Is there a “hyperon puzzle” problem in neutron star study?

Ang LI 李昂

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Xiamen Univ.

Many thanks to Organizers!

XVIth Quark Confinement and the Hadron Spectrum Conference

19-24 Aug 2024 Cairns, Queensland, Australia

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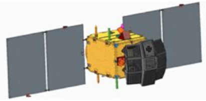
XVIth Quark Confinement and the Hadron Spectrum Conference
19-24 Aug 2024 Cairns, Queensland, Australia

厦門大學天文學系
Department of Astronomy , Xiamen University

18 faculty members
11 postdocs
70 graduate students

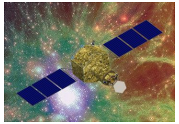
Electromagnetic waves

Insight/ HXMT

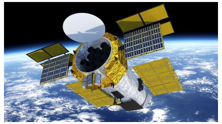


Einstein Probe

Radio	mm/sub-mm	FIR	MIR	NIR	V	NUV	UV	Soft X-ray	Hard X-ray	γ-ray



HUBS



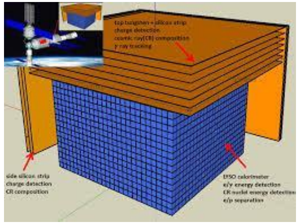
eXTP

Neutrinos

JUNO

Cosmic Rays

HERD



web: https://astro.xmu.edu.cn/

Our group: Welcome to visit!

arXiv:2402.02799 PRD
arXiv:2312.17102 ApJ
arXiv:2312.12185 ApJ
arXiv:2312.04305 MNRAS
arXiv:2305.16058 PRC
arXiv:2305.08401 ApJ
arXiv:2304.12050 PRD
arXiv:2211.04978 PRD
arXiv:2211.02007 ApJ
arXiv:2205.10631 ApJ
arXiv:2204.05560 ApJ
arXiv:2203.04798 PRD
arXiv:2201.12053 PRC
arXiv:2108.00560 ApJ
arXiv:2107.13997 ApJL
arXiv:2107.07979 MNRAS
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

Zhenyu Zhu 朱镇宇

Many-body theory;
Merger simulation
Numerical relativity

Graduated in 2021; postdoc in CCRG-RIT

Zhiqiang Miao 缪志强

Hybrid star;
Quark matter;
Bayesian analysis
GR

Graduated in 2023; postdoc in TDLee inst.

Zhonghao Tu 涂中豪

Superfluidity;
Neutron star cooling;
Nuclear pinning force

Wenli Yuan 苑文莉

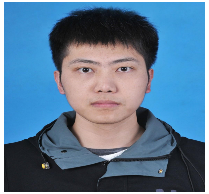
Quark matter;
QCD phase diagram

Graduated in 2023; postdoc in PKU

Peng Liu 刘鹏

Glitch;
Pulsar observation

Xiangdong Sun 孙向东



Nuclear matter;
Hyperon matter;
Many-body theory

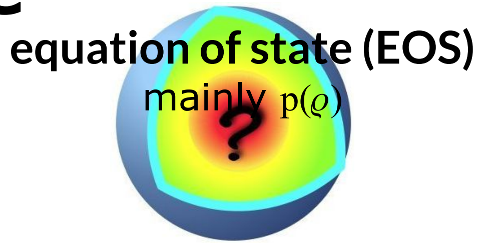
Shuochong iHan 韩烁冲

Many-body theory;
Nuclear transport

with 4 undergraduate students

Outline

- **Basic** for neutron star structure and the EOS
- **Recent work** towards the determination of the #(hyper)nuclear force and NS properties from multimessenger astronomy
- **Summary and Exciting future**

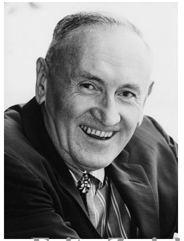


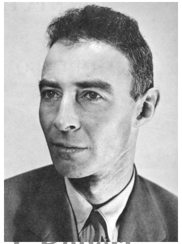
What is the nature of the particles that make up neutron stars?

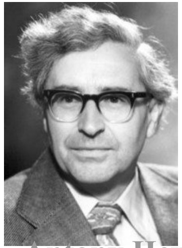

Lev Landau


James Chadwick


Walter Baade


Fritz Zwicky


J. Robert Oppenheimer


Antony Hewish

Nobel prize 1974


Dame Jocelyn Bell Burnell

1967

Fundamental Physics Breakthrough Prize 2018

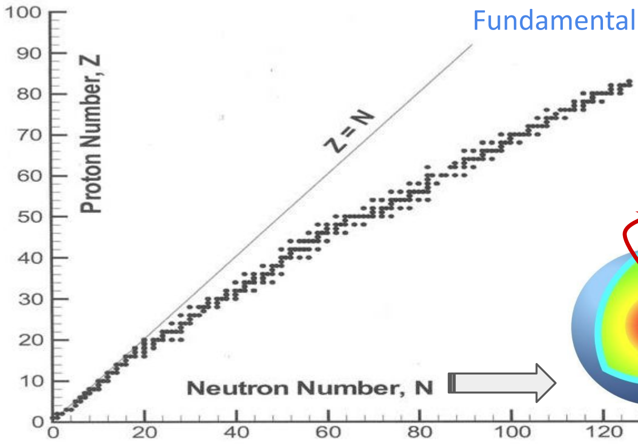
1932-

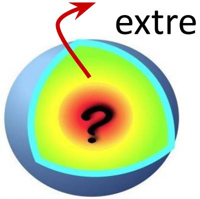
“the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.”

A ~ 10^{57}; For R=10 km, M=1.4 $M_\odot$,
average density ~(2-3) nuclear density ϱ_0

~several hundreds MeV (nonperturbative)

Extreme conditions make it impossible to attain by theo./exp. methods only.





beta equilibrium;
charge neutrality;
extremely neutron-rich

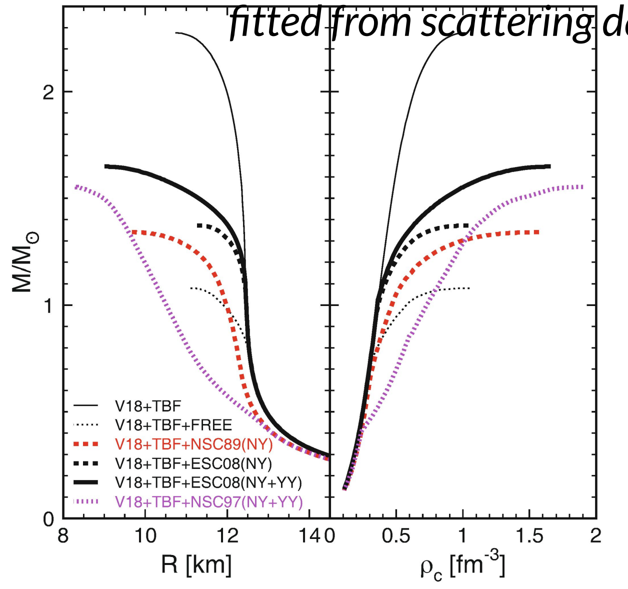
EOS uncertainty from QCD **phase uncertainty** and **model uncertainty**

- Hyperon **puzzle**; Δ(1232)/hyperon/Kaon/quark **complication**
- 1) Unified crust-core; 2) High-density extrapolation

Hyperon puzzle: Heavy pulsars larger than $2M_{\odot}$ is a pain

BHF (NN + NNN + NY)

fitted from scattering data



Schulze & Rijken 2016

RMF(NN+NY+YY)

consistent with hypernuclei data

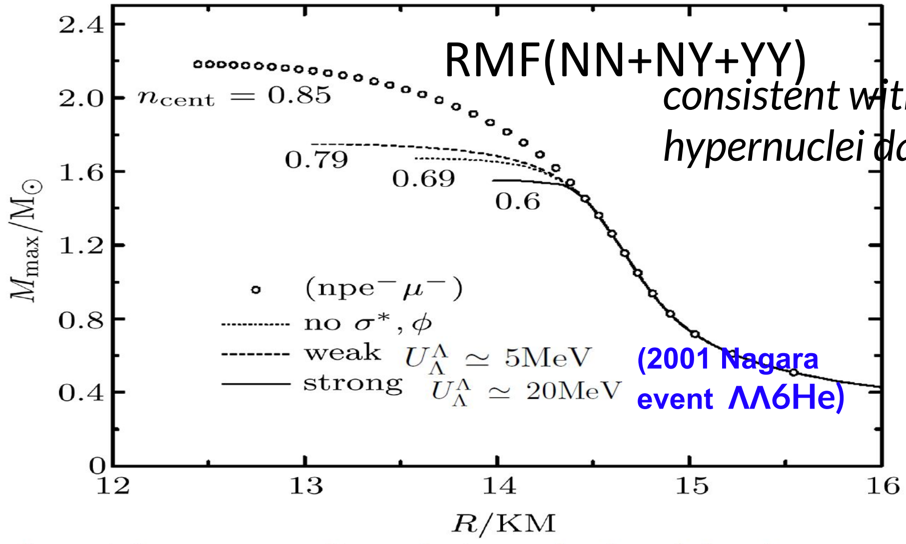


Fig.3. The mass–radius relation calculated for the strong and weak hyperon–hyperon interaction models, in comparison with the one without strange mesons ($\sigma*, \phi$), and also the results without hyperons. See text for details.

Li et al. 2007

Is it possible to combine NS multi-messenger (2017-) observations with hypernuclei experiments to understand better the hypernuclear force? **How**? **What new**?

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

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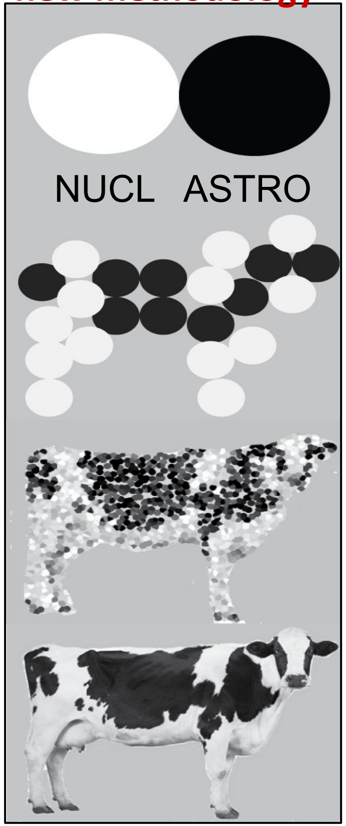
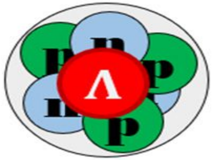
new methodology



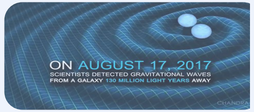
Combining (binary) NS observations with hypernuclei experiments

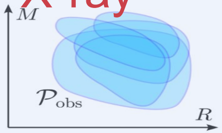
p(**θ**,D) ∝ π(**θ**) × L(D|**θ**,𝕄))



Assuming the sources are hyperon stars:

Formerly: GW + X-ray

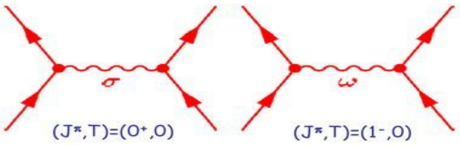


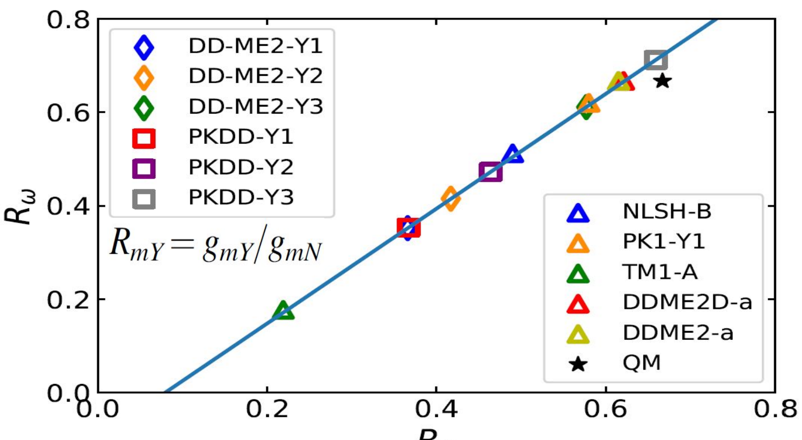


Presently: GW + X-ray + NUCL

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

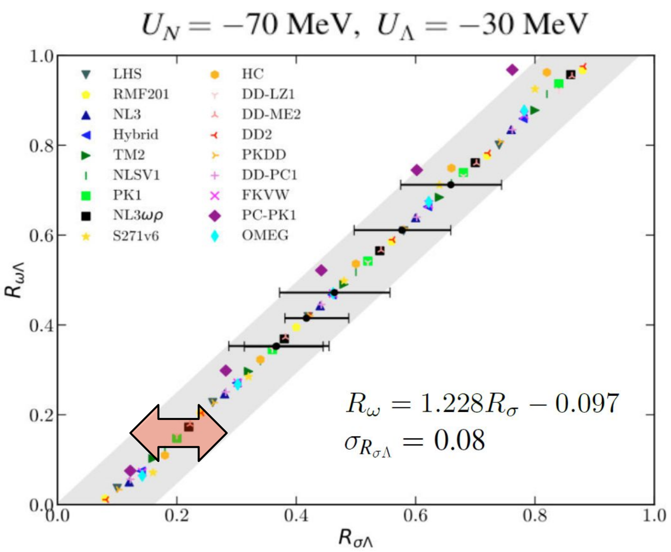
Strong linear $R_{\sigma\Lambda}$-$R_{\omega\Lambda}$ relations from fitting (with some statistical error) calculated Λ separation energies of **eleven** A ≥ 12 single Λ hypernuclei *(Rong, Tu & Zhou, 2021)*: $R_\omega = 1.228 R_\sigma - 0.097$





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

Linear $R_{\sigma\Lambda}$-$R_{\omega\Lambda}$ relations consistent with both finite-range meson-exchange and zero-range PC models



For finite-range interactions:

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

For zero-range PC

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

- Meson-exchange

$$\mathcal{L} = \mathcal{L}^B_{\text{free}} + \mathcal{L}^B_{\text{int}} + \mathcal{L}_m + \mathcal{L}_{\text{NL}}$$

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

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

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

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

- Point-coupling

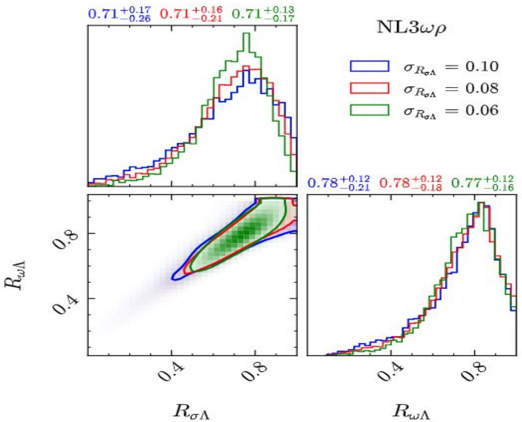
$$\mathcal{L}_{PC} = \mathcal{L}^B_{\text{free}} + \mathcal{L}^B_{\text{4f}} + \mathcal{L}^B_{\text{hot}}$$

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

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

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

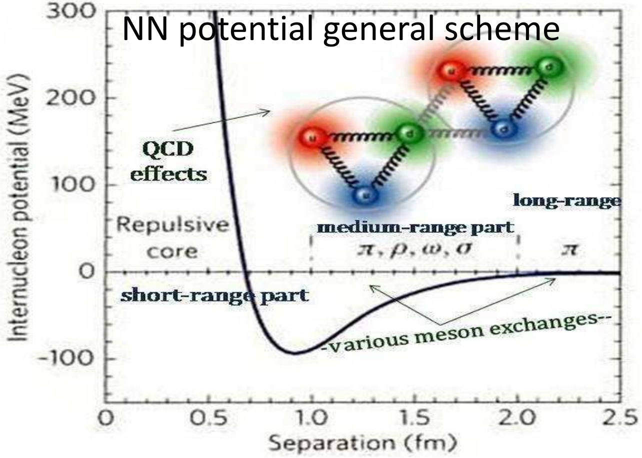
#different statistical errors



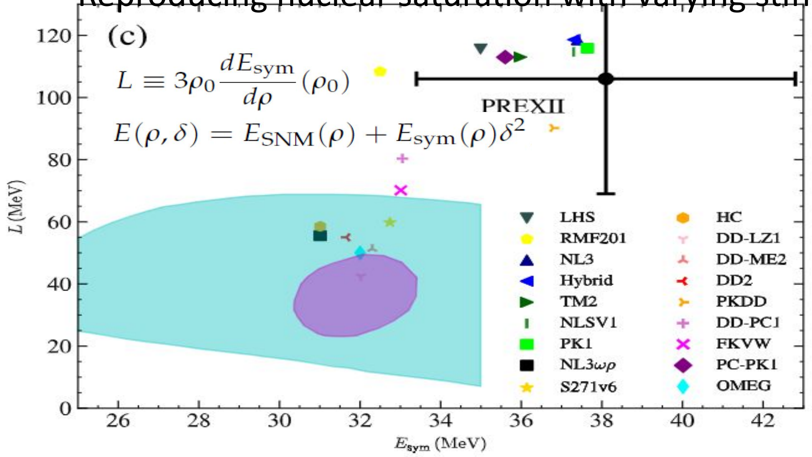
Hyperon star properties do NOT rely sensitively on the choice of the statistical error.

Employed 18 stiff relativistic EOSs with 7 types of variation of the RMF effective interactions

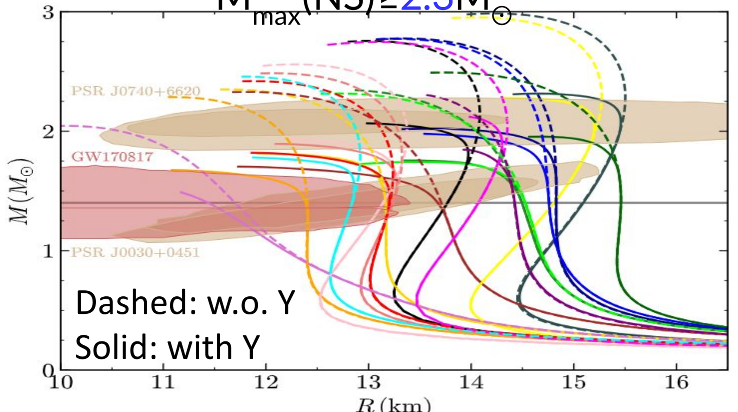
NN potential general scheme



Reproducing nuclear saturation with varying stiffness



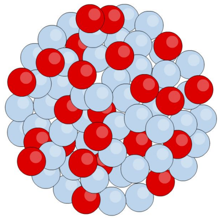
$M_{max}(NS) \geq 2.3 M_{\odot}$

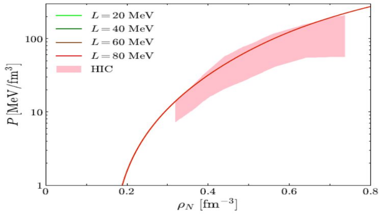


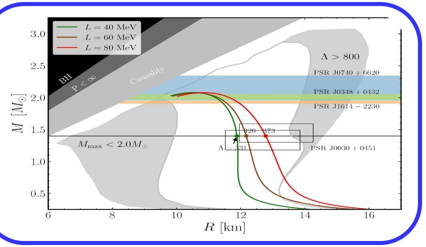
1) Original linear Walecka model,
2) Nonlinear Walecka model with σ **self-interacting** mesons
3) Nonlinear Walecka model with σ, ω **self-interacting** mesons,
4) Nonlinear Walecka model with σ, ω **self-interacting** mesons and possible mesonic **cross** terms,
5) Models in which the parameters that couple the baryons with the mesons are **density-dependent**,
6) Models with the inclusion of $\boldsymbol{\delta}$ mesons, i.e., $a_0(980)$,
7) **Point-coupling (PC)** models without exchanging mesons.

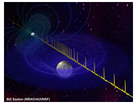
Prepare EoS prior starting for a RMF parameter set

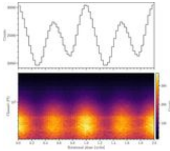
1. Model for interaction between particles → $\hat{\mathcal{H}}\Psi = E\Psi$ → **2. the EOS** → $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$ → **3. NS observations (M-R relation, Lambda)**

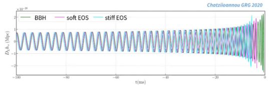


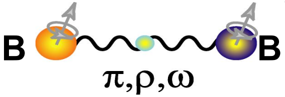












(P, I, J symmetry)

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

Static approximation considered in the Lagrangian on mesons so that their time components are neglected;

Spatial part of **ω** meson disappears for the time reversal symmetry;

Infinite nuclear matter has translational invariance, removing the partial part of the coordinate space.

Eqs. of motion of baryons and mesons can be generated by the Euler-Lagrangian eq. from the Lagrangian:

$$\left[i\gamma^\mu\partial_\mu - M_B^* - \gamma^0\left(g_{\omega B}\omega + g_{\phi B}\phi + \frac{g_{\rho B}}{2}\rho\tau_3\right)\right]\psi_B = 0,$$
$$m_\sigma^2\sigma + g_2\sigma^2 + g_3\sigma^3 = \sum_B g_{\sigma B}\rho_B^s,$$
$$m_\omega^2\omega + c_3\omega^3 + 2\Lambda_v\left(g_{\omega N}^2\omega\right)\left(g_{\rho N}^2\rho^2\right) = \sum_B g_{\omega B}\rho_B^v,$$
$$m_\rho^2\rho + 2\Lambda_v(g_{\omega N}^2\omega^2)(g_{\rho N}^2\rho) = \sum_B \frac{g_{\rho B}}{2}\rho_B^{v3},$$

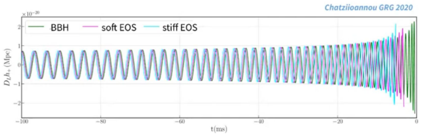
Then, p & ε (with arbitrary isospin asymmetry) from nuclear part can be generated by the energy-momentum tensor.

Bayesian inference of hyperon-nucleon interaction strengths from combining (binary) NS observations with hypernuclei experiments

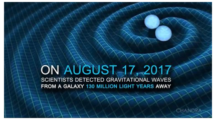
- Finite size effects of the merging star alter late inspiral GW signal:

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

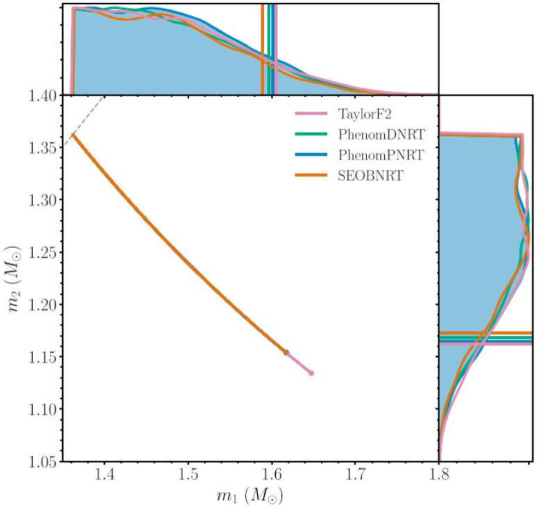
$$\boldsymbol{\theta}_{\rm GW} = \{M_1, M_2, \Lambda_1, \Lambda_2, \chi_{1z}, \chi_{2z}, \varphi, \Psi, \theta_{\rm jn}, t_c, d_L, \mathrm{R.A.}, \mathrm{Decl.}\}$$

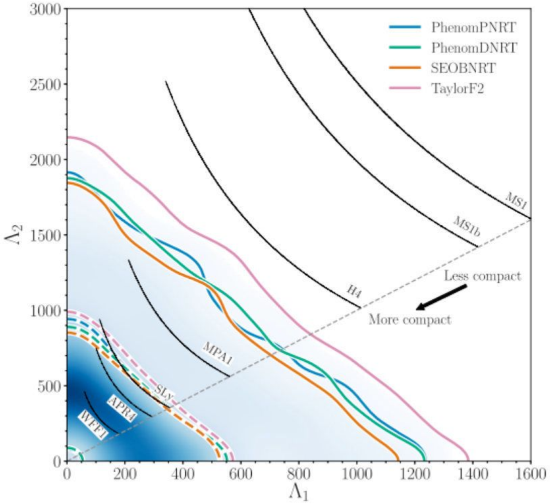


waveform depending on 17(4) parameters



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





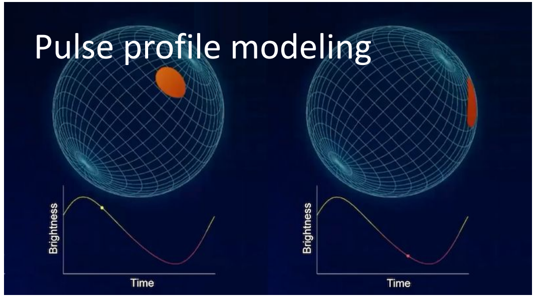
$$Q_{ij} = -\Lambda(EOS, m) m^5 \varepsilon_{ij}$$

Bayesian inference of hyperon-nucleon interaction strengths from combining (binary) NS observations with hypernuclei experiments

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

Kernel density estimation

Trace rays from hot spots on NS surface:



PSR J0030+0451

Miller et al, ApJL, 2019

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

Riley et al, ApJL, 2019

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

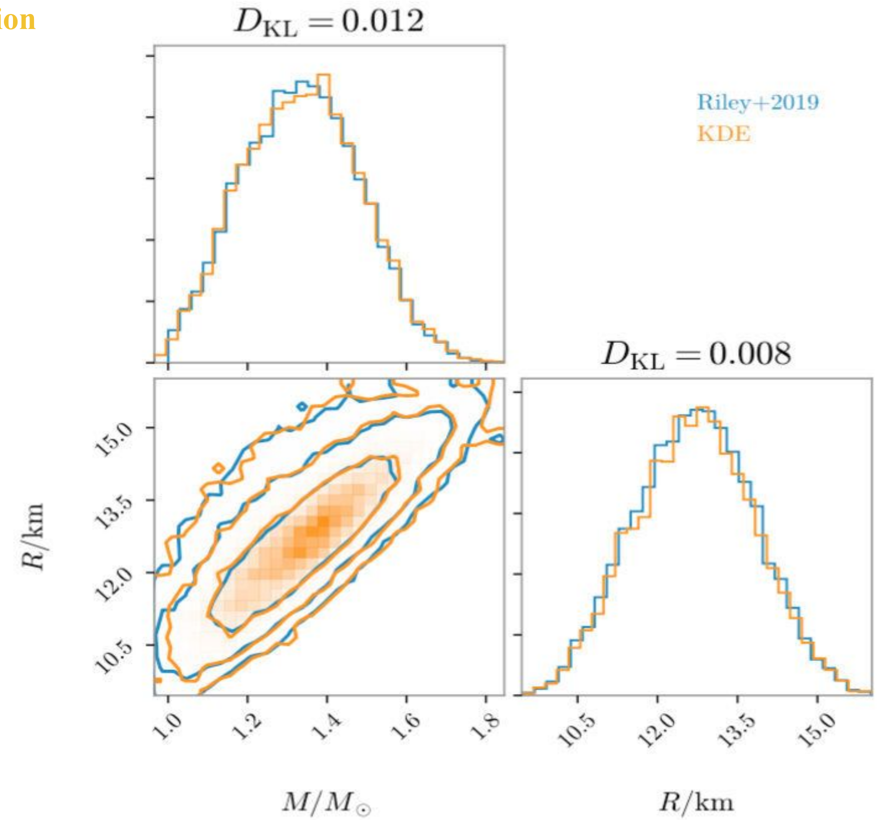
PSR J0740+6620

Miller et al, ApJL, 2021

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

Riley et al, ApJL, 2021

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



Bayesian inference of #hyperon-nucleon interaction strengths from combining (binary) NS observations with hypernuclei experiments

Likelihood Prior

Posterior

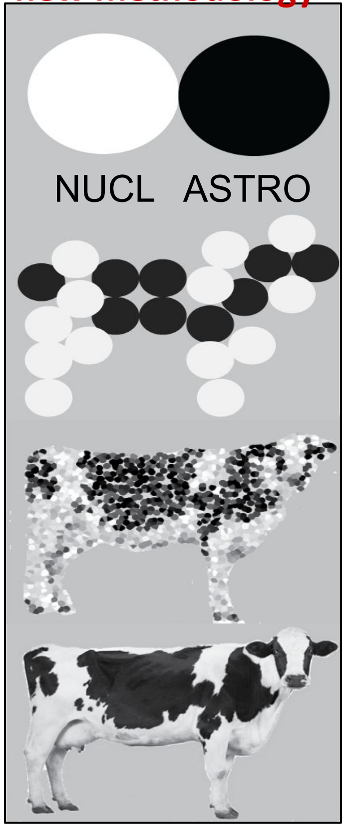
$$p(\boldsymbol{\theta}|D, \mathbb{M}) = \frac{\mathcal{L}(D|\boldsymbol{\theta}, \mathbb{M})\pi(\boldsymbol{\theta})}{\int p(D|\boldsymbol{\theta}, \mathbb{M})\pi(\boldsymbol{\theta})d\boldsymbol{\theta}}$$

Parameter Data Model

Likelihood

- $$\mathcal{L}_{\rm NUCL}(d_{\rm NUCL}|\boldsymbol{\theta}_{\rm EOS}) \propto \exp\left[-\frac{1}{2}\frac{(R_{\sigma\Lambda} - \bar{R}_{\sigma\Lambda})^2}{\sigma^2_{R_{\sigma\Lambda}}}\right]$$
- $$\mathcal{L}_{\rm GW}(d_{\rm GW}|\boldsymbol{\theta}_{\rm GW}, \mathbb{M}) \propto \exp\left[-2\int_0^\infty \frac{|\tilde{d}(f) - \tilde{h}(f, \boldsymbol{\theta}_{\rm GW})|^2}{S_n(f)}df\right],$$
- $$\mathcal{L}_{\rm NICER}(M, R|\boldsymbol{\theta}_{\rm EOS} \cup \{\varepsilon_c\}, \mathbb{M}) = P_{\rm KDE}(M(\boldsymbol{\theta}_{\rm EOS}; \varepsilon_c), R(\boldsymbol{\theta}_{\rm EOS}; \varepsilon_c)),$$

new methodology



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).*

Span uncertainty in YN interaction

#parameters and priors

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

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

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

- ONLY explore the couplings of Λ hyperons;
- Keep Σ, Ξ hyperon couplings fixed to thei empirical values or based on SU(3) symmetry.

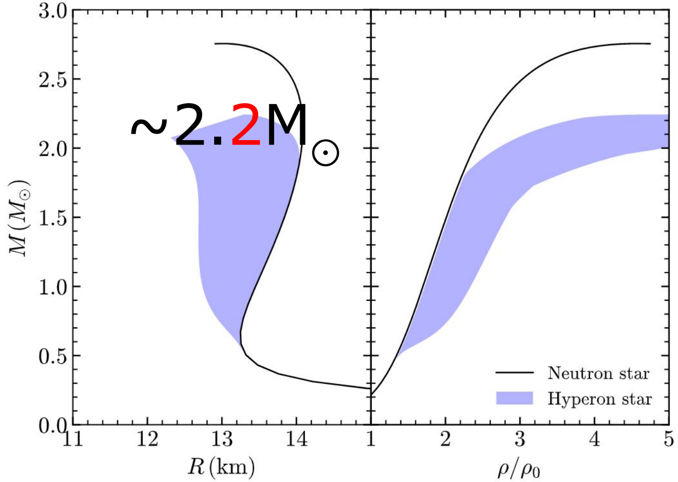
#posteriors

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 YN interaction

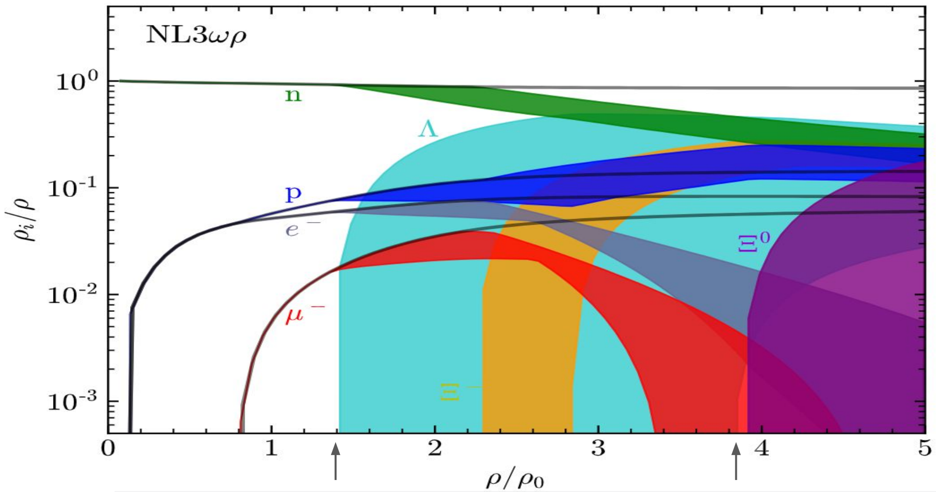
- Taking the NL3ωρ one as an exemplary stiffest one;



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.

2205.10631



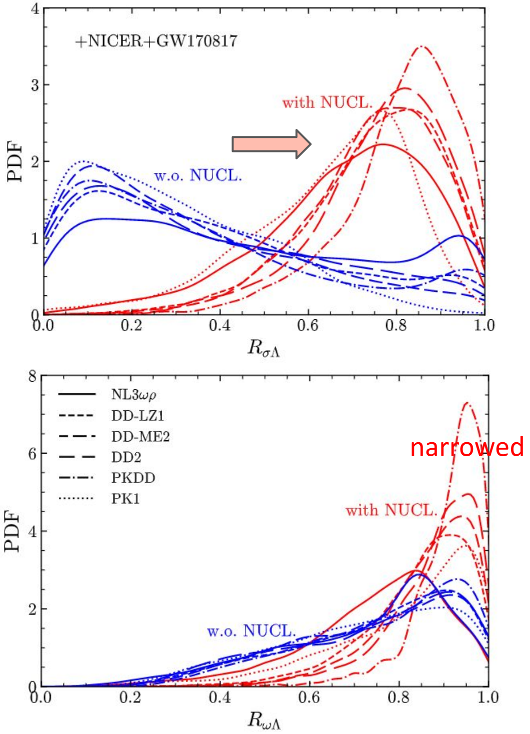
threshold density of Λ hyperons: 1.4-3.8ρ_0

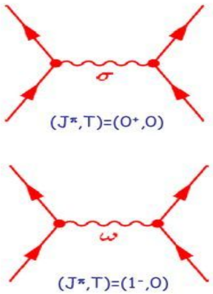
Unclear whether Λ or Ξ− appear first.

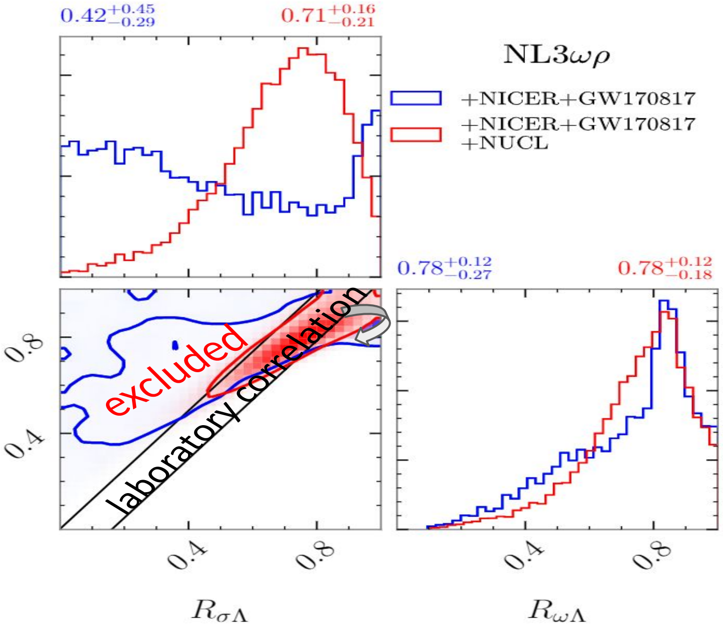
future: +a few ΛΛ hypernuclei, Ξ hypernuclei

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 $R_{\omega\Lambda}$.







No existence of hyperon puzzle?!

Perform Bayesian inference to find the golden EoS (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

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

2022

+mocked MoI (radio) 2107.07979
+DM 2204.05560

2023

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

2024

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

Black box = EoS microphysics

Procedure used until now

$$\Gamma = (\rho + P)(dP/d\rho)/P$$

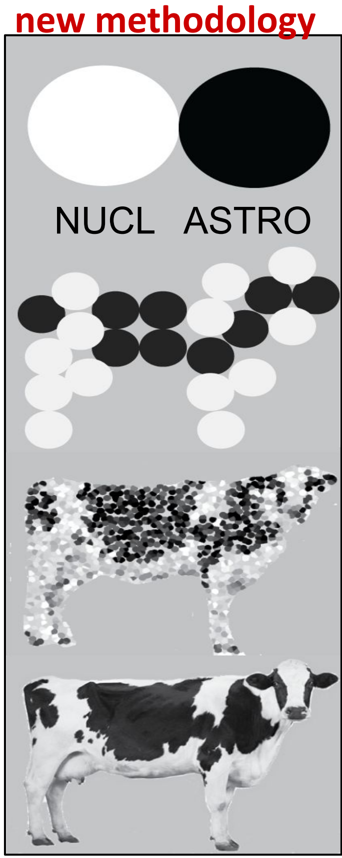
- ❑ Piecewise polytrope EoS: Logarithm of the adiabatic index (Γ) of the EoSs are treated as polynomial: **Little to no microphysics;**

Better procedure

- ❑ More physics at the EoS modelling stage;
- ❑ Support quantitative studies of the EoS at **different** density regimes;
- ❑ With prior **explicitly** considering phase transition;
- ❑ Allow for **straightforward** extensions to higher-dimensional models, accommodating the inclusion of additional particles within NSs, even dark matter;
- ❑ Can discuss the **composition** of matter and the underlying strong **interaction**;
- ❑ Facilitate a **connection** with the ongoing research efforts in the field of relativistic HIC.

Summary and Exciting future

- We incorporate new information from hypernuclei calculations to addresses a long-standing issue in NS physics;
- We 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}~**$2.2M_{\odot}$** ;
- Comprehensive analysis of multi-messenger, multi-wavelength data ongoing to probe the EOS at **different** density regimes…



Thank you! 🌹