第二届“无中微子双贝塔衰变及相关物理研讨会”

Hyperon star and hyperon-nucleon interaction research base on astronomical observation

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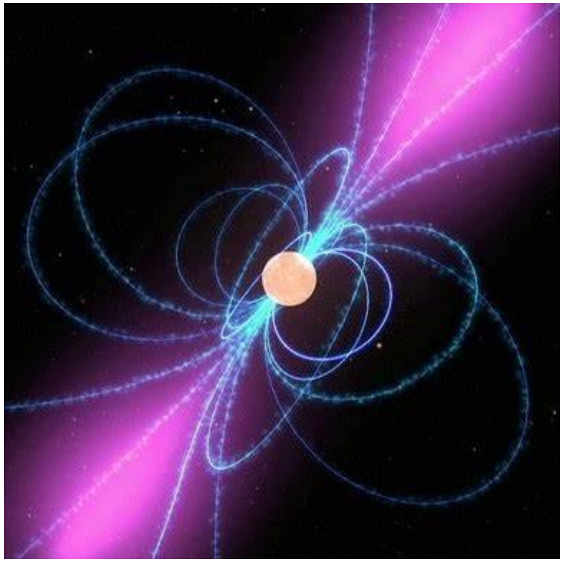
arxiv:2205.10631 APJ

Outline

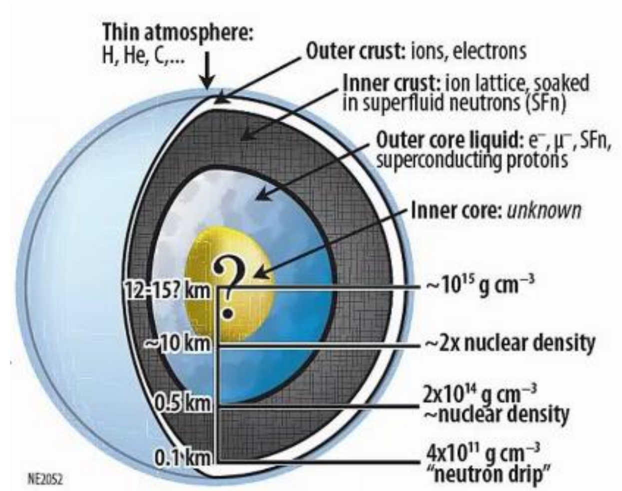
- Background & motivation
- Theoretical framework
- Bayesian analysis
- Discussion
- Summary

Background



- 1932 Landau et al. proposed the existence of neutron star

- 1967 Bell et al. discovered the first neutron stars



(image credit: NASA, NICER Team)

- GW170817 opens the era of GW multi-messenger astronomy

- Inner composition?

Background

➢ Inner core component: Λ 、Σ、Ξ 、Δ、Ω…

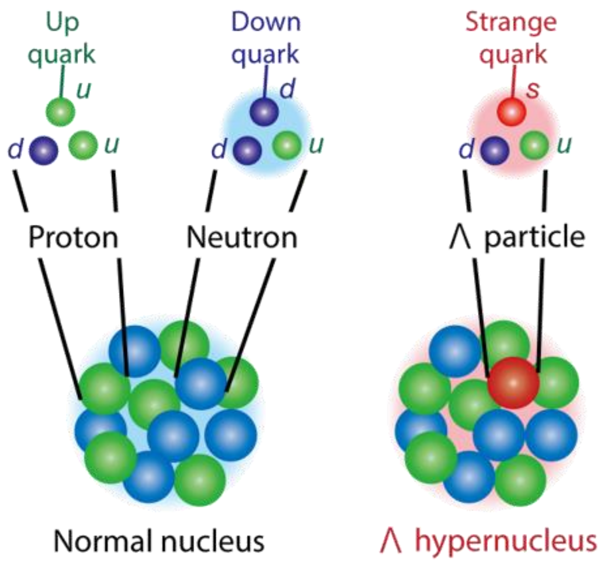

LHC(EUR)


JLab(US)


J-PARC(JPN)


FAIR(GER)


HIAF(CHN)



➢ Laboratory experiments: Extracting baryon-baryon interactions from hyperon-nucleon scattering, structure of the hypernucleus and reactions, (half-life period ~10^{-10}s)

➢ Some available experimental data for single Λ separation energy

➢ The inner core of neutron stars might contain hyperons - Hyperon stars

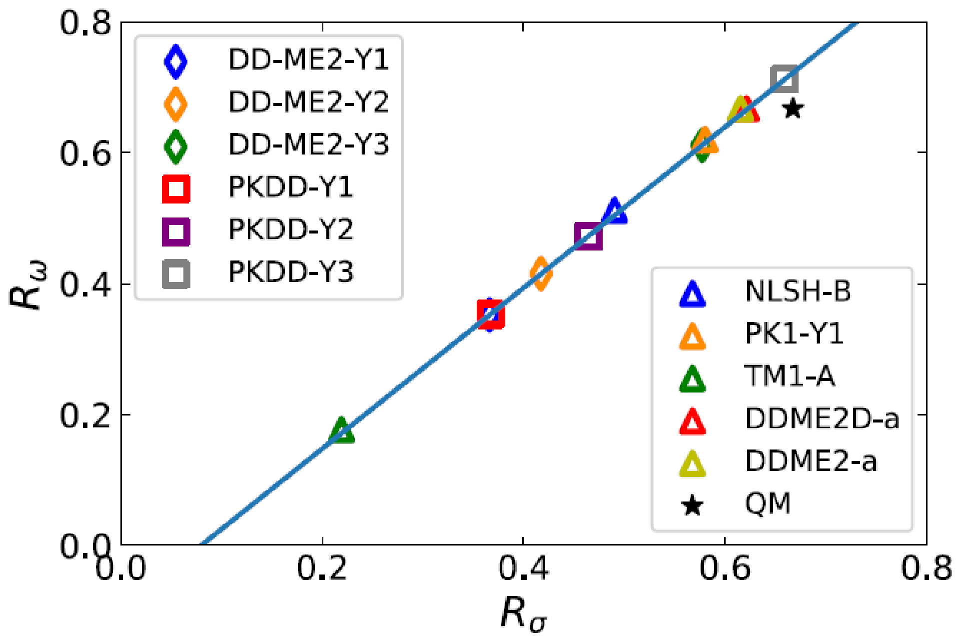
➢ Difficulty : Model dependent; SU(3) symmetry

Motivation

Meson-nucleon coupling constant: $g_{\sigma N}$, $g_{\omega N}$

Meson-hyperon coupling constant: $g_{\sigma Y}$, $g_{\omega Y}$

$$R_{mY} = g_{mY}/g_{mN}\ (m = \sigma,\ \omega,\ \rho,\ \delta)$$



Rong et al PHYSICAL REVIEW C 104, 054321 (2021)

Y. T. Rong et al. 2021 PRC
X. S. Wang et al.2013 CTP
C. M. Keil et al. 2000 PRC

- Motivation: To combine the NICER mass, radii data of pulsars as well as GW170817 data and the strong correlation between hyperon nucleon interaction (Rong et al.), to perform Bayesian analysis to Λ hyperon nucleon interaction, and to constrain Λ hyperon nucleon interaction parameter space as well as the properties of hyperon stars.

Theoretical model

➤ Model: Relativistic Mean Field (Baryon octet)

$$\mathcal{L}^B_{\text{free}} = \sum_B \bar{\psi}_B[i\gamma_\mu\partial^\mu - m_B]\psi_B;$$

$$\mathcal{L}^B_{\text{int}} = \sum_B \bar{\psi}_B[-g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho B}\gamma_\mu\vec{\rho}^\mu \cdot \vec{\tau}]\psi_B;$$

$$\mathcal{L}_m = -\frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu};$$

$$\mathcal{L}_{\text{NL}} = -\frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 + \Lambda_v(g_{\omega B}^2\omega_\mu\omega^\mu)(g_{\rho B}^2\rho_\mu\rho^\mu);$$

$$\mathcal{L}^B_{\text{4f}} = -\frac{1}{2}\sum_B \alpha_S^{NB}(\rho)(\bar{\psi}_N\psi_N)(\bar{\psi}_B\psi_B) - \frac{1}{2}\sum_B \alpha_V^{NB}(\rho)(\bar{\psi}_N\gamma_\nu\psi_N)(\bar{\psi}_B\gamma_\nu\psi_B) - \frac{1}{2}\sum_B \alpha_{TS}^{NB}(\rho)(\bar{\psi}_N\vec{\tau}\psi_N)(\bar{\psi}_B\vec{\tau}\psi_B) - \frac{1}{2}\sum_B \alpha_{TV}^{NB}(\rho)(\bar{\psi}_N\vec{\tau}\gamma_\nu\psi_N)(\bar{\psi}_B\vec{\tau}\gamma_\nu\psi_B);$$

$$\mathcal{L}^B_{\text{hot}} = -\frac{1}{3}\beta_S^{NN}(\bar{\psi}_N\psi_N)^3 - \frac{1}{4}\gamma_S^{NN}(\bar{\psi}_N\psi_N)^4 - \frac{1}{4}\gamma_V^{NN}[(\bar{\psi}_N\gamma_\mu\psi_N)][(\bar{\psi}_N\gamma^\mu\psi_N)]^2,$$

➤ Nucleon-nucleon interaction:

17 effective RMF interactions:
Walecke、DDRMF、NLRMF、DD-PC、NL-PC

➤ hyperon-nucleon interaction:

$R_{\sigma\Lambda}$ $R_{\omega\Lambda}$: Relax SU(3) symmetry, [0 – 1]

$R_{\sigma\Sigma}$、$R_{\omega\Sigma}$、$R_{\rho\Sigma}$、$R_{\sigma\Xi}$、$R_{\omega\Xi}$、$R_{\rho\Xi}$:

- ✓ Vector coupling: SU(3) symmetry
- ✓ Scalar coupling: Potential depth

U_Σ = +34 MeV
U_Ξ = −14 MeV
$R_{\sigma\Sigma}$ = 0.443
$R_{\sigma\Xi}$ = 0.302

Fortin et al. 2017 PRC;
Colucci & Sedrakian 2013 PLB

Bayesian Formula

- software: Python Bilby, PyMultiNest, Toast, Corner

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

$P(\boldsymbol{\theta})$ is the prior probability of the parameter set $\boldsymbol{\theta}$

$P(\boldsymbol{D}|\boldsymbol{\theta})$ is total likelihood function

$P(\theta)$

$R_{\sigma\Lambda} \sim U[0,\ 1]$ $R_{\omega\Lambda} \sim U[0,\ 1]$. NUCL

$\varepsilon_c \sim U[0.6\times10^{15},\ 3\times10^{15}]\,\mathrm{g/cm^3}$

$\varepsilon_c \sim U[0.3\times10^{15},\ 1\times10^{15}]\,\mathrm{g/cm^3}$

NICER: PSR J0740+6620, PSR J0030+0451

$\mathcal{M} \sim U[1.18,\ 1.21]\,M_\odot$

$q \sim U[0.5,\ 1]$

GW170817

Bayesian Formula

➢ **NICER**: PSR J0740+6620 and PSR J0030+0451

$$P_{\rm NICER}(d_{\rm NICER}|\theta) = \prod_j P_j(M(\theta), R(\theta))$$

Abbott et al. 2017 PRL
Abbott et al. 2019 PRX

we equate the individual likelihood P_j to the joint posterior density distribution of M and R

➢ GW170817:

$$P_{\rm GW}(d_{\rm GW}|\theta) = F(\Lambda_1(\theta; M_1), \Lambda_2(\theta; M_2), \mathcal{M}, q)$$

Abbott et al. 2017 PRL
Abbott et al. 2019 PRX
Hernandez et al. 2020 MNRAS

$F(\cdot)$ is the interpolation function

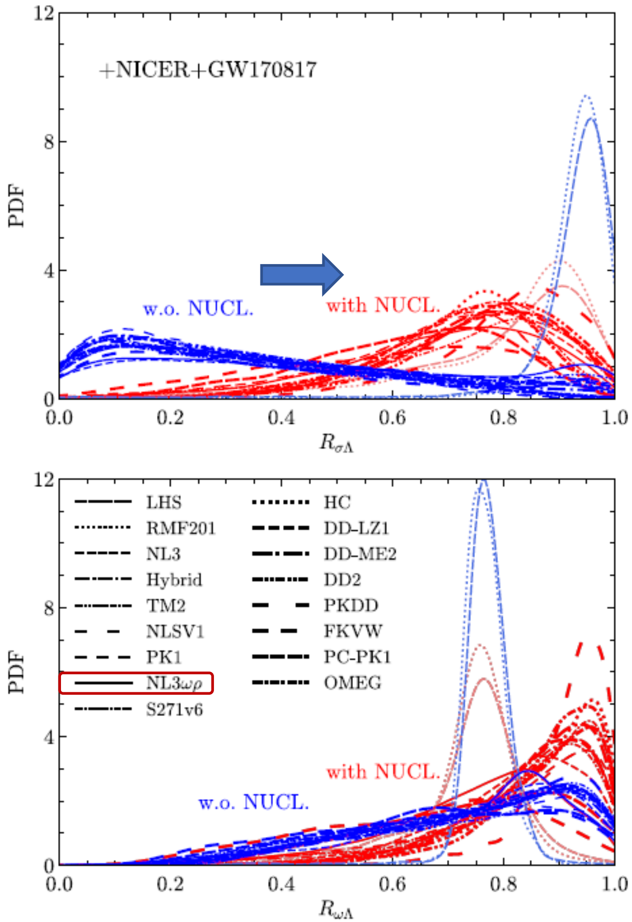
M_1 and M_2 are related to the chirp mass $\mathcal{M}$ and the mass ratio $q = M_2/M_1$

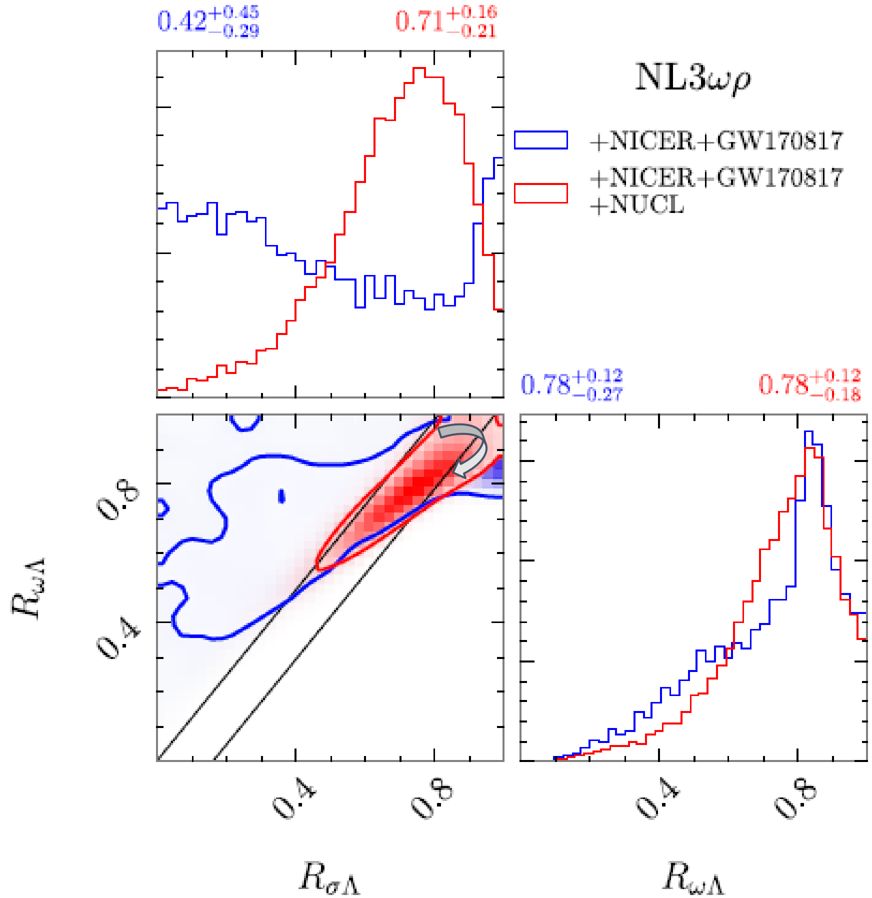
➢ NUCL: Single Λ separation energy constraint

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

Rong et al. 2021 PRC

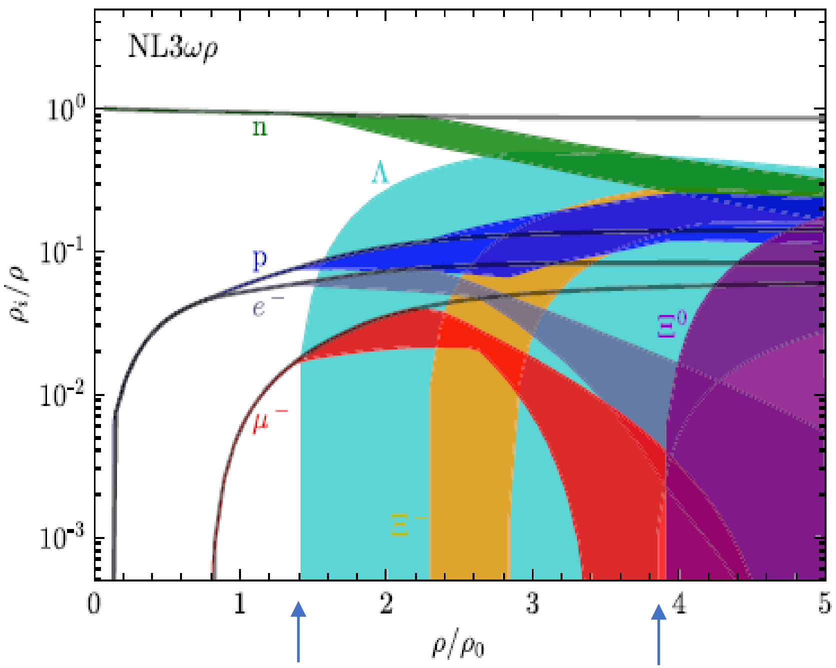
Λ hyperon-nucleon interaction



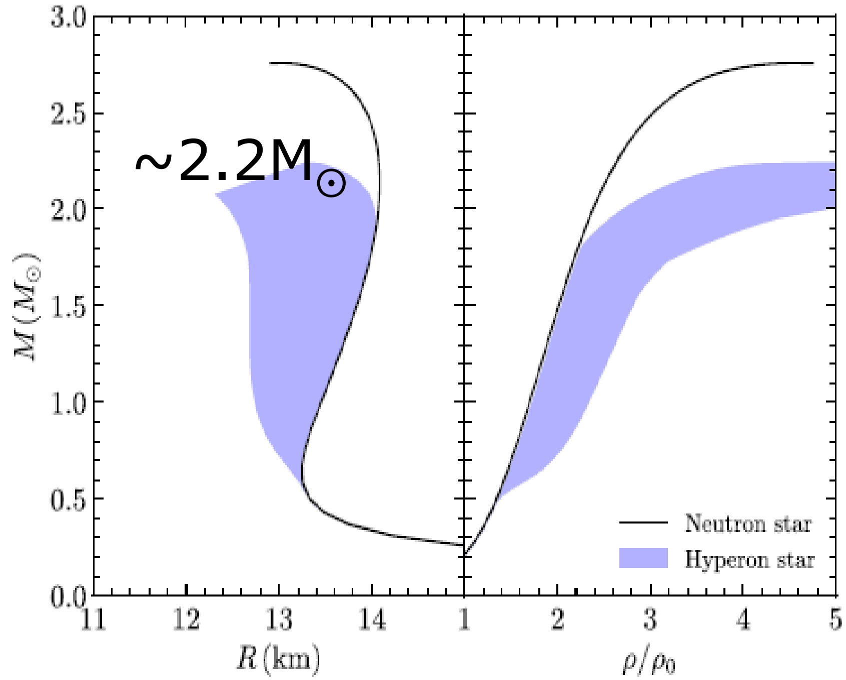


- Hypernuclei constraint **favors large values of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$** and disfavors small values of both couplings
- The addition of astrophysical observational data on top of the laboratory $R_{\sigma\Lambda}$-$R_{\omega\Lambda}$ correlation **rotates the linear correlation slightly** towards the direction of small values of $R_{\omega\Lambda}$

Properties of hyperon stars



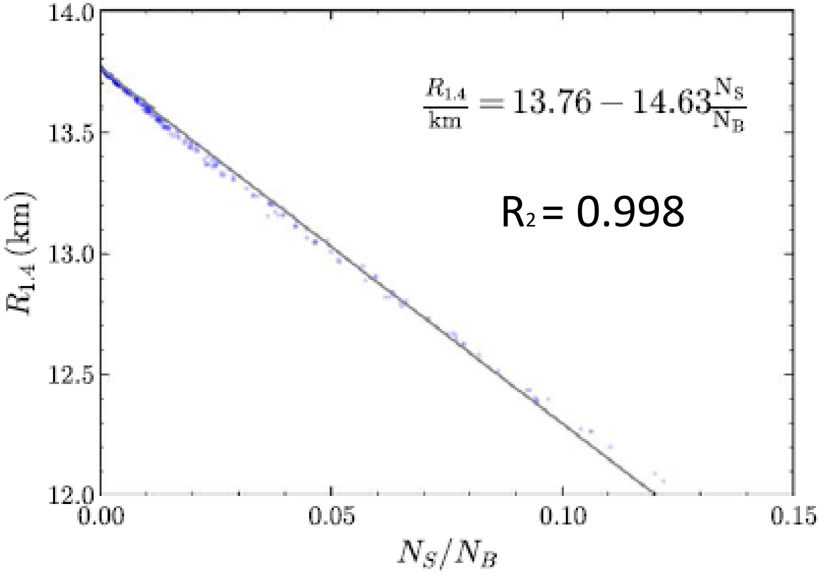
Threshold density of Λ hyperons: ~1.4-3.8ρ_0

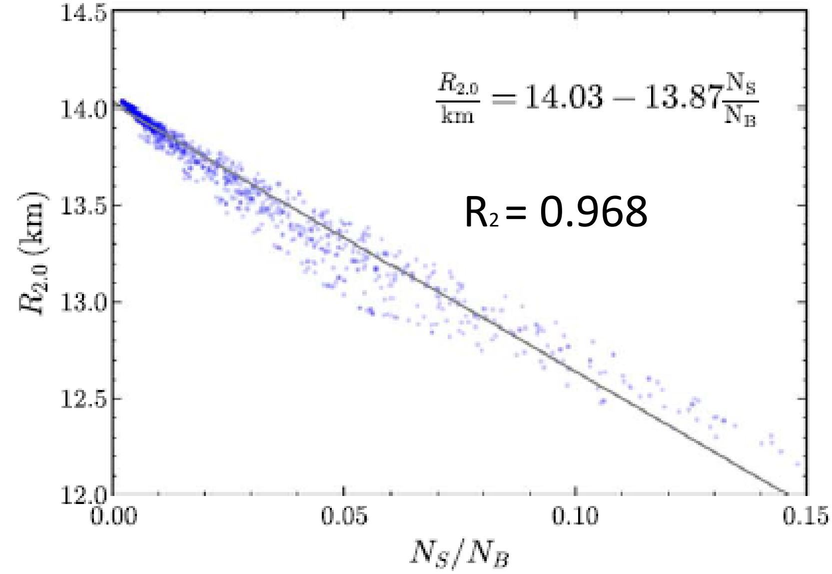


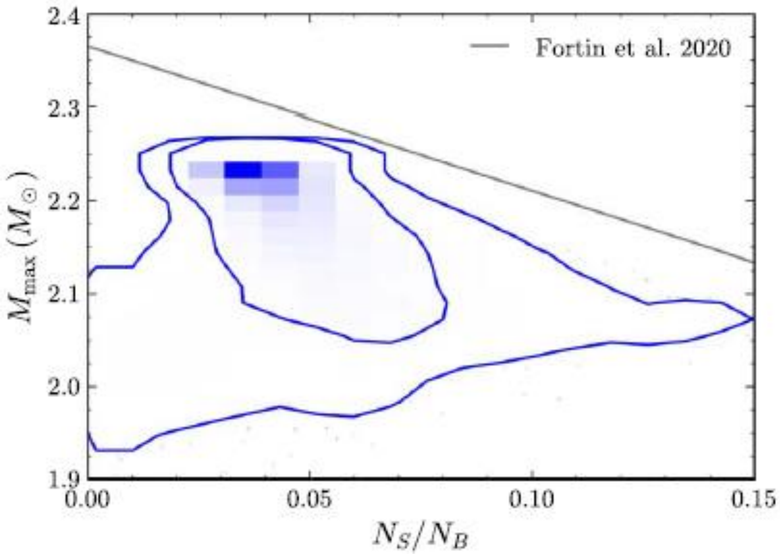
Due to hyperons, the maximum mass is lowered by ~20%: $M_{\max} = 2.176^{+0.085}_{-0.202}\, M_\odot$ **(68% credible interval).**

From the 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."

Strangeness abundance







- Excellent **linear anticorrelations** between N_S/N_B and $R_{1.4}$ as well as $R_{2.0}$, with the determination coefficients of R_2 = 0.998 and R_2 = 0.968.
- There appears also an anticorrelation between N_S/N_B and M_{max} of hyperon stars.

Summary

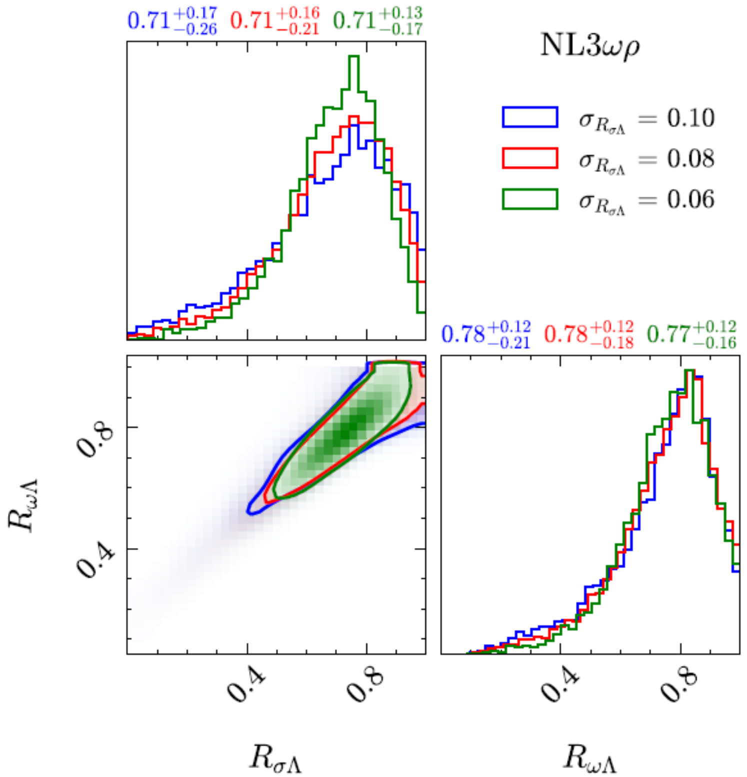
- We combine the **NICER &GW170817** data and the **strong correlations** of Λ hyperon-nucleon interactions to perform the Bayesian analysis with 17RMF models.

- We foucus Λ hyperon, we **relax** the SU(3) symmetry, take accurately measured mass, radius (for **PSR J0030+0451** and **PSR J0740+6620**), and **tidal deformability** (for GW170817) and laboratory constraint from the **single Λ hypernuclei data.**

- The **laboratory constraint** from the single Λ hypernuclei data determines the phenomenological interactions, **preventing a small scalar coupling** through a strong positive correlation between the scalar and vector ones.

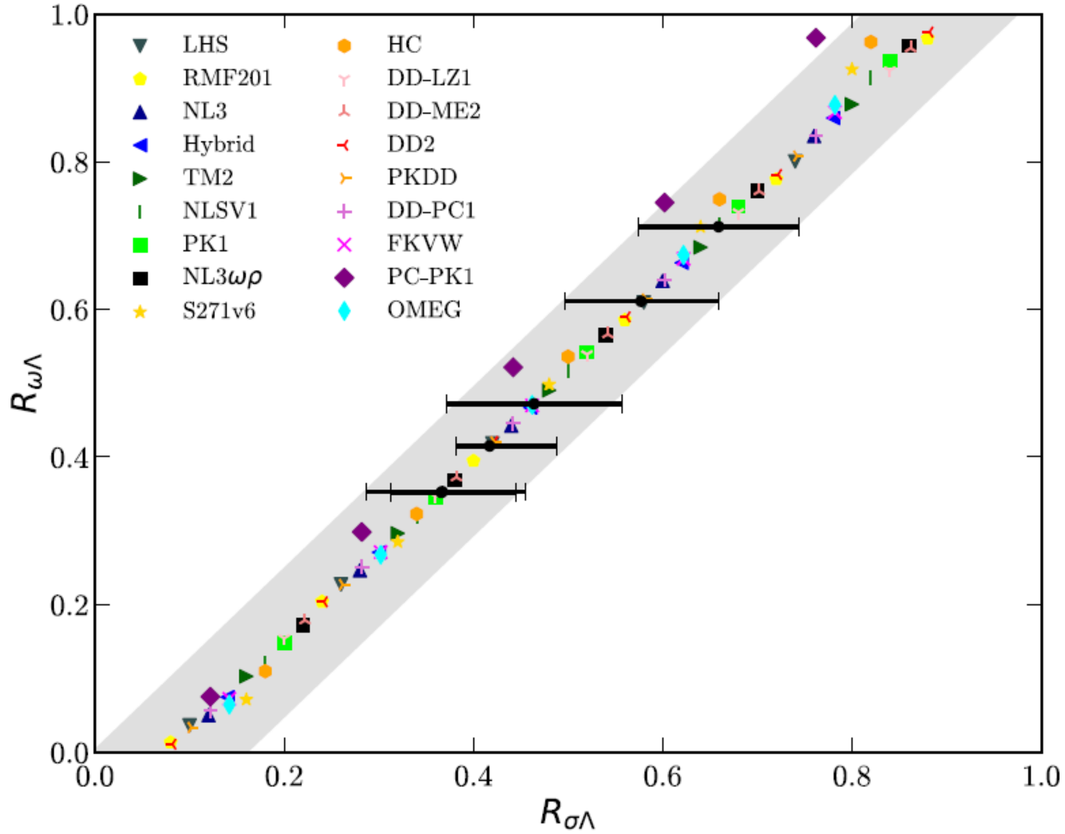
- We find the hyperon **threshold can be as low as ~1.4 times** the nuclear saturation density, and the hyperon star EOS is moderately stiff(M_{max}=2.2$M_{\odot}$).

- The decrease of the radii of typical 1.4 $M_{\odot}$ and 2.0 $M_{\odot}$ stars can both be **linearly depicted as functions of the strangeness fraction** in hyperon stars.



	$R_{\sigma\Lambda}$	$R_{\omega\Lambda}$	$M_{\max}/M_\odot$	ρ_c/ρ_0	$R_{2.0}$/km	$R_{1.4}$/km	$\Lambda_{1.4}$
$\sigma_{R_{\sigma\Lambda}} = 0.10$	$0.707^{+0.174}_{-0.261}$	$0.777^{+0.116}_{-0.209}$	$2.180^{+0.062}_{-0.228}$	$4.865^{+0.055}_{-0.565}$	$13.980^{+0.088}_{-1.533}$	$13.769^{+0.000}_{-1.086}$	$940.165^{+0.000}_{-448.040}$
$\sigma_{R_{\sigma\Lambda}} = 0.08$	$0.712^{+0.157}_{-0.215}$	$0.778^{+0.121}_{-0.183}$	$2.176^{+0.085}_{-0.202}$	$4.846^{+0.046}_{-0.501}$	$13.968^{+0.096}_{-1.512}$	$13.769^{+0.000}_{-1.084}$	$940.165^{+0.000}_{-443.756}$
$\sigma_{R_{\sigma\Lambda}} = 0.06$	$0.710^{+0.135}_{-0.173}$	$0.772^{+0.120}_{-0.159}$	$2.168^{+0.075}_{-0.186}$	$4.966^{+0.032}_{-0.475}$	$13.950^{+0.075}_{-1.423}$	$13.769^{+0.000}_{-1.064}$	$940.165^{+0.000}_{-430.676}$

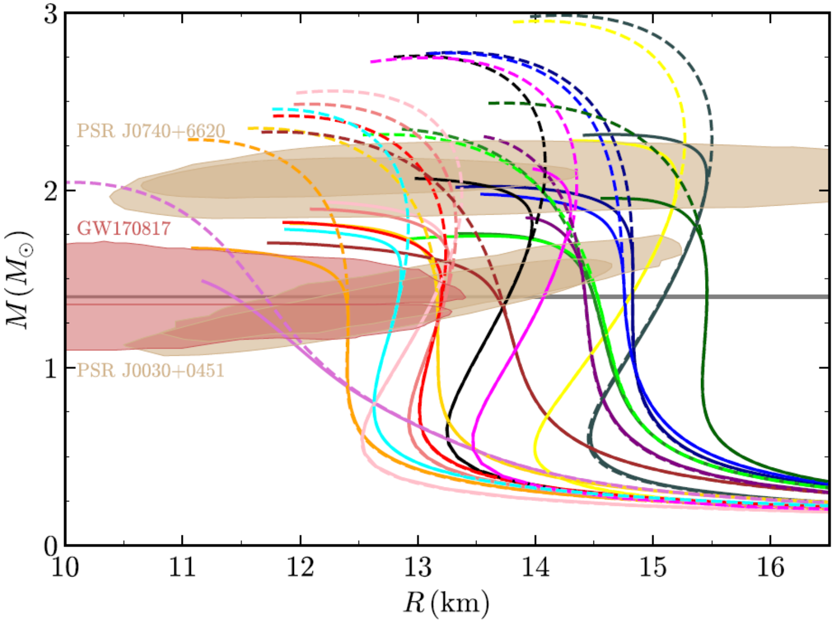
Appendix

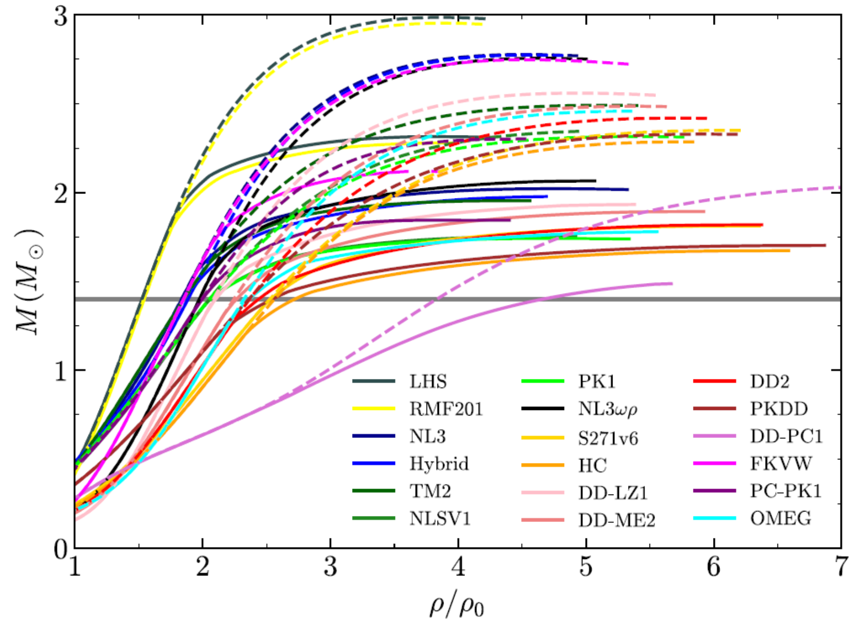


$$R_{\omega\Lambda} \approx \frac{-g_{\sigma N}\sigma}{U_N - g_{\sigma N}\sigma} R_{\sigma\Lambda} + \frac{U_\Lambda}{U_N - g_{\sigma N}\sigma}$$

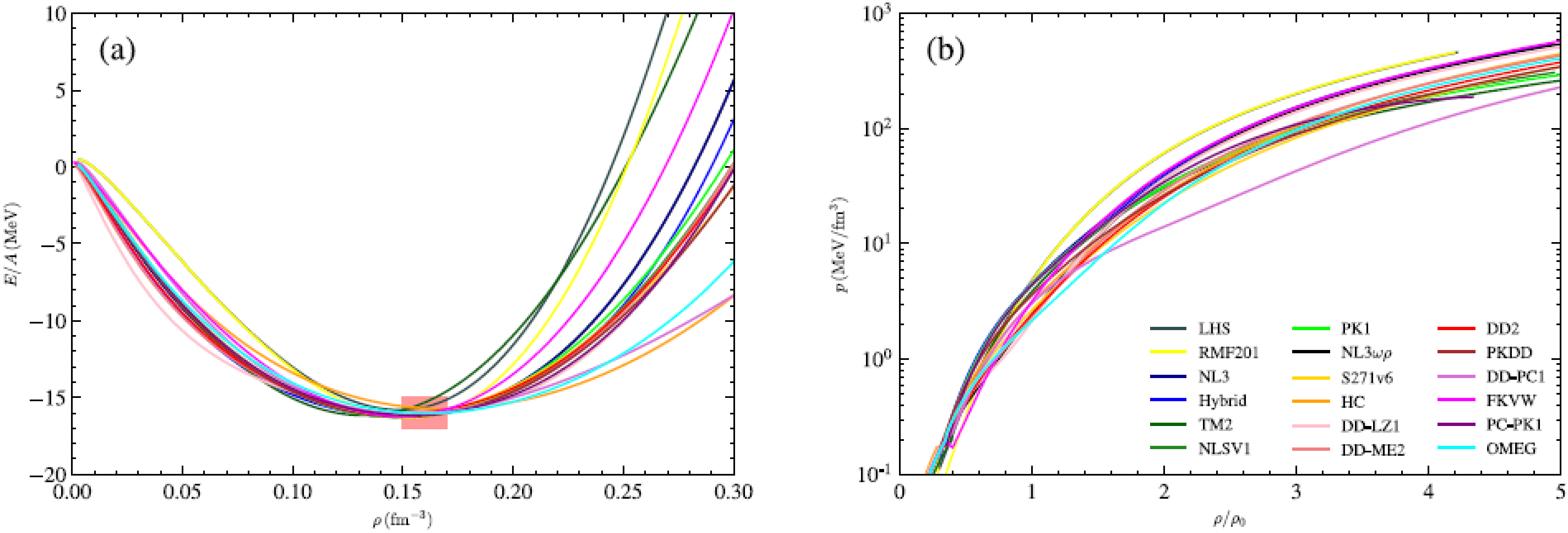
$$R_{\omega\Lambda} \approx \frac{-\alpha_S^{NN}\rho_S}{U_N - \alpha_S^{NN}\rho_S - \beta_S^{NN}\rho_S^2 - \gamma_S^{NN}\rho_S^3 - \gamma_V^{NN}\rho_V^3 - \alpha_S^{N\Lambda}\rho_S^\Lambda - \alpha_V^{N\Lambda}\rho_V^\Lambda} R_{\sigma\Lambda} + \frac{U_\Lambda}{U_N - \alpha_S^{NN}\rho_S - \beta_S^{NN}\rho_S^2 - \gamma_S^{NN}\rho_S^3 - \gamma_V^{NN}\rho_V^3 - \alpha_S^{N\Lambda}\rho_S^\Lambda - \alpha_V^{N\Lambda}\rho_V^\Lambda},$$

Appendix


PSR J0740+6620
GW170817
PSR J0030+0451
$M\,(M_\odot)$
$R\,(\mathrm{km})$


$M\,(M_\odot)$
ρ/ρ_0
LHS
RMF201
NL3
Hybrid
TM2
NLSV1
PK1
NL3$\omega\rho$
S271v6
HC
DD-LZ1
DD-ME2
DD2
PKDD
DD-PC1
FKVW
PC-PK1
OMEG

Appendix



(a)
E/A (MeV)
ρ (fm^{-3})
(b)
p (MeV/fm^3)
ρ/ρ_0
LHS
RMF201
NL3
Hybrid
TM2
NLSV1
PK1
NL3ωρ
S271v6
HC
DD-LZ1
DD-ME2
DD2
PKDD
DD-PC1
FKVW
PC-PK1
OMEG