Constraints on the maximum mass of neutron stars with strangeness

Ang Li
Xiamen Univ.
liang@xmu.edu.cn

Miao & Li, 2107.07979
Miao, Jiang, Li+ 2021 ApJL, 2107.13997
Li+, 2021 ApJ, 2103.15119
Li+, 2021 MNRAS, 2009.12571
Miao, Li+, 2020 ApJ, 2006.00839

Outline

- Intro. on neutron star (NS) and dense matter equation of state (EOS)
- NS maximum mass from LIGO/Virgo and NICER with microscopic EOSs
- Take-home message

NSs: Densest and smallest stars observed in the Universe

- Radius: R ~ 10 - 15 km; Mass M ~ 1 - 3 $M_{\odot}$;
- For R = 10 km, M = 1.4 $M_{\odot}$, average number density ~ 0.4 fm^{-3} ; average (energy) density: ~ 6.9 $\times$1014 g/cm^3 ~ (2-3)ϱ_0, exceeding the ordinary nuclear density;
- Equation of state (EOS), mainly p(ε), informative of the composition and inner structure of a NS; Such extreme conditions make it impossible to attain EOS by experimental methods only!

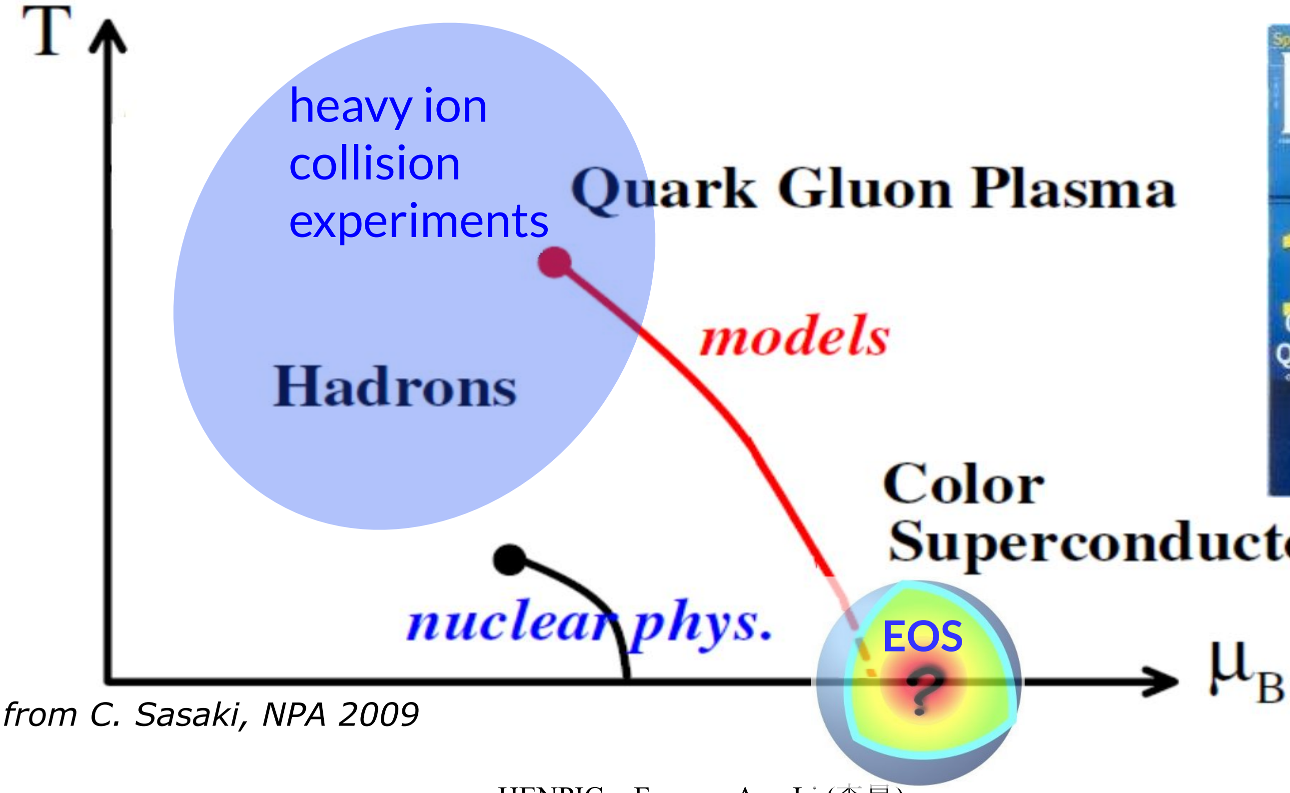
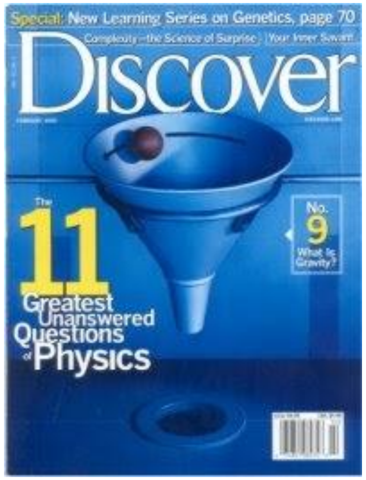


Fig. from C. Sasaki, NPA 2009

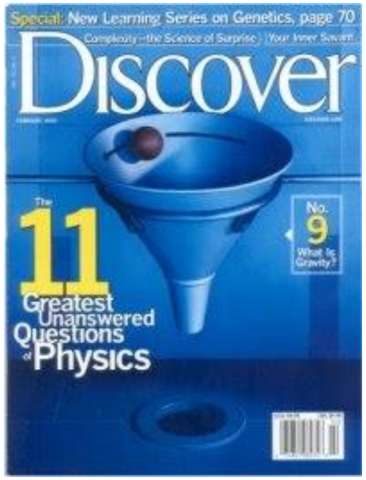


Discover
February 2002

NSs: Densest and smallest stars observed in the Universe

- Dense matter EOS: One of 11 unanswered questions of Physics whose resolutions could provide a new era in science!
- Eelectronmagetic (EM) and gravitational wave (GW) observations of NSs are ideal probe of dense QCD;
- Macroscopic properties (e.g., M, R) of NSs have an intrinsic correlation with microphysical EOS.

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultra-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. **Are there new states of matter at ultrahigh temperatures and densities?**
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the Universe begin?



Discover
February 2002

NSs described in terms of General Relativity

EOS,
mainly $p(\varepsilon)$

+

$$\frac{dy}{dr} = -\frac{1}{r}[y^2 + yF(p,\varepsilon) + r^2 Q(p,\varepsilon)]$$

$$\frac{dp}{dr} = -\frac{(\varepsilon + p)(m + 4\pi r^3 p)}{r(r-2m)}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

Tolman-Oppenheimer-Volkoff
(TOV) equation:
GR version of the hydrostatic equilibrium

M_{TOV}; M-R relations

M

R

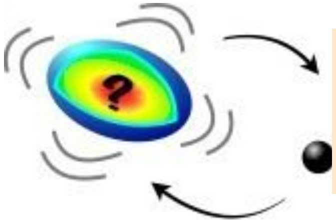
$y_R \equiv y(R)$

$$k_2 = \frac{1}{20}\left(\frac{R_s}{R}\right)^5 \left(1-\frac{R_s}{R}\right)^2 \left[2 - y_R + (y_R - 1)\frac{R_s}{R}\right] \left\{\frac{R_s}{R}\left(6 - 3y_R + \frac{3R_s}{2R}(5y_R - 8)\right) + \frac{1}{4}\left(\frac{R_s}{R}\right)^3 \left[26 - 22y_R + \frac{R_s}{R}(3y_R - 2) + \left(\frac{R_s}{R}\right)^2 (y_R + 1)\right] + 3\left(1-\frac{R_s}{R}\right)^2 \left[2 - y_R + (y_R - 1)\frac{R_s}{R}\right] \ln\left(1 - \frac{R_s}{R}\right)\right\}^{-1}$$

$$F(r) = \frac{r - 4\pi r^3[\mathcal{E}(r) - P(r)]}{r - 2M(r)},$$

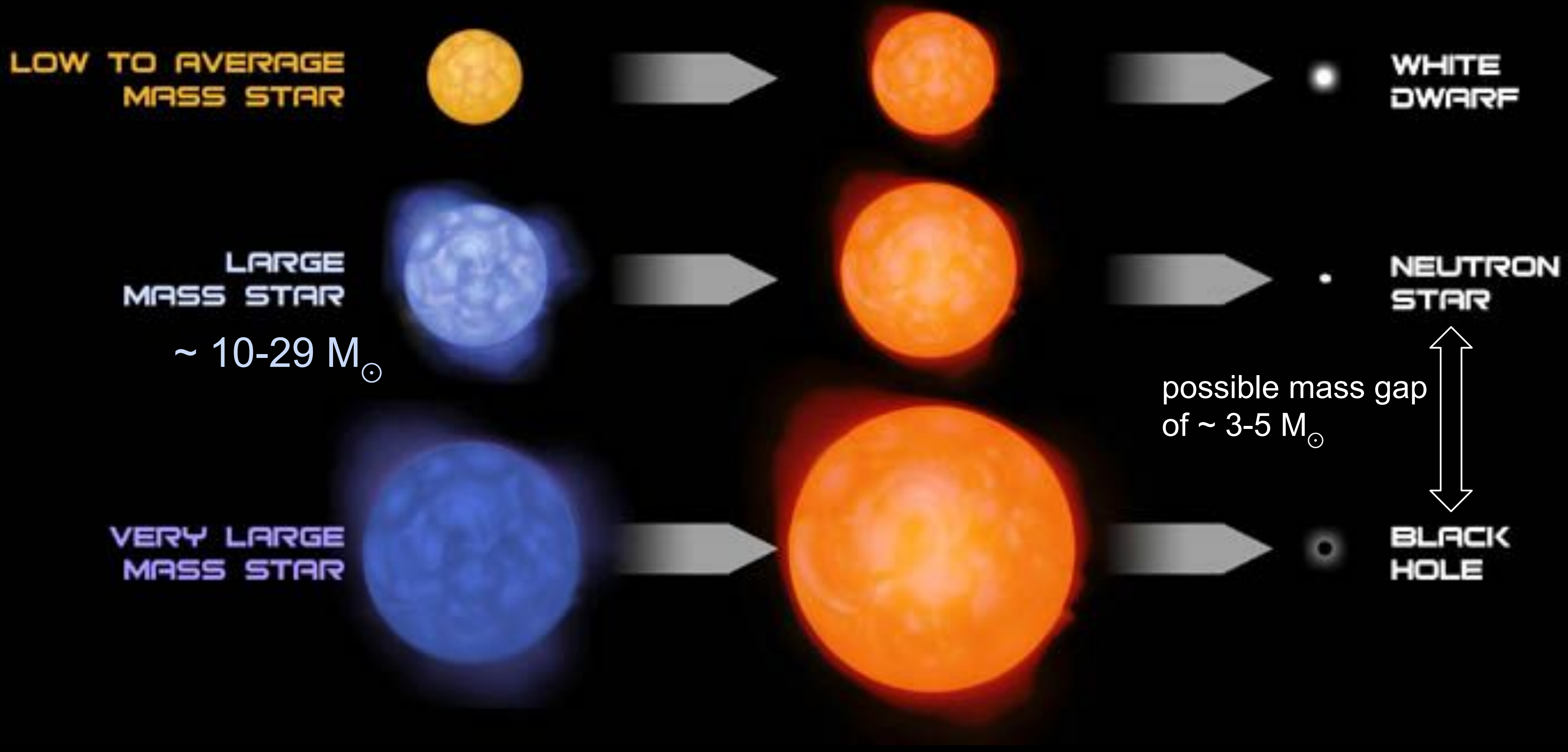
$$Q(r) = \frac{4\pi r\left[5\mathcal{E}(r) + 9P(r) + \frac{\mathcal{E}(r)+P(r)}{c_s^2} - \frac{6}{4\pi r^2}\right]}{r - 2M(r)} - 4\left\{\frac{M(r) + 4\pi r^3 P(r)}{r[r - 2M(r)]}\right\}^2.$$

tidal deformability



$$\lambda = \frac{2}{3} k_2 R^5$$

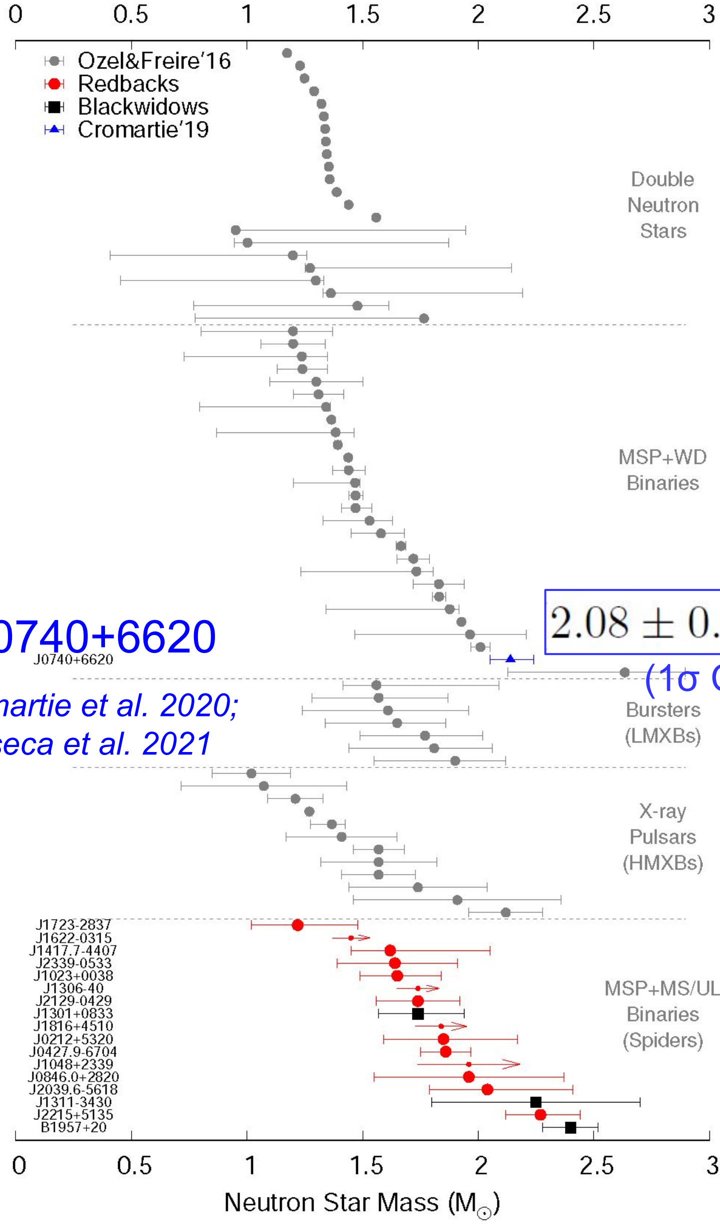
NS maximum mass and the mass gap between NS and BH



~ 10-29 $M_{\odot}$

possible mass gap
of ~ 3-5 $M_{\odot}$

Neutron star maximum mass: Observational



J0740+6620

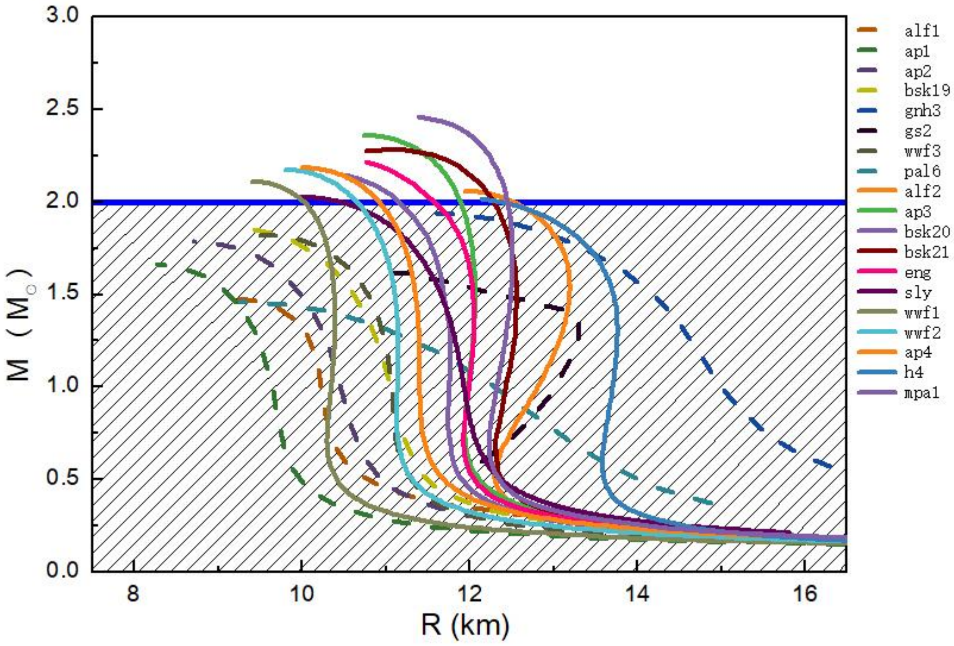
Cromartie et al. 2020;
Fonseca et al. 2021

2.08 ± 0.07

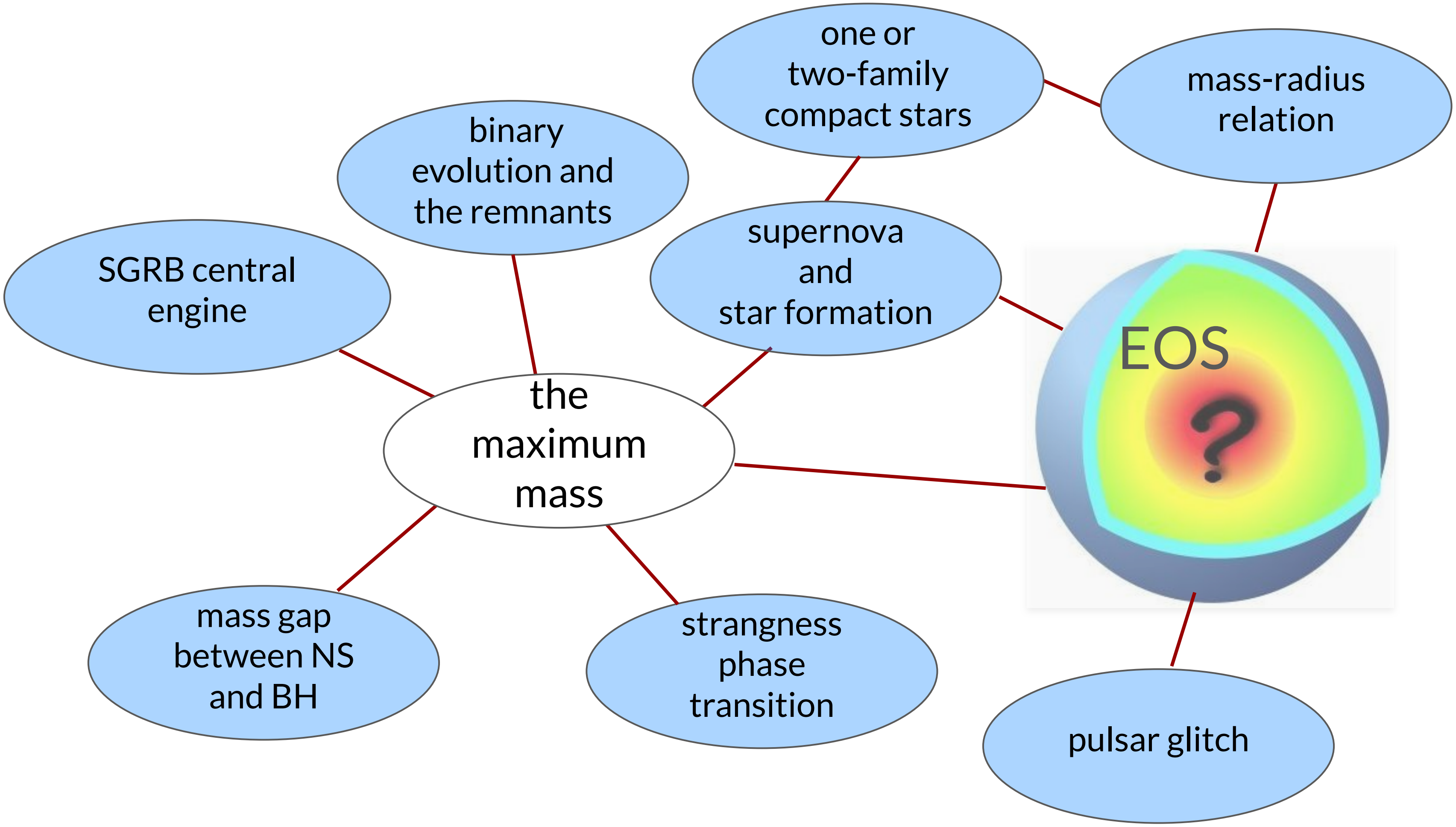
(1σ C.I.)

arXiv:1910.09572

M_{TOV} (EOS) ≥ all measured neutron star masses.



Why is understanding the NS EOS important?



one or two-family compact stars

mass-radius relation

binary evolution and the remnants

SGRB central engine

supernova and star formation

EOS

?

the maximum mass

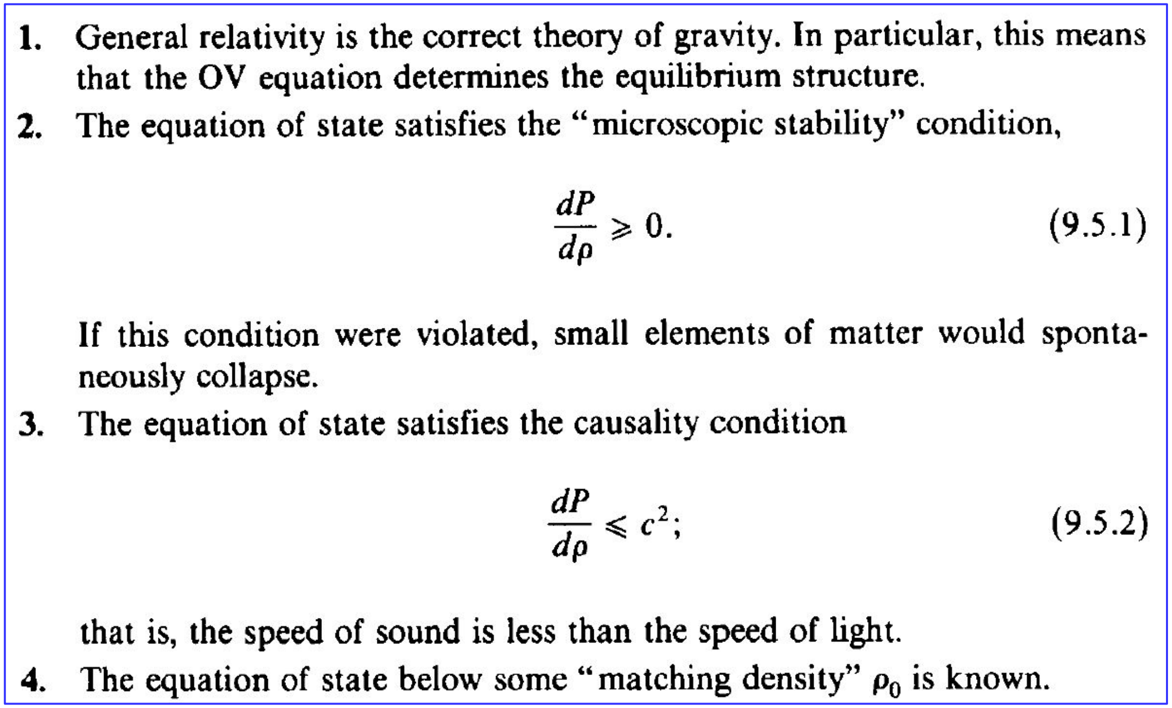
mass gap between NS and BH

strangeness phase transition

pulsar glitch

EOS insensitive constraints on the maximum mass ~3.2$M_\odot$

A general treatment of M_{TOV} was given by Rhoades and Ruffini (1974), under the following set of assumptions:



1. General relativity is the correct theory of gravity. In particular, this means that the OV equation determines the equilibrium structure.
2. The equation of state satisfies the "microscopic stability" condition,

$$\frac{dP}{d\rho} \geqslant 0. \tag{9.5.1}$$

   If this condition were violated, small elements of matter would spontaneously collapse.
3. The equation of state satisfies the causality condition

$$\frac{dP}{d\rho} \leqslant c^2; \tag{9.5.2}$$

   that is, the speed of sound is less than the speed of light.
4. The equation of state below some "matching density" ρ_0 is known.

extreme causal EOS (1974)

the EOS is uncertain above a fiducial density of ϱ_0, the region in which they assumed that the equation of state is the stiffest possible, producing a sound velocity equal to the velocity of light,

$$P = P_0 + (\rho - \rho_0)c^2, \qquad \rho \geqslant \rho_0.$$

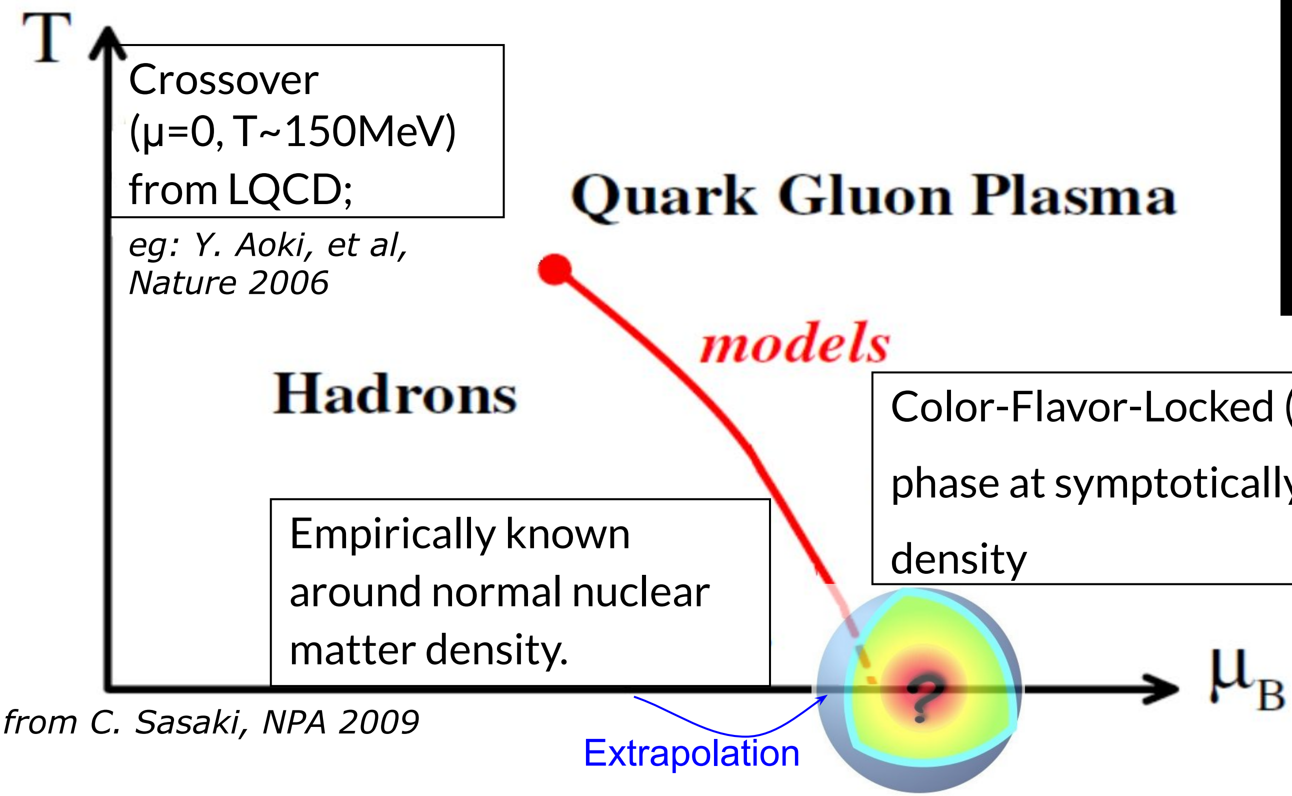
$$\boxed{M_{\max} \simeq 3.2 \left(\frac{\rho_0}{4.6 \times 10^{14} \text{ g cm}^{-3}} \right)^{-1/2} M_\odot}$$

Outline

- Intro. on neutron star (NS) and dense matter equation of state (EOS)
- **NS maximum mass from LIGO/Virgo and NICER with microscopic EOSs**
- Take-home message

Maximum mass exact value is determined by the EOS

- M_{TOV} depends upon the strong interaction part of the EOS, e.g, Oppenheimer & Volko (1939) used an EOS for degenerate Fermi gas, obtaining a maximum mass of only 0.7 $M_{\odot}$;
- The problem is to find the EOS in a regime where laboratory measurements of particle interactions are inadequate and the necessary theories of multi-body interactions are still incomplete.
-



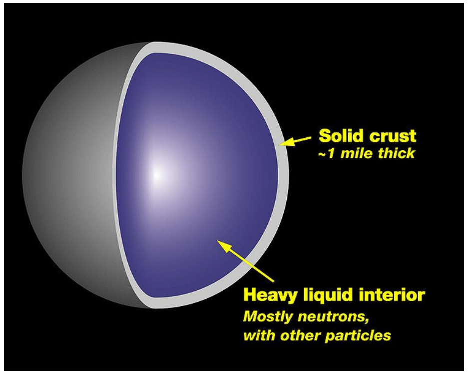
Crossover (μ=0, T~150MeV) from LQCD;

eg: Y. Aoki, et al, Nature 2006

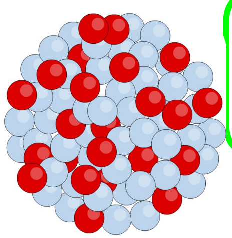
Empirically known around normal nuclear matter density.

Color-Flavor-Locked (CFL) phase at symptotically high density

Fig. from C. Sasaki, NPA 2009



Connecting neutron star observations and nuclear experiment consistently



Finite nuclei experiments

Heavy ion collision experiments

Emperical properties of nuclear matter around normal nuclear density

reproduce

Nuclear many-body theory:

Some EOSs (P(n), Ourput: M_{TOV}, M(R), Λ, etc.)

application

M & R **from NICER**

(PSR J0040, 0740)

Λ **from LVC**

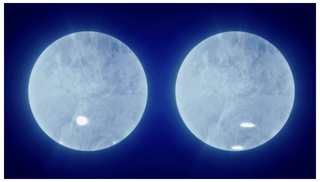
(GW170817, GW190425)

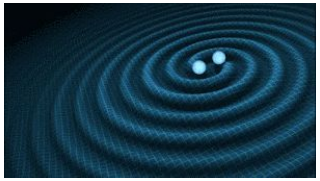
Supernovae

Gamma-Ray Bursts

Neutron stars

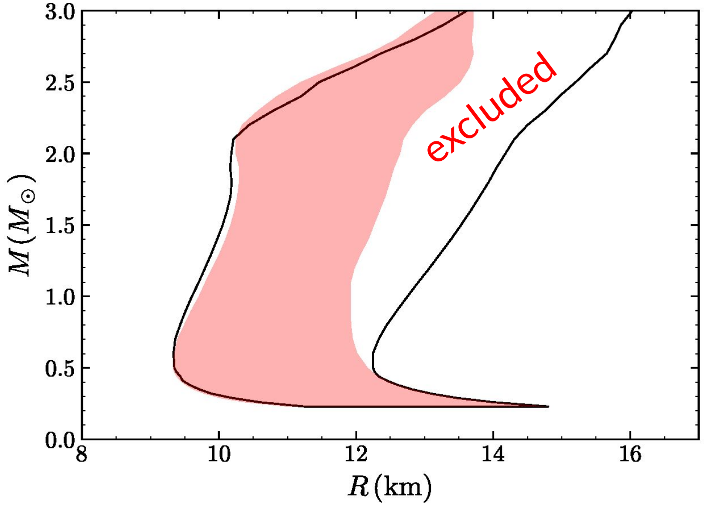
Binary mergers

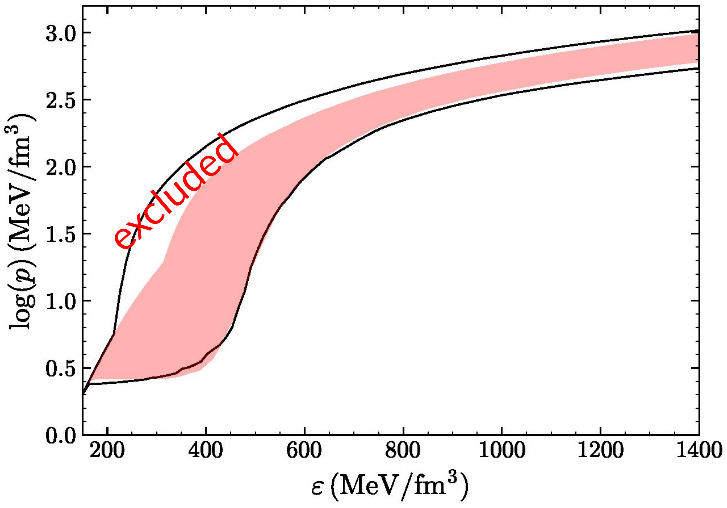




Important EOS constraints: Λ, I measurements

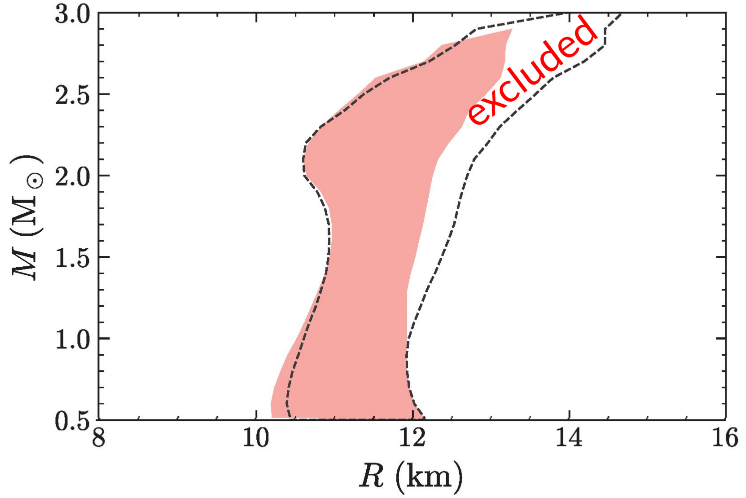
GW170817 Λ measurement

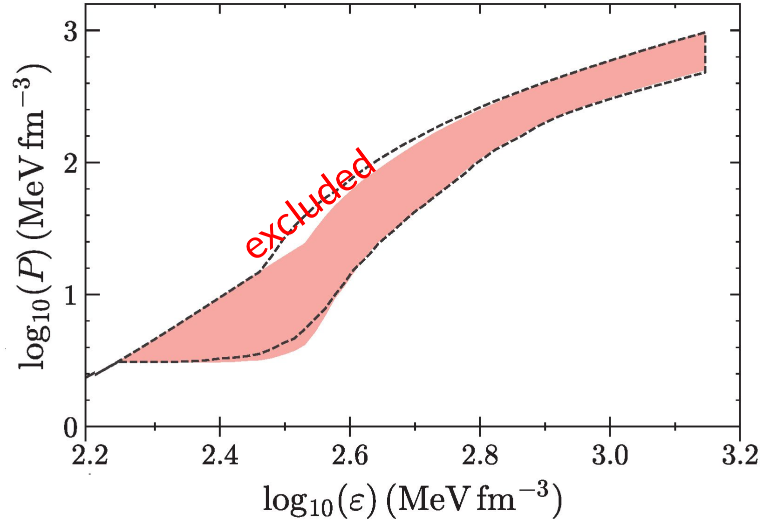




Ska

mocked J0737's I measurement (from e.g., SKA)



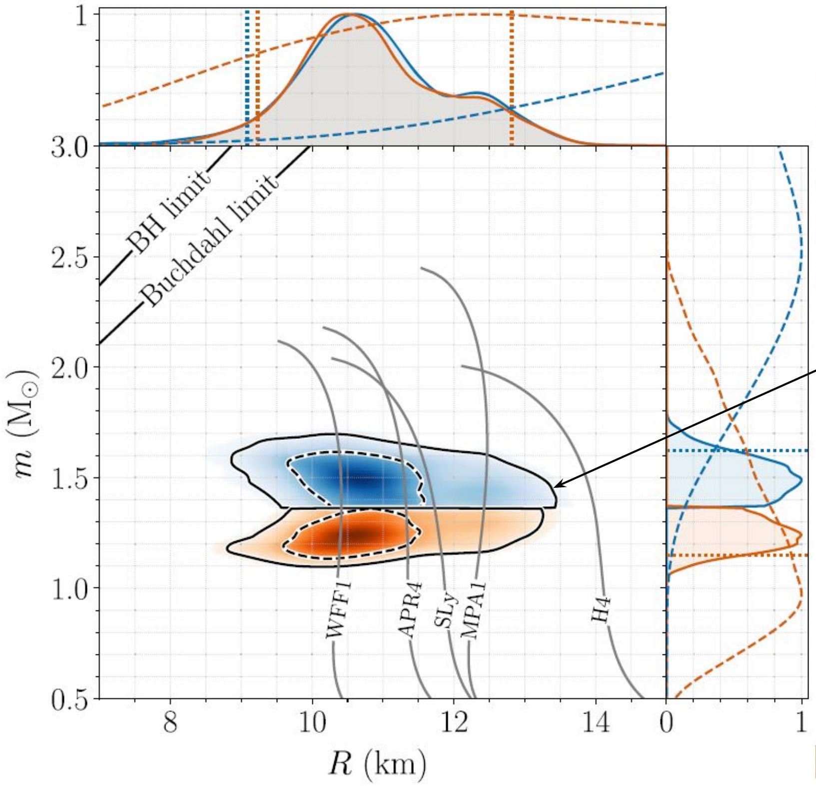


PHYSICAL REVIEW LETTERS **121,** 161101 (2018)

Editors' Suggestion

GW170817: Measurements of Neutron Star Radii and Equation of State

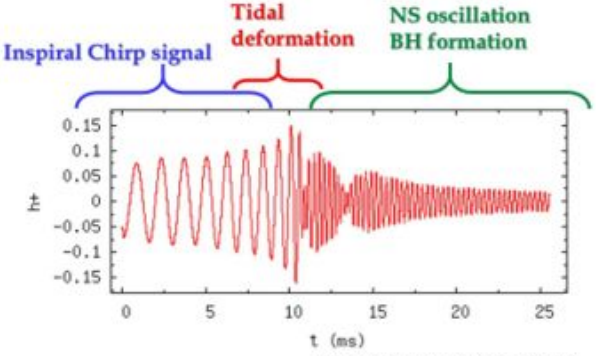
B. P. Abbott *et al.*[*]
(The LIGO Scientific Collaboration and the Virgo Collaboration)



$(1.36, 1.60)\ M_\odot$
$(1.16, 1.36)\ M_\odot$

Our results are comparable and consistent with studies that use the tidal measurement from [5] to obtain bounds on NS radii. Using our bound of $\Lambda_{1.4} < 800$ (the only tidal parameter in [5], which assumed a common EOS for both NSs) and different EOS parametrizations, several studies found $R_{1.4} \lesssim 13.5$ km [56,58,62,64].

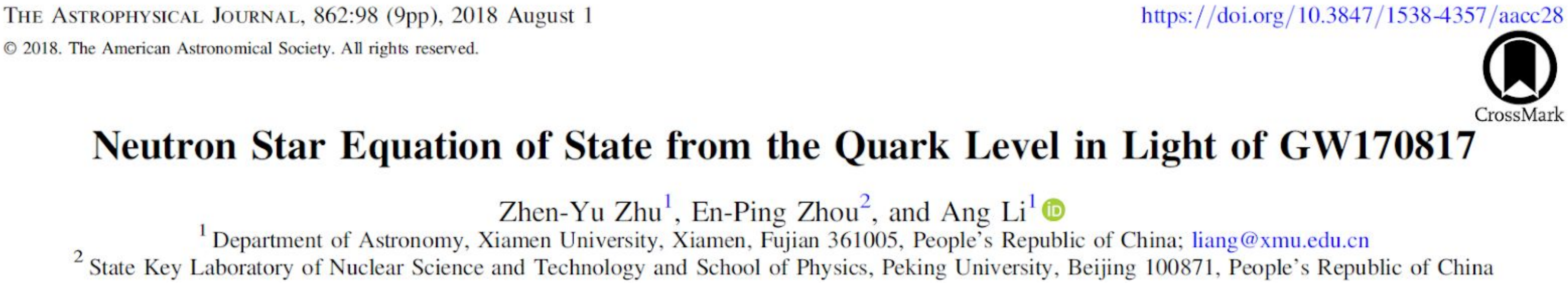
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$



First suggested by Shibata (2005)

[56] E.-P. Zhou, X. Zhou, and A. Li, Phys. Rev. D **97**, 083015 (2018).

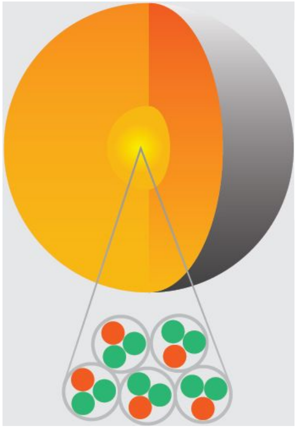
Exemplary quark mean-field (QMF) NS EOS in the light of GW170817



The Astrophysical Journal, 862:98 (9pp), 2018 August 1
https://doi.org/10.3847/1538-4357/aacc28

Neutron Star Equation of State from the Quark Level in Light of GW170817

Zhen-Yu Zhu[1], En-Ping Zhou[2], and Ang Li[1]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn
[2] State Key Laboratory of Nuclear Science and Technology and School of Physics, Peking University, Beijing 100871, People's Republic of China



$$\mathcal{L} = \overline{\psi}\left(i\gamma_\mu\partial^\mu - M_N^* - g_{\omega N}\omega\gamma^0 - g_{\rho N}\rho\tau_3\gamma^0\right)\psi$$

$$-\frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4$$

$$+\frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2 + \frac{1}{2}(\nabla\omega)^2 + \frac{1}{2}m_\omega^2\omega^2$$

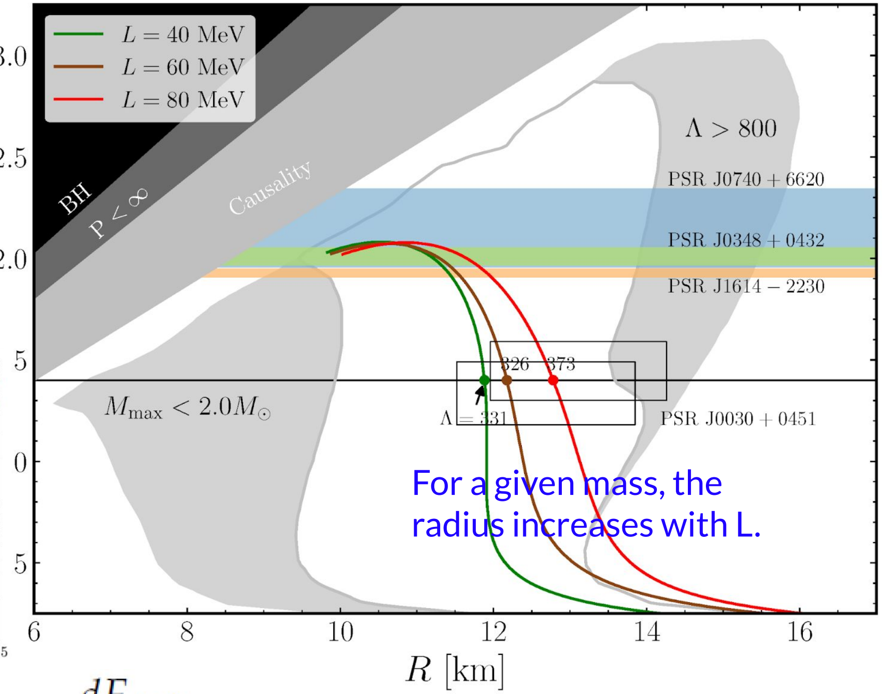
$$+\frac{1}{2}g_{\rho N}^2\rho^2\Lambda_v g_{\omega N}^2\omega^2$$

$$[\gamma^0(\epsilon_q - g_{\omega q}\omega - \tau_{3q}g_{\rho q}\rho)$$

$$-\vec{\gamma}\cdot\vec{p} - (m_q - g_{\sigma q}\sigma)$$

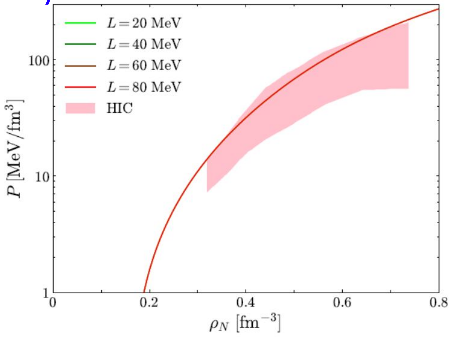
$$-U(r)]\psi_q(\vec{r}) = 0$$

Microscopic NS EOS from the quark level, connecting consistently nuclear experiments and GW+EM observations.

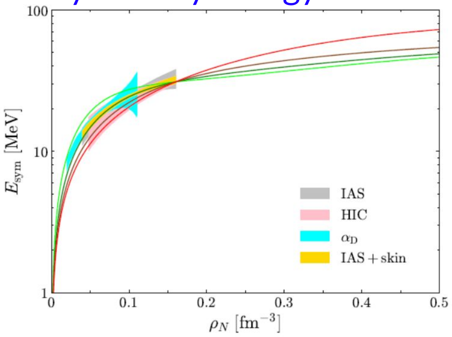


For a given mass, the radius increases with L.

symmetric nuclear matter EOS



symmetry energy



$$E(\rho,\delta) = E_{\rm SNM}(\rho) + E_{\rm sym}(\rho)\delta^2\,,\; L \equiv 3\rho_0\frac{dE_{\rm sym}}{d\rho}(\rho_0)$$

Many nuclear many-body models can be employed

Green’s Function Monte Carlo

Chiral Perturbation Theory (ChPT)

Variational Many-Body (VMB; e.g., APR)

$V_{\text{low}k}$ + Renormalization Group

Brueckner-Hartree-Fock (BHF)

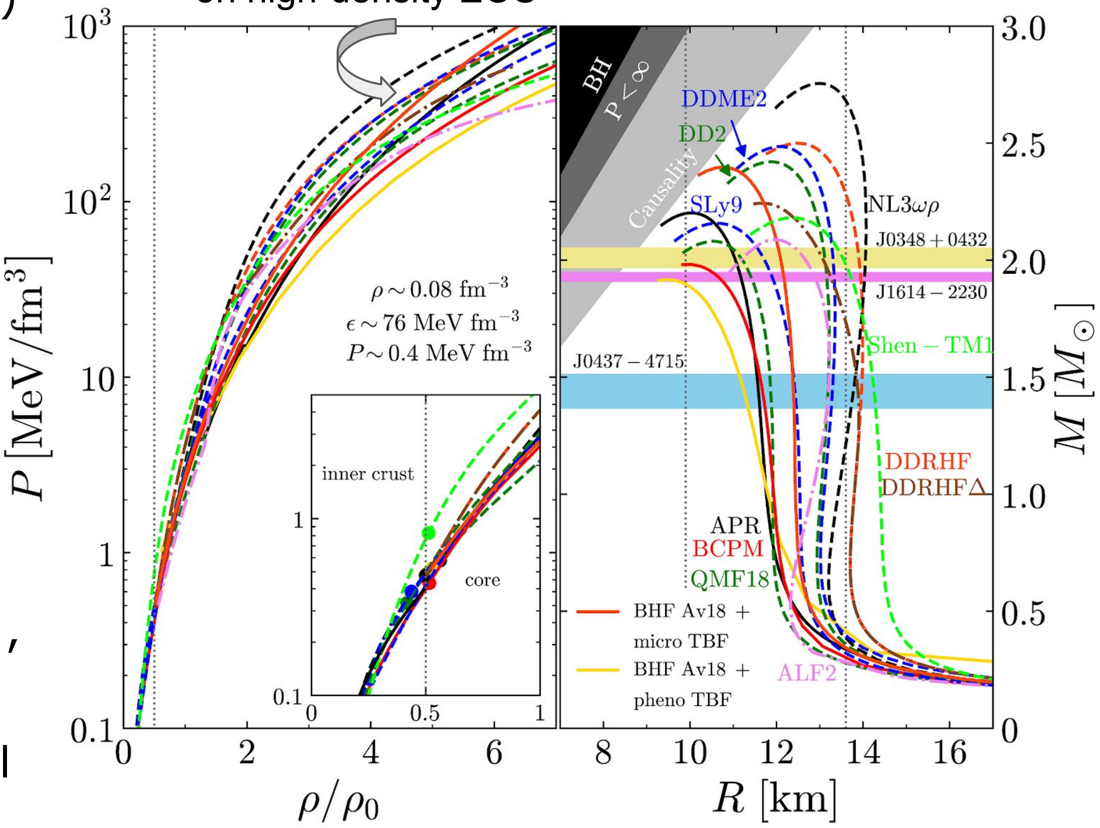
Dirac-Brueckner-Hartree-Fock (DBHF)

Quark mean-field (QMF)

Quark Meson Coupling (QMC)

Relativistic mean-field (RMF; e.g., DD2, NL3, TM1)

Skyrme energy density functional (e.g., BSk20, Sly)...



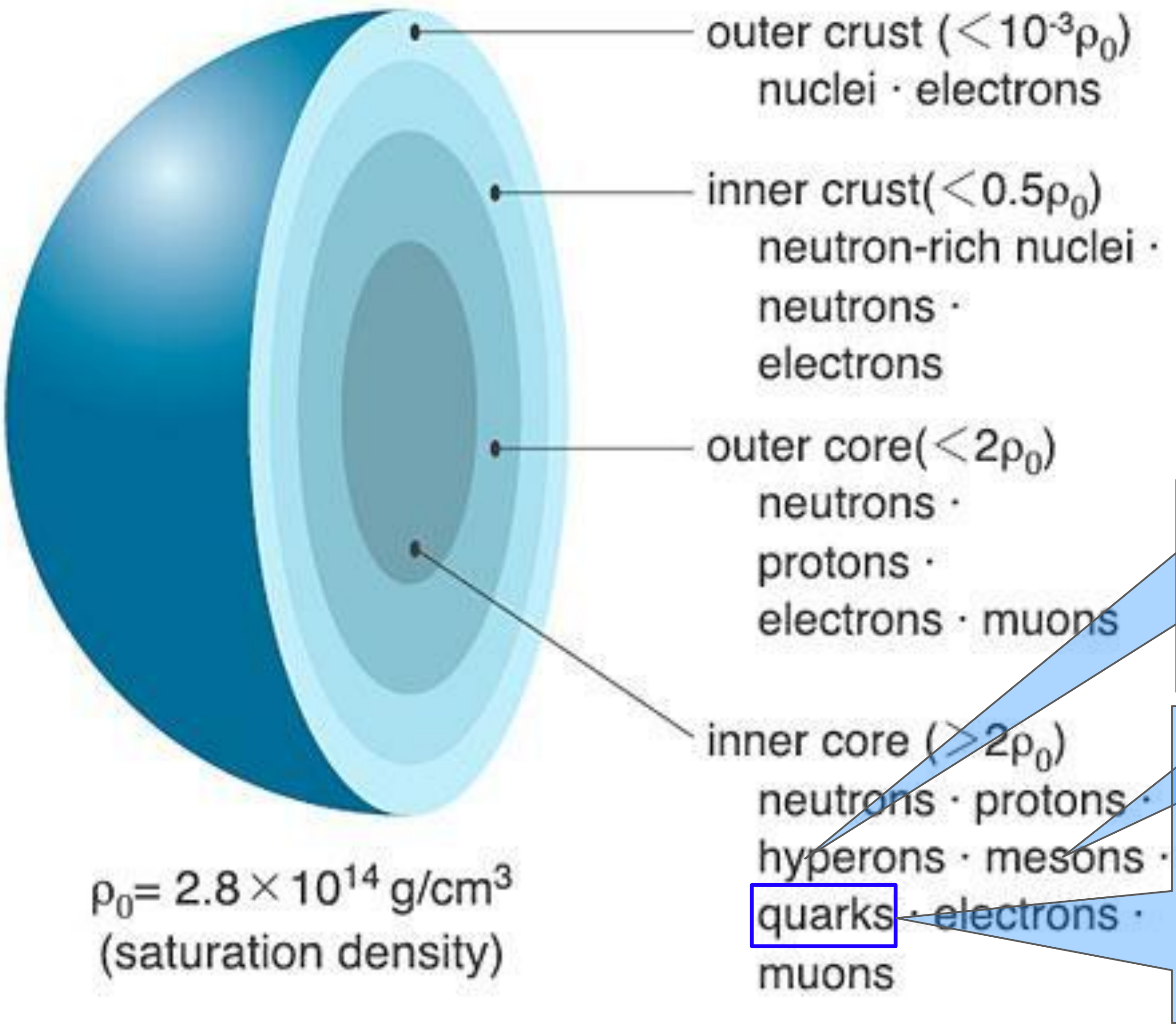
a fan of different prediction on high-density EOS

《致密物质状态方程：中子星与奇异星》李昂等，2019 原子核物理评论

http://www.npr.ac.cn/article/doi/10.11804/NuclPhysRev.36.01.001

Hyperon puzzle; hyperon/kaon/quark competition

《Neutron star equation of state: Modeling and applications》
Ang Li et al. 2020 Journal of High Energy Astrophysics 2007.05116

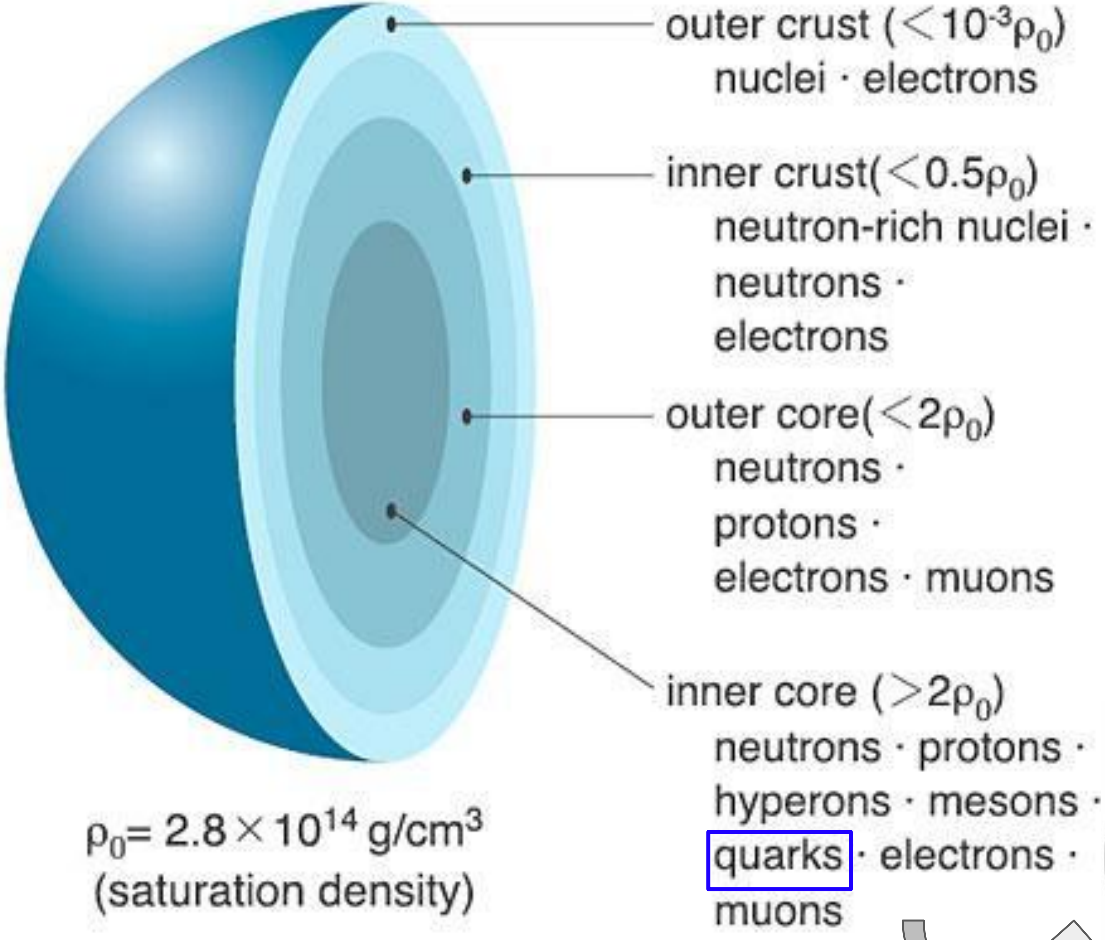


~~should appear, but unlikey due to hyperon puzzle (**Li** et al. 2007; Burgio, Schuzle, **Li** 2011);~~

~~high throeshold; likely not relevant to compact stars (**Li** et al. 2006, 2010);~~

√ should appear early; hinder other strangeness; massive stars still possible (**Li** et al. 2015; Miao, **Li** et al. 2020);

Phase transition and hybrid stars



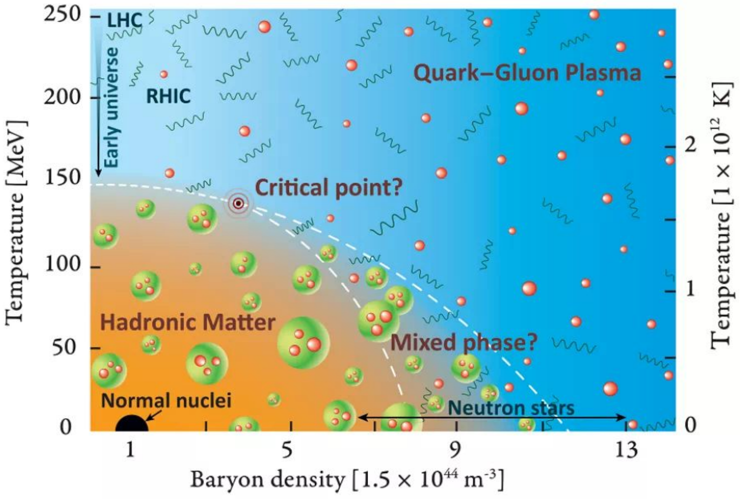
outer crust ($<10^{-3}\rho_0$)
nuclei · electrons

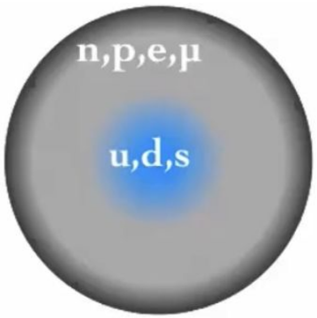
inner crust($<0.5\rho_0$)
neutron-rich nuclei ·
neutrons ·
electrons

outer core($<2\rho_0$)
neutrons ·
protons ·
electrons · muons

inner core ($>2\rho_0$)
neutrons · protons ·
hyperons · mesons ·
quarks · electrons ·
muons

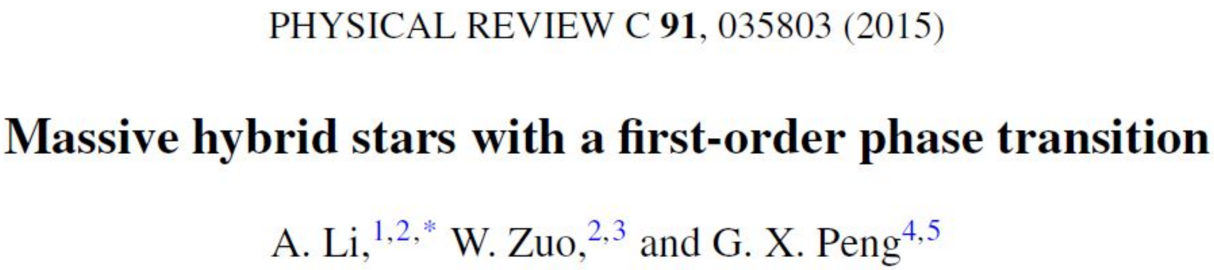
$\rho_0 = 2.8\times10^{14}$ g/cm^3
(saturation density)





Assuming 1st-order hadron-quark phase transition: Most promising scenario to be tested or distinguished from pure hadronic matter by future observations.

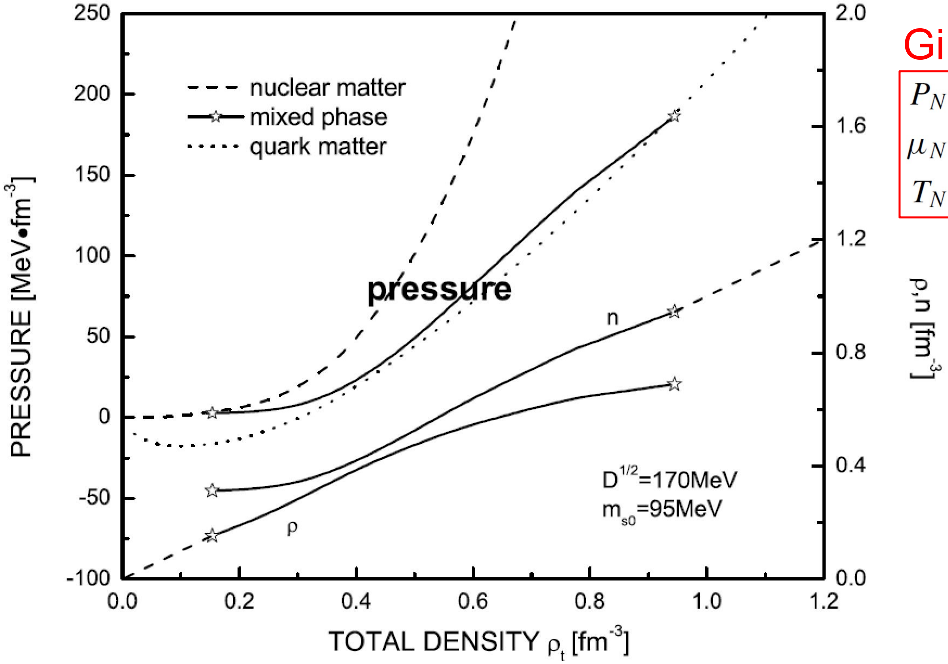
Massive stars could be hybrid stars with a stiff quark-matter core

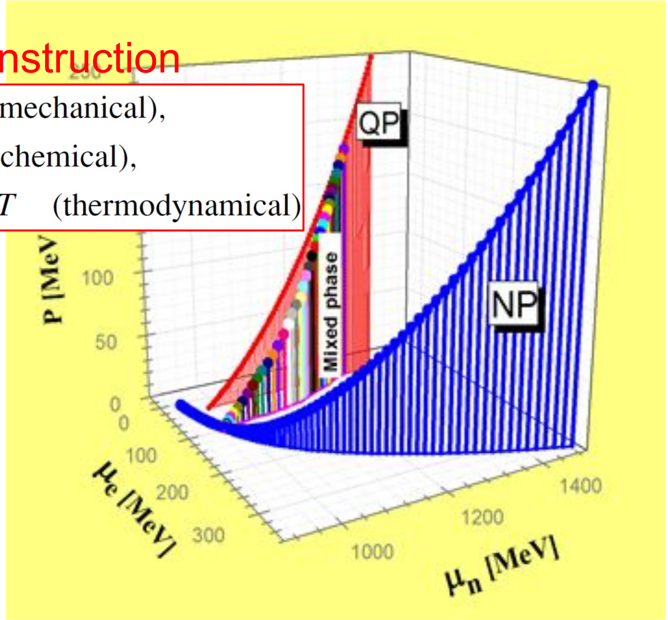


PHYSICAL REVIEW C **91**, 035803 (2015)

Massive hybrid stars with a first-order phase transition

A. Li,[1,2,*] W. Zuo,[2,3] and G. X. Peng[4,5]





Gibbs construction

$$P_N = P_q \quad \text{(mechanical)},$$
$$\mu_N = \mu_q \quad \text{(chemical)},$$
$$T_N = T_q \equiv T \quad \text{(thermodynamical)}$$

Many models of quark matter do exist, but they all contain a high degree of uncertainty; Here CDDM used;

->To constrain M_{max} (EOS) and **quark deconfinement phase transition** paramters from current observations, also to stimulate new oriented observations.

The Astrophysical Journal, 904:103 (12pp), 2020 December 1 https://doi.org/10.3847/1538-4357/abbd41

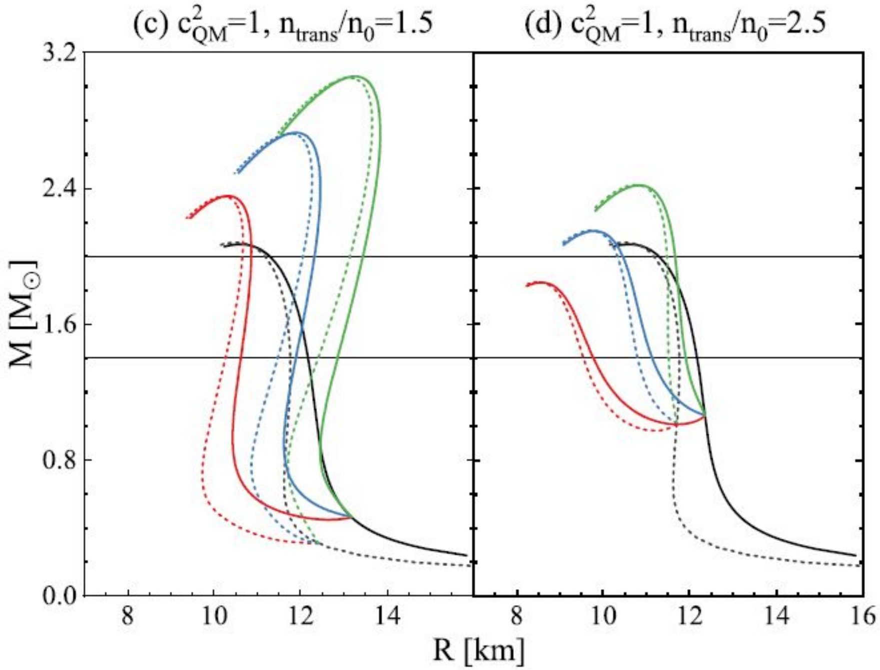
Constraining Hadron-quark Phase Transition Parameters within the Quark-mean-field Model Using Multimessenger Observations of Neutron Stars

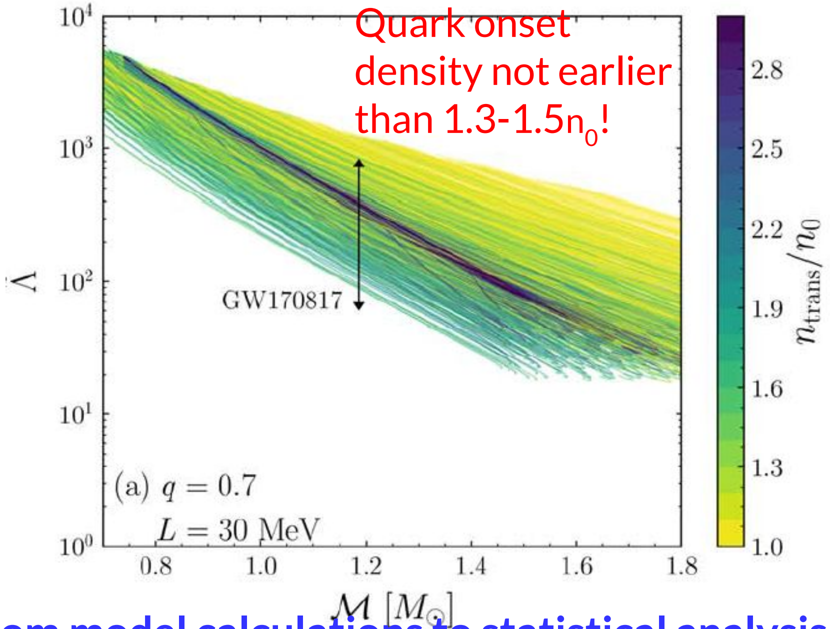
Zhiqiang Miao[1], Ang Li[1,5], Zhenyu Zhu[1,2], and Sophia Han[3,4]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn
[2] Institute for Theoretical Physics, D-60438 Frankfurt am Main, Germany
[3] Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA
[4] Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA

QMF hadronic EOS plus CSS (n_{trans}, $\Delta\varepsilon$, c_{QM}) characterize the high-density (quark matter) phase:

$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm HM}(p), & p < p_{\rm trans} \\ \varepsilon_{\rm HM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}), & p > p_{\rm trans} \end{cases}$$

Constant-speed-of-sound (CSS) scheme is a general parametrization suitable for expressing experimental constraints in a model-independent way.





Quark onset density not earlier than 1.3-1.5n_0!

from model calculations to statistical analysis->

Bayesian inference of the NS EOS parameter space from LIGO/Virgo and NICER

- Assuming the sources are NSs;
- Considering quark deconfinement phase transition in the EOS prior;
- Limiting EOS by the lower bound on M_{TOV} from heaviest MSP J0740+6620.

The Bayes's theorem

$$p(\boldsymbol{\theta}\,|\,\boldsymbol{d},\mathbb{M}) = \frac{p(\boldsymbol{\theta}\,|\,\mathbb{M})p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M})}{p(\boldsymbol{d}\,|\,\mathbb{M})} \propto p(\boldsymbol{\theta}\,|\,\mathbb{M})p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M})$$

full parameter space rom 1/sqrt(3) (the conformal limit in perturbative QCD matter) to 1 (the causal limit)

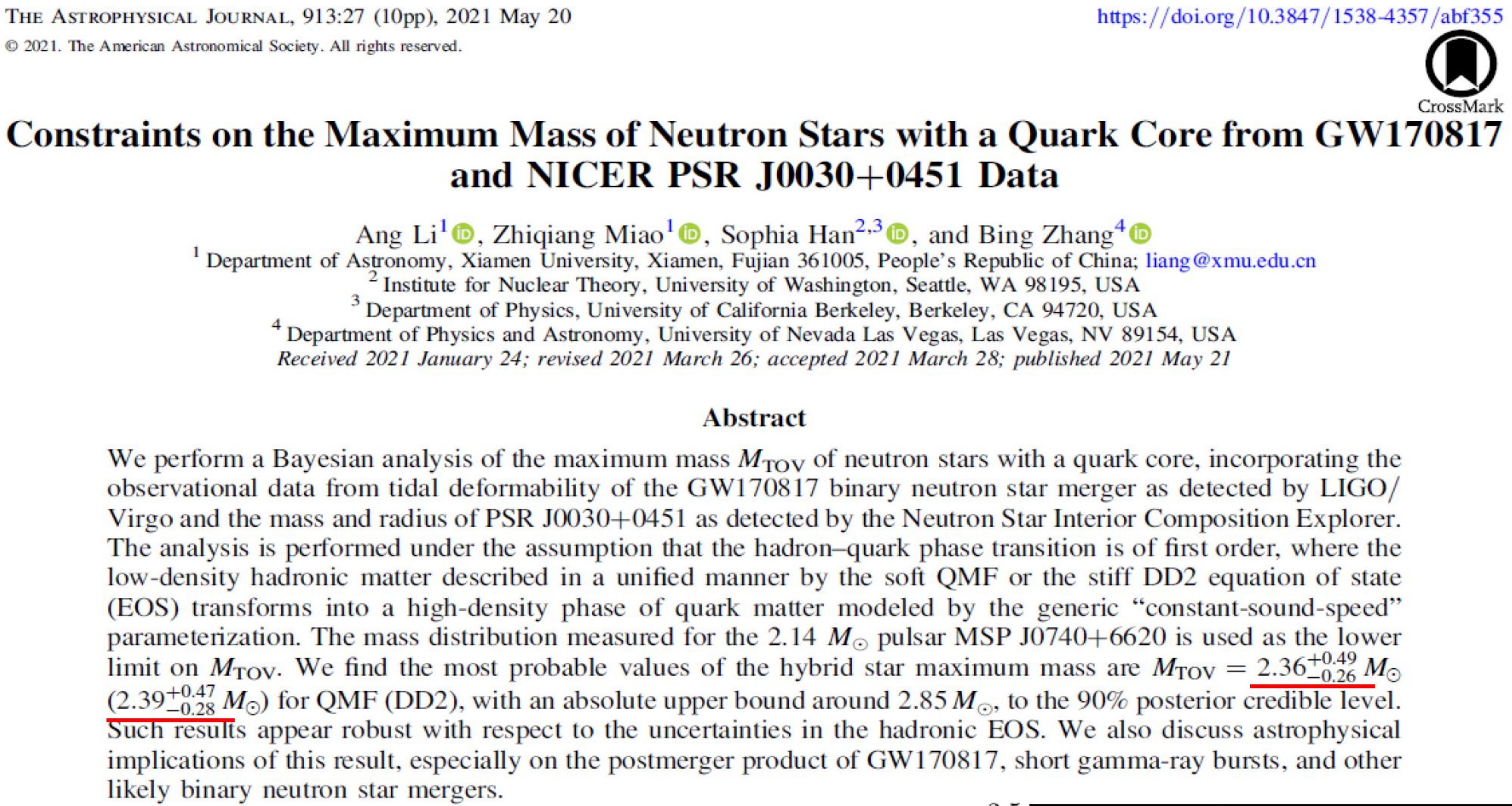
$\mathbb{M}$: The QMF+CSS/DD2+CSS model

$\boldsymbol{\theta}$: parameters, including EOS parameters $\boldsymbol{\theta}_{\rm EOS} = \{n_{\rm trans}/n_0, \Delta\varepsilon/\varepsilon_{\rm trans}, c^2_{\rm QM}\}$ and $\boldsymbol{\theta}_{\rm GW}$

$\boldsymbol{d}$: observational data, including three measurements: the mass of MSP J0740+6620, the tidal deformability from GW170817 and mass-radius of PSR J0030+0451

$p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M})$: likelihood, which can be expressed as $p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M}) = \mathscr{L}_{M_s} \times \mathscr{L}_{\rm GW} \times \mathscr{L}_{\rm PSR}$

$p(\boldsymbol{\theta}\,|\,\mathbb{M})$: prior for the parameters


The Astrophysical Journal, 913:27 (10pp), 2021 May 20
https://doi.org/10.3847/1538-4357/abf355

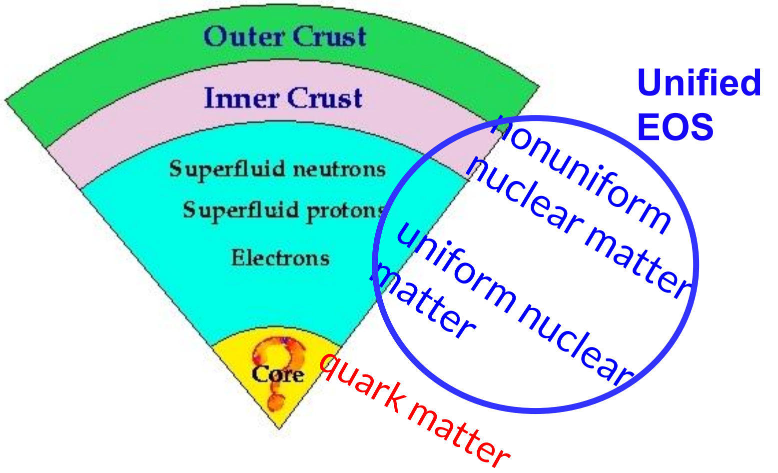
Constraints on the Maximum Mass of Neutron Stars with a Quark Core from GW170817 and NICER PSR J0030+0451 Data

Ang Li[1], Zhiqiang Miao[1], Sophia Han[2,3], and Bing Zhang[4]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn
[2] Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA
[3] Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA
[4] Department of Physics and Astronomy, University of Nevada Las Vegas, Las Vegas, NV 89154, USA

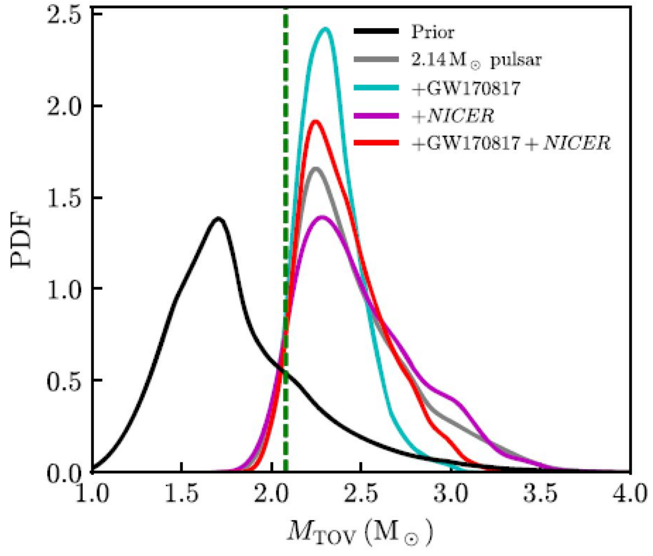
Received 2021 January 24; revised 2021 March 26; accepted 2021 March 28; published 2021 May 21

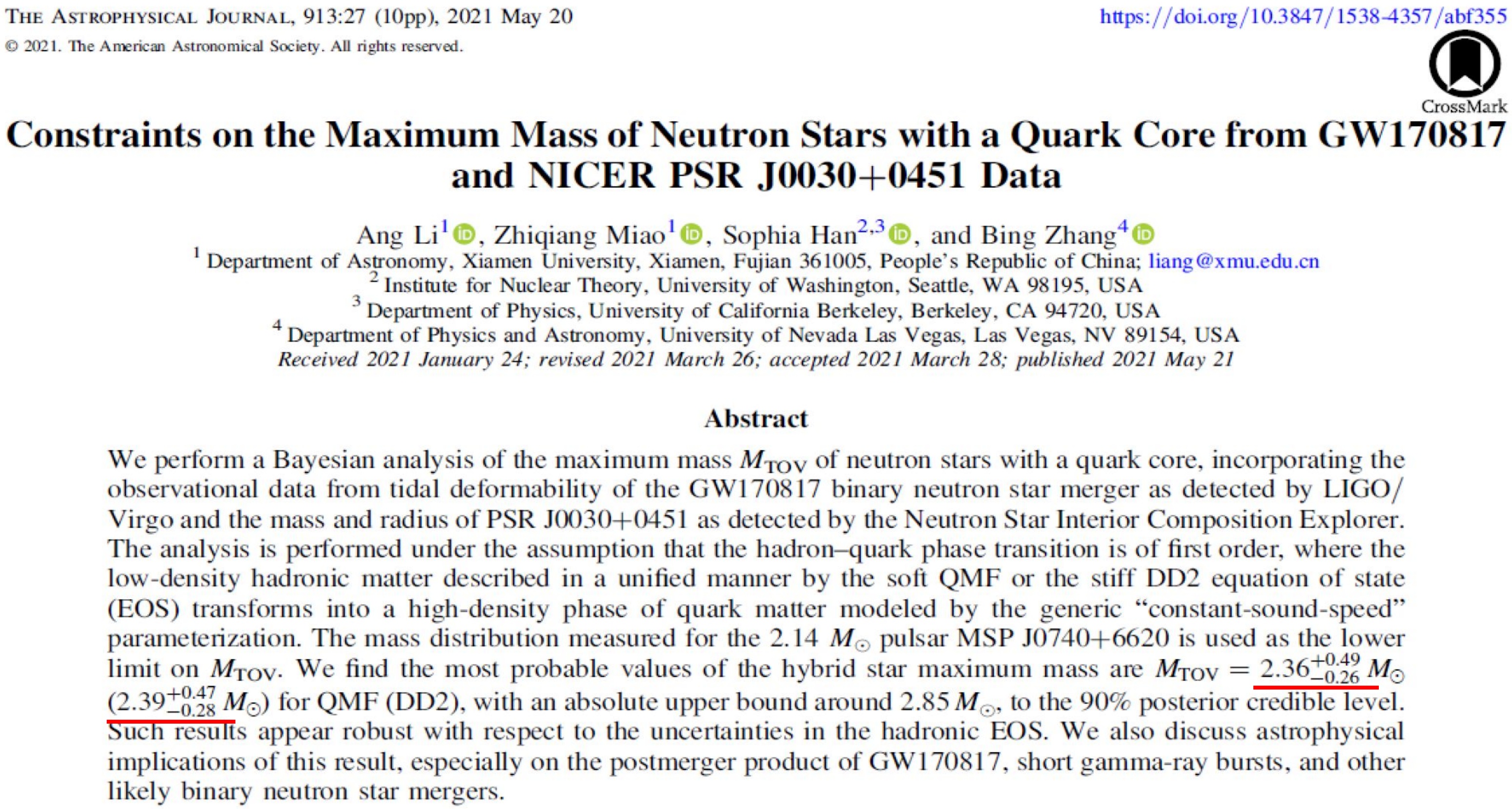
Abstract

We perform a Bayesian analysis of the maximum mass $M_{\rm TOV}$ of neutron stars with a quark core, incorporating the observational data from tidal deformability of the GW170817 binary neutron star merger as detected by LIGO/Virgo and the mass and radius of PSR J0030+0451 as detected by the Neutron Star Interior Composition Explorer. The analysis is performed under the assumption that the hadron–quark phase transition is of first order, where the low-density hadronic matter described in a unified manner by the soft QMF or the stiff DD2 equation of state (EOS) transforms into a high-density phase of quark matter modeled by the generic "constant-sound-speed" parameterization. The mass distribution measured for the 2.14 $M_\odot$ pulsar MSP J0740+6620 is used as the lower limit on $M_{\rm TOV}$. We find the most probable values of the hybrid star maximum mass are $M_{\rm TOV} = 2.36^{+0.49}_{-0.26}\,M_\odot$ ($2.39^{+0.47}_{-0.28}\,M_\odot$) for QMF (DD2), with an absolute upper bound around 2.85 $M_\odot$, to the 90% posterior credible level. Such results appear robust with respect to the uncertainties in the hadronic EOS. We also discuss astrophysical implications of this result, especially on the postmerger product of GW170817, short gamma-ray bursts, and other likely binary neutron star mergers.



Unified EOS





The Astrophysical Journal, 913:27 (10pp), 2021 May 20 https://doi.org/10.3847/1538-4357/abf355

Constraints on the Maximum Mass of Neutron Stars with a Quark Core from GW170817 and NICER PSR J0030+0451 Data

Ang Li[1], Zhiqiang Miao[1], Sophia Han[2,3], and Bing Zhang[4]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn
[2] Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA
[3] Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA
[4] Department of Physics and Astronomy, University of Nevada Las Vegas, Las Vegas, NV 89154, USA

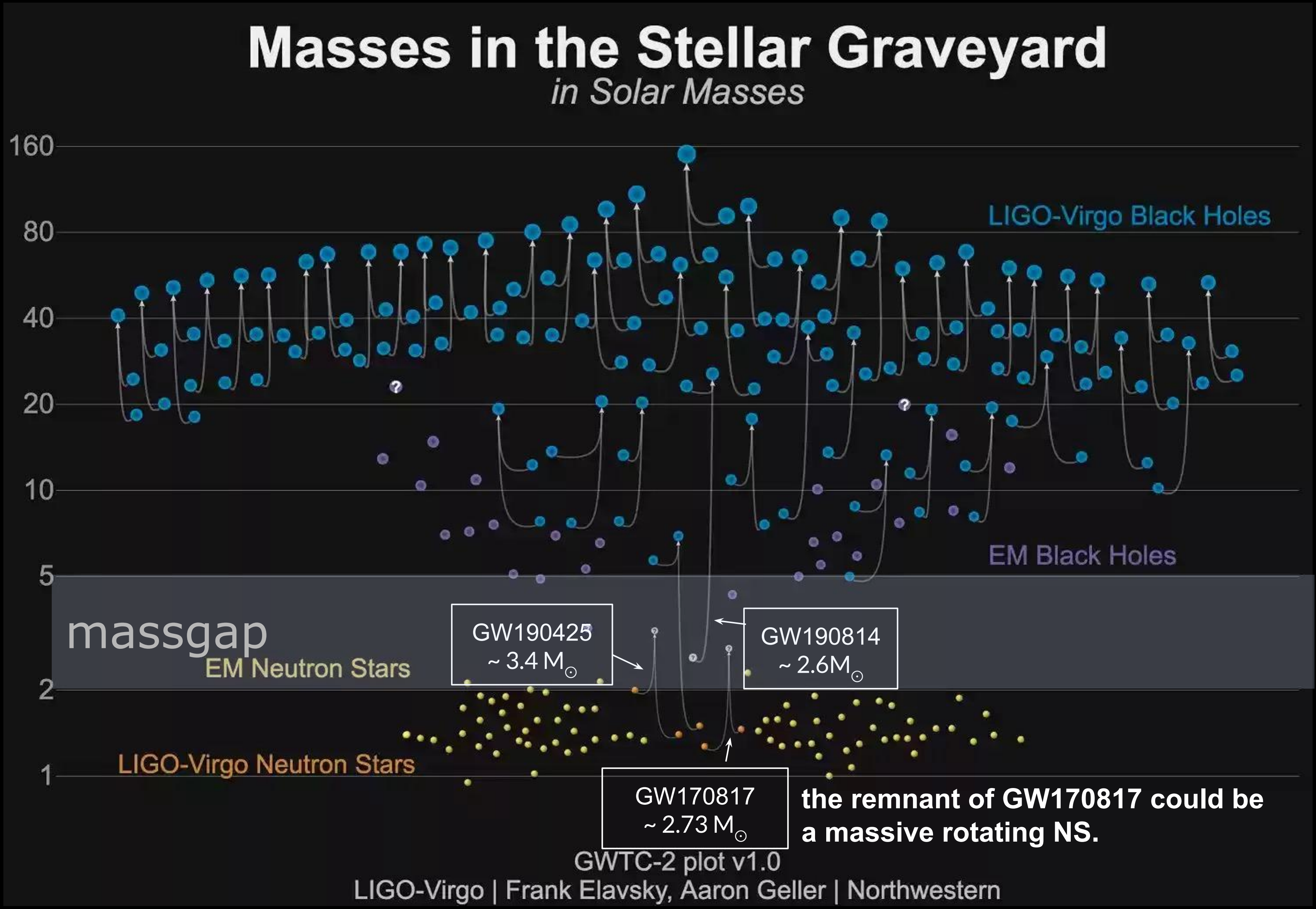
Received 2021 January 24; revised 2021 March 26; accepted 2021 March 28; published 2021 May 21

Abstract

We perform a Bayesian analysis of the maximum mass $M_{\rm TOV}$ of neutron stars with a quark core, incorporating the observational data from tidal deformability of the GW170817 binary neutron star merger as detected by LIGO/Virgo and the mass and radius of PSR J0030+0451 as detected by the Neutron Star Interior Composition Explorer. The analysis is performed under the assumption that the hadron–quark phase transition is of first order, where the low-density hadronic matter described in a unified manner by the soft QMF or the stiff DD2 equation of state (EOS) transforms into a high-density phase of quark matter modeled by the generic "constant-sound-speed" parameterization. The mass distribution measured for the 2.14 $M_\odot$ pulsar MSP J0740+6620 is used as the lower limit on $M_{\rm TOV}$. We find the most probable values of the hybrid star maximum mass are $M_{\rm TOV} = \underline{2.36^{+0.49}_{-0.26}}\, M_\odot$ $\underline{(2.39^{+0.47}_{-0.28}}\, M_\odot)$ for QMF (DD2), with an absolute upper bound around 2.85 $M_\odot$, to the 90% posterior credible level. Such results appear robust with respect to the uncertainties in the hadronic EOS. We also discuss astrophysical implications of this result, especially on the postmerger product of GW170817, short gamma-ray bursts, and other likely binary neutron star mergers.

- The general requirements adopted here (e.g., causality) should also apply to any alternative hadron–quark phase transition scenarios or other types of strangeness phase transitions ;
- Our conclusions are valid and useful for identifying compact objects' nature with their mass falling into the possible mass gap.

NS maximum mass~2.4$M_\odot$: Help to identify the nature of compact objects with the mass falling into the NS-BH gap



massgap

GW190425
~ 3.4 $M_\odot$

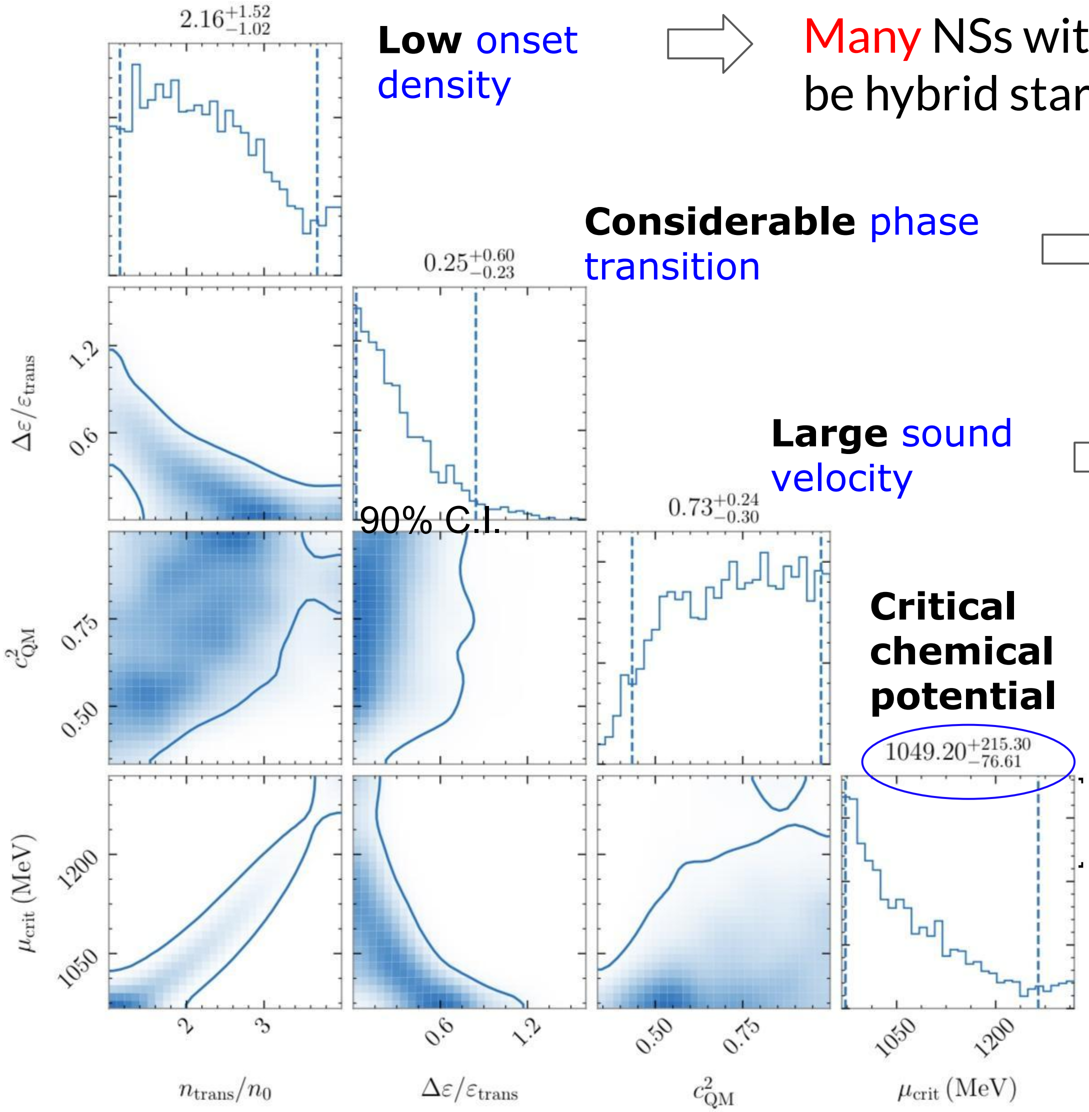
GW190814
~ 2.6$M_\odot$

GW170817
~ 2.73 $M_\odot$

the remnant of GW170817 could be a massive rotating NS.

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

general results on the hadron-quark phase transition described by the CSS parametrization



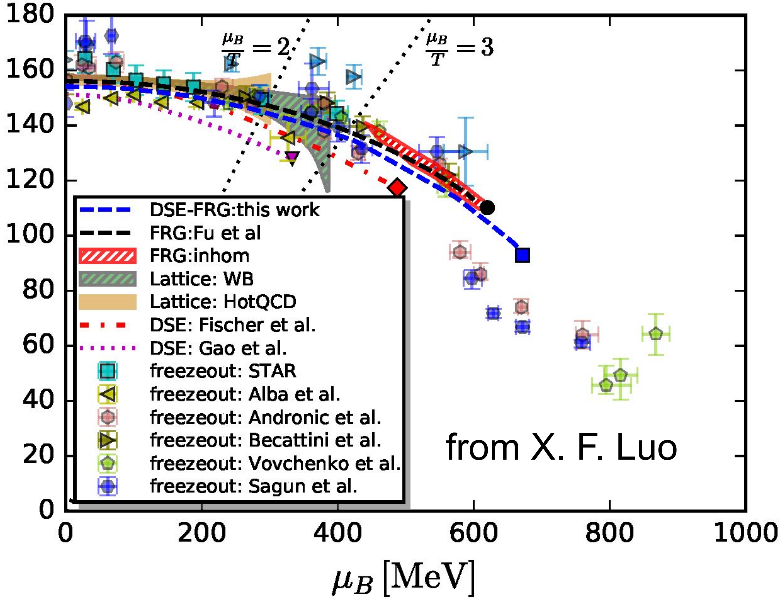
90% C.I.

Low onset density → Many NSs with mass above ~1.4$M_\odot$ should be hybrid stars!

Considerable phase transition → Subseqnet support on the critical point

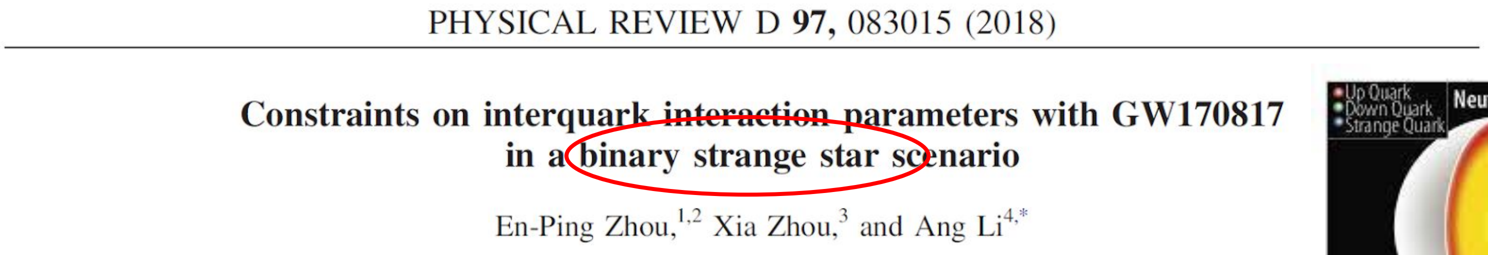
Large sound velocity → Large NS mass needs large sound speed!

Critical chemical potential



from X. F. Luo

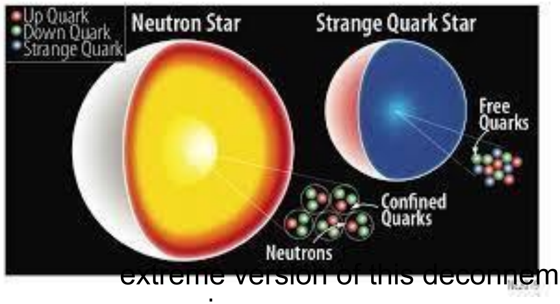
GW170817's tidal deformability are compatible with a binary–quark-star merger!



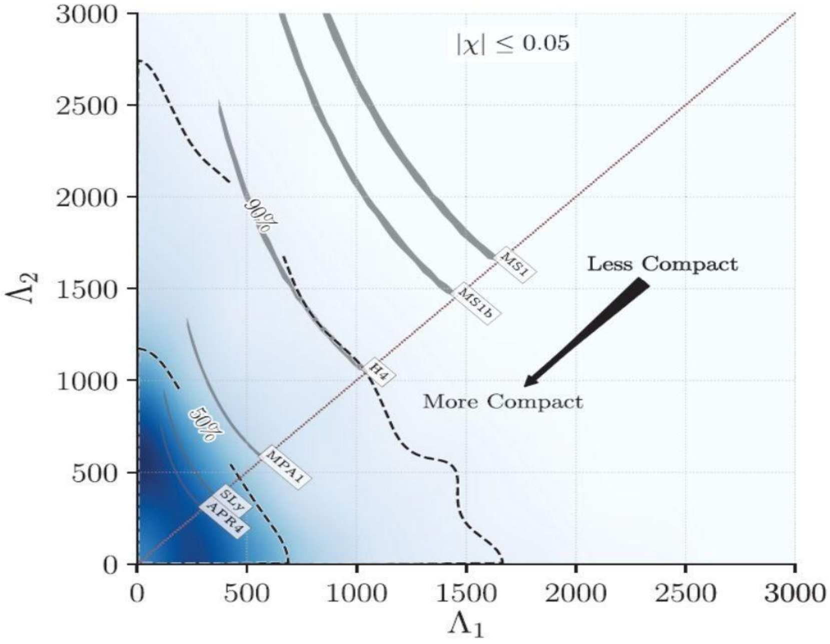
PHYSICAL REVIEW D **97,** 083015 (2018)

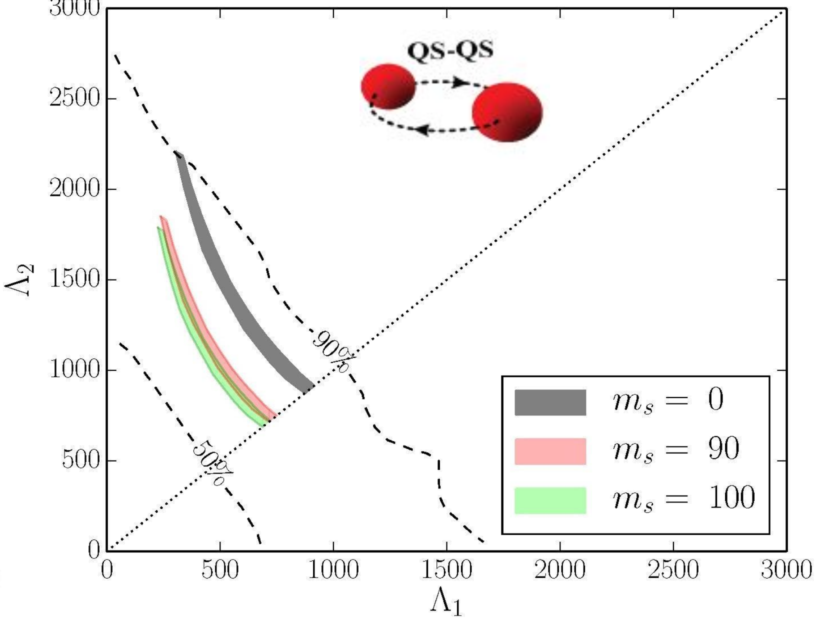
Constraints on interquark interaction parameters with GW170817 in a binary strange star scenario

En-Ping Zhou,[1,2] Xia Zhou,[3] and Ang Li[4,*]

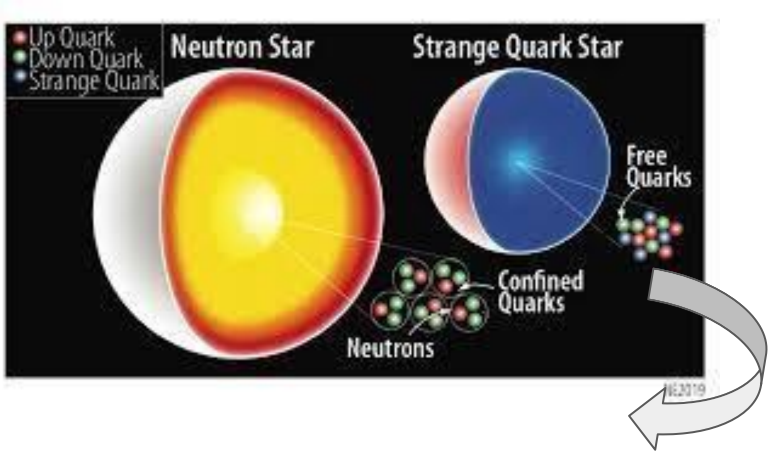


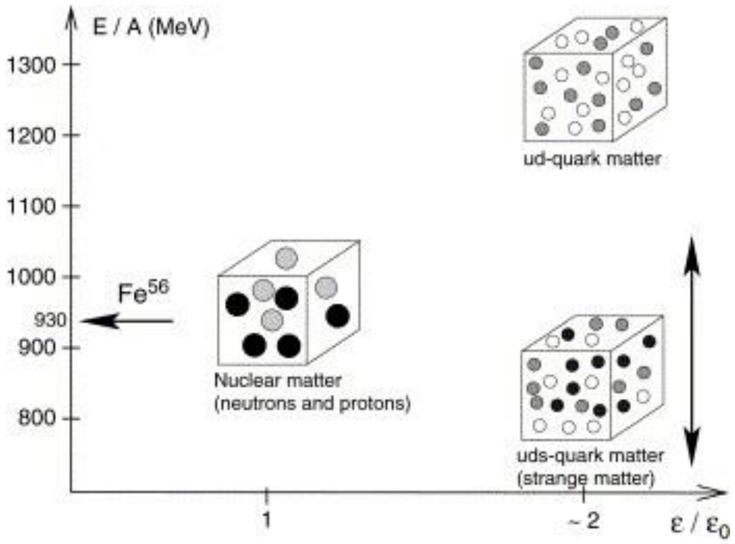
extreme version of this deconfinemen
scenario





One or two-family scenario for compact stars



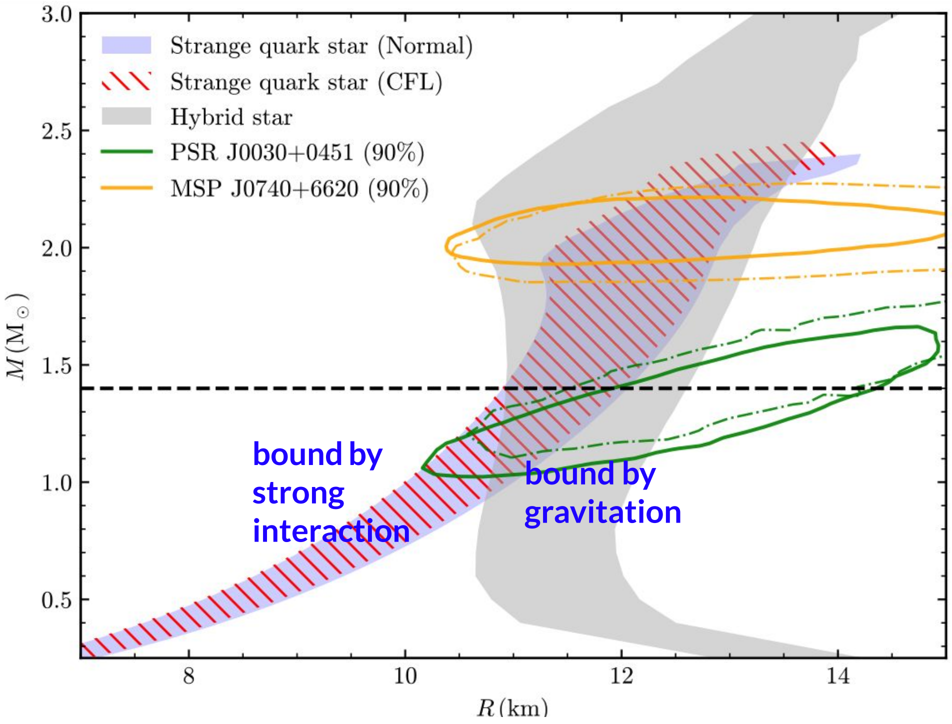


Strange quark matter being the true ground state of matter?

—Bodmer-Witten conjecture

Bodmer 1971; Witten 1984

NS+QS two-families scenario or NS/QS one famlily scenario?



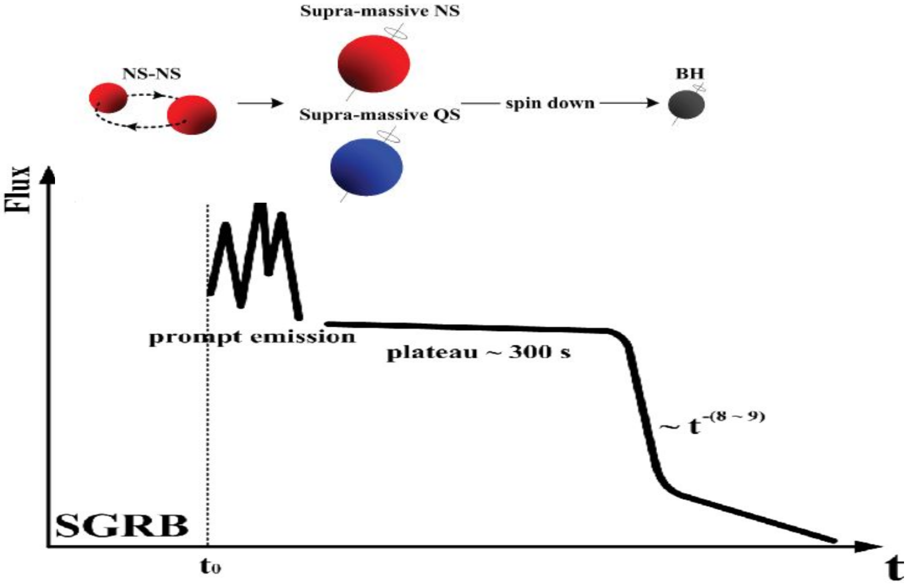
bound by strong interaction

bound by gravitation

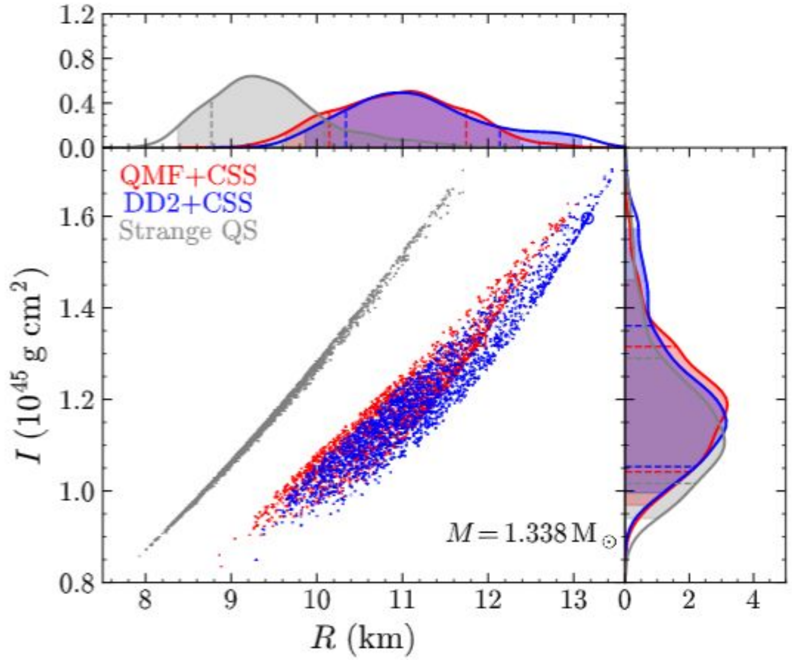
How to distinguish?

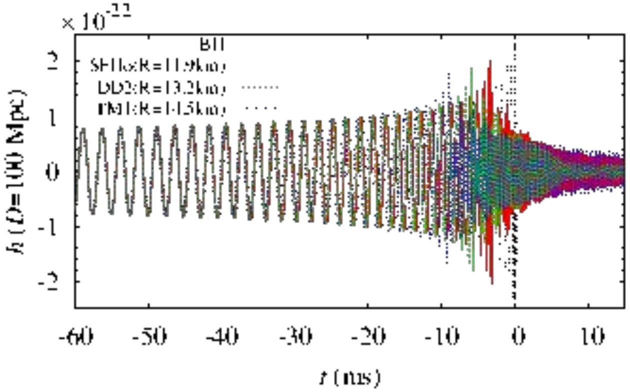
How to distinguish?

combined analysis of SGRBs and kilonovae events (Li et al. 2016, 2017);



<~1km accuracy radius (+MoI) measurement (Miao & Li 2021);



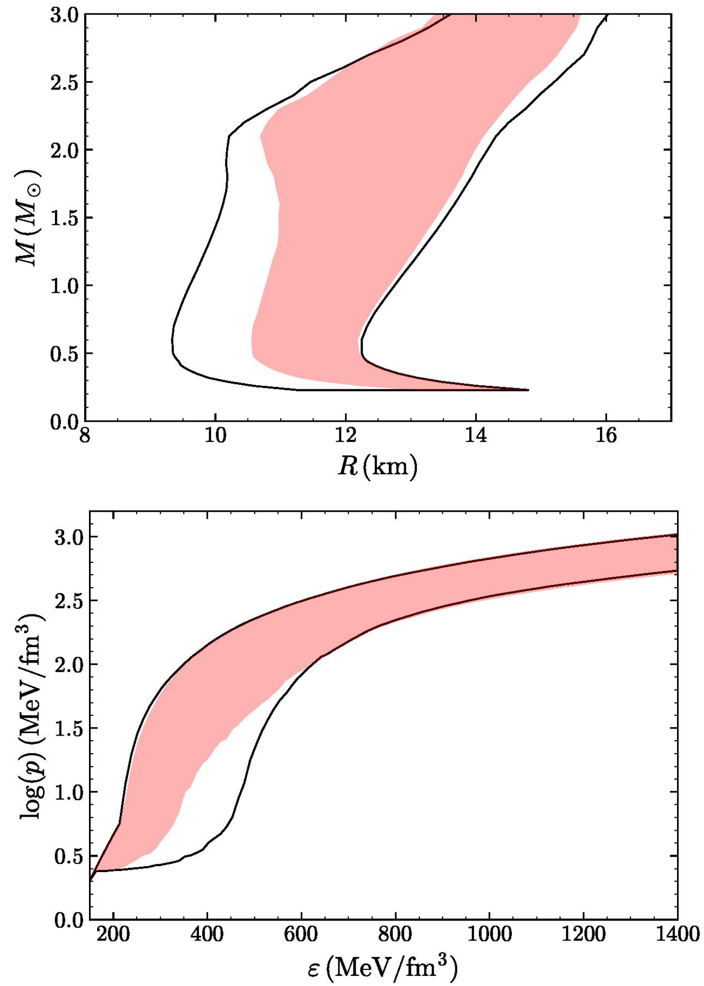


post-merger GW signals (possibly from O5 until maybe 2030) with the help of merger simulation (in progress).

Radius measurement of massive NSs is vital

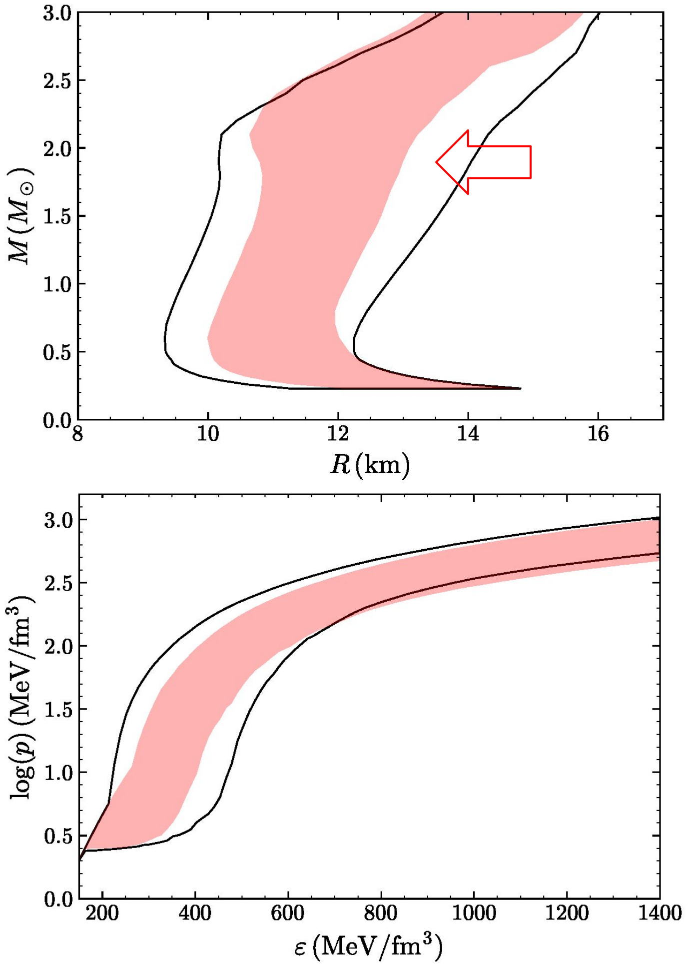
~1.4M$_\odot$ J0030's M,R measurement

$$1.34^{+0.15}_{-0.16}\,M_\odot \quad \text{and} \quad 12.71^{+1.14}_{-1.19}\ \text{km}$$

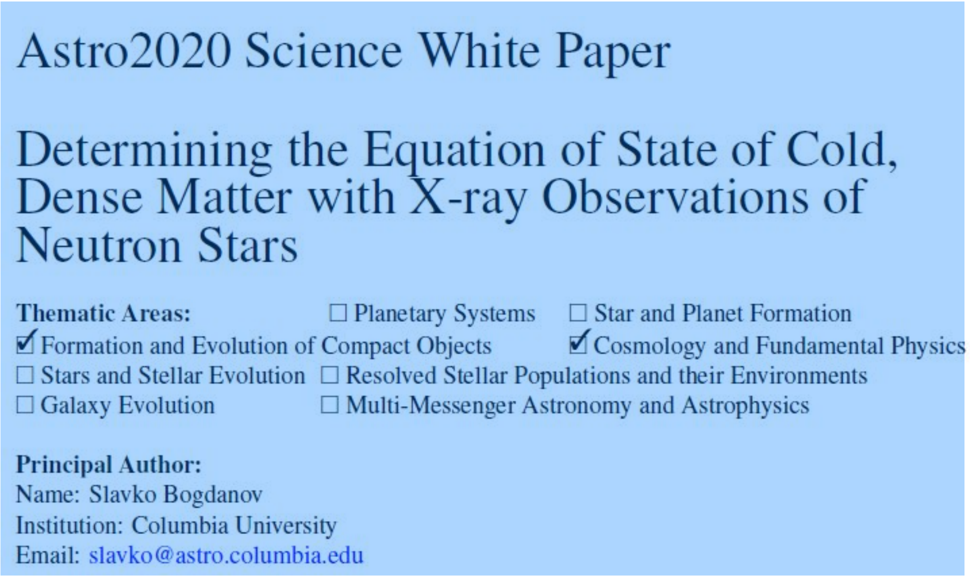


~2M$_\odot$ J0740's M,R measurement

$$2.072^{+0.067}_{-0.066}\ \mathrm{M}_\odot \ \text{and} \ 12.39^{+1.30}_{-0.98}\ \text{km}$$



Radius measuring: one of primary goal of next generation of hard x-ray timing instruments

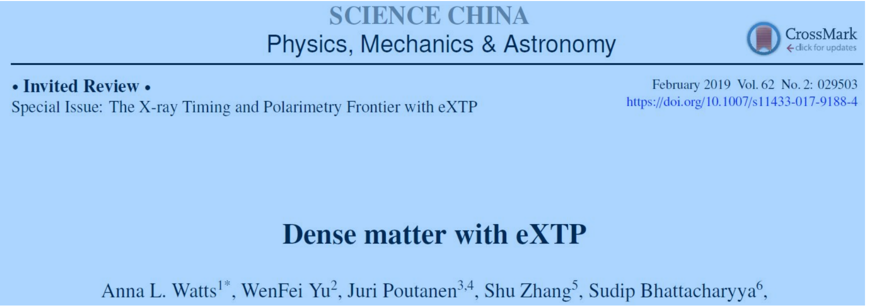


Astro2020 Science White Paper

Determining the Equation of State of Cold, Dense Matter with X-ray Observations of Neutron Stars

Thematic Areas:
☐ Planetary Systems
☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects
☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution
☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution
☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Slavko Bogdanov
Institution: Columbia University
Email: slavko@astro.columbia.edu



SCIENCE CHINA
Physics, Mechanics & Astronomy

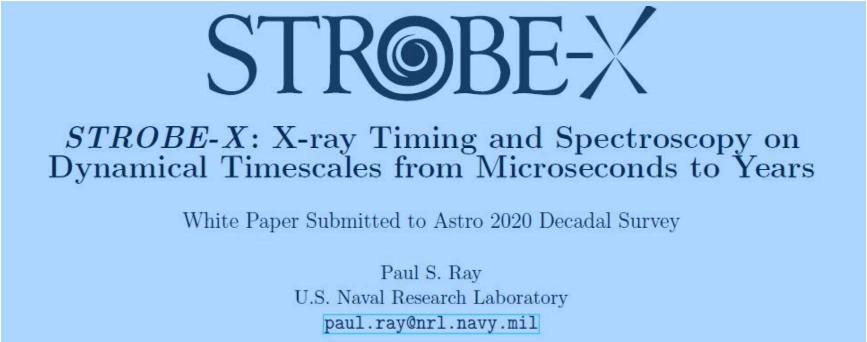
CrossMark

• Invited Review •
Special Issue: The X-ray Timing and Polarimetry Frontier with eXTP

February 2019 Vol. 62 No. 2: 029503
https://doi.org/10.1007/s11433-017-9188-4

Dense matter with eXTP

Anna L. Watts[1*], WenFei Yu[2], Juri Poutanen[3,4], Shu Zhang[5], Sudip Bhattacharyya[6],

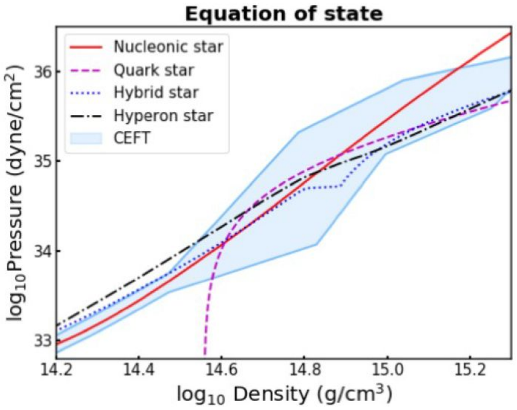


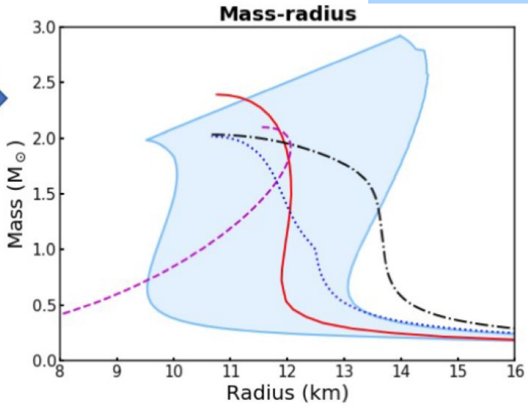
STROBE-X

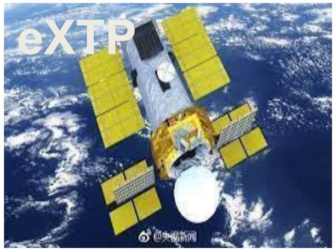
STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years

White Paper Submitted to Astro 2020 Decadal Survey

Paul S. Ray
U.S. Naval Research Laboratory
`paul.ray@nrl.navy.mil`







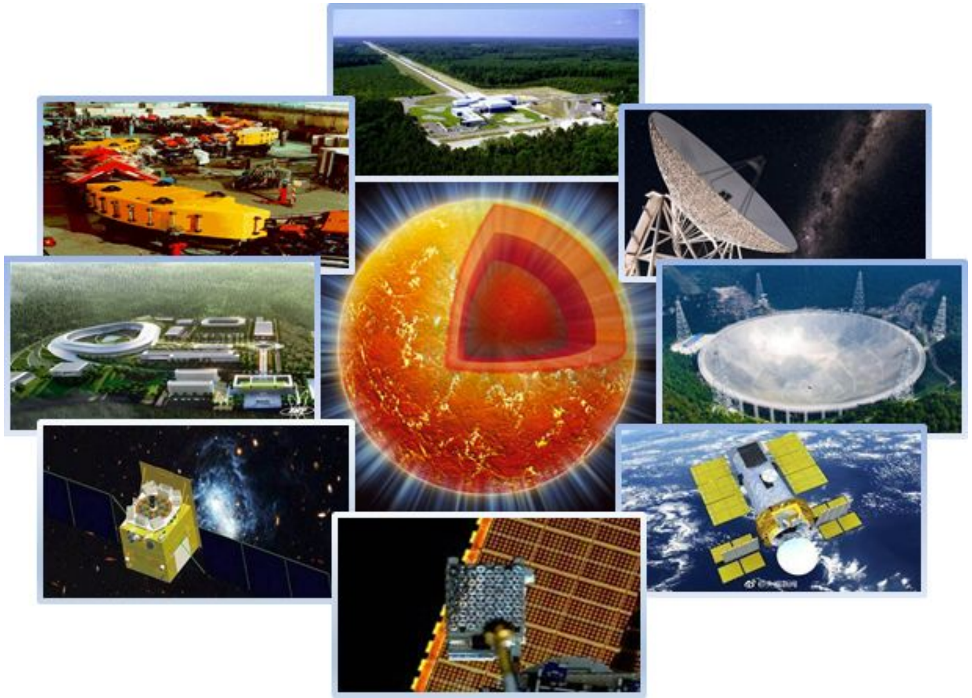
lauch by 2025 (IHEP)

ready for construction in the 2020s (NASA)

Magenta - quark star, composed entirely of quark matter from **Li et al., 2016**

Take-home message

- Connect consistently nuclear exp. and LIGO/Virgo+NICER obs. for “quantitative” studies of neutron stars;
- Current limits on M_{max} (EOS): ~2.08(observational) ~2.4(theoretical);
- Joint efforts from nuclear and astro. for probing the phase state of dense QCD matter: theory + simulation + data!



Thank you and Q&A !