Phases of Matter Inside Neutron Stars

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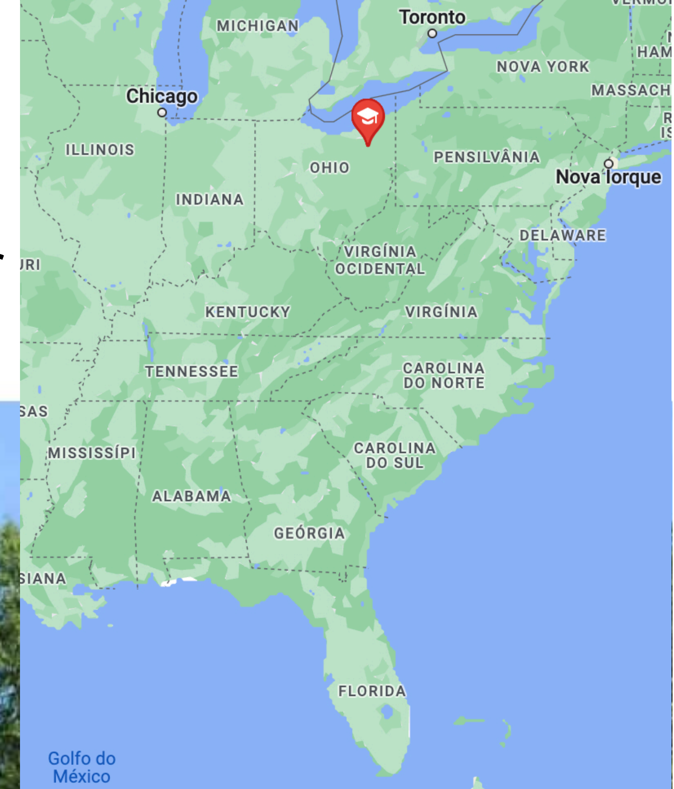


Overview

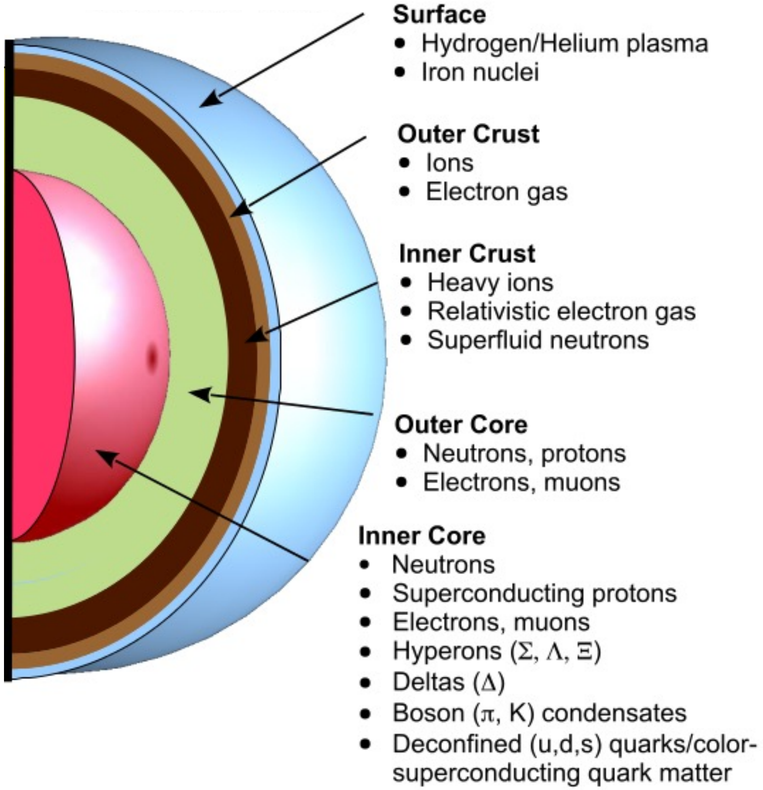
- ✶ Introduction to neutron stars and the dense-matter equation of state (EoS)
- ✶ Neutron-star astrophysical observables and relation to dense-matter EoS
- ✶ Comparison with other systems
- ✶ Where to find dense-matter and neutron-star EoS's

Introduction to dense-matter EoS

- Official meaning: a thermodynamic equation relating state variables
- Stiffer EoSs provide larger pressure (for a given energy density)
- 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) …

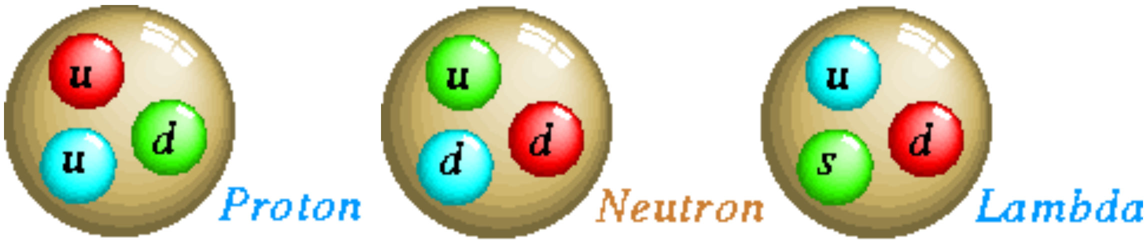
EoS ingredients

- ✶ Low-density EoS with nuclei
- ✶ High-density EoS with
  bulk hadronic matter: nucleons, hyperons, deconfined quarks, …

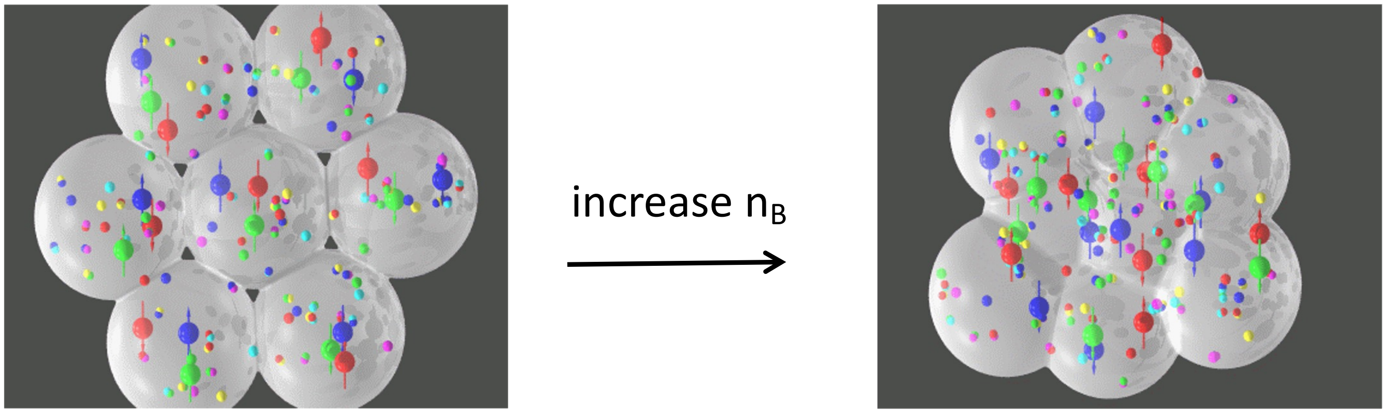


Mod.Phys.Lett.A 29 (2014) 1430022
e-Print: 1408.0079

- Baryons (hadrons made up of 3 quarks)

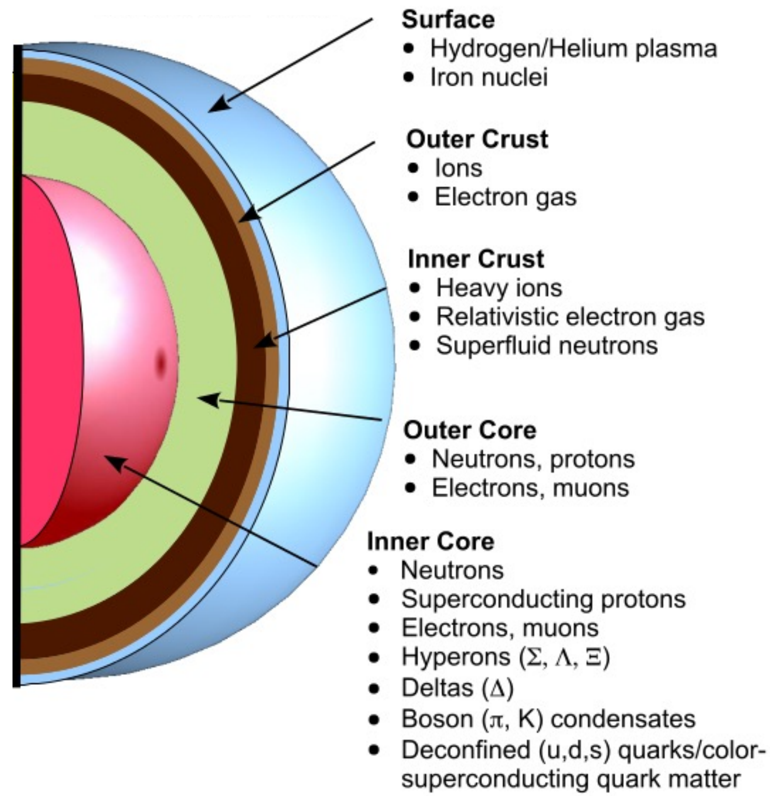


- With more massive quarks generating more massive hadrons
- Appearance of Lambdas and other hyperons at large densities ~ 2 nuclear saturation density (n_{sat})
- Leptons (electrons, muons) are also present
- Eventually, quarks inside hadrons are deconfined

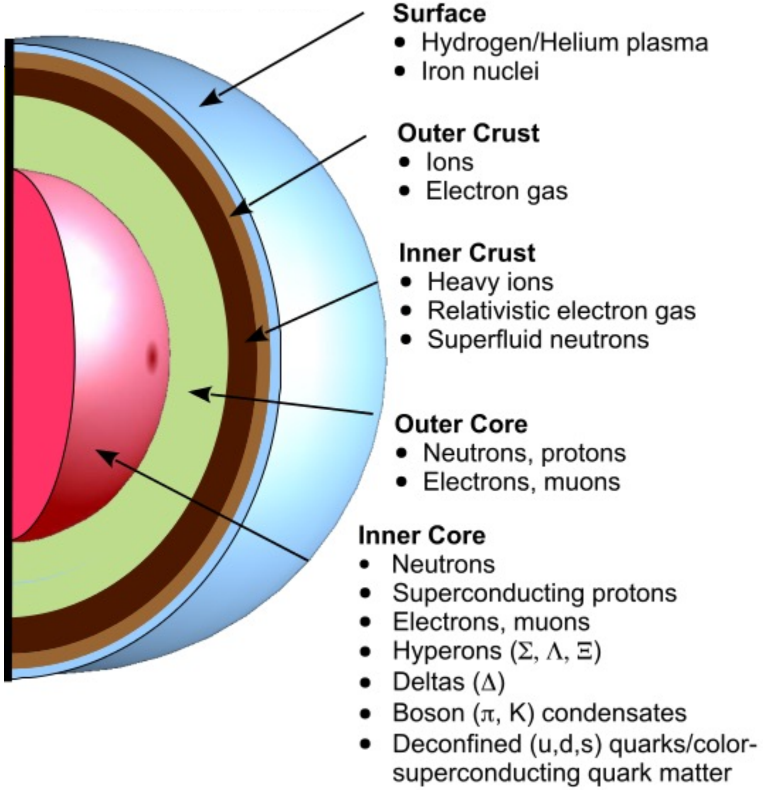


EoS ingredients

- ✶ Low-density EoS with nuclei
- ✶ High-density EoS with bulk hadronic matter: nucleons, hyperons, deconfined quarks, …
- ✶ Quantum relativistic description
- ✶ Reproduce chiral symmetry restoration (masses from medium)



EoS ingredients

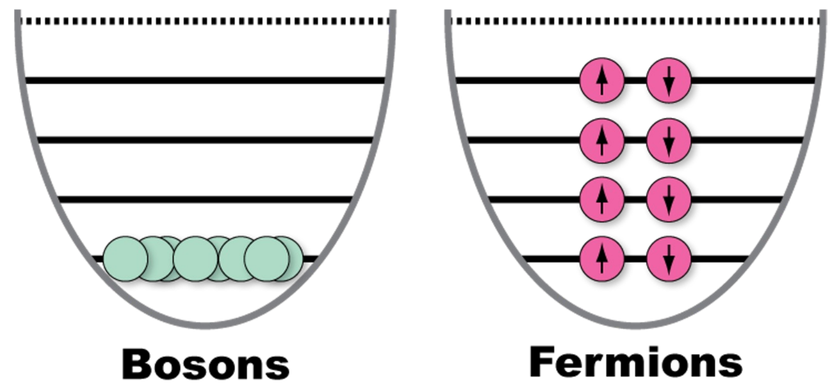


- ✶ Low-density EoS with nuclei
- ✶ High-density EoS with bulk hadronic matter: nucleons, hyperons, deconfined quarks, …
- ✶ Quantum relativistic description
- ✶ Reproduce chiral symmetry restoration
- ✶ Reproduce lattice QCD results at finite temperature
- ✶ In agreement with heavy-ion collision physics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

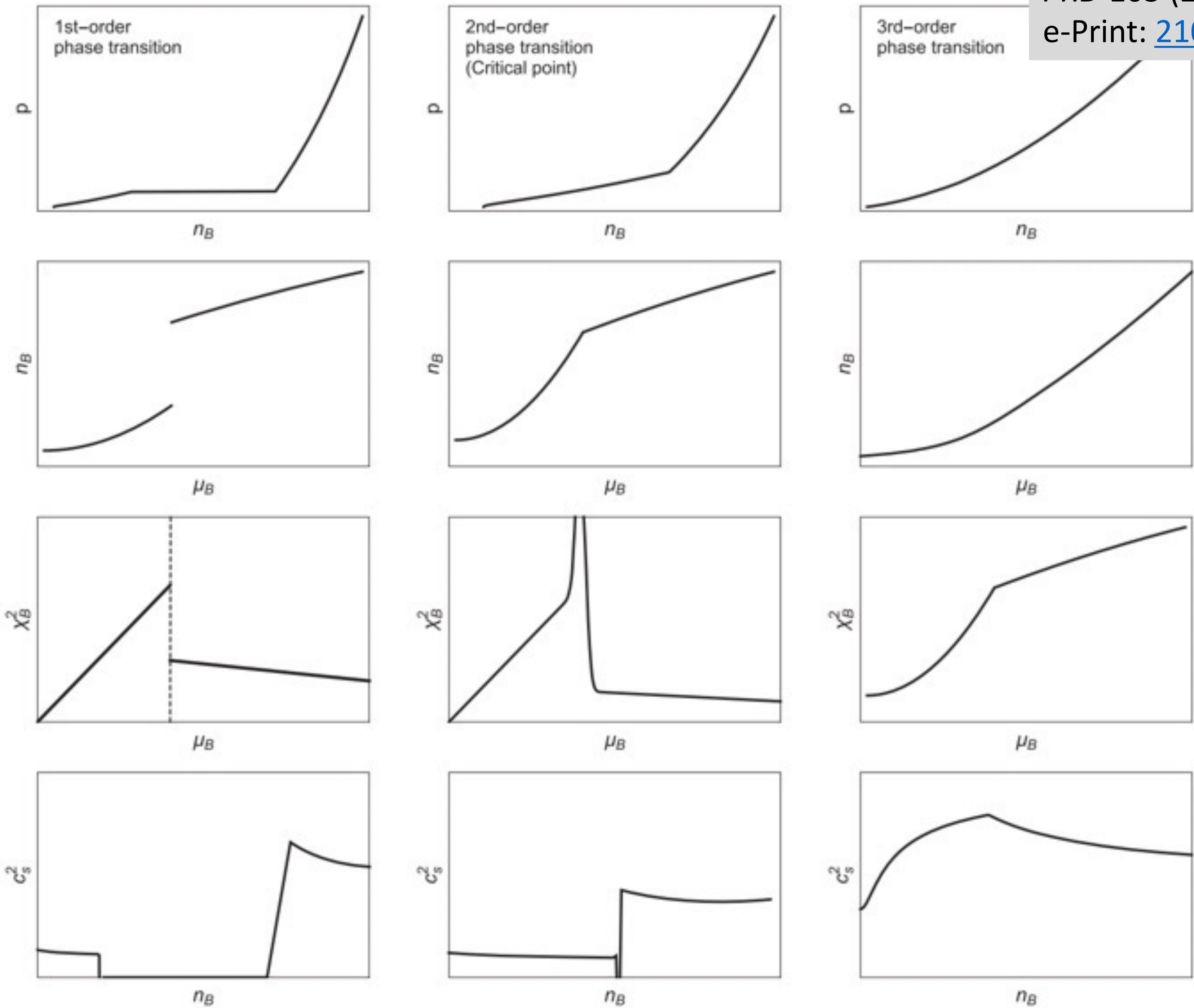
Neutron star composition

- Different exotic matter associated with different phase transitions

Energy Levels

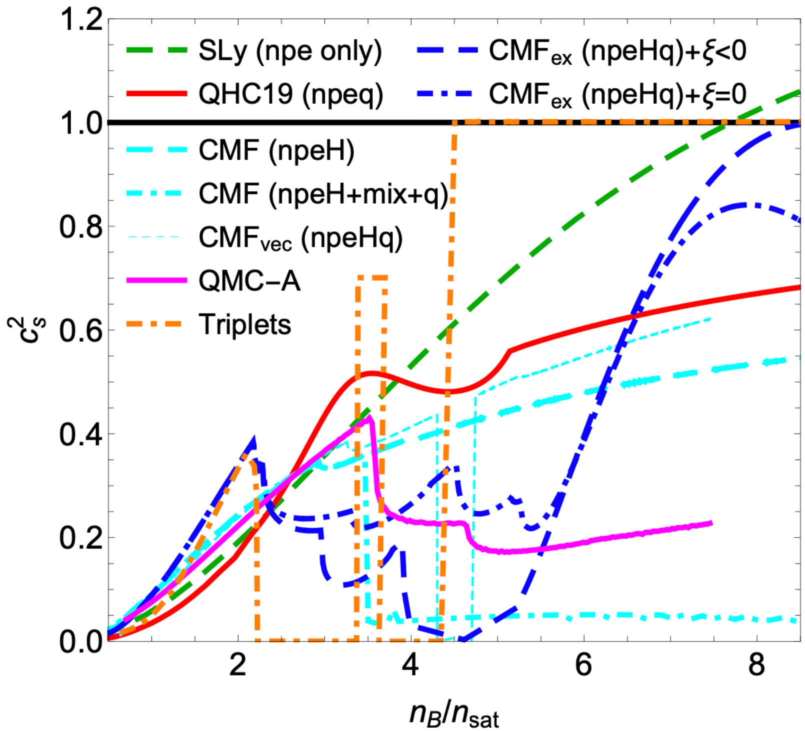


PRD 105 (2022) 2, 023018
e-Print: 2106.03890



Neutron star composition

- Different exotic matter associated with different phase transitions
- Not noticable in the EoS, but easily seen in speed of sound (dP/dε)



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Neutron star composition

- Different exotic matter associated with different phase transitions
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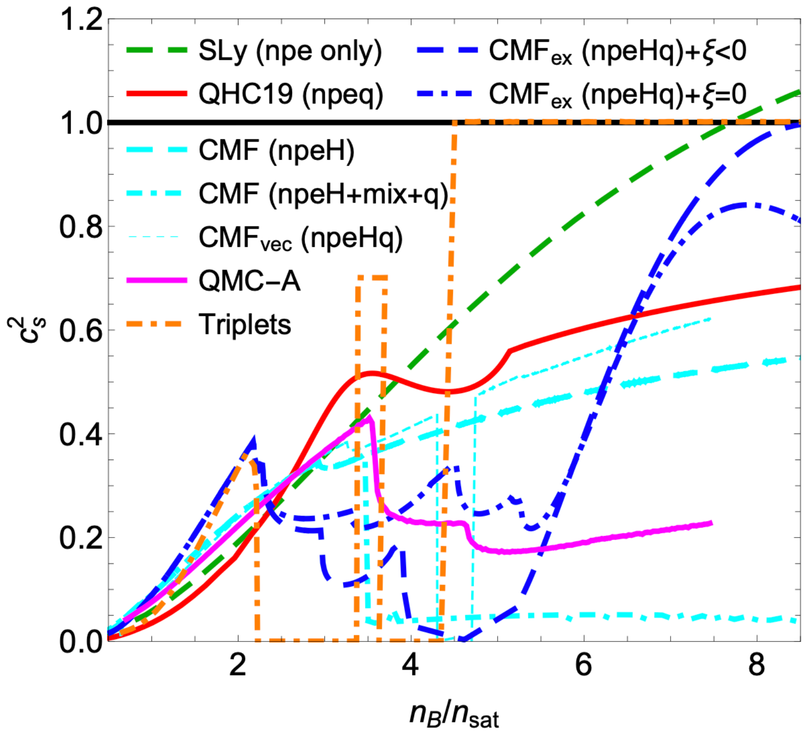

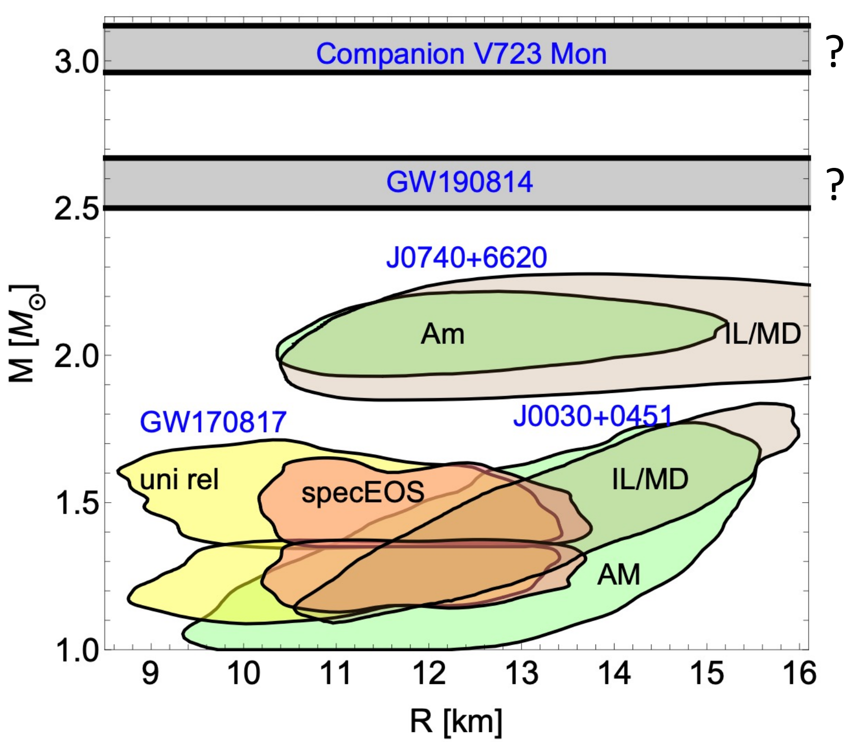

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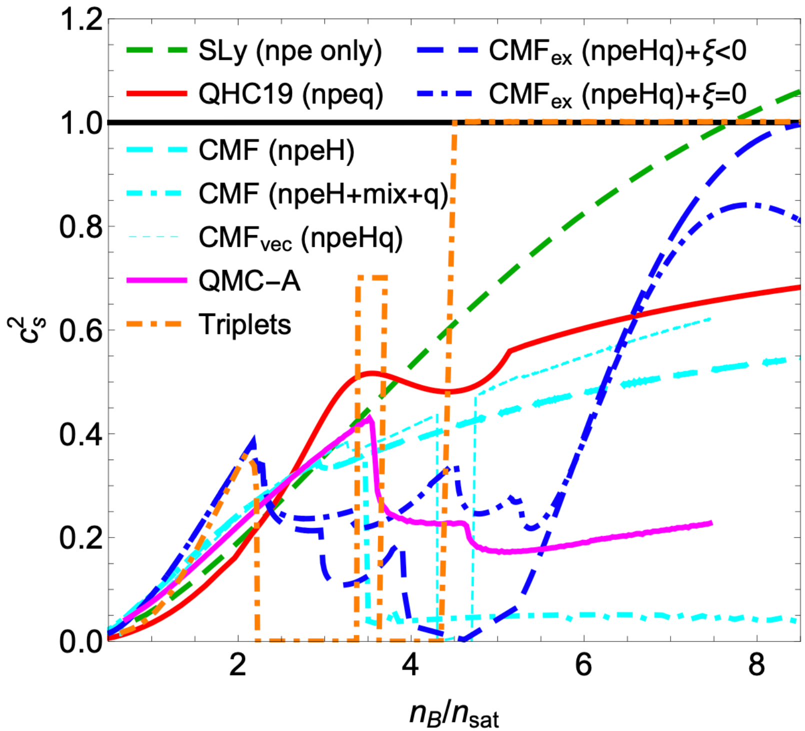

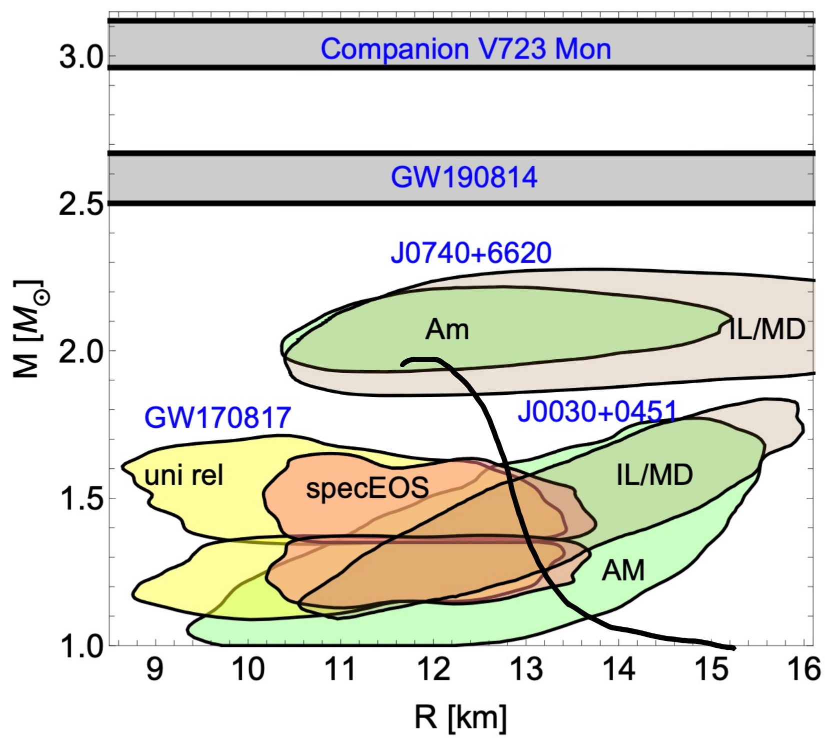

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Parametric approach

- 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

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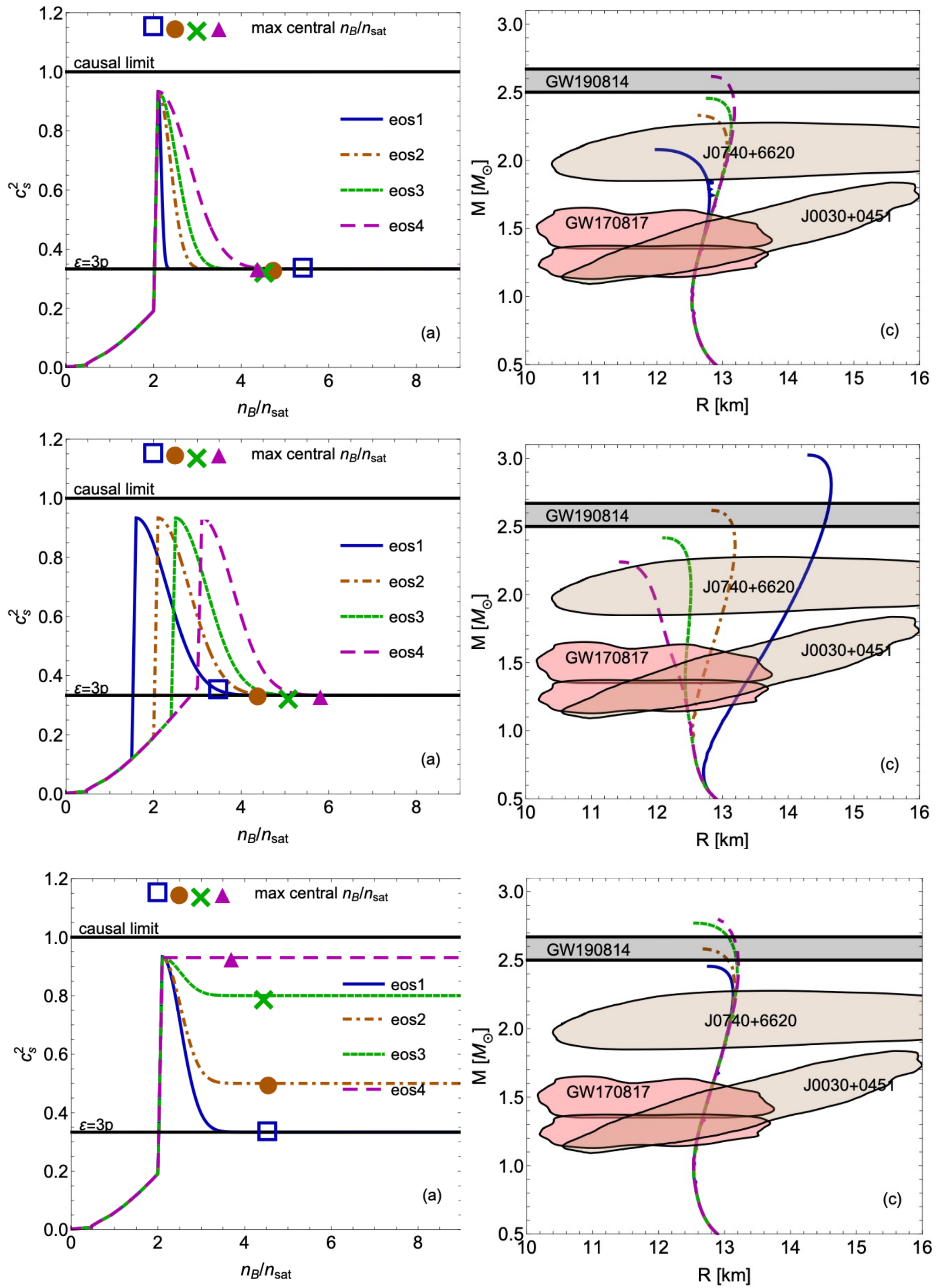
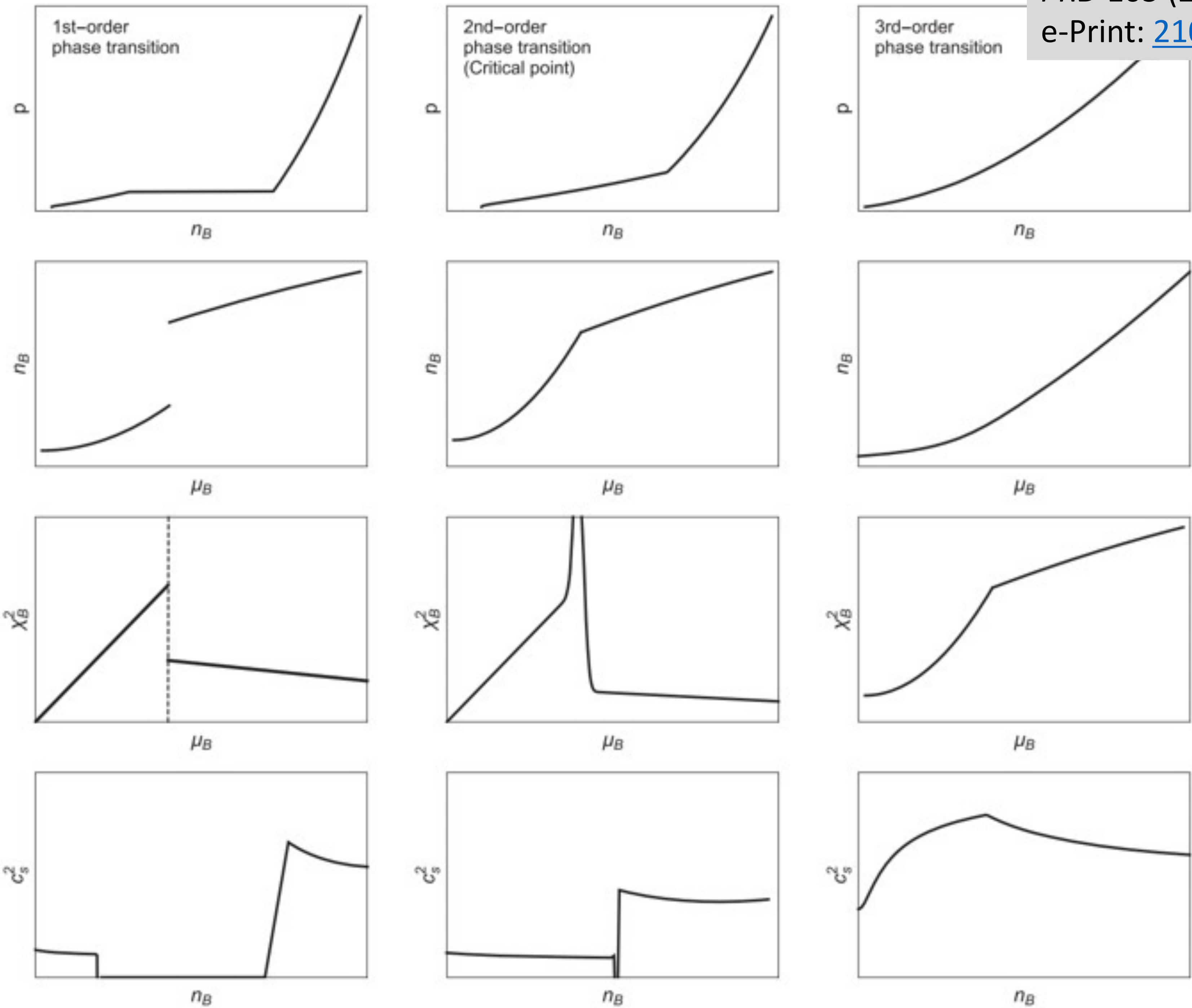


With 1st order phase transition



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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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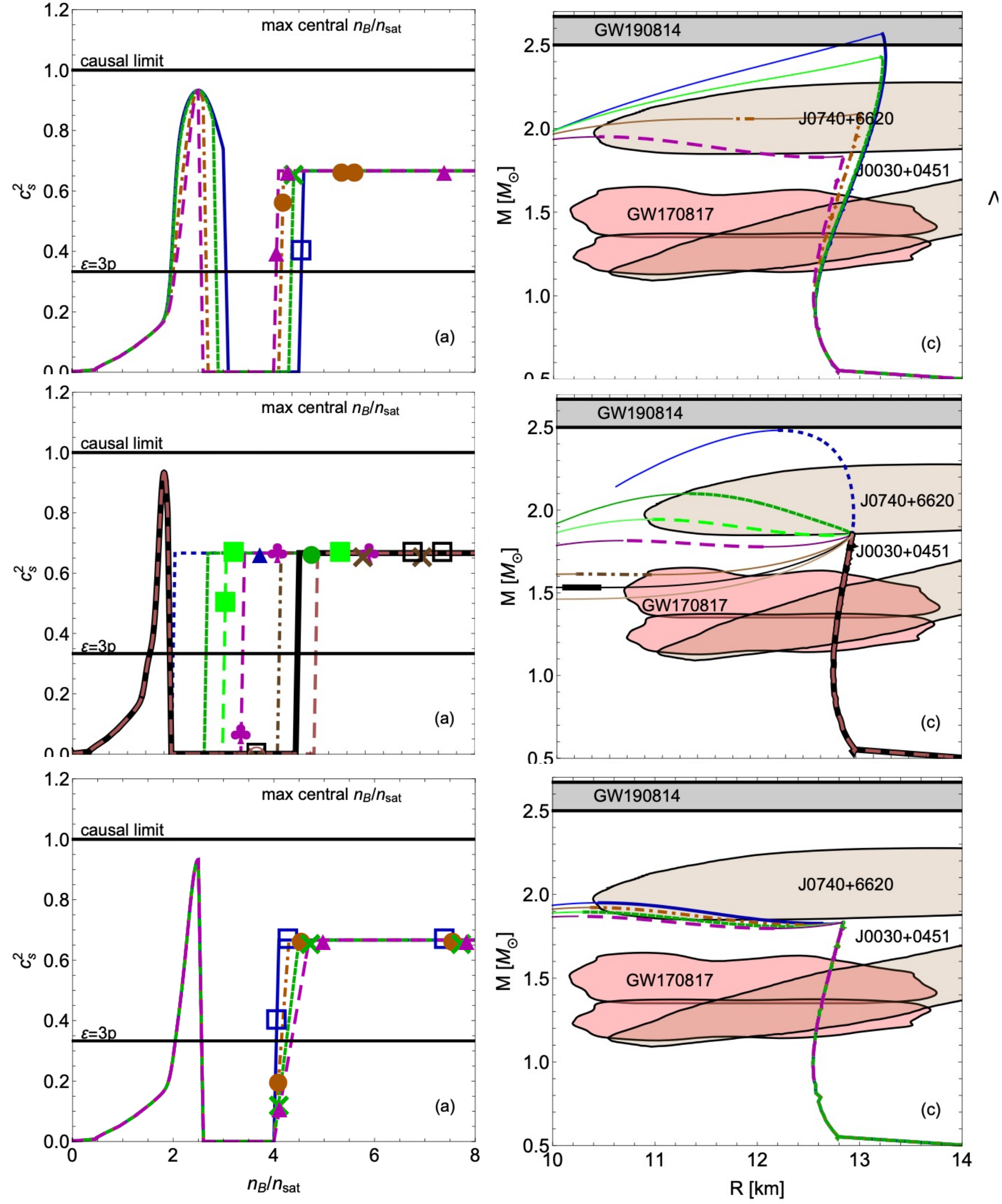
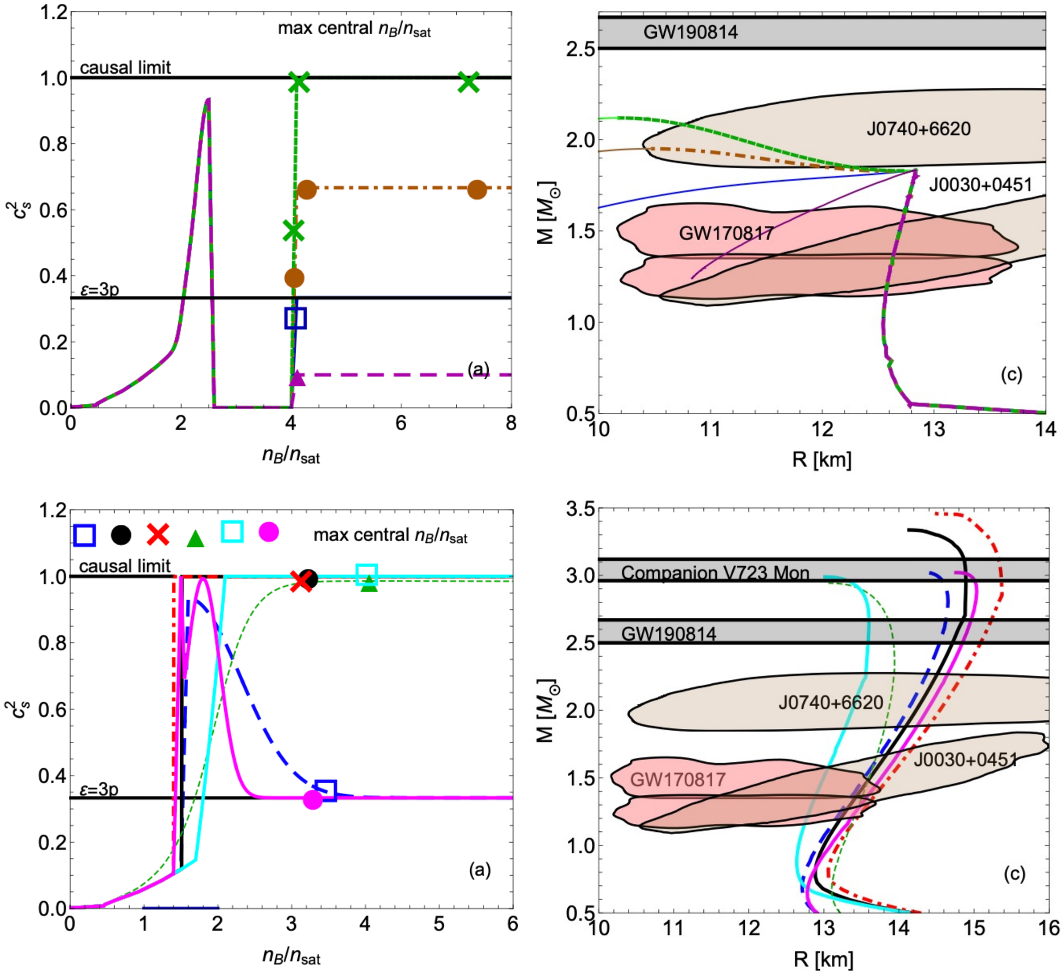


High-density limit

- ✶ There are many degeneracies
- ✶ But high-density behavior could be determined by large mass, small radius measurement
- ✶ $M \geq 2.91 \pm 0.08\ M_{Sun}$ implies $n_{cent} \lesssim 4\ n_{sat}$



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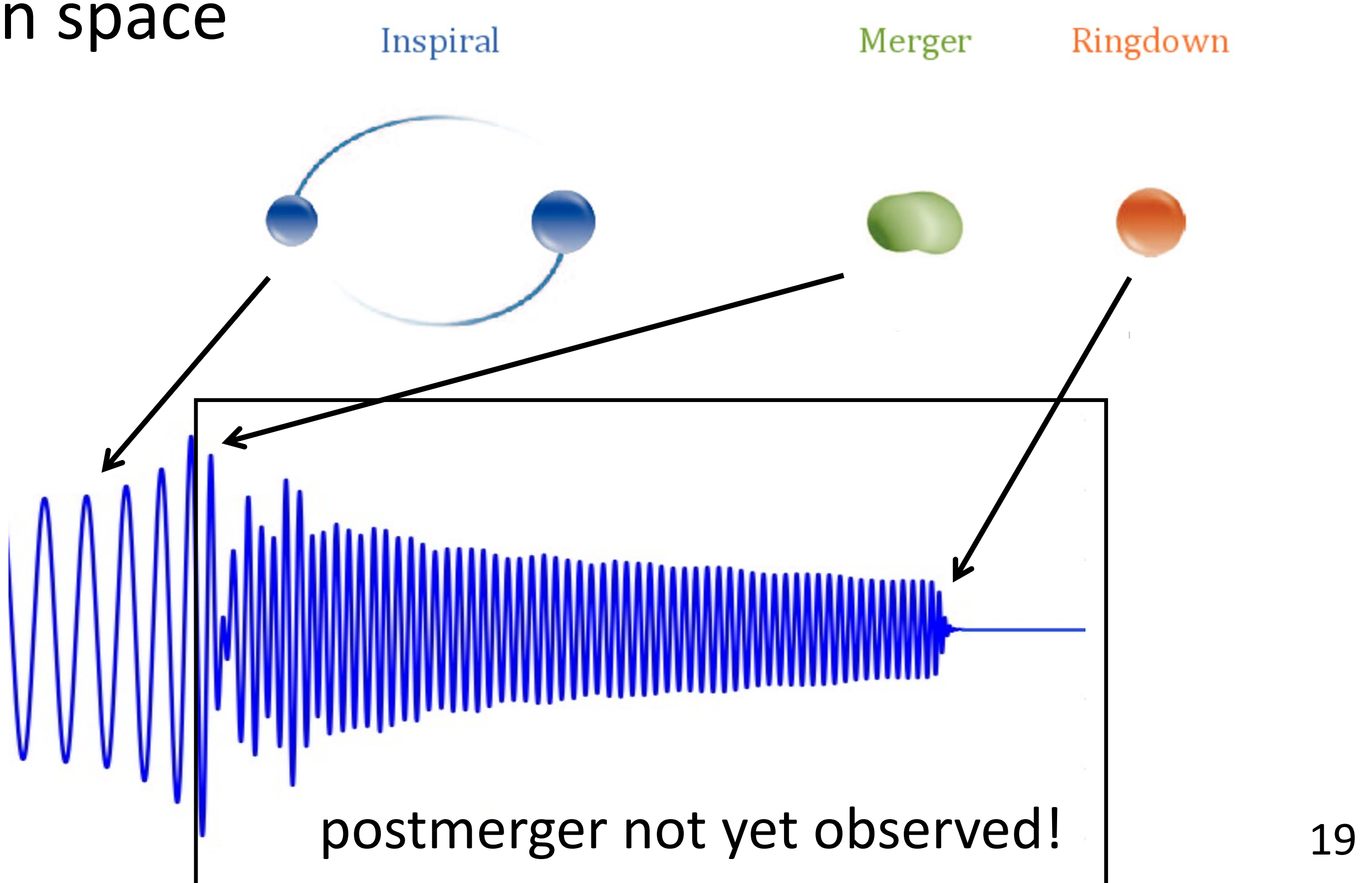
Neutron Star Merger 170817

- Observed by LIGO/VIRGO in 17 August 2017
- From galaxy NGC 4993 140 million light-years away
- Observed electromagnetically by 70 observatories on 7 continents and in space



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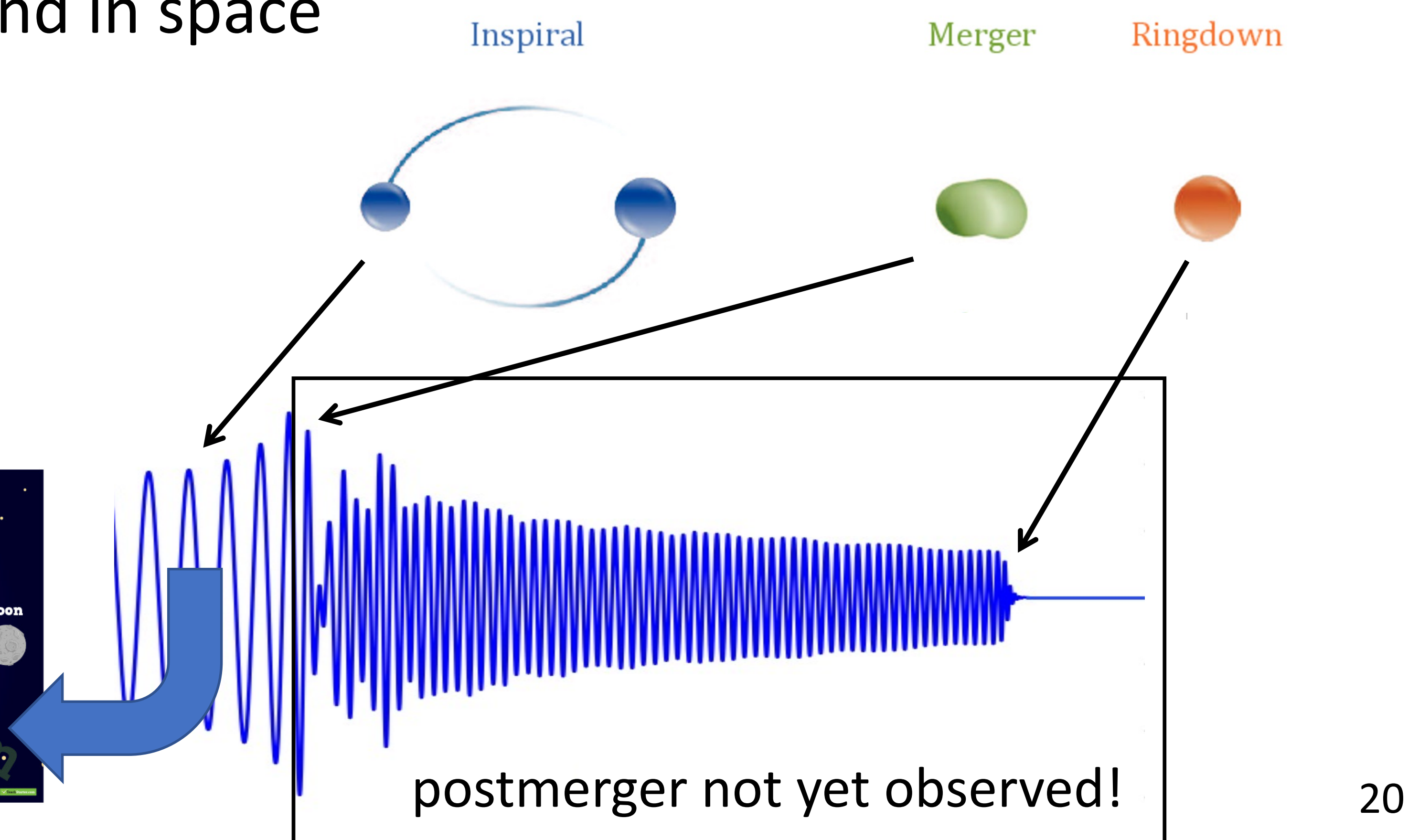
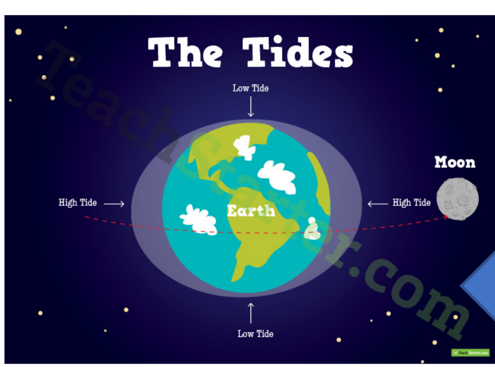
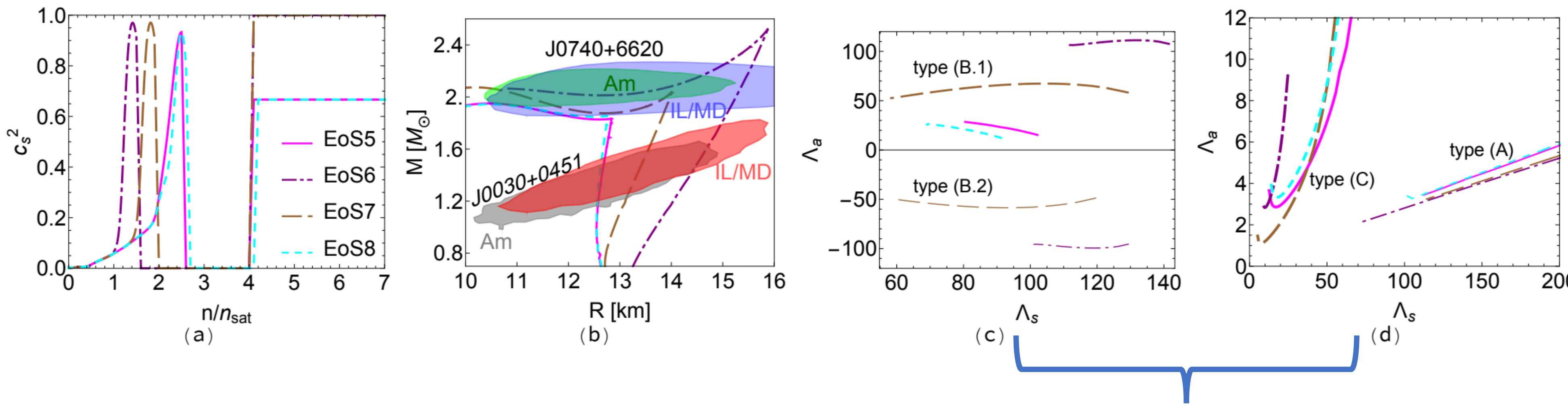




Tidal deformability

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



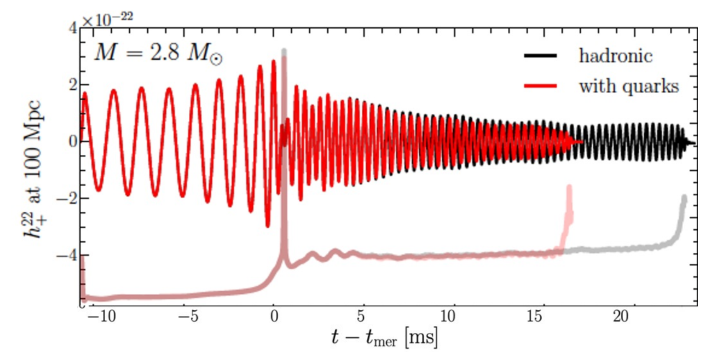
- ✶ Can create structure in the binary Love relations: slope, hill, drop, and swoosh

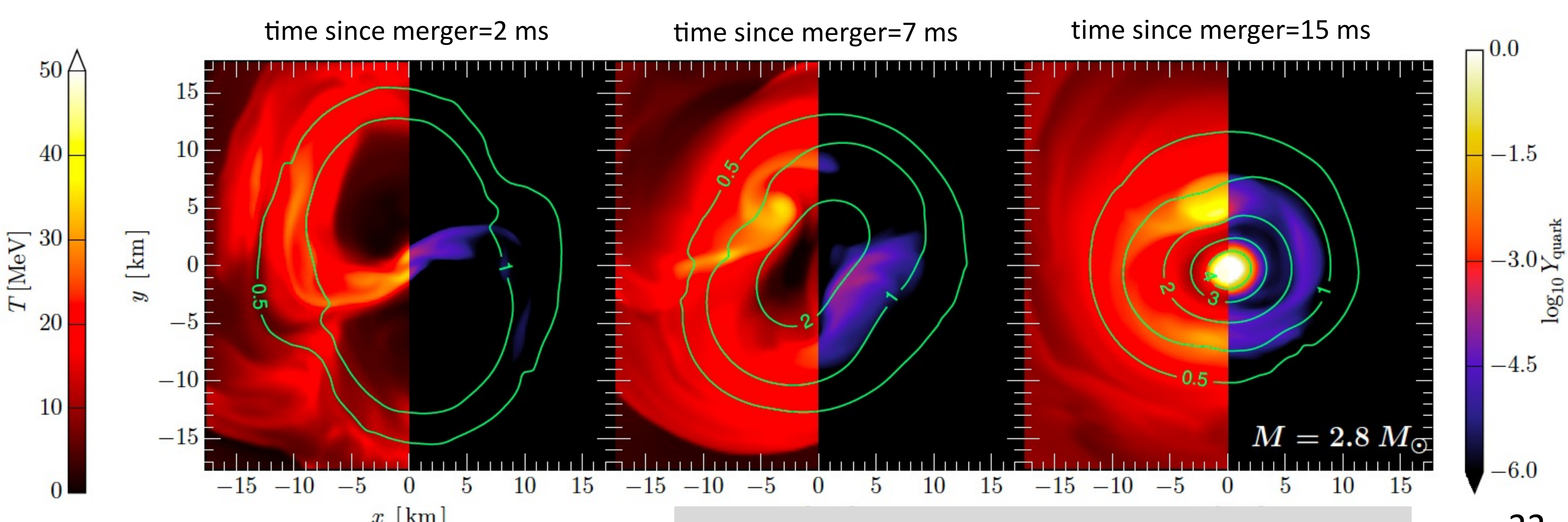
- ✶ Structure could be observed in near future

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

Neutron-star merger simulation

- 3D (T,n_B,Y_Q) CMF tables with 1st order phase transition
- Into coupled Einstein-hydrodynamics system (*Frankfurt/IllinoisGRMHD* code)
- Hot ring forms first, then a very hot region in the center with quarks

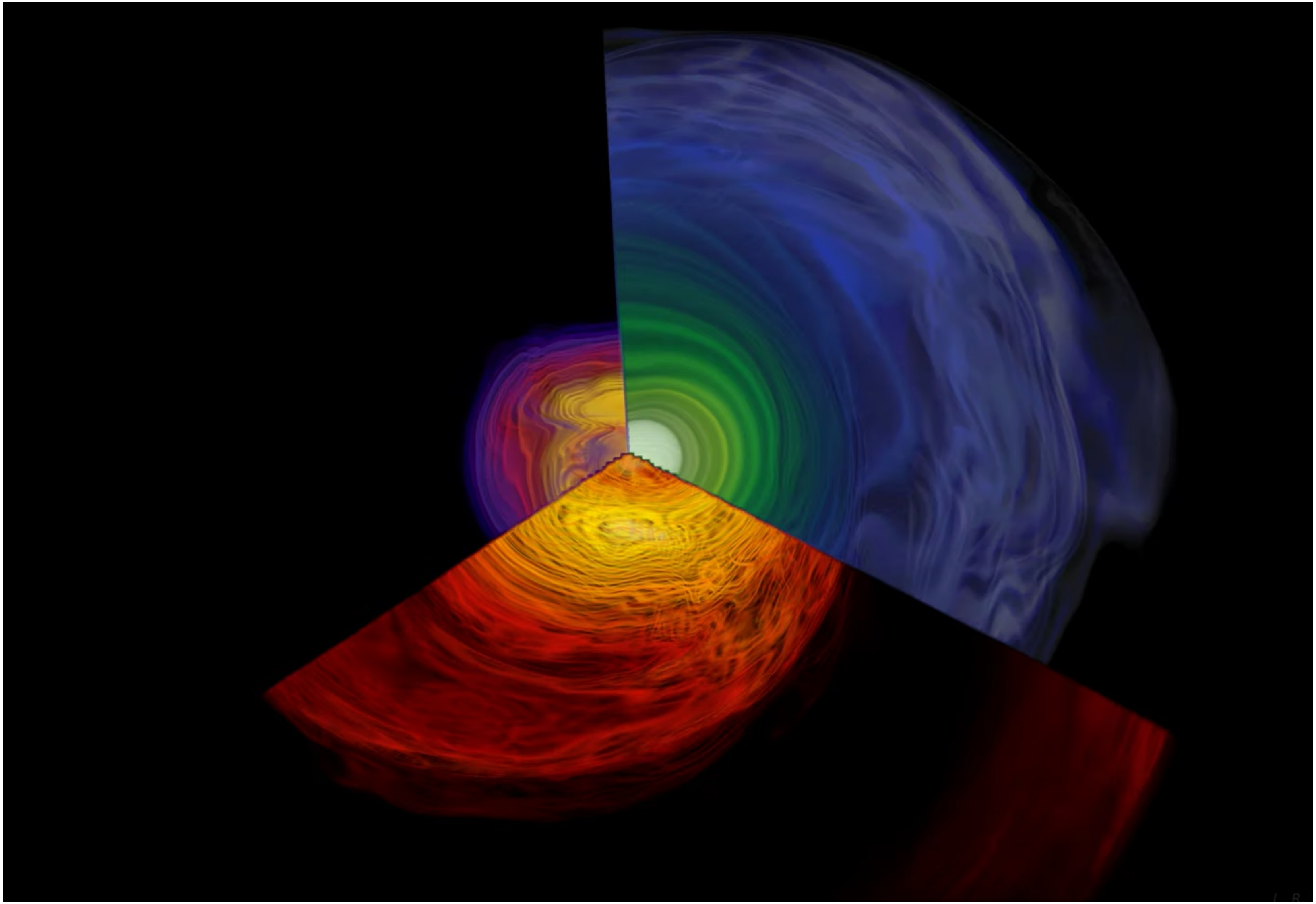




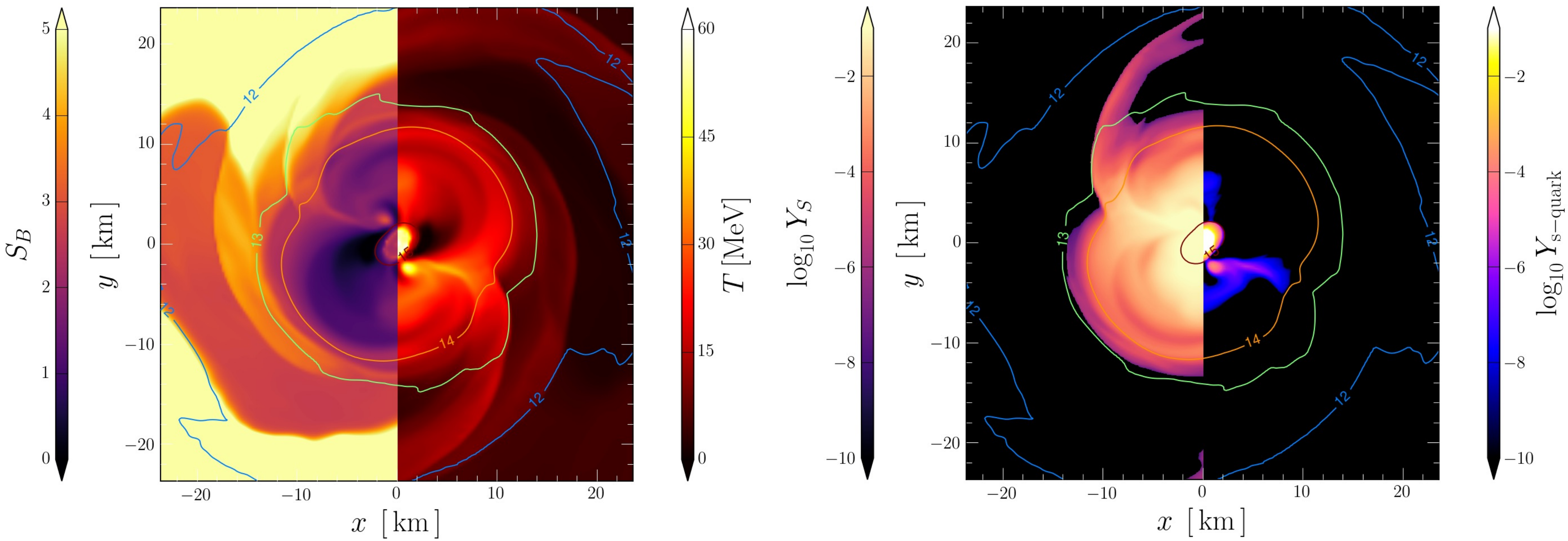
PRL 122 (2019) 6, 061101 e-Print: 1807.03684

Simulation

- [Our simulation (Youtube)](#) *PRL* 122 (2019) 6, 061101 e-Print: 1807.03684



Inside hypermassive neutron star



- ⋆ Increase of temperature, entropy per baryon, and s-quark fraction at phase transition

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

- ⋆ Total strangeness (hyperons ➜ s-quarks) remains the same

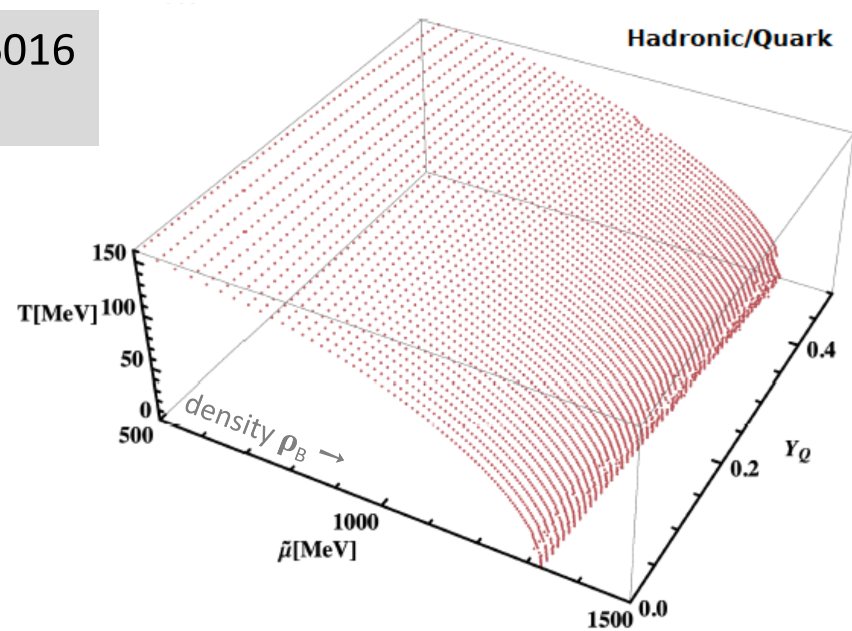
3D QCD phase diagrams (Y_S=0)

- 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



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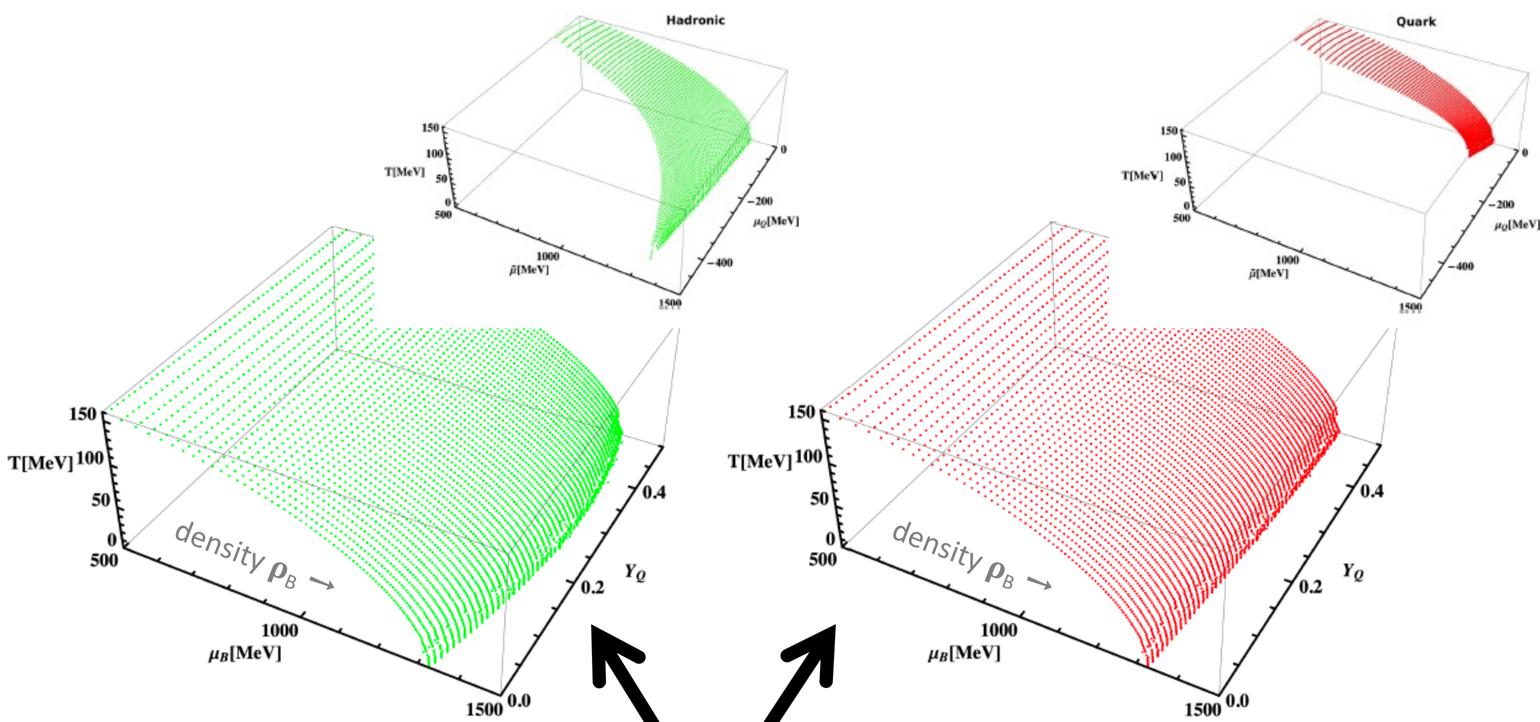
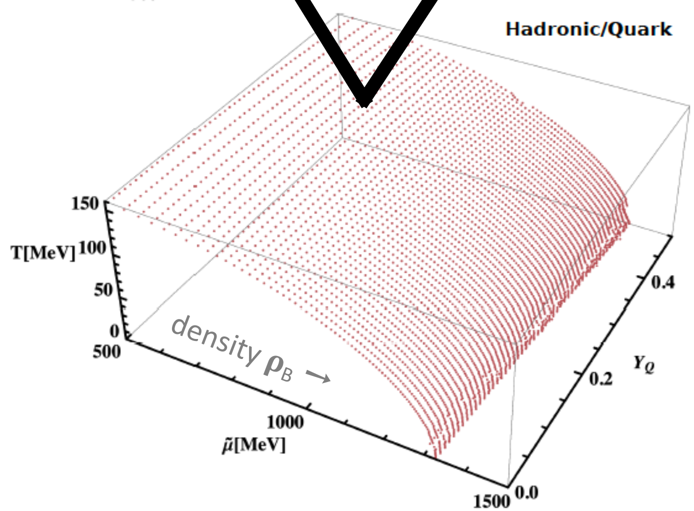




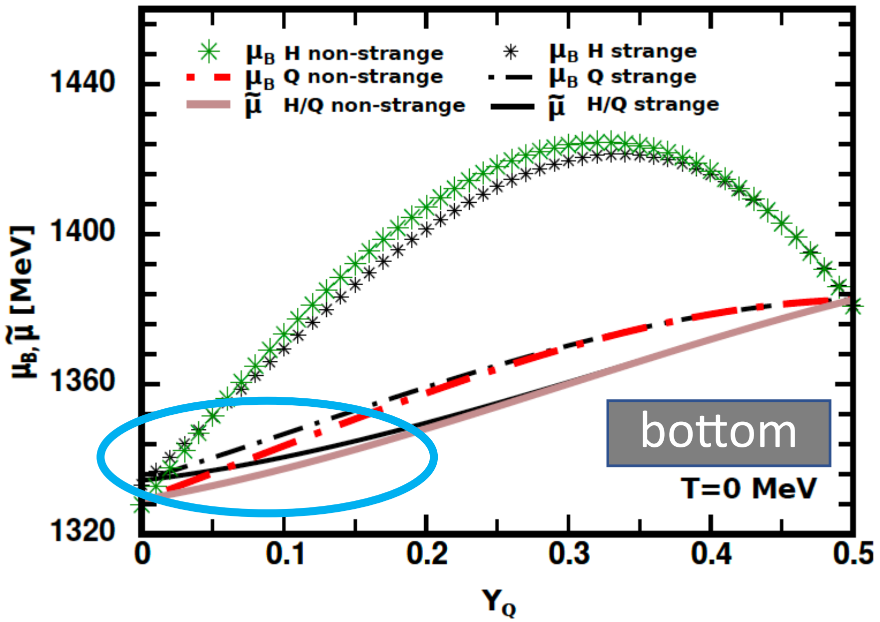
Gibbs free energy per baryon

$\widetilde{\mu} = \mu_B + Y_Q \mu_Q$

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

Slices of 3D QCD phase diagrams (Y_S=0, Y_S ≠/0 in black)

- For finite net strangeness $Y_S \neq 0$, deconfinement takes place at larger free energy/ baryon chemical potential



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

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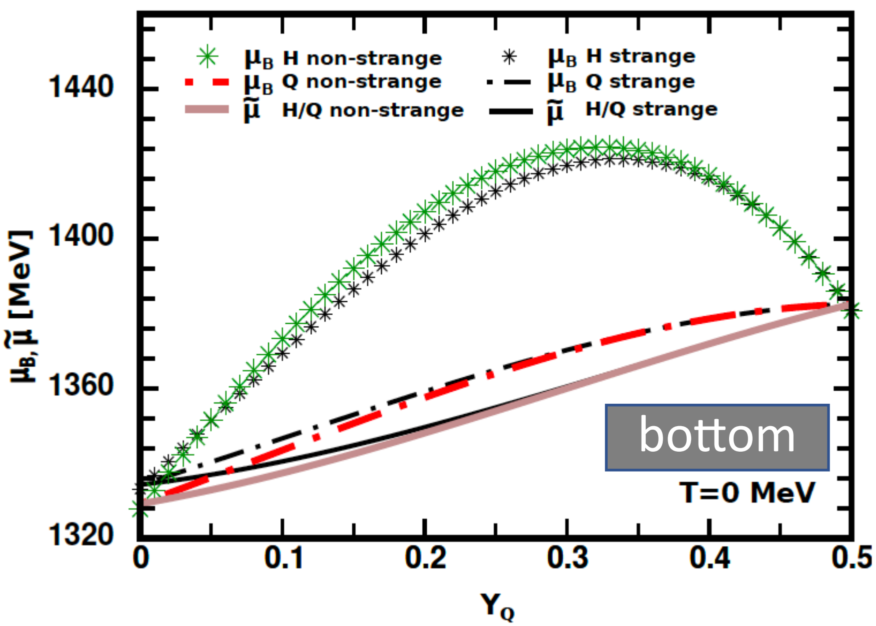
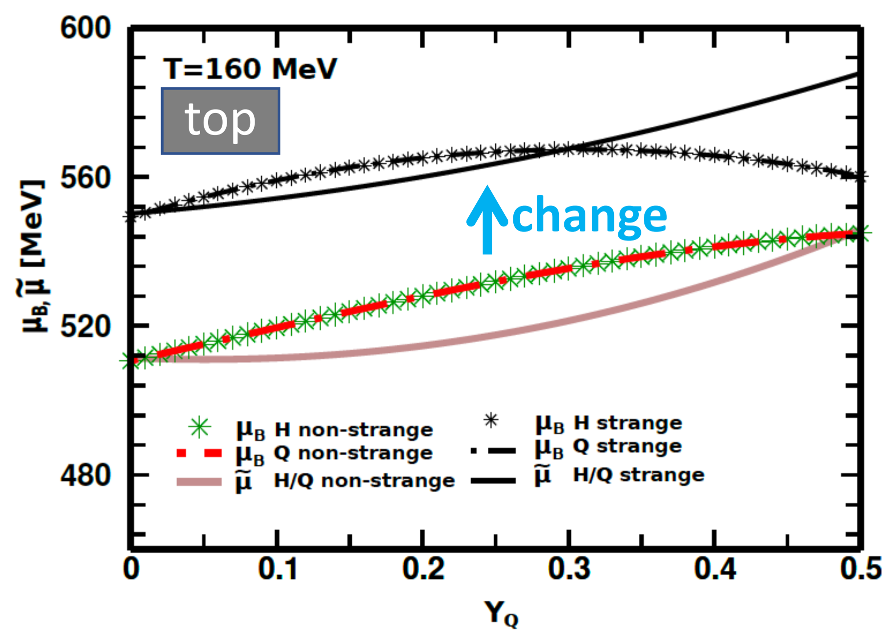
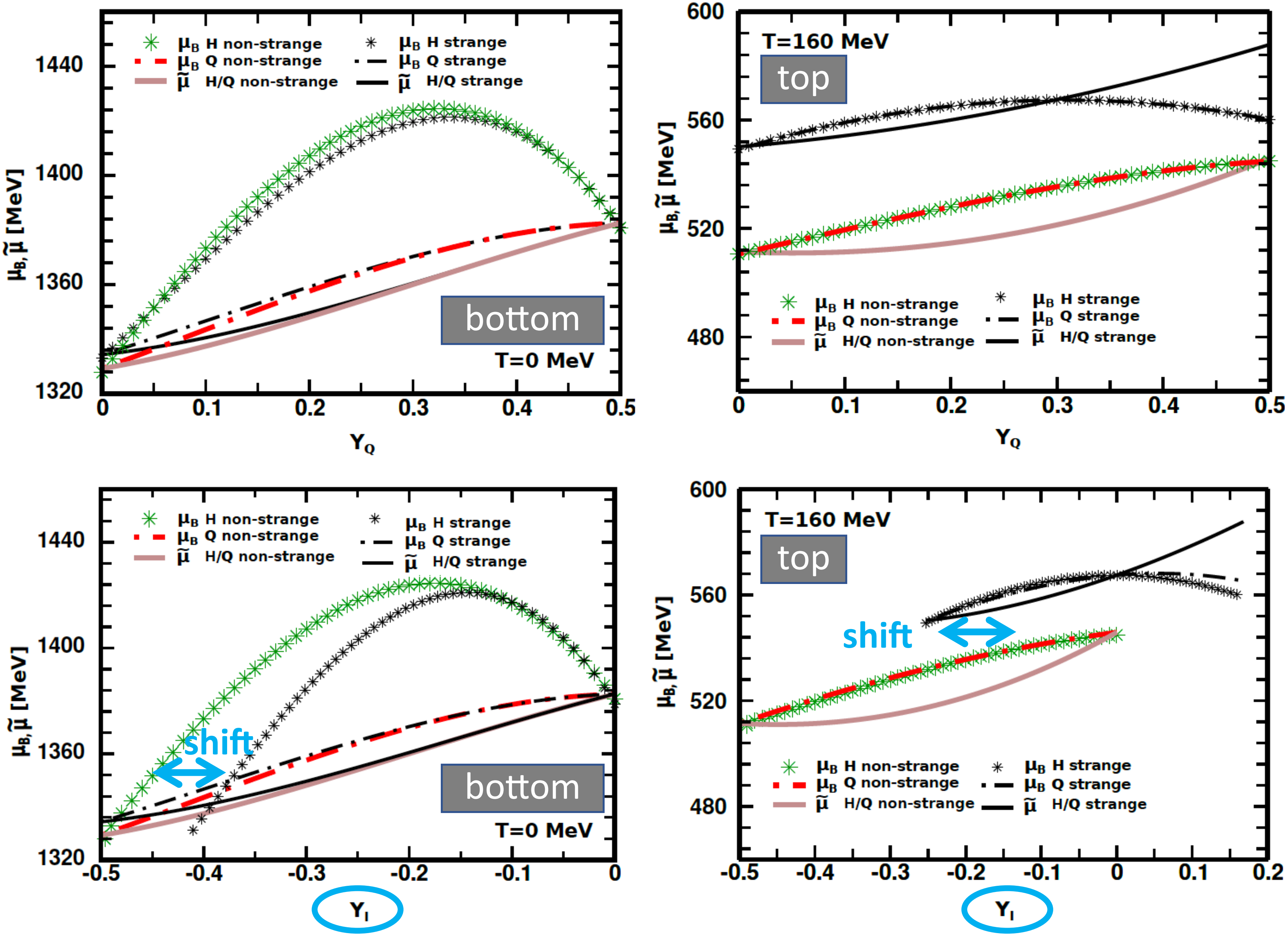




PRD 102 (2020) 7, 076016 e-Print: 2004.03039

- For finite net strangeness $Y_S \neq 0$, isospin and charge fraction relation is not trivial $Y_I = Y_Q - 0.5 + \frac{1}{2}Y_S$



Heavy-ion collisions

- ✶ CMF 3D EoS (n_B, T, Y_Q)

  Astron.Astrophys. 608 (2017) A110 e-Print: 1706.09191

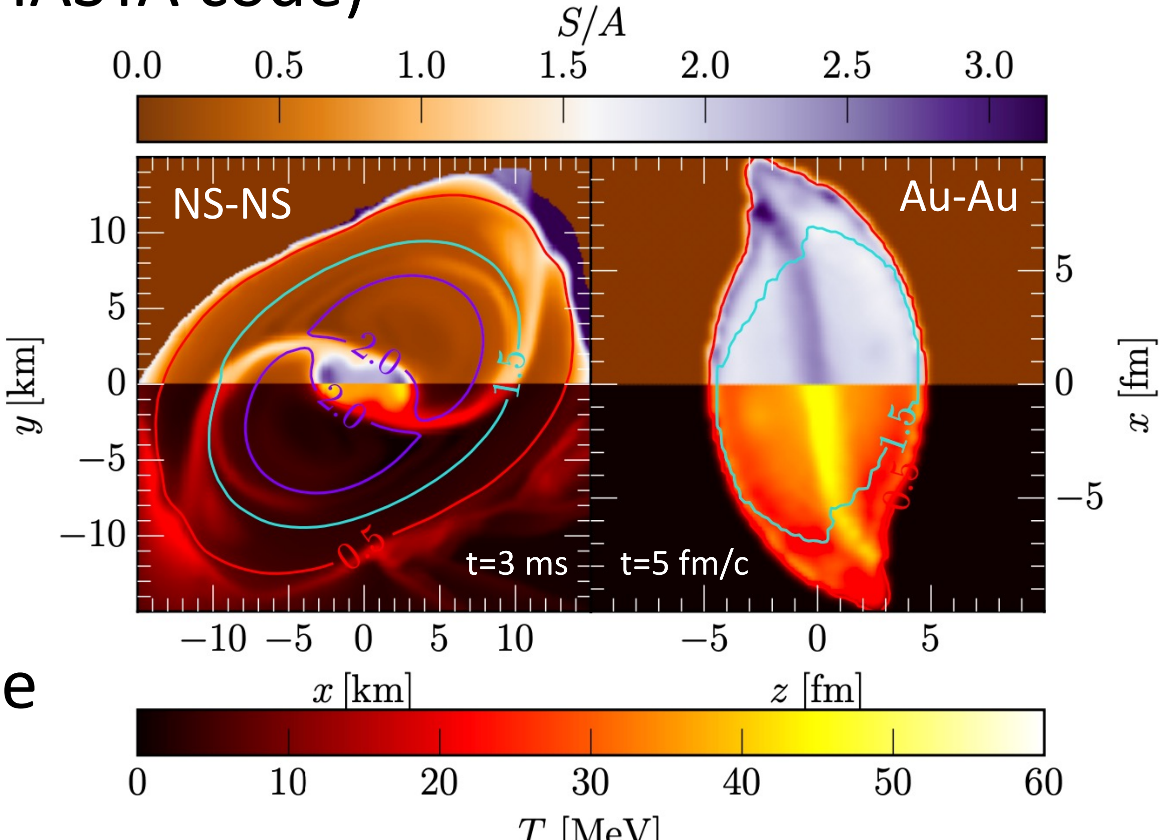
  e-Print: 2201.13150

  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)

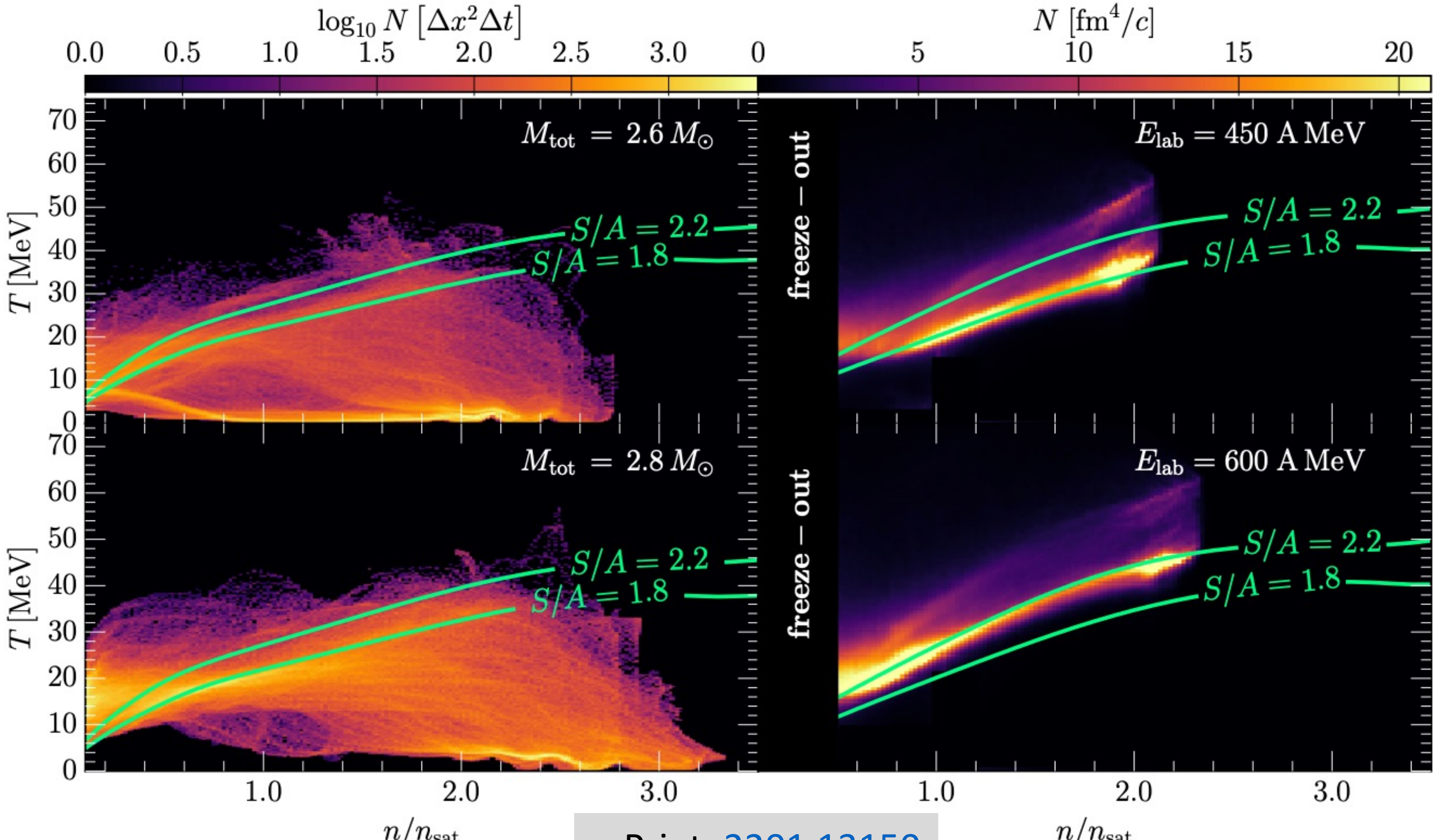
- ✶ Final merger mass of 2.9 M_{Sun} and low-energy collision with E_{lab} = 450 MeV

- ✶ Similar geometry and properties across 18 orders of magnitude



Comparison of phase diagrams

- Similar trajectories (other than stellar cold center and hot ring) allow connection of merger mass with lab energy



e-Print: [2201.13150](2201.13150)

Modern sources for EoS's

- CompOSE

  CompStar Online Supernovae Equations of State
  https://compose.obspm.fr
  (Stefan Typel, Micaela Oertel, Thomas Klaehn)

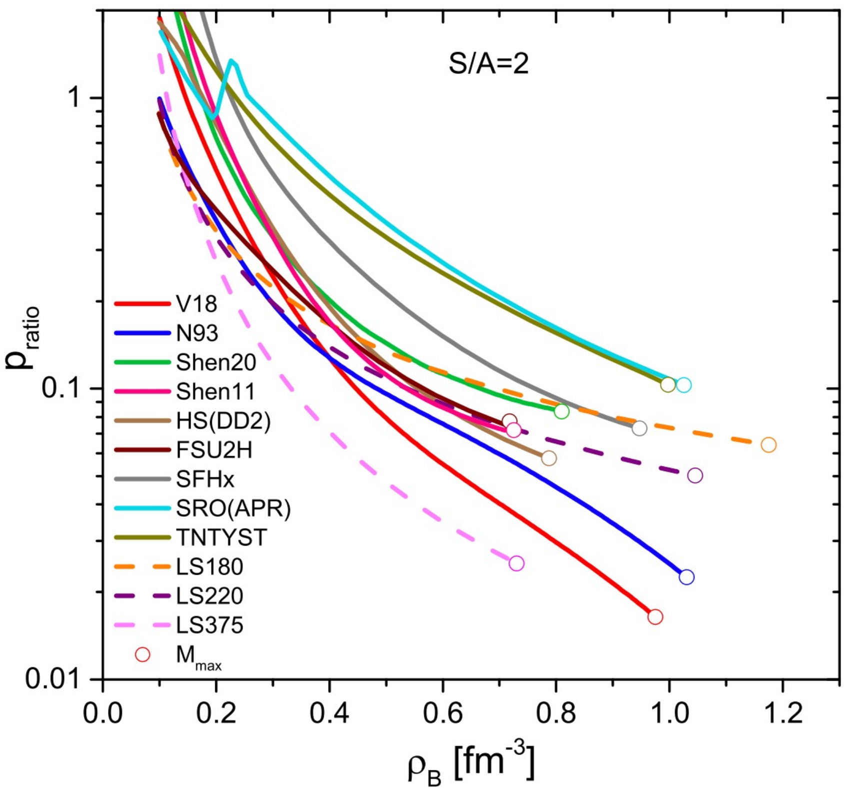
- Online service provides standardize 1D, 2D, 3D EoS tables for astrophysical applications

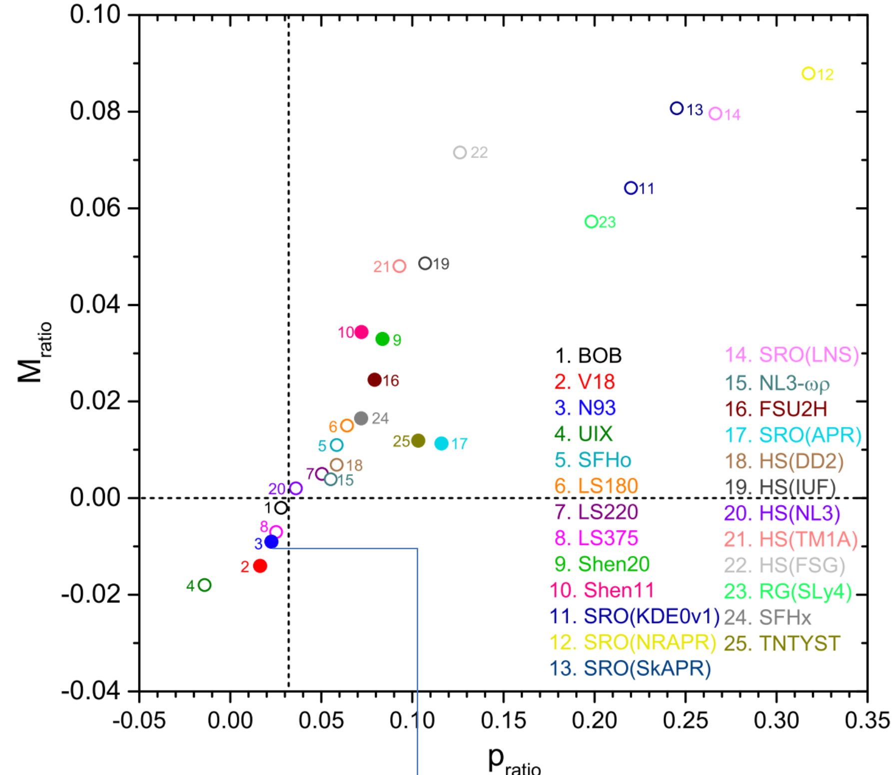
- Additional software to combine or interpolate data, calculate additional quantities, and graph EoS dependencies

- Instruction manual e-Print: 2203.03209
  with summarized providers quick guide and users quick guide

CompOSE

⋆ Example: young (hot) β-equilibrated stars





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

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

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

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

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

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 1^{st} 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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11. Toru Kojo; Central China Normal University
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Conclusions and outlook

- ✶ New tight constraints on neutron-star masses and radii can inform us about dense (T=0) neutron-star matter
- ✶ Neutron-star mergers create unique ideal conditions to achieve and detect new phases of matter
- ✶ EoS repositories help speeding up understanding of dense matter
- ✶ LIGO, Virgo, and KAGRA are coordinating O4 observing run in March 2023