Net strangeness and isospin fractions in the EoS

as probed by protoneutron stars, binary neutron star mergers, and heavy ion collisions

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Overview

- Can we find a flexible common parametrization of the EOS, applicable to neutron star calculations and different types of heavy-ion collisions simulations?

  Yes! Effective models:

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  Yes! Effective models:

  - flexibility in terms of conditions and ranges,

  - input from many different constraints

  - errors estimated from large parameter studies

  muses

Overview

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- ✶ What other observables could enable the extraction of the EOS?

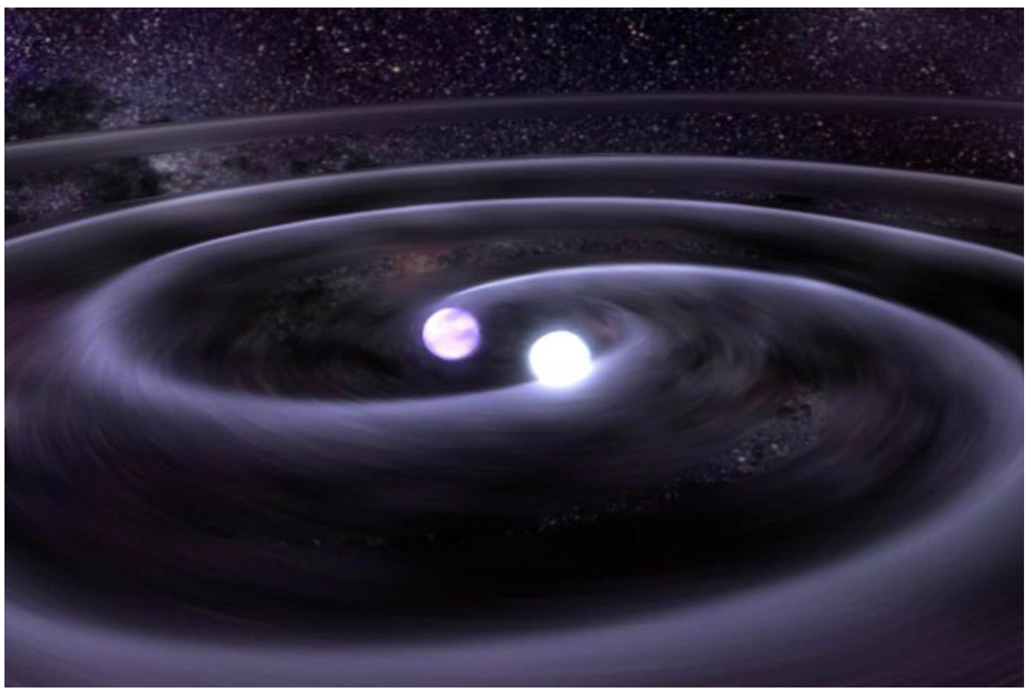
  - tidal deformability measured with smaller error

  - post-merger part of gravitational waves from neutron-star mergers *PRL* 122 (2019) 6, 061101 e-Print: 1807.03684

  - neutron star surface temperature e-Print: 2206.01679

Astrophysics vs. Heavy-Ion Collisions

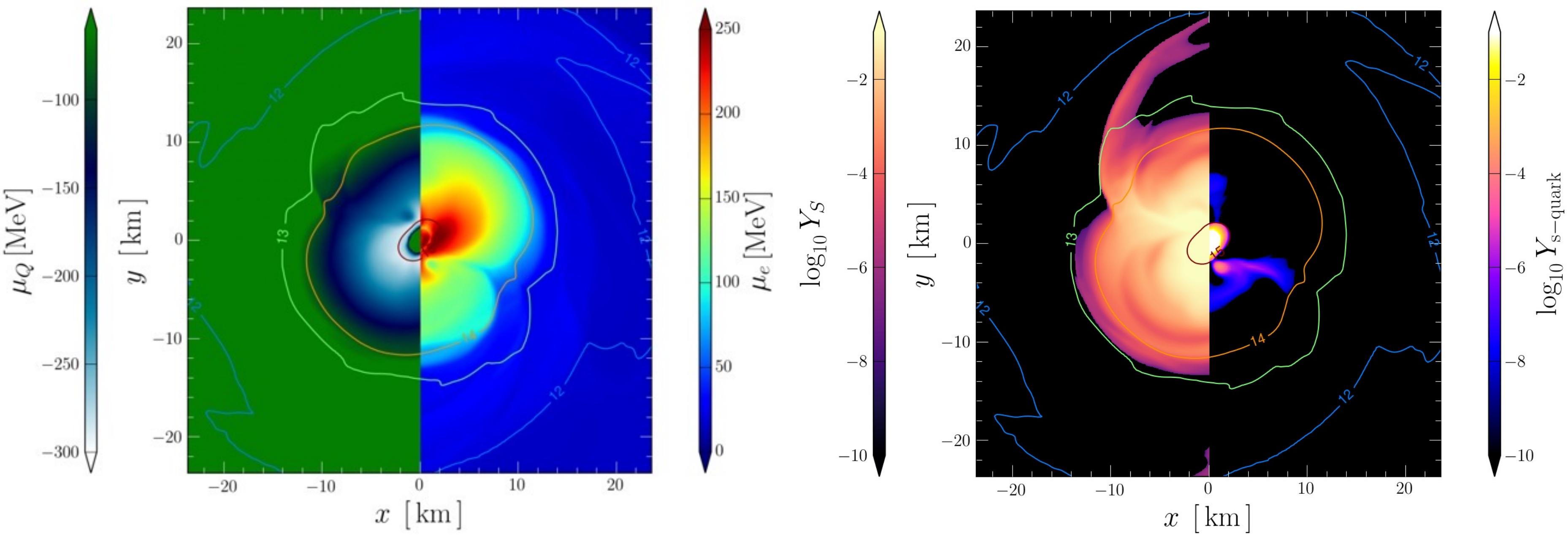
- Fully evolved neutron stars cores: Y_Q=Q/B= 0 → 0.2 (0.1)
- Heavy-ion collisions: Y_Q = 0.4 → 0.5 (0.5), also have Y_S=S/B=0
- Supernovae explosions/proto-neutron stars: Y_Q = 0.1 → 0.5 (0.4)
- Neutron-star mergers ? Y_Q < 0.15



Neutron Star Mergers

- ✶ 3D (T,n_B,Y_Q) CMF table with 1st-order phase transition into coupled Einstein-hydrodynamics system (Frankfurt/IllinoisGRMHD code)

EPJA 56 (2020) 2, 59 e-Print: [1910.13893](1910.13893)



- ✶ $\boldsymbol{\mu}_Q$ ($\neq \boldsymbol{\mu}_e$) doesn’t grow much in absolute value, so doesn’t Y_Q
- ✶ Total strangeness (hyperons ➜ s-quarks) grows to Y_S∽40%

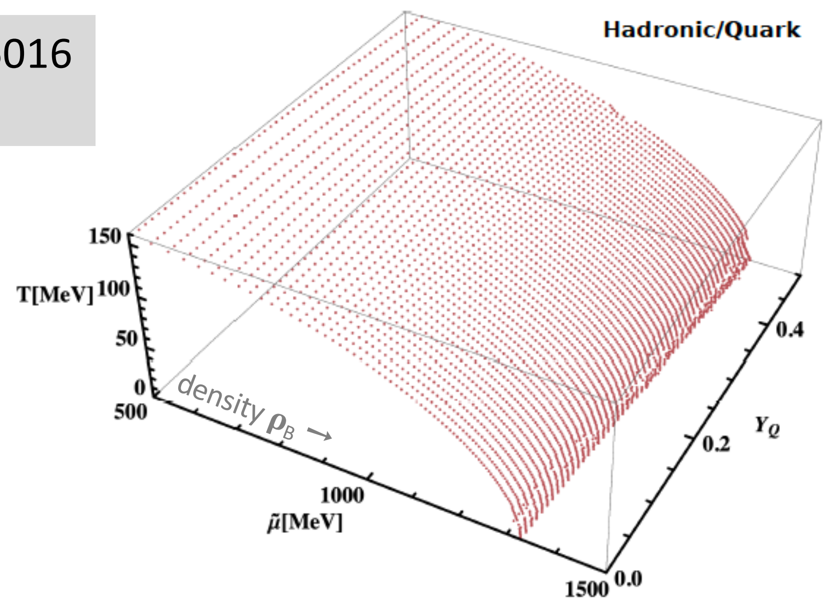
3D QCD phase diagrams (Y_S=0)

- T, $\widetilde{\mu}$, Y_Q with charge fraction $Y_Q = Q/B$ = 0 → 0.5
  and Gibbs free energy per baryon $\widetilde{\mu} = \mu_B + Y_Q \mu_Q$

3D QCD phase diagrams (Y_S=0)

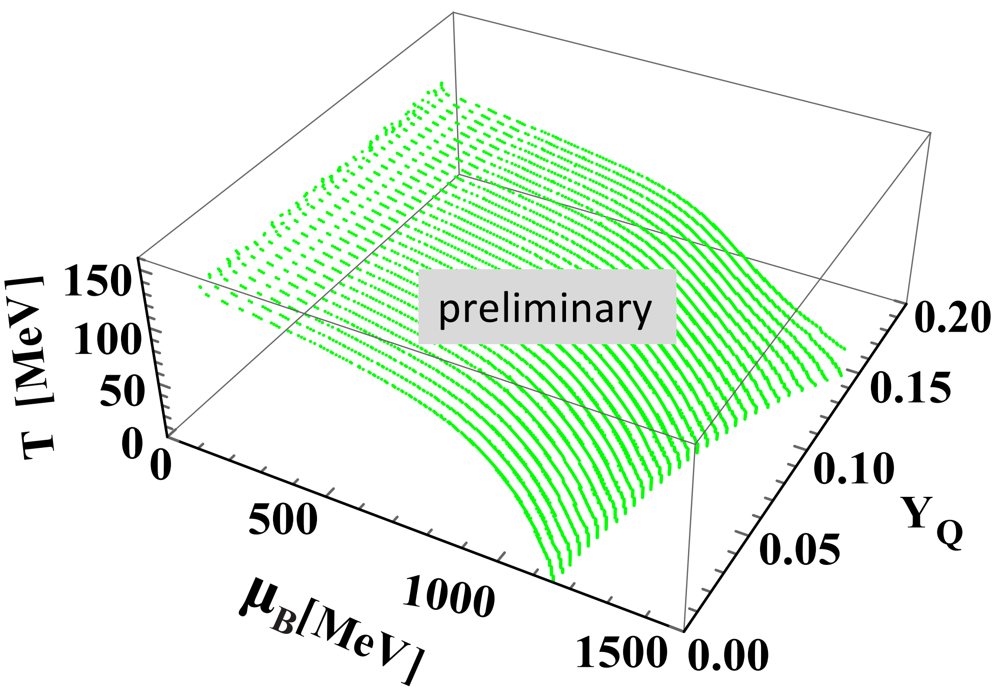
- T, $\widetilde{\mu}$, Y_Q with charge fraction $Y_Q = Q/B$ = 0 → 0.5
  and Gibbs free energy per baryon $\widetilde{\mu} = \mu_B + Y_Q \mu_Q$
- Larger Y_Q (at fixed T) pushes the phase transition to larger $\widetilde{\mu}$
- Lower Y_Q (at fixed T) pushes the phase transition to lower $\widetilde{\mu}$!
- Changes due to Y_Q effects on stiffness (particle population) on each side

PRD 102 (2020) 7, 076016
e-Print: 2004.03039



Weaker phase transition

- Different parametrization *Eur.Phys.J.A* 58 (2022) 5, 96 reproducing a much weaker phase transition ($Y_S \neq 0$) enhances Y_Q effect



- For small Y_Q's, $\widetilde{\mu} \backsim \mu_B$ (hadron)$\backsim \mu_B$ (quark)

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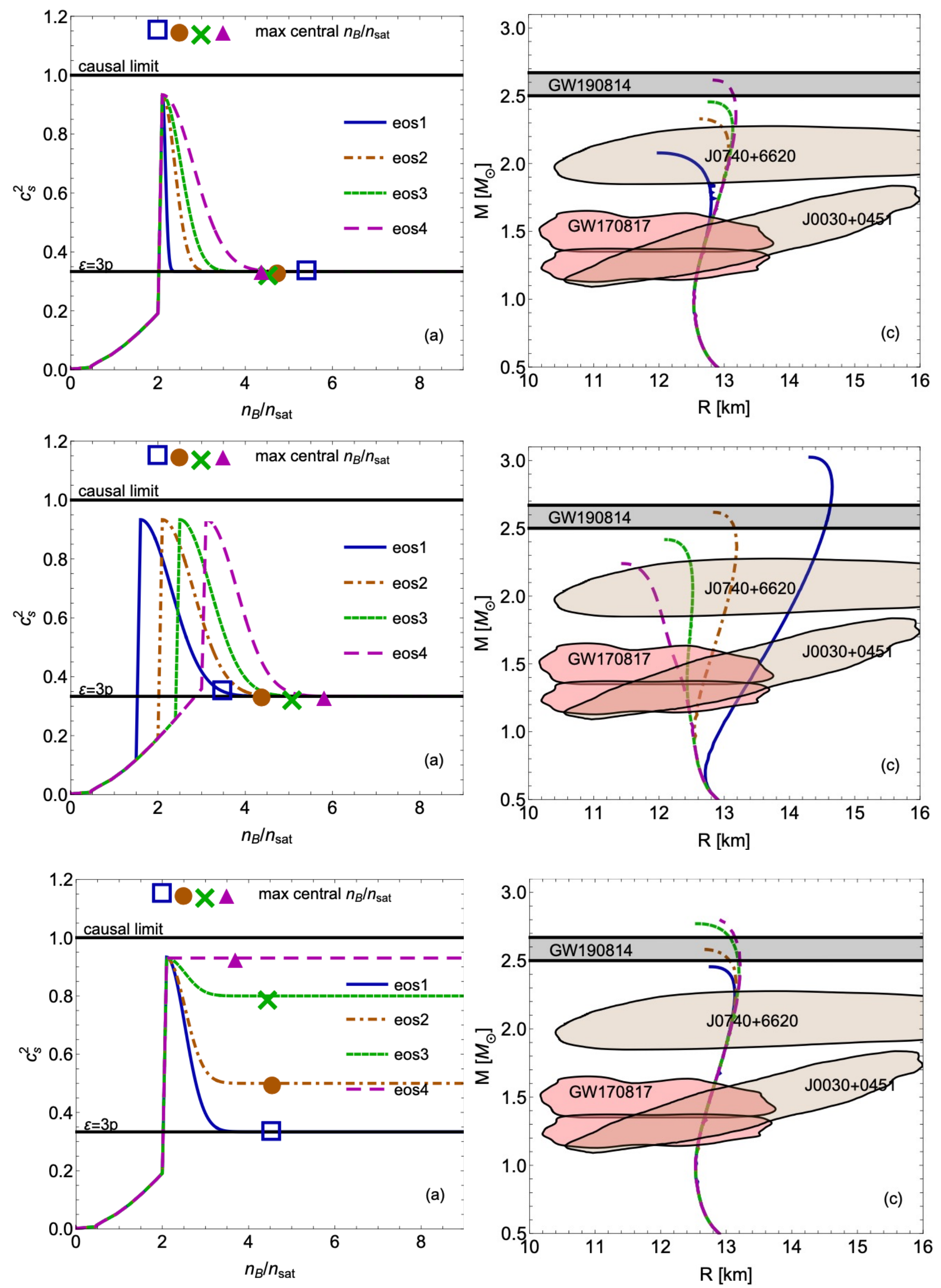
Parametric approach

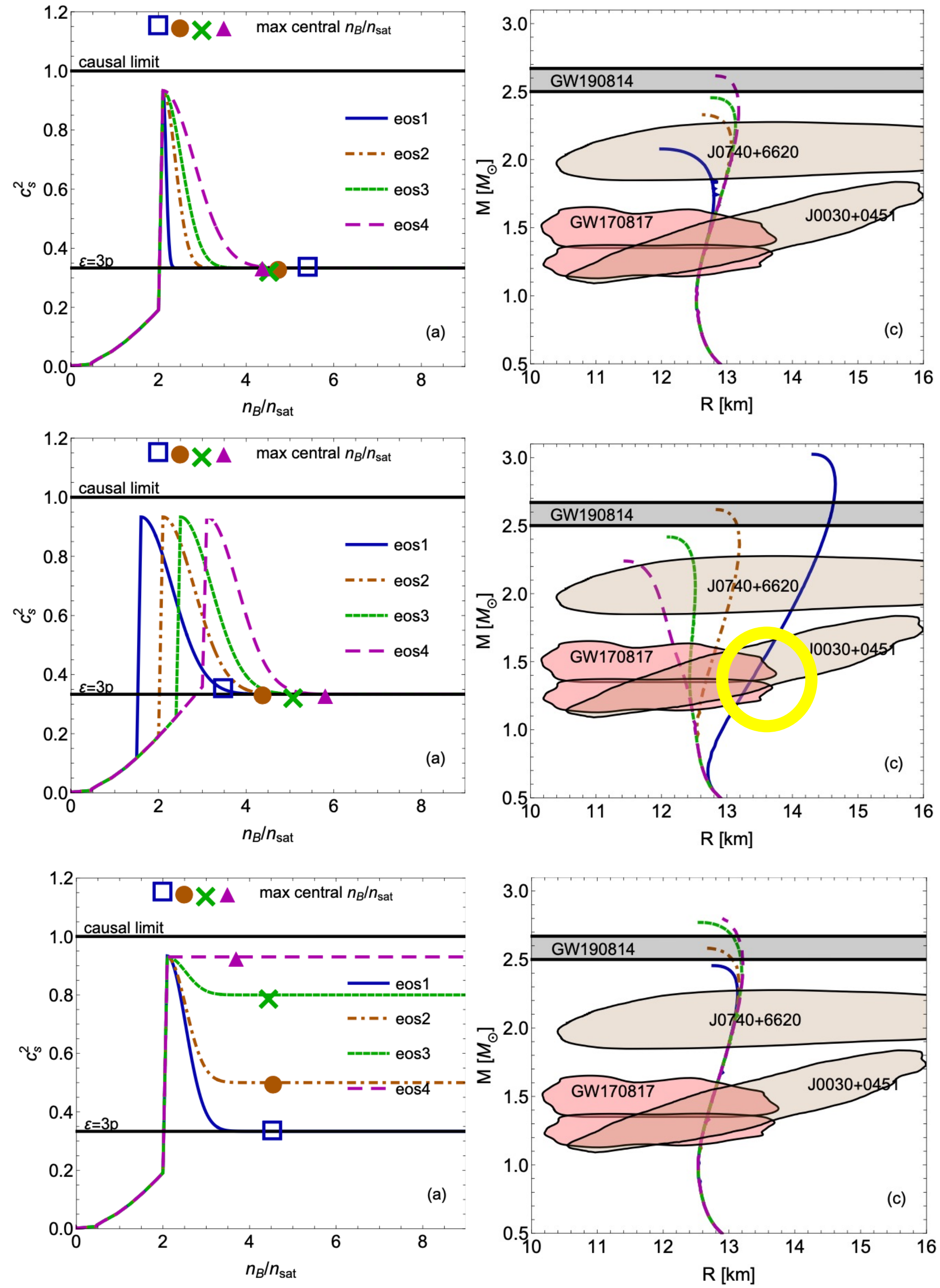
- ✶ More systematic parametric form for the speed of sound can help to determine neutron-star composition
- ✶ Maximum stellar mass and radius can determine width, density, and height of bumps

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



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, plus central density of stars



With 1st order phase transition

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

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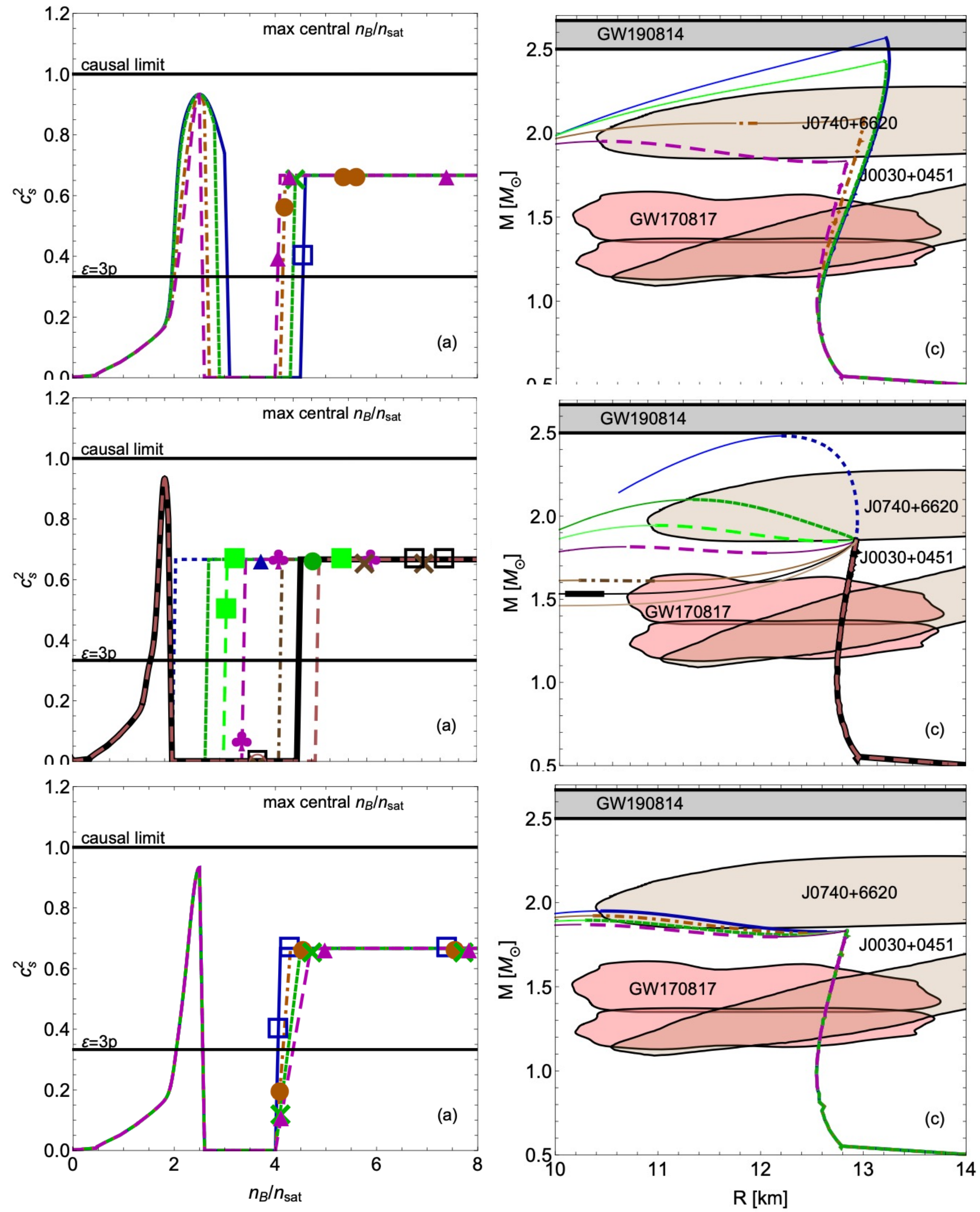
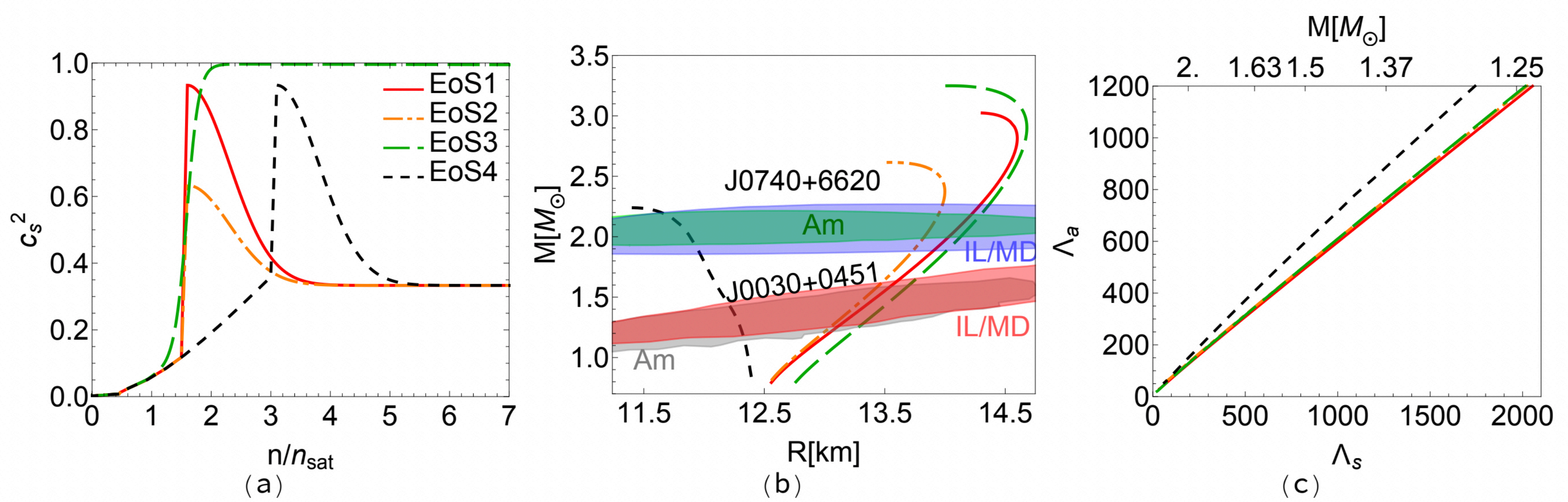


Tidal deformability

✶ Bumps tilt the mass-radius diagram



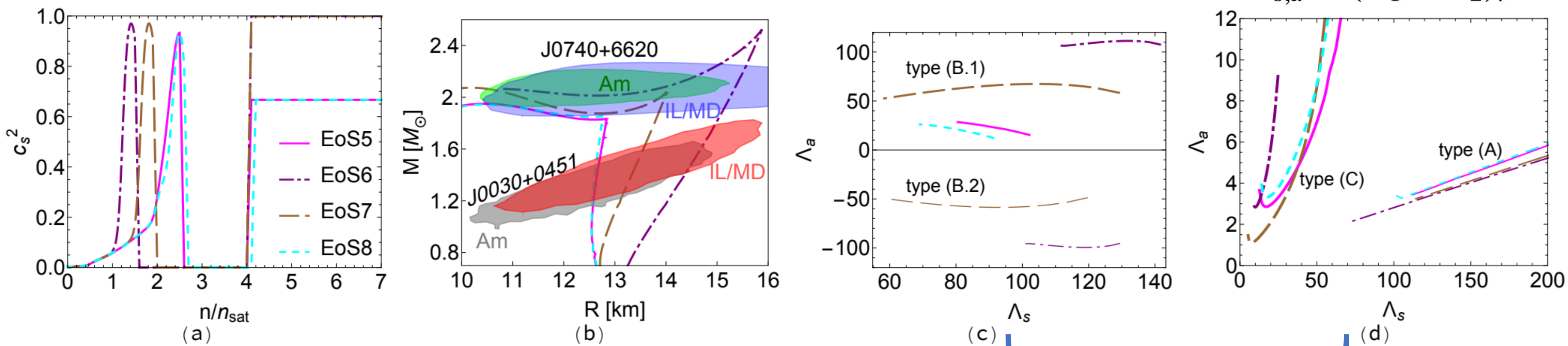
and the binary Love relations ($\Lambda_{s,a} = (\Lambda_1 \pm \Lambda_2)/2$)

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

Tidal deformability

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

$$\Lambda_{s,a} = (\Lambda_1 \pm \Lambda_2)/2$$



and create structure in the binary Love relations: slope, hill, drop, and swoosh (associated with twin stars)

- ✶ Structure could be observed in near future

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Conclusions and outlook

- Effective models are an ideal tool to construct multi-dimensional tables for any regime of Y_Q and Y_S to translate results between astrophysics and heavy-ion collisions
- At T=0 simpler tools can be used that allow us to interpret mass, radius, and tidal deformability as a measurement of the nuclear equation of state stiffness
- LIGO, Virgo, and KAGRA are coordinating O4 observing run in March 2023