Structure in the speed of sound: from neutron stars to heavy-ion collisions

Nanxi Yao[1], Agnieszka Sorensen[2], Dmytro Oliinychenko[2], Veronica Dexheimer[3] and Jacquelyn Noronha-Hostler[1]

1 Illinois Center for Advanced Studies of the Universe, Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801
2 Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA
3 Department of Physics, Kent State University, Kent, OH 44243, USA

ILLINOIS

FUNDED BY US-DOE
DE-SC0019175

Introduction

Cold neutron stars (NS) equations of state (EOS) can sustain heavy neutron stars over 2 $M_\odot$ [1]

- Need large, rapid rise in the speed of sound (c_s^2)
- Cold NS contain few positively charged particles ($Y_Q = n_Q/n_B \lesssim 0.2$)
- EOS is also probed in heavy-ion collisions (HIC) but for nearly symmetric nuclear matter ($Y_Q \sim 0.39$).

Switch EOS from NS to HIC using symmetry energy expansion

- Use EOS method from [2] that produces NS with >2 M⊙; has QHC crust [3] + large bump in cs2
- Rewrite symmetry energy expansion to reach $Y_Q \sim 0.39$
- Define $Y_{Q,QCD}^{const} = \frac{Z}{A}$; $Y_{Q,QCD}$ is the charge fraction of NS and depends on n_B
- Apply the symmetry energy expansion with 4 coefficients [4]
- Test for causality and positivity limits (0≤cs2≤1) for both NS and HIC
- For different YQ slices (needed for numerical relativity simulations)

Question: What does a large bump in c_s^2 look like in HIC?

Formalism

1) Subtract lepton contributions to Fermi energy.
2) We first use symmetry energy expansion with $Y_{Q,QCD}(n_B)$ to obtain energy density (ϵ) of HIC from energy density of NS: $\epsilon_{HIC} = \epsilon_{NS} - 4[E_{sym,0} + \frac{L_{sym}}{3}\left(\frac{n_B}{n_0}-1\right) + \frac{L_{sym}}{3}\left(\frac{n_B}{n_0}-1\right)^2 + \frac{J_{sym}}{162}\left(\frac{n_B}{n_0}-1\right)^3\left[(Y_{Q,QCD}^{const} - Y_{Q,QCD}\right) + \left((Y_{Q,QCD}\right)^2 - (Y_{Q,QCD}^{const})^2)]n_B$
3) Then we obtain pressure(p) by derivative:
   - p= $n_B^2 \frac{d\frac{\epsilon}{n_B}}{dn_B}$
4) We then obtain the speed of sound c_s^2:
   - $c_s^2 = \frac{dP}{d\epsilon}$
5) We first apply 3 constraints to converted EOS
   - 0.14 fm^{-3} <saturation density <0.18 fm^{-3}
   - At saturation density, $-18\text{MeV} < \frac{\epsilon_{HIC}}{n_B} - m_N < -14$ MeV
   - $0 < c_s^2 < 1$ for $n_B > 0.9\ n_{sat}$
6) Range of symmetry energy coefficients [4]:
   - $E_{sym,0}$ in [27.5, 40.5] MeV
   - L_{sym} in [30, 130] MeV
   - K_{sym} in [−220, 180] MeV
   - J_{sym} in [200, 800] MeV

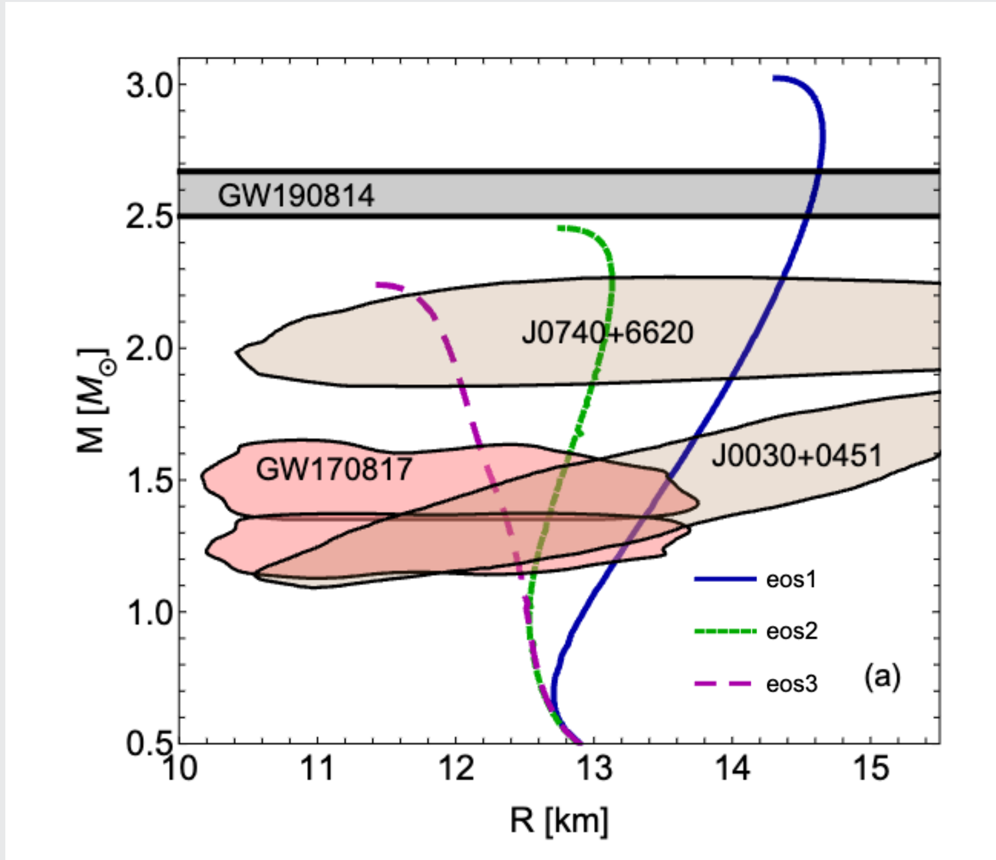
Conclusions & references

- A corner plot shows that K_{sym} is constrained from -200 to 200 MeV, whereas J_{sym} is constrained from -50 MeV to 500 MeV.
- L_{sym} < 50 MeV preferred.
- Next step: using the converted EOS in SMASH[5,6]: a hadronic transport approach to provide descriptions of heavy-ion reactions at low and intermediate beam energy
- Compare HIC observables simulated from SMASH with experimental data

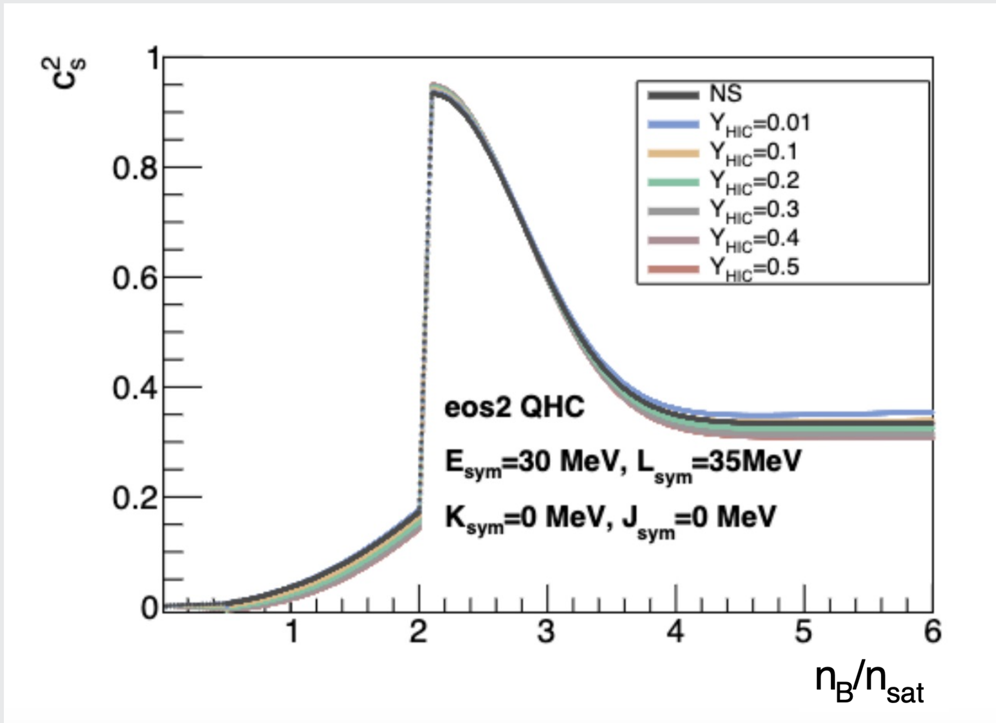
[1] Bedaque & Steiner *Phys.Rev.Lett.* 114 (2015) 3, 031103, arXiv:1408.5116 [nucl-th]
[2] Tan et al, *Phys.Rev.D* 105 (2022) 2, 023018, arXiv:2106.03890 [astro-ph.HE]
[3] H. Togashi, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki and M. Takano, Nucl. Phys. A 961, 78 (2017), arXiv:1702.05324 [nucl-th]
[4] B.-A. Li, B.-J. Cai, W.-J. Xie, and N.-B. Zhang, Universe 7, 182 (2021), arXiv:2105.04629 [nucl-th].
[5] J. Weil et al. (SMASH), Phys. Rev. C 94, 054905 (2016), arXiv:1606.06642 [nucl-th]
[6] D. Oliinychenko, A.Sorensen, V. Koch,and L. McLerran, arXiv: 2208. 11996 [nucl-th] (2022)

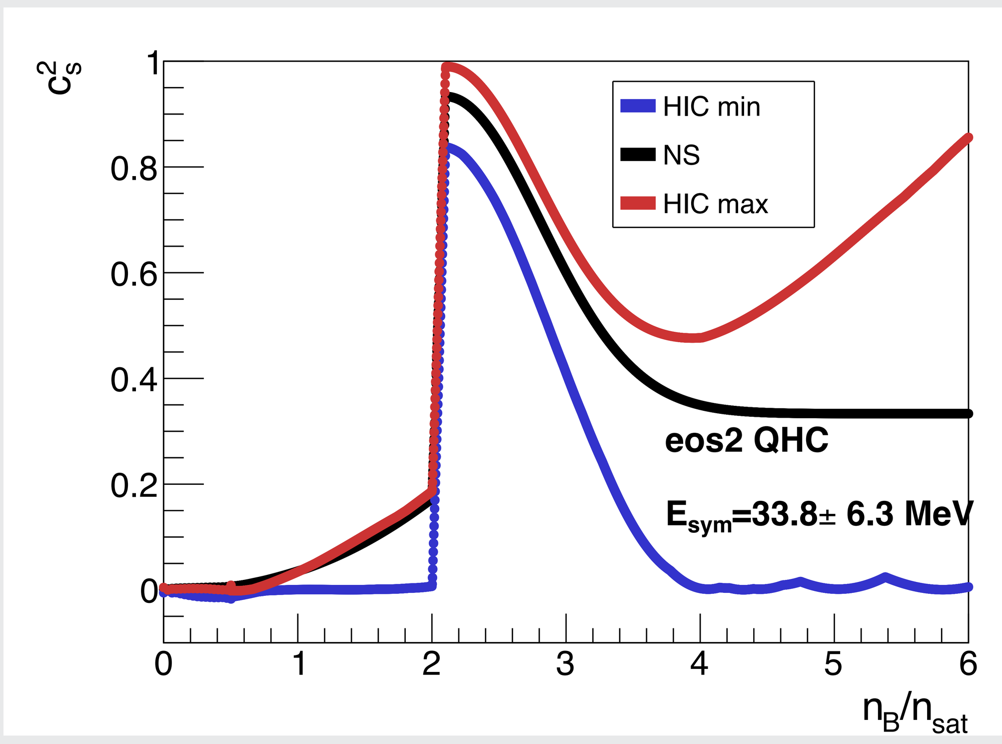
Results

M-R relations of 3 EOS



Speed of sound for EOS2





Corner plots of 4 symmetry energy coefficients