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

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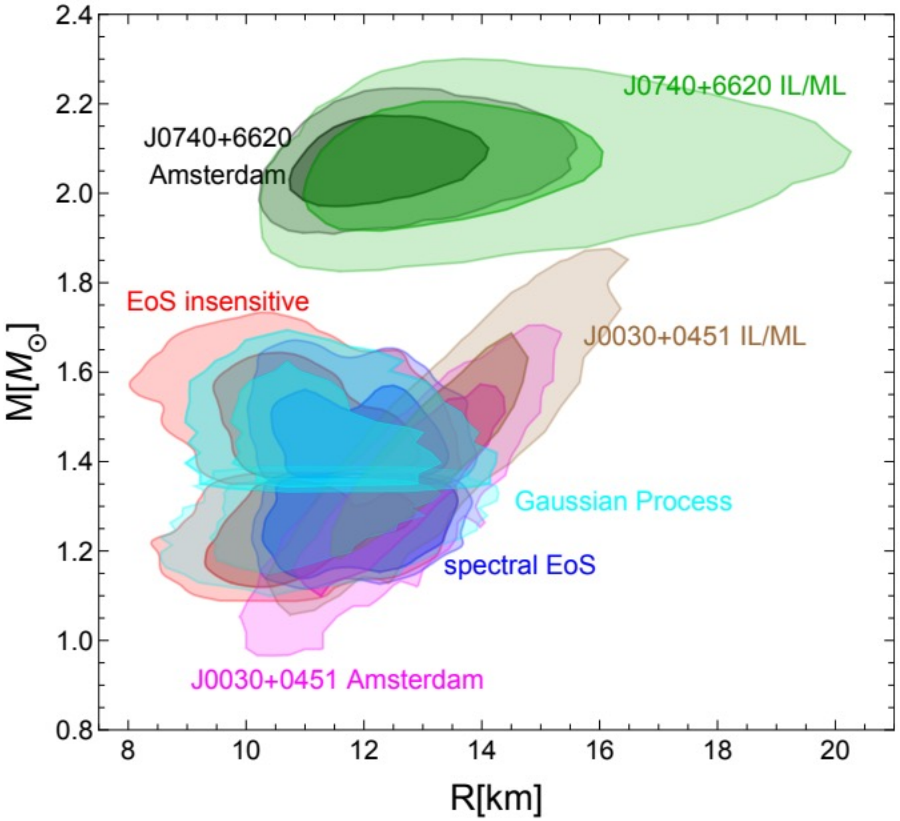
Physical Review C 109 (6), 065803

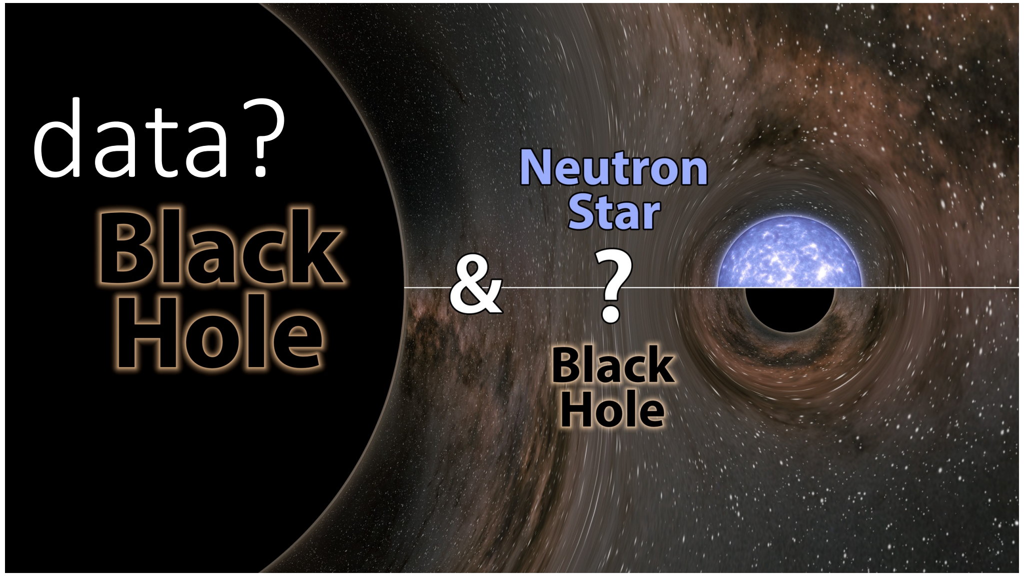
Nuclear Equation of State (EOS)

- To describe the relationship between properties of nuclear matter (e.g. energy density, pressure) and quantifies the structure of different nuclear matter and the interactions
- Perturbative QCD calculation for EOS is very limited at high density
  - need to use astrophysical observations, HIC, and etc to constrain the EOS
- M-R constraints on the right from T=0 NS EOS

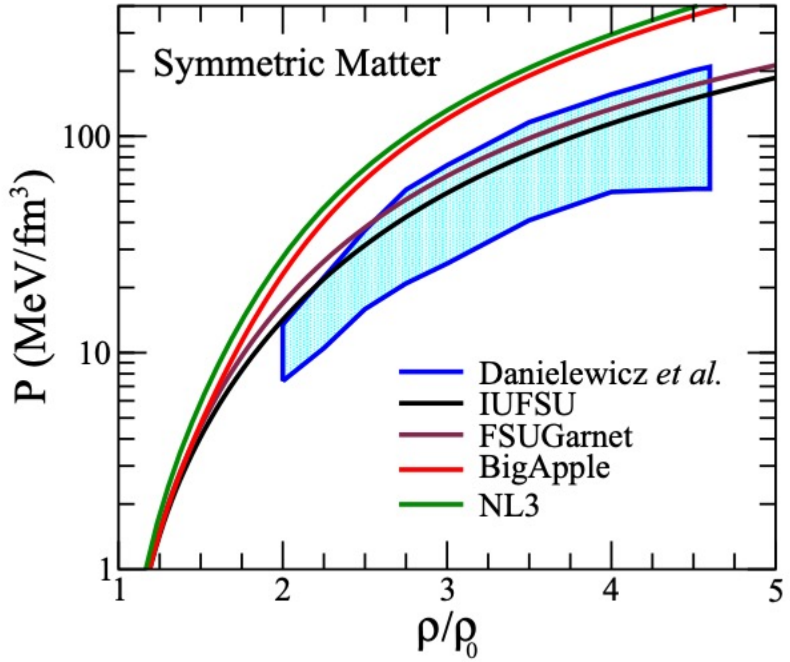
MUSES Collaboration. Rajesh Kumar (Kent State U.) et al. 2303.17021.



Is NS compatible with HIC data?



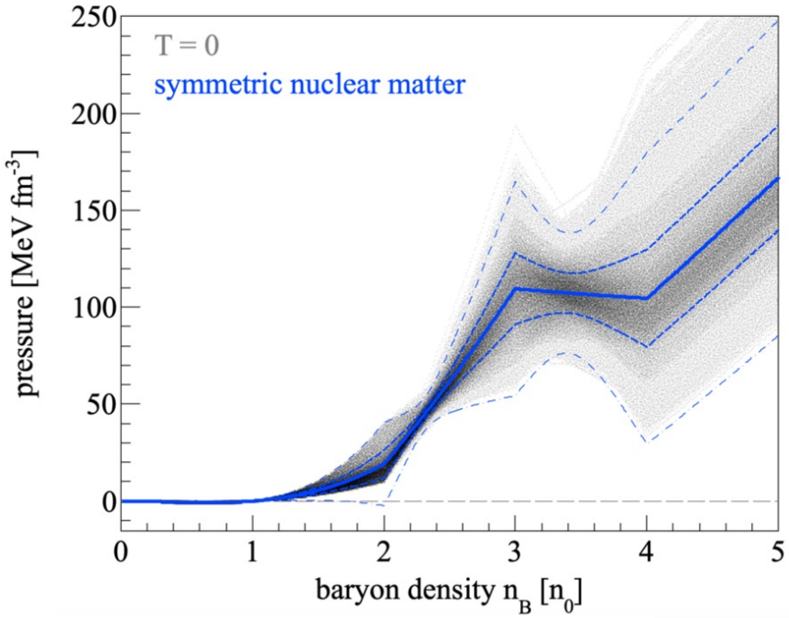
- "Determination of the equation of state of dense matter." Danielewicz et al. Science 298 (2002), pp. 1592–1596.
  - Analyzes flow of matter in nuclear collision
  - Obtain predictions for EOS of neutron matter
- Observations of GW190814
- Previous studies: EOS of NS with mass >2.6 $M_{\odot}$ not consistent with HIC data (F. J. Fattoyev et al. Phys. Rev. C **102**, 065805)
  - Assumed hadronic degrees of freedom

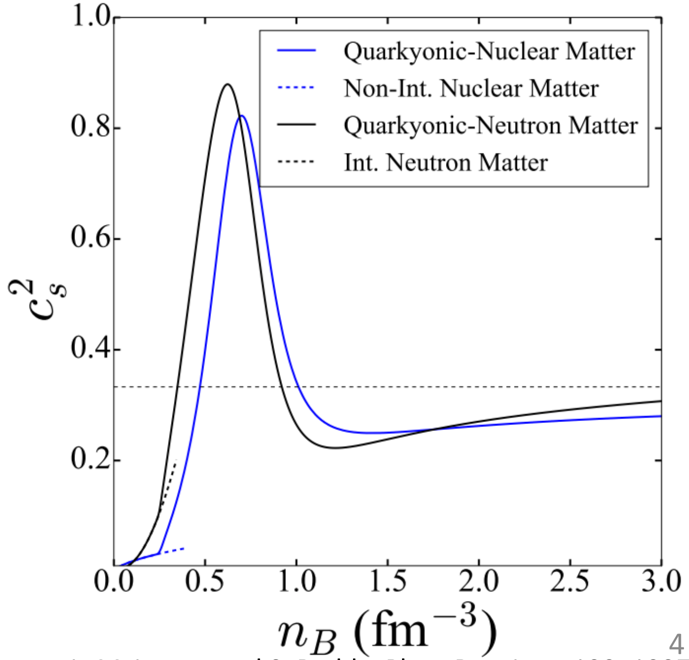


Is NS compatible with HIC data?

- Cold neutron stars (NS) equations of state (EOS) can sustain heavy neutron stars over 2 $M_{\odot}$
  - Need large, rapid rise in the speed of sound (c_s^2)
- We want to investigate this with NS EOS where we add a bump to c_s^2
  - associated with higher-order repulsive terms in the description of the strong force among nucleons and hyperons
  - Quarkyonic matter, deconfinement crossover phase transition, new hadronic degrees of freedom

D. Oliinychenko, A. Sorensen, V. Koch, and L. McLerran, Phys. Rev. C 108, 034908 (2023)

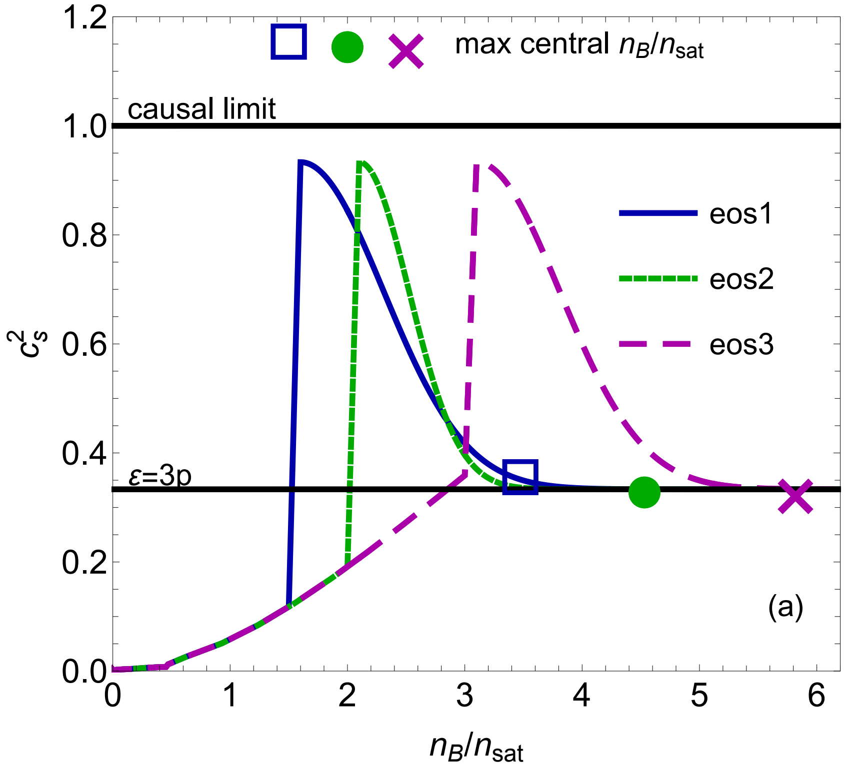


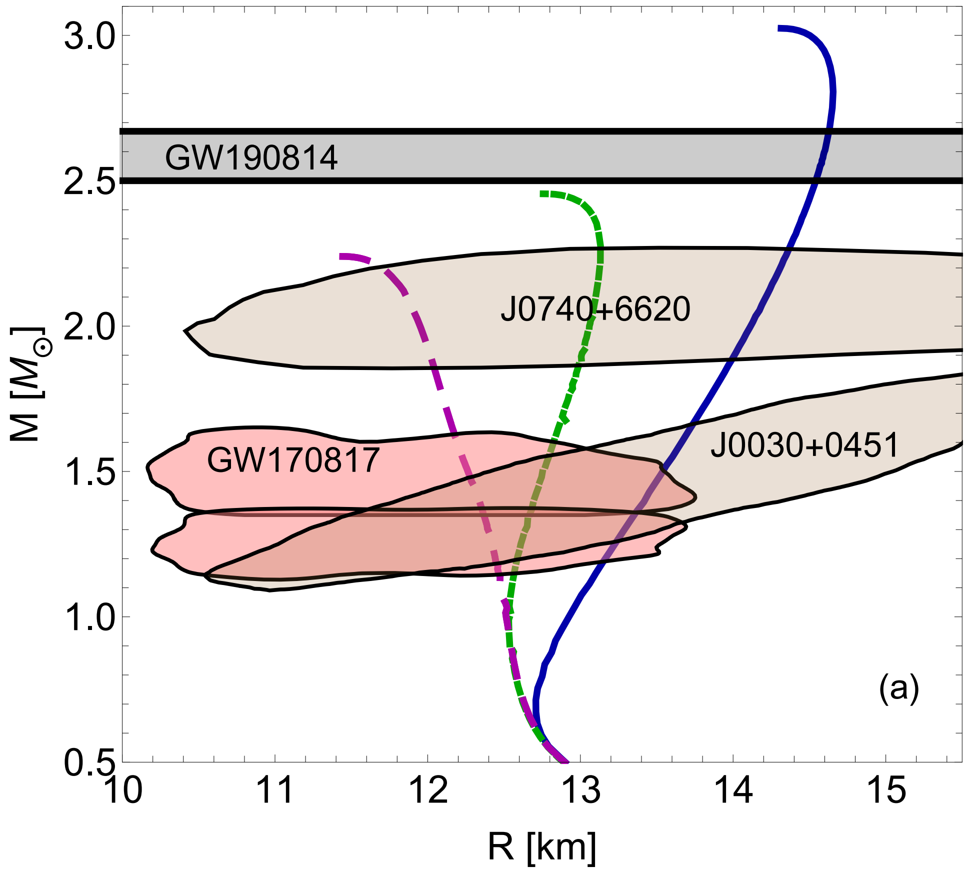


L. McLerran and S. Reddy, Phys. Rev. Lett. 122, 122701 (2019)

Neutron Star EOS of Interest

- Easily create a family of EoSs that reach M ≥ 2.5 $M_{\odot}$, either by implementing a narrow peak at low n_B or a wide peak at higher n_B
- EOS 1 – extreme heavy NS
- EOS 2&3 –consistent with most of the experimental data

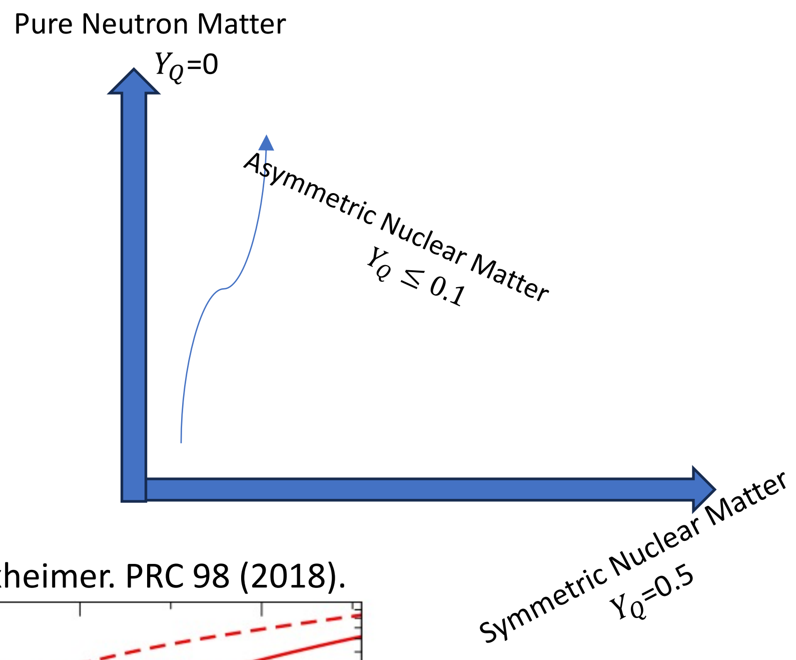




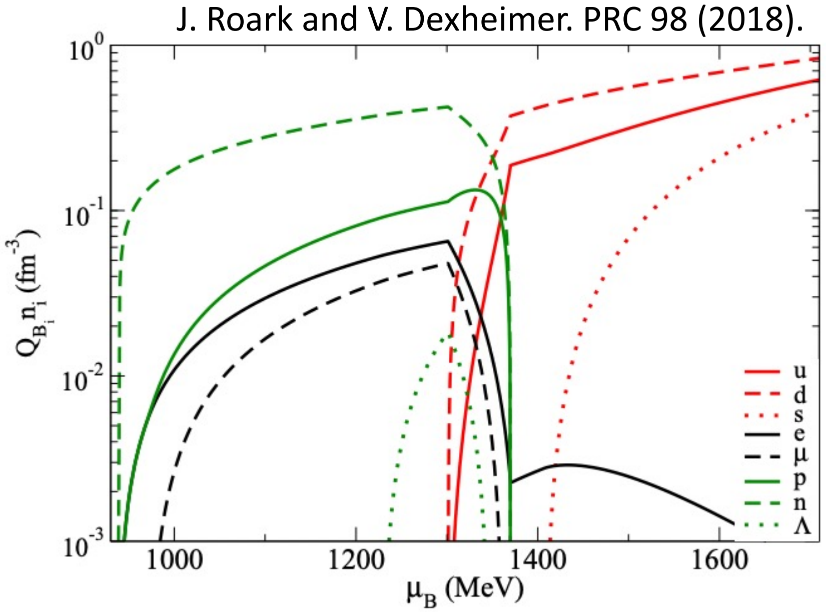
H. Tan, J. Noronha-Hostler, and N. Yunes, Phys. Rev. Lett. 125, 261104 (2020)

HIC vs Neutron Star

- NS is asymmetric nuclear matter(ANM), and HIC is symmetric nuclear matter(SNM)
    - $Y_{Q,QCD} \equiv n_{Q,QCD}/n_B$
- Cold NS are at T=0 and contain few positively charged particles
    - $Y_{Q,QCD}$ is dependent on n_B and ≤ 0.1 for NS,
- $Y_{Q,QCD}$ for HIC is 0.38~0.5
    - Example: for Au, Y_Q=79/197=0.4



J. Roark and V. Dexheimer. PRC 98 (2018).



Symmetry Energy Expansion

- Energy per nucleon E(n, δ) is the most basic term used to obtain EOS of NS, regardless of model used
  - n≡ baryon number density, $\delta \equiv$ isospin asymmetry
  - δ=1-2 Y_Q
- E(n, δ) has a symmetry energy term E_{sym} which quantifies the energy needed to make nuclear matter more neutron rich
- $E_{sym}(\mathrm{n},\delta) = E_{asym} - (E_{sym,0} + \frac{L_{sym}}{3}\left(\frac{n_B}{n_0} - 1\right) + \frac{k_{sym}}{18}\left(\frac{n_B}{n_0} - 1\right)^2 + \frac{J_{sym}}{162}\left(\frac{n_B}{n_0} - 1\right)^3)\delta^2$
  - Magnitude of the symmetry energy: $\mathrm{E_{sym}}(\mathrm{n} = \mathrm{n_{sat}})$, 31.7 ± 3.2 MeV[1]
  - Slope: $\mathrm{L_{sym}} \equiv 3\mathrm{n}\frac{\mathrm{dE_{sym}}}{\mathrm{dn}}|\mathrm{n} = \mathrm{n_{sat}}$, 58.7 ± 28.1 MeV[1] or 106 $\pm$ 37 MeV, PREXII
  - Curvature: $\mathrm{K_{sym}} \equiv 9\mathrm{n}^2\frac{\mathrm{d^2E_{sym}}}{\mathrm{dn^2}}|\mathrm{n} = \mathrm{n_{sat}}$, -120^{+80}_{-100} MeV[2]
  - Skewness: $\mathrm{J_{sym}} \equiv 27\mathrm{n}^3\frac{\mathrm{d^3E_{sym}}}{\mathrm{dn^3}}|\mathrm{n} = \mathrm{n_{sat}}$, 300 ± 500 MeV[3]

[1]M. Oertel et al. Rev. Mod. Phys. 89, 015007 (2017)
[2]W.-J. Xie et al, Astrophys. J. 899, 4 (2020)
[3]I, TEWS et al. Astrophys. J. 848, 105 (2017)

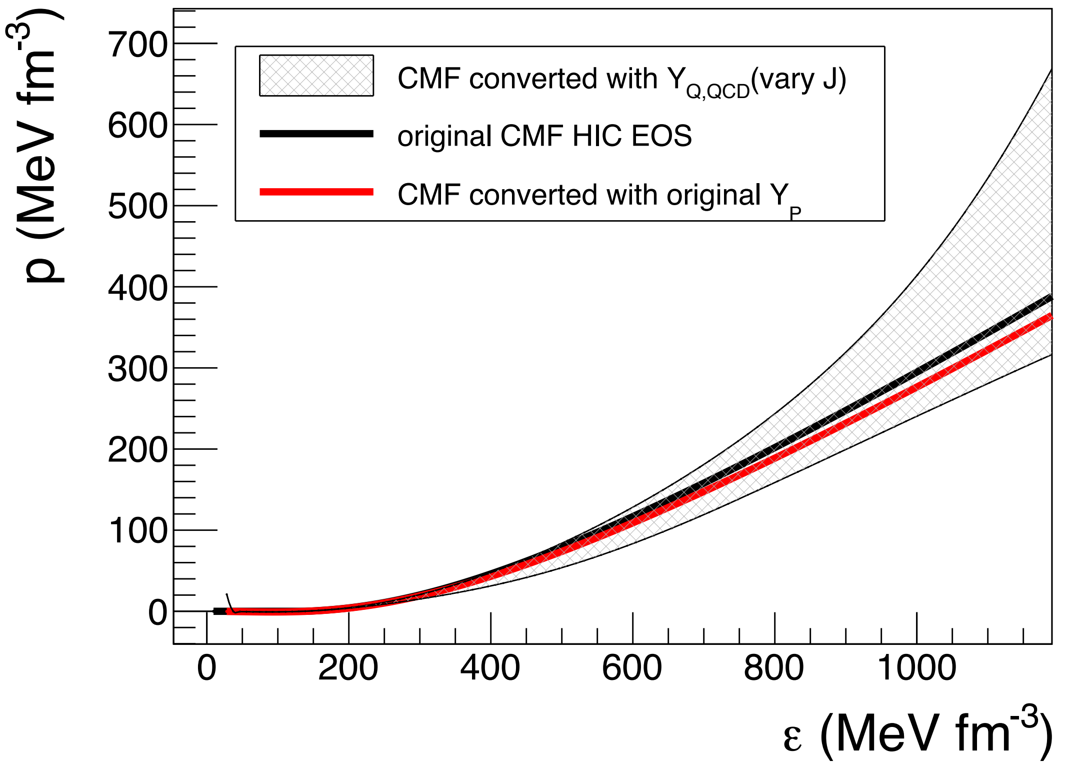
Nuclear Symmetry Energy Expansion

- For HIC, we do not have perfectly symmetry nuclear matter
  - $Y_{Q,HIC} = 0.39$
- Thus, we obtain the asymmetric energy density for HIC from symmetric energy density through a double expansion:

$$\epsilon_{HIC} = \epsilon_{NS} - 4\left[E_{sym,0} + \frac{L_{sym}}{3}\left(\frac{n_B}{n_0} - 1\right) + \frac{K_{sym}}{18}\left(\frac{n_B}{n_0} - 1\right)^2 + \frac{J_{sym}}{162}\left(\frac{n_B}{n_0} - 1\right)^3\right]\left[\left(Y_{Q,QCD}^{const} - \boldsymbol{Y_{Q,QCD}(n_B)}\right) + \left(\boldsymbol{Y_{Q,QCD}^2(n_B)} - \boldsymbol{Y_{Q,QCD}^{const\,2}}\right)\right] n_B$$

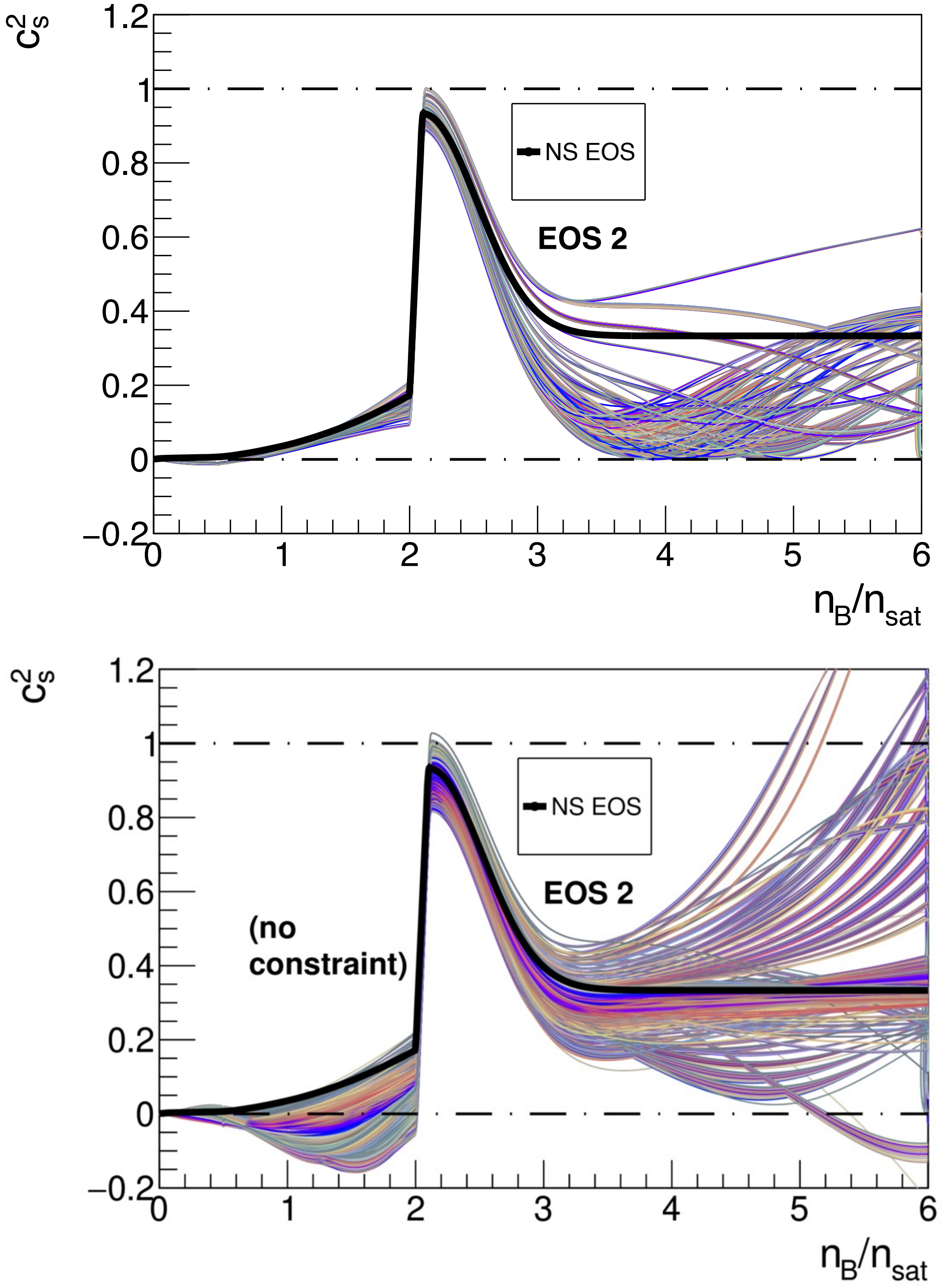
Conversion Process

- Input:
  - NS beta-equilibrated EOS at T=0 with a bump at speed of sound
  - A range of symmetry energy coefficients
- Subtract lepton contribution: $\varepsilon_{QCD} = \varepsilon - \varepsilon_{lep}$
- Convert ε_{QCD} with symmetry energy expansion
- Calculate pressure via $\mathrm{p} = n_B^2 \frac{d(\varepsilon/n_B)}{dn_B}$
- Calculate $c_s^2 = \frac{\mathrm{d}p}{d\varepsilon}$

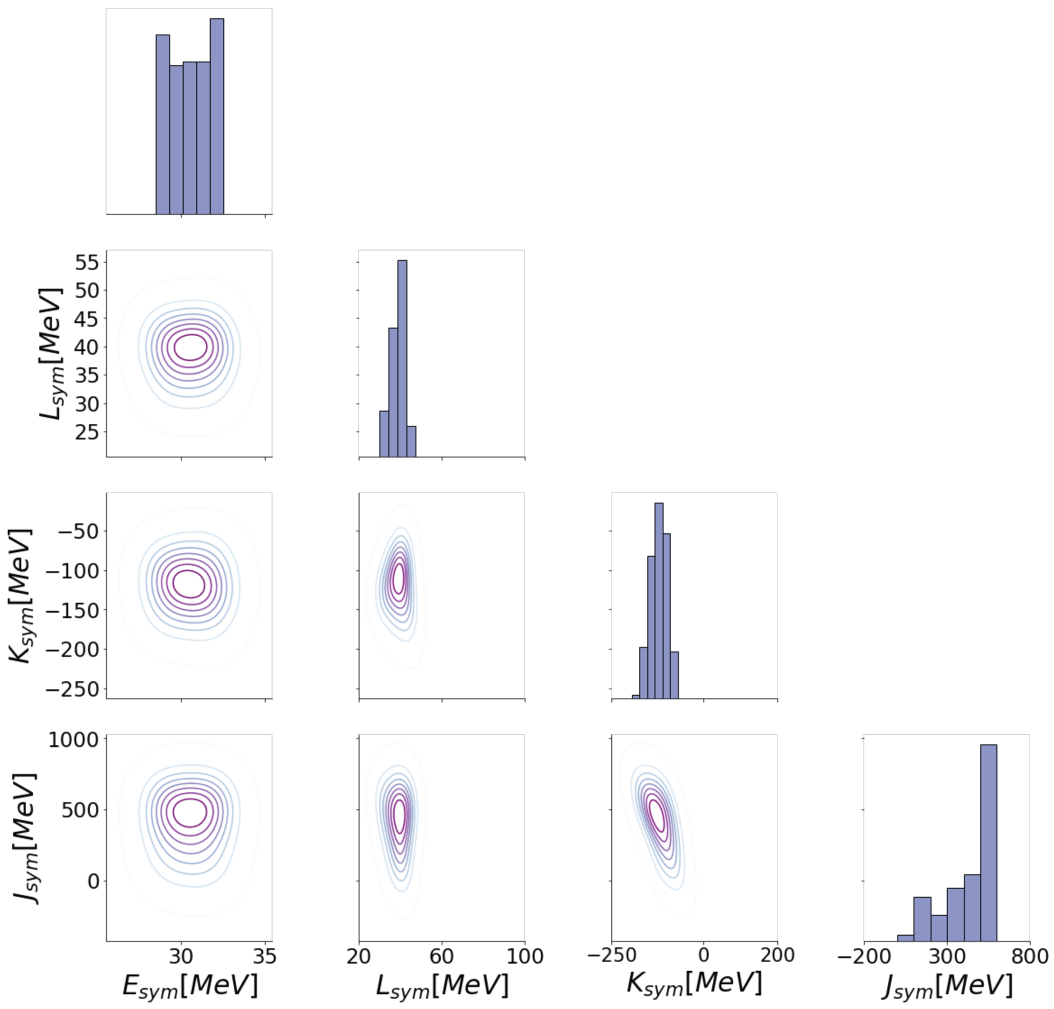


Converted EOS Band

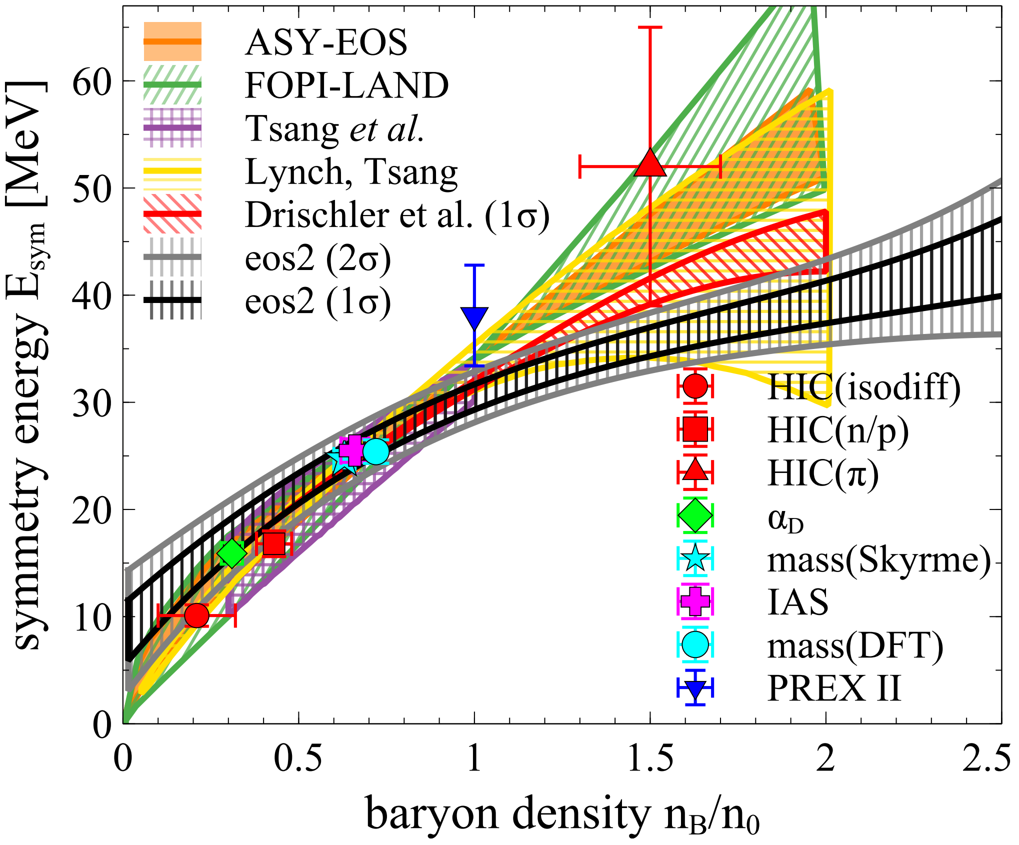
- Converted at $Y_{Q,QCD}^{const}$ = 0.5
- Same location of the peak, shifted magnitude
- Constraints on the converted EOS:
  - Stability and causality ($c_s^2 > 0$ for $n_B \geq 0.9 n_{sat}$ and $c_s^2 < 1$)
  - Saturation properties
    - $0.14\ fm^{-3} < n_{sat} < 0.18\ fm^{-3}$
    - $-18\ \mathrm{MeV} < \mathrm{B} < -14\ MeV$



Symmetry Energy Coefficients



- $30 < L_{sym} < 50\ MeV$
- $K_{sym} < 0$

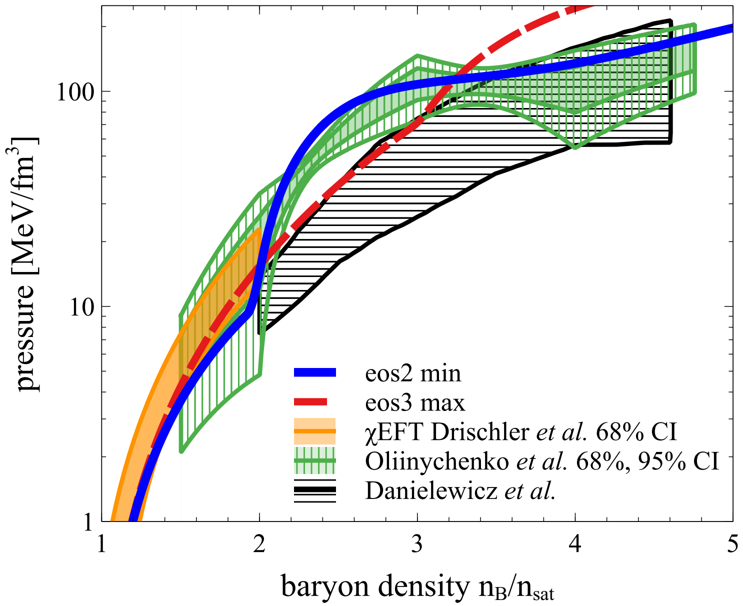


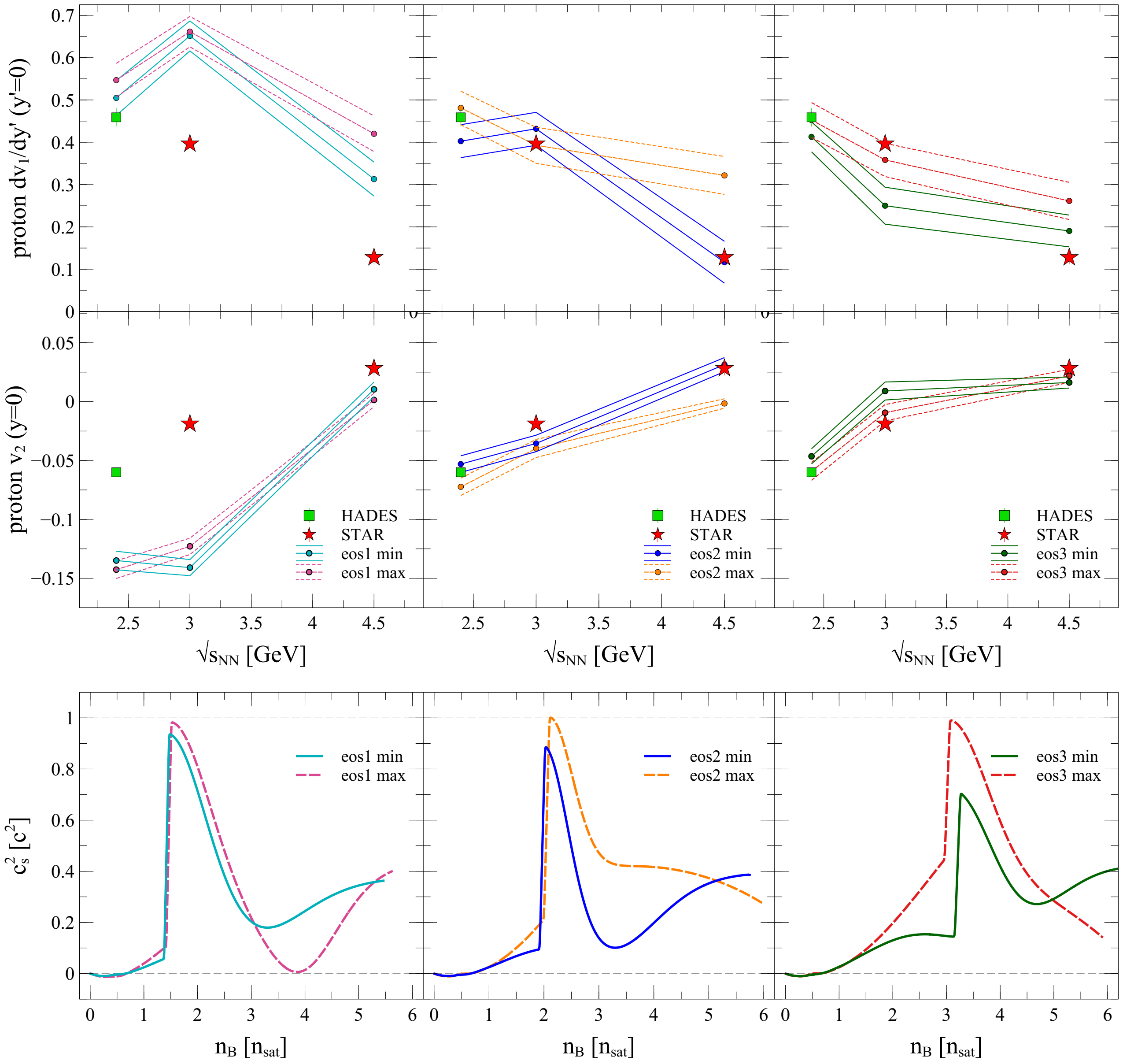
Comparison with HIC data

- At lower $\sqrt{S_{NN}}$, we have very high n_B and lower $T_{\max}$
- Interplay between the QGP phase and the hadrons
- Best described by hybrid models – relativistic hydrodynamics with a hadronic transport.
- Current relativistic viscous hydrodynamic calculations coupled with the hadronic transport code SMASH provide a reasonable description of particle production down to $\sqrt{S_{NN}}$, = 4.3 GeV (E_{kin} = 8 AGeV)
    - use mean-field potentials dependent on vector baryon density
    - No complex temperature dependence

Comparison with HIC experimental data

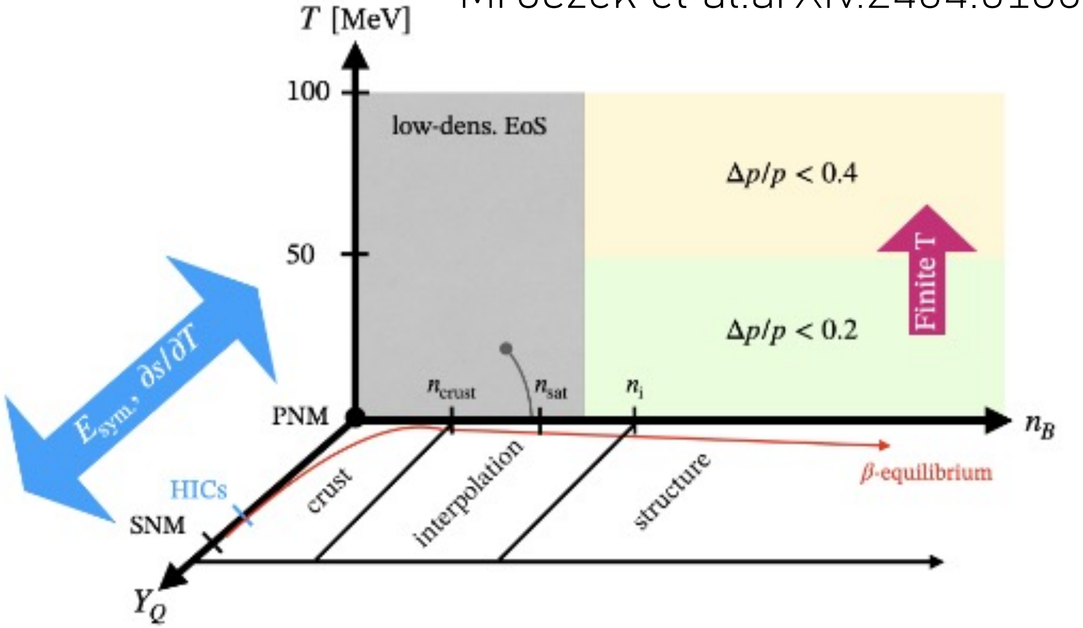
- To ensure $\varepsilon/n_B \to m_N$ and $c_s^2 \to 0$ as $n_B \to 0$, match the converted EOS to an EOS obtained from the density functional (VDF) model.
- EOS with sharp rise at $2n_B$ is favored by the flow data

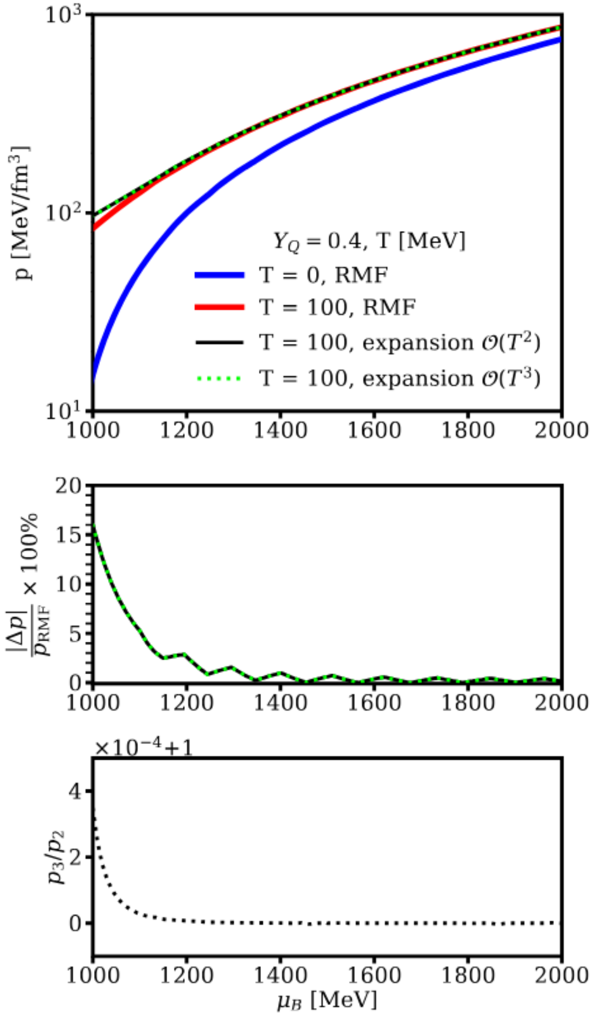




Mroczek et al.arXiv:2404.01658.

Temperature Expansion?





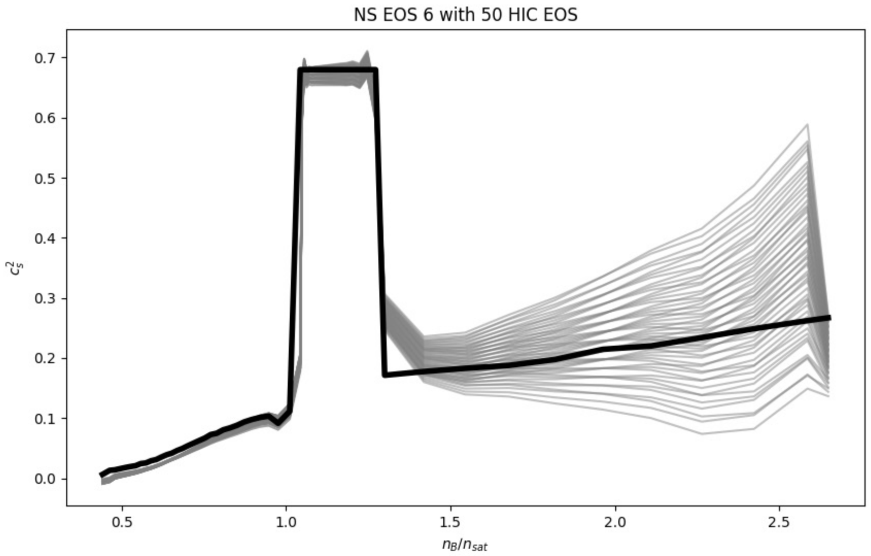
- *"Finite-temperature expansion of the dense-matter equation of state."*
  - Expansion of EOS of dense matter from pure neutron to isospin symmetric nuclear matter, from 0 to finite temperatures (up to T =100 MeV)
  - Model independent
  - can be used to describe neutron star mergers and core-collapse supernova explosions

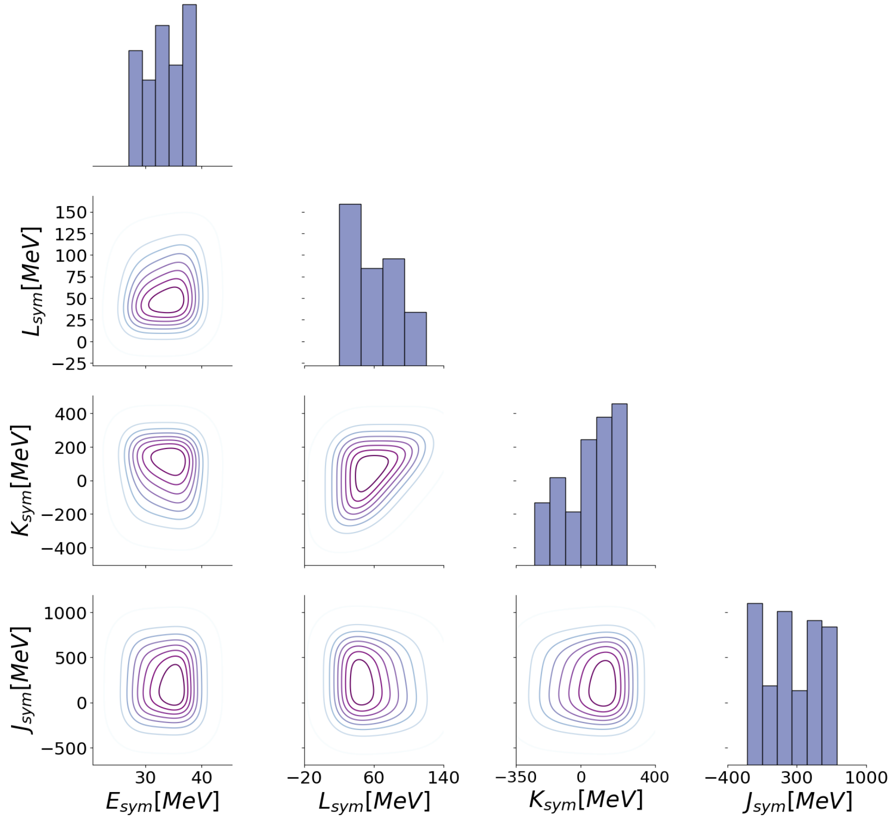
- $p(T,\vec{\mu}) = p_{T=0} + \left.\frac{\partial p}{\partial T}\right|_{T=0,\vec{\mu}} T + \frac{1}{2}\left.\frac{\partial^2 p}{\partial T^2}\right|_{T=0,\vec{\mu}} + \frac{1}{6}\left.\frac{\partial^3 p}{\partial T^3}\right|_{T=0,\vec{\mu}} + \mathcal{O}(T^4)$

Mroczek et al.arXiv:2404.01658.

Coupled with EOS from Modified Gaussian Process…

- Takes 100,000 NS EOS generated with modified Gaussian process
  - meet the requirements informed by GW190817 and PSR J0030+0451, mass cut $M_{max} \geq 1.8\ M_{\odot}$
  - Apply symmetry energy expansion on these NS EOS with causality/stability constraints applied





Conclusion & Outlook

- Converted HIC EOS preserve the large rise of c_s^2
- Constrained the symmetry energy coefficients further
- A heavy neutron star could be compatible with HIC data!
- MC simulation for symmetry energy expansion for Bayesian analysis
    - Numerically challenging - 10^9 $EOSs$ as input to hadronic transport
- Consider inclusion of strangeness and quark degrees of freedom
- Hadronic transport model also need to consider momentum dependence of the potentials, in-medium cross sections, etc

Back-up slides