NP3M

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NSF

Center for Nuclear Research

KENT STATE UNIVERSITY

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Hybrid Equations of State for Neutron Stars with Hyperons and Deltas

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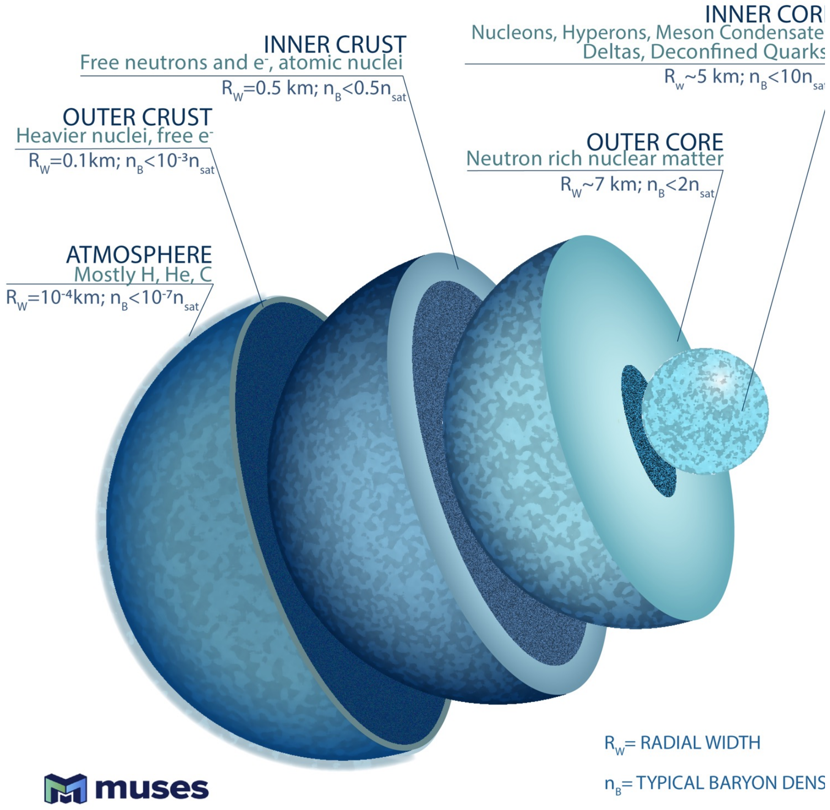
Motivation

- 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 will 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).



Constraints on Equation of States

- We must produce EoS's that are physical!
- They must be casual ($0 < c^2 < 1$)
- Must reproduce nuclear physics at n_0
- Must include expected composition at a given energy
- They must produce maximum masses >2.0 M_{sun}.
- Stellar radii and tidal deformability have high uncertainties, so they do not impose strong constraints at this point.
- Must reproduce features of QCD

R. Kumar et al. [MUSES], [arXiv:2303.17021 [nucl-th]].

Chiral Mean Field (CMF)

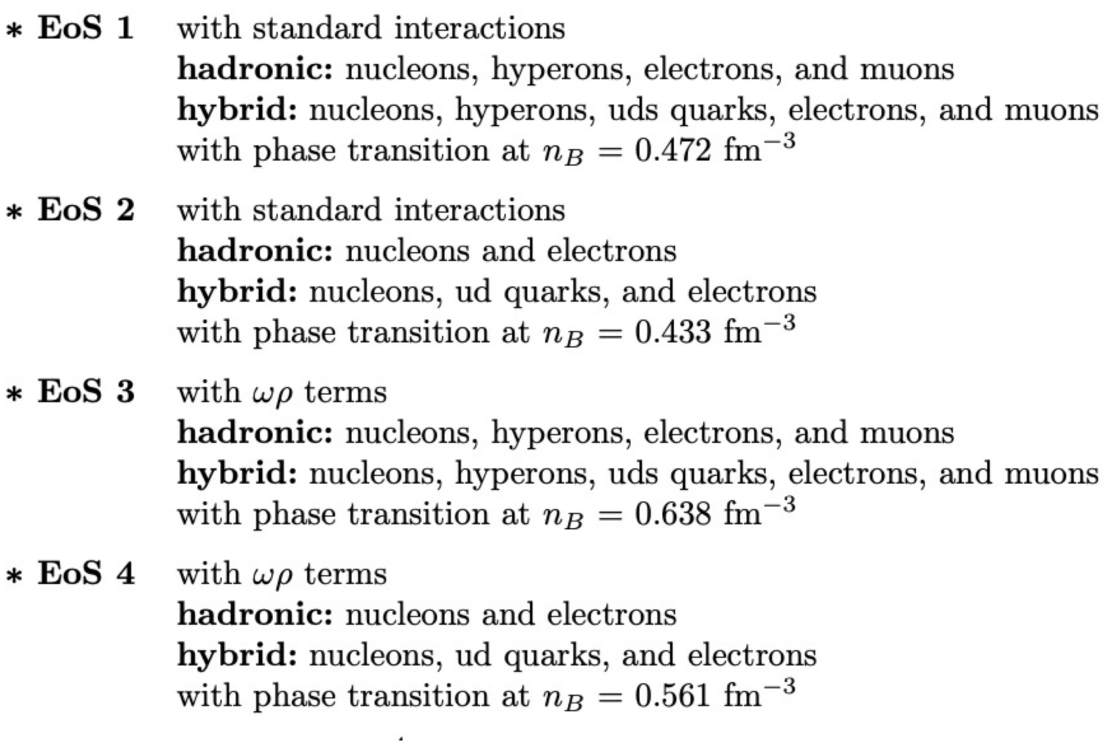
- Effective relativistic model of QCD that approximates strong force interactions as exchanges of scalar and vector mesons.
- Fitted to reproduce nuclear, astrophysical and lattice QCD data.
- Scalar mesons carry attractive part of strong force, while vector mesons carry the repulsive part.
- Includes 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.

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

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.
- We then considered EoS's with some of these additional 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
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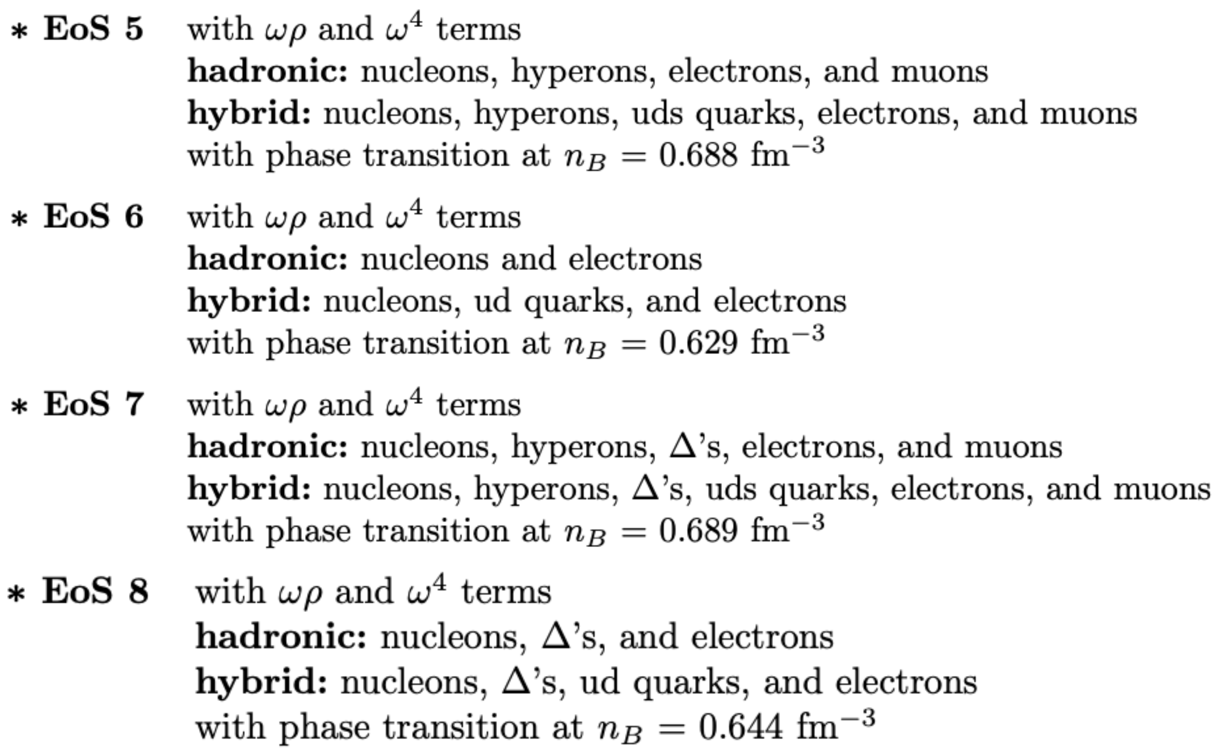
  with phase transition at $n_B = 0.561\ \mathrm{fm}^{-3}$



- **EoS 5** with $\omega\rho$ and ω^4 terms
  hadronic: nucleons, hyperons, electrons, and muons
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  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
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- **EoS 8** with $\omega\rho$ and ω^4 terms
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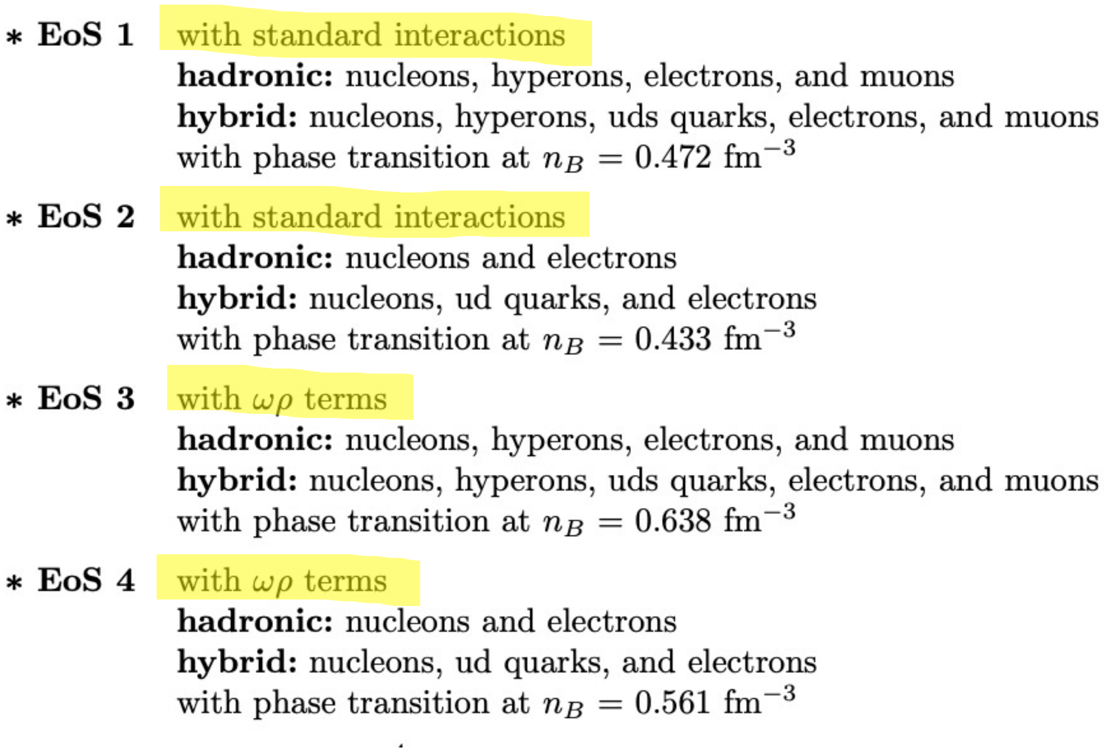
CMF parameterizations



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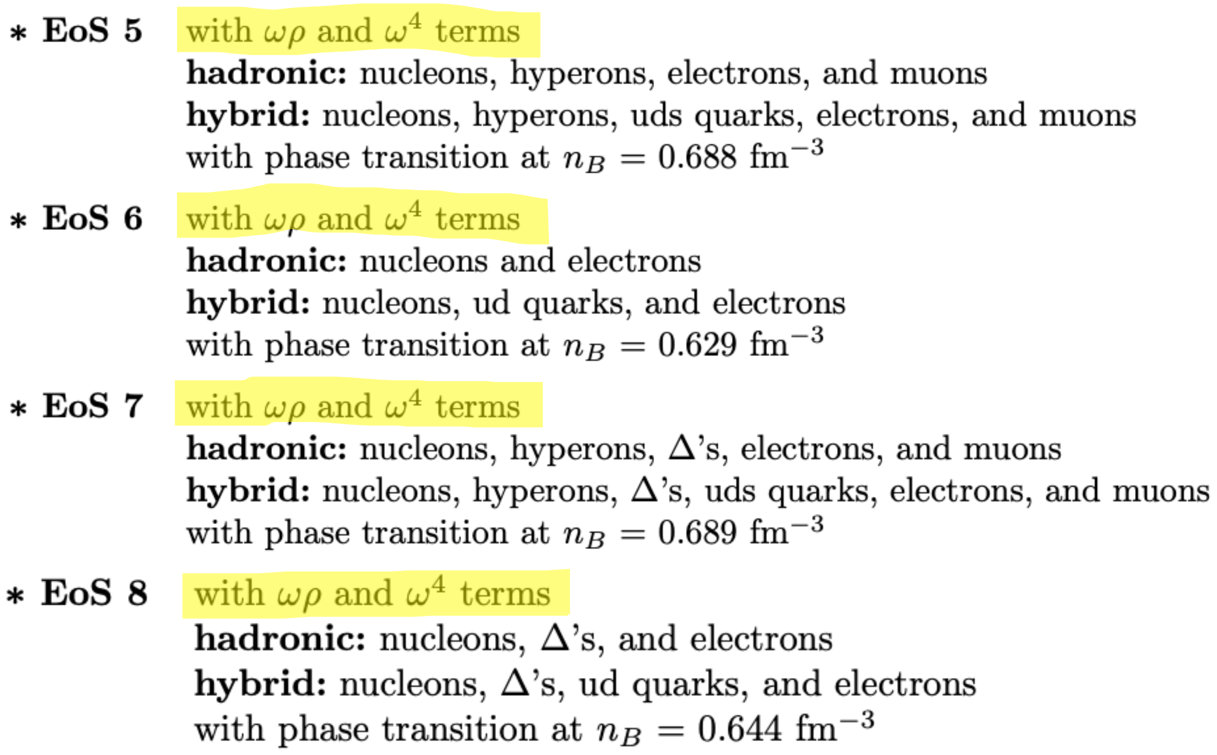

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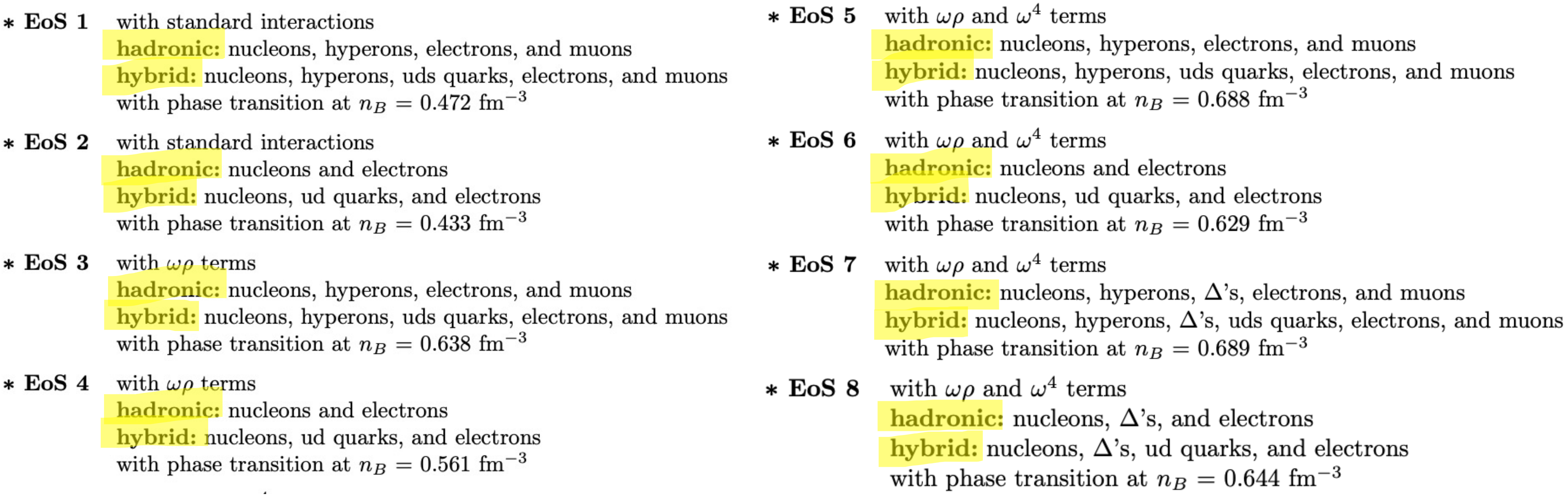

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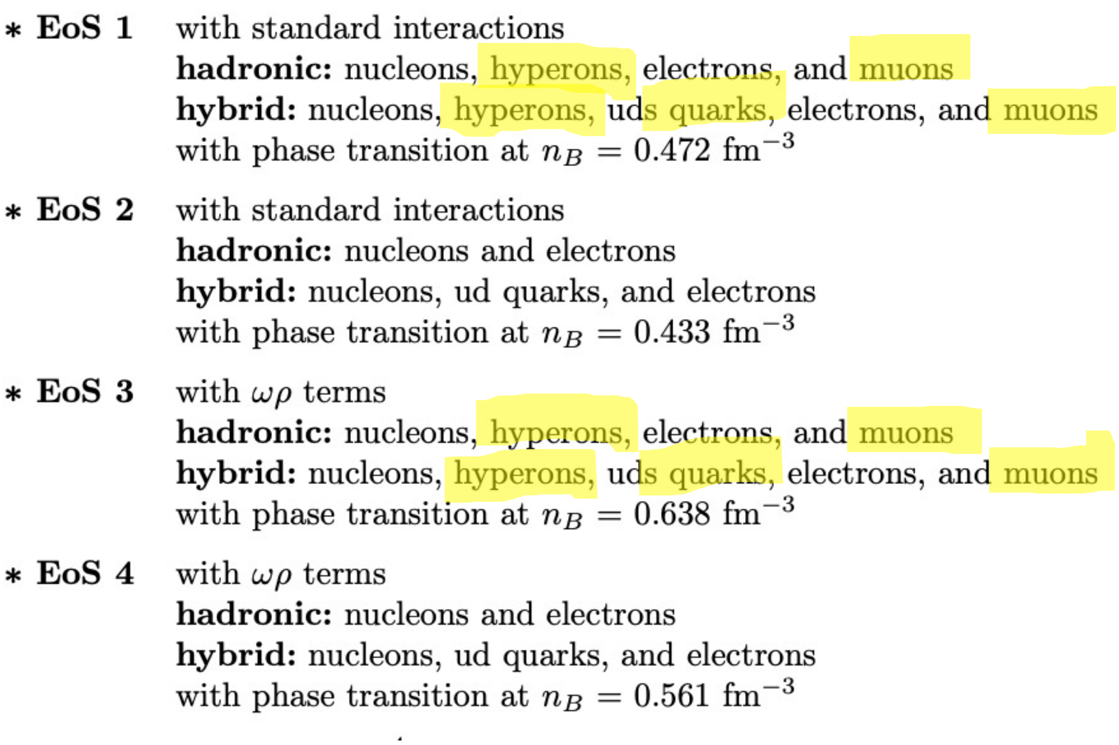

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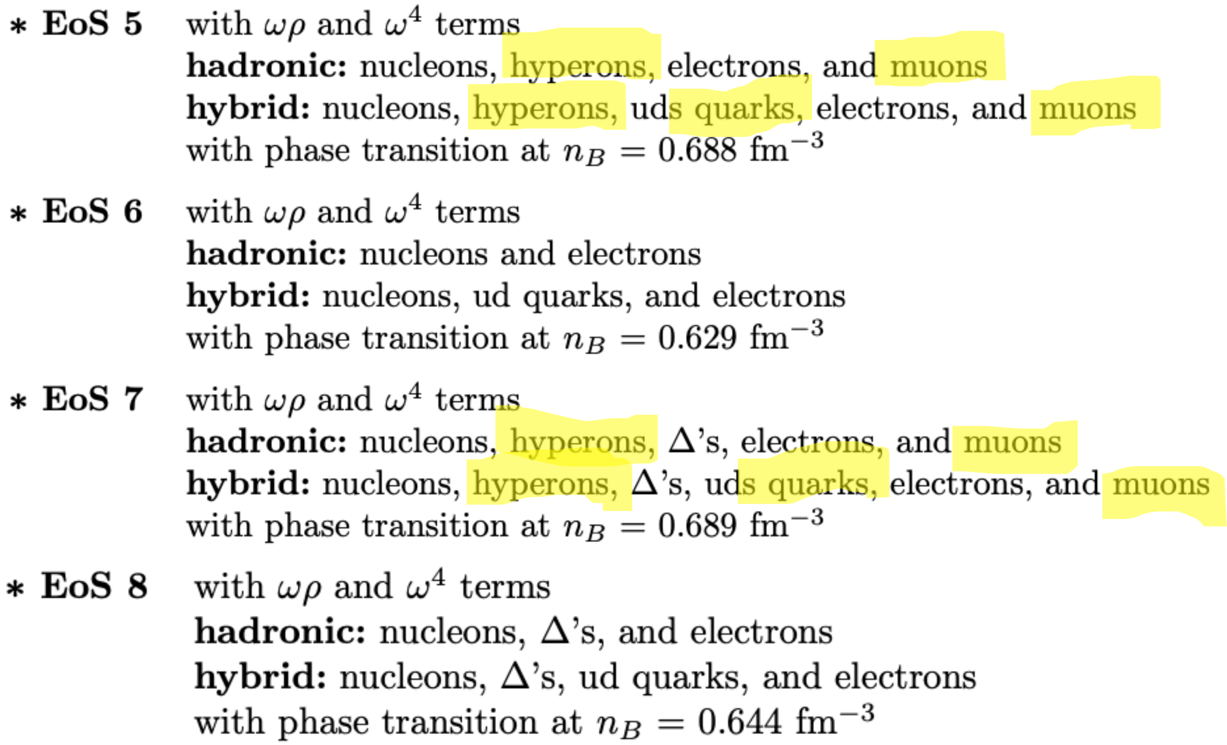

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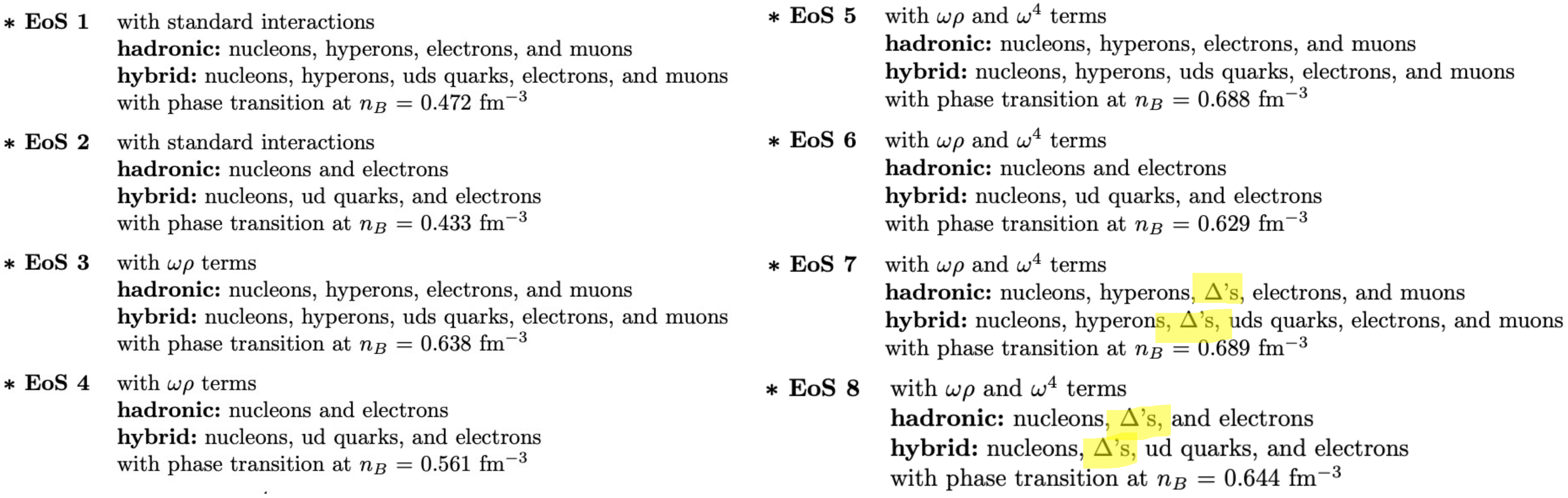

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Nuclear Properties

For isospin symmetric matter:

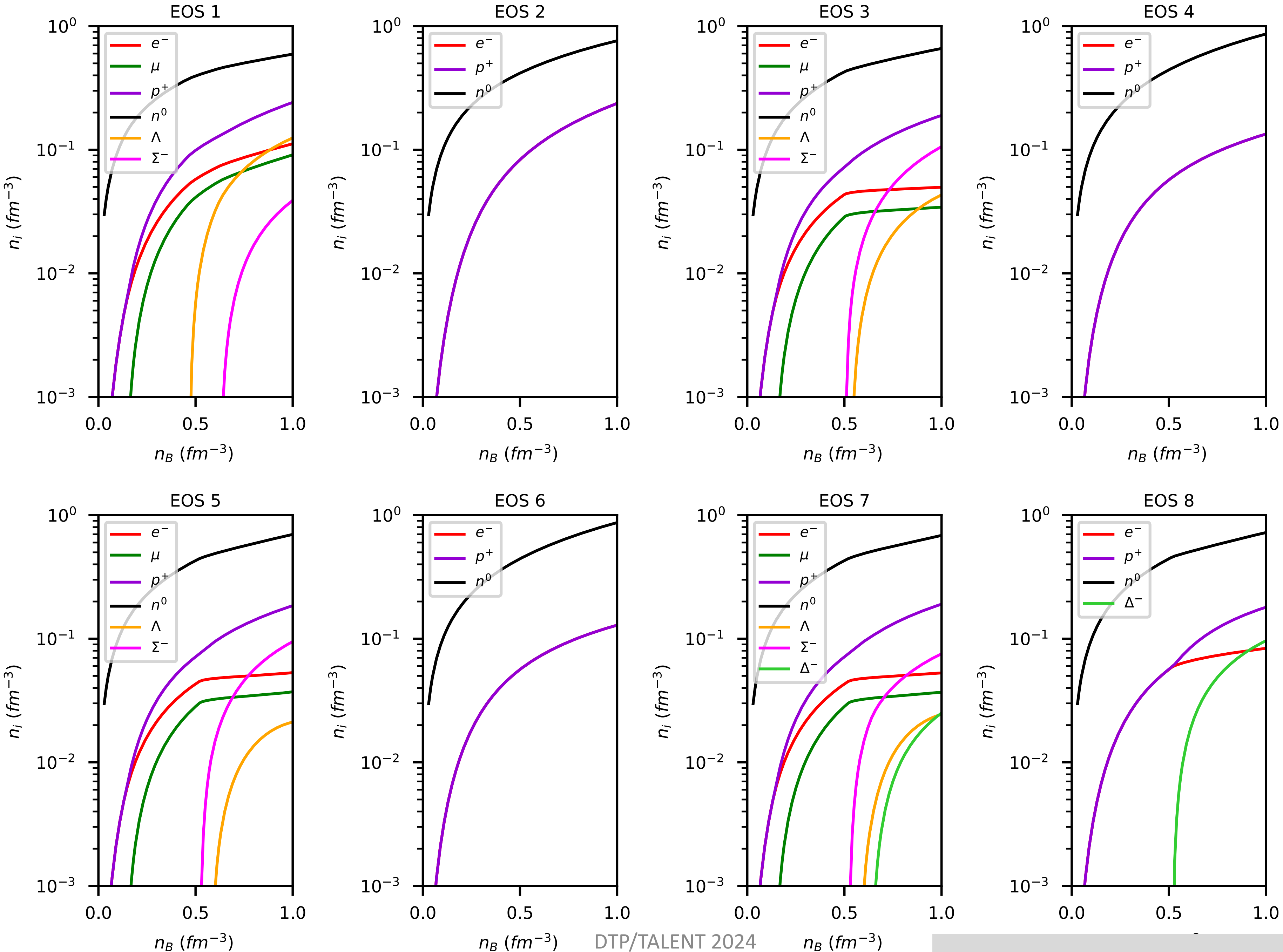
- Saturation density, $n_B = 0.15$ fm^{-3}
- Binding energy per nucleon, $B = -16$ MeV
- Compressibility, $K = 300$ MeV
- Symmetry Energy, $E_{sym} = 30$ MeV
- The symmetry energy slope, L = 88 MeV or 75 MeV when $\omega\rho$ interactions are included.

Hyperon potentials for symmetric matter at saturation are:

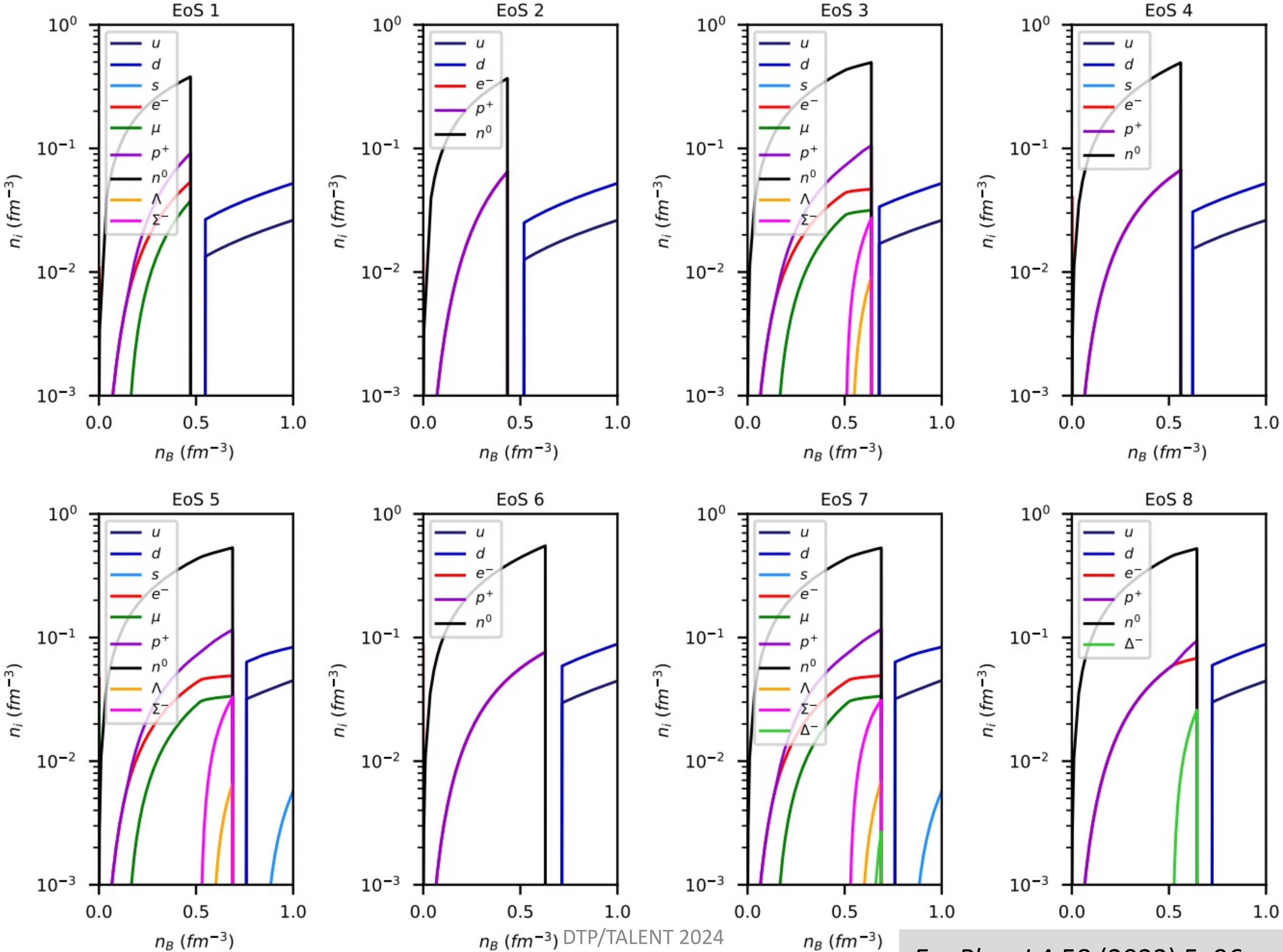
- U_Λ = −28 or -27 MeV (ω^4)
- U_Σ = 5 or 6 MeV (ω^4)
- U_Ξ = −18 or -17 MeV (ω^4)
- $U_\Delta = 64$ MeV (ω^4)

Population Plots

- 1D tables
- Charge Neutral
- Zero Temperature
- In chemical equilibrium
- Hybrid plots show a relatively weak first-order phase transition which allows for stable stars with no mixed phase.



Eur.Phys.J.A 58 (2022) 5, 96, e-Print: 2205.00559



Eur.Phys.J.A 58 (2022) 5, 96, e-Print: [2205.00559](https://arxiv.org/abs/2205.00559)

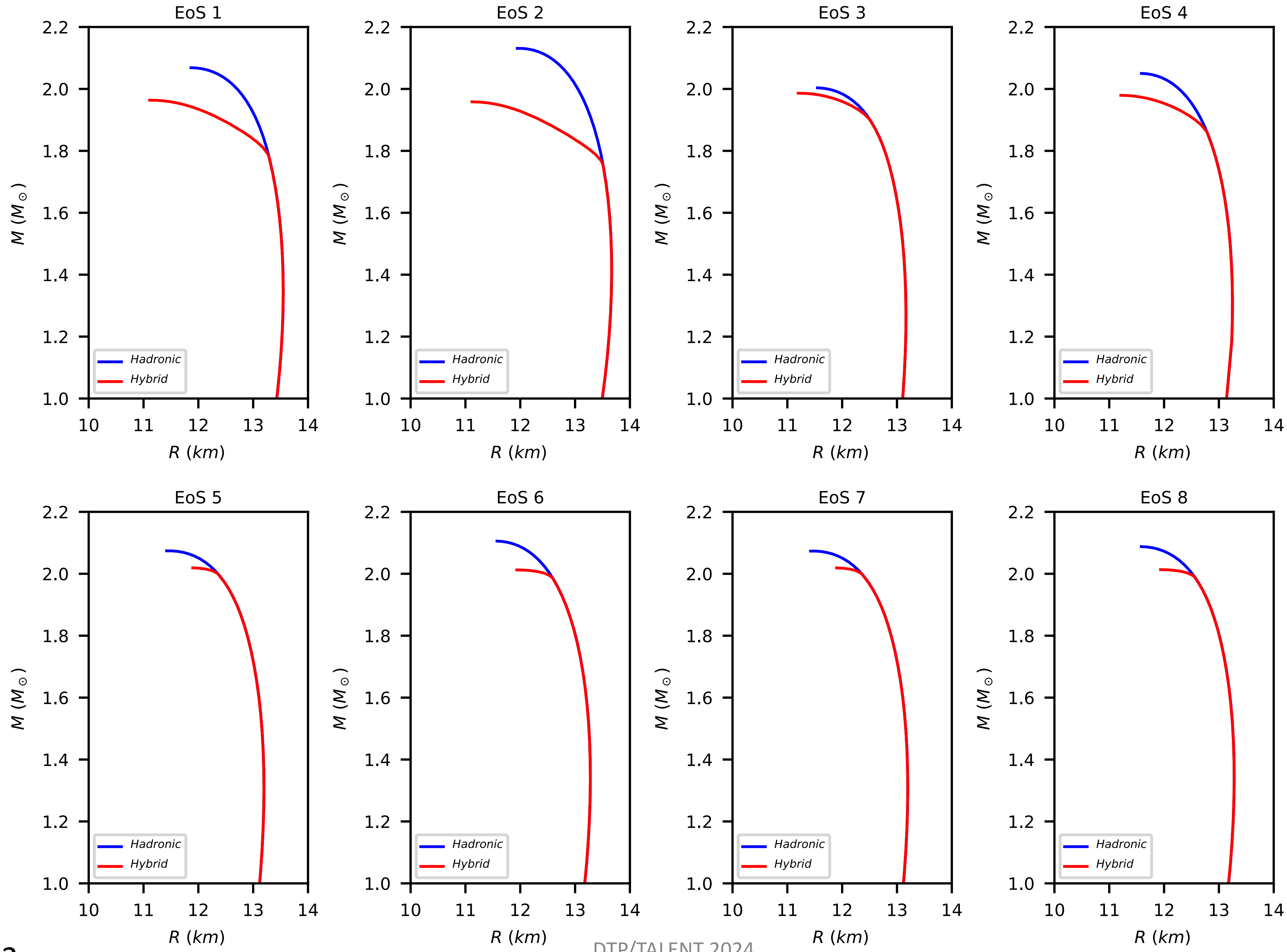
Results

- $\omega\rho$ 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

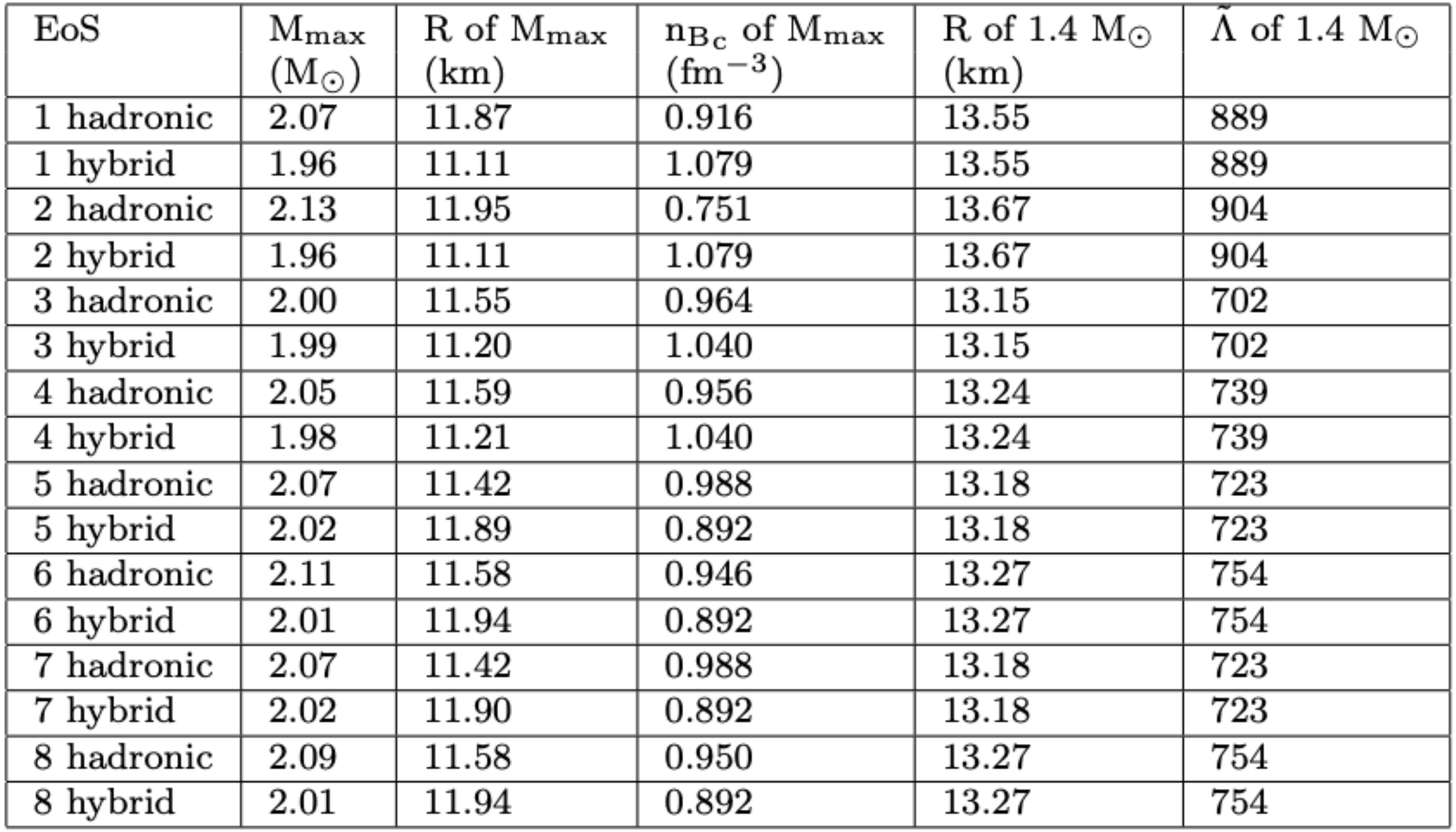
- To consider macroscopic properties, we must include the effects of nuclei.
- We added a zero-temperature, beta-equilibrated crust to each EoS from Gulminelli and Raduta from CompOSE.
- We chose specific crusts so that the symmetry energy slope does not jump between crust and core.
- Using the TOV equation,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

S. Typel, M. Oertel, T. Klähn et al, arxiv:2203.03209
https://compose.obspm.fr/



CSQCD IX 2022

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

Results

- EoS's with hyperons produced lower M_{max} , as well as EoS's with quark deconfinement.
- Regardless of composition, $\omega\rho$ 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.

Conclusions

- CMF model offers an ideal 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 some of both.
- We can produce EoS's with exotic matter that still satisfy constraints from nuclear and astrophysics.

Future Work

- 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 with the NP3M collaboration to study the effects of phase transitions in this context.
- We are also developing a framework to study higher-order phase transitions within the CMF model.

NP3M

Milena Albino
Peter Hammond
David Radice
Constança Providência
Veronica Dexheimer

muses

- Modular Unified Solver of the Equation of State
- It will provide an open-source cyberinfrastructure to generate equations of state for use in astrophysics, nuclear physics and heavy ion physics.
- Alpha release and v1.0 will be available in the coming months.

- https://muses.physics.illinois.edu/