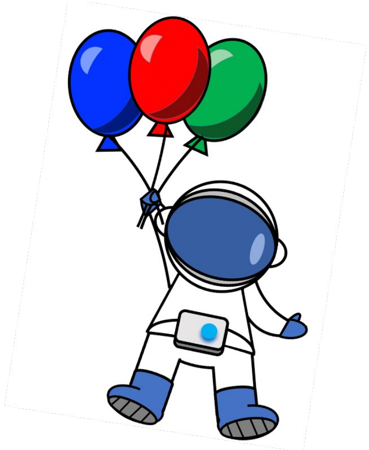


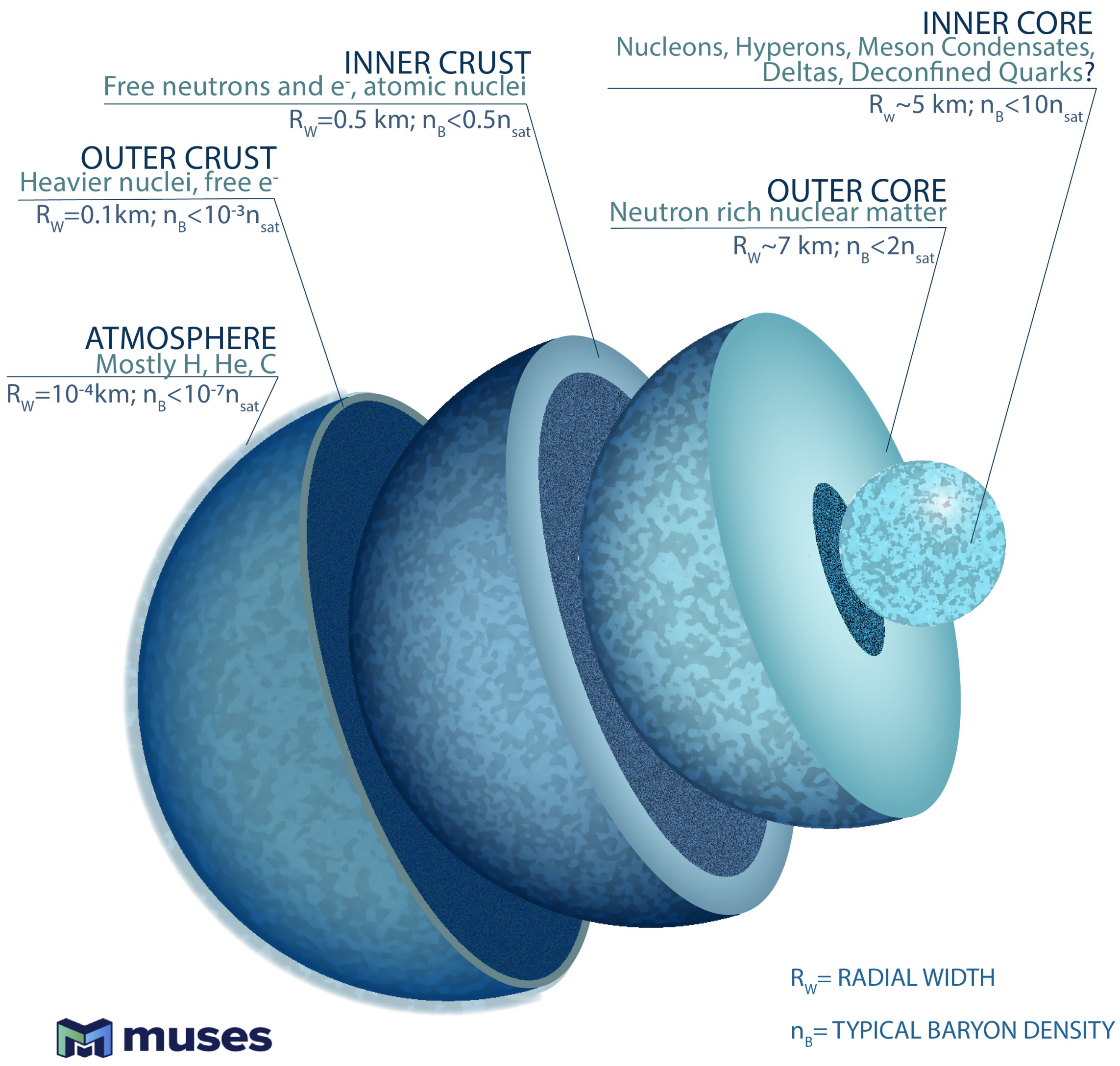
Higher Order Phase Transitions in Neutron Stars

Alexander Clevinger

Kent, Ohio, USA

Quark Matter 2023

Milena Albino
Peter Hammond
David Radice
Constança Providência
Veronica Dexheimer



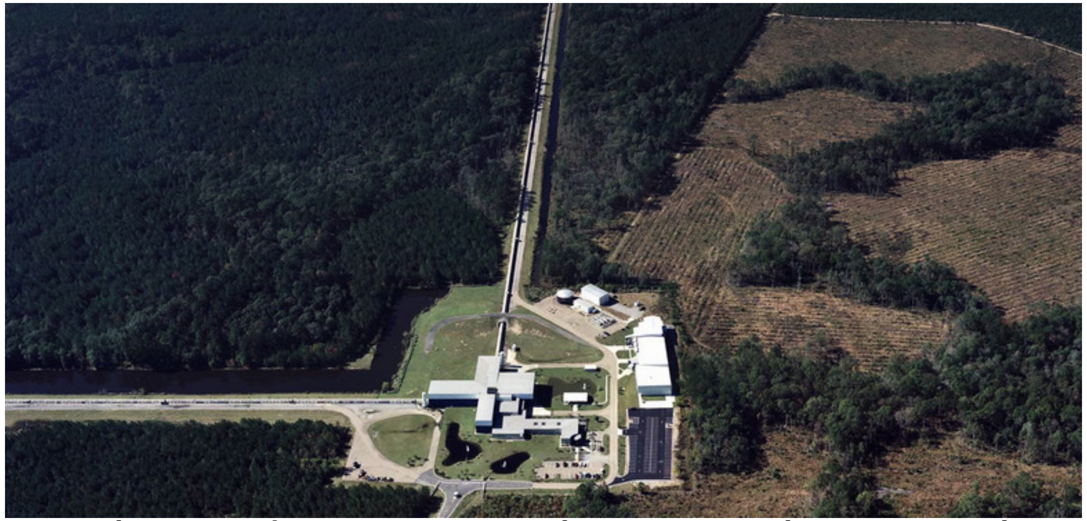
Neutron Stars

- In the cores of neutron stars, we expect densities $>2n_0$.
- This could mean that there is a phase transition to quark matter in the core.

How can we find evidence of this?

Neutron-Star Mergers

- The first binary neutron-star (BNS) merger was detected in 2017 by LIGO/Virgo. (GW170817)
- Several more have been detected since and with increasing sensitivity to detect GW's we expect more events in the coming years.



What should we look for in these detections that may hint at phase transitions in neutron stars?

Outline

1. Construct realistic EoS's with different orders of phase transition
2. Determine if they are physical
3. Obtain MR curves
4. Test them in neutron-star merger simulations

Constraints on Equation of States

- We must produce EoS's that are physical!
- Pressure must be continuous
- 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]].

- 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.
- https://compose.obspm.fr/

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

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.

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

V. A. Dexheimer and S. Schramm, Phys. Rev. C 81, 045201 (2010).

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 (1-2) or 75 MeV (3-8)

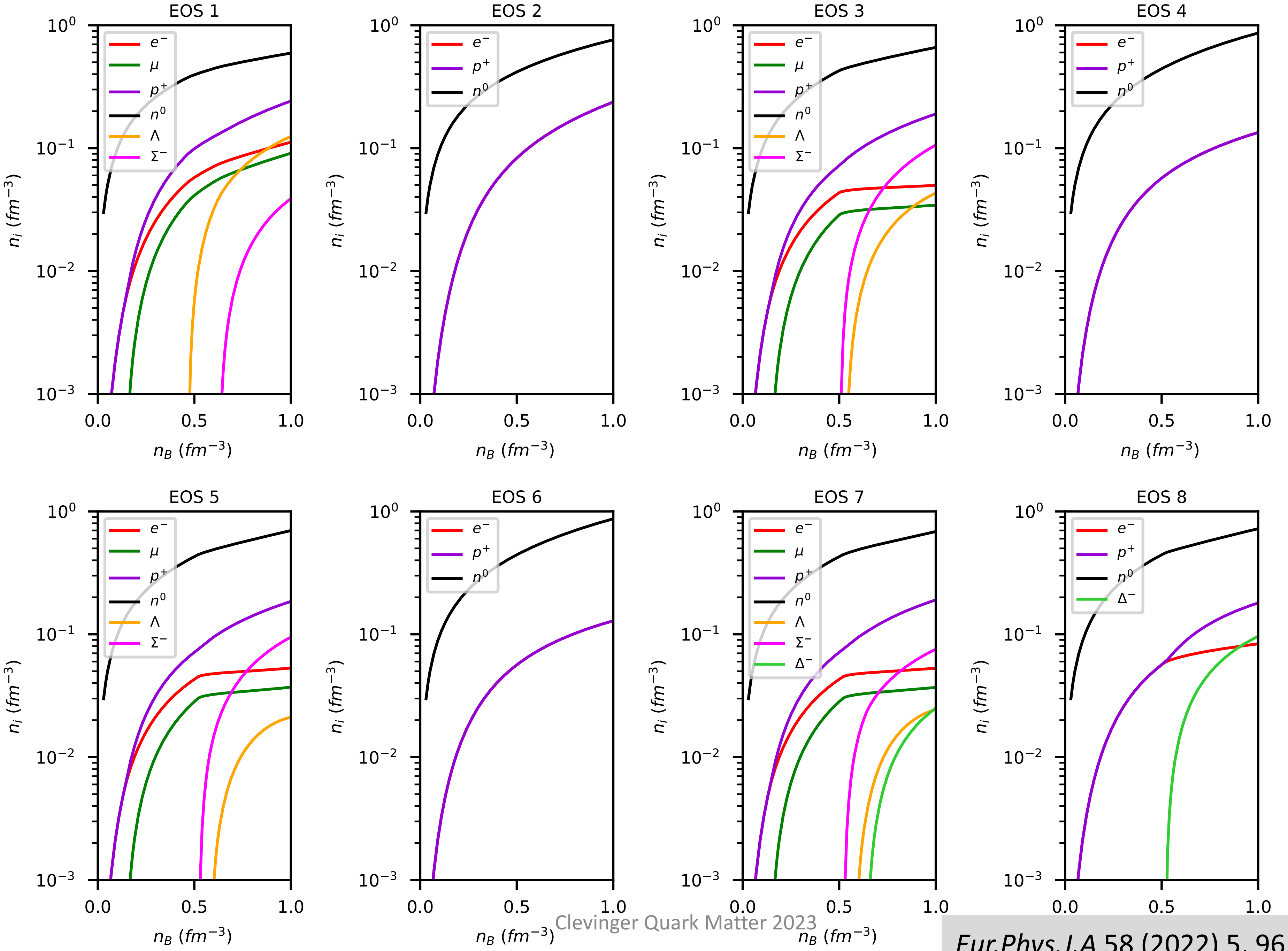
Hyperon potentials for symmetric matter at saturation are:

- U_Λ = −28, -27 MeV
- U_Σ = 5, 6 MeV
- U_Ξ = −18, -17 MeV
- $U_\Delta = 64$ MeV

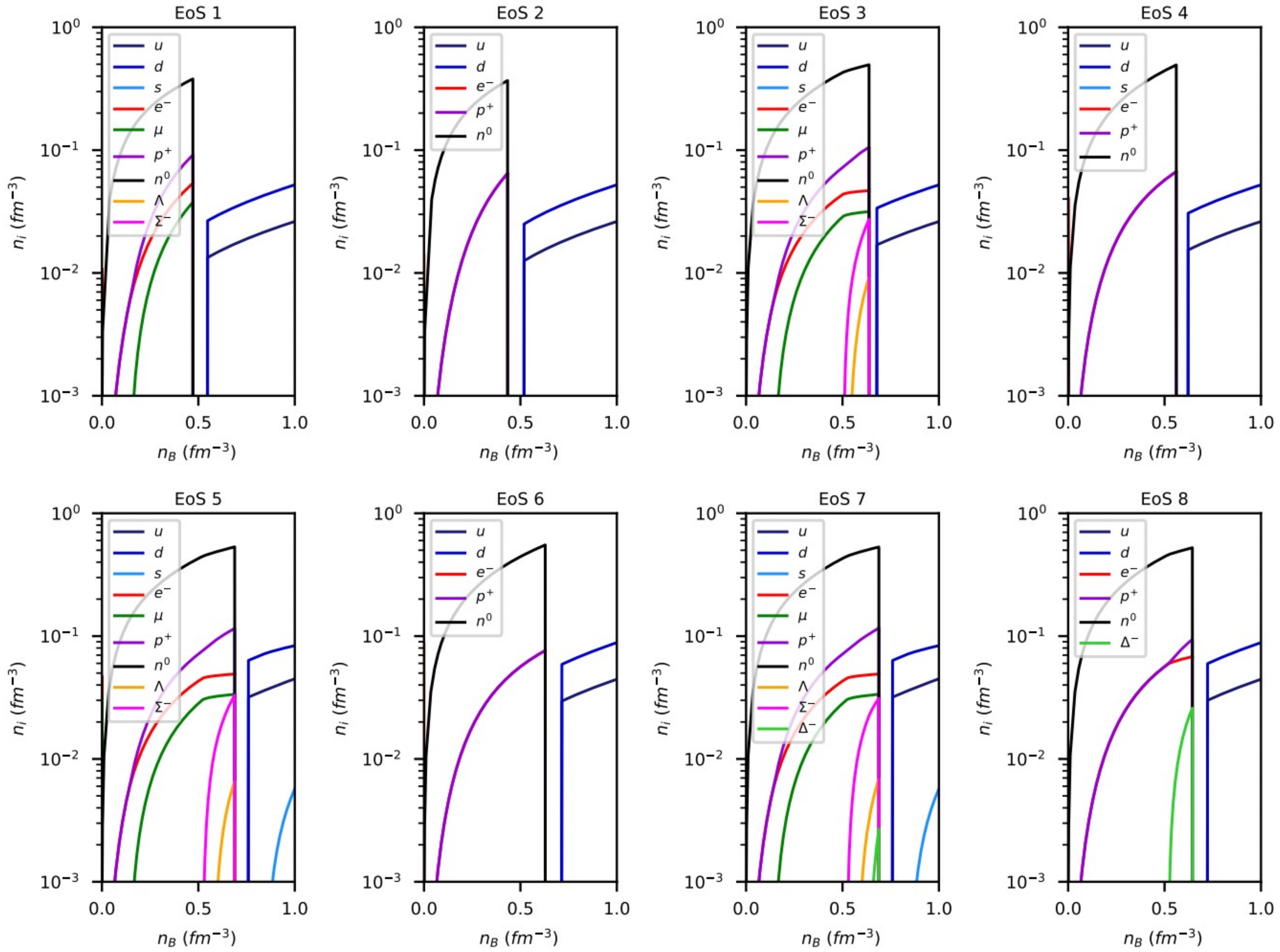
Population Plots

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

This is due to a μ_B^2 dependence in deconfinement potential vs μ_B^4 in previous CMF models.



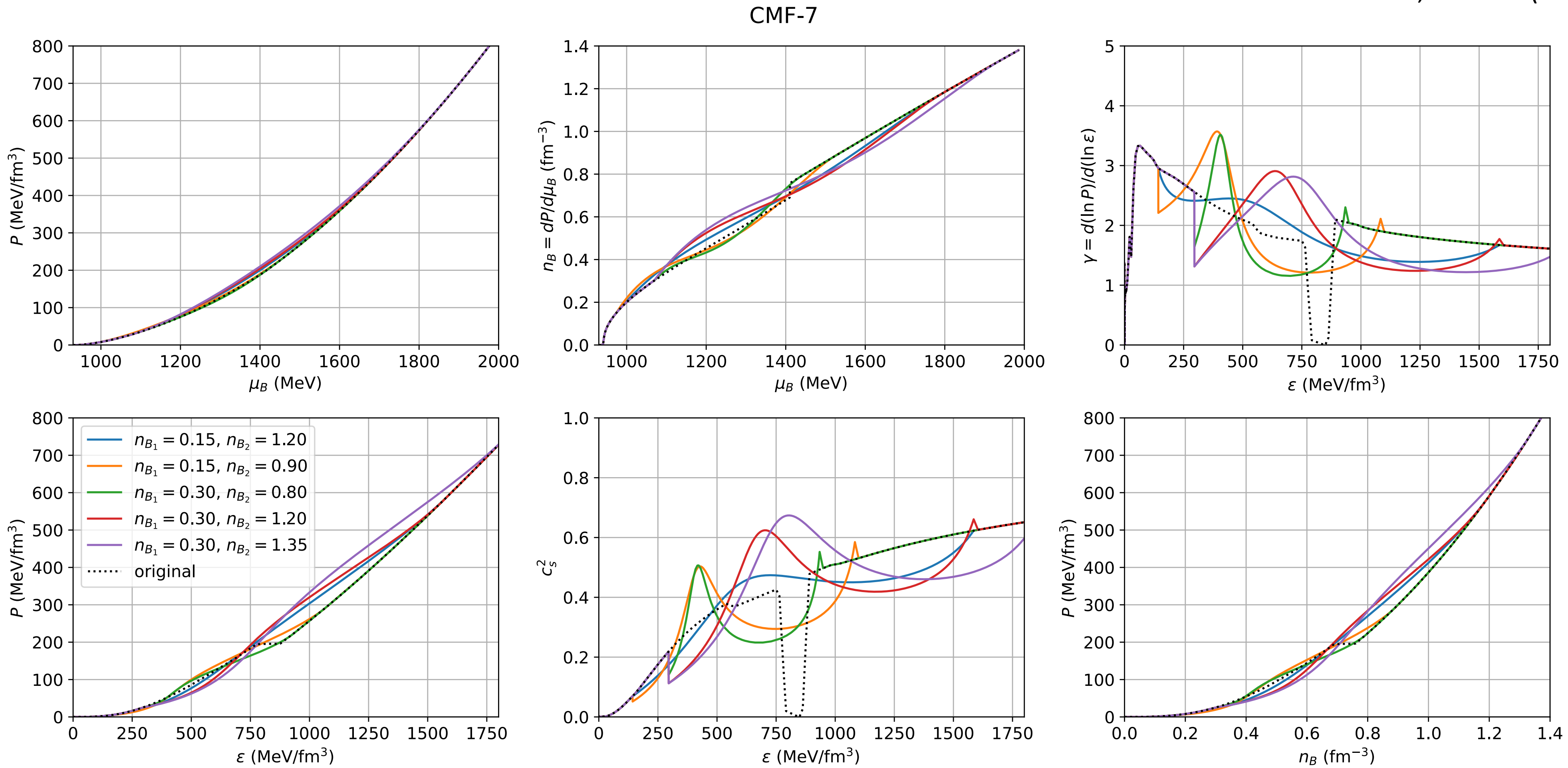
Eur.Phys.J.A 58 (2022) 5, 96, e-Print: [2205.00559](2205.00559)



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

Constructed EoS’s

H. Tan, J. Noronha-Hostler and N. Yunes, Phys. Rev. Lett. 125, 261104 (2020)

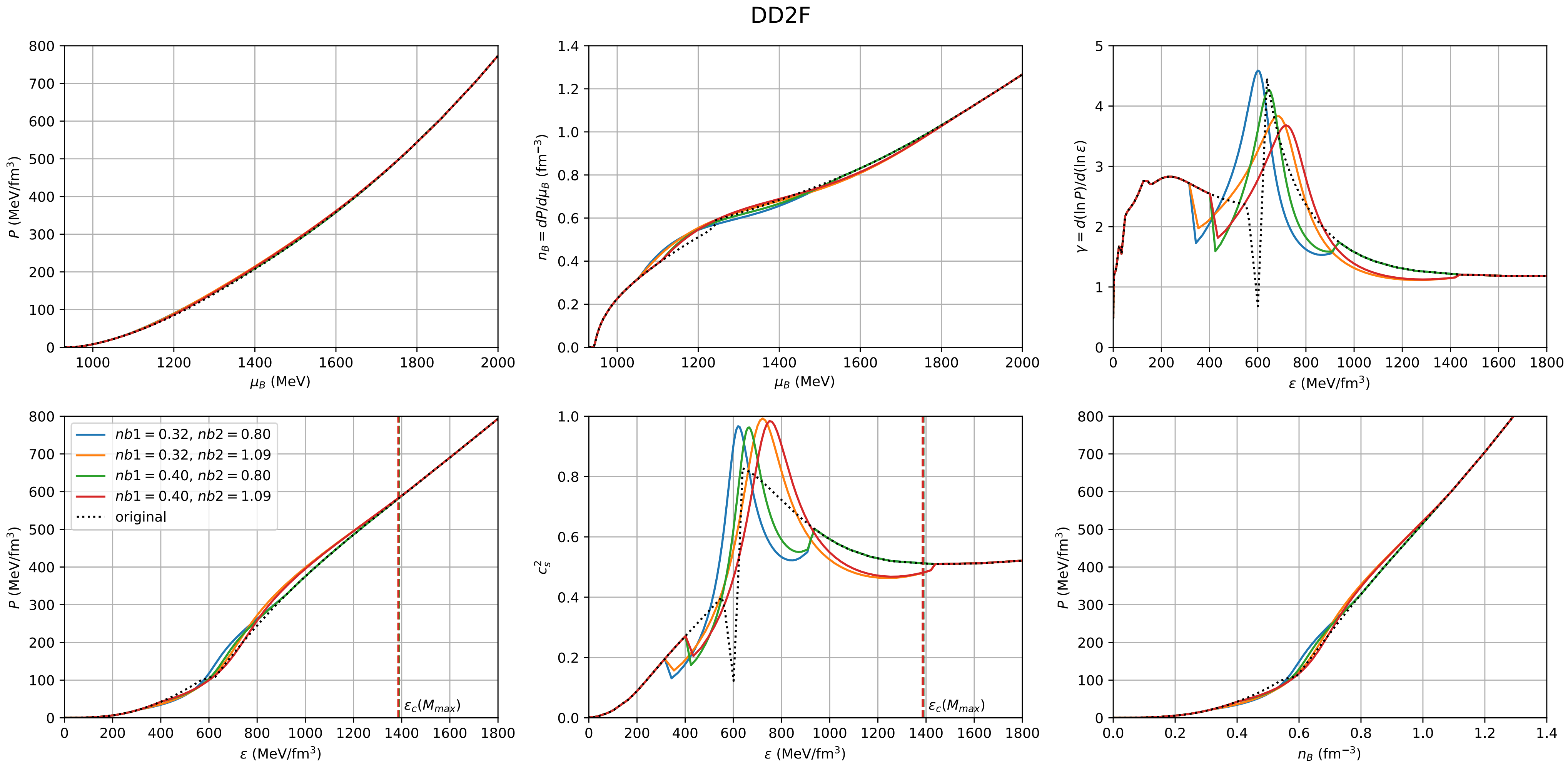


RDF(DD2F-SF) model

- This EoS comes from a relativistic density functional approach.
- Uses a DD2F for hadronic part and NJL for quark part.
- Has a correction from DD2 for the flow constraint.
- Also has first order phase transition
- Does well at reproducing nuclear properties with similar values as CMF.

Bastian, N.-U. F. 2021, Phys. Rev. D, 103, 023001, doi: 10.1103/PhysRevD.103.023001

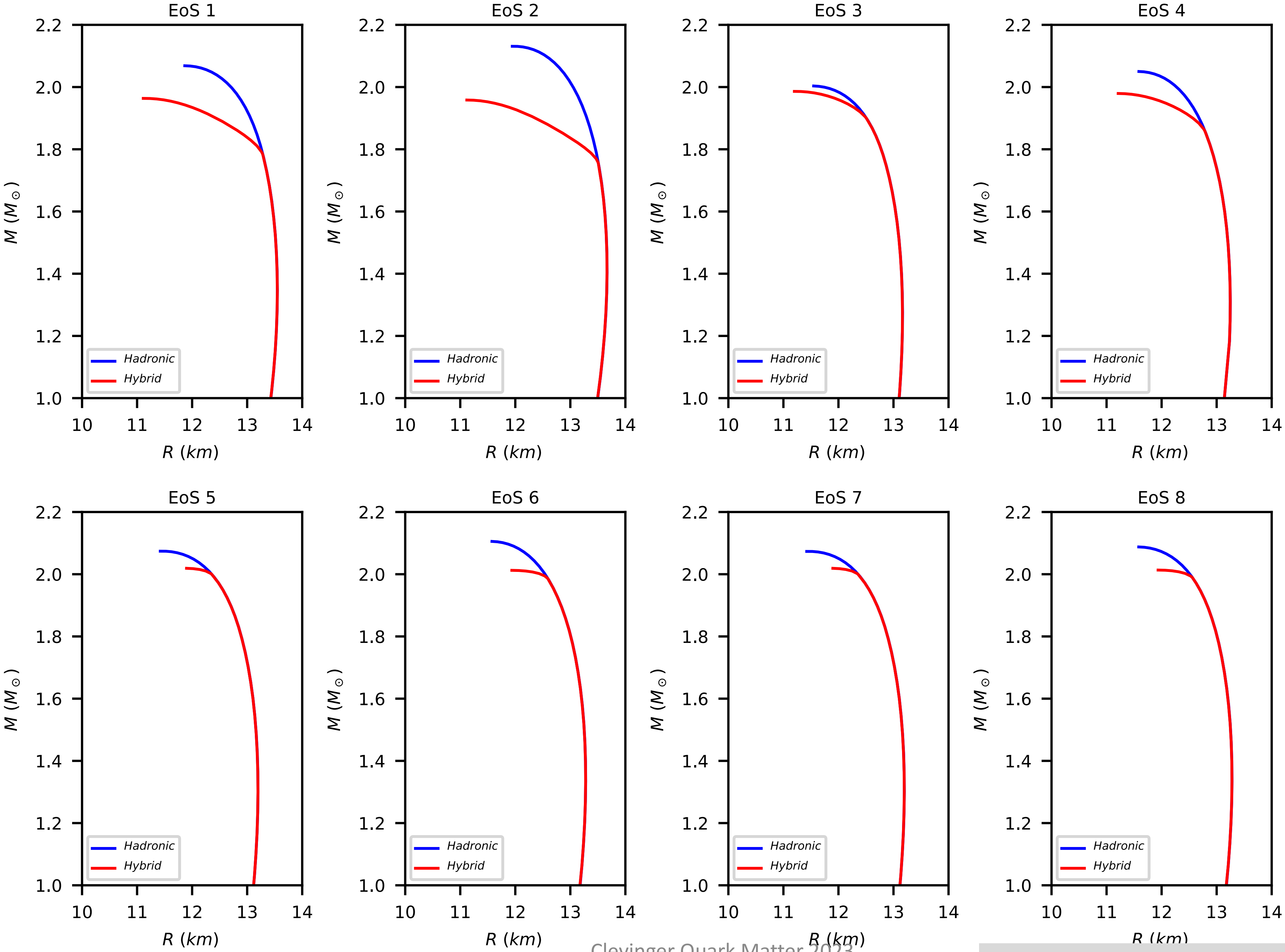
Constructed EoS's



Macroscopic properties

- We also must attach crusts to our EoS as our models do not describe effects of nuclei to study macroscopic properties.
- These crusts come from other models in CompOSE
- We use TOV equations to create MR curves.

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$



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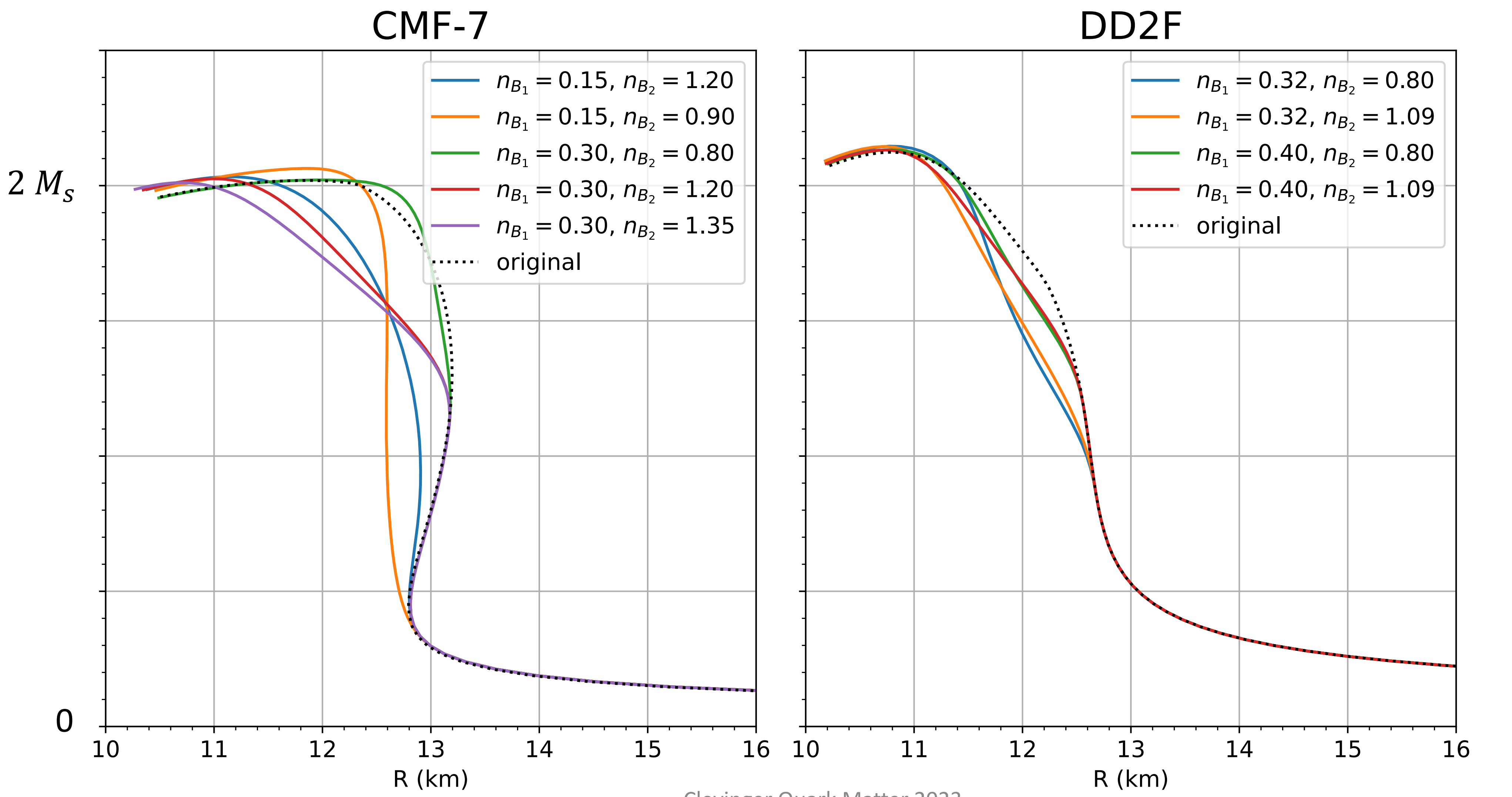
Constructed EoS's



Conclusions and Future

- Can we determine the composition in our newly constructed mixed phases?
- Can we expand this construction of higher order phase transitions to more dimensions?
- We are working on neutron merger simulations using some of the EoS shown.
- What effects of these will we see in neutron star mergers?
- All the EoS's with first order phase transitions are available in CompOSE. Our constructed EoS's with higher order phase transitions will be available soon.

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