Recent works on neutron star equation of state

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Many thanks for the invitation!

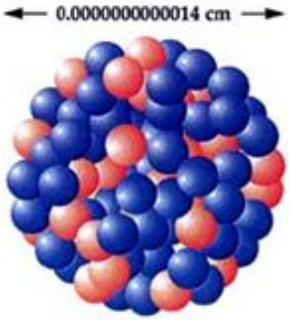
arXiv:2205.10631 submitted
arXiv:2203.04798 PRD
arXiv:2201.12053 PRC
arXiv:2108.00560 ApJ
arXiv:2107.13997 ApJL
arXiv:2103.15119 ApJ
arXiv:2011.11934 ApJ
arXiv:2009.12571 MNRAS
arXiv:2007.05116 JHEAp (review)
arXiv:2006.00839 ApJ
arXiv:2005.12875 ApJS
arXiv:2005.02677 PRD
arXiv:2001.03859 PRC

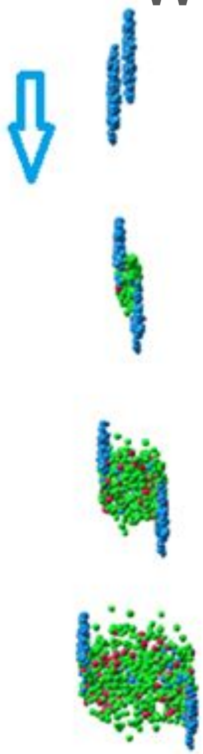
Outline

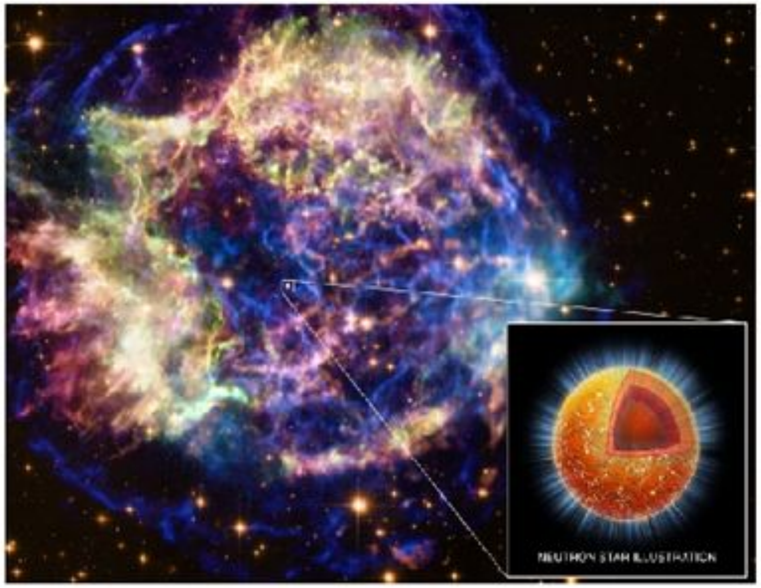
- Intro. on dense matter in neutron stars (NSs)
- Recent works on NS EOS and the hyperon interaction

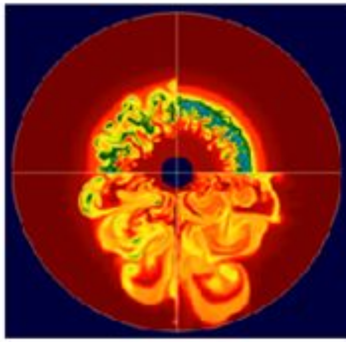
  (Biased selected results; Highlighing work done by our group)
- Summary

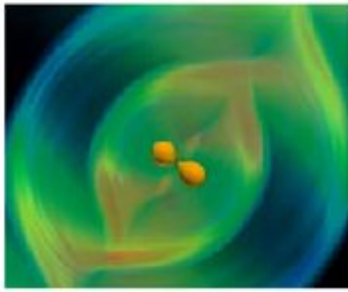
Where is dense matter?







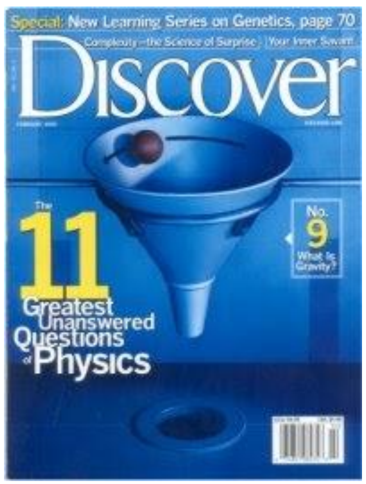




- atomic nuclei: : T~0, $\rho \sim\rho_0$
- heavy ion collision: T ~50-150 MeV, $\rho \sim 10^{-3}$-$2\rho_0$
- neutron star: T ~0, $\rho \sim 10^{-3}$-$10\rho_0$
- protoneutron star: T ~1-50 MeV, $\rho \sim 10^{-3}$-$10\rho_0$
- supernovae simulation: T ~1-50 MeV, $\rho \sim 10^{-10}$-$2\rho_0$
- neutron star merger: T ~0-150 MeV, $\rho \sim 10^{-10}$-$10\rho_0$

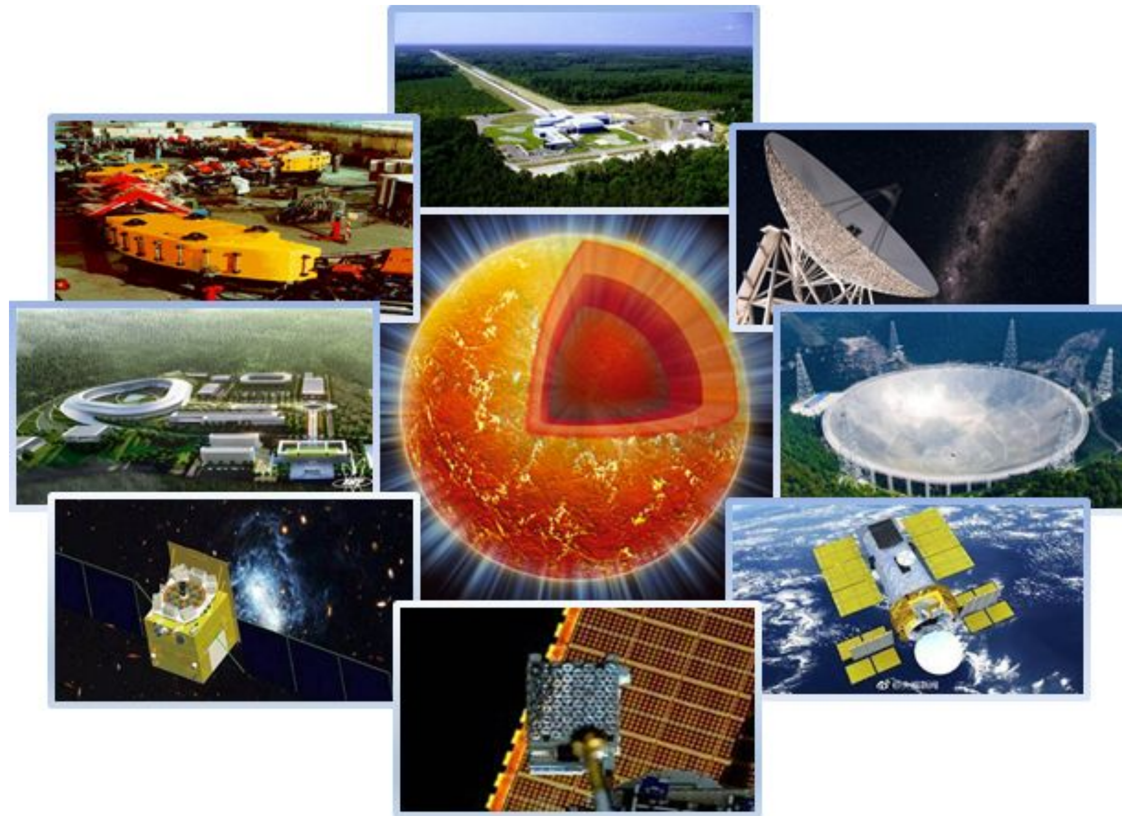
Dense matter EOS: One of 11 unanswered questions of Physics whose resolutions could provide a new era in science

- Understanding the properties of matter under these extreme conditions through astronomical observations, advances in theory and simulations and terrestrial experiments continues to be **a grand challenge** for nuclear physics and astrophysics.



Discover
February 2002

Q7: "Are there new states of matter at ultrahigh temperatures and densities?"



Dense matter EOS: One of 11 unanswered questions of Physics whose resolutions could provide a new era in science

Key physical ingredients

- the EOS of nuclear matter (**the relationship between density and pressure**);
- the possibility of exotic degrees of freedom in dense nuclear matter (hyperons, kaons, or deconfined quarks);
- the nature of neutron superfluidity and proton superconductivity;
- the interactions of neutrinos with nuclear matter; ...

《White paper on nuclear astrophysics..》Prog. Part. Nucl. Phys. 94 (2017) 1-67

open questions

- What is the neutron star mass-radius relation and the maximum neutron star mass?
- What are the constraints on the equation of state of nuclear matter provided by astronomical determinations of the mass-radius relation? How do such astronomical constraints **compare** to those extracted from laboratory measurements?
- What does the phase diagram of dense matter at low temperatures look like? How can we **combine** neutron star observations, laboratory measurements, and theoretical developments to learn about those phases?
- What are glitches and why do they occur? What is the trigger that couples the superfluid to the crust over a timescale of less than one minute?
- What is the origin of the intense surface magnetic fields as large as 10^{15} Gauss found in magnetars?
- Is there a limit to the spin frequency of milli-second pulsars? If so, why?
- …

Exemplary quark mean-field (QMF) neutron star EOS

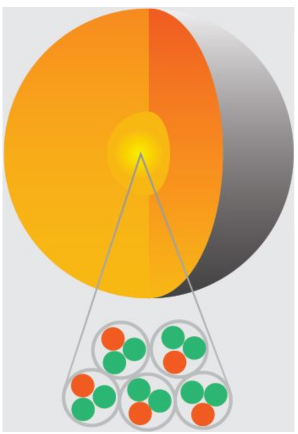
THE ASTROPHYSICAL JOURNAL, 862:98 (9pp), 2018 August 1 https://doi.org/10.3847/1538-4357/aacc28

-入选2020年IOP高引论文

CrossMark

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



$$\mathcal{L} = \overline{\psi}\left(i\gamma_\mu\partial^\mu - M_N^* - g_{\omega N}\omega\gamma^0 - g_{\rho N}\rho\tau_3\gamma^0\right)\psi$$
$$-\frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4$$
$$+\frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2 + \frac{1}{2}(\nabla\omega)^2 + \frac{1}{2}m_\omega^2\omega^2$$
$$+\frac{1}{2}g_{\rho N}^2\rho^2\Lambda_v g_{\omega N}^2\omega^2$$

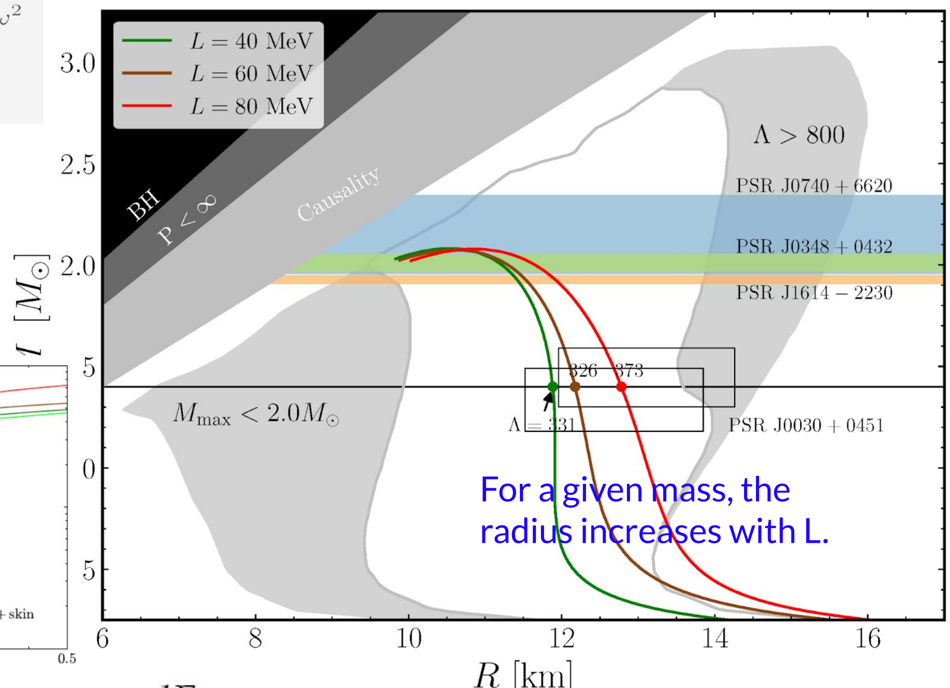
nucleonic many-body systems

$$[\gamma^0(\epsilon_q - g_{\omega q}\omega - \tau_{3q}g_{\rho q}\rho) - \vec{\gamma}\cdot\vec{p} - (m_q - g_{\sigma q}\sigma) - U(r)]\psi_q(\vec{r}) = 0$$

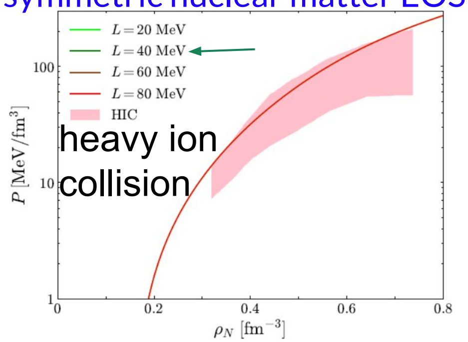
single nucleon

consistently

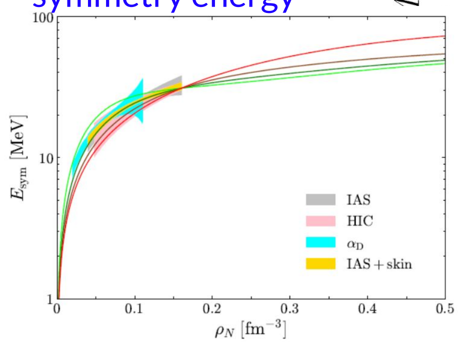
Microscopic NS EOS from the quark level, connecting consistently nuclear experiments and GW+EM observations.



symmetric nuclear matter EOS



symmetry energy



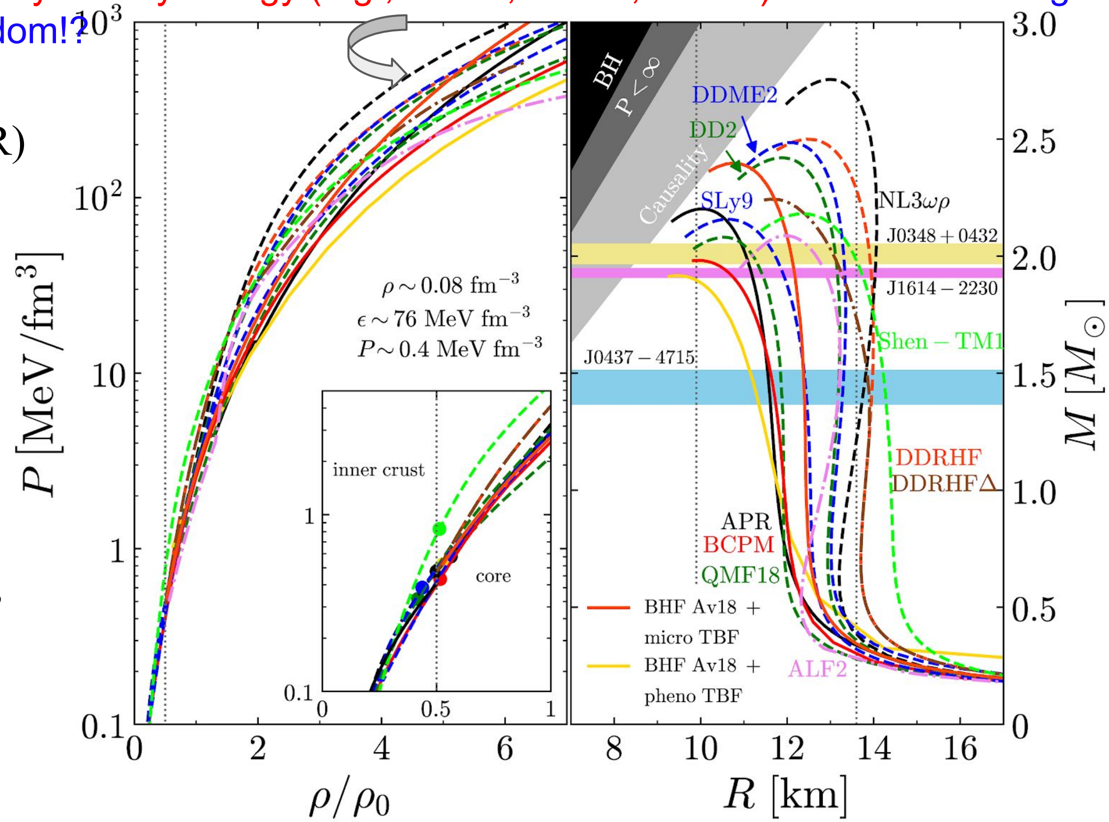
$$E(\rho,\delta) = E_{\mathrm{SNM}}(\rho) + E_{\mathrm{sym}}(\rho)\delta^2\,,\; L \equiv 3\rho_0\frac{dE_{\mathrm{sym}}}{d\rho}(\rho_0)$$

Neutron star EOS mainly determined by strong interaction

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 (LQCD, χEFT, etc).

a fan of different predictions on high-density EOS; better knowledge on nuclear symmetry energy (e.g., PREX, CREX, MREX)! non-nucleon degree of freedom!?

- Green's Function Monte Carlo
- Chiral Perturbation Theory (ChPT)
- Variational Many-Body (VMB; e.g., APR)
- V_{lowk} + 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)...



《致密物质状态方程：中子星与奇异星》李昂 胡金牛 鲍世绍 申虹 徐仁新, 2019 原子核物理评论

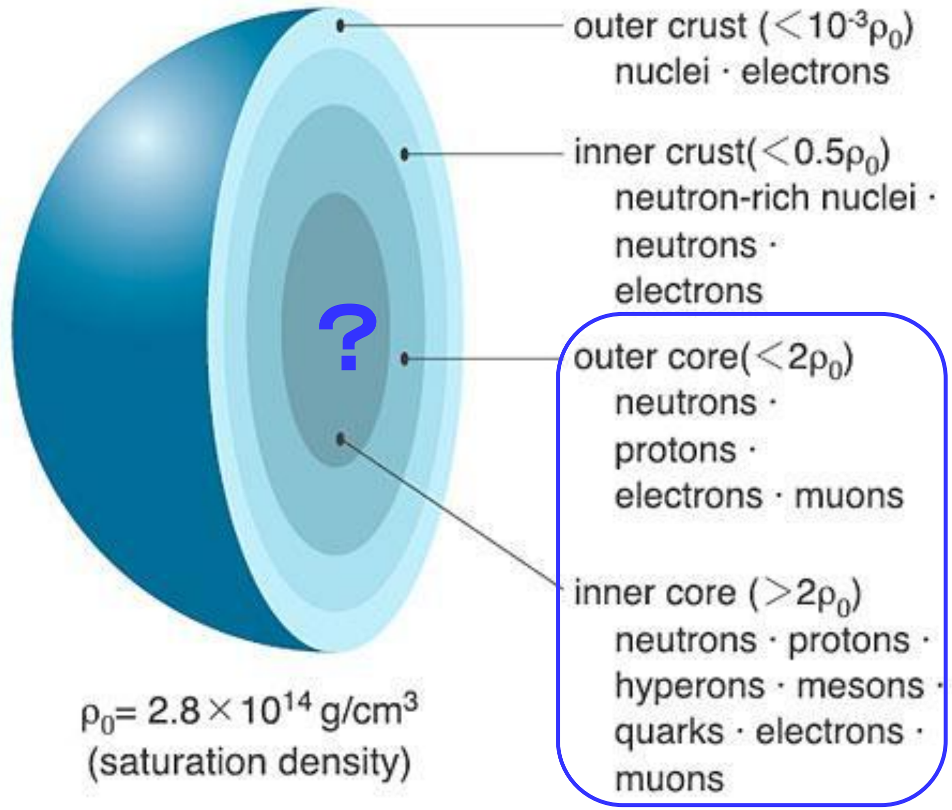
《Neutron star equation of state...》Li, Zhu, Zhou, Dong, Hu, & Xia 2020 Journal of High Energy Astrophysics

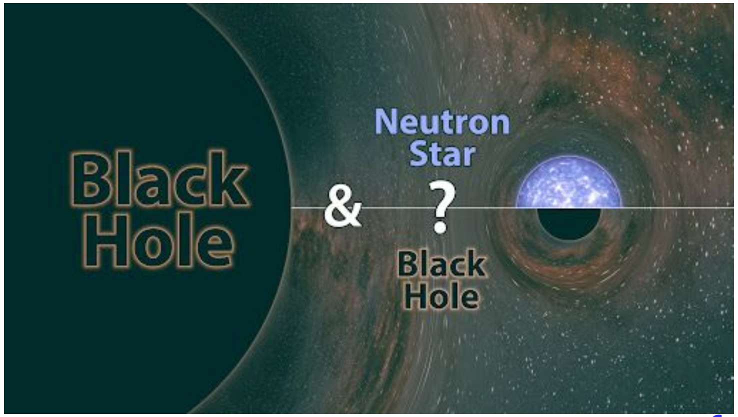
–2018年以来JHEAp官方引用排名榜首

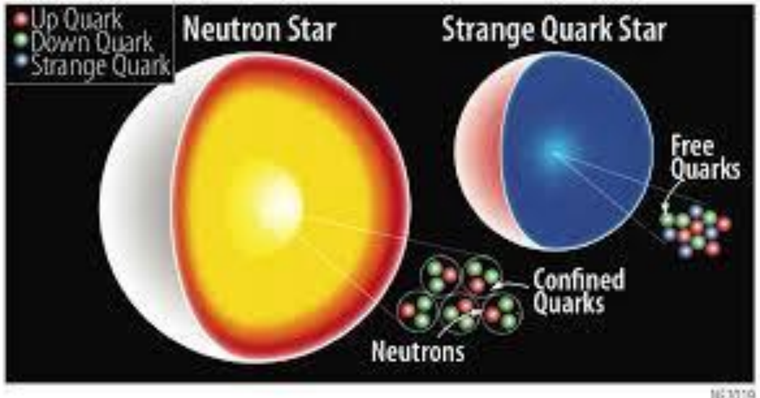
Neutron star core

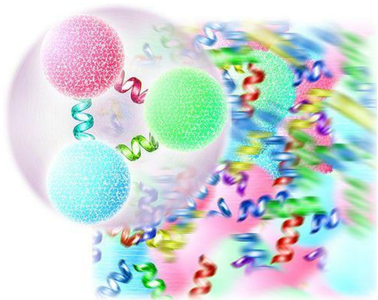
Core EOS and phase state unknown;

Related to nonperturbative QCD; strangeness phase transition; hyperon puzzle; mass-radius relation; the maximum mass, short gamma-ray burst central engine; NS/QS binary evolution and the remnants; supernova and star formation; one or two-family compact stars? mass-gap between NS and BH?









from NS observations to the phase state of NS (inner) core->

Outline

- Intro. on dense matter in neutron stars (NSs)
- Recent works on NS EOS and the hyperon coupling

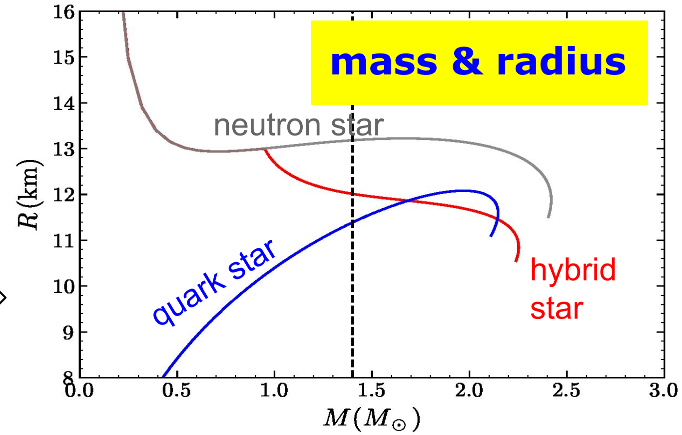
  (Biased selected results; Highlighing work done by our group)
- Summary

Multi-Messenger neutron star observations

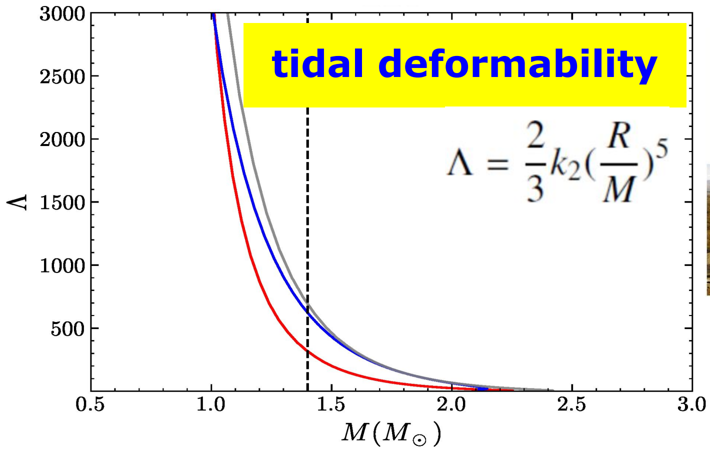
- Neutron stars emit GW, neutrinos, photons (from radio to gamma ray);

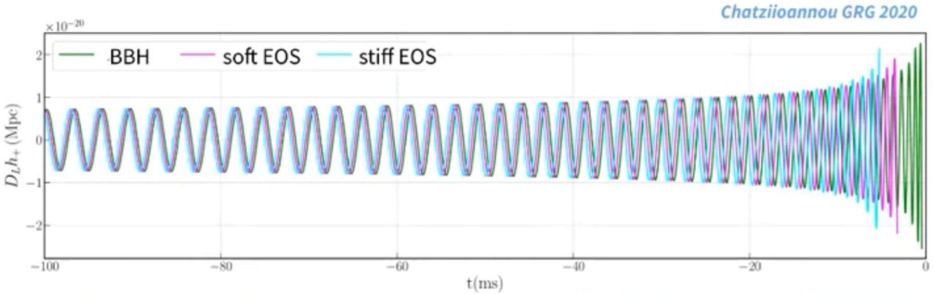
EOS, mainly $p(\varepsilon)$

Hydrostatic equlibrium



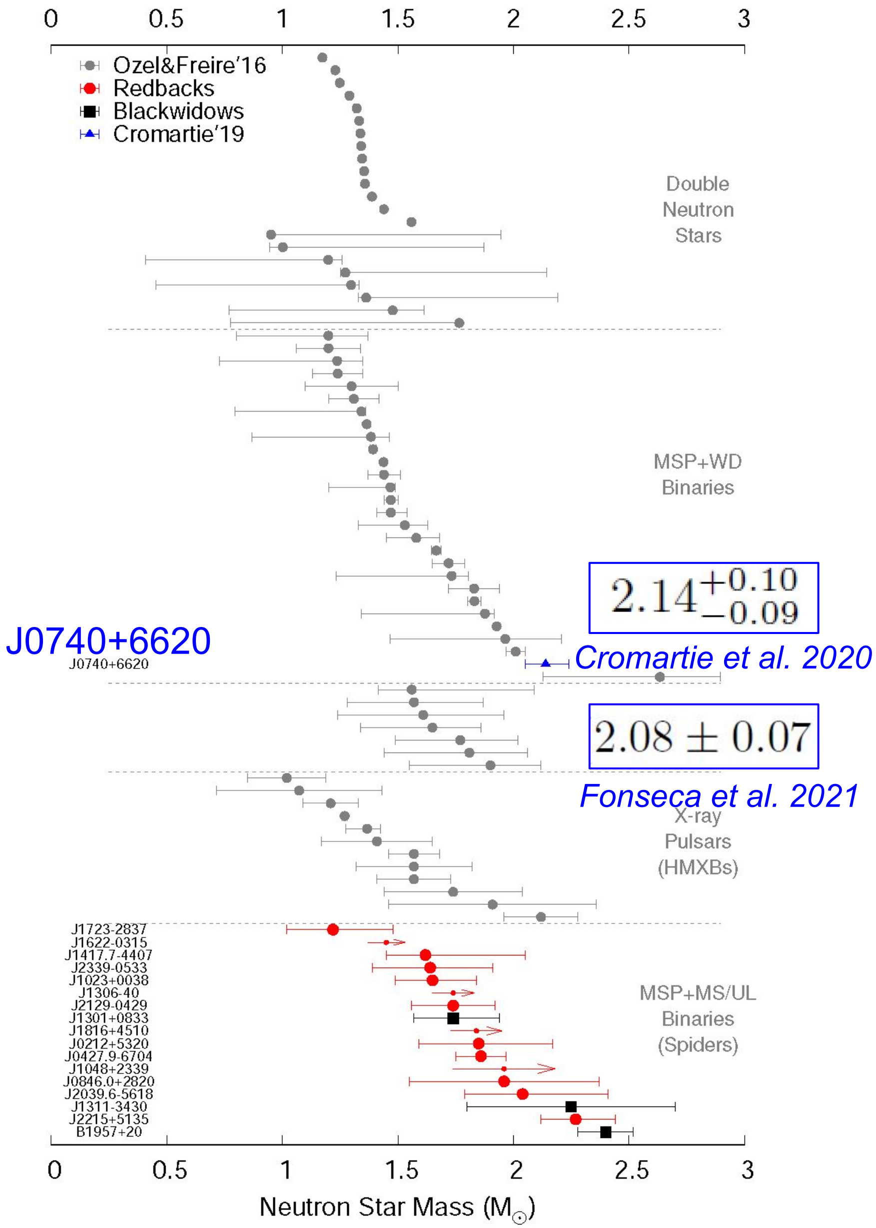
Perturbed hydrostatic equlibrium



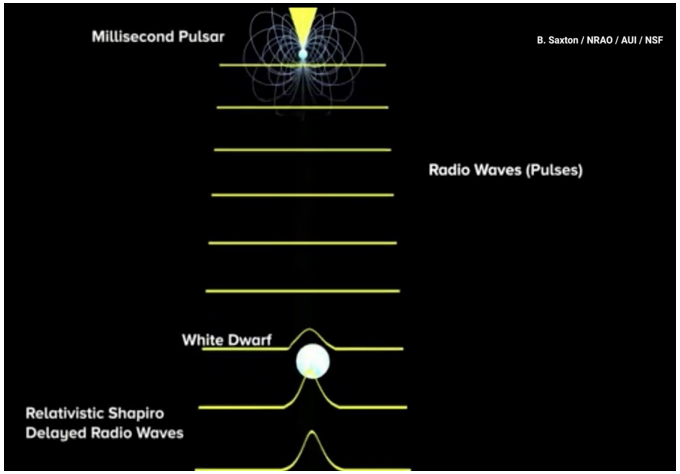


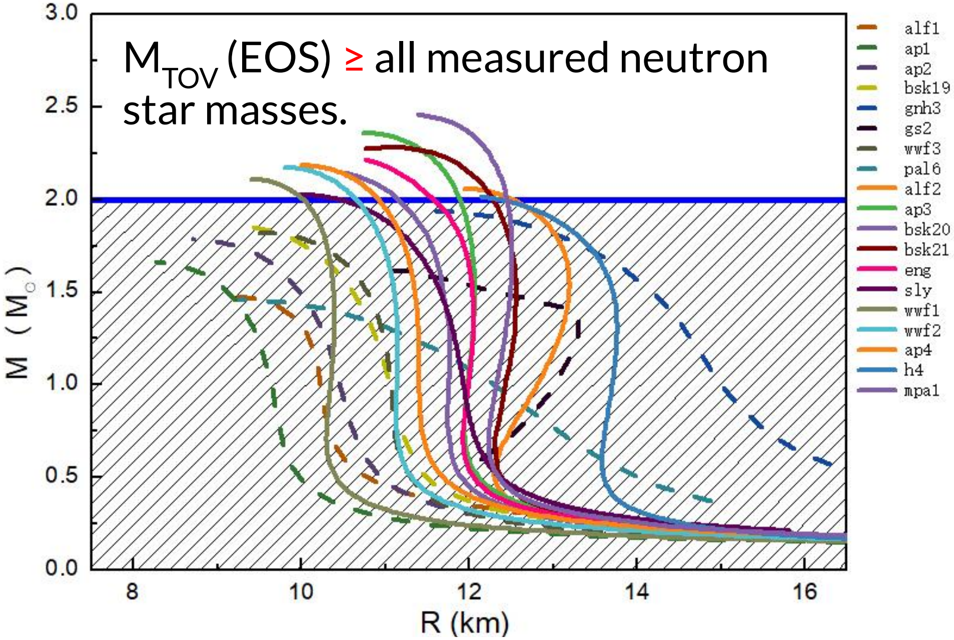
Very exciting future: LIGO/Virgo/KAGRA, CE, ET, HXMT, NICER, eXTP, STROBE-X, FAST, SKA,...

Important EOS constraints: heavy pulsars



arXiv:1910.09572





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

SCIENCE CHINA
Physics, Mechanics & Astronomy
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• Invited Review •
Special Issue: The X-ray Timing and Polarimetry Frontier with eXTP

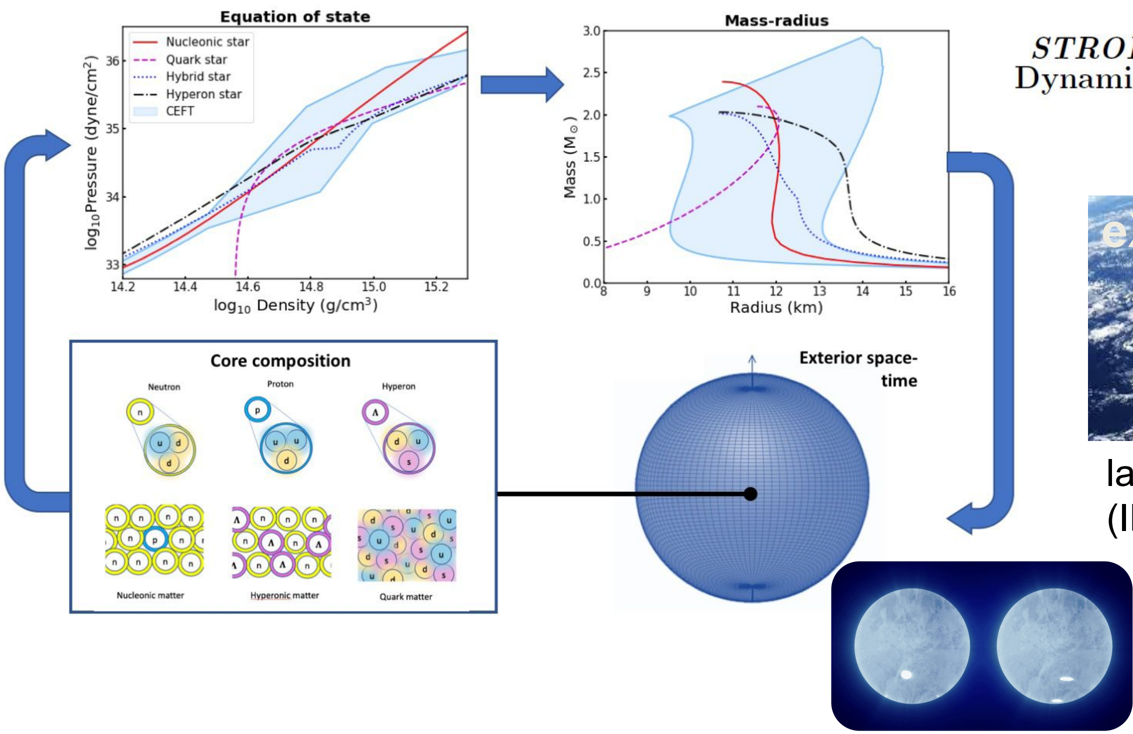
February 2019 Vol. 62 No. 2: 029503
https://doi.org/10.1007/s11433-017-9188-4

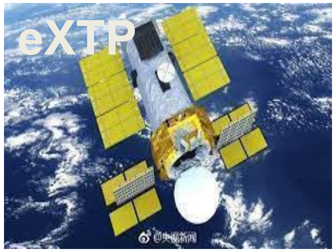
Dense matter with eXTP

STROBE-X

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

White Paper Submitted to Astro 2020 Decadal Survey





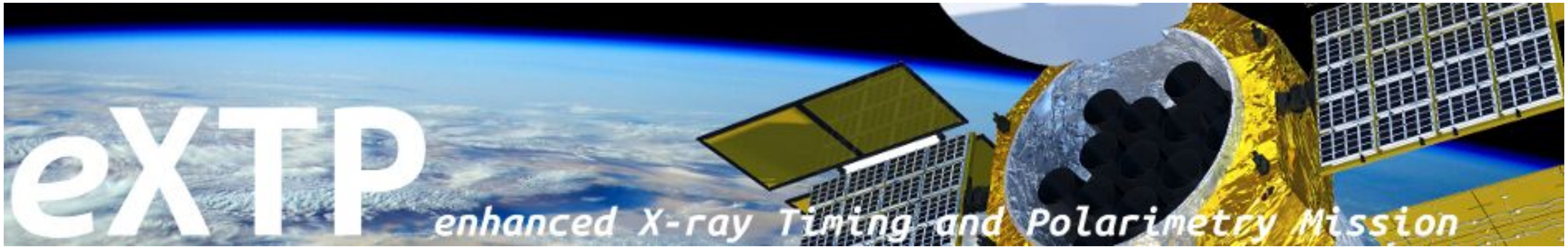
lauch by 2025 (IHEP)

ready for construction in the 2020s (NASA)

(10 × NICER)

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

-我们提出的quark star EOS 被下一代X射线空间任务写在科学白皮书.



https://www.isdc.unige.ch/extp/

1 奇-黑洞

2 星-中子星和夸克星

3 极端-引力、磁场、密度

eXTP Teams

- WG1 - Dense Matter
- WG2 - Strong Field Gravity
- WG3 - Strong Magnetism
- WG4 - Observatory Science
- WG5 - Synergy with GWs
- WG6 - Simulations
- Instrument Working Group
- Consortium

SCIENCE CHINA
Physics, Mechanics & Astronomy
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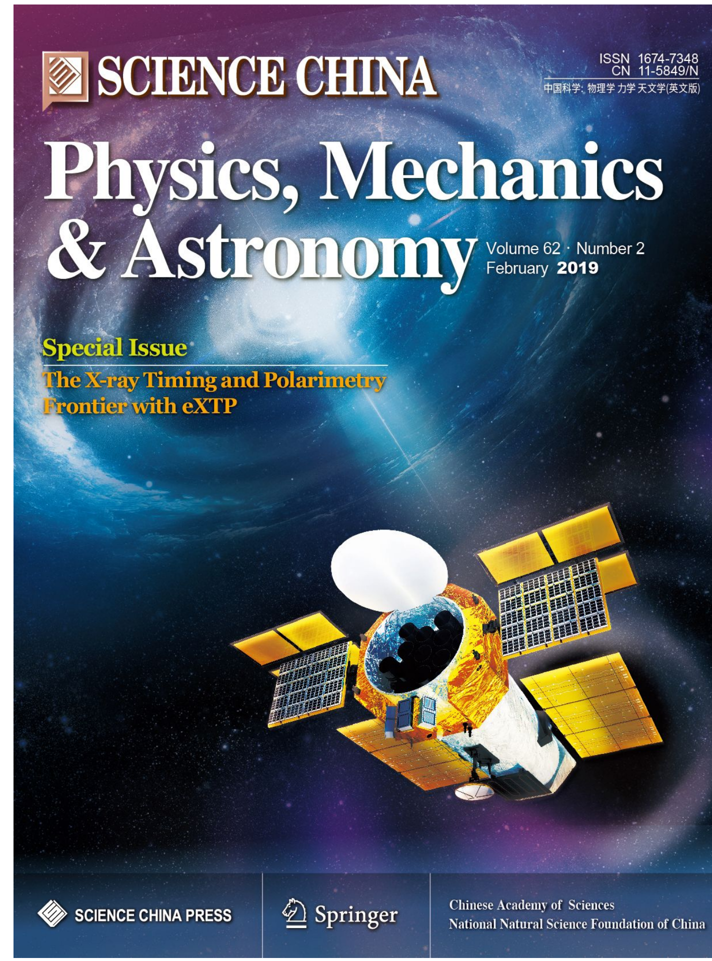
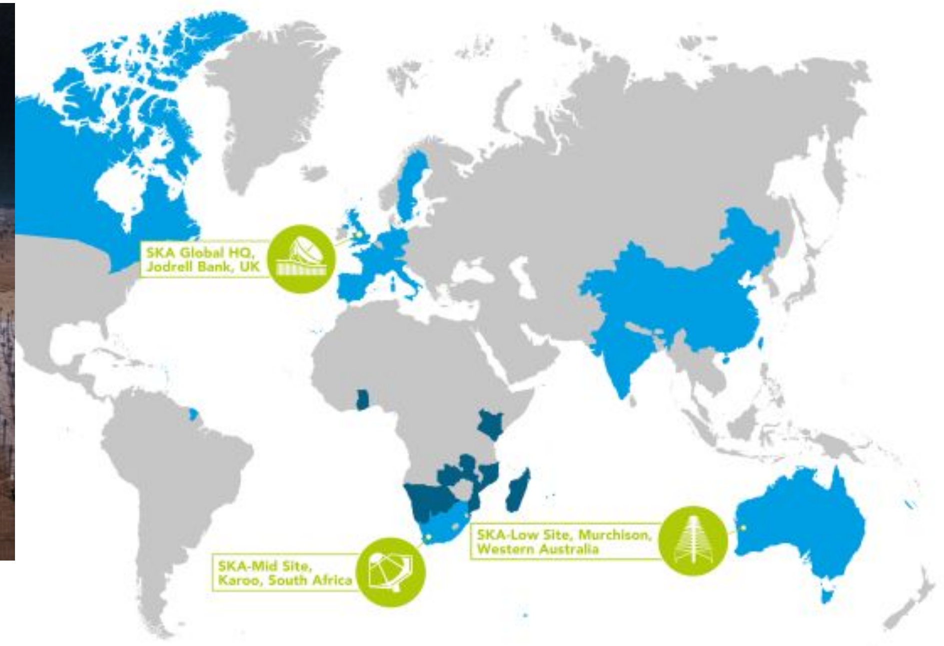
• Invited Review •
Special Issue: The X-ray Timing and Polarimetry Frontier with eXTP

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

Dense matter with eXTP

https://link.springer.com/article/10.1007/s11433-017-9188-4





SKA Partners – includes Members of the SKA Organisation, precursor to the SKAO –, current SKAO Member States*, and SKAO Observers (as of January 2022)

African Partner Countries

1: Epoch of Reionisation
2: Cosmology
3: Fundamental Physics with Pulsars
4: The Transient Universe
5: The Continuum Universe
6: Magnetism
7: The Cradle of Life
8: The Hydrogen Universe
9: Synergies and Other Science

PROCEEDINGS OF SCIENCE

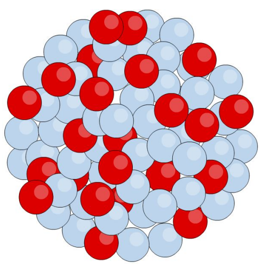
Probing the neutron star interior and the Equation of State of cold dense matter with the SKA

科技部平方公里阵列射电望远镜（SKA）专项（国家重点研发计划）

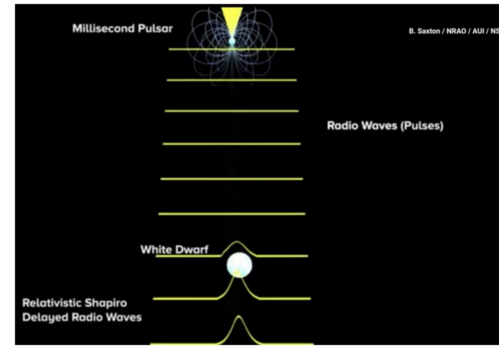
序号	项目编号	项目名称
1	2020SKA0110100	宇宙再电离探测的观测数据处理
2	2020SKA0110200	面向宇宙再电离探测的低频实验与观测
3	2020SKA0110300	低频射电干涉阵列的高精度校准方法
4	2020SKA0110400	宇宙再电离理论与数值模拟
5	2020SKA0120100	脉冲星测时和检验引力理论
6	2020SKA0120200	SKA 脉冲星搜寻预研
7	2020SKA0120300	脉冲星理论研究支撑

Neutron star EOS in multimessenger/multiscale era

- ❑ finite nuclei (especially superheavy, neutron-rich);
- ❑ collective flow/transport/meson production in heavy ion collision;

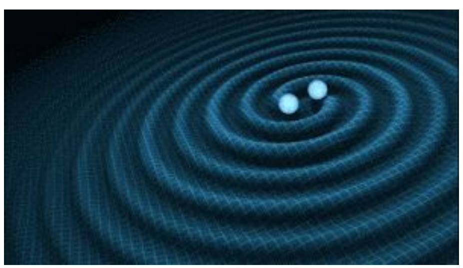


- ❑ PSR J1614-2230 *(Demorest et al. 2010; Fonseca et al. 2016)*;
- ❑ PSR J0348+0432 *(Antoniadis et al. 2013)*;
- ❑ PSR J0740+6620 *(Cromartie et al. 2019)*



2.08 ± 0.07 $M_\odot$ (90%CL) *(Fonseca et al. 2021)*

- ❑ neutron star binary: GW+SGRB+kilonova



- ❑ PSR J0740+6620

$$M = 2.072^{+0.067}_{-0.066}\, M_\odot, \quad R = 12.39^{+1.30}_{-0.98}\,\mathrm{km}$$

(Riley et al. 2021)

$$M = 2.062^{+0.090}_{-0.091}\, M_\odot,\ R = 13.71^{+2.61}_{-1.50}\,\mathrm{km}$$

(Miller et al. 2021)

- ❑ PSR J0030+0451

$$M = 1.34^{+0.15}_{-0.16}\, M_\odot, \quad R = 12.71^{+1.14}_{-1.19}\,\mathrm{km}$$

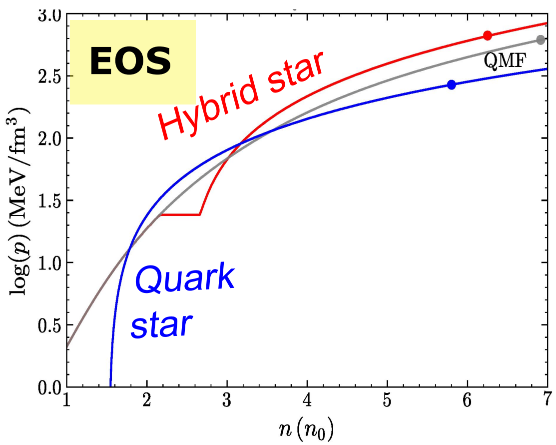
(Riley et al. 2019)

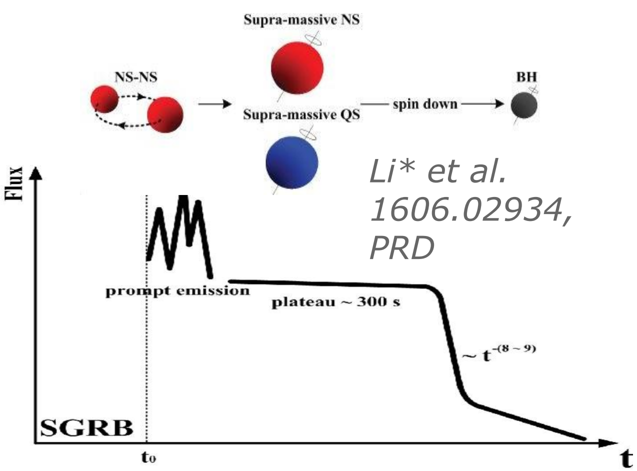
$$M = 1.44^{+0.15}_{-0.14}\, M_\odot,\ R = 13.02^{+1.24}_{-1.06}\,\mathrm{km}$$

(Miller et al. 2019)

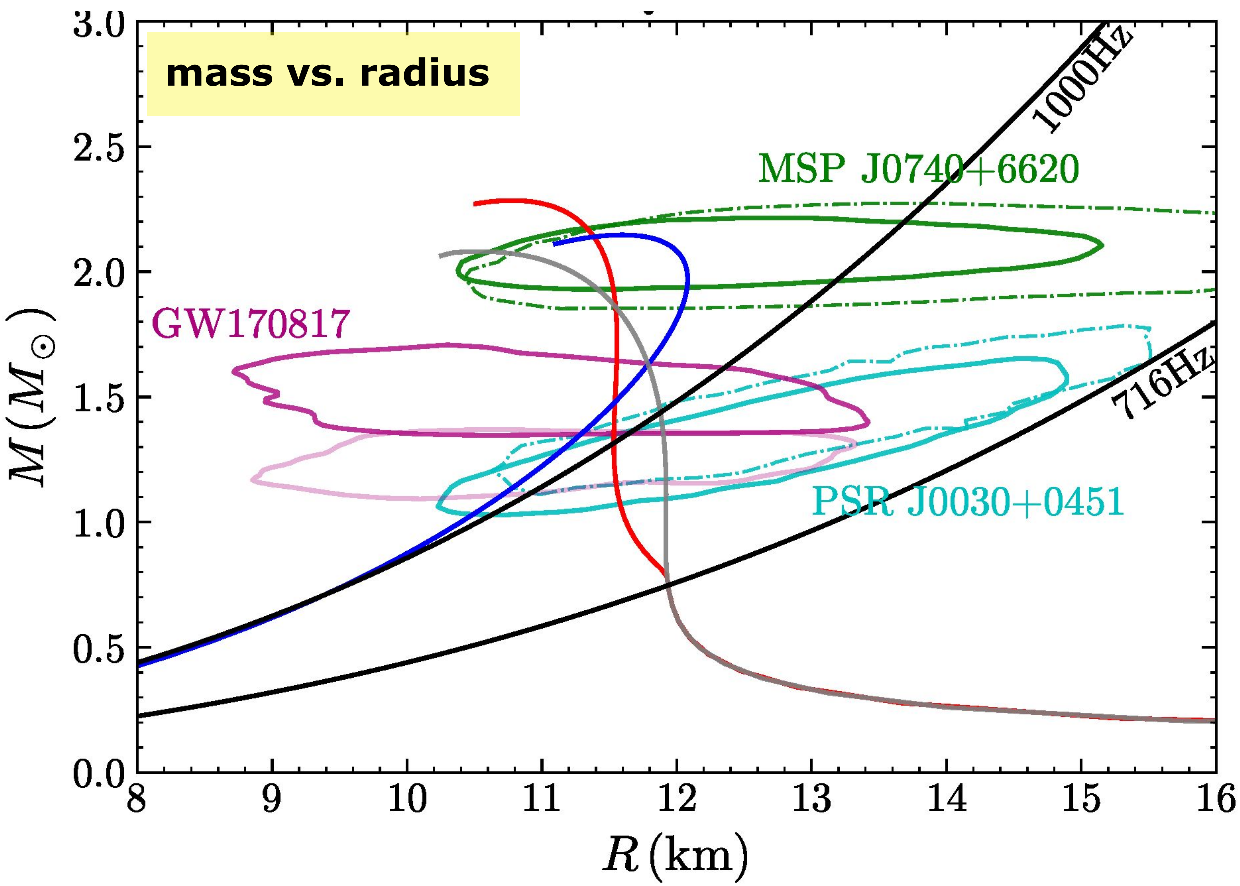
Neutron star EOS in multimessenger/multiscale era

- Different types of compact stars still NOT distinguishable from the available data.





Li et al. 1606.02934, PRD*



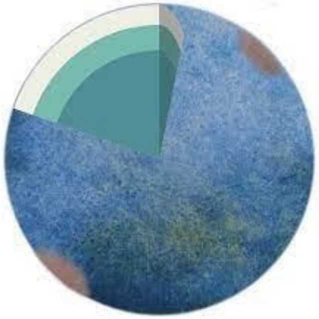
《Can we distinguish quark stars from neutron stars with measurements of global properties?》Li Ang, EPJ Web Conf. 260, 04001 (2022) Proceeding of the16th International Symposium on Nuclei in the Cosmos (NIC-XVI)

Vela pulsar structure from an EOS

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 223:16 (8pp), 2016 March
doi:10.3847/0067-0049/223/1/16

STRUCTURES OF THE VELA PULSAR AND THE GLITCH CRISIS FROM THE BRUECKNER THEORY

A. Li[1], J. M. Dong[2], J. B. Wang[3], and R. X. Xu[4]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, China; liang@xmu.edu.cn
[2] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[3] Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China
[4] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

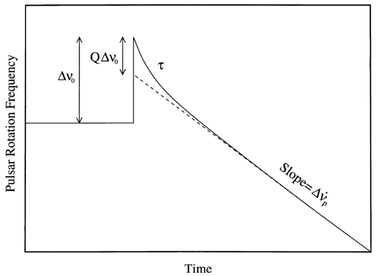


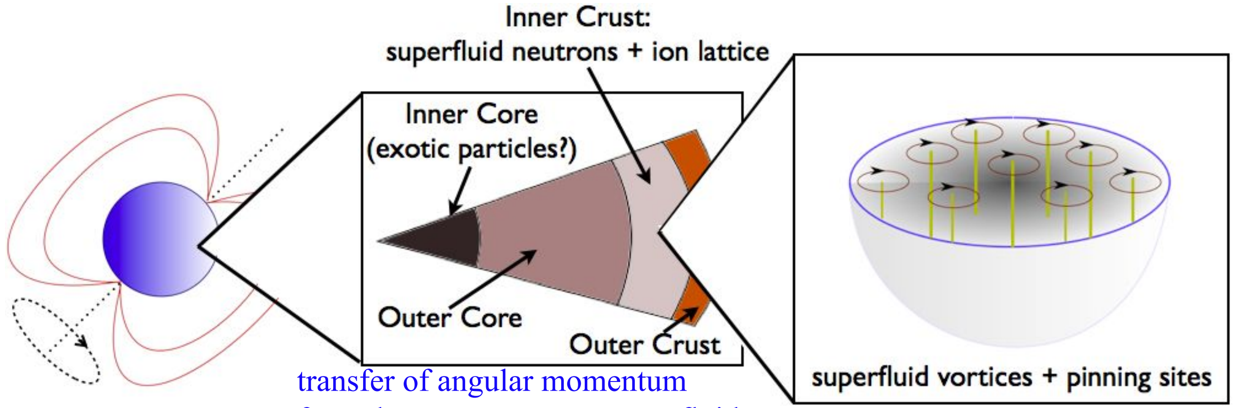
Predictions for the properties of the Vela pulsar (PSR J0835-4510 or PSR B0833-45) with a spin period of 89.33 ms; Taking the pulsar mass ranging from 1to 2Msun.

Mass	Cent.	Mass			Radius				Moment of Inertia	
		Core	icrust	ocrust	Total	Core	icrust	ocrust	Total	Fraction
1.0	0.403	0.97	0.026	4.59	11.79	10.33	0.81	0.64	0.894	5.33
1.1	0.427	1.08	0.024	4.15	11.80	10.50	0.73	0.57	1.029	4.51
1.2	0.452	1.18	0.022	3.72	11.80	10.64	0.66	0.51	1.170	3.84
1.3	0.480	1.28	0.020	3.37	11.79	10.75	0.59	0.45	1.318	3.29
1.4	0.508	1.38	0.019	3.05	11.78	10.84	0.53	0.41	1.474	2.82
1.5	0.536	1.48	0.017	2.73	11.76	10.92	0.48	0.36	1.638	2.41
1.6	0.567	1.58	0.016	2.46	11.73	10.97	0.43	0.32	1.809	2.06
1.7	0.602	1.69	0.014	2.18	11.67	10.99	0.39	0.29	1.987	1.76
1.8	0.643	1.79	0.013	1.94	11.58	10.98	0.35	0.26	2.170	1.49
1.9	0.696	1.89	0.011	1.67	11.45	10.92	0.31	0.22	2.358	1.24
2.0	0.764	1.99	0.0093	1.39	11.26	10.81	0.26	0.19	2.552	1.00

$\times 10^{-5}$ $\times 10^{45}$ g/cm^2

Pulsar glitch





transfer of angular momentum
from the **crutal** neutron superfluid to
the rest of the star

The Astrophysical Journal Supplement Series, 223:16 (8pp), 2016 March
doi:10.3847/0067-0049/223/1/16

CrossMark

STRUCTURES OF THE VELA PULSAR AND THE GLITCH CRISIS FROM THE BRUECKNER THEORY

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Glitch size
+
short-time
relaxation

The Astrophysical Journal, 923:108 (9pp), 2021 December 10
https://doi.org/10.3847/1538-4357/ac2e94

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Revisiting the Post-glitch Relaxation of the 2000 Vela Glitch with the Neutron Star Equation of States in the Brueckner and Relativistic Brueckner Theories

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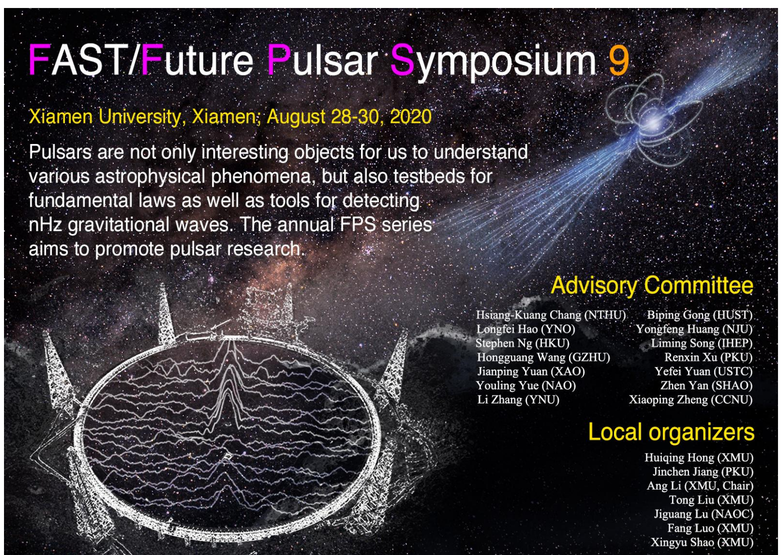
3. 星系结构与星系演化
4. 宇宙学和暗物质
5. 射电光谱和脉泽源
6. 低频多波束接收机和VLBI的设计预研

"Pulsar glitch and the inner structure of neutron stars"

PID	PI	Email Address	Expiration Time	Time Length (hour)
PT2020_0176	ANG LI	liang@xmu.edu.cn	2021-07-31 00:00:00	6.0



中子星的温度/频率演化和r模流体不稳定性

THE ASTROPHYSICAL JOURNAL, 910:62 (7pp), 2021 March 20 https://doi.org/10.3847/1538-4357/abe538

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R-mode Stability of GW190814's Secondary Component as a Supermassive and Superfast Pulsar

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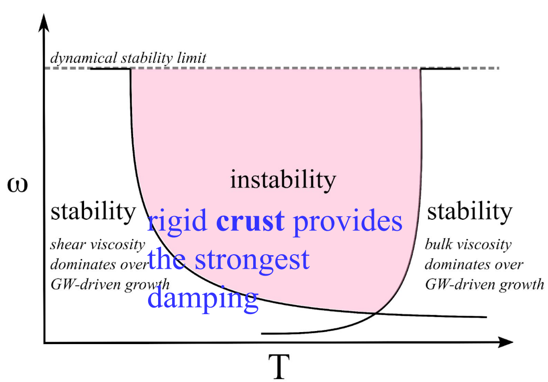
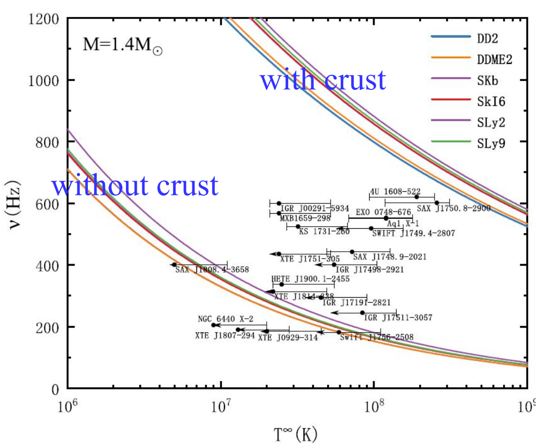
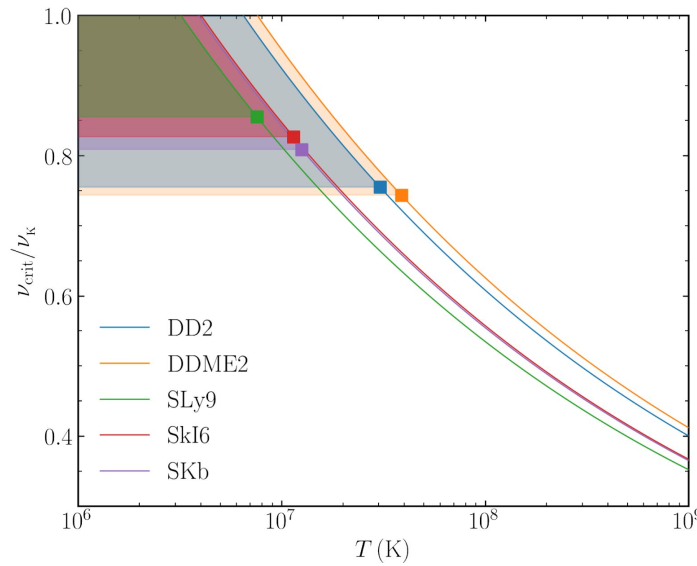
GW190814的2.6M$_\odot$天体是脉冲星的温度-频率参数空间

- 结合19个低质量X射线双星(LMXB)的观测;
- 采用满足所有目前已知天体物理和核物理约束条件的中子统一(unified)状态方程.







基于LIGO和NICER多信使观测研究高密物质奇异相变参数

THE ASTROPHYSICAL JOURNAL, 904:103 (12pp), 2020 December 1 https://doi.org/10.3847/1538-4357/abd41

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

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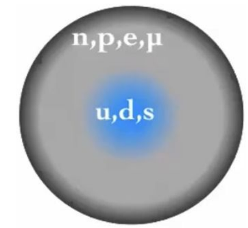
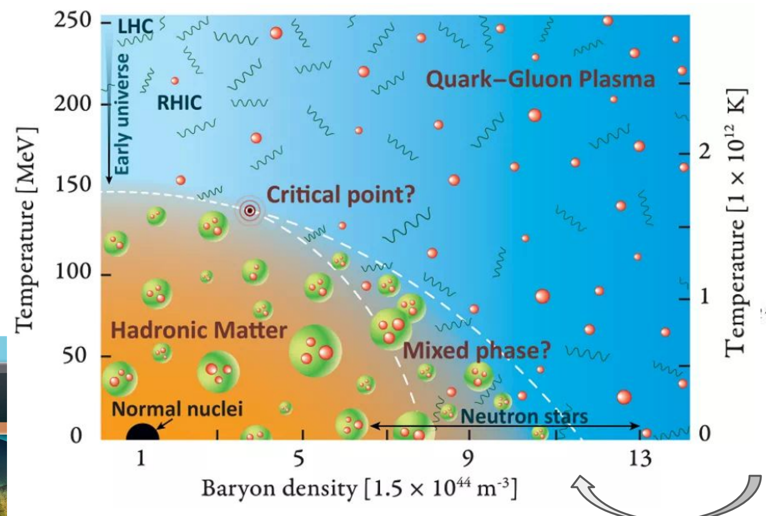
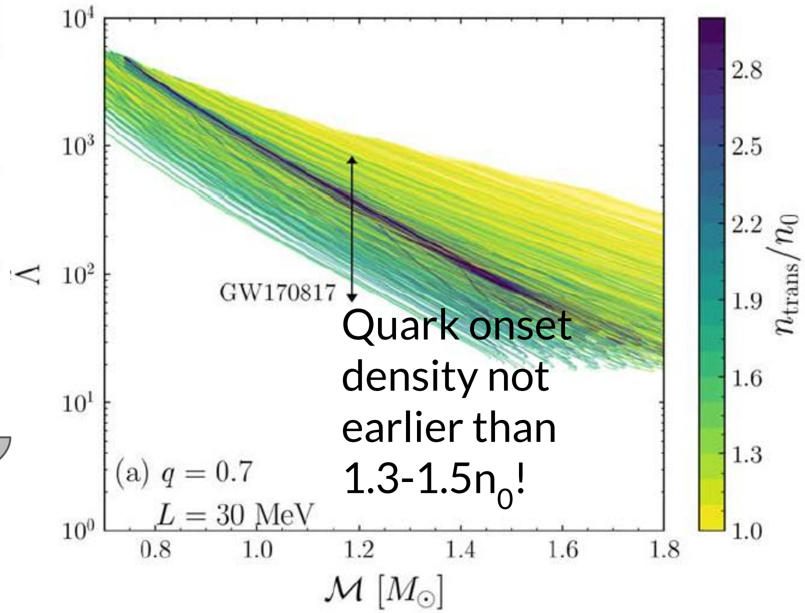


QMF hadronic EOS plus CSS (n_{trans}, $\Delta\mathcal{E}$, c_{QM}) characterize the high-density (quark matter) phase;

Mass-weighed tidal deformability accurately measured during the inspiral:

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4}{(m_1+m_2)^5}\Lambda_1 + (1 \leftrightarrow 2)$$



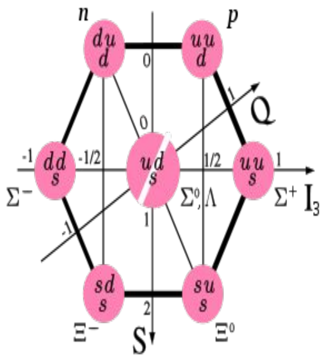


Quark onset density not earlier than 1.3-1.5n_0!

HIAF, CEE,
FAIR, NICA,
RIKEN, FRIB,
ROAN, …

- Astrophysical implications on hyperon couplings and hyperon star properties with relativistic equations of states

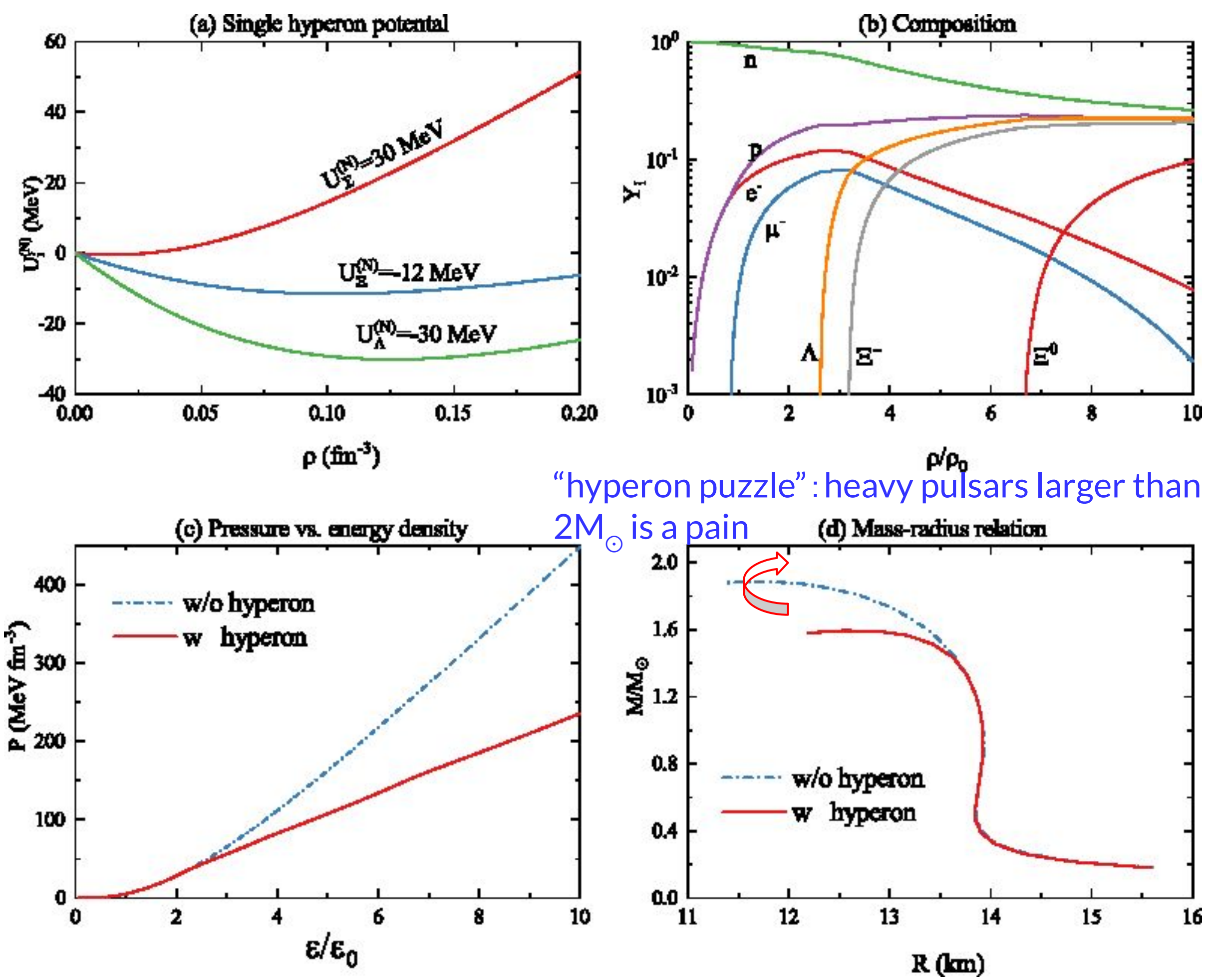
  arXiv:2205.10631



Many theoretical and experimental ambiguities regarding hyperon interaction (NY,YY,...)

- **Microscopic** scheme, e.g., BHF;
- Nijmegen soft-core NY potentials (NSC89/ESC08...) model, fitted to the available experimental NY scattering data: presently, 4233 NN data, 52 NY data;

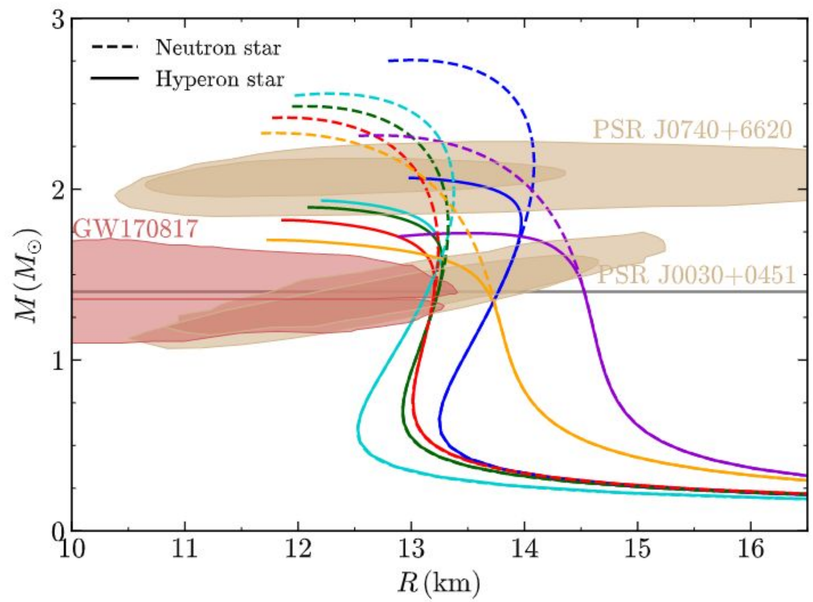
- **Phenomenological** scheme, e.g., RMF/QMF;
- Dressed baryon-meson($\sigma\omega\varrho$...) coupling constants, fitted to hypernuclei data, e.g., weak ΛΛ attraction (Nagara event, 2001).



《Neutron star equation of state...》Li, Zhu, Zhou, Dong, Hu, & Xia 2020 Journal of High Energy Astrophysics

Bayesian inference of the phenomenological hyperon-nucleon interactions from LIGO/Virgo and NICER

- Assuming the sources are hyperon stars;
- six RMF effective interactions: NL3ωρ , DD-LZ1, DD- ME2, DD2, PKDD, PK1 w. M_{TOV}(NS)≥2.3$M_{\odot}$
- Using the tidal-deformability measurement of the GW170817 binary NS merger as detected by LIGO/Virgo and the mass-radius measurements of PSR J0030+0541 & PSR J0740+6620 as detected by NICER;



- The Bayes's theroem

$$P(\boldsymbol{\theta}|\boldsymbol{D}) = \frac{P(\boldsymbol{D}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{\int P(\boldsymbol{D}|\boldsymbol{\theta})P(\boldsymbol{\theta})\mathrm{d}\boldsymbol{\theta}} ,$$

$$P_{\mathrm{GW}}(\boldsymbol{d}_{\mathrm{GW}}|\boldsymbol{\theta}) = F(\Lambda_1(\boldsymbol{\theta}; M_1), \Lambda_2(\boldsymbol{\theta}; M_2), \mathcal{M}, q) ,$$

$$P_{\mathrm{NICER}}(\boldsymbol{d}_{\mathrm{NICER}}|\boldsymbol{\theta}) = \prod P_j(M(\boldsymbol{\theta}), R(\boldsymbol{\theta})) ,$$

$$P_{\mathrm{NUCL}}(\boldsymbol{d}_{\mathrm{NUCL}}|\boldsymbol{\theta}) = \exp\left[-\frac{1}{2}\frac{(R_{\sigma\Lambda} - \bar{R}_{\sigma\Lambda})^2}{\sigma^2_{R_{\sigma\Lambda}}}\right]$$

correlation between $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ from fitting calculated Λ separation energies to experimental values of eleven A ≥ 12 Λ hypernuclei (Rong, Tu, Zhou, 2021).

$$\boldsymbol{\theta}_{\mathrm{EOS}} = \{R_{\sigma\Lambda}, R_{\omega\Lambda}\}$$

$$R_{\sigma\Lambda} = g_{\sigma\Lambda}/g_{\sigma N},\ R_{\omega\Lambda} = g_{\omega\Lambda}/g_{\omega N}$$

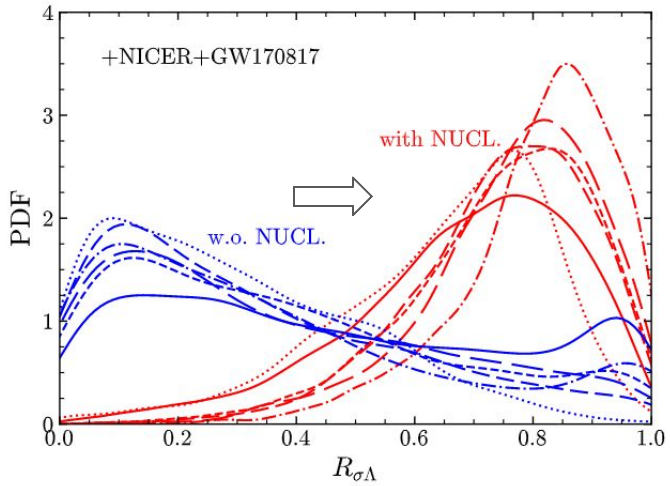
$$R_{\sigma\Lambda} \sim U[0,1] \text{ and } R_{\omega\Lambda} \sim U[0,1]$$

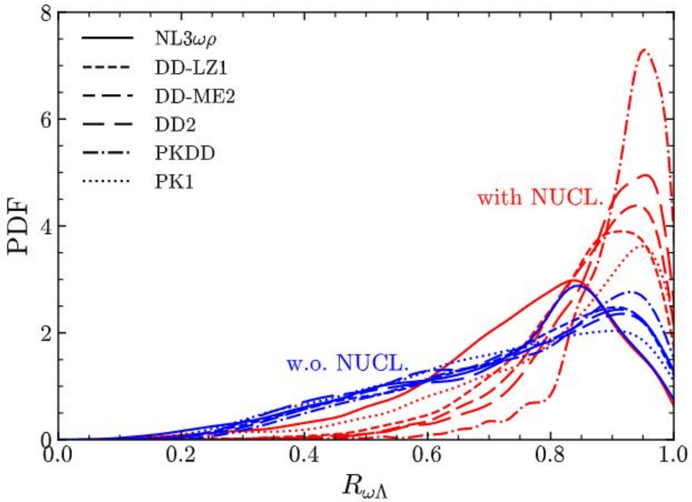
$$g_{\omega N} : g_{\omega\Lambda} : g_{\omega\Sigma} : g_{\omega\Xi} = 3 : 2 : 2 : 1$$

$$g_{\rho N} : g_{\rho\Lambda} : g_{\rho\Sigma} : g_{\rho\Xi} = 1/2 : 0 : 1 : 1/2$$

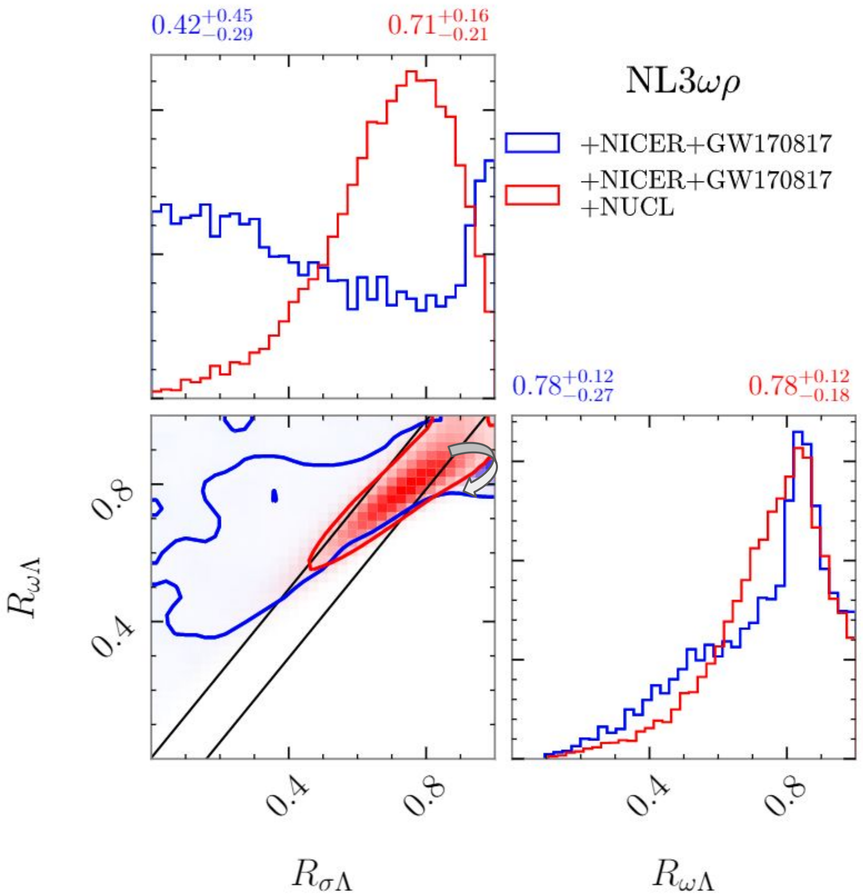
Hyperon-nucleon interactions in the relativistic Lagrangian

- Hypernuclei constraint favors large values of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ and disfavors small values of both couplings;



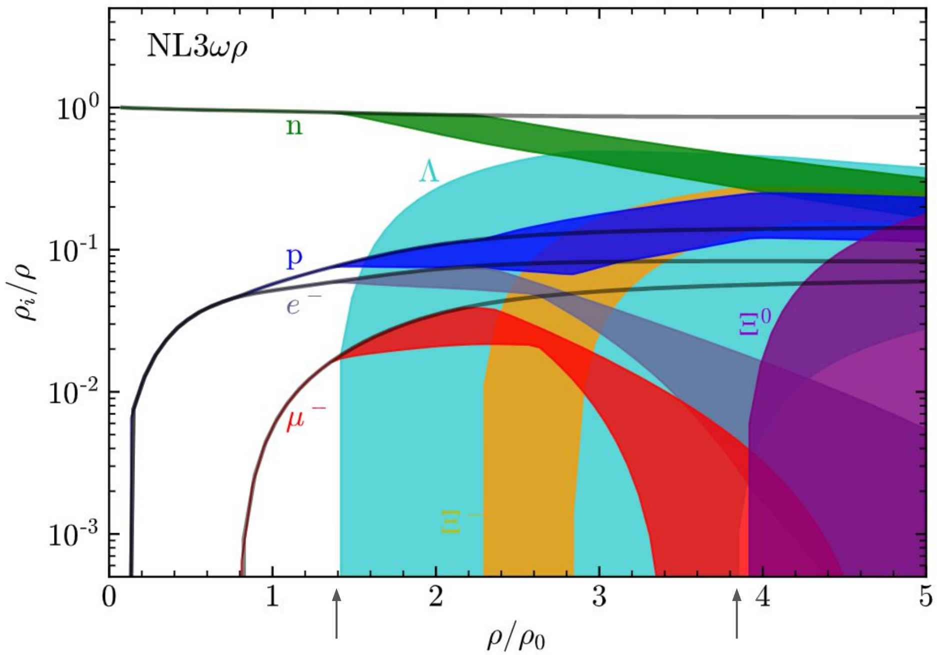


- The addtion of astrophysical observational data on top of the laboratory $R_{\sigma\Lambda}$-$R_{\omega\Lambda}$ correlation rotates the linear correlation slightly towards the direction of small values of $R_{\omega\Lambda}$.

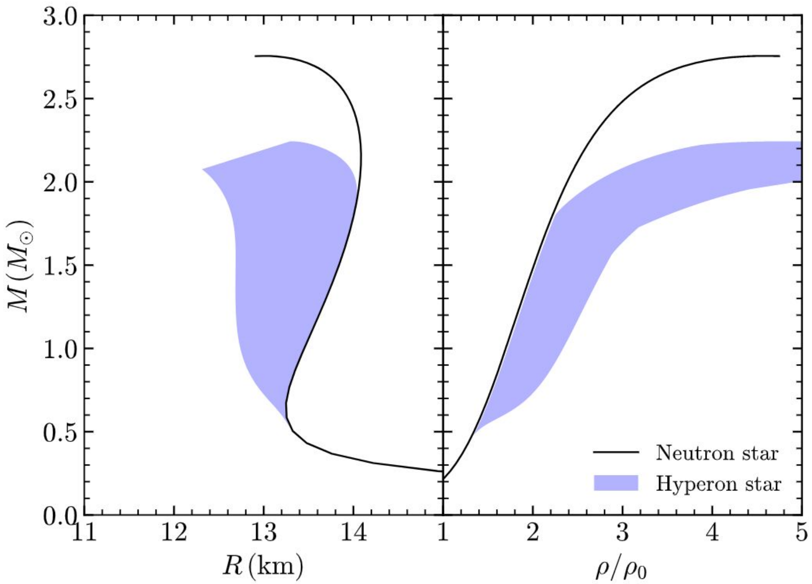


some quantitative features for hyperon stars in the light of the statistical results with NL3ωρ

- Taking the NL3ωρ one as an exemplary stiffest one;
- Only explore the preferred coupling constants of Λ hyperons, while keeping the Σ and Ξ hyperon couplings fixed to their empirical values.



threshold density of Λ hyperons: ~1.4-3.8ρ_0



Due to hyperons, the maximum mass is lowered by ~20% ($M_{\max} = 2.176^{+0.085}_{-0.202}\, M_\odot$; 68% credible interval);

And the steller radius is smaller above ~0.5 $M_\odot$ and grows with the stellar mass.

Summary on recent works

- developed microscopic NS EOSs connecting consistently nuclear experiments and GW+EM observations (入选2020年IOP高引论文);
- revealed preliminarily the complex structure of the dense core of NSs (对中子星半径的理论预言被NICER合作组引用);
- identified and relaxed the glitch crisis in the superfluity model (获《中国科学报》等报道);
- developed a set of quark star EOSs following the observed posterior mass distribution of binary NS mergers (被eXTP等白皮书引用);
- pointed out that GW170817 may have originated from the merger of double QSs (LIGO/Virgo合作组引用);
- matched laboratory hypernuclei data with astrophysical data for better understanding the EOS with hyperons; More hypernuclear data necessary to undersand hyperon interaction: theory+exp.+obs.!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Thank you.