Equations of State for Dense Matter

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Motivation

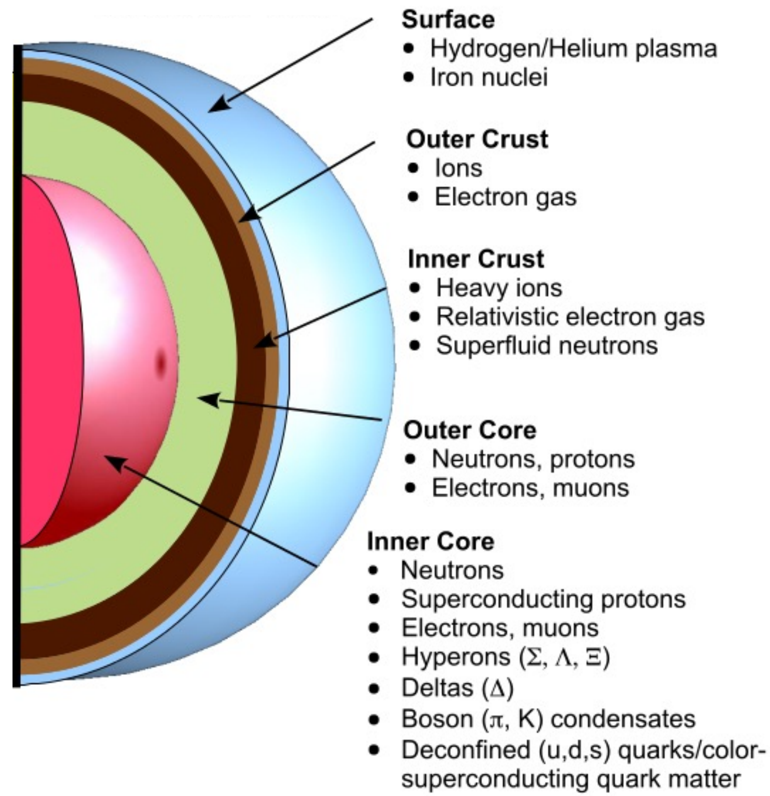
- ✶ Introduction to dense-matter equation of state (EoS)
- ✶ Ingredients
- ✶ Modern sources for EoS's
- ✶ Astrophysical constraints
- ✶ Neutron-star EoS's
- ✶ Conclusions

Introduction to dense-matter EoS

- Official meaning: a thermodynamic equation relating state variables (usually including the pressure)
- In astrophysics we (when available) also provide/expect:
  - full thermodynamic list of variables
  - particle composition
  - microscopic information
  - stellar properties …
- 1D or 2D (usually for neutron stars or isospin symmetric)
- 3D (usually n_B, T, Y_Q) …

Ingredients

- Low-density EoS with nuclei
- High-density EoS with bulk hadronic matter: nucleons, hyperons, deconfined quarks, …
- Quantum relativistic description
- Reproduce chiral symmetry restoration
- Reproduce lattice QCD results at finite temperature
- In agreement with heavy-ion collision physics at finite temperature
- Reproduce perturbative QCD results in the relevant regime



Mod.Phys.Lett.A 29 (2014) 1430022
e-Print: [1408.0079]

Modern sources for EoS's

- CompOSE
  CompStar Online Supernovae Equations of State
  https://compose.obspm.fr
  (Stefan Typel, Micaela Oertel, Thomas Klaehn)
- Online service provides 1D, 2D, 3D EoS tables for astrophysical applications
- Additional software to combine or interpolate data, calculate additional quantities, and graph EoS dependencies

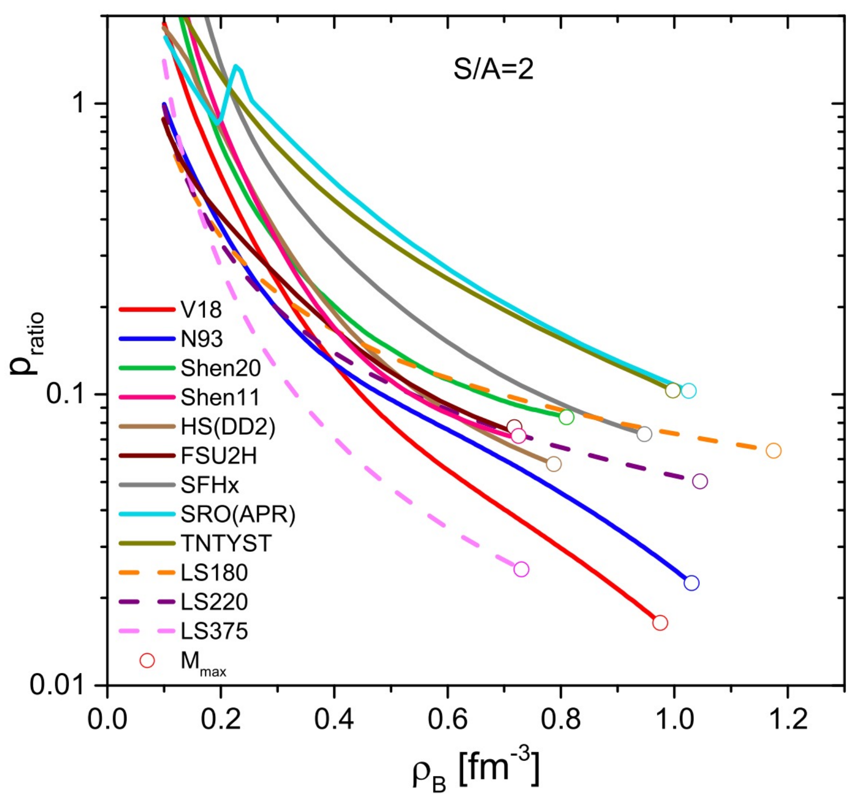
e-Print: 2203.03209

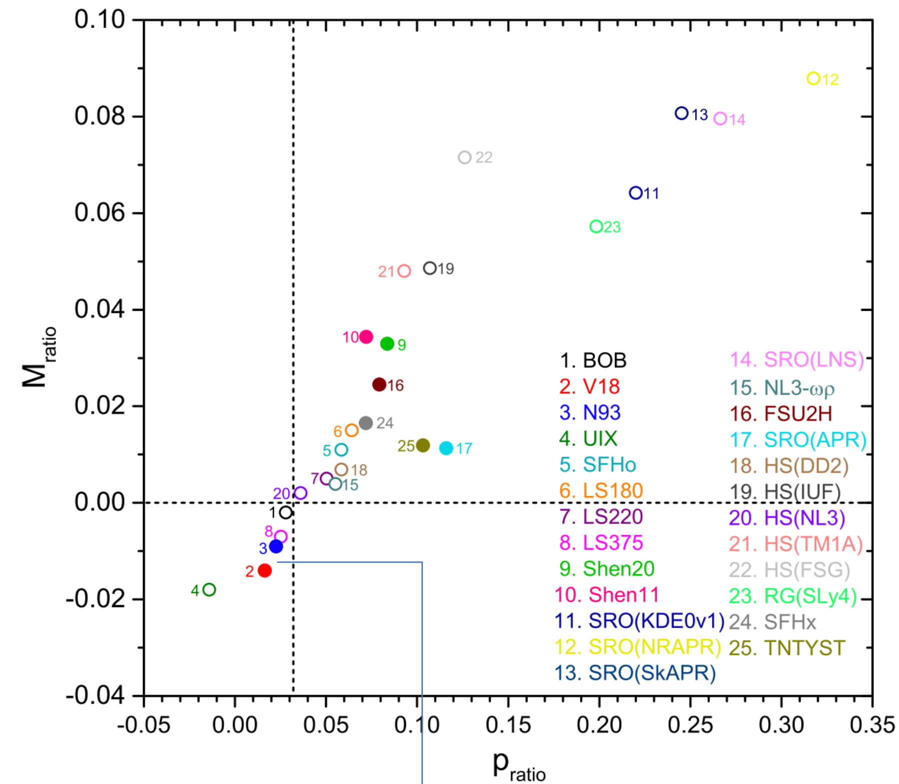
- Instruction manual
  with summarized providers quick guide and users quick guide

CompOSE

Phys.Rev.C 104 (2021) 6, 065806
e-Print: 2112.05323

- Example: young (hot) β-equilibrated stars





$$2.1 < M_{\rm max}/M_\odot < 2.4$$

$$p_{\rm ratio} \equiv \frac{p_{\rm th}}{p_0}(\rho, T)$$

$$p_{\rm th}(\rho, T) \equiv p(\rho, x_T, T) - p(\rho, x_0, 0)$$

$$M_{\rm ratio} \equiv \frac{M_{\rm max}^{\rm hot} - M_{\rm max}^{\rm cold}}{M_{\rm max}^{\rm cold}}$$

muses

- ✶ Modular Unified solver of the Equation of state https://muses.physics.illinois.edu/
- ✶ Modular: while at low μ_B the EoS is known from 1st principles, at high μ_B there will be different models for the user to choose
- ✶ Unified: different modules will be merged together to ensure maximal coverage of the phase diagram
- ✶ Developers: physicists + computer scientists will work together to develop the software that generates EoS's over large ranges of temperature and chemical potentials to cover the whole phase diagram
- ✶ Users: interested scientists from different communities, who provide input to the future open-source cyberinfrastructure

muses

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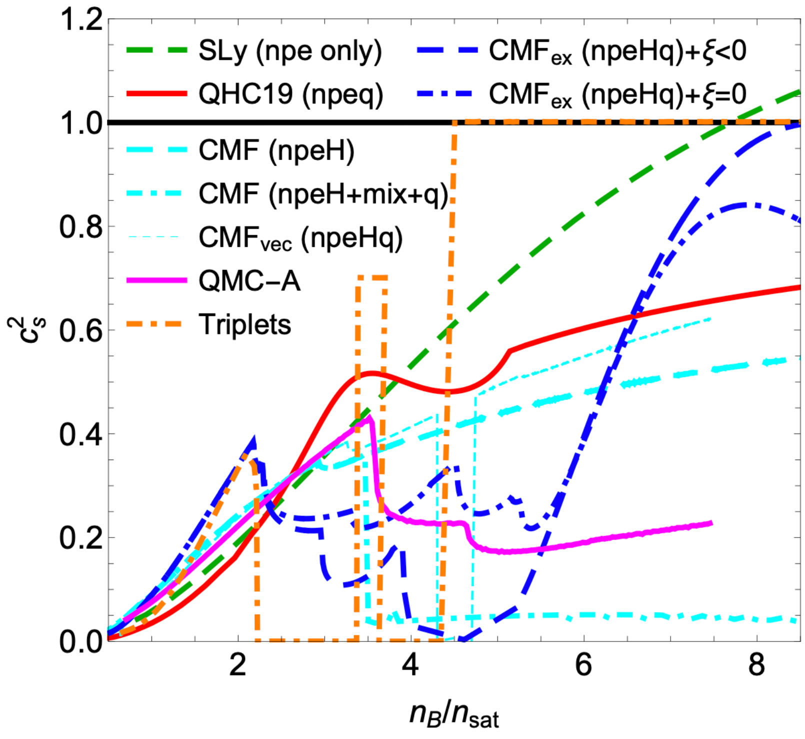
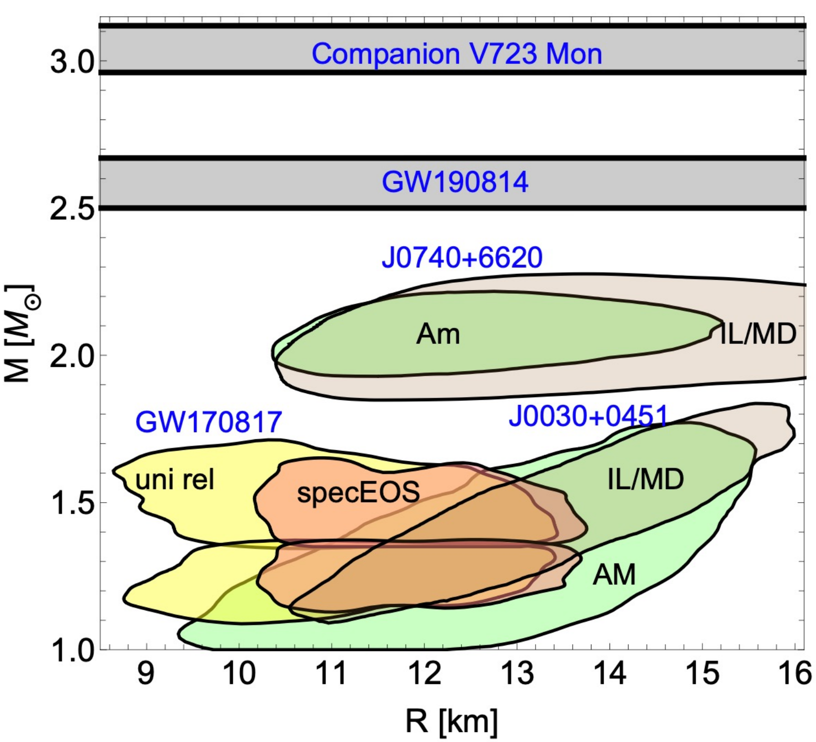
Astrophysical constraints

- Different exotic matter associated with different phase transitions
- Can easily be seen in speed of sound but not necessarily in mass-radius





PRD 105 (2022) 2, 023018 e-Print: 2106.03890

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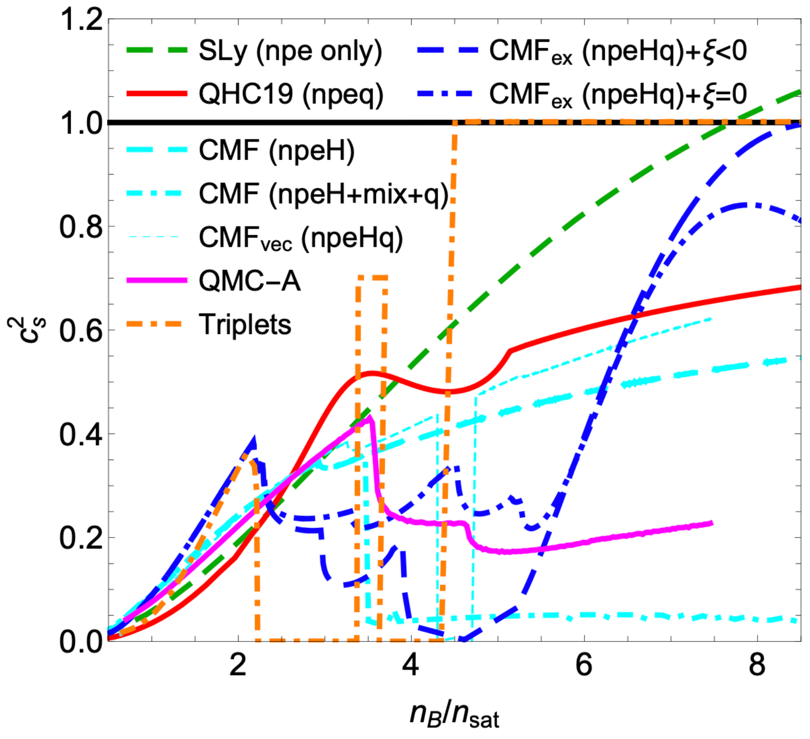

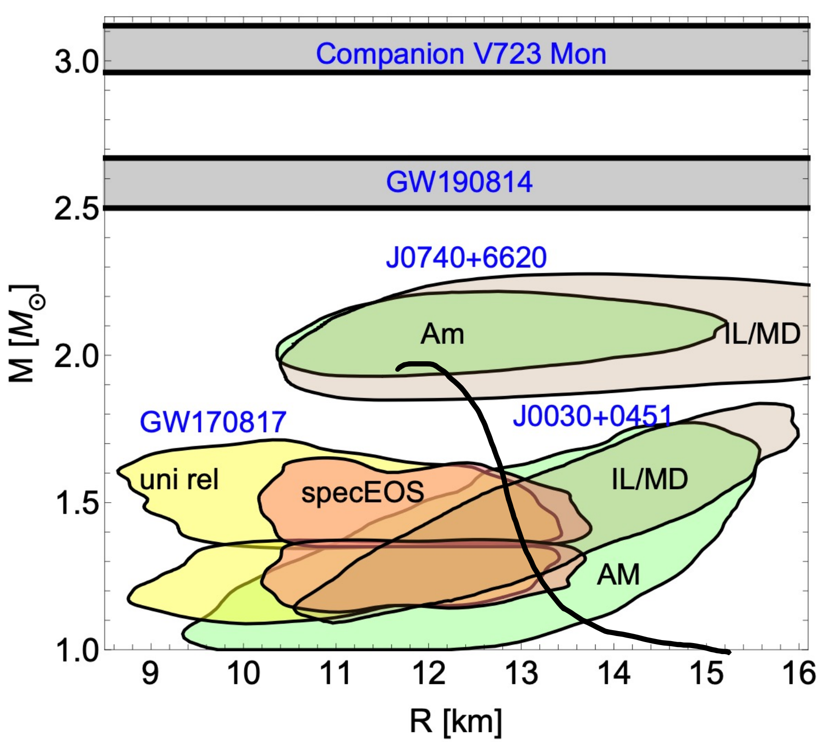

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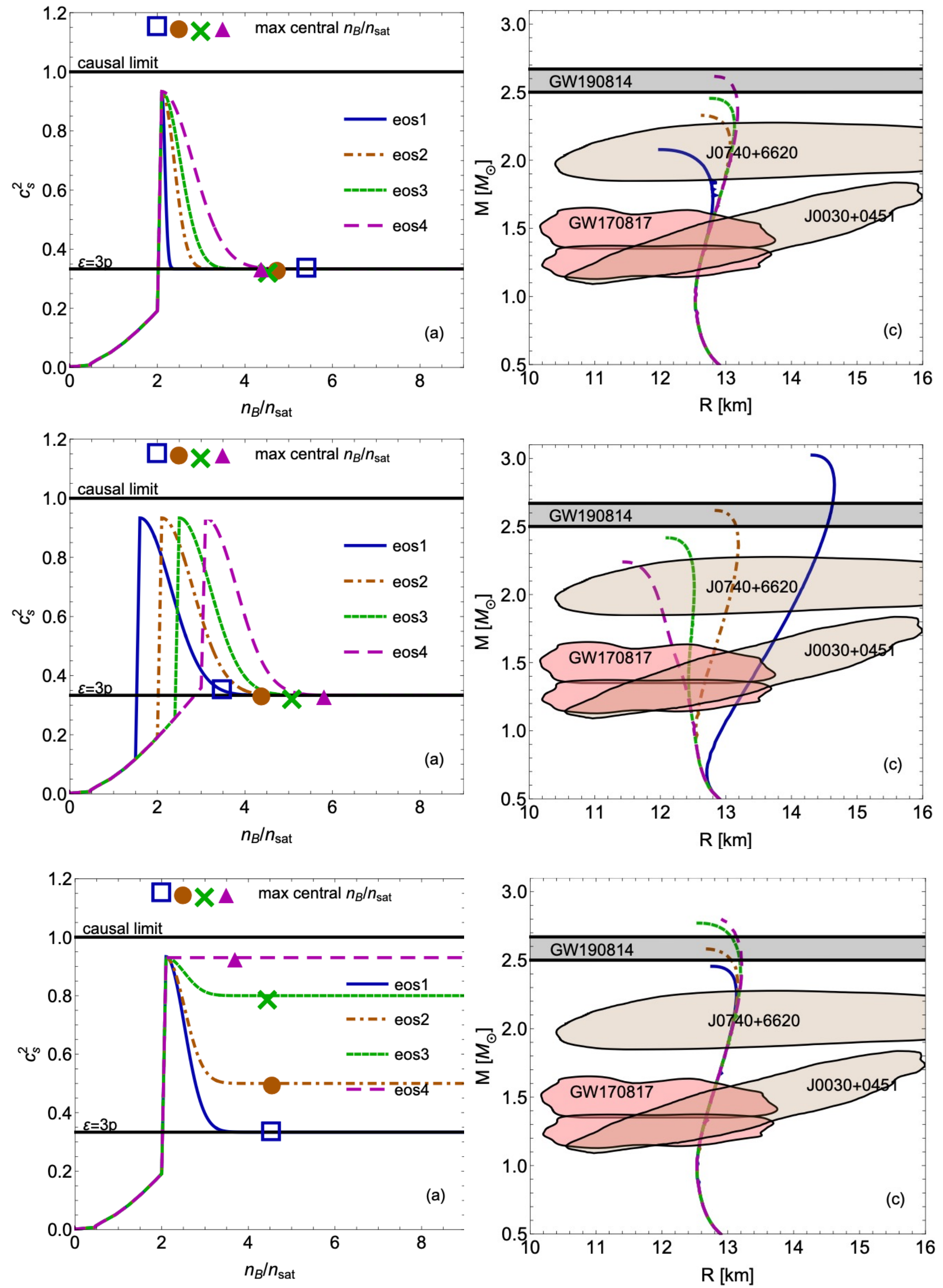
Parametric approach

- More systematic parametric form for the speed of sound can help to determine neutron-star composition
- Maximum stellar mass and radius can determine width, density, and height of bumps

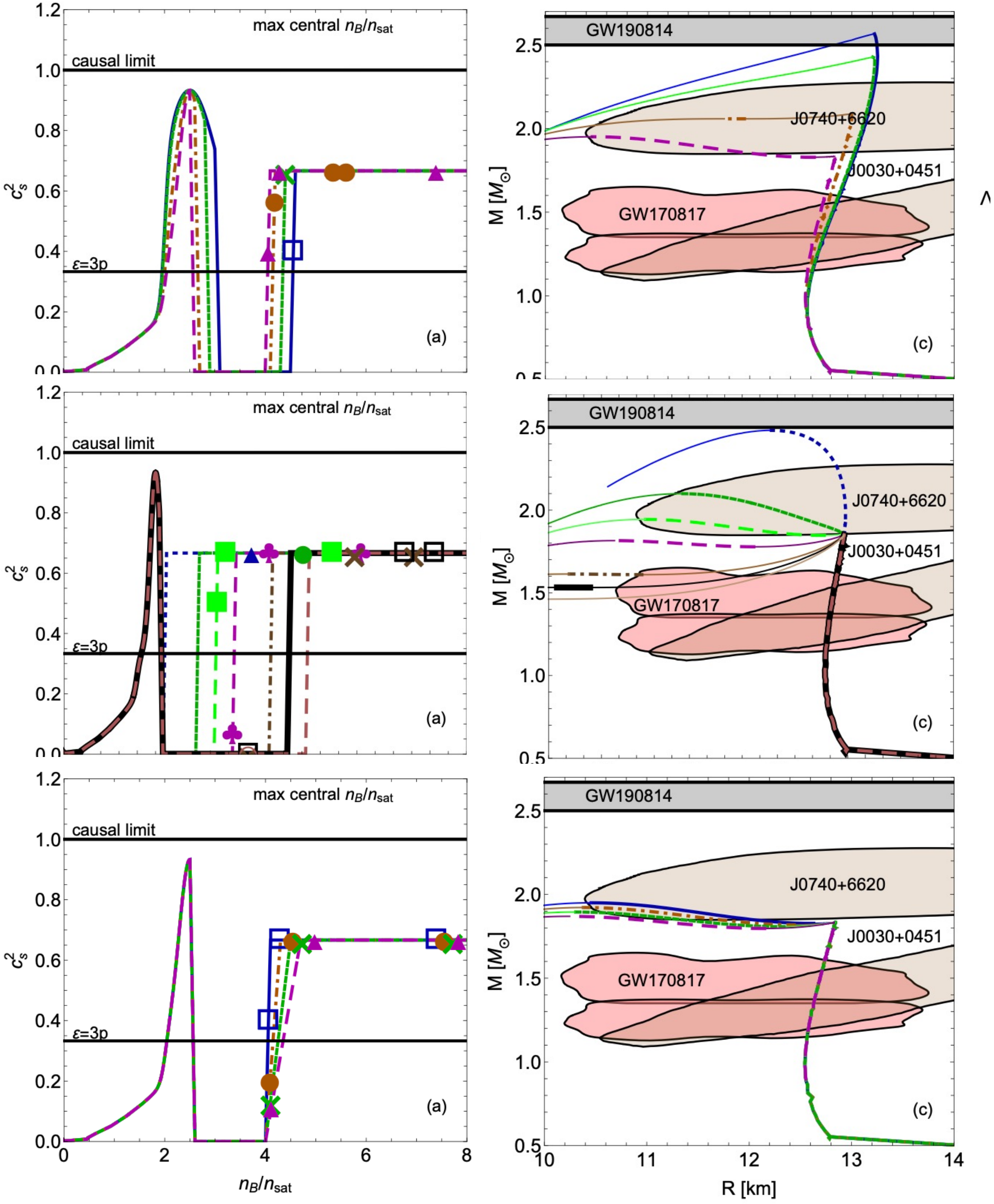
PRD 105 (2022) 2, 023018
e-Print: [2106.03890]()



With 1st order phase transition

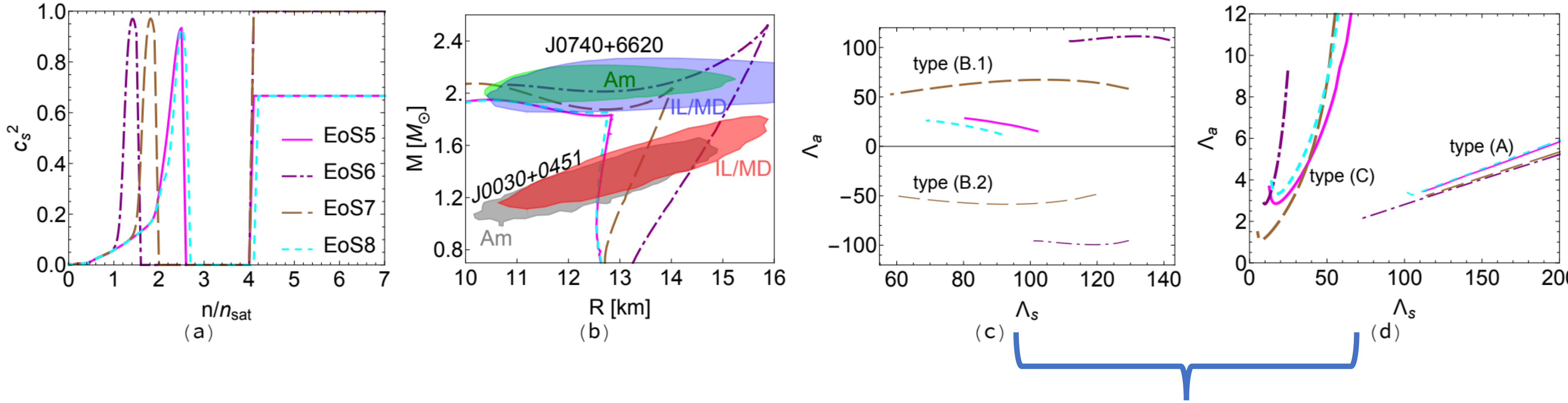
- ✶ Zero speed of sound not ruled out by observation of massive stars
- ✶ But constrained by extremely massive objects

PRD 105 (2022) 2, 023018
e-Print: [2106.03890]



Tidal Deformability

- ✶ Bumps and 1st –order phase transitions tilt the mass-radius diagram



- ✶ Can create structure in the binary Love relations: slope, hill, drop, and swoosh

- ✶ Structure could be observed in near future

Phys.Rev.Lett. 128 (2022) 16, 161101
e-Print: 2111.10260

CMF model simulations

- CMF 3D EoS (n_B, T, Y_Q) *Astron.Astrophys.* 608 (2017) A110 e-Print: 1706.09191

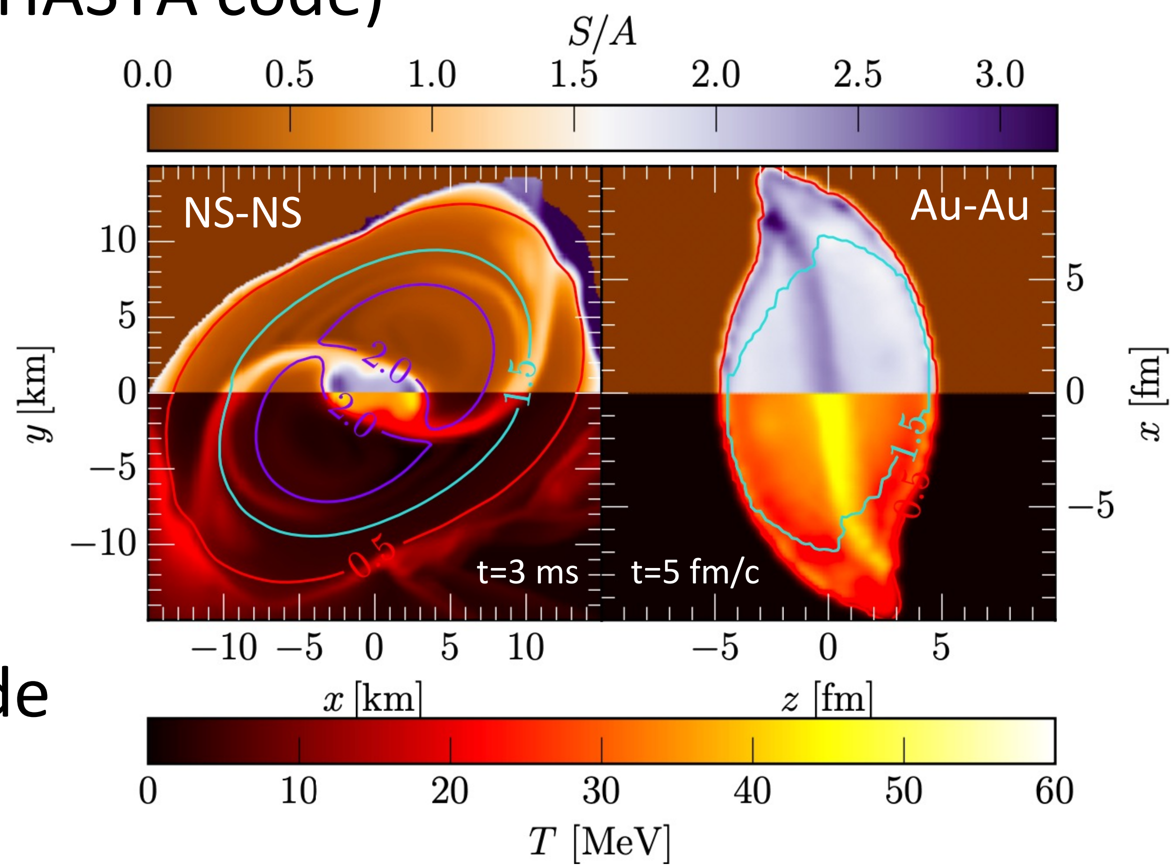
  e-Print: 2201.13150

  PRC 101 (2020) 3, 034904 e-Print: 1905.00866

- Relativistic hydrodynamics simulations of **neutron-star mergers** (Frankfurt/Illinois GRMHD code) and **heavy-ion collisions** (Frankfurt SHASTA code)

- Final merger mass of 2.9 M_{Sun} and low-energy collision with E_{lab} = 450 MeV

- Similar geometry and properties across 18 orders of magnitude



Conclusions

- New tight constraints from experiment, observation, and theory are slowly determining dense matter and neutron-star core properties
- EoS repositories help speeding up understanding of dense matter
- Parametric models are great for studying the T=0 EoS thoroughly
- Gravitational waves are providing new ways to study the dense matter EoS
- LIGO, Virgo, and KAGRA are coordinating O4 observing run in March 2023