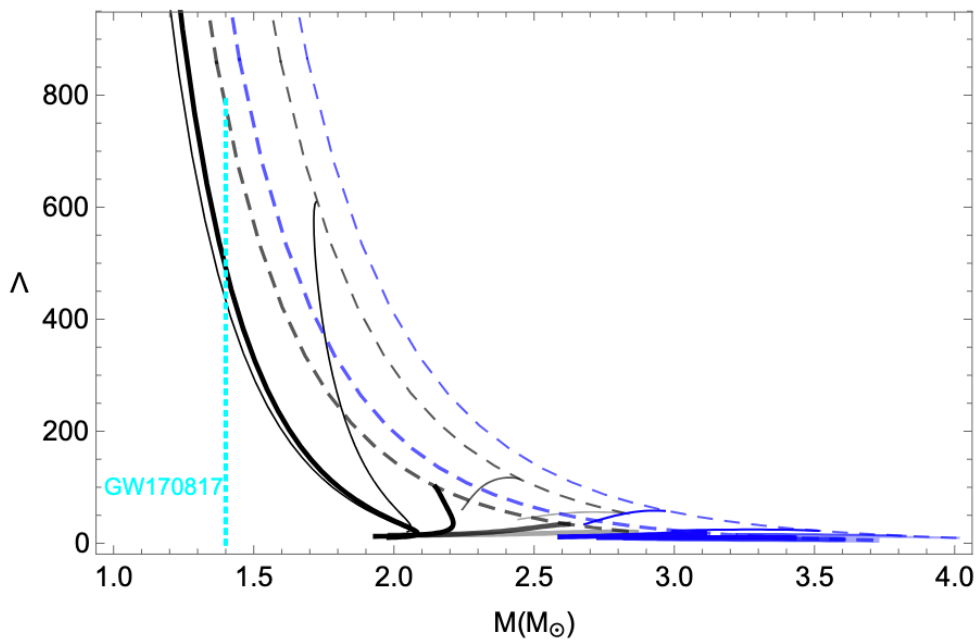
$B = 20$ (black), 35 (blue), 50 (red) MeV/fm^3

$a_4 = a_{4,\min},\ (a_{4,\min} + a_{4,\max})/2,\ a_{4,\max}$

Hybrid Strangeon Star (HybSS)

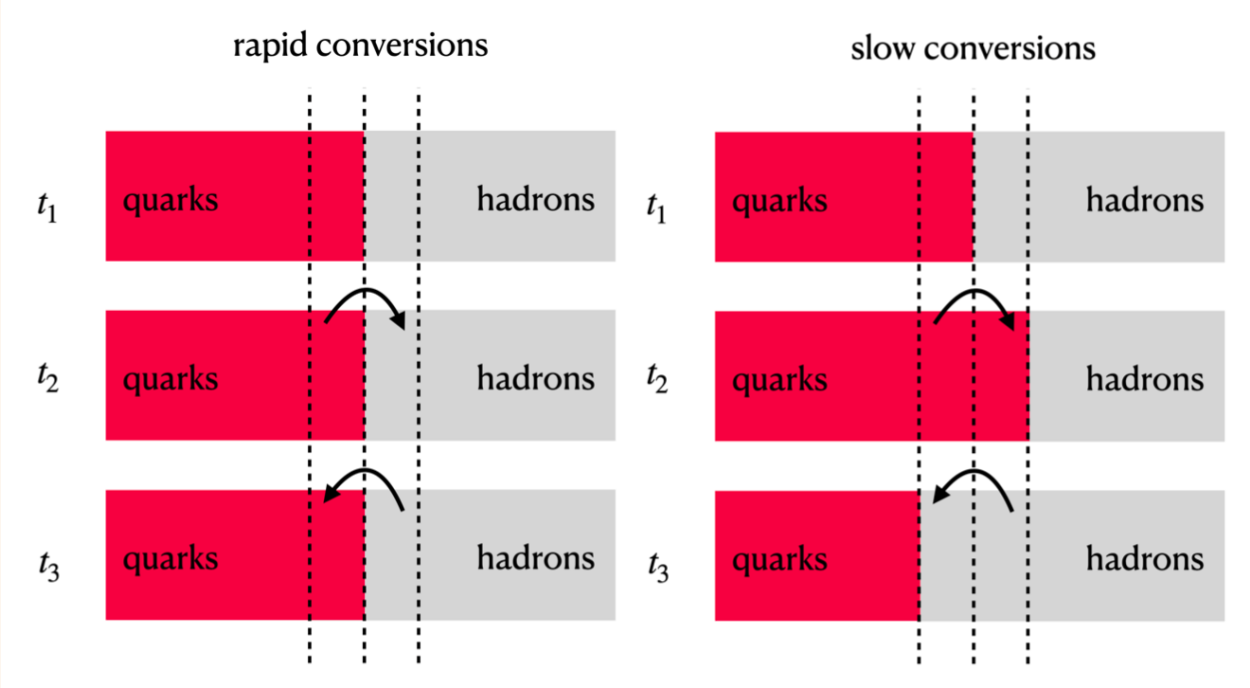
C. Zhang, Y Gao , CJ Xia, RX Xu Phys.Rev.D 108 (2023) 12, 12

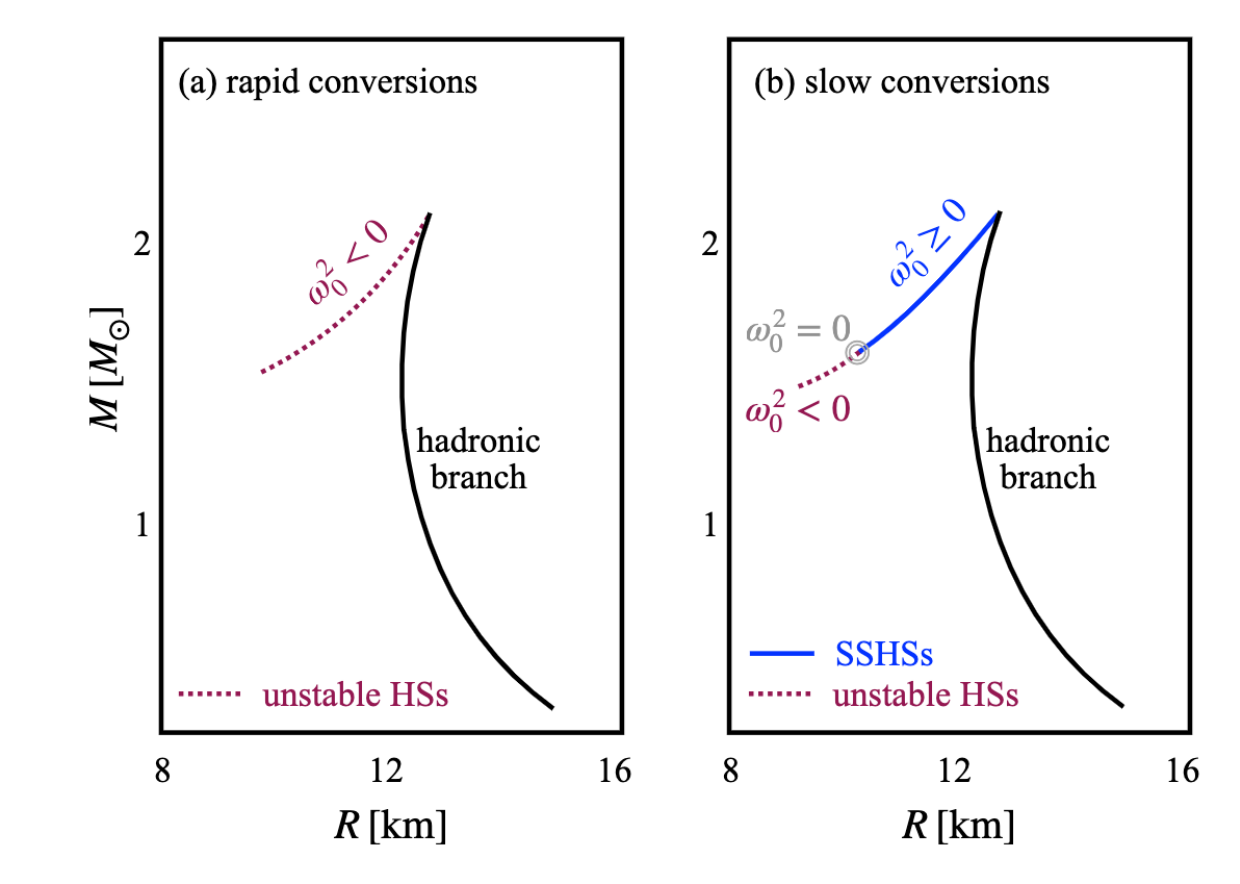




Slow Stable Hybrid star (SSHS)

- Conventional Hybrid stars

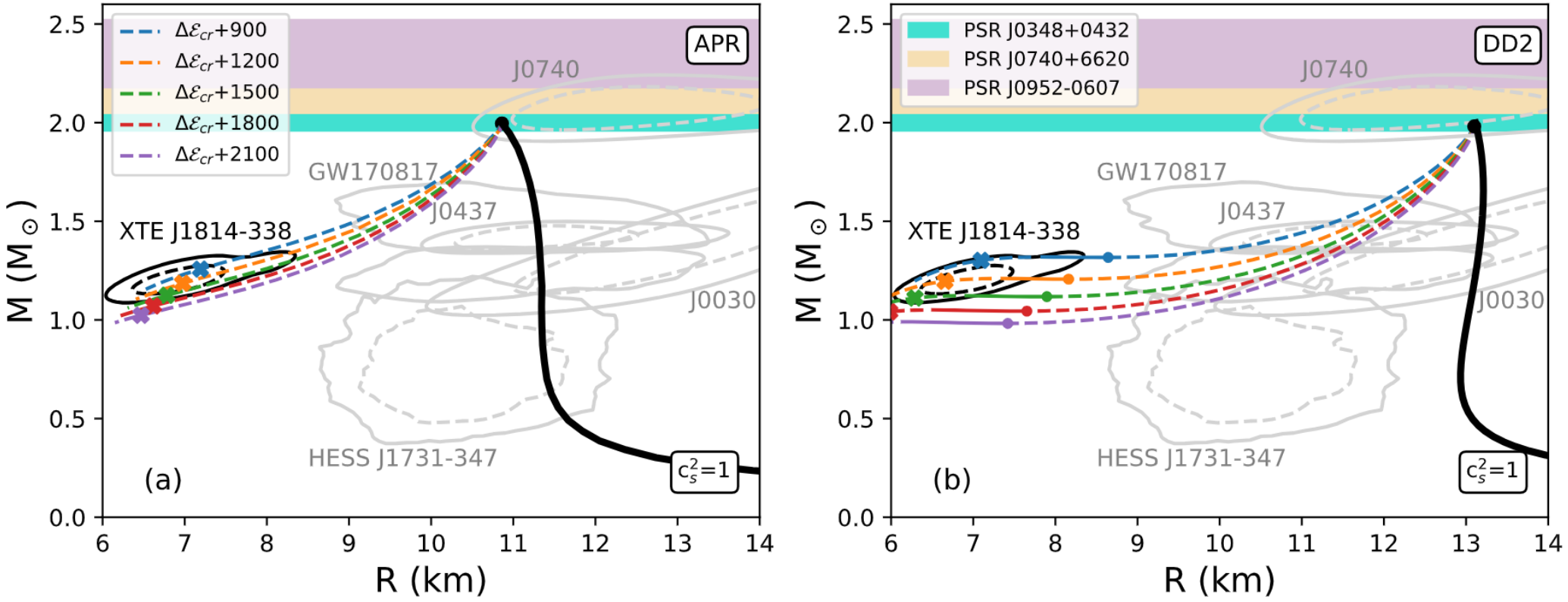




Graph adapted from Lugones, G., & Grunfeld, A. G. (2021). *Universe*, *7*(12), 493.

SSHS for explaining XTE J1814-338

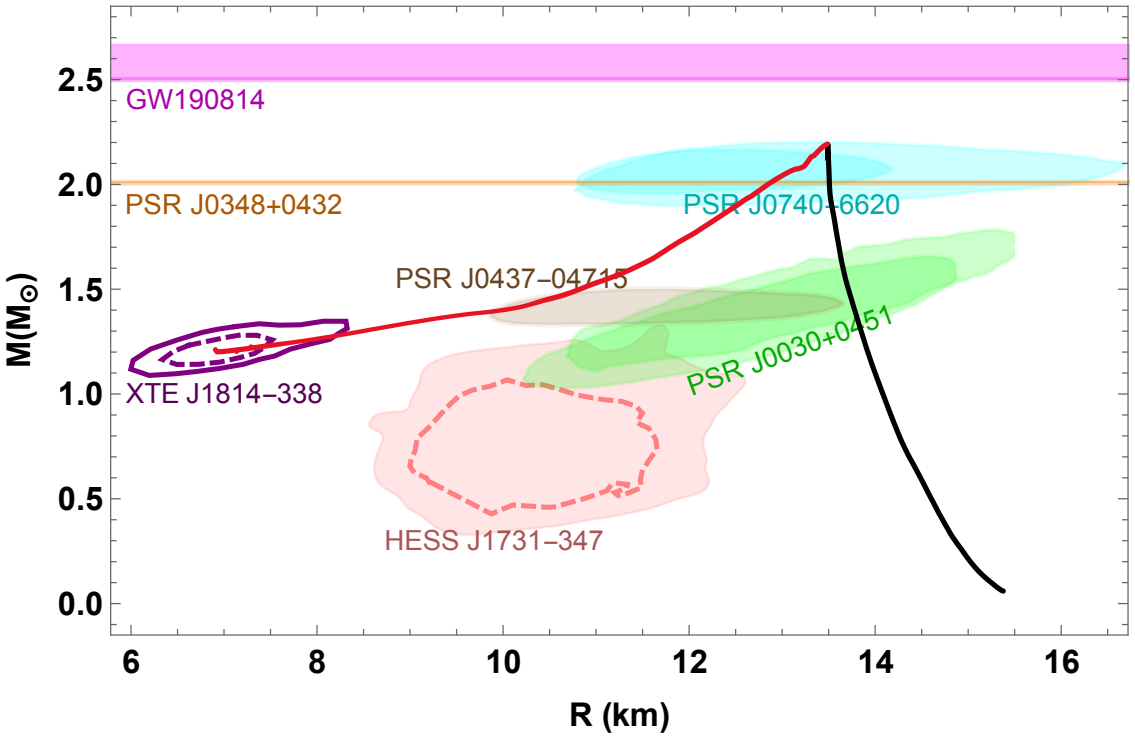
"XTE J1814-338: A potential hybrid star candidate" Patkos and Moustakidis PRD (2025)

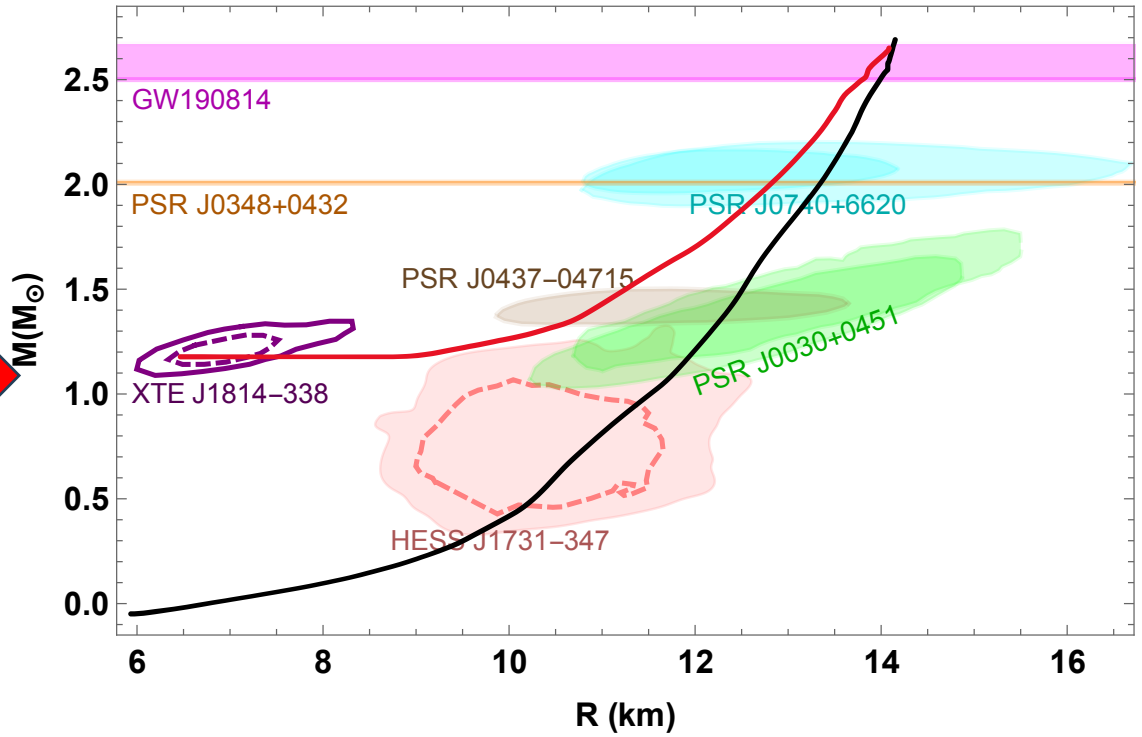


Slow stable Self-bound Hybrid star

C Zhang, JMZ Pretel, RX Xu arXiv:2507.01371 [astro-ph.HE]

A rough sketch





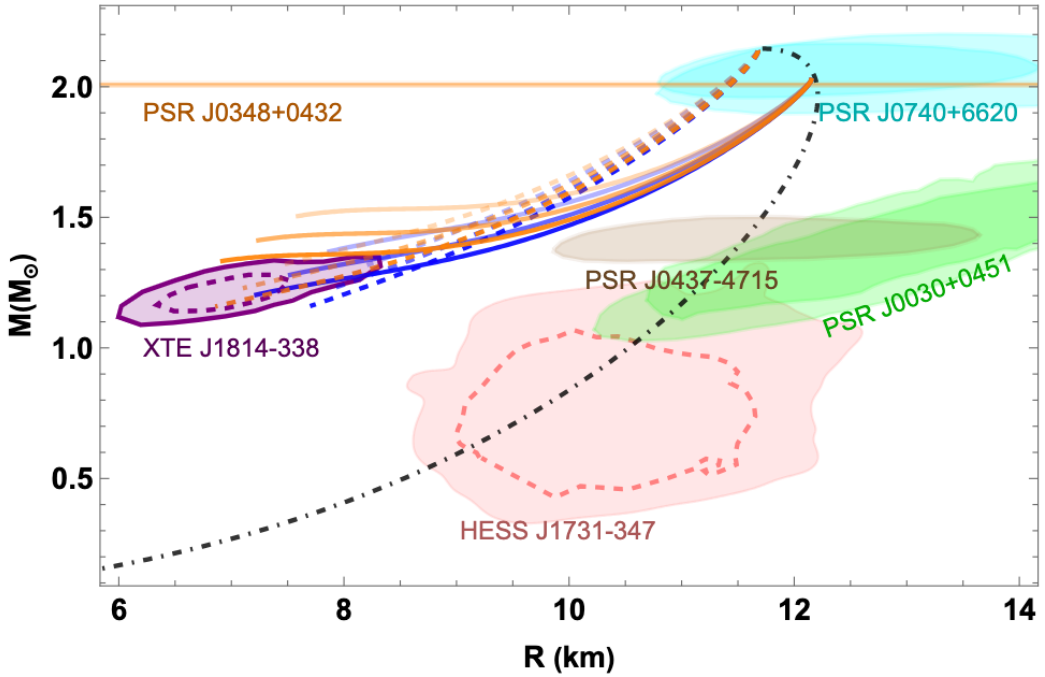
Two Scenarios:

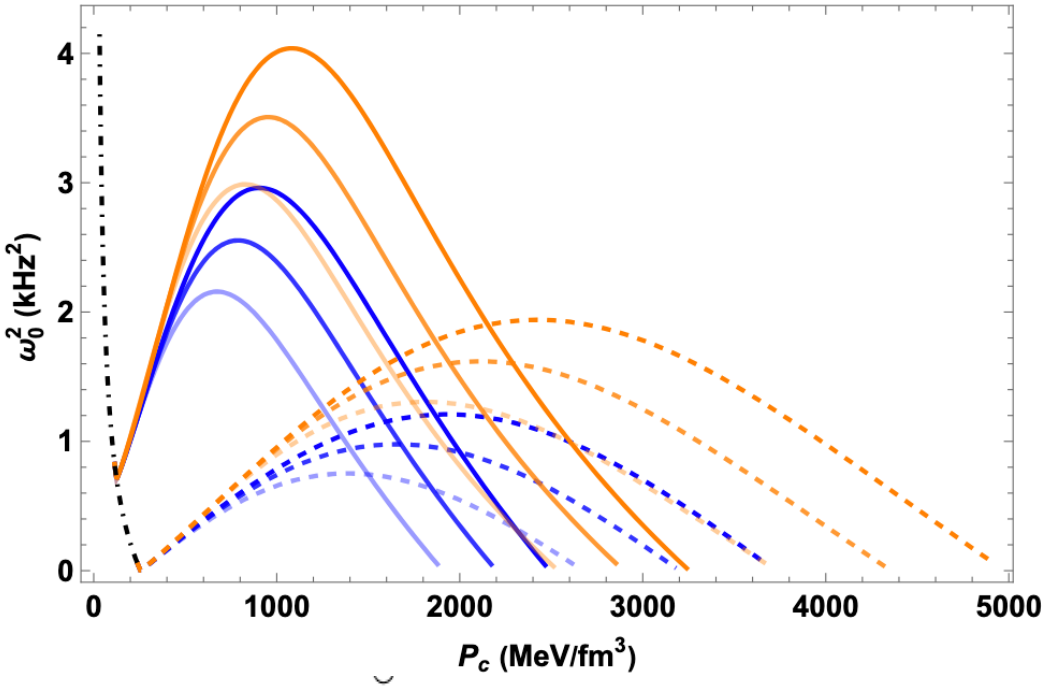
1. **non-hybrid branch can meet GW170817's constraint**
2. **Or not**

Scenario 1: Slow Stable HybQS

$$P = \frac{1}{3}(\rho - 4B), \quad P < P_{\rm trans}$$

$$P = c_s^2(\rho - \rho_{\rm trans} - \Delta\rho) + P_{\rm trans}, \quad P > P_{\rm trans}$$



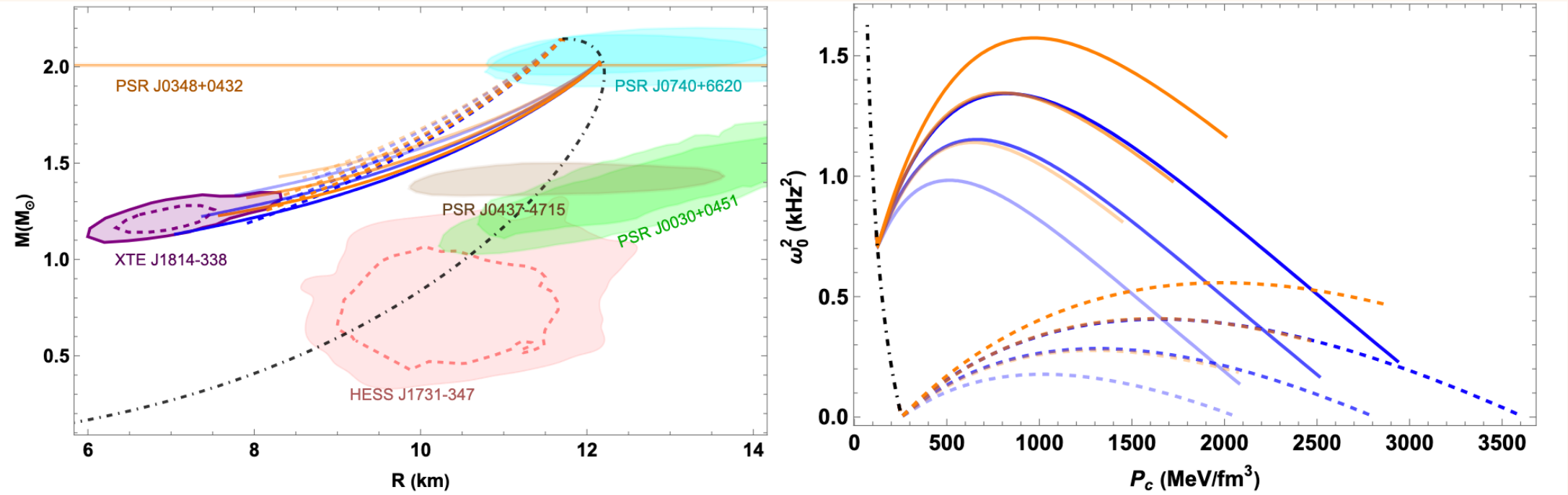


$B = 50.3\,\mathrm{MeV/fm^3}$ for the quark matter crust. Blue ($c_s^2 = 0.6$) and orange ($c_s^2 = 1$) curves darken with larger $\Delta\rho/\rho_{\rm trans}$ $(1.5, 1.8, 2.1)$

Scenario 1: Slow Stable IHS

$$P = \frac{1}{3}(\rho - 4B), \quad P < P_{\rm trans}$$

$$P = K\rho^{\gamma}, \quad P > P_{\rm trans}$$



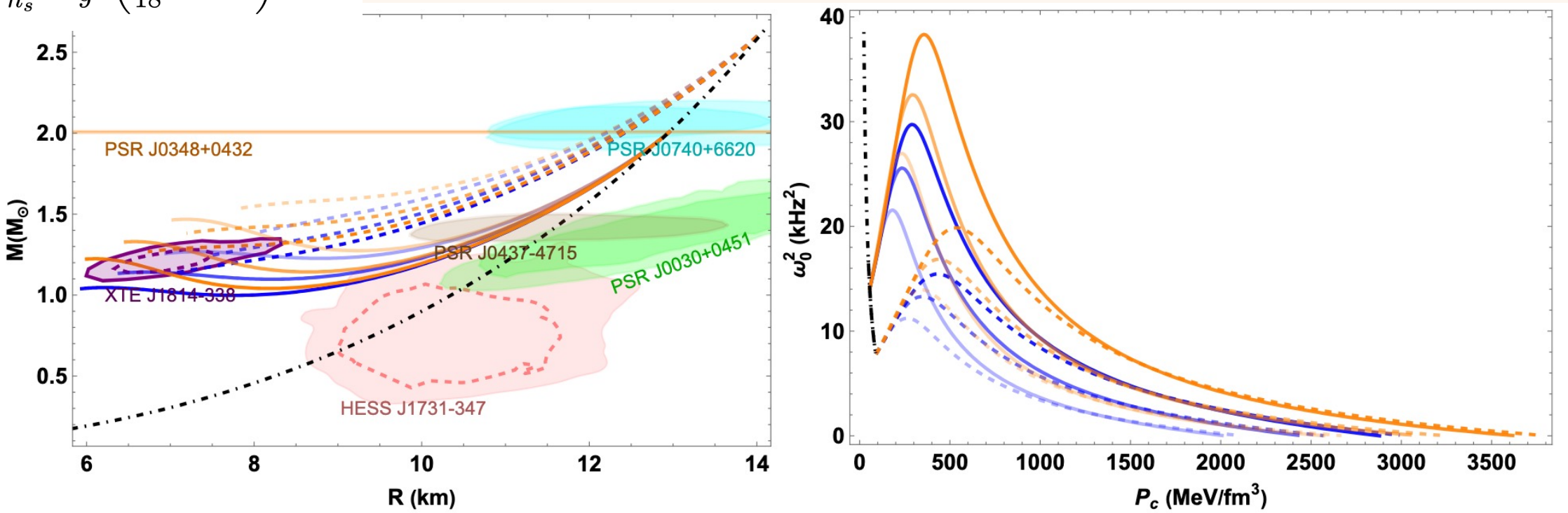
$B = 50.3\,\mathrm{MeV/fm^3}$ for the quark matter crust. Blue ($\gamma = 2.1$) and orange ($\gamma = 2.3$) curve darken with increasing $\Delta\rho/\rho_{\rm trans}$ (1, 1.2, 1.4)

Scenario 1: Slow Stable HybSS

$$\frac{P}{n_s} = \frac{2\,a}{9}\tilde{\epsilon}\left(\frac{1}{9}\bar{n}^5 - \bar{n}^3\right),$$
$$\frac{\rho}{n_s} = \frac{a}{9}\tilde{\epsilon}\left(\frac{1}{18}\bar{n}^5 - \bar{n}^3\right) + m_q\bar{n}$$

$P < P_{\rm trans}$

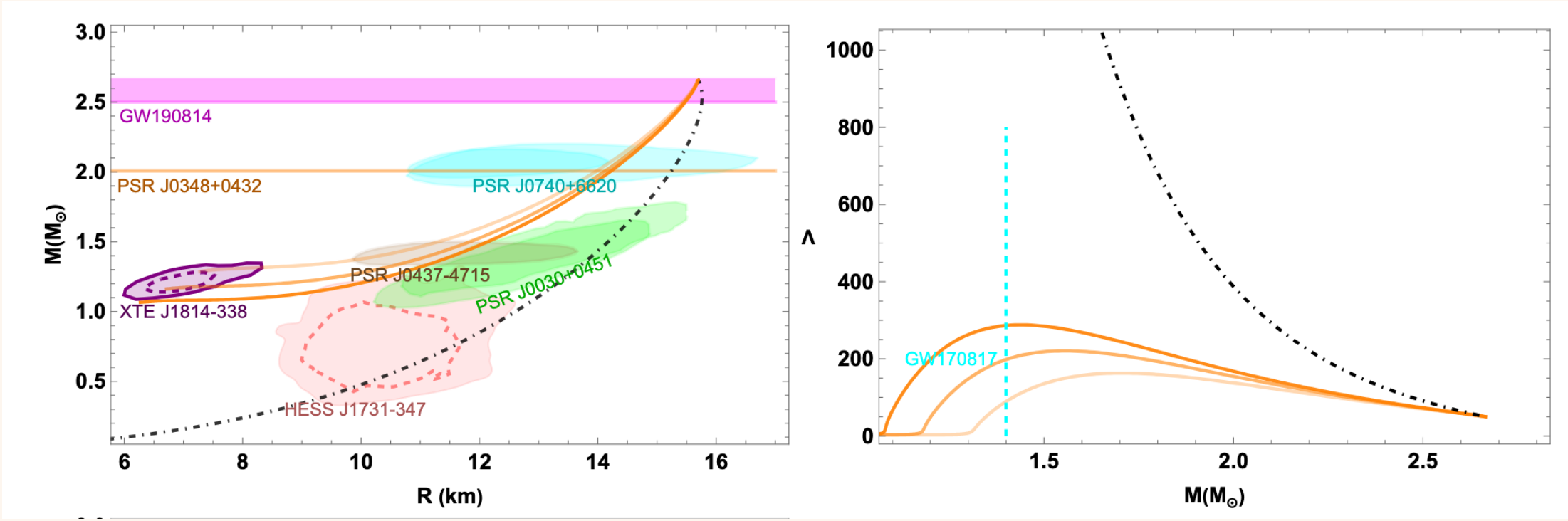
$$P = c_s^2(\rho - \rho_{\rm trans} - \Delta\rho) + P_{\rm trans}, \quad P > P_{\rm trans}$$



$\epsilon/N_q = 80/9$ MeV/fm³ for the strangeon matter fixing $n_s = 0.3\,\mathrm{fm}^{-3}$. Blue ($c_s^2 = 0.6$) and orange ($c_s^2 = 1$) curves darken with larger $\Delta\rho/\rho_{\rm trans}$ $(4, 5, 6)$

XTE区域甚至可以在快相变 (相变时标远小于振动时标) 下仍然稳定!

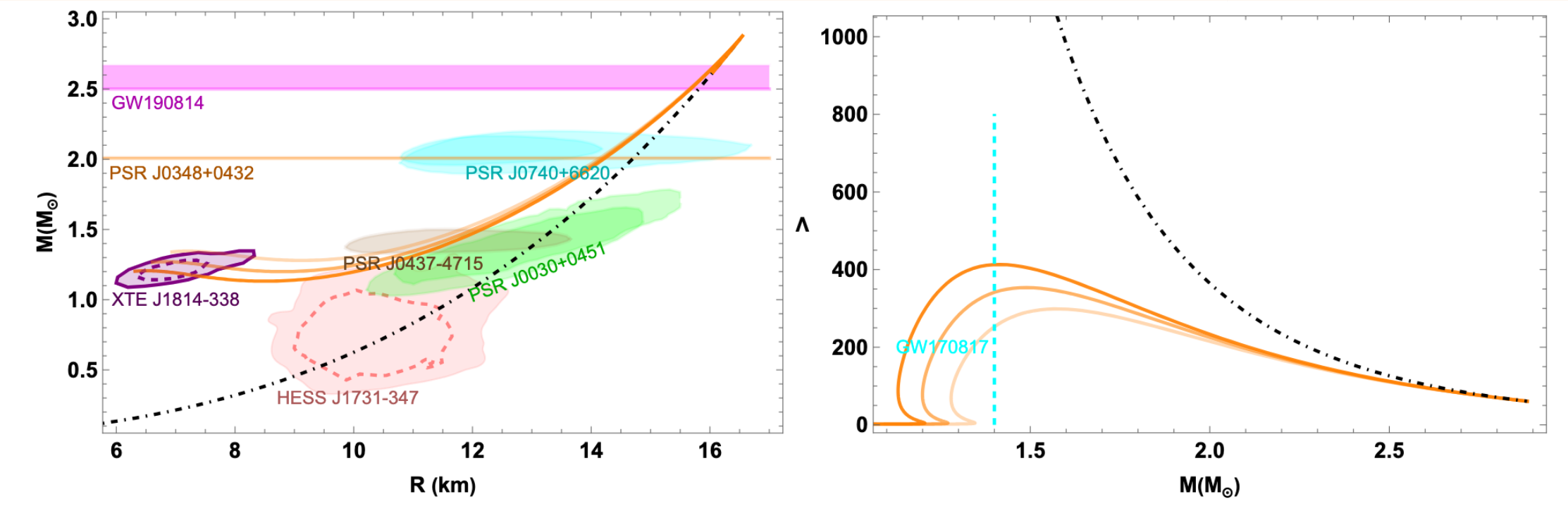
Scenario 2: Slow Stable HybQS



$B = 30\,\mathrm{MeV/fm^3}$ for the crust quark matter

Orange $(c_s^2 = 1)$ curves darken with larger $\Delta\rho/\rho_{\mathrm{trans}}$ $(4, 5, 6)$

Scenario 2: Slow Stable HybSS



$\epsilon/N_q = 200/9$ MeV/fm^3 for the crust strangeon matter $n_s = 0.3\,\mathrm{fm}^{-3}$. Orange ($c_s^2 = 1$) curves darken with larger $\Delta\rho/\rho_{\mathrm{trans}}$ $(8, 9, 10)$

Summary

1. 自束缚混杂星可以由夸克星或奇子星内部发生相变形成

2. 所有种类的慢稳自束缚星都可以在满足传统天文限制的前提下满足HESS J1731-347和XTE J1814338限制。

3. 自束缚的特点帮助满足HESS J1731-347, 慢稳的特点满足XTE J1814-338.

4. 混杂夸克星和混杂奇子星不仅能满足 HESS J1731-347 and XTE J1814338， 还有GW190814的2.6倍太阳质量伴星



Thanks!