多信使天文学时代的中子星状态方程研究

Ang LI 李昂
liang@xmu.edu.cn
Xiamen Univ.

Many thanks to Organizers!

第九届手征有效场论研讨会 2024年10月18日-22日 长沙

Aziz et al. AAPPS Bulletin (2021) 31:18
https://doi.org/10.1007/s43673-021-00018-z

AAPPS Bulletin
亚太物理学会联合会

Scope of nuclear astrophysics

Review article **Open Access**

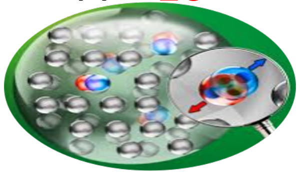
Progress in nuclear astrophysics of east and southeast Asia

Azni Abdul Aziz[1], Nor Sofiah Ahmad[2], S. Ahn[3], Wako Aoki[4], Muruthujaya Bhuyan[2], Ke-Jung Chen[5], Gang Guo[6,7], K. I. Hahn[8,9], Toshitaka Kajino[4,10,11*], Hasan Abu Kassim[2], D. Kim[12], Shigeru Kubono[13,14], Motohiko Kusakabe[11,15], A. Li[15], Haining Li[16], Z. H. Li[17], W. P. Liu[17*], Z. W. Liu[18], Tohru Motobayashi[14], Kuo-Chuan Pan[19,20,21,22], T.-S. Park[12], Jian-Rong Shi[16,23], Xiaodong Tang[24,25*], W. Wang[26], Liangjian Wen[27], Meng-Ru Wu[5,6], Hong-Liang Yan[16,23] and Norhasliza Yusof[2]

The important questions in our field include but not limited to :

- What is the origin of the elements in the cosmos?
- What is the nature of neutron stars and dense nuclear matter?
- What are the nuclear reactions that drive the evolution of stars and stellar explosions?

A ~ 10^{57}



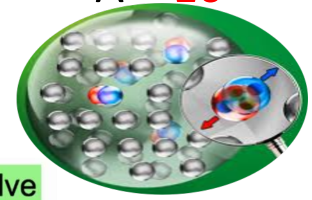
EoS, mainly $p(\rho)$

Solving nuclear many-body problem for the EoS: Not computable?

$$\hat{H}\Psi = E\Psi \qquad \Psi = \Psi(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_A;s_1,s_2,\ldots,s_A;t_1,t_2,\ldots,t_A)$$

3A nucleon coordinates in r-space | nucleon spins: ±1/2 | nucleon isospins (p or n): ±1/2

A ~ 10^{57}



micro

Green's Function Monte Carlo

Chiral Perturbation Theory (χPT)

V_{lowk} + Renormalization Group

Variational Many-Body (VMB)

Brueckner-Hartree-Fock (BHF)

…

pheno

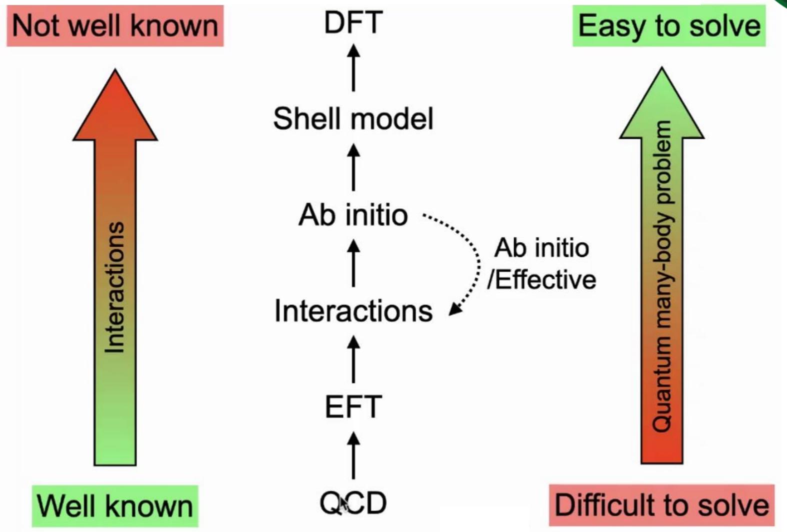
Quark mean-field (QMF)

Quark Meson Coupling (QMC)

Relativistic mean-field (RMF)

Skyrme energy density functional

…



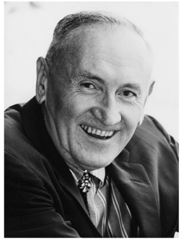
- Particle interactions are inadequate
- Theories of multi-body problem are still incomplete

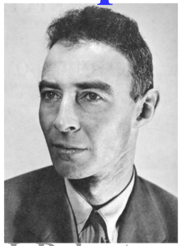
Neutron star can help!

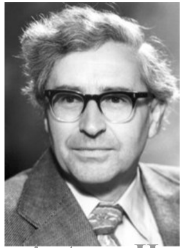

Lev Landau


James Chadwick


Walter Baade


Fritz Zwicky


J. Robert Oppenheimer


Antony Hewish


Dame Jocelyn Bell Burnell

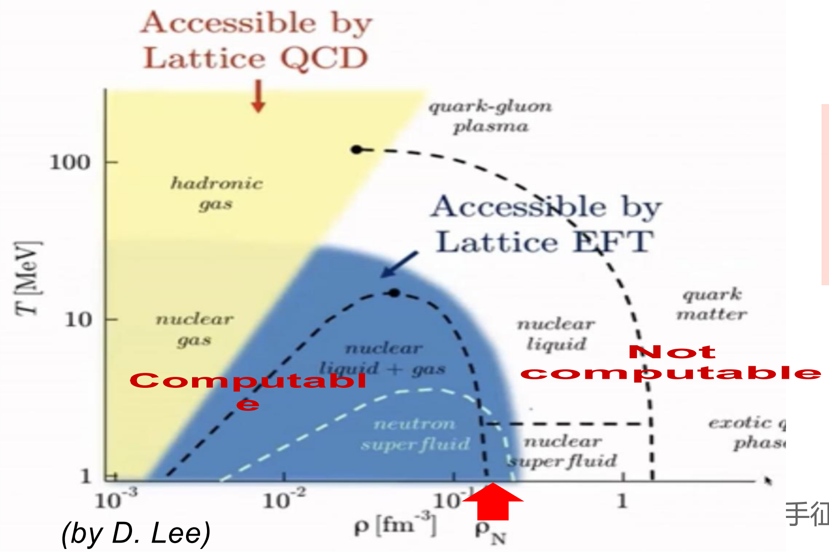
1932-

"the density of matter becomes so great that atomic nuclei come in close contact, forming one ***gigantic nucleus****."*

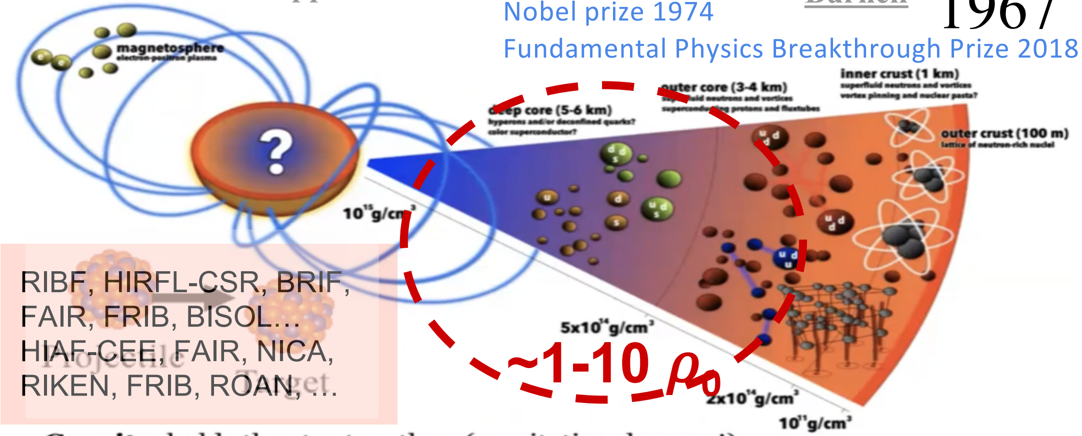
1967

Nobel prize 1974

Fundamental Physics Breakthrough Prize 2018



(by D. Lee)



RIBF, HIRFL-CSR, BRIF, FAIR, FRIB, BISOL…
HIAF-CEE, FAIR, NICA, RIKEN, FRIB, ROAN, …

Gravity, holds the star together (gravitational waves!)

Electromagnetism, makes pulsars pulse and magnetars flare

Strong interaction, determines the internal composition

Weak interaction, affects reaction rates - cooling and internal viscosity

GW, photons, neutrinos

LIGO/Virgo/KAGRA, CE, ET, NICER, eXTP, EP, SWOM, FAST, Tianma, QTT, SKA,...

Outline

- **Basic** for neutron star structure and the EoS
- **Recent works** towards the determination of the nuclear force and NS properties from **#multimessenger #multiwavength** astronomy
- **Take-home messages**

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

“new frontier”

Neutron star group @XMU “博新” 计划入选者2人

[arXiv:2408.15022](https://arxiv.org/abs/2408.15022) submitted
[arXiv:2402.02799](https://arxiv.org/abs/2402.02799) PRD
[arXiv:2312.17102](https://arxiv.org/abs/2312.17102) ApJ
[arXiv:2312.12185](https://arxiv.org/abs/2312.12185) ApJ
[arXiv:2312.04305](https://arxiv.org/abs/2312.04305) MNRAS
[arXiv:2305.16058](https://arxiv.org/abs/2305.16058) PRC
[arXiv:2305.08401](https://arxiv.org/abs/2305.08401) ApJ
[arXiv:2304.12050](https://arxiv.org/abs/2304.12050) PRD
[arXiv:2211.04978](https://arxiv.org/abs/2211.04978) PRD
[arXiv:2211.02007](https://arxiv.org/abs/2211.02007) ApJ
[arXiv:2205.10631](https://arxiv.org/abs/2205.10631) ApJ
[arXiv:2204.05560](https://arxiv.org/abs/2204.05560) ApJ
[arXiv:2203.04798](https://arxiv.org/abs/2203.04798) PRD
[arXiv:2201.12053](https://arxiv.org/abs/2201.12053) PRC
[arXiv:2108.00560](https://arxiv.org/abs/2108.00560) ApJ
[arXiv:2107.13997](https://arxiv.org/abs/2107.13997) ApJL
[arXiv:2107.07979](https://arxiv.org/abs/2107.07979) MNRAS
[arXiv:2103.15119](https://arxiv.org/abs/2103.15119) ApJ
[arXiv:2011.11934](https://arxiv.org/abs/2011.11934) ApJ
[arXiv:2009.12571](https://arxiv.org/abs/2009.12571) MNRAS
[arXiv:2007.05116](https://arxiv.org/abs/2007.05116) JHEAp (review)
[arXiv:2006.00839](https://arxiv.org/abs/2006.00839) ApJ
[arXiv:2005.12875](https://arxiv.org/abs/2005.12875) ApJS
[arXiv:2005.02677](https://arxiv.org/abs/2005.02677) PRD
[arXiv:2001.03859](https://arxiv.org/abs/2001.03859) PRC

Nucl_Astrophys_xmu (厦大天文核天体物理小组)

Zhenyu Zhu 朱镇宇

Many-body theory;
Merger simulation
Numerical relativity

Graduated in 2021;
postdoc in CCRG-RIT

Zhiqiang Miao 缪志强

NS oscillation
Hybrid star;
Bayesian analysis

Graduated in 2023;
postdoc in TDLee inst.

Zhonghao Tu 涂中豪

Superfluidity;
Neutron star cooling;
Nuclear pinning force

Wenli Yuan 苑文莉

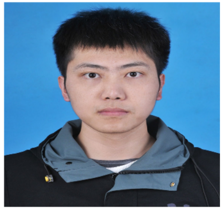
Quark star;

Graduated in 2023;
postdoc in PKU

Peng Liu 刘鹏

Glitch;
Pulsar observation

Xiangdong Sun 孙向东



Hyperon matter;
Many-body theory

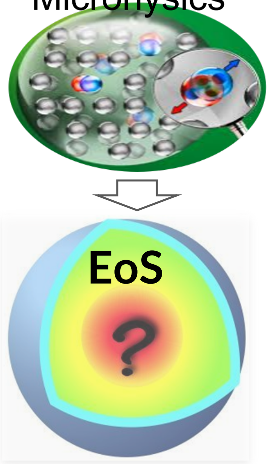
Shuochong Han 韩烁冲

Many-body theory;
Nuclear transport

https://astro.xmu.edu.cn/People/Faculty/la.htm

with 5 undergraduate students

some neutron star EM & GW observables have an intrinsic correlation with EoS



Hydrostatic equilibrium

(GR version)

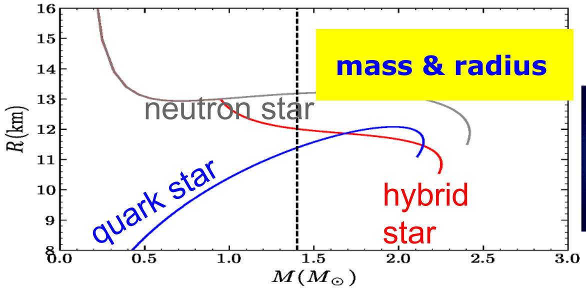
TOV eq.

Perturbed hydrostatic equilibrium

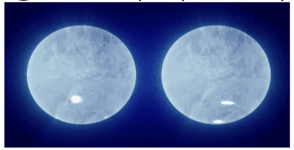
(Newtonian version)

Equations governing stellar structure :

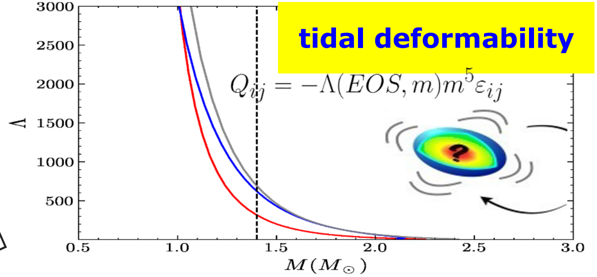
1. $\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$: hydrostatic pressure balance
2. ~~$\frac{dL}{dr} = 4\pi r^2 \rho[\epsilon_n(r) - \epsilon_\nu]$: energy generation~~
3. ~~$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2}$: energy transport~~
4. $P = P(\rho, T)$: equation of state
5. $\frac{dM}{dr} = 4\pi r^2 \rho$: mass-radius relation



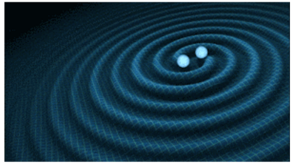
@NICER, ..., eXTP;



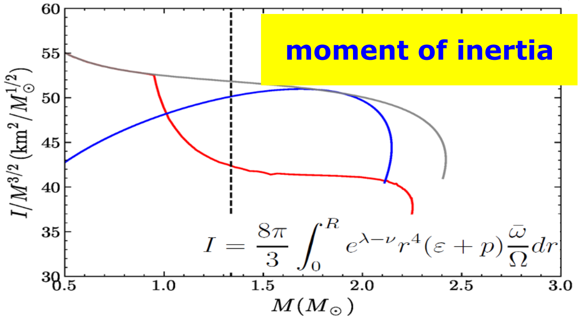
PSR J0030+0415
PSR J0740+6620



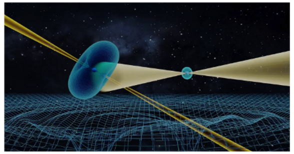
@LIGO/Virgo/KAGRA, ... CE, ET;



GW170817
GW190425



@平方公里陣列射電望遠鏡(SKA)



PSR J0737-3039

Combining uncertain measurements !

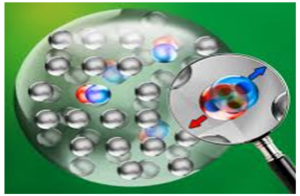
1. Model for interaction between particles

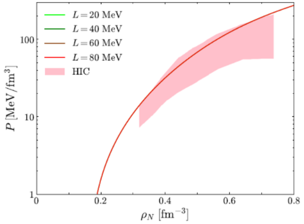
$\hat{\mathcal{H}}\Psi = E\Psi$

2. EoS prior pasting test

$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$

3. EoS inference from NS obs. (GW, photons, neutrinos)



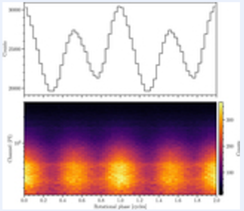


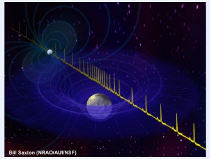
Posterior

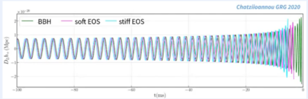
$p(\boldsymbol{\theta} | D, \mathbb{M})$

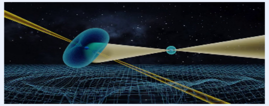
Parameter   Data   Mod

Physics on the EoS, the composition and the underlying strong interaction



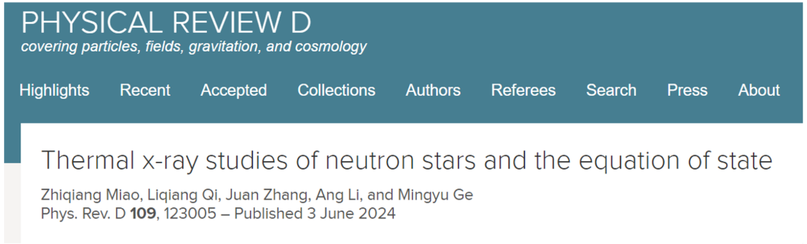


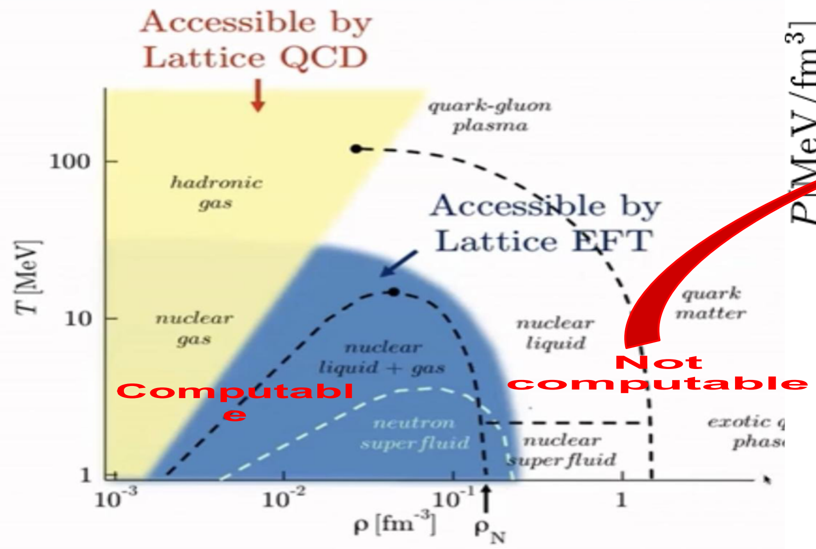


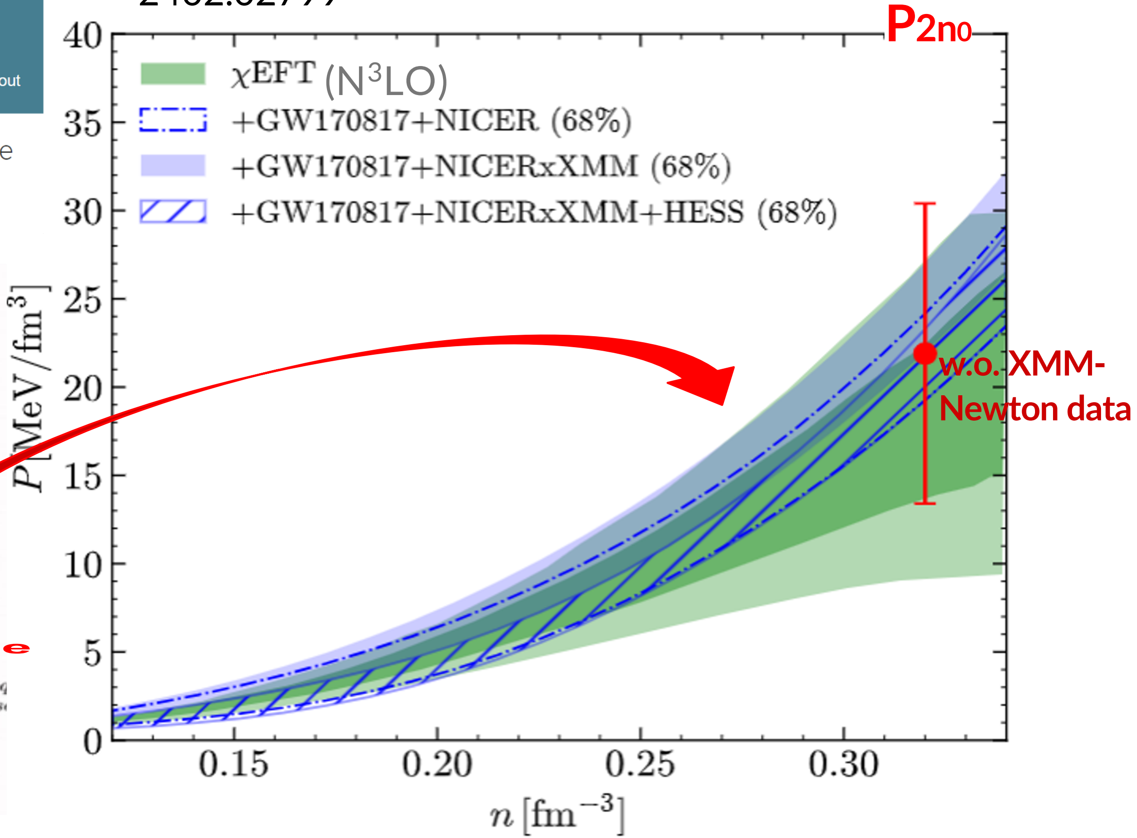


Constraint on the pressure at densities ~1-3n_0 effectively tightened

2402.02799





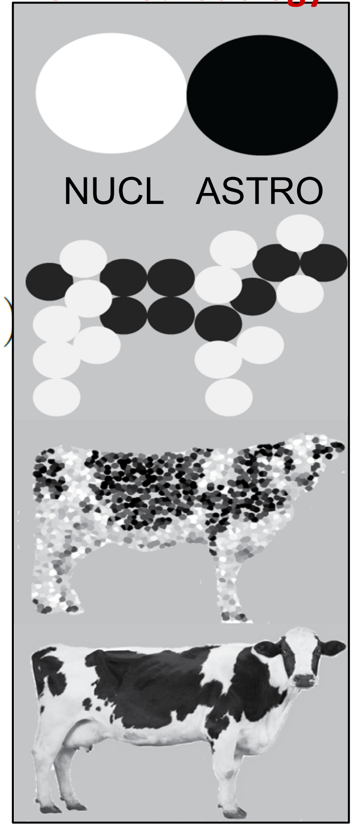


Bayesian inference of #hyperon couplings from combining (binary) NS observations with hypernuclei experiments

new methodology

$$\underbrace{p(\boldsymbol{\theta}|D,\mathbb{M})}_{\text{Posterior}} = \frac{\overbrace{\mathcal{L}(D|\boldsymbol{\theta},\mathbb{M})}^{\text{Likelihood}}\overbrace{\pi(\boldsymbol{\theta})}^{\text{Prior}}}{\int p(D|\boldsymbol{\theta},\mathbb{M})\pi(\boldsymbol{\theta})d\boldsymbol{\theta}}$$

Parameter ($\boldsymbol{\theta}$), Data (D), Model ($\mathbb{M}$)



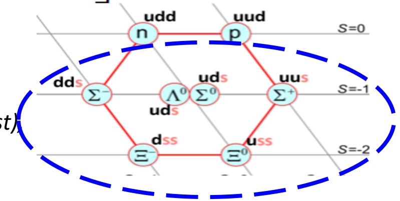
Likelihood

$$\mathcal{L}_{\mathrm{NICER}}(M,R|\boldsymbol{\theta}_{\mathrm{EOS}}\cup\{\varepsilon_c\},\mathbb{M}) = P_{\mathrm{KDE}}(M(\boldsymbol{\theta}_{\mathrm{EOS}};\varepsilon_c),R(\boldsymbol{\theta}_{\mathrm{EOS}};\varepsilon_c))$$

$$\mathcal{L}_{\mathrm{GW}}(d_{\mathrm{GW}}|\boldsymbol{\theta}_{\mathrm{GW}},\mathbb{M}) \propto \exp\left[-2\int_0^\infty \frac{|\tilde{d}(f)-\tilde{h}(f,\boldsymbol{\theta}_{\mathrm{GW}})|^2}{S_n(f)}df\right],$$

$$\mathcal{L}_{\mathrm{NUCL}}(d_{\mathrm{NUCL}}|\boldsymbol{\theta}_{\mathrm{EOS}}) \propto \exp\left[-\frac{1}{2}\frac{(R_{\sigma\Lambda}-\bar{R}_{\sigma\Lambda})^2}{\sigma^2_{R_{\sigma\Lambda}}}\right]$$

$$R_{mY} = g_{mY}/g_{mN}$$



#software

Bilby *(Ashton et al. 2019, version 0.5.5, https://git.ligo.org/lscsoft/bilby/),*
PyMultiNest *(Buchner 2016, version 2.6, https://github. com/JohannesBuchner/PyMultiNest),*
Toast *(Hernandez Vivanco et al. 2020, https://git.ligo.org/francisco.hernandez/toast),*
Corner *(Foreman-Mackey 2016, https://github.com/dfm/corner.py).*

The Astrophysical Journal, 942:55 (13pp), 2023 January 1 https://doi.org/10.3847/1538-4357/ac9d9a

2205.10631

Astrophysical Implications on Hyperon Couplings and Hyperon Star Properties with Relativistic Equations of States

Xiangdong Sun[1], Zhiqiang Miao[1], Baoyuan Sun[2], and Ang Li[1]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn
[2] Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China

From Referee "The present article addresses a long-standing issue in neutron star physics, namely the hyperon puzzle. The authors incorporate new information from hypernuclei calculations and **treat the hyperon couplings in a more general way** than what exists in the present literature. This is an interesting work that can have important future implications."

an RMF with density dependent couplings. The authors of Sun et al. (2023) have recently developed a Bayesian inference approach, in the framework of several nuclear RMF, to determine how GW and NICER measurements constrain the $\Lambda-\sigma$ and $\Lambda-\omega$ couplings, while fixing the Σ and Ξ couplings to reasonable values. A major advantage of this methodology is the possibility, once the inference is completed, to discuss the possible composition of matter or the nuclear properties. In the present study, we will base our approach

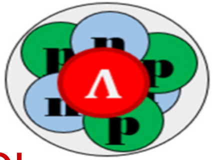
A **major advantage** of this methodology is the possibility, once the inference is completed, to discuss the possible composition of matter or the nuclear properties.

Huang, Raaijmakers, Watts, Tolos, & Providência, 2303.17518 MNRAS

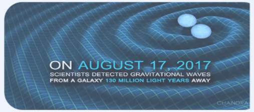
Combining (binary) NS observations with hypernuclei experiments

p(**θ**,D) ∝ π(**θ**) × L(D|**θ**,𝕄))

2205.10631

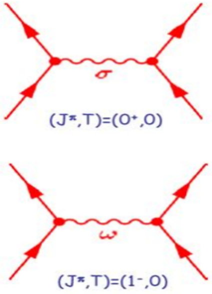


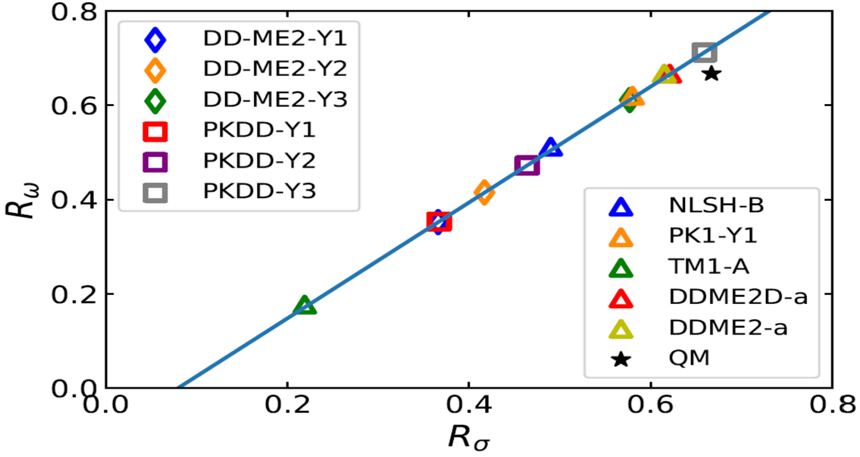
Formerly:
GW + X-ray



Presently: GW + X-ray + NUCL

$$\mathcal{L}_{\rm NUCL}(d_{\rm NUCL}|\boldsymbol{\theta}_{\rm EOS}) \propto \exp\left[-\frac{1}{2}\frac{(R_{\sigma\Lambda}-\bar{R}_{\sigma\Lambda})^2}{\sigma^2_{R_{\sigma\Lambda}}}\right]$$





Hypernuclei	Exp.
$^{12}_{\Lambda}$C	11.36 ± 0.20
$^{13}_{\Lambda}$C	12.0 ± 0.2
$^{16}_{\Lambda}$O	13.0 ± 0.2
$^{28}_{\Lambda}$Si	17.2 ± 0.2
$^{32}_{\Lambda}$S	17.5 ± 0.5
$^{40}_{\Lambda}$Ca	18.7 ± 1.1
$^{51}_{\Lambda}$V	21.5 ± 0.6
$^{52}_{\Lambda}$V	21.8 ± 0.3
$^{89}_{\Lambda}$Y	23.6 ± 0.5
$^{139}_{\Lambda}$La	25.1 ± 1.2
$^{208}_{\Lambda}$Pb	26.9 ± 0.8

Span uncertainty in hyperon couplings

2205.10631

#parameters and priors

$$\boldsymbol{\theta}_{\rm EOS} = \{R_{\sigma\Lambda}, R_{\omega\Lambda}\}$$
$$R_{\sigma\Lambda} \sim U[0,1]$$
$$\text{and } R_{\omega\Lambda} \sim U[0,1]$$

- ONLY explore the couplings of Λ hyperons: >~40 Λ hypernuclei;
- Keep Σ, Ξ hyperon couplings fixed to their empirical values or based on SU(3) symmetry;
- Future: +a few ΛΛ hypernuclei, Ξ hypernuclei

#posteriors

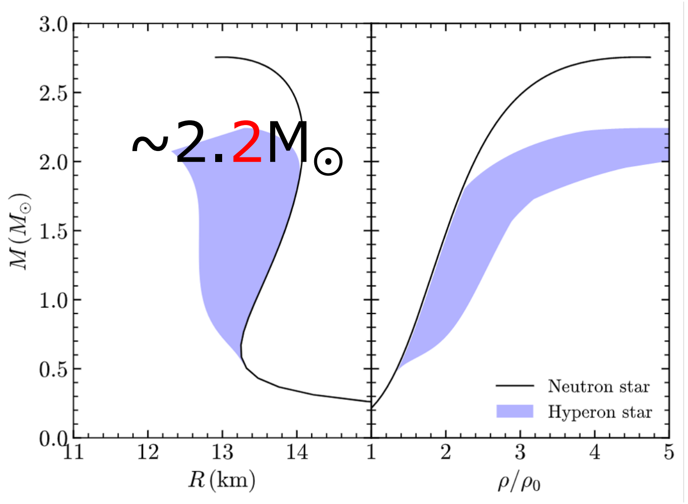
Most Probable Intervals of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ (68% Credible Intervals)

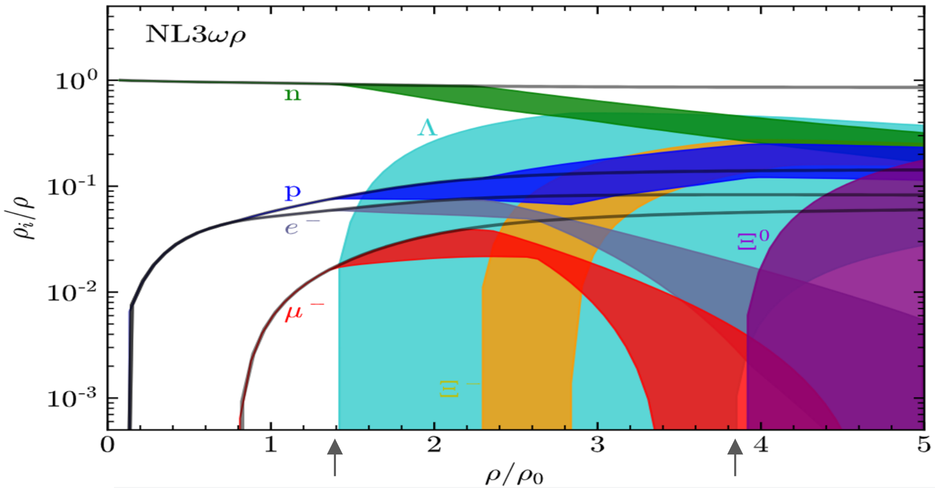
EOS	+NICER		+NICER +NUCL		+NICER +GW170817		+NICER +GW170817 +NUCL	
	$R_{\sigma\Lambda}$	$R_{\omega\Lambda}$	$R_{\sigma\Lambda}$	$R_{\omega\Lambda}$	$R_{\sigma\Lambda}$	$R_{\omega\Lambda}$	$R_{\sigma\Lambda}$	$R_{\omega\Lambda}$
LHS	$0.821^{+0.125}_{-0.463}$	$0.755^{+0.073}_{-0.155}$	$0.865^{+0.074}_{-0.208}$	$0.658^{+0.130}_{-0.194}$	$0.941^{+0.035}_{-0.048}$	$0.763^{+0.034}_{-0.028}$	$0.658^{+0.163}_{-0.251}$	$0.752^{+0.049}_{-0.095}$
RMF201	$0.760^{+0.186}_{-0.520}$	$0.759^{+0.081}_{-0.224}$	$0.658^{+0.172}_{-0.249}$	$0.672^{+0.138}_{-0.215}$	$0.949^{+0.032}_{-0.056}$	$0.769^{+0.035}_{-0.028}$	$0.842^{+0.090}_{-0.250}$	$0.754^{+0.061}_{-0.136}$
NL3	$0.424^{+0.330}_{-0.293}$	$0.746^{+0.156}_{-0.261}$	$0.681^{+0.171}_{-0.247}$	$0.768^{+0.136}_{-0.214}$	$0.399^{+0.379}_{-0.291}$	$0.794^{+0.128}_{-0.216}$	$0.765^{+0.130}_{-0.191}$	$0.840^{+0.101}_{-0.163}$
Hybrid	$0.363^{+0.381}_{-0.265}$	$0.807^{+0.132}_{-0.276}$	$0.750^{+0.130}_{-0.179}$	$0.865^{+0.096}_{-0.157}$	$0.305^{+0.388}_{-0.217}$	$0.764^{+0.143}_{-0.254}$	$0.777^{+0.118}_{-0.181}$	$0.869^{+0.090}_{-0.147}$
TM2	$0.311^{+0.330}_{-0.221}$	$0.751^{+0.179}_{-0.494}$	$0.736^{+0.145}_{-0.201}$	$0.856^{+0.102}_{-0.193}$	$0.323^{+0.487}_{-0.237}$	$0.784^{+0.158}_{-0.300}$	$0.772^{+0.137}_{-0.239}$	$0.870^{+0.086}_{-0.204}$
NLSV1	$0.252^{+0.285}_{-0.183}$	$0.756^{+0.167}_{-0.281}$	$0.688^{+0.117}_{-0.227}$	$0.863^{+0.100}_{-0.199}$	$0.247^{+0.279}_{-0.177}$	$0.744^{+0.182}_{-0.259}$	$0.689^{+0.122}_{-0.225}$	$0.866^{+0.100}_{-0.206}$
PK1	$0.254^{+0.273}_{-0.185}$	$0.756^{+0.172}_{-0.250}$	$0.687^{+0.139}_{-0.222}$	$0.869^{+0.099}_{-0.216}$	$0.248^{+0.271}_{-0.170}$	$0.754^{+0.176}_{-0.247}$	$0.683^{+0.130}_{-0.220}$	$0.867^{+0.101}_{-0.222}$
NL3$\omega\rho$	$0.384^{+0.393}_{-0.280}$	$0.773^{+0.147}_{-0.247}$	$0.690^{+0.163}_{-0.208}$	$0.759^{+0.131}_{-0.176}$	$0.420^{+0.448}_{-0.294}$	$0.777^{+0.127}_{-0.269}$	$0.712^{+0.157}_{-0.215}$	$0.778^{+0.121}_{-0.183}$
S271v6	$0.287^{+0.290}_{-0.207}$	$0.775^{+0.158}_{-0.232}$	$0.750^{+0.105}_{-0.144}$	$0.886^{+0.080}_{-0.128}$	$0.304^{+0.286}_{-0.083}$	$0.782^{+0.157}_{-0.230}$	$0.740^{+0.118}_{-0.161}$	$0.884^{+0.083}_{-0.147}$
HC	$0.266^{+0.253}_{-0.192}$	$0.517^{+0.316}_{-0.370}$	$0.733^{+0.110}_{-0.156}$	$0.902^{+0.070}_{-0.134}$	$0.266^{+0.304}_{-0.189}$	$0.783^{+0.157}_{-0.226}$	$0.737^{+0.106}_{-0.160}$	$0.902^{+0.072}_{-0.134}$
DD- LZ1	$0.298^{+0.321}_{-0.218}$	$0.775^{+0.152}_{-0.251}$	$0.769^{+0.122}_{-0.190}$	$0.871^{+0.083}_{-0.148}$	$0.327^{+0.381}_{-0.223}$	$0.792^{+0.142}_{-0.254}$	$0.772^{+0.128}_{-0.177}$	$0.870^{+0.087}_{-0.139}$
DD-ME2	$0.275^{+0.337}_{-0.192}$	$0.771^{+0.167}_{-0.299}$	$0.770^{+0.120}_{-0.172}$	$0.885^{+0.078}_{-0.137}$	$0.267^{+0.345}_{-0.188}$	$0.776^{+0.160}_{-0.237}$	$0.767^{+0.128}_{-0.168}$	$0.883^{+0.079}_{-0.124}$
DD2	$0.292^{+0.346}_{-0.205}$	$0.775^{+0.163}_{-0.252}$	$0.783^{+0.121}_{-0.173}$	$0.901^{+0.071}_{-0.135}$	$0.305^{+0.392}_{-0.221}$	$0.785^{+0.153}_{-0.276}$	$0.789^{+0.119}_{-0.157}$	$0.900^{+0.069}_{-0.120}$
PKDD	$0.267^{+0.347}_{-0.185}$	$0.806^{+0.140}_{-0.244}$	$0.820^{+0.095}_{-0.153}$	$0.930^{+0.051}_{-0.090}$	$0.282^{+0.420}_{-0.210}$	$0.813^{+0.136}_{-0.248}$	$0.835^{+0.102}_{-0.147}$	$0.932^{+0.047}_{-0.083}$
FKVW	$0.327^{+0.343}_{-0.236}$	$0.677^{+0.217}_{-0.260}$	$0.647^{+0.196}_{-0.250}$	$0.706^{+0.171}_{-0.211}$	$0.353^{+0.356}_{-0.240}$	$0.696^{+0.272}_{-0.203}$	$0.658^{+0.177}_{-0.254}$	$0.716^{+0.158}_{-0.217}$
PC-PK1	$0.283^{+0.310}_{-0.210}$	$0.701^{+0.215}_{-0.134}$	$0.650^{+0.150}_{-0.205}$	$0.770^{+0.147}_{-0.214}$	$0.282^{+0.319}_{-0.211}$	$0.703^{+0.212}_{-0.139}$	$0.651^{+0.148}_{-0.208}$	$0.771^{+0.146}_{-0.215}$
OMEG	$0.272^{+0.298}_{-0.194}$	$0.778^{+0.156}_{-0.244}$	$0.726^{+0.117}_{-0.171}$	$0.880^{+0.089}_{-0.153}$	$0.273^{+0.275}_{-0.188}$	$0.775^{+0.163}_{-0.242}$	$0.731^{+0.119}_{-0.167}$	$0.889^{+0.082}_{-0.152}$

Current status of the hypernuclear matter and hyperon star properties due to the uncertain hyperon interaction

- Taking the NL3ωρ one as an exemplary stiffest one;

2205.10631





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.

threshold density of Λ hyperons: 1.4-3.8ρ_0

Unclear whether Λ or Ξ− appear first.

Comprehensive analysis of multi-messenger, multi-wavelength data ongoing to probe the EoS at different density regimes (2021-)

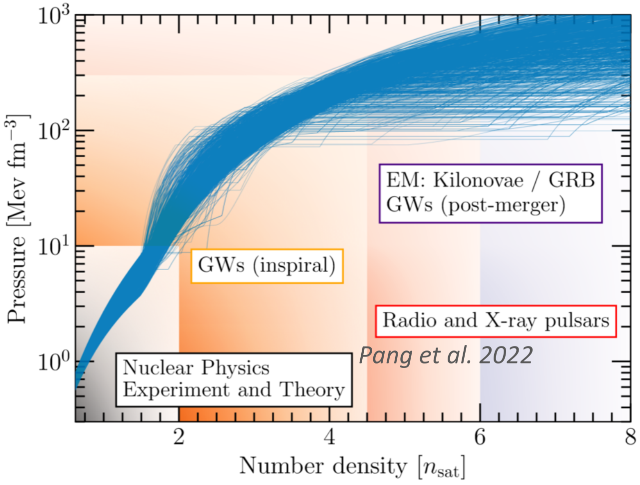
Data:

GW event of GW170817(+GW190425) & **kilonova** light curve of AT2017gfo,

NICER⊠⊠**×XMM-Newton**'s measurement of mass and radius of 2 PSRs,

(Mocked) **SKA**'s moment of inertia measurement on PSR J0737-3039,

Neutron-skin from PREX-II, CREX and the ab initio predictions on ^{208}Pb, ^{48}Ca;



2021 2024 2022 2023

Massive PSRs (radio)
+ GW (static tide)
+ X-ray (NICER)
2103.15119

+mocked MoI (radio)
2107.07979
+DM
2204.05560

+n skin
2305.16058
+hypernuclei
2205.10631
+kilonova (optical+)
2211.02007

+GW (dynamic tide)
2305.08401
+X-ray (XMM-Newton)
2402.02799

What we learn so far: short summary

- ❑ Produce self-consistent framework for EoS modeling
- ❑ Check if constraints from all available constrains are fulfilled

  Demonstrate the consistency between laboratory and astrophysical nuclear matter in neutron stars by considering low-density nuclear physics constraints (from ^{208}Pb neutron-skin thickness) and high-density astrophysical constraints (from neutron star global properties).
- ❑ Prepare priors for a set of EoS parameters, also incorporating phase transitions
- ❑ Statistically establish the effective stiffness of neutron star EoS

  General requirements adopted (e.g., causality) indicate the EoS is moderately stiff, with sound speed squared peaked at $\sim 0.8c_s^2$ in NS matter, not subject to the type of phase transitions.
- ❑ Examine whether current data favour strong 1st-order phase transition inside NS cores

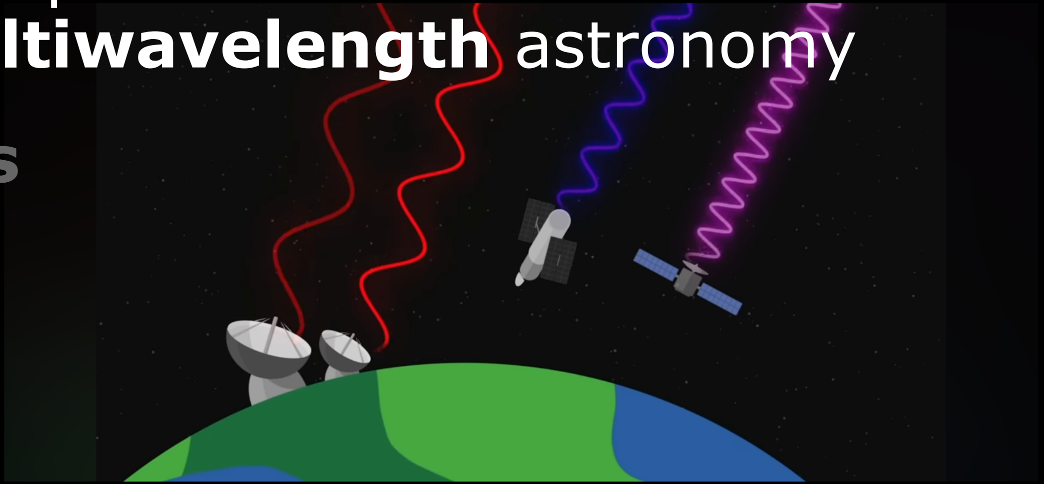
  Current data compatible with both possibilities; Evidence of a phase transition strengthened for stiff hadronic EoSs (like DD2).
- ❑ Confront single Λ-hypernuclei data with the neutron star observational data

  With the relaxation of the commonly-assumed SU(3) symmetry, the data of single Λ hypernuclei ensures a large enough scalar hyperon coupling to match the large vector hyperon coupling;
- ❑ Suggest possibility to distinguish neutron stars with quark stars from simultaneous measurement of the stellar radius and the moment of inertia

  If the MOI is measured large for PSR J0737-3039 A, $I_A \gtrsim 1.4\times10^{45}$g cm^2, it is most likely a quark star rather than a neutron star with or without a quark core, provided that the accuracy of the radius measurement is at least~1 km.
- ❑ Comprehensive analysis of multi-messenger, multi-wavelength data ongoing to probe the EoS at different density regimes…

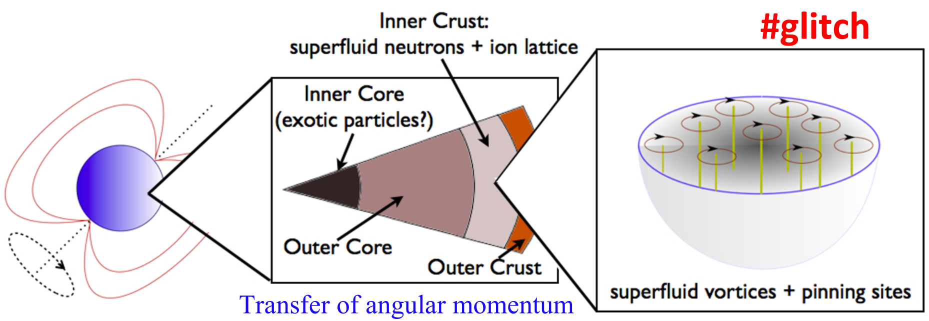
Outline

- **Basic** for neutron star structure and the EoS
- **Recent works** towards the determination of the nuclear force and NS properties from #multimessenger **#multiwavelength** astronomy
- **Take-home messages**



A realistic calculation of NS dynamics must go beyond the EoS relation!

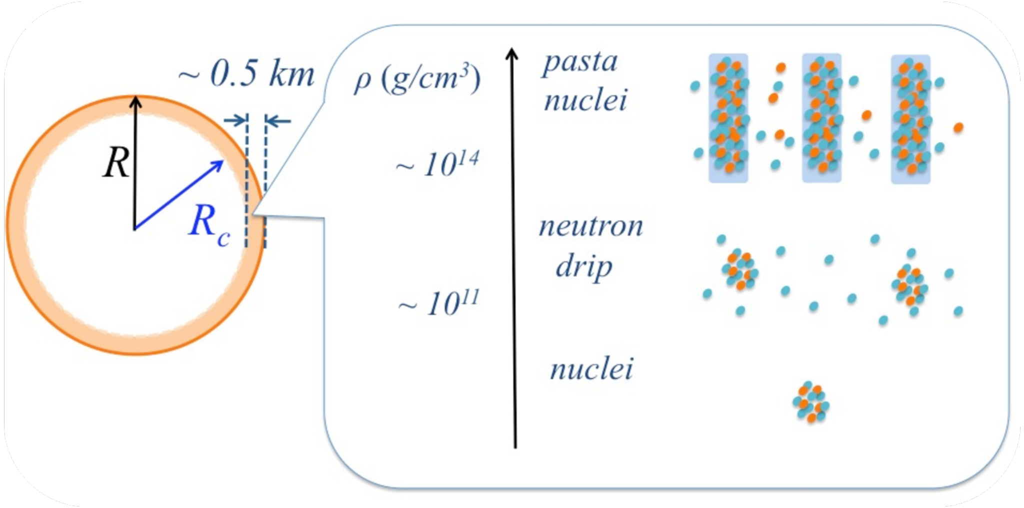
- Although the EoS, i.e., ε = ε(p) is the only relation required from the thermodynamics to solve the TOV eq., it is NOT sufficient to describe the complete thermodynamical state of NS matter;



Transfer of angular momentum from the neutron superfluid to the rest of the star

- Idealy, all stellar matter should be described with SAME nuclear interaction, e.g., unified EOS:

A bulk part obtained from the (BHF) calculations for core **uniform** nuclear matter,
PLUS
+the phenomenological **surface** part,
+the **Coulomb** part,
+the **spin-orbit** part,
+the **pairing**
for **non-uniform** nuclear matter at crust.

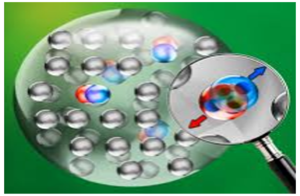


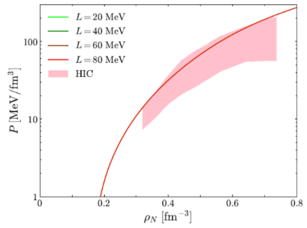
From nuclear force to multimessenger/multiwavelength astronomy

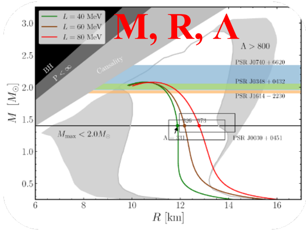
$$\hat{\mathcal{H}}\Psi = E\Psi$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

1. Model for interaction between particles → **2. The EoS p(ρ)** → **3. NS observations on #global properties (GW, photons, neutrinos)**



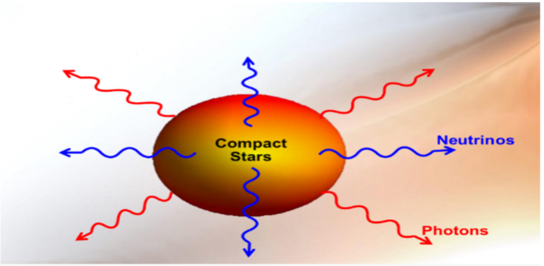




plus

-s. p. properties (e.g., neutron superfluidity);

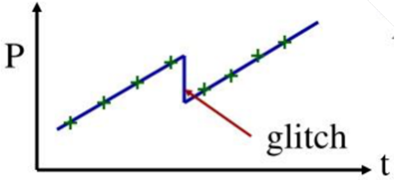
-thermal conductivity; specific heat capacity; bulk/shear viscosity; neutrino emissivity;...



NS dynamiccs:

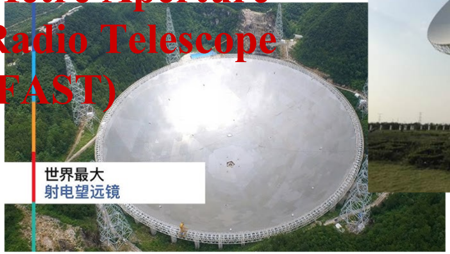
e.g., pulsar glitch (this talk)

周期跃变



Connecting to real telescope data

Five Hundred Metre Aperture Radio Telescope (FAST)



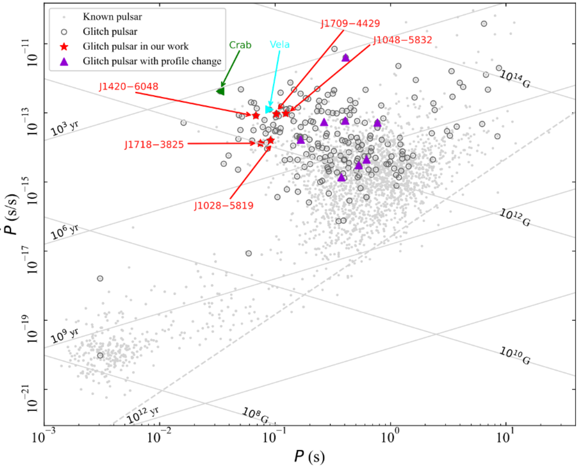
Tian Ma 65-m Radio Telescope

NanShan 25-m Radio Telescope

Fermi Gamma-ray Space Telescope

Parkes 64-m Radio Telescope

MeerKAT radio telescope

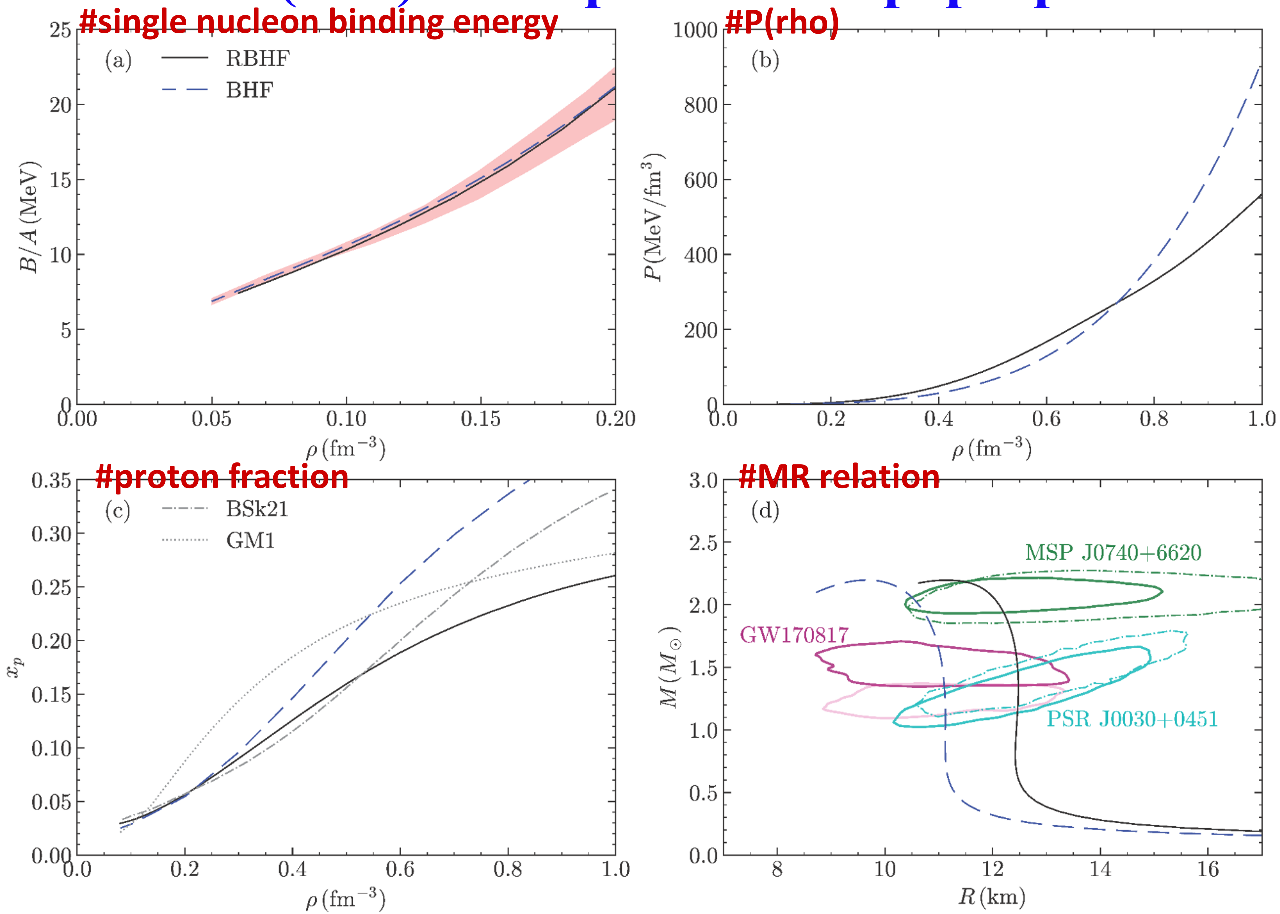


To date ~679 glitches in ~226 objects reported in the Jodrell Bank catalogue, http://www.jb.man.ac.uk/pulsar/glitches/gTable.html

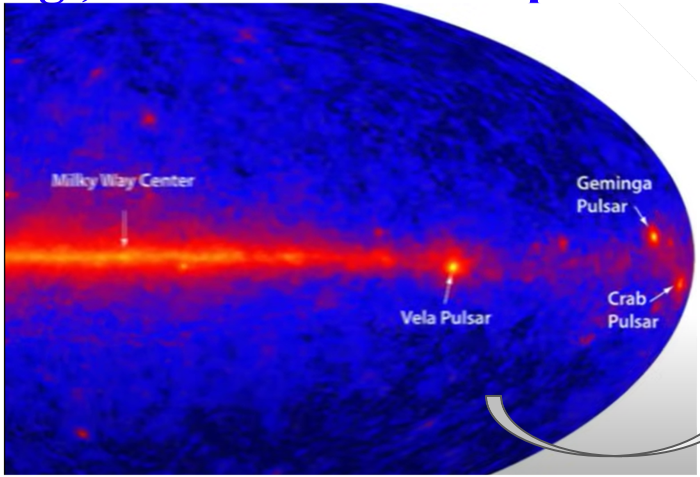
Realistic NS model: Bulk (EoS) + composition + s.p. properties

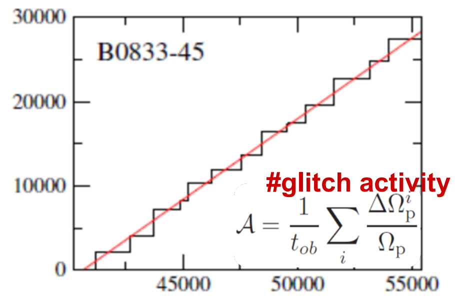
- **Input**: Bare NN interaction (AV18, Bonn,...) and many-body forces;
- State-of-art (BHF) calculation of the thermodynamics of dense nuclear matter provides NS properties consistent with astrophysical observations on e.g., mass, radius, tidal deformability.

2108.00560

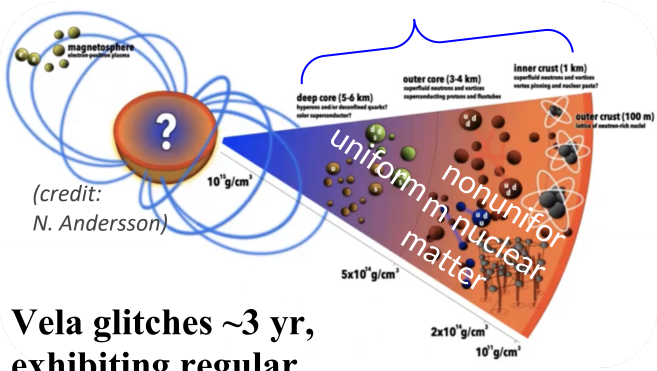


e.g., structure of Vela pulsar (spin period 89.33 ms) from unified BHF EOS





The accumulated $\sum_i \Delta\Omega_p^i/\Omega_p$ ($\times 10^{-9}$) as a function of the modified Julian date



(credit: N. Andersson)

Vela glitches ~3 yr, exhibiting regular, GIANT glitches.

1512.00340

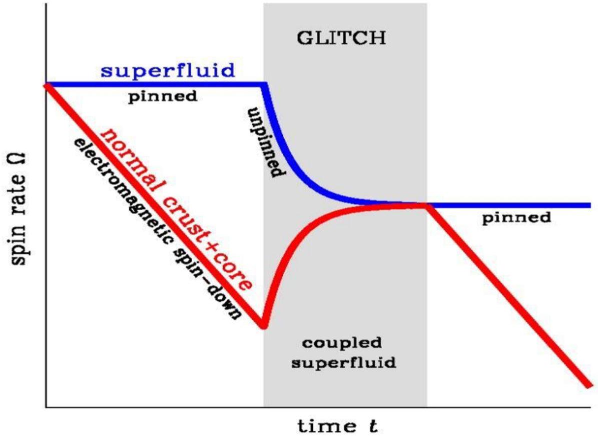
Mass	Cent.	Mass			Radius				Moment of Inertia	
		Core 核心	icrust 内壳层	ocrust 外壳层	Total	Core 核心	icrust 内壳层	ocrust 外壳层	Total	Fraction
1.0	0.403	[illegible]	[illegible]	[illegible]	11.79	[illegible]	[illegible]	[illegible]	0.894	5.33
1.1	0.427	1.08	0.024	4.15	11.80	10.50	0.73	0.57	1.029	4.51
1.2	0.452	1.18	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

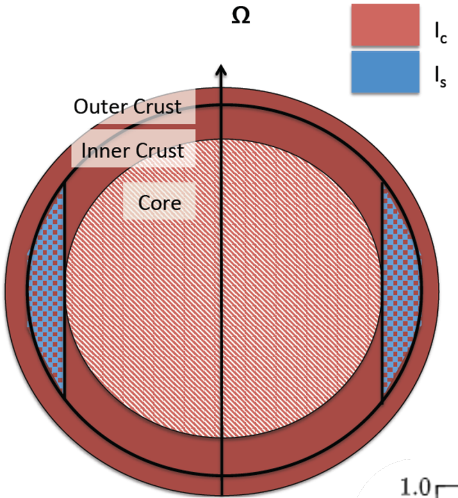
$\times 10^{-5}$

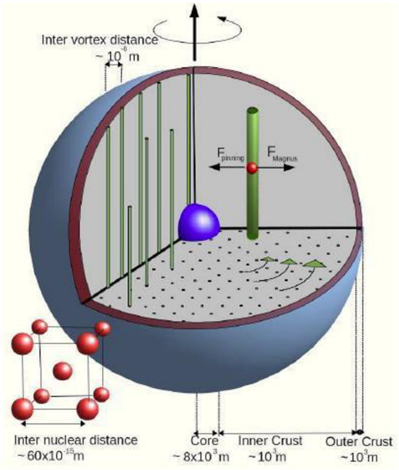
$\times 10^{45}$ g/cm^2

Microphysical state of the matter and the glitch

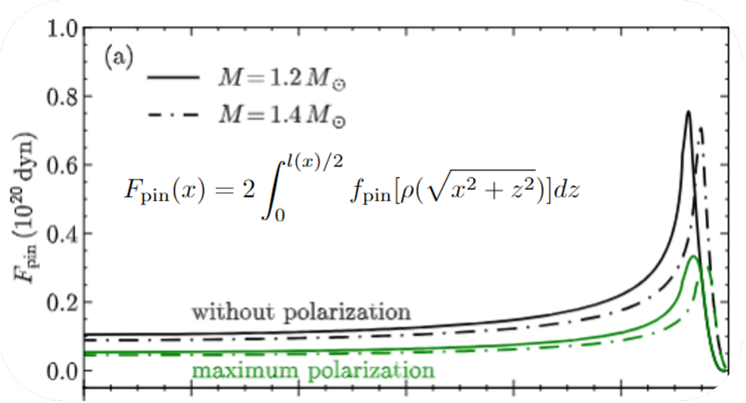
#the two-component model







Decouple/Recouple/Decouple/Recouple…



- Superfuid near the surface, from neutron drip density (4×10^{11} g/cm^3) to nuclear saturation density (2.8×10^{14}g/cm^3) in $^1S_0$ state: microphysical state of the matter needed;
- **Pinned**/Unpinned/Pinned/Unpinned…

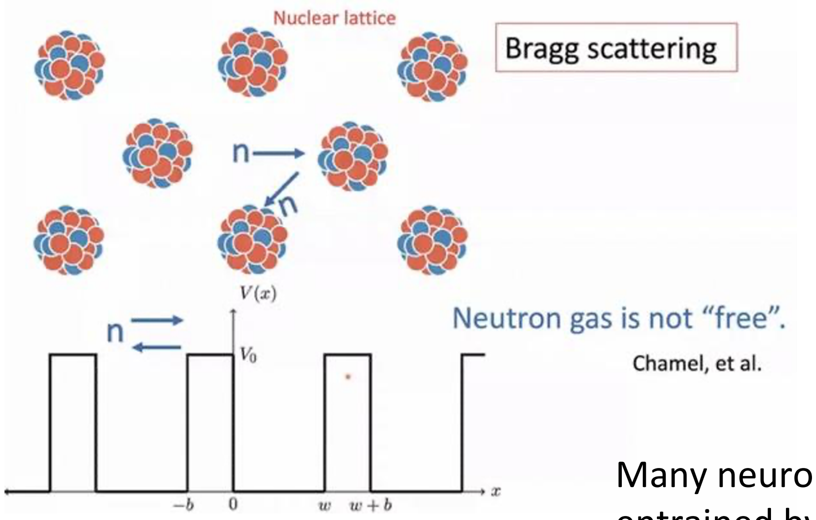
Glitch crisis? Is there enough superfluid reservoir?

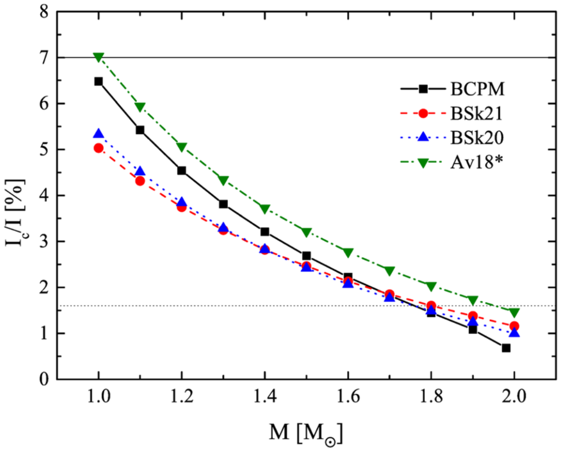
Require enough angular momentum transferred to trigger big Vela-like glitches:

$$2\tau_c A_g \lesssim \frac{I_n}{I_p}$$

PSR	τ_c (kyr)	$\mathcal{A}$ ($\times 10^{-9}/d$)	I_n/I (%)
J0537-6910	4.93	2.40	0.9
B0833-45 (Vela)	11.3	1.91	1.6
J0631+1036	43.6	0.48	1.5
B1338-62	12.1	1.31	1.2
B1737-30	20.6	0.79	1.2
B1757-24	15.5	1.35	1.5
B1758-23	58.4	0.24	1.0
B1800-21	15.8	1.57	1.8
B1823-13	21.5	0.78	1.2
B1930+22	38.8	0.95	2.7
J2229+6114	10.5	0.63	0.5

Andersson et al. 2012





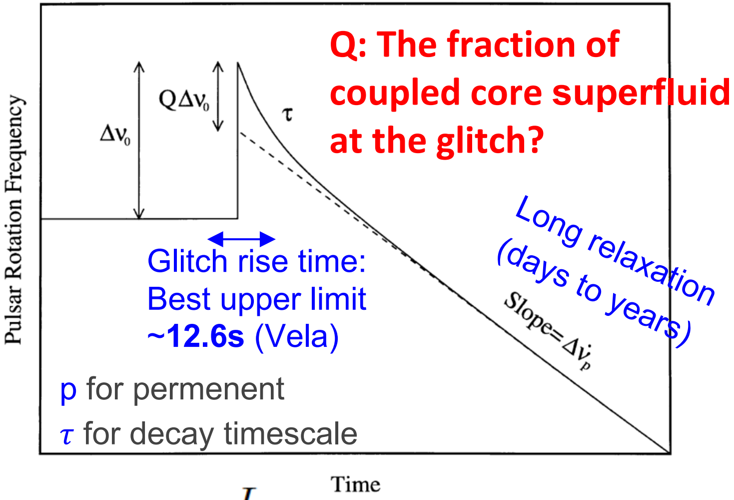
Many neurons are entrained by crust;

Entrainment reduce I_n by factor of ~5

1512.00340

Testing the standard superfluid glitch theory go beyond the two-component model

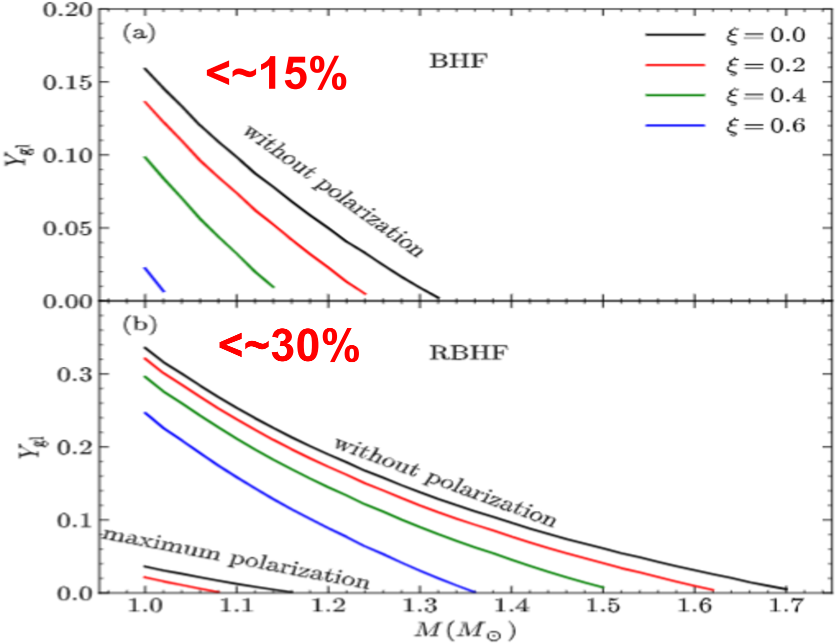
2108.00560

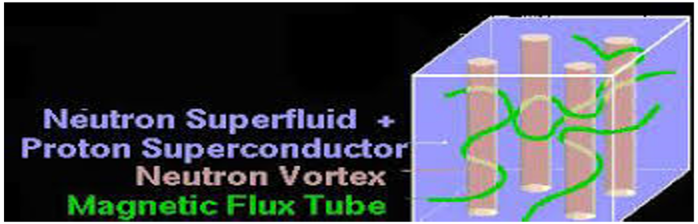


$$2\tau_c A_g \lesssim \frac{I_n}{I_p}$$

- Entrainment reduce I_n by factor of ~5;
- I_p reduced by factor of 2~1000, since core superfluid coupling on timescales larger than glitch rise time.

NO crisis even with entrainment!





Is it possible to fit both the glitch size and the short-term relaxation from the 2000 Vela glitch?

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

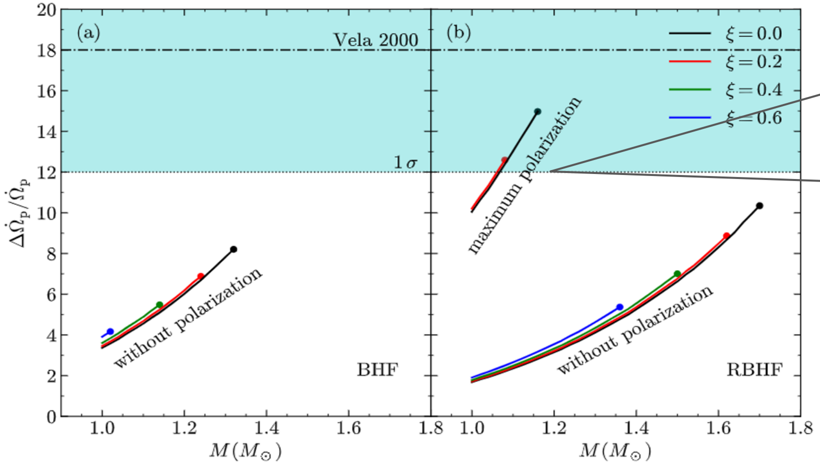
The Astrophysical Journal, 923:108 (9pp), 2021 December 10
https://doi.org/10.3847/1538-4357/ac2e94

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

Xinle Shang[1,2] and Ang Li[3]
[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
[2] CAS Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
[3] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn

Glitch size
+
short-time relaxation

$$\frac{\Delta\dot{\Omega}_p}{\dot{\Omega}_p} = \frac{Q(1-Y_{gl})}{1-Q(1-Y_{gl})}$$



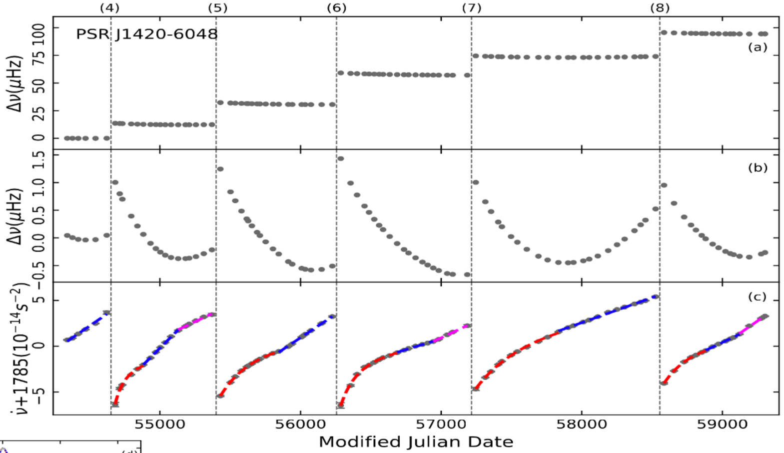
possible if

- a small fraction (less than~30%) of pinned neutron vorticity in the stellar core;
- a strong suppression/reduction of the **pairing gap in the nuclear medium**;
- a stiff **EoS** (resulting in a typical stellar radius larger than~12.5 km).

To quantitatively determine the EoS from connecting consistently nuclear physics and astronomy

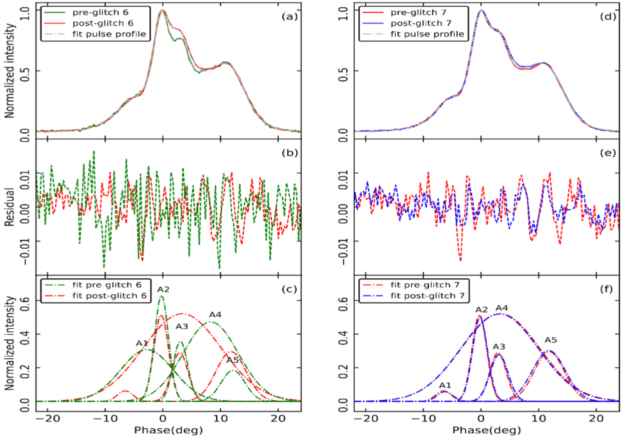
#NEW glitch event

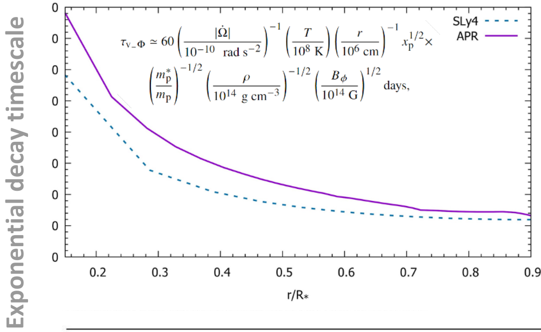
Pulsar Name (PSR)	Gl. No.	Epoch (MJD)	$\Delta\nu/\nu$ (10^{-9})	$\Delta\dot{\nu}/\dot{\nu}$ (10^{-3})	NEW? (Y/P)	Q	τ_d (d)	RMS (μs)	Data span (MJD)
J1028−5819	1	57904(6)	2284.1(5)	20(2)	P	0.0061(2)	62(7)	624	57359 – 58243
J1420−6048	4	54653(19)	940(3)	6.5(12)	P	0.0122(2)	49(27)	28	54879 – 54562
	5	55400(9)	1366(3)	5.1(8)	P	0.016(1)	212(148)	605	55035 – 55765
	6	56256(1)	1974(4)	15(3)	P	0.011(2)	20(4)	1619	55747 – 56731
	7	57216(12)	1206(3)	5.0(4)	P	0.016(2)	93(15)	813	56853 – 57752
	8	58555(2)	1481(2)	6.3(5)	P	0.0097(1)	69(17)	332	58136 – 58842
J1709−4429	4	54691(2)	2777(4)	63(15)	P	0.0103(5)	72(4)	819	55415 – 55167
						0.006(3)	4(1)		
	5	56339(2)	2962(2)	9.7(5)	P	0.0079(4)	60(5)	833	56025 – 56663
	6	58175(2)	2438(2)	12(1)	P	0.0066(4)	33(5)	1202	57980 – 58523
J1718−3825	1	54952(44)	1.8(1)	-0.47(3)	P	–	–	186	54498 – 55400
	2	57950(14)	7.7(1)	-0.17(3)	P	–	–	148	57309 – 58410
	3	59121(8)	2.0(1)	-0.32(4)	Y	–	–	138	58578 – 59962



#NEW relaxation behaviour

#NEW correlation between pre- and post-glitch



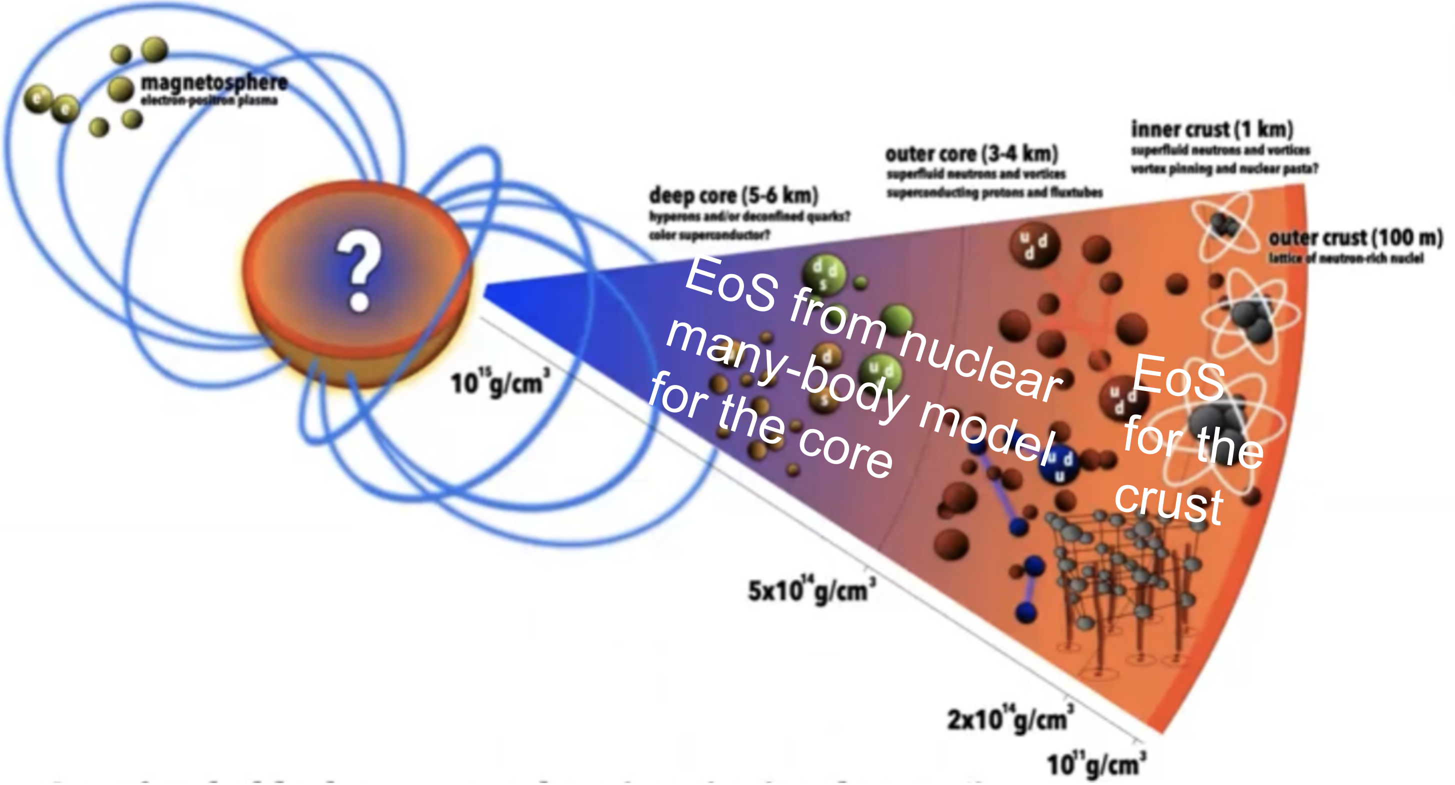


$$\tau_{v-\Phi} \simeq 60 \left(\frac{|\dot{\Omega}|}{10^{-10}\ \mathrm{rad\ s^{-2}}}\right)^{-1} \left(\frac{T}{10^8\ \mathrm{K}}\right) \left(\frac{r}{10^6\ \mathrm{cm}}\right)^{-1} x_p^{1/2} \times \left(\frac{m_p^*}{m_p}\right)^{-1/2} \left(\frac{\rho}{10^{14}\ \mathrm{g\ cm^{-3}}}\right)^{-1/2} \left(\frac{B_\phi}{10^{14}\ \mathrm{G}}\right)^{1/2} \mathrm{days},$$

#NEW connection with EoS microphysics

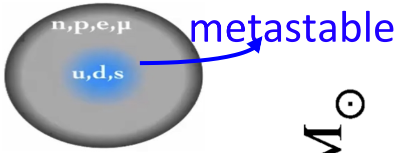
Glitch No	$t_{ig,obs}$ (days)	t_g (days)	I_A/I (10^{-3})	I_B/I (10^{-3})	I_{cs}/I (10^{-2})
6	2261(19)	2290(69)	2.48(1)	16.6(7)	3.13(7)
7	2456(26)	2661(405)	2.05(22)	15.6(25)	2.60(25)

The context
in most of the studies

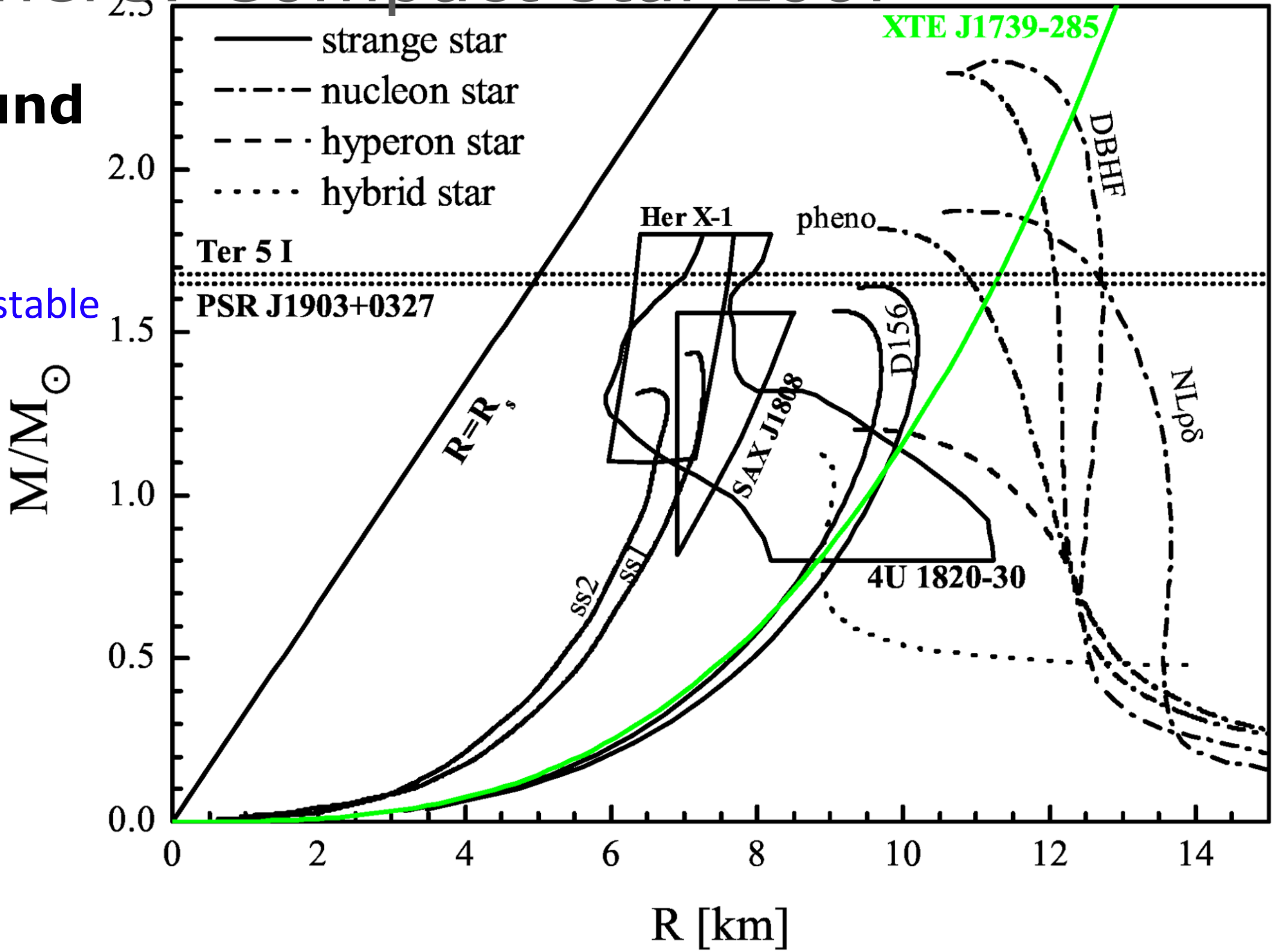


Caution here: Compact star zoo!

gravity-bound



self-bound

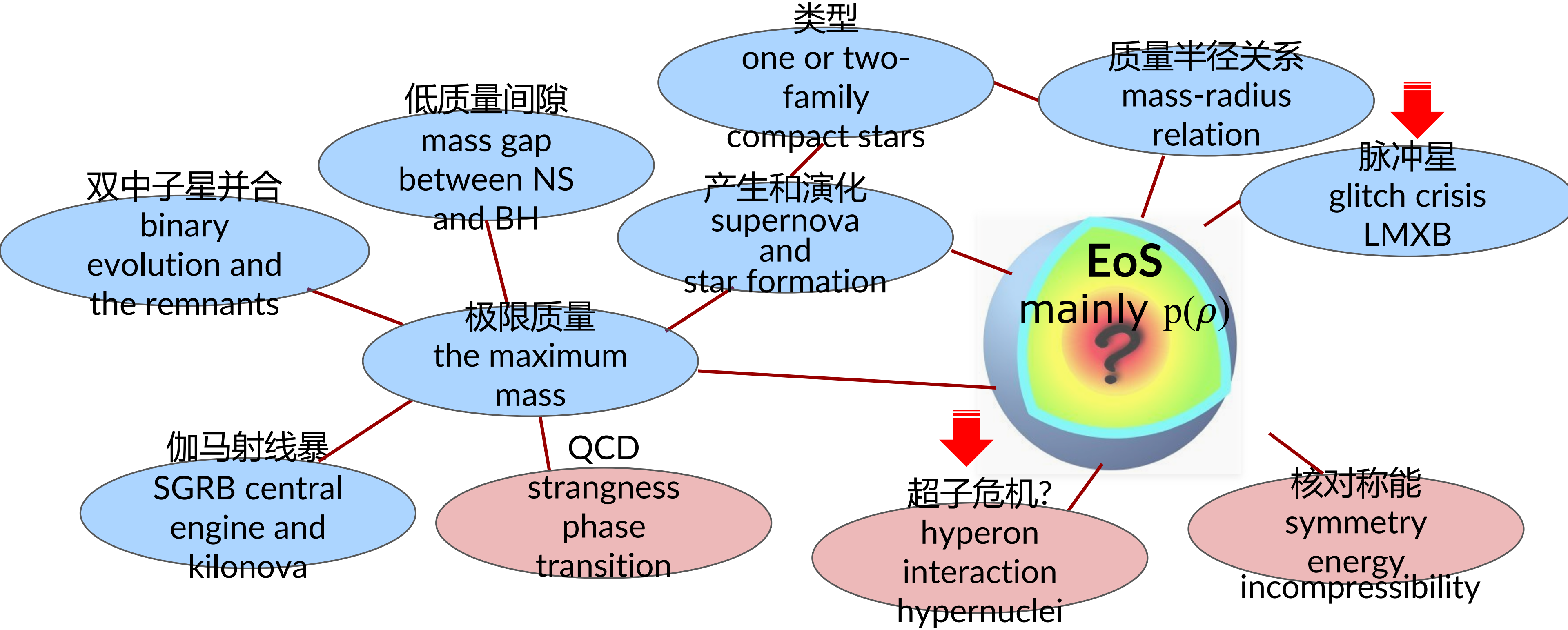


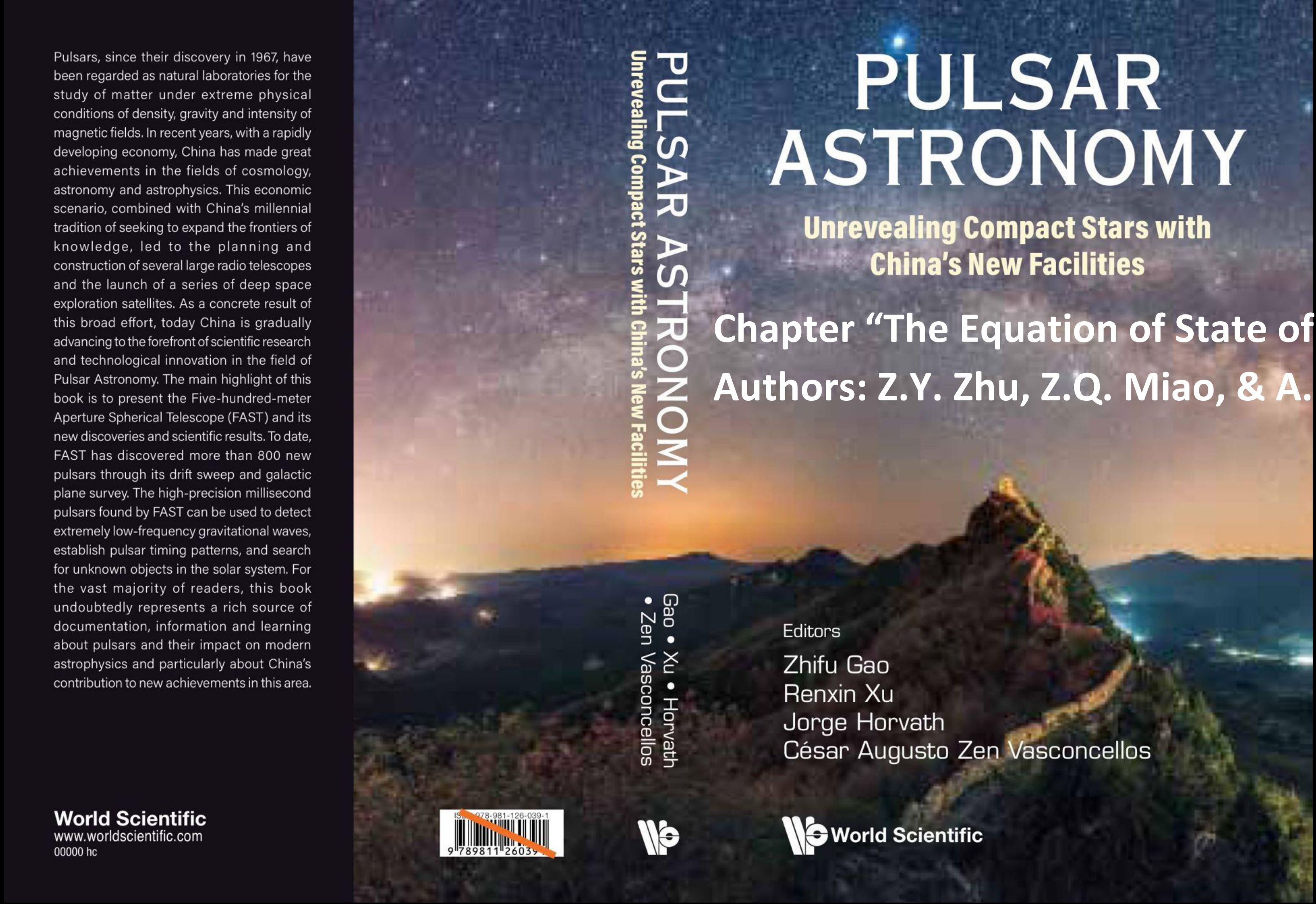
AL et al. 2011

https://www.nature.com/articles/d41586-020-00590-8

The golden age of neutron star has arrived!

-why is understanding the EoS important for nuclear/astrophysicists?





Chapter "The Equation of State of Pulsars"

Authors: Z.Y. Zhu, Z.Q. Miao, & A. Li

Take-home message

PSRs J0835-4510 (Vela)
J1048-5832,
J1028−5819,
J1420−6048,
J1509−5850,
J1709−4429,
J1718−3825,...

- The multi-messenger/multi-wavelength era of EoS study!
- We apply **complete** thermodynamical state of dense matter from bare NN+NNN force to the study of pulsar spin evolution, focusing on the glitch, and find various constraints on the **nuclear force in medium**, as well as the star properties;
- We also find that the strong correlation between the scalar and vector channel of YN interactions indicated by s.p. separation energy of available Λ **hypernuclei** ENSURE that there is sufficient (vector) repulsion and a prediction of hyperon stars with M_{max}~**2.2**$\mathbf{M_\odot}$.
- Glitch (and others) provides **unique** insights into the internal structure of neutron stars: Many exciting ways to **combine** various fields!


Thank you
Welcome to XMU