Hybrid Equations of State for Neutron Stars with Hyperons and Deltas

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Contents

Hybrid equations of state for neutron stars with hyperons and deltas

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GW190814 as a massive rapidly rotating neutron star with exotic degrees of freedom

V. Dexheimer, R. O. Gomes, T. Klähn, S. Han, and M. Salinas
Phys. Rev. C **103**, 025808 – Published 22 February 2021

Hybrid equations of state for neutron stars with hyperons and deltas

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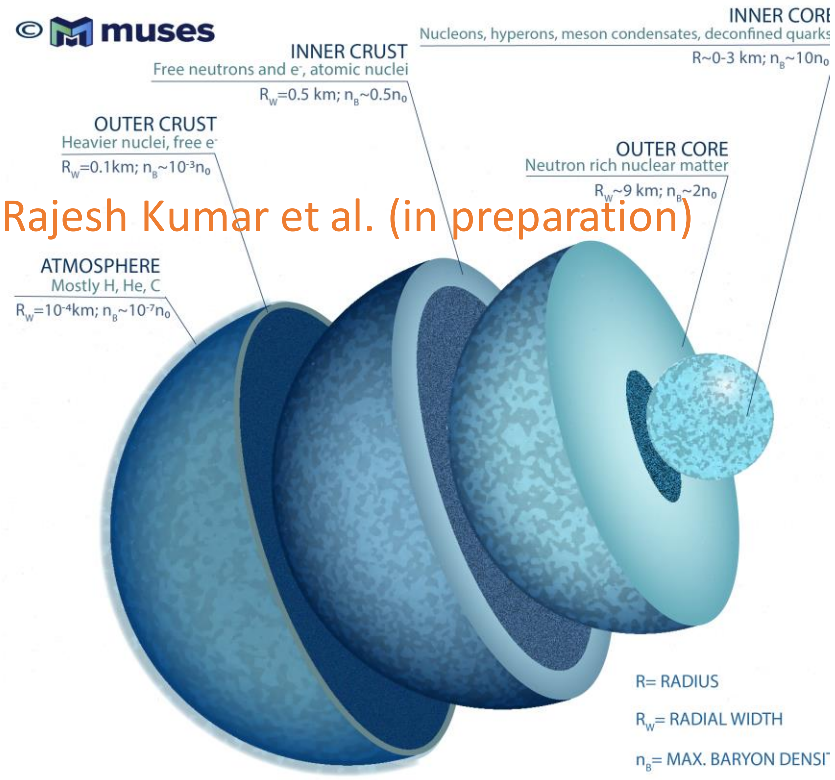
Motivation

- **Bulk baryonic matter** makes up ~**90%** of the radii of neutron stars.
- This could all be made of strictly **hadronic matter** but at **high density** there may be a **phase transition** to **quark matter**.
- At several times saturation density, **baryons begin to overlap** and quark **deconfinement** occurs.
- In my research group's work, we have considered this possibility in our models for neutron star equations of state (EoS).



Rajesh Kumar et al. (in preparation)

COMPOSITION OF A TYPICAL NEUTRON STAR

Chiral Mean Field (CMF)

- Effective relativistic model of QCD that approximates strong force interactions as **exchanges of scalar and vector mesons**.
- Scalar mesons carry **attractive** part of strong force, while vector mesons carry the **repulsive** part.
- **Fitted** to reproduce nuclear, astrophysical and lattice QCD data.
- Includes a **deconfinement potential** that allows for hadrons to break down into quark matter at high densities in a **first order phase transition**.
- Reproduces **chiral symmetry restoration** at high densities.
- This model includes **nucleons, leptons, hyperons, deltas and uds quarks**.

$$L = L_{Kin} + L_{Int} + L_{Self} + L_{SB} - U,$$

$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B} + g_{B\Phi}\Phi^2$$
$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q} + g_{q\Phi}(1 - \Phi)$$

Chiral Mean Field (CMF)

- In this model, we keep **attractive terms fixed** to reproduce **vacuum masses** of hadrons.
- Repulsive (**vector**) terms are **constrained** to reproduce **isospin-symmetric matter** saturation properties.
- We can vary **isovector** terms and **higher order vector terms**.

CMF parameterizations

- **EoS 1** with standard interactions
  hadronic: nucleons, hyperons, electrons, and muons
  hybrid: nucleons, hyperons, uds quarks, electrons, and muons
  with phase transition at $n_B = 0.472\ \mathrm{fm}^{-3}$
- **EoS 2** with standard interactions
  hadronic: nucleons and electrons
  hybrid: nucleons, ud quarks, and electrons
  with phase transition at $n_B = 0.433\ \mathrm{fm}^{-3}$
- **EoS 3** with $\omega\rho$ terms
  hadronic: nucleons, hyperons, electrons, and muons
  hybrid: nucleons, hyperons, uds quarks, electrons, and muons
  with phase transition at $n_B = 0.638\ \mathrm{fm}^{-3}$
- **EoS 4** with $\omega\rho$ terms
  hadronic: nucleons and electrons
  hybrid: nucleons, ud quarks, and electrons
  with phase transition at $n_B = 0.561\ \mathrm{fm}^{-3}$
- **EoS 5** with $\omega\rho$ and ω^4 terms
  hadronic: nucleons, hyperons, electrons, and muons
  hybrid: nucleons, hyperons, uds quarks, electrons, and muons
  with phase transition at $n_B = 0.688\ \mathrm{fm}^{-3}$
- **EoS 6** with $\omega\rho$ and ω^4 terms
  hadronic: nucleons and electrons
  hybrid: nucleons, ud quarks, and electrons
  with phase transition at $n_B = 0.629\ \mathrm{fm}^{-3}$
- **EoS 7** with $\omega\rho$ and ω^4 terms
  hadronic: nucleons, hyperons, Δ's, electrons, and muons
  hybrid: nucleons, hyperons, Δ's, uds quarks, electrons, and muons
  with phase transition at $n_B = 0.689\ \mathrm{fm}^{-3}$
- **EoS 8** with $\omega\rho$ and ω^4 terms
  hadronic: nucleons, Δ's, and electrons
  hybrid: nucleons, Δ's, ud quarks, and electrons
  with phase transition at $n_B = 0.644\ \mathrm{fm}^{-3}$

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Nuclear Properties

For isospin symmetric matter:

- Saturation density, $n_B = 0.15$ fm^{-3}
- Binding energy per nucleon, $B = -16$ MeV
- Compressibility, $K = 300$ MeV
- Symmetry Energy, $E_{sym} = 30$ MeV

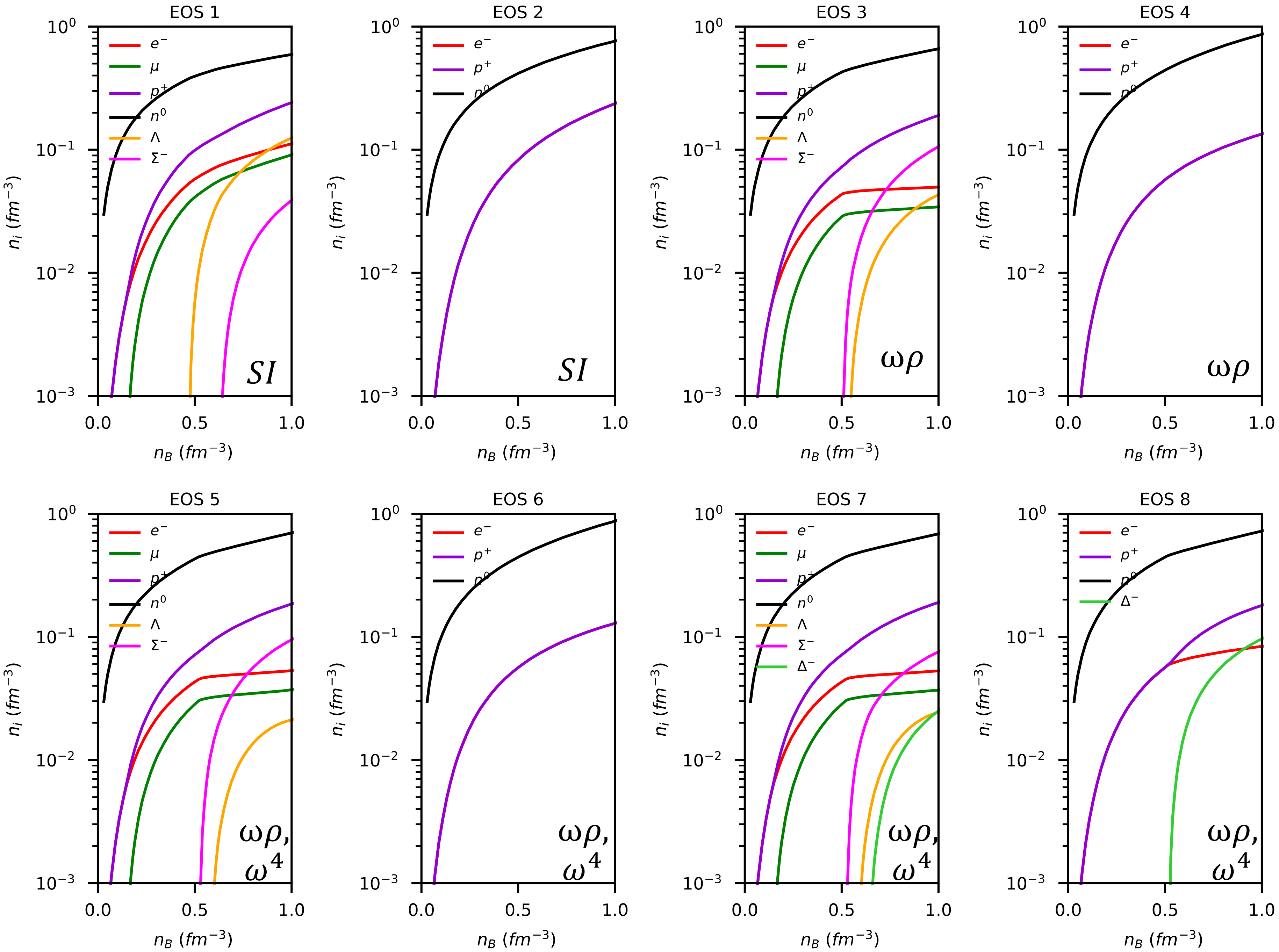
Hyperon potentials for symmetric matter at saturation are:

- U_Λ = −28 or -27 MeV (ω^4)
- U_Σ = 5 or 6 MeV (ω^4)
- U_Ξ = −18 or -17 MeV (ω^4)
- $U_\Delta = 64$ MeV (ω^4)
- The symmetry energy slope, L = 88 MeV or 75 MeV when $\boldsymbol{\omega\rho}$ **interactions** are **included**.

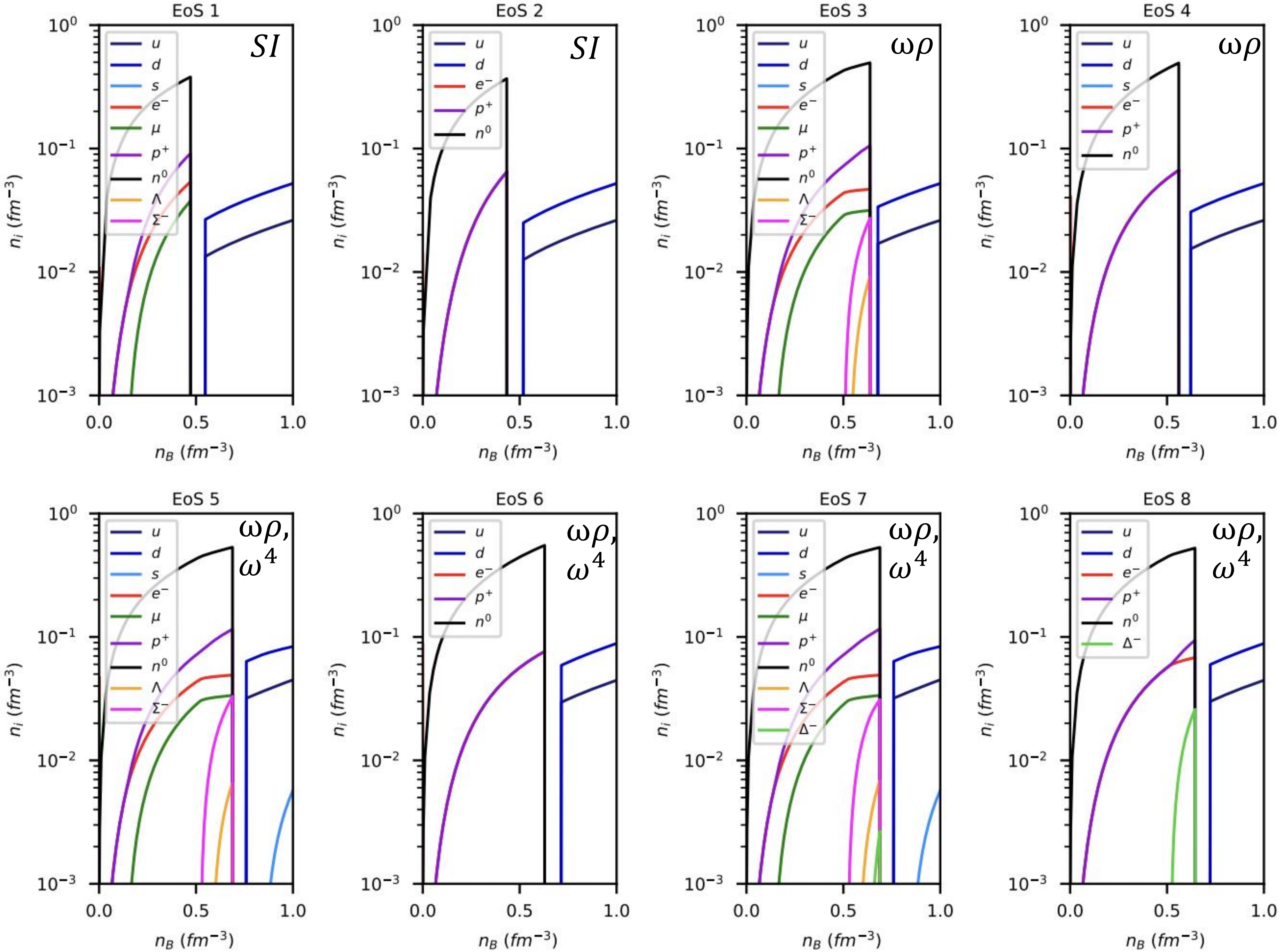
Population Plots

- 1D tables
- Charge Neutral
- Zero Temperature
- In chemical equilibrium

Hadronic


EOS 1
EOS 2
EOS 3
EOS 4
EOS 5
EOS 6
EOS 7
EOS 8
e^-
μ
p^+
n^0
Λ
Σ^-
Δ^-
$n_i\ (fm^{-3})$
$n_B\ (fm^{-3})$
10^0
10^{-1}
10^{-2}
10^{-3}
0.0
0.5
1.0
SI
$\omega\rho$
$\omega\rho,$
ω^4

Hybrid



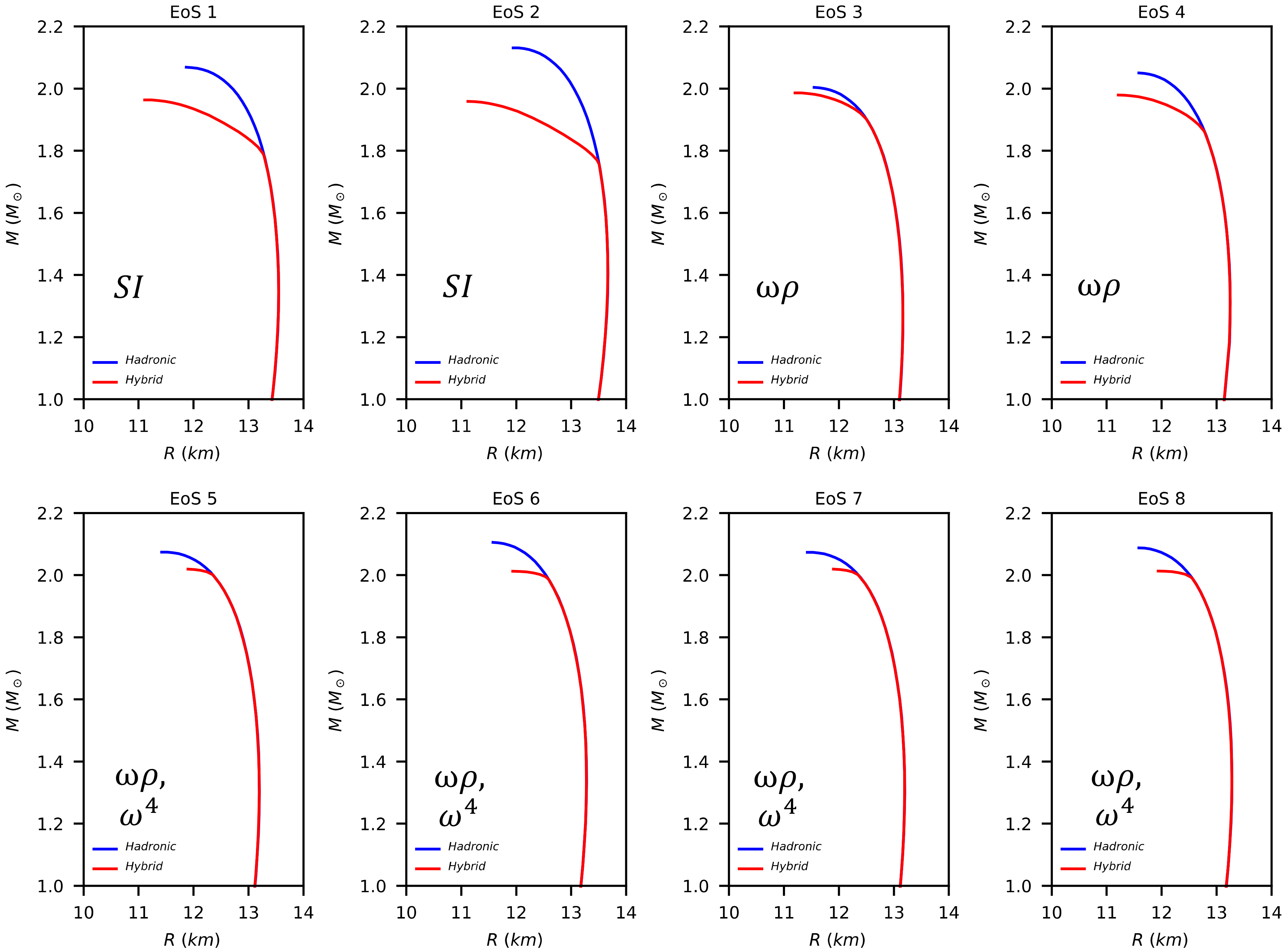
EoS 1
SI
EoS 2
SI
EoS 3
ωρ
EoS 4
ωρ
EoS 5
ωρ, ω^4
EoS 6
ωρ, ω^4
EoS 7
ωρ, ω^4
EoS 8
ωρ, ω^4
u
d
s
e⁻
μ
p⁺
n⁰
Λ
Σ⁻
Δ⁻
n_i (fm⁻³)
n_B (fm⁻³)
10^0
10^-1
10^-2
10^-3
0.0
0.5
1.0

Results

- $\omega\rho$ **reduces** the **cost of producing** isospin asymmetry thus **lowering** the $L = 75$ MeV.
- This cause **hyperons** to appear in a **different order**.
- $\omega\rho$ **softens** EoS at **lower** density, while ω^4 **stiffens** at **high** density.
- **Adding** the $\omega\rho$ and ω^4 terms **pushed** the phase transition to **higher** densities.
- **Absence** of **hyperons** makes the phase transition **stronger.**
- **Strange quarks** do not appear in very **large** quantities due to its **large bare mass**.

Effects on Neutron Star Properties

- To consider **macroscopic** properties, we must include the effects of **nuclei**.
- We added a zero-temperature **beta-equilibrated crust** to each EoS from Gulminelli and Raduta.
- We **chose** these crusts so that the symmetry energy slope does not **jump** between crust and core.
- Using the TOV equation, we obtained MR curves for each EoS and compared **hadronic** vs **hybrid** for each EoS.


EoS 1
EoS 2
EoS 3
EoS 4
EoS 5
EoS 6
EoS 7
EoS 8
M ($M_\odot$)
R (km)
Hadronic
Hybrid
SI
ωρ
ωρ, ω^4

Results

EoS	M_{max} ($M_\odot$)	R of M_{max} (km)	n_{B_c} of M_{max} (fm^{-3})	R of 1.4 $M_\odot$ (km)	$\tilde{\Lambda}$ of 1.4 $M_\odot$
1 hadronic	2.07	11.87	0.916	13.55	889
1 hybrid	1.96	11.11	1.079	13.55	889
2 hadronic	2.13	11.95	0.751	13.67	904
2 hybrid	1.96	11.11	1.079	13.67	904
3 hadronic	2.00	11.55	0.964	13.15	702
3 hybrid	1.99	11.20	1.040	13.15	702
4 hadronic	2.05	11.59	0.956	13.24	739
4 hybrid	1.98	11.21	1.040	13.24	739
5 hadronic	2.07	11.42	0.988	13.18	723
5 hybrid	2.02	11.89	0.892	13.18	723
6 hadronic	2.11	11.58	0.946	13.27	754
6 hybrid	2.01	11.94	0.892	13.27	754
7 hadronic	2.07	11.42	0.988	13.18	723
7 hybrid	2.02	11.90	0.892	13.18	723
8 hadronic	2.09	11.58	0.950	13.27	754
8 hybrid	2.01	11.94	0.892	13.27	754

$\omega\rho$ (rows 3–4)

$\omega\rho$, ω^4 (rows 5–8)

Results

- EoS's with **hyperons** produced **lower** M_{max} , as well as EoS's with **quark deconfinement**.
- Regardless of composition, $\boldsymbol{\omega\rho}$ **term decreases** stellar **radii** and tidal **deformability**, while increasing central density of M_{max}.
- ω^4 **increases** the stellar mass and slightly increases stellar radii.
- Most of our EoS's have $M_{max} \cong 2.0\, M_{\odot}$, which is consistent with observations.
- Hybrid star maximum masses only vary by $0.06\, M_{\odot}$, but the hybrid branches differ significantly in size.

Rotating Neutron Stars

Introduction

- GW190814 **reported** merger of **Black Hole** 23.2+1.1-1.0 M_{sun} a **compact object** having mass 2.59+0.08-0.09 M_{sun} .
- The companion object lies within the **mass-gap category**.

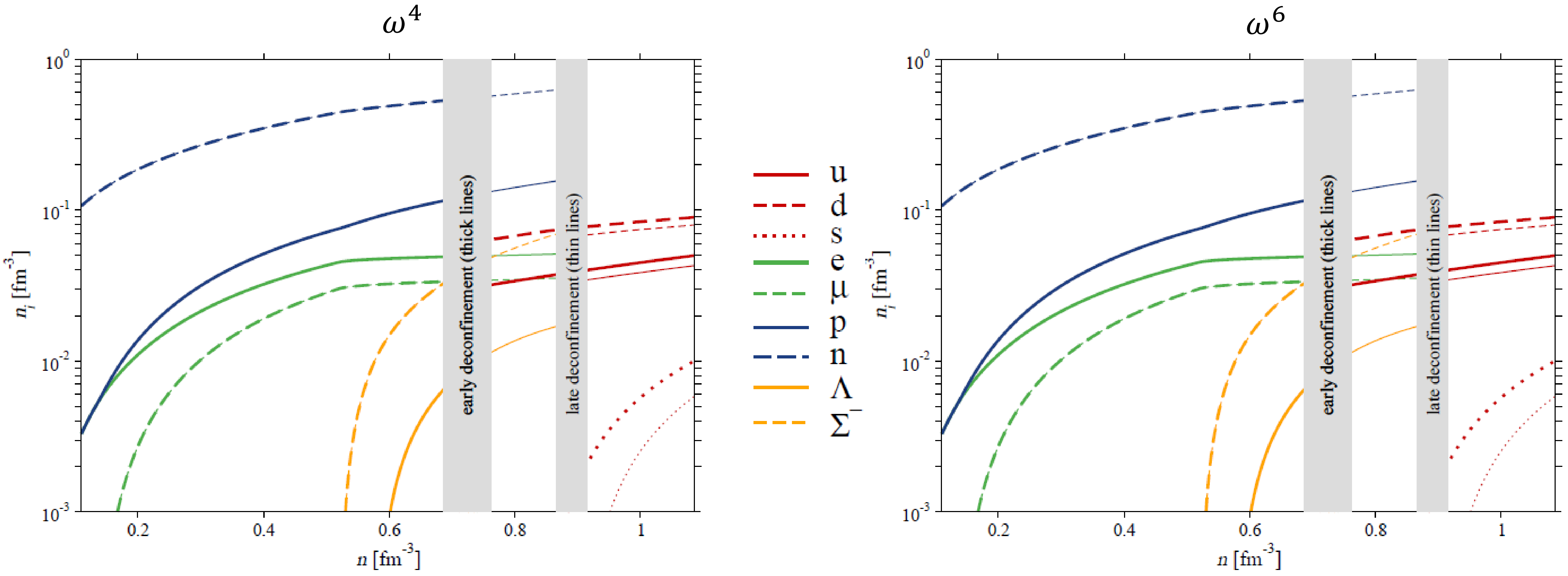
CMF Model

- **Higher order vector** coupling ω^4 and ω^6 .
- Deconfinement potential **parameterization**.

$$U = (a_o T^4 + a_1 \mu_B^4 + a_2 T^2 \mu_B^2)\Phi^2 + a_3 T_o^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4),$$

V. Dexheimer, R. O. Gomes, T. Klähn, S. Han, and M. Salinas Phys. Rev. C **103**, 025808, 2021.

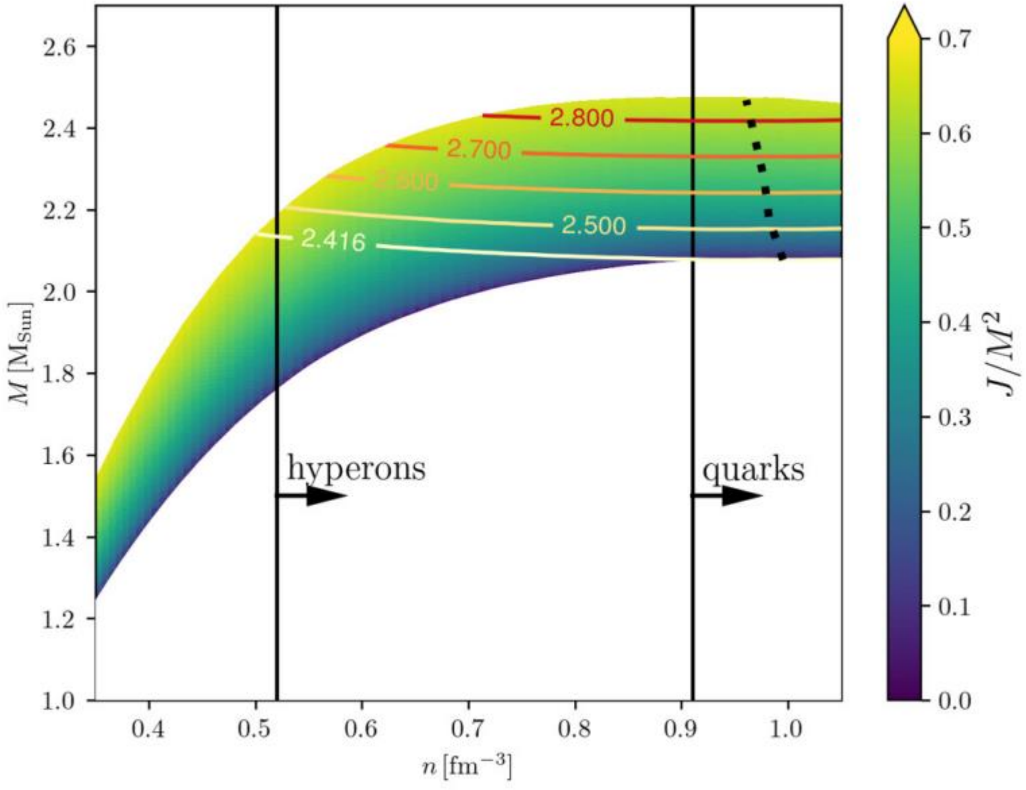
Observations: Population Plots



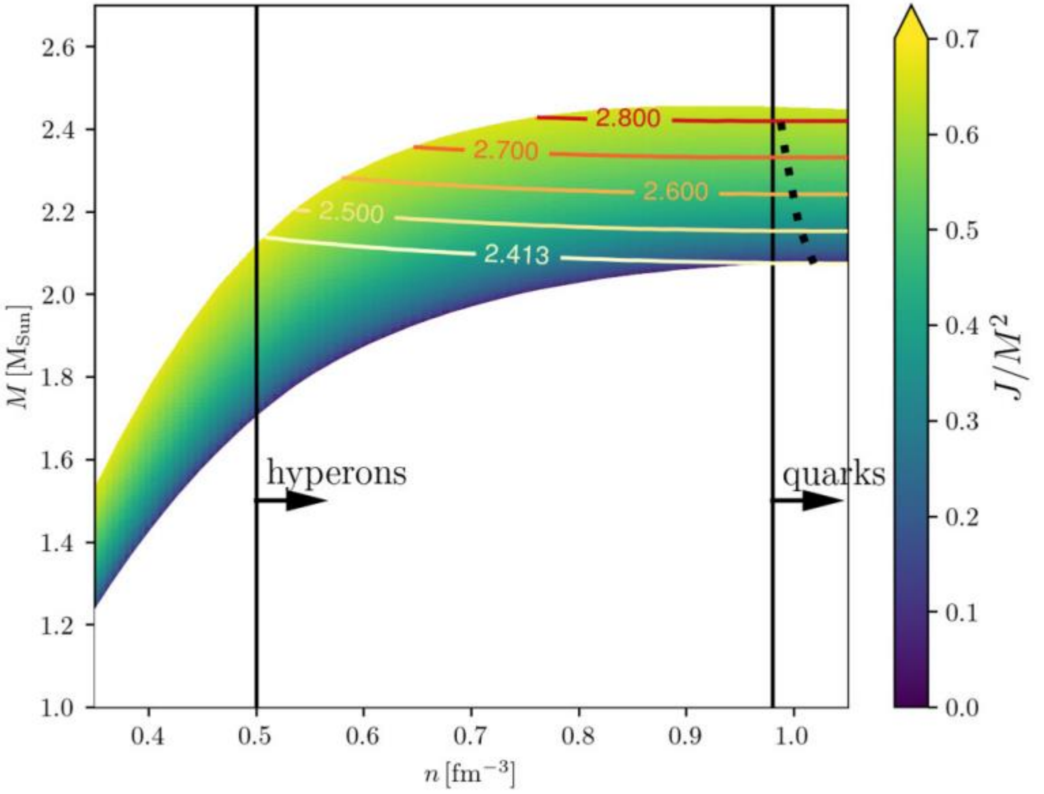
V. Dexheimer, R. O. Gomes, T. Klähn, S. Han, and M. Salinas Phys. Rev. C **103**, 025808, 2021.

Observations: Mass of NSs

ω^4



ω^6



V. Dexheimer, R. O. Gomes, T. Klähn, S. Han, and M. Salinas Phys. Rev. C **103**, 025808, 2021.

Results

- A neutron star can have mass ~ 2.5 M_{sun} and still can have **exotic** degrees of freedom.
- For ω^4 interactions the star can have **considerable** amount of quarks and hyperons.
- For ω^6 interactions the star can have **considerable** amount of hyperons but quarks become **insignificant**.

TABLE II. Gravitational mass M, rotational frequency f, and central stellar density n_c for the most massive maximally spinning configuration involved.

EoS model	$M(M_{Sun})$	f (kHz)	n_c (n_0)
CMF $\omega^4 \neq 0$ H+Q $*$	2.474	1.38	0.88
CMF $\omega^6 \neq 0$ H+Q $*$	2.455	1.39	0.89

V. Dexheimer, R. O. Gomes, T. Klähn, S. Han, and M. Salinas Phys. Rev. C **103**, 025808, 2021.

Conclusions and Future Work

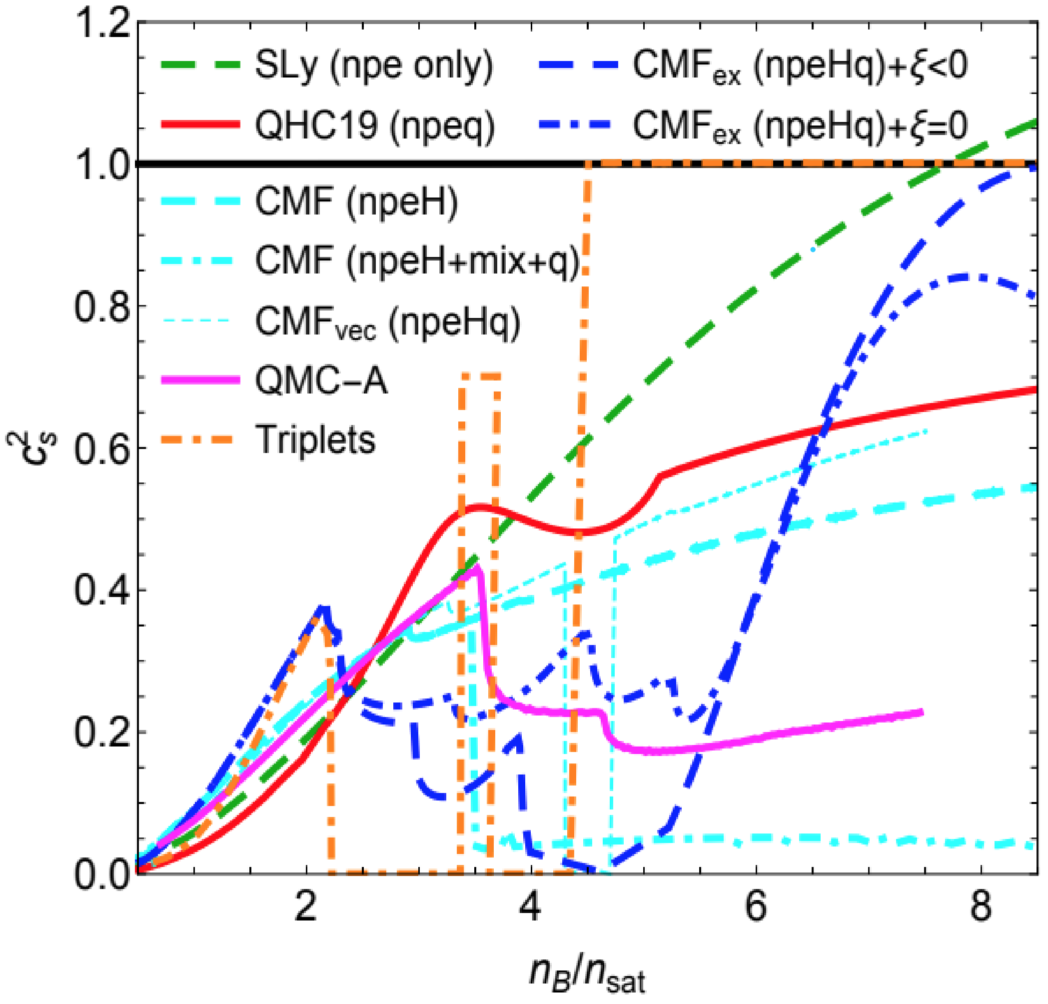
- CMF model offers a way to produce EoS's for astrophysical purposes.
- To **fit** EoS's to particular nuclear and astrophysical properties, an EoS may not be just stiff or soft but **sum** of both.
- **Inclusion** of exotic degrees of freedom in the CMF can attain $M_{max} \cong 2.0\, M_{\odot}$.
- **Higher order** of vector couplings can support the heavy $M_{max} \cong 2.5\, M_{\odot}$ with **rotations**.
- We are in the process of extending some of the EoS's into **3D tables** allowing **for finite temperature** and **out of beta-equilibrium** charge fractions.
- We then are working to **run** simulations of **neutron-star mergers** with these EoS's.

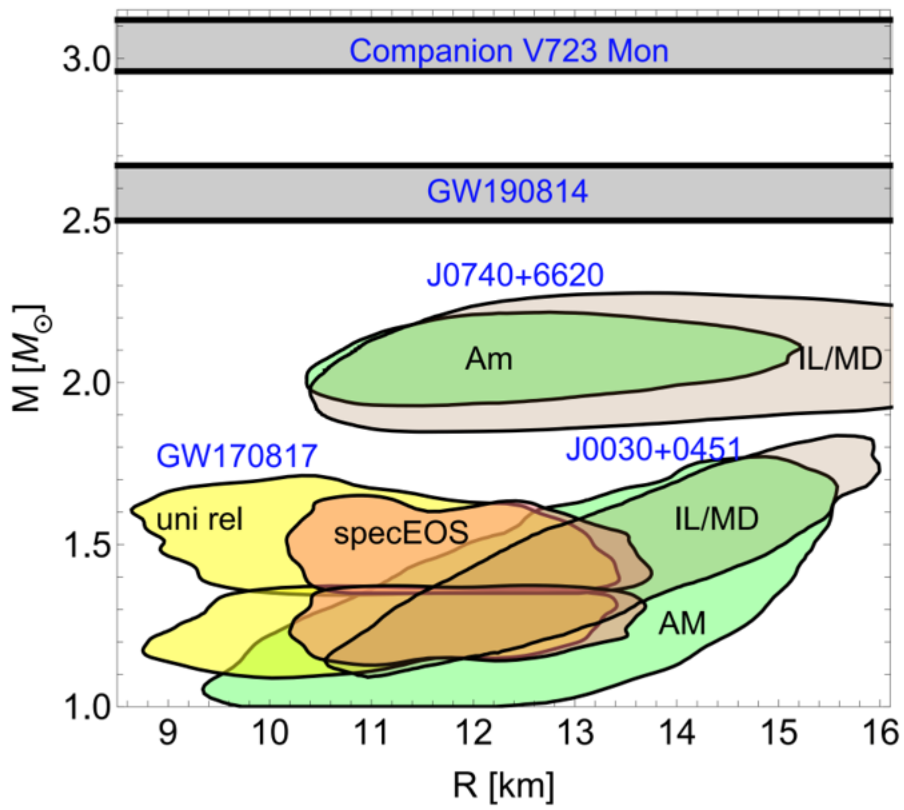
Thanks

CompOSE

- Compstar Online Supernovae Equations of State
- Provides tables of thermodynamical, compositional, microscopic, and other data for EoS's in a common format.
- Format allows for 1D, 2D and 3D tables for astrophysical applications.
- Has instruction manual for users and providers.
- Our EoS's with and without crust are available on CompOSE.
- https://compose.obspm.fr/

S. Typel, M. Oertel, T. Klähn et al, arxiv:2203.03209





Hung Tan, Travis Dore, Veronica Dexheimer, Jacquelyn Noronha-Hostler, and Nicolás Yunes Phys. Rev. D **105**, 023018, 2021

In-medium mesons in the CMF model

- Analysis of pseudoscalar and scalar D mesons and charmonium decay width in hot magnetized asymmetric nuclear matter.

  Rajesh Kumar and Arvind Kumar, Phys. Rev. C 101 , 015202 (2020).

- Kaons and phi meson mass and decay width in strange hadronic matter.

  Rajesh Kumar and Arvind Kumar, Phys. Rev. C 102, 045206 (2020).

To encourage necessary developments, needed for putting a meaningful constraint on the EOS, the following questions will be considered at the workshop:

– Can we reconcile data from current and previous experiments?

– What other observables could enable the extraction of the EOS?

– Are the nuclear matter EOSs from astrophysics consistent with heavy-ion collision observables in the range rho < 4.0rho_0?

– Can we find a flexible common parametrization of the EOS, applicable to neutron star calculations and different types of heavy-ion collisions simulations?

– What improvements on the constraints on the EOS can we expect from future heavy-ion experiments?

– What development is necessary for transport codes to address the above questions?