Exotic Matter in Neutron Stars

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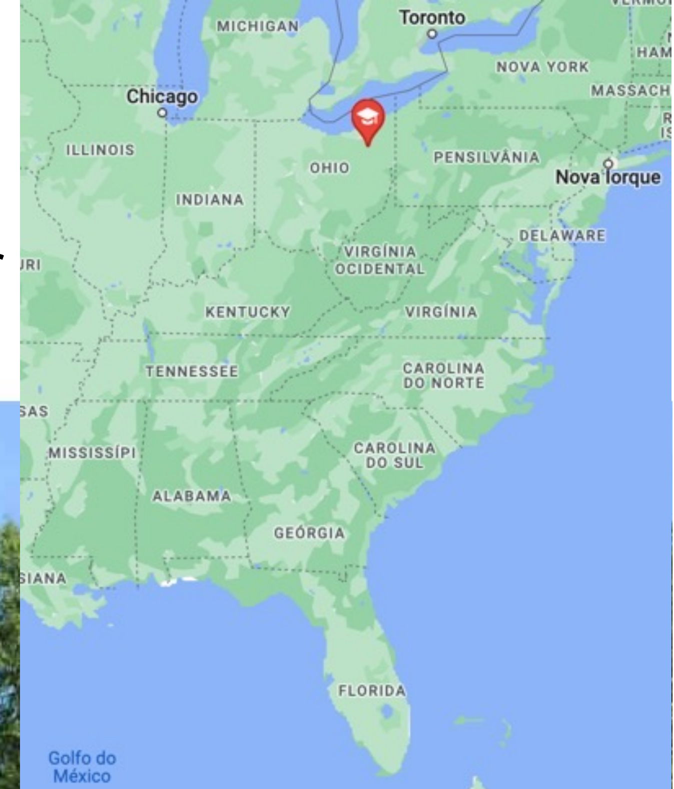
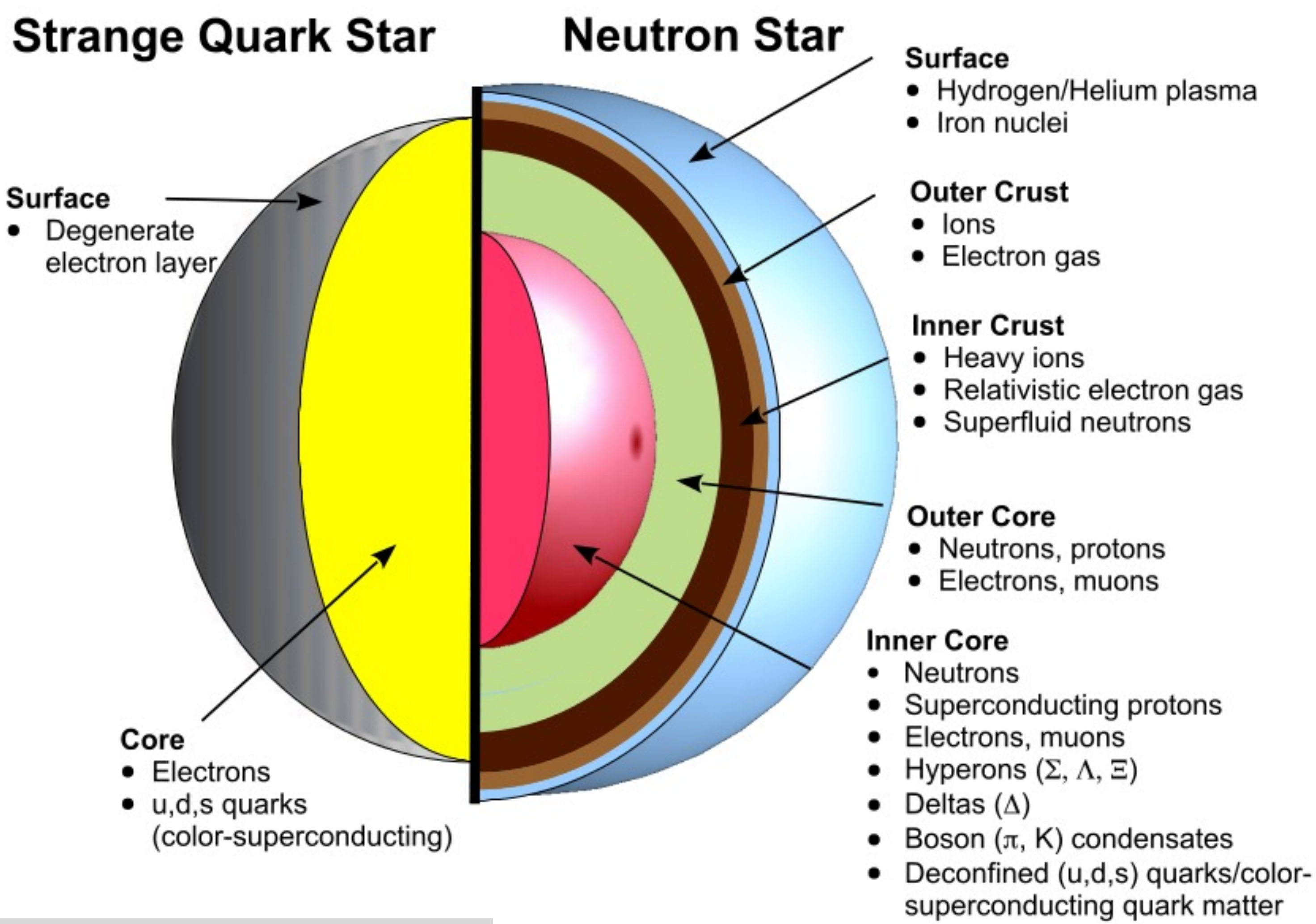


Overview

- ✶ 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

NS vs. Strange Quark Star structure



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

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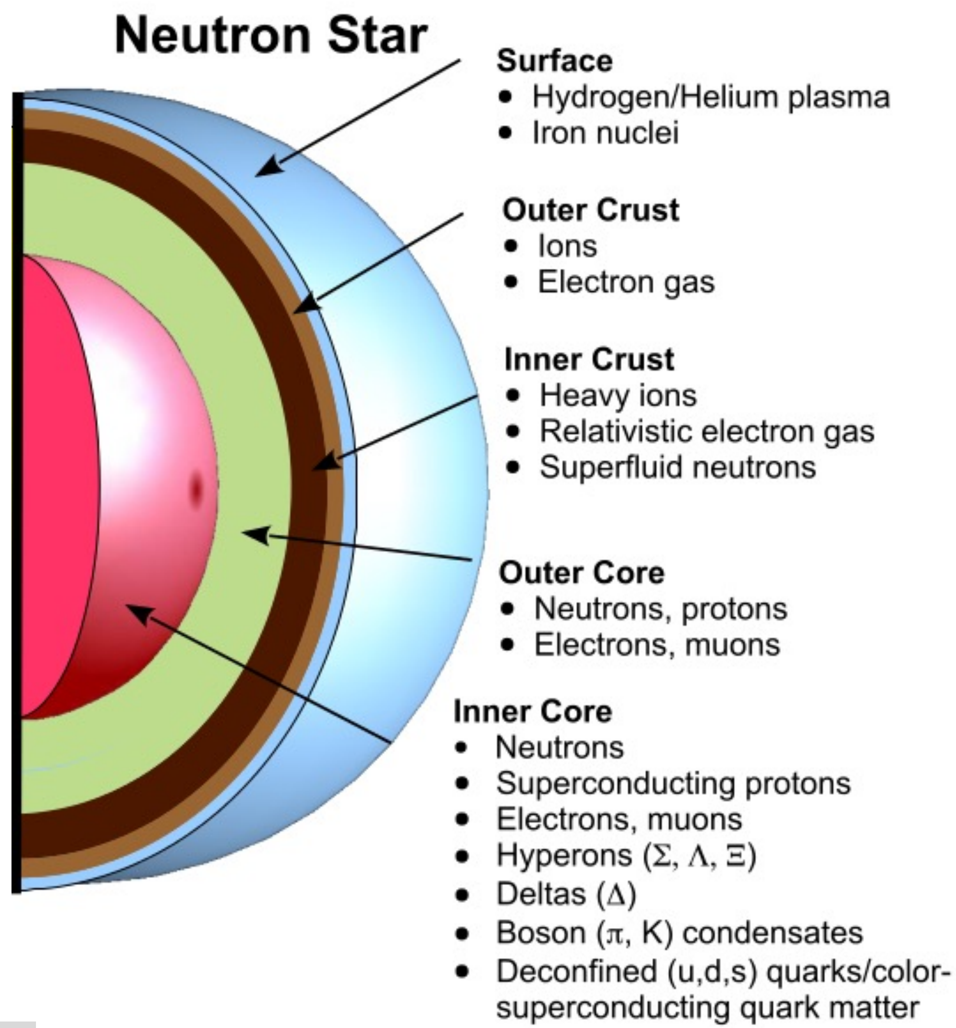

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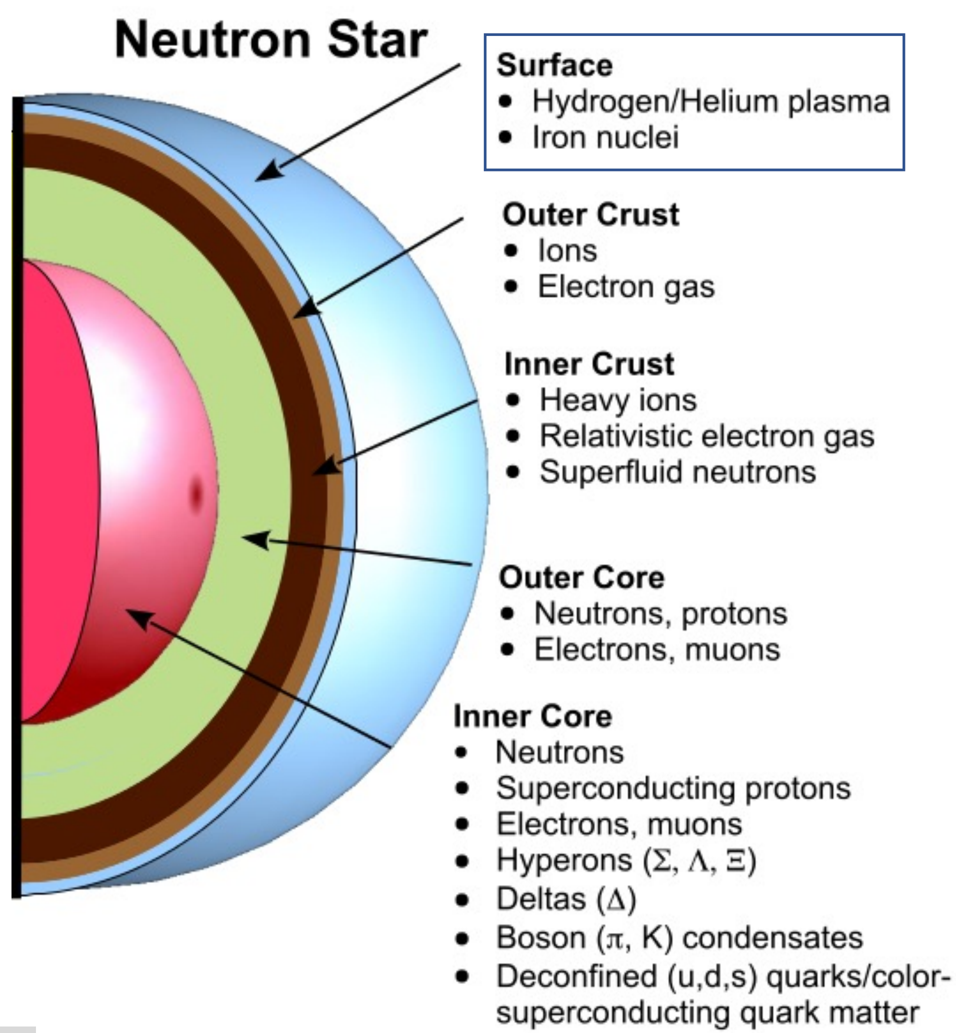

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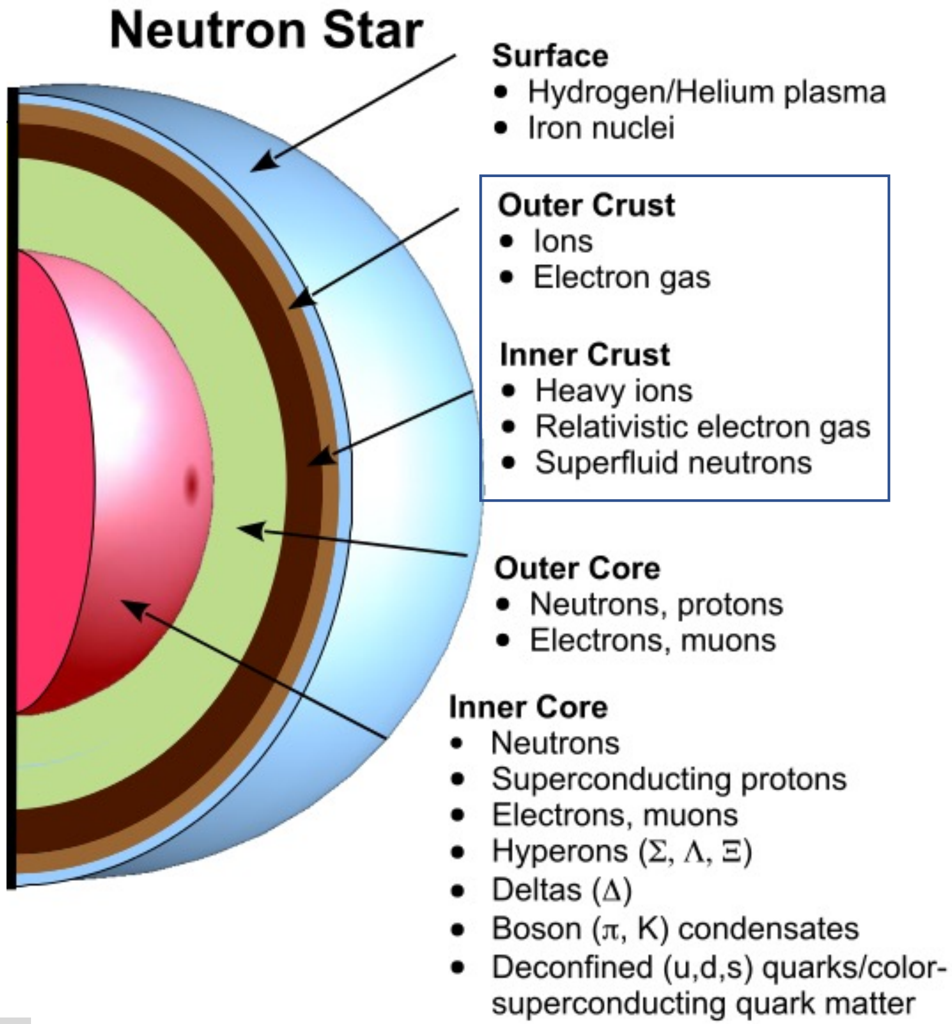

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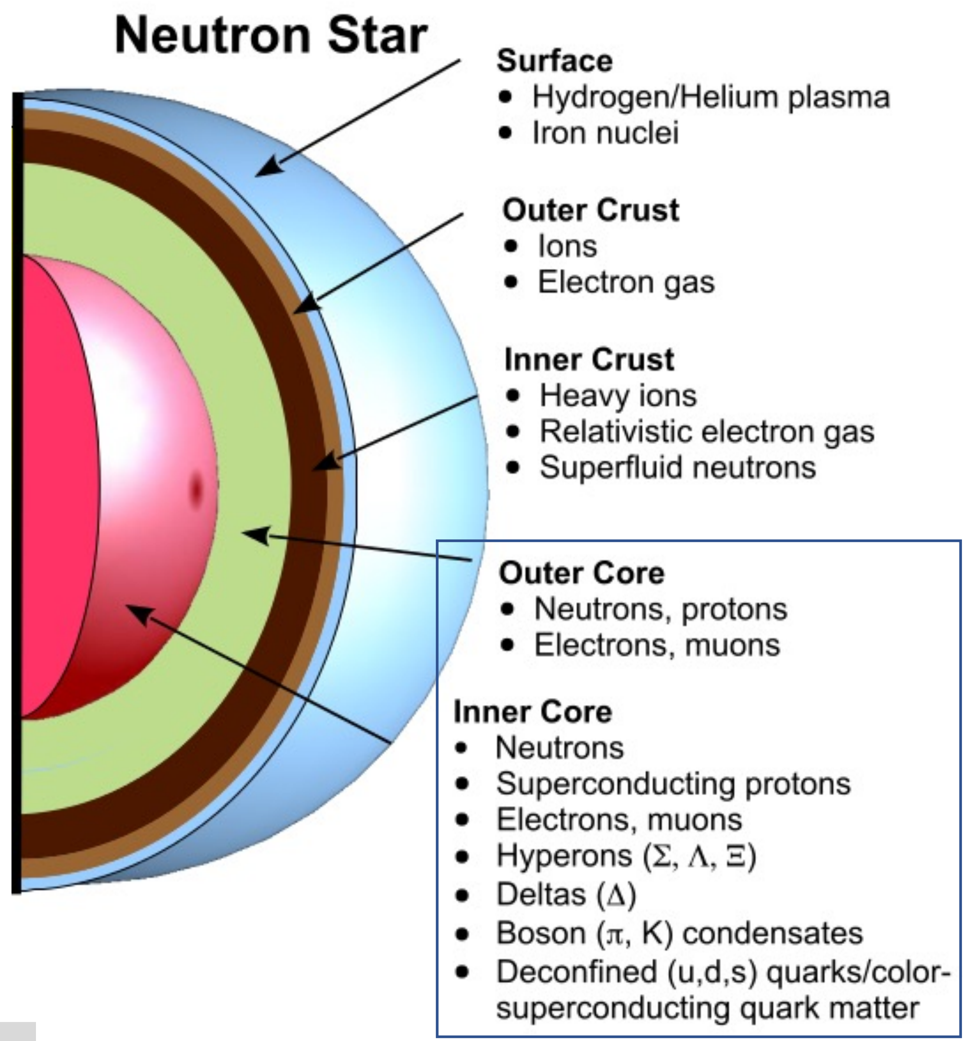

Mod.Phys.Lett.A 29 (2014) 1430022
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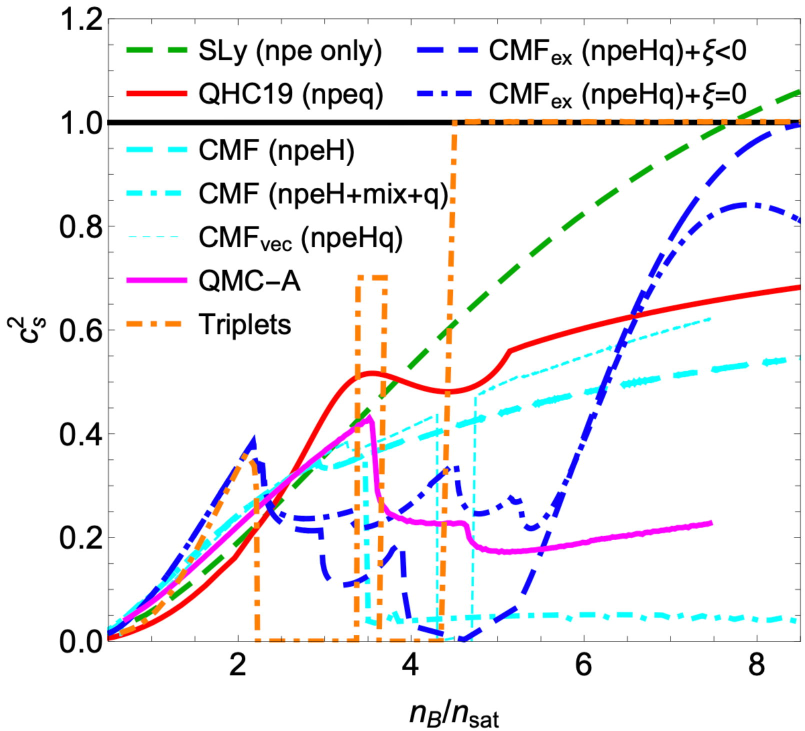
Neutron-star core composition

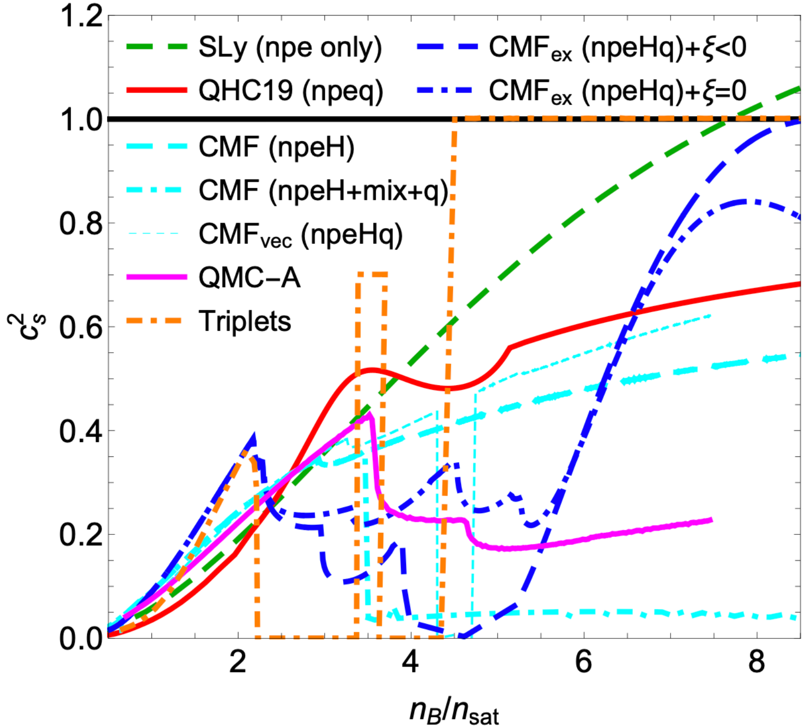
- Different exotic matter associated with different phase transitions
- Not noticeable in the EoS (P vs. ε), but easily seen in speed of sound ($dP/d\varepsilon$)

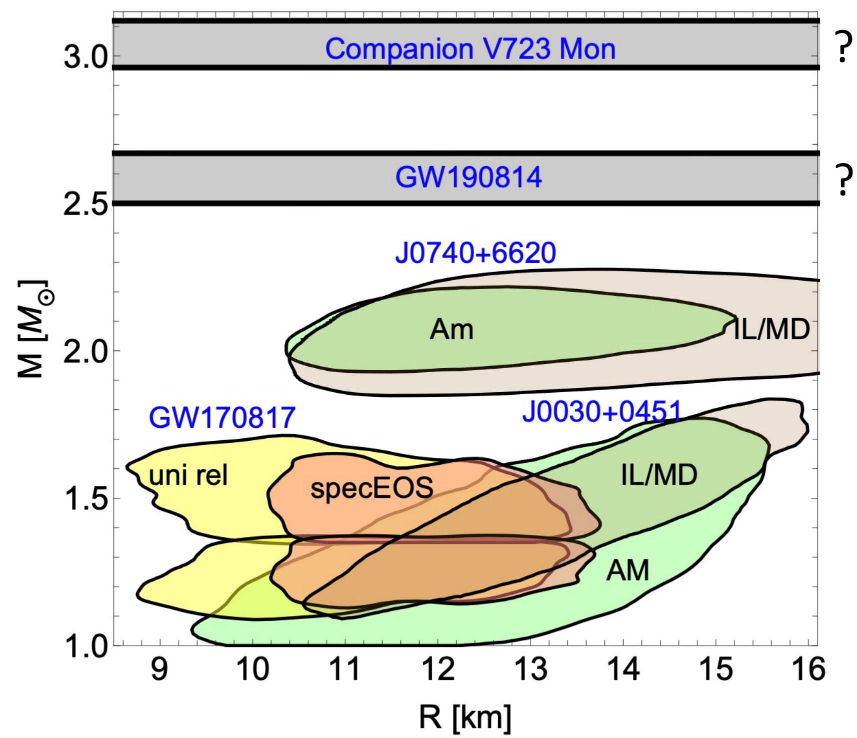


PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)

Neutron-star core composition

- ✶ Different exotic matter associated with different phase transitions
- ✶ Not noticeable in the EoS (P vs. ε), but easily seen in speed of sound (dP/dε) … and mass-radius?





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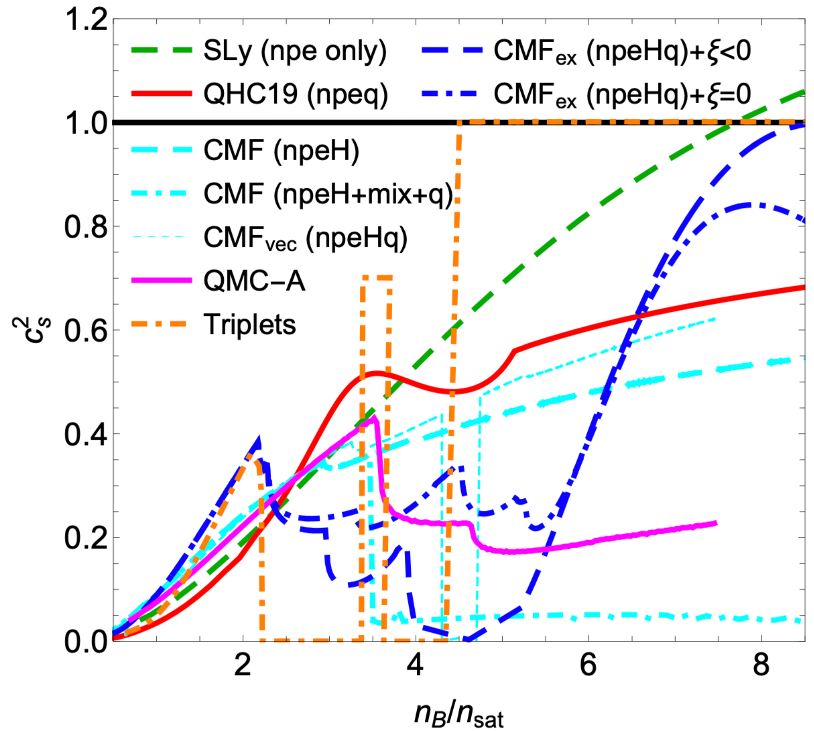

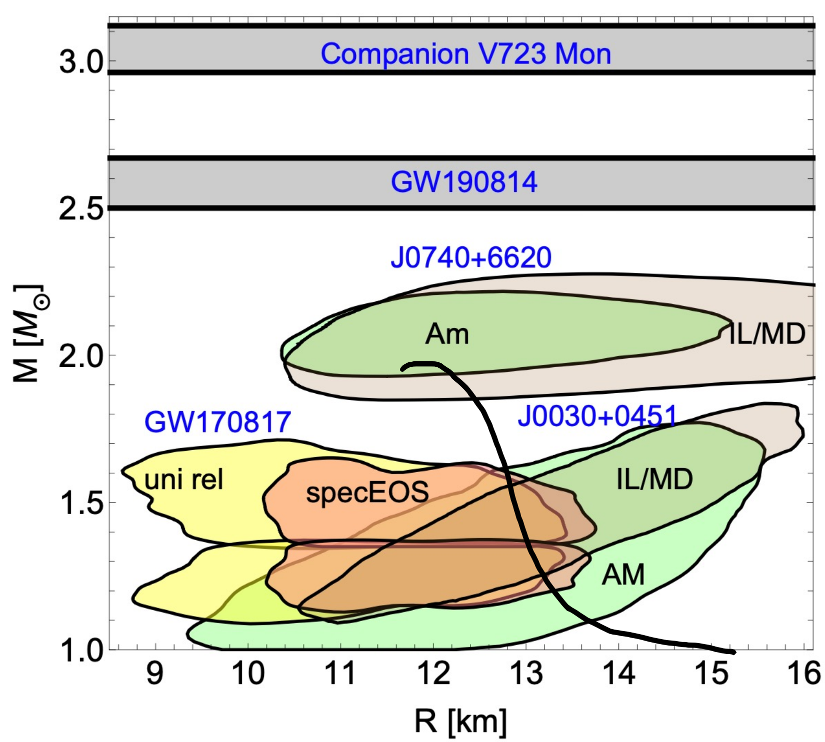

PRD 105 (2022) 2, 023018 e-Print: 2106.03890

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

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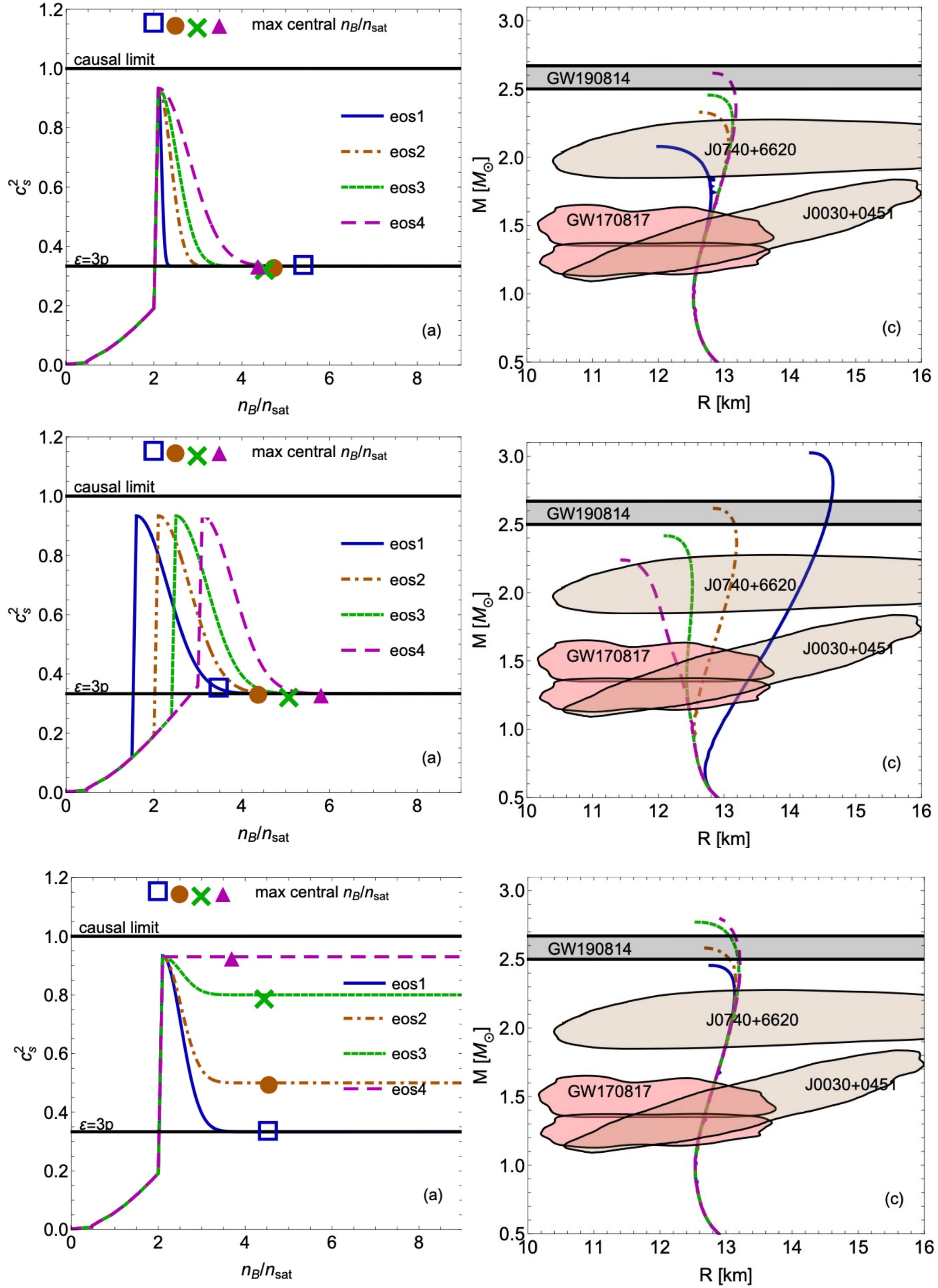
e-Print: [2106.03890](2106.03890)



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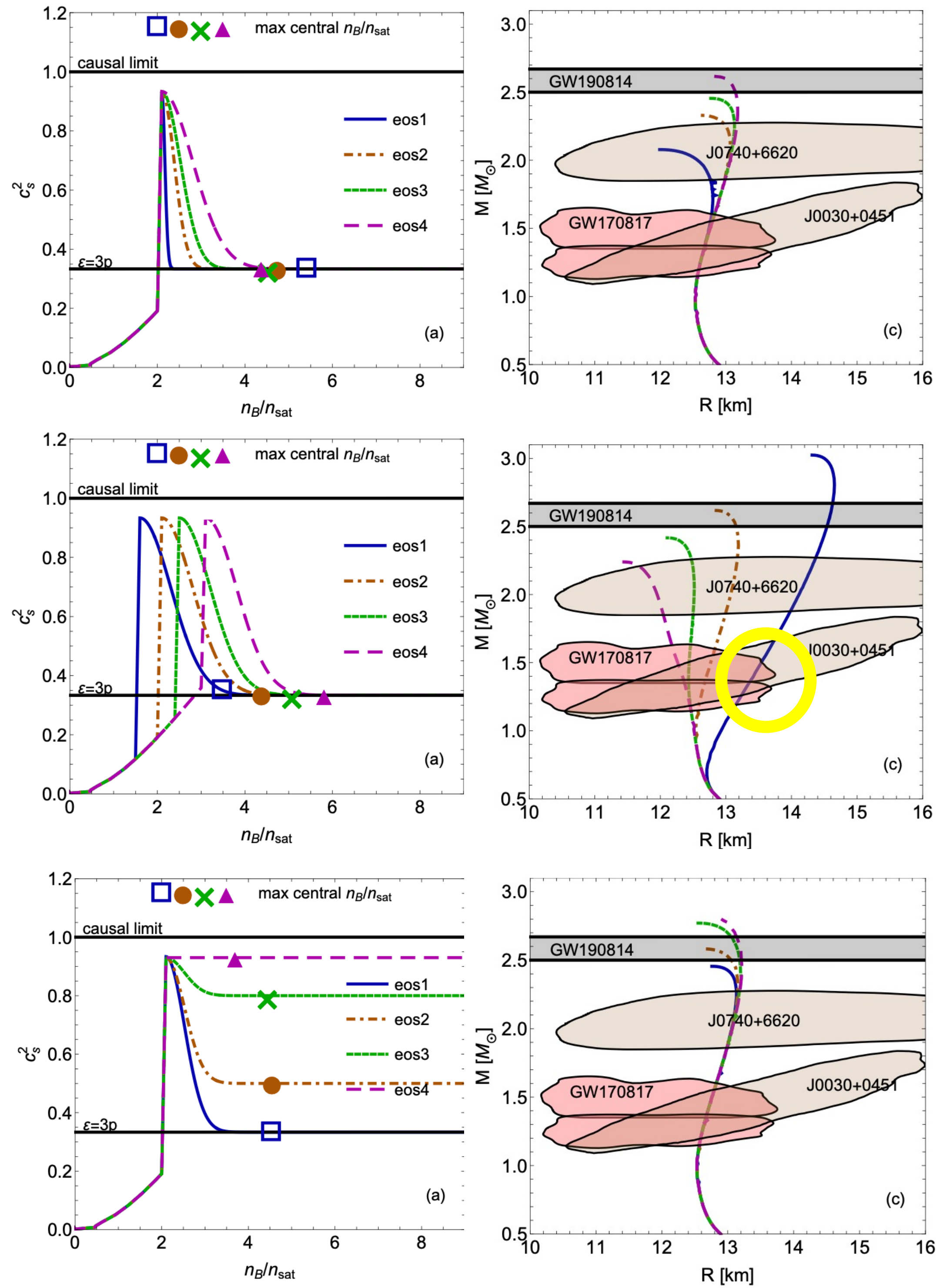
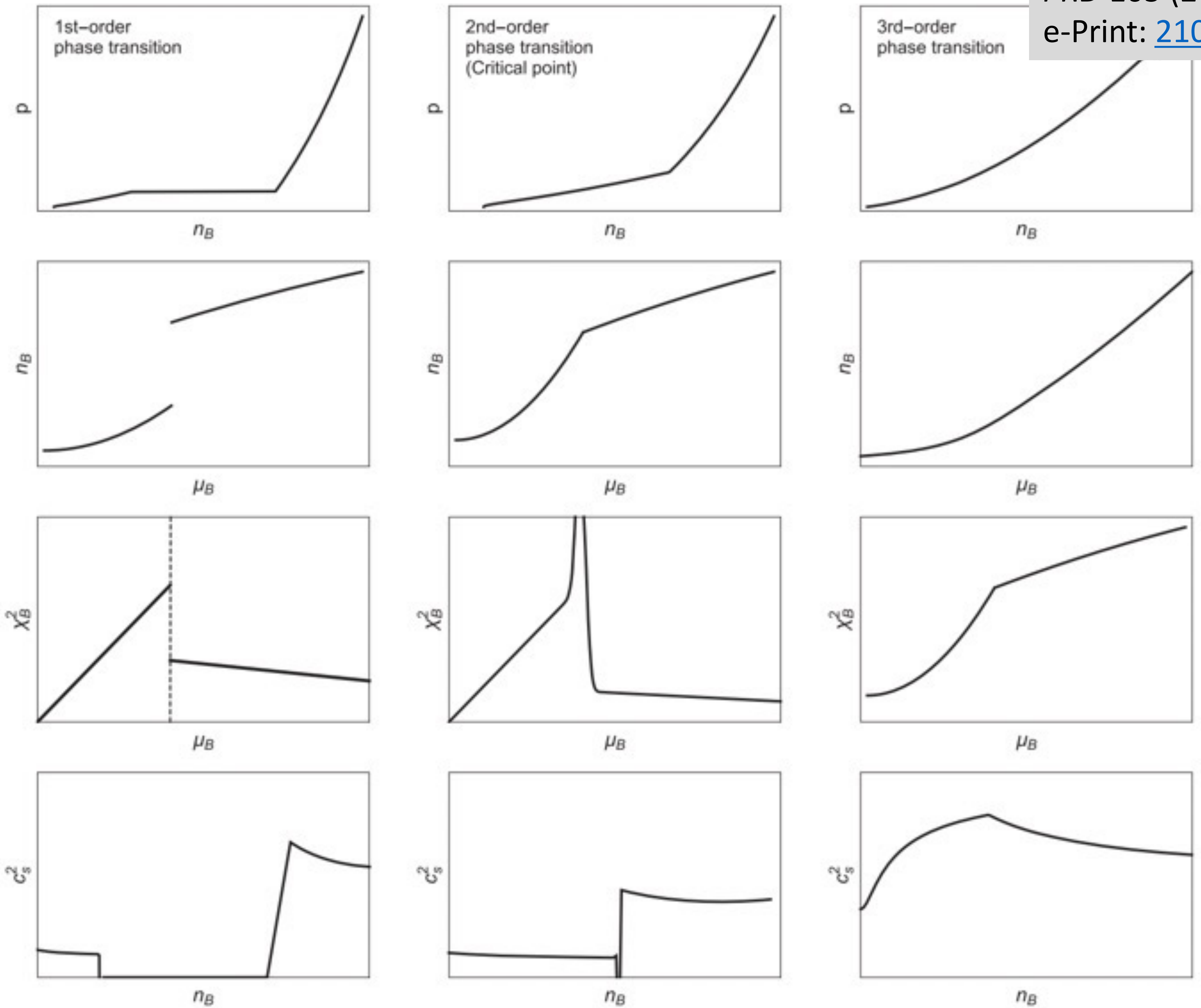


With 1st order phase transition



PRD 105 (2022) 2, 023018
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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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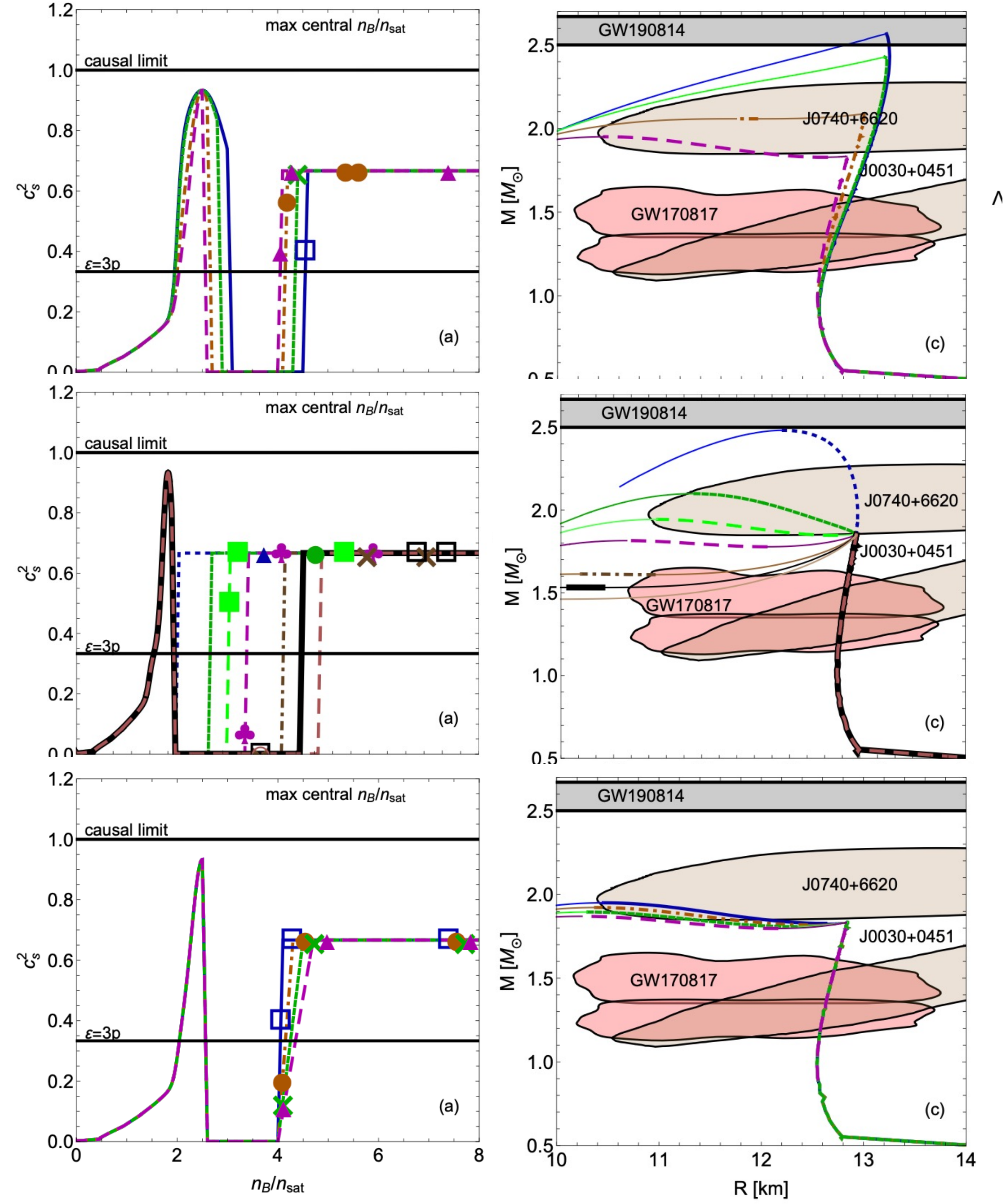
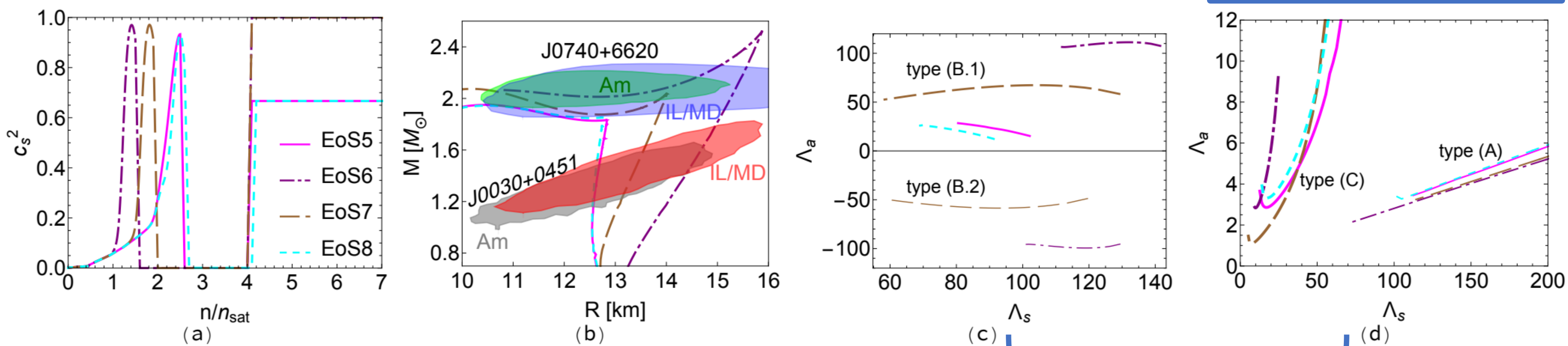


Tidal deformability

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

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



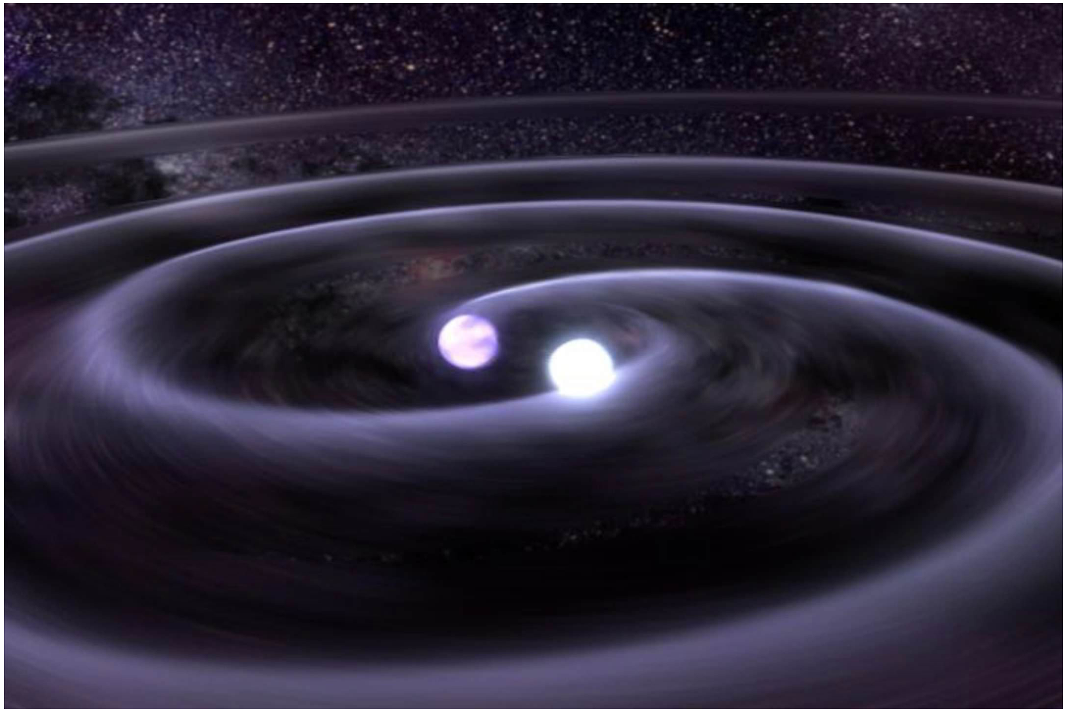
and can create structure in the binary Love relations: slope, hill, drop, and swoosh

- ✶ Structure could be observed in near future

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

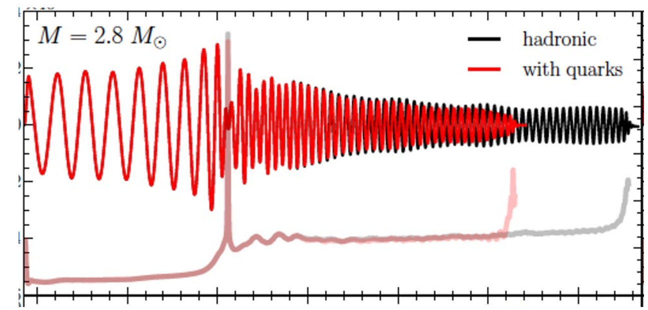
Comparison with other systems

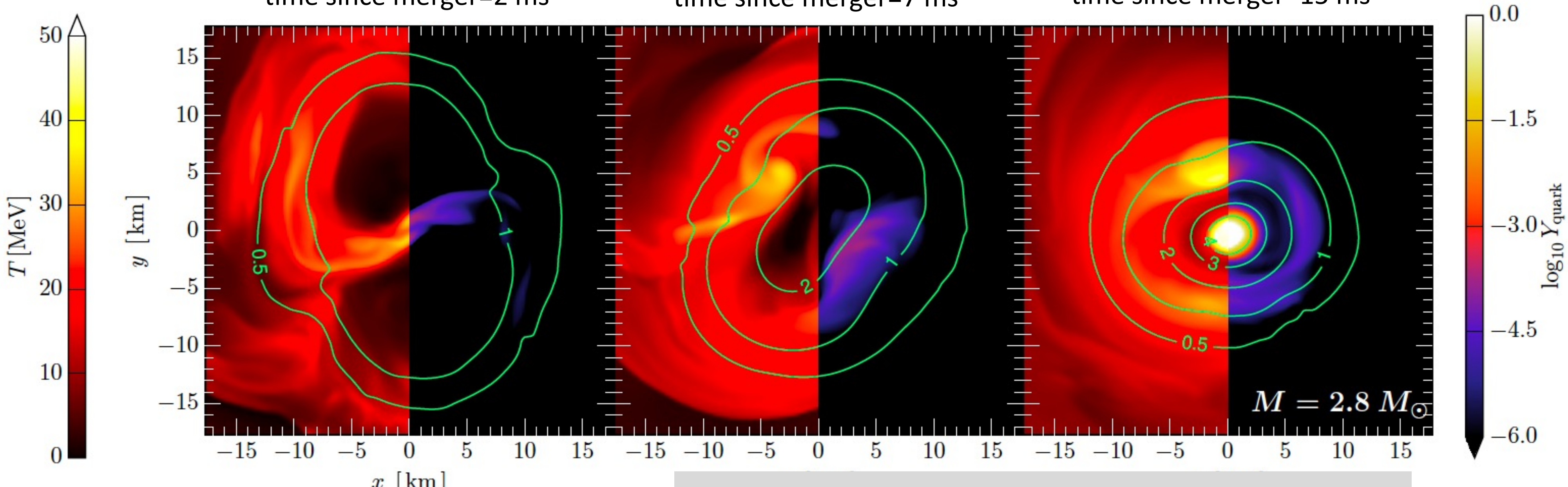
- Fully-evolved neutron-star cores: $Y_Q = Q/B = 0 \rightarrow 0.2$ (0.1)
- Heavy-ion collisions: $Y_Q = 0.4 \rightarrow 0.5$ (also have $Y_S = S/B = 0$)
- Supernovae explosions/proto-neutron stars: $Y_Q = 0.1 \rightarrow 0.5$ (0.4)
- Neutron-star mergers ?



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

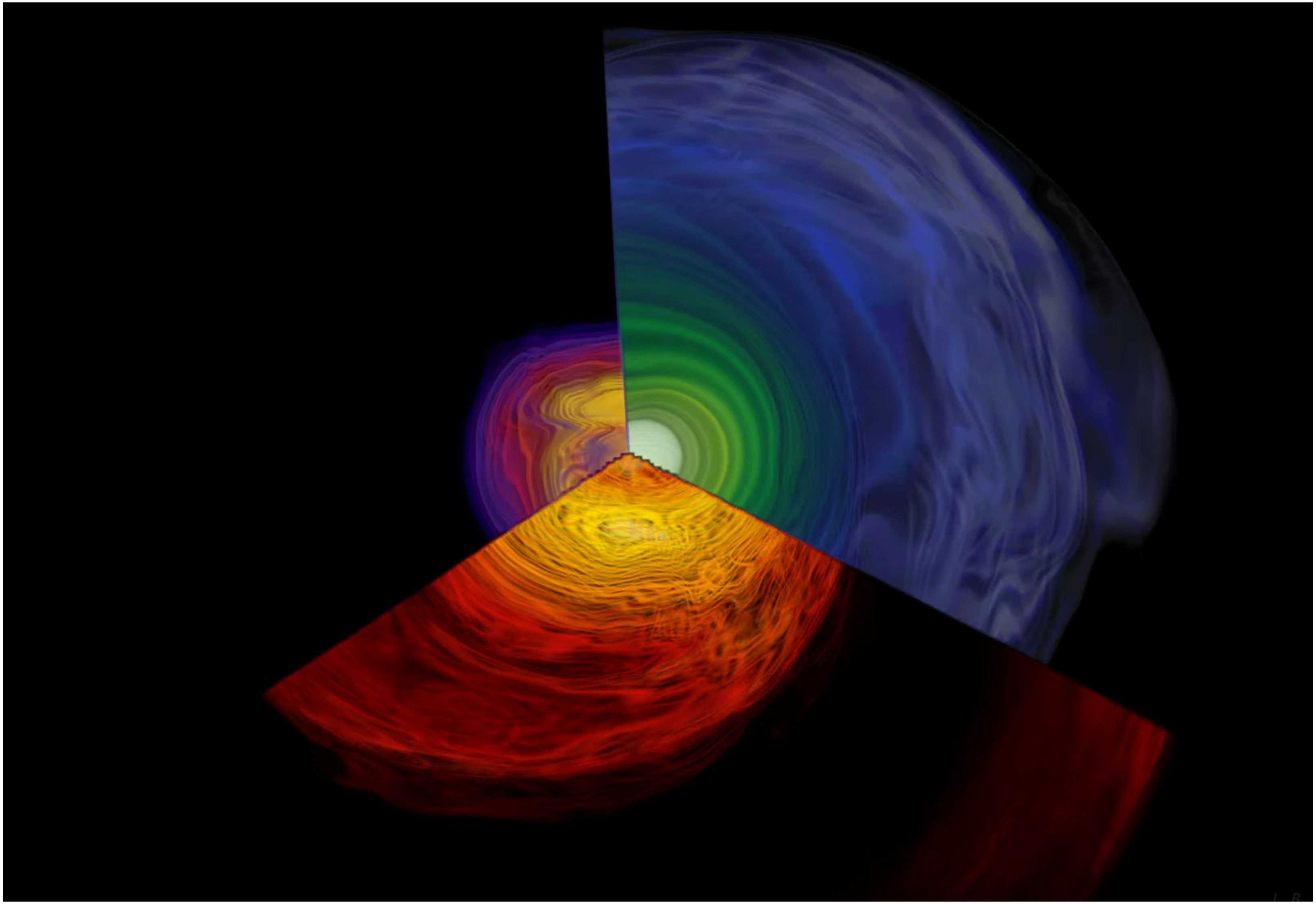




PRL 122 (2019) 6, 061101 e-Print: 1807.03684

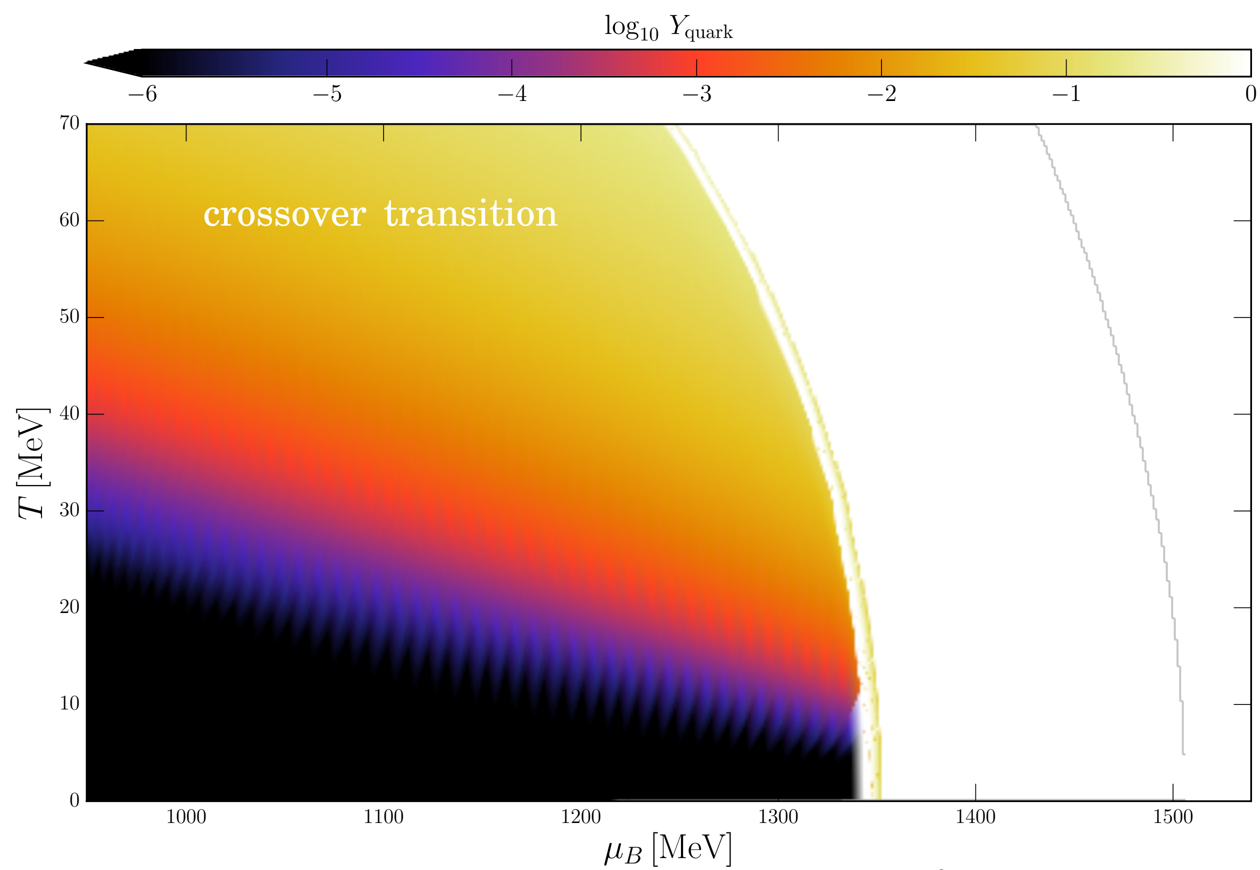
Simulation

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



Merger in the QCD phase diagram

- Background: 2D (T, n_B) CMF EoS with 1st order phase transition for $Y_Q = Q/B = 0.05$

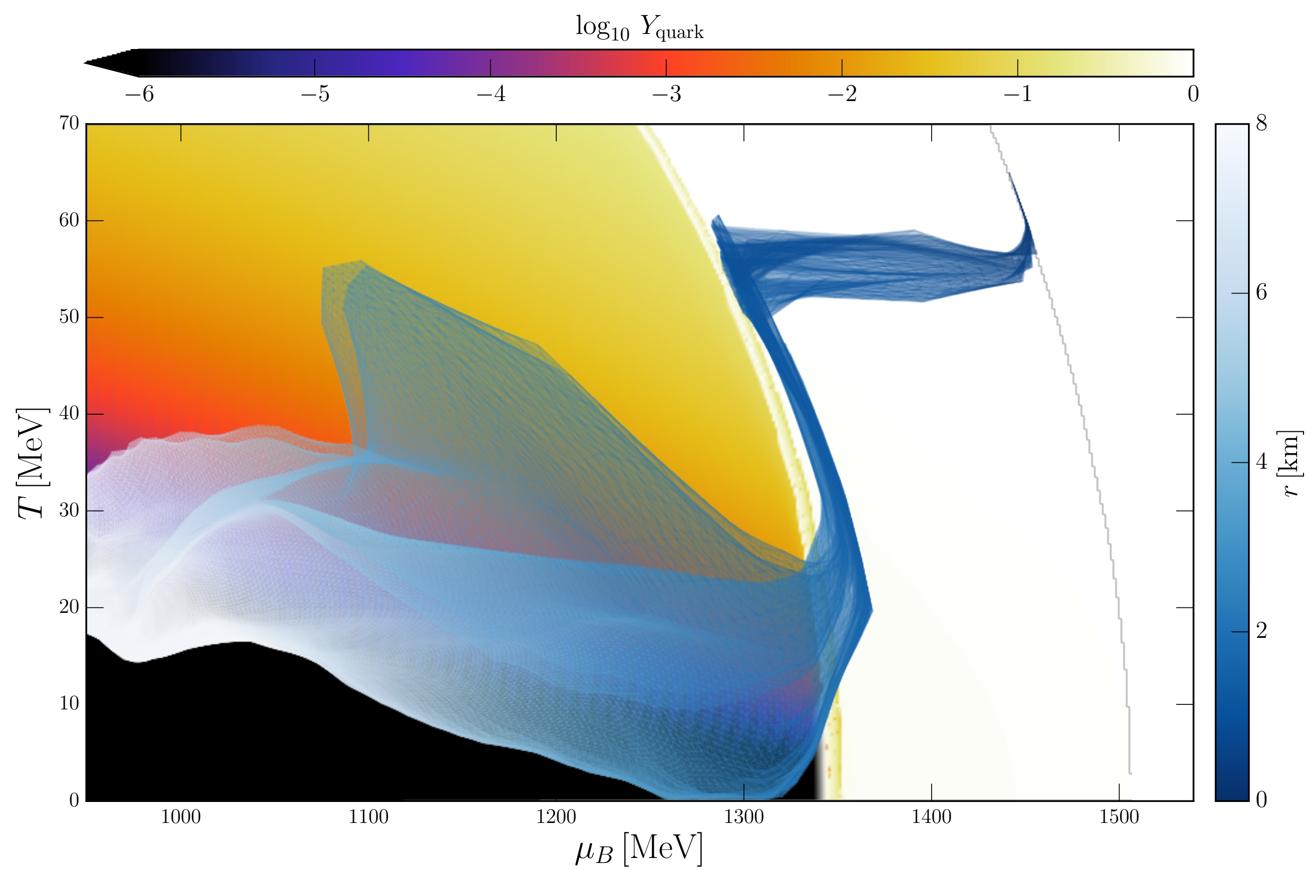


density ρ_B →

PRL 122 (2019) 6, 061101
e-Print: [1807.03684](https://arxiv.org/abs/1807.03684)

Merger in the QCD phase diagram

- 3D CMF EoS with 1st order phase transition
- Hypermassive star with final mass of 2.9 M_{Sun} at ~5 ms (after deconfinement but before collapse to black hole)

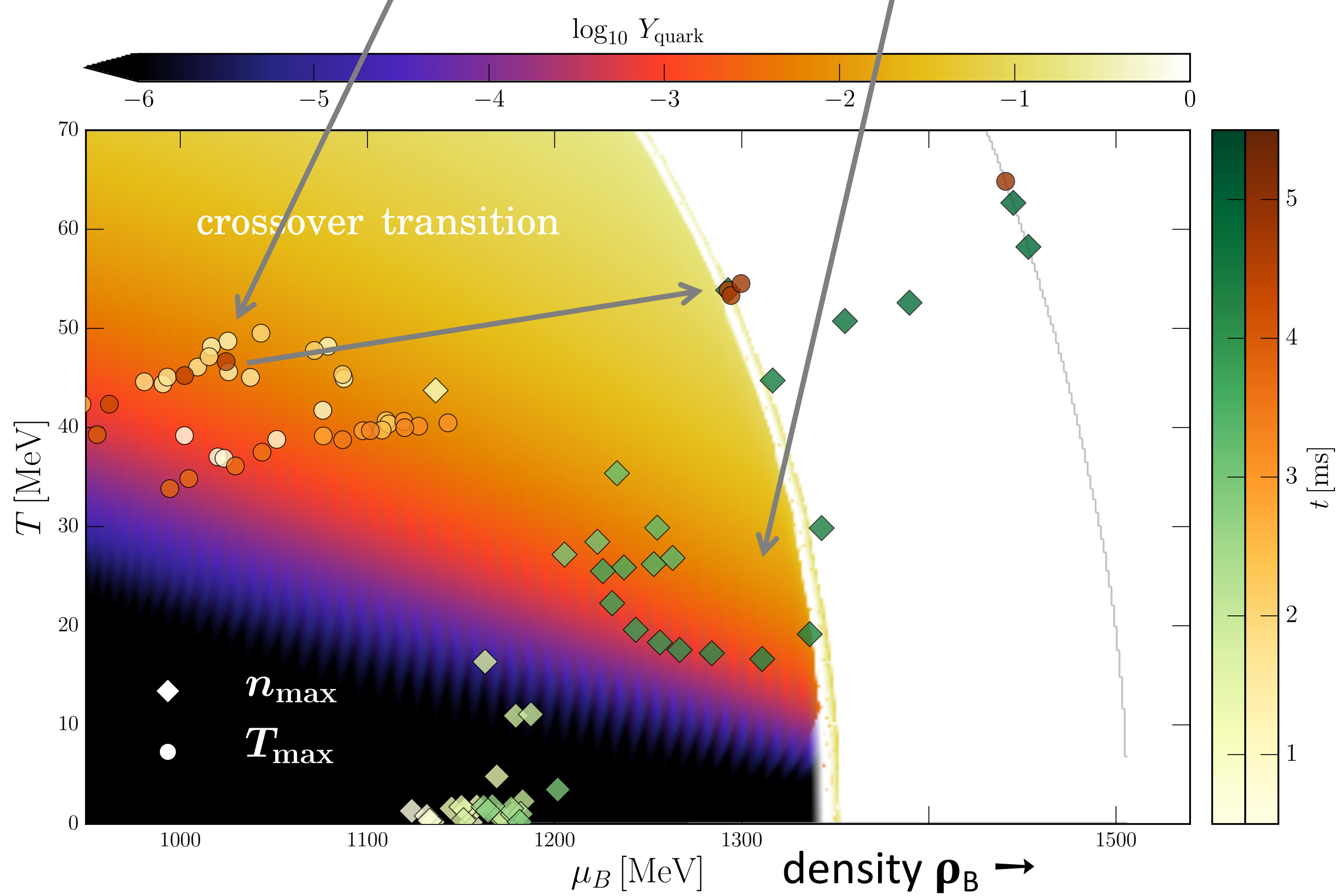


density ρ_B →

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

Merger in the QCD phase diagram

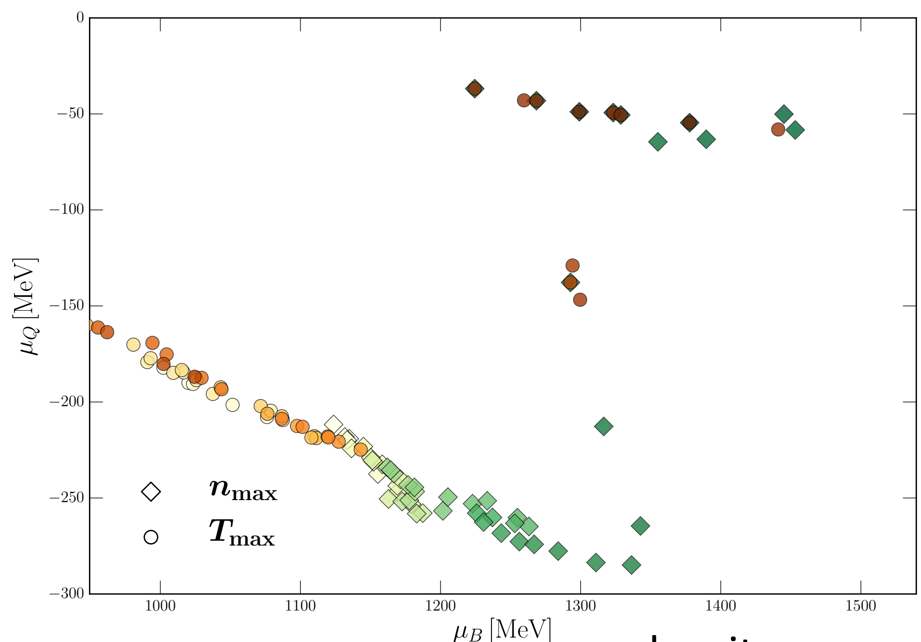
- Tracking maximum temperature ● and density ◆ during merger

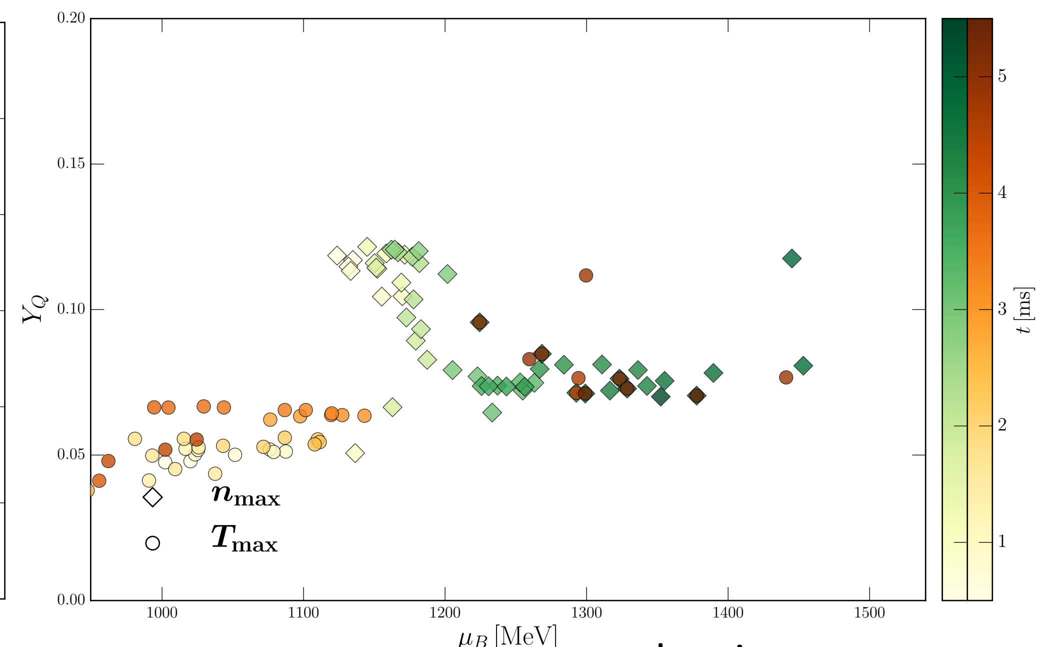


PRL 122 (2019) 6, 061101
e-Print: [1807.03684](1807.03684)

More merger phase diagrams

- ⋆ Tracking maximum temperature ● and density ◆





- ⋆ Increase in abs. value of charged chemical potential until phase transition, when it drops

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

- ⋆ Decrease in charge fraction of core when quarks appear (never reaching heavy-ion/supernovae conditions)

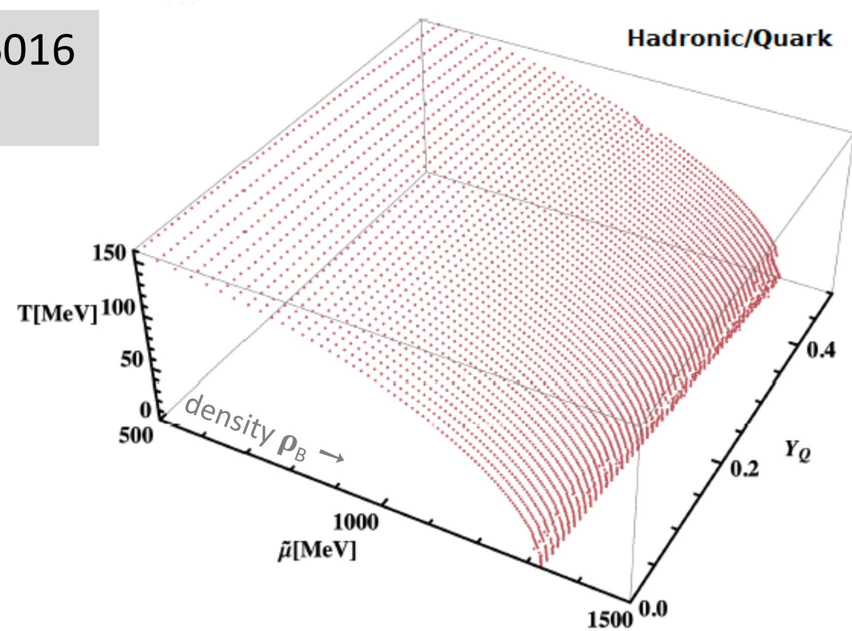
3D QCD phase diagrams (Y_S=0)

- 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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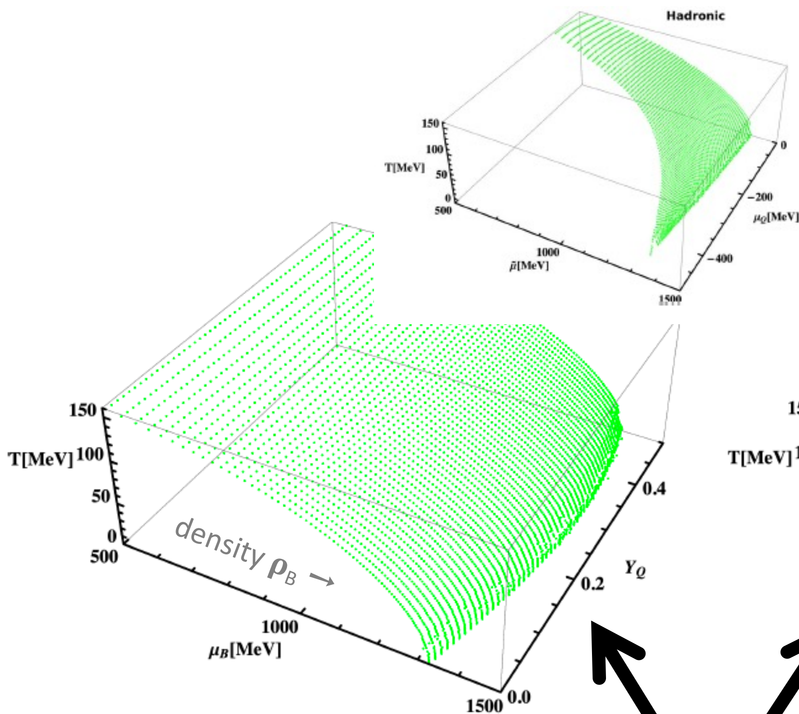
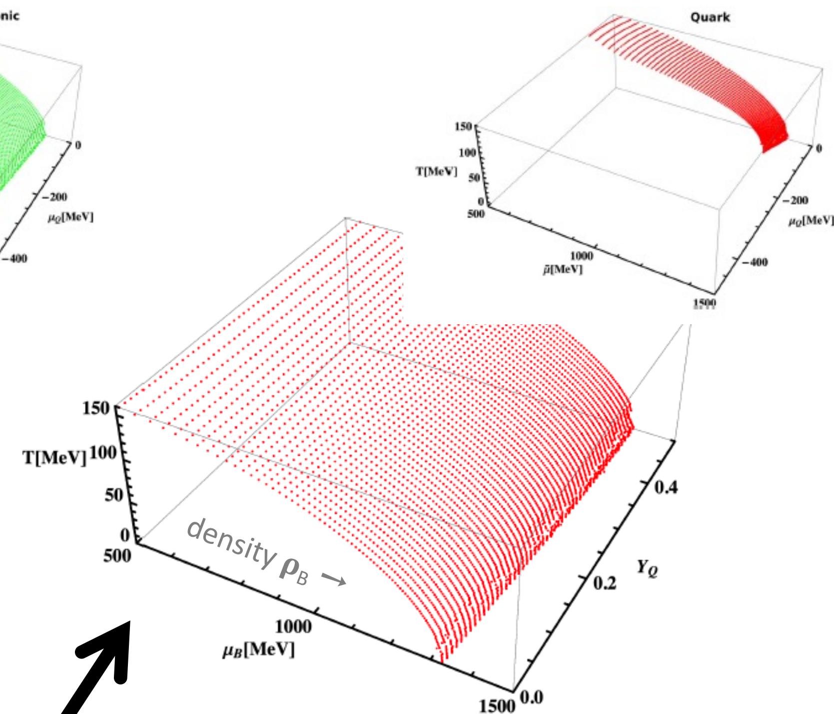
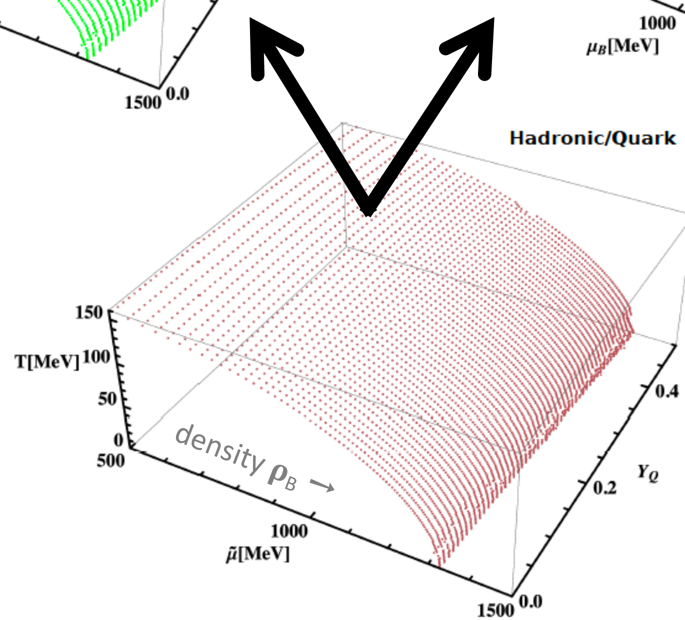






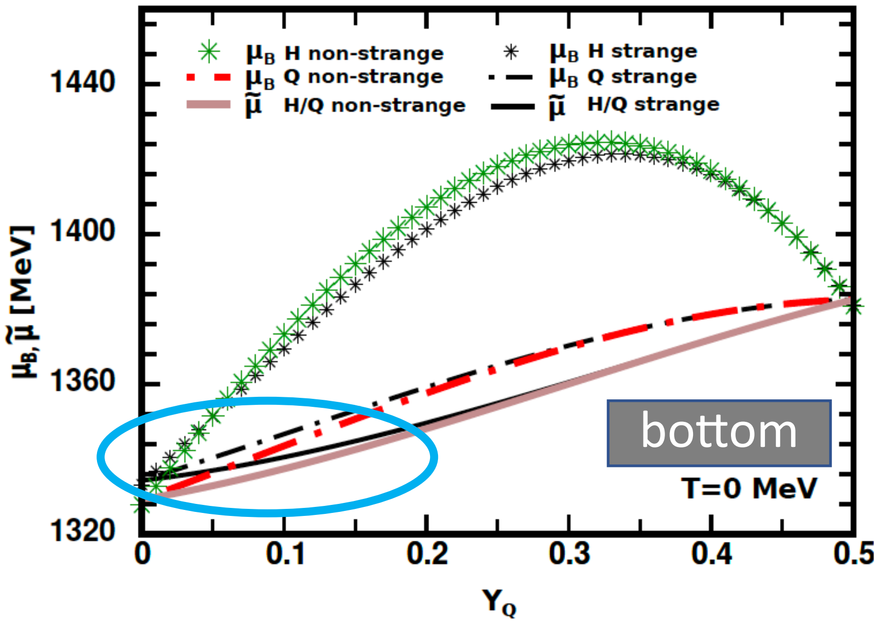
Gibbs free energy per baryon

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

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

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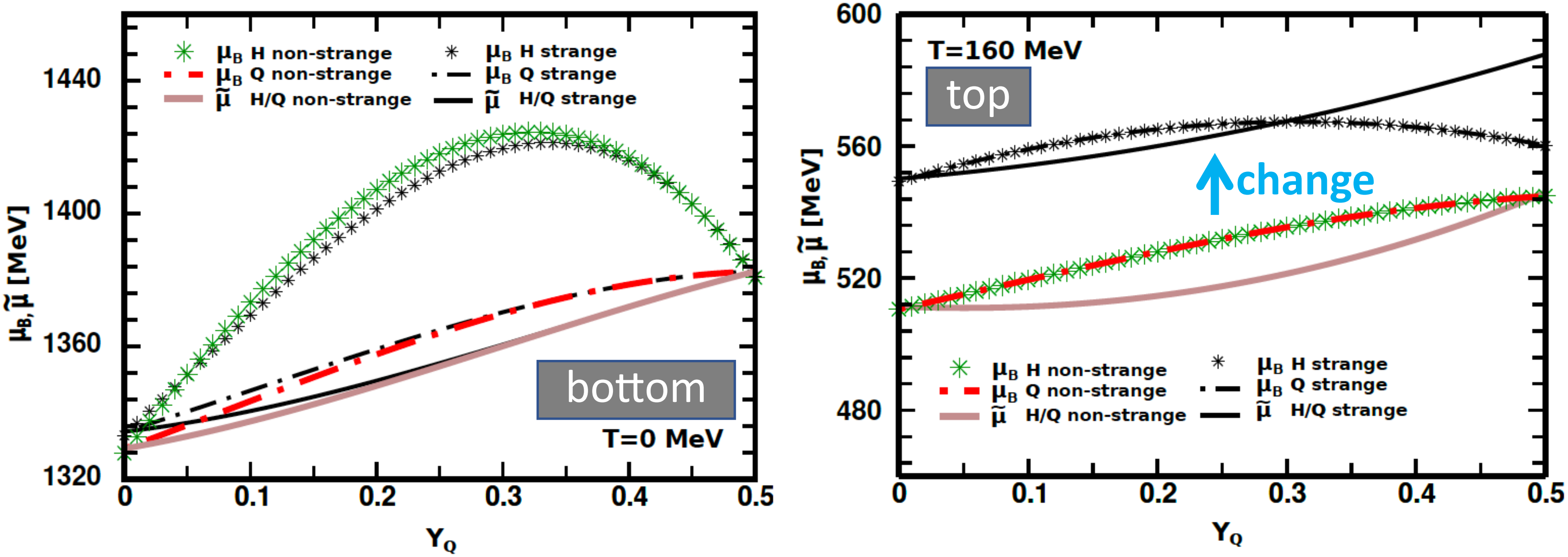
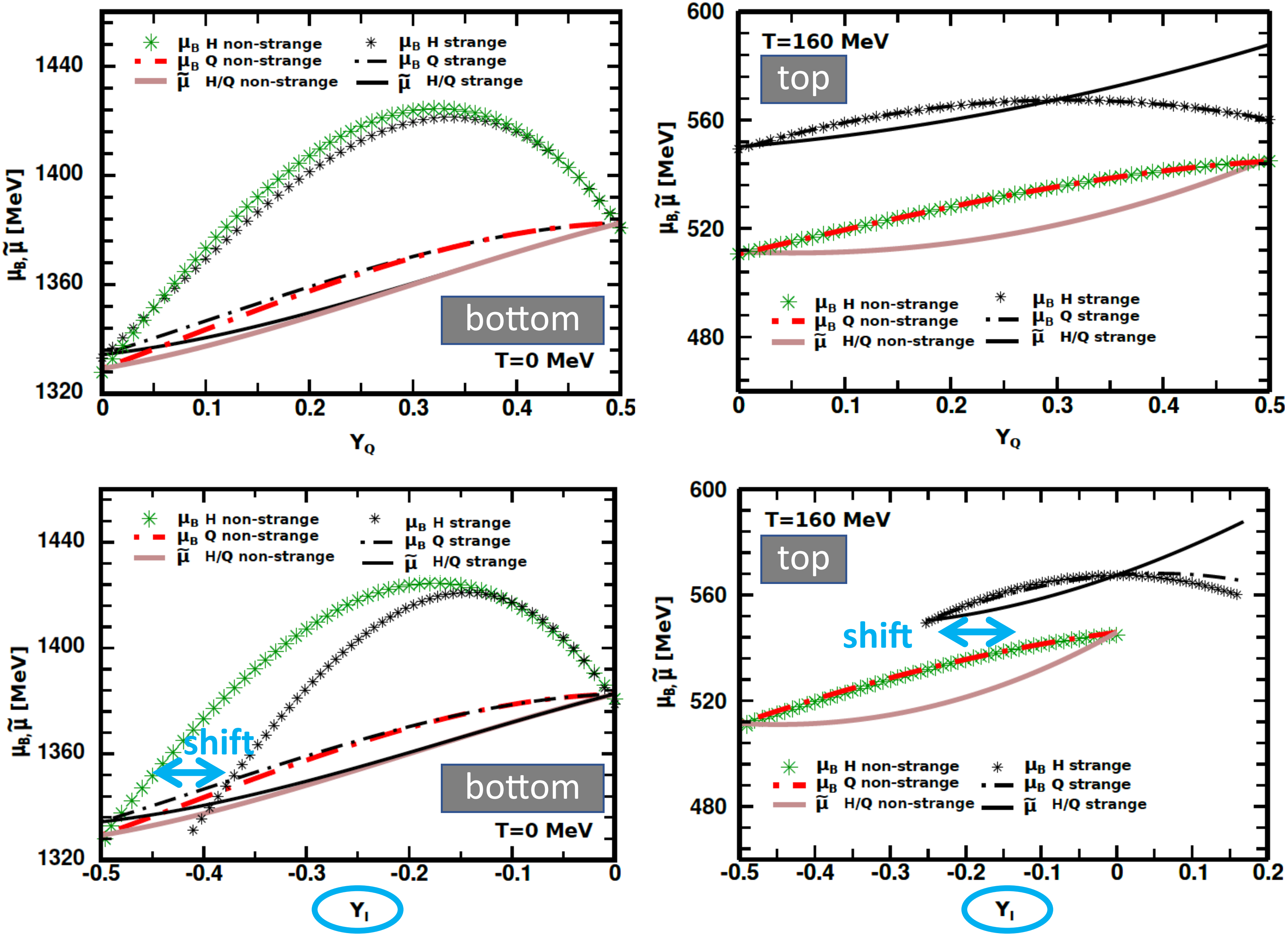


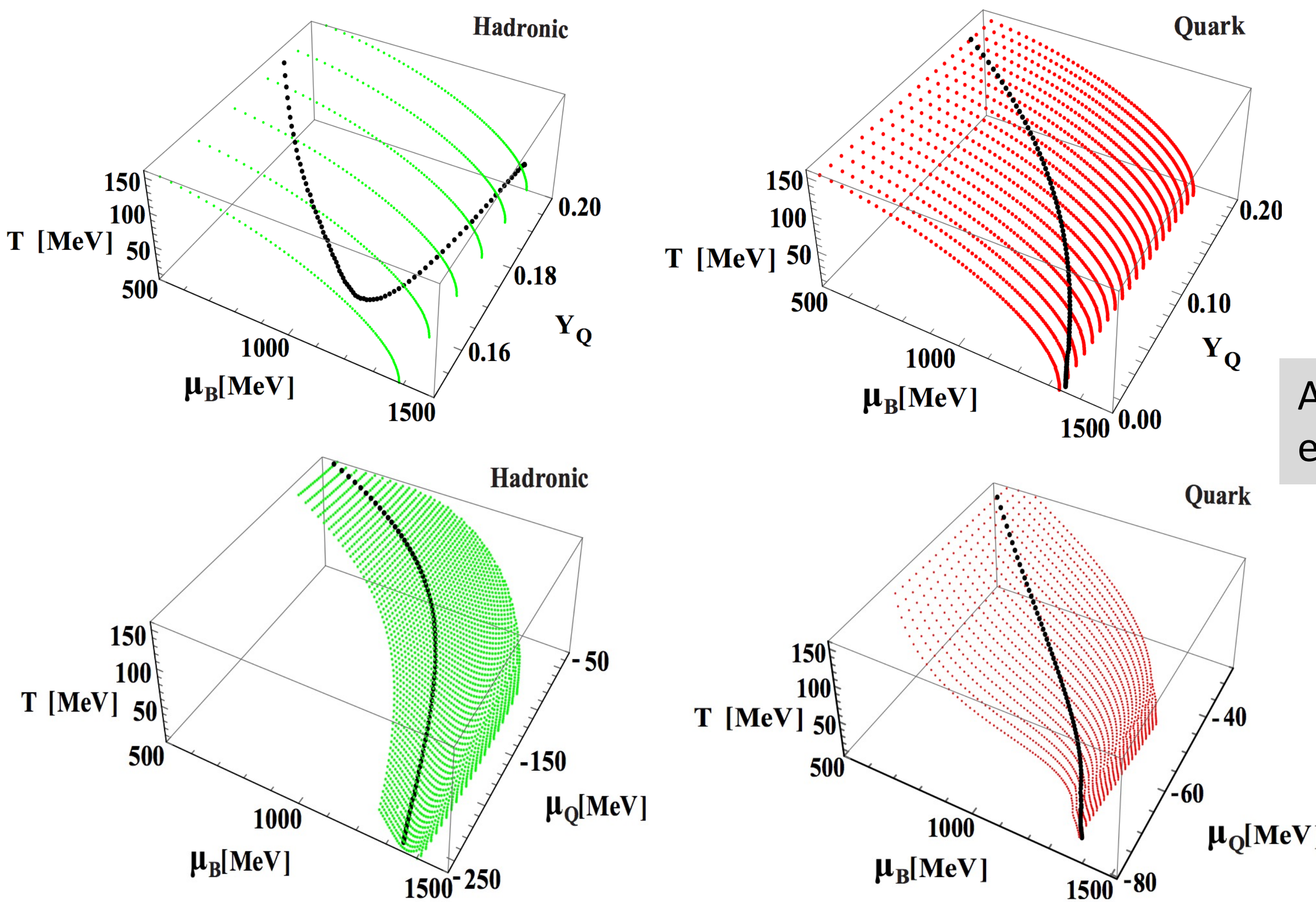
PRD 102 (2020) 7, 076016 e-Print: 2004.03039

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



Chemical equilibrium lines

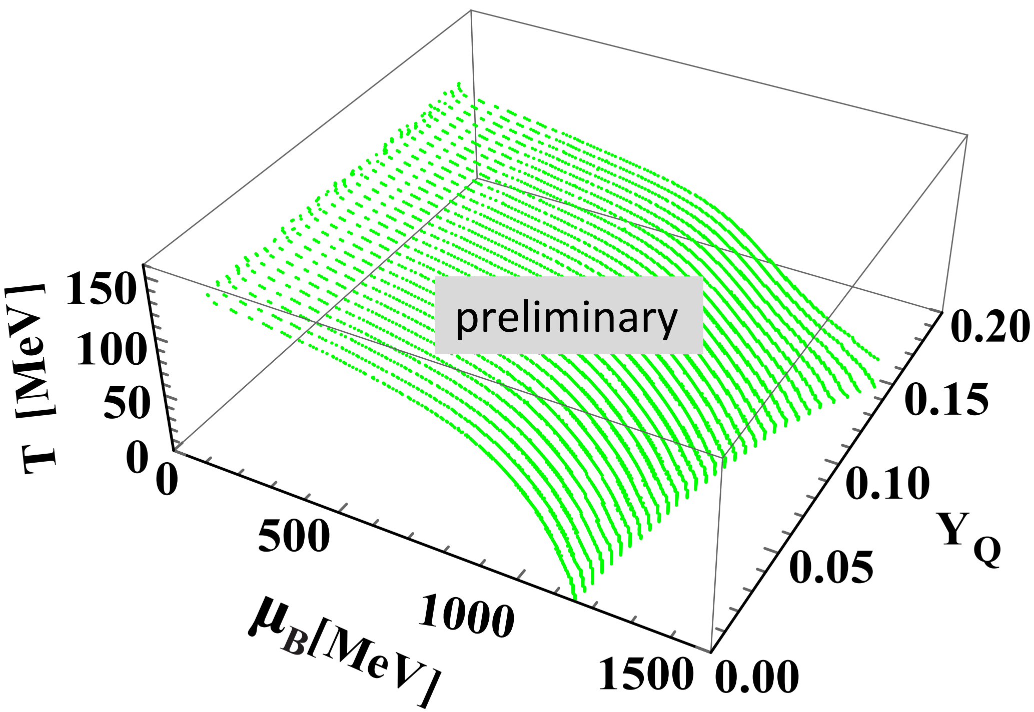
- Leptons in chemical equil. with baryons/quarks $\mu_Q = -\mu_{e,\mu}$
- Charge neutrality $Y_Q = Y_{lepton}$, finite strangeness $Y_S \neq 0$



Astron.Nachr. 342 (2021)
e-Print: 2011.11686

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)

Comparison with low-energy collision

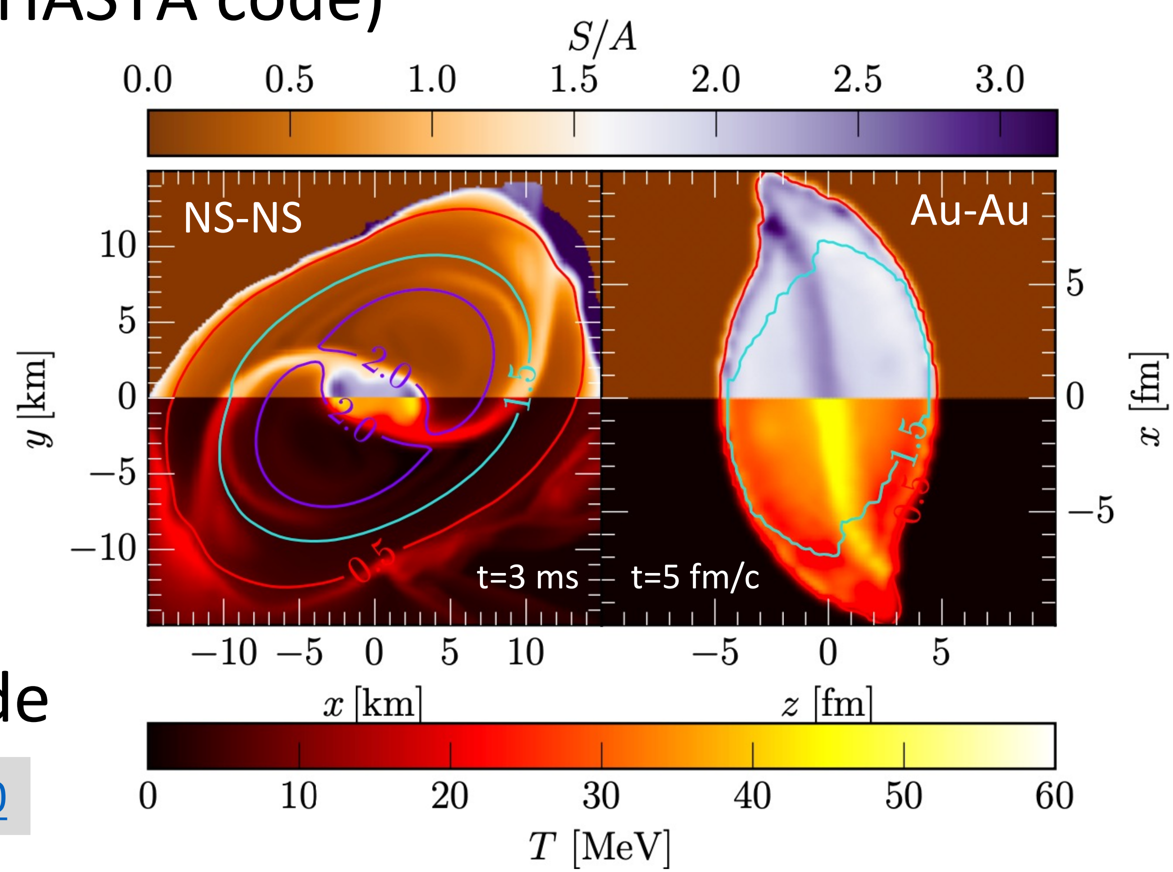
- CMF 3D EoS (n_B, T, Y_Q)

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

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

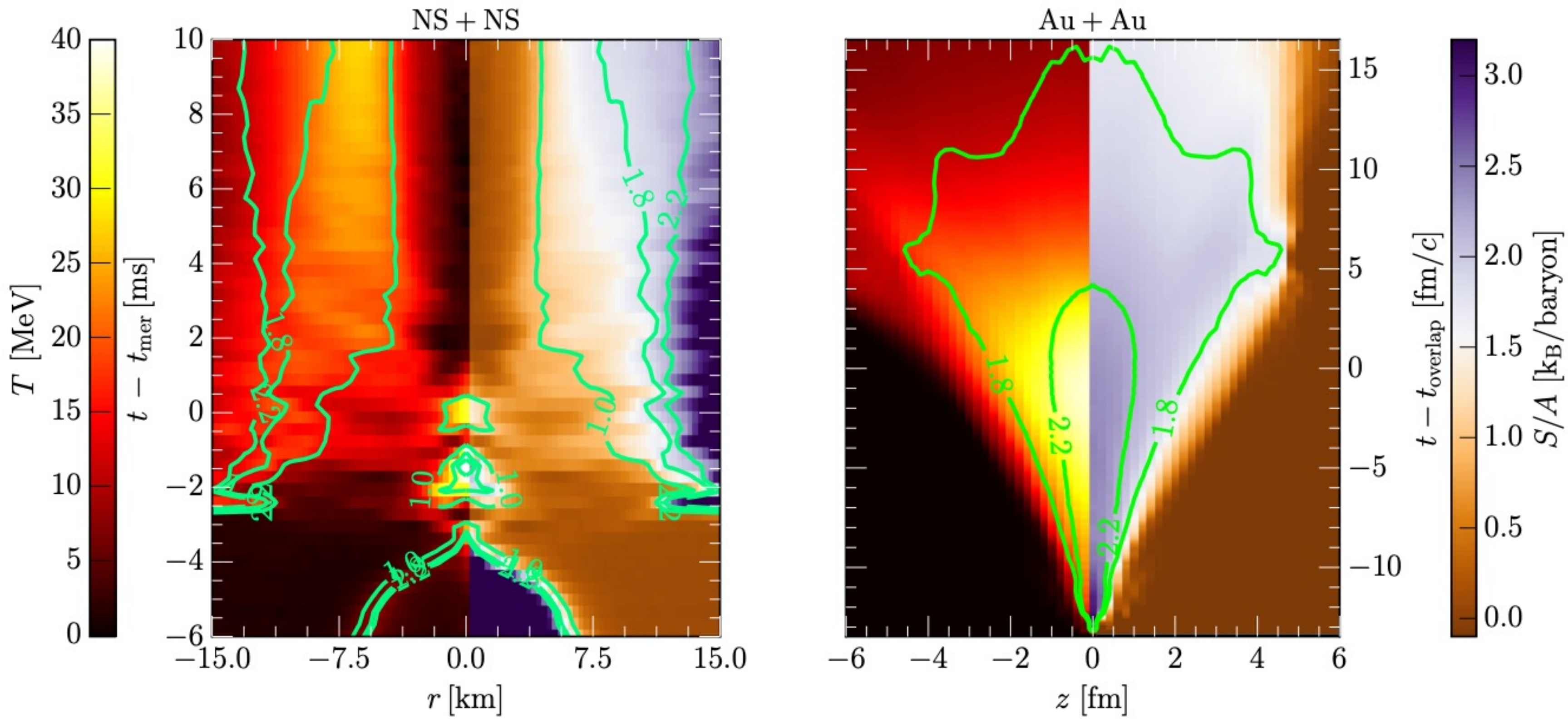
- Relativistic hydrodynamics simulations of **neutron-star mergers** (Frankfurt/Illinois GRMHD code) and **heavy-ion collisions** (Frankfurt SHASTA code)
- Final merger mass of 2.9 M_{Sun} and low-energy collision with E_{lab} = 450 MeV
- Similar geometry and properties across 18 orders of magnitude

e-Print: [2201.13150](2201.13150)



Comparison with low-energy collision

- ✶ Present similar temperatures/entropies per baryon

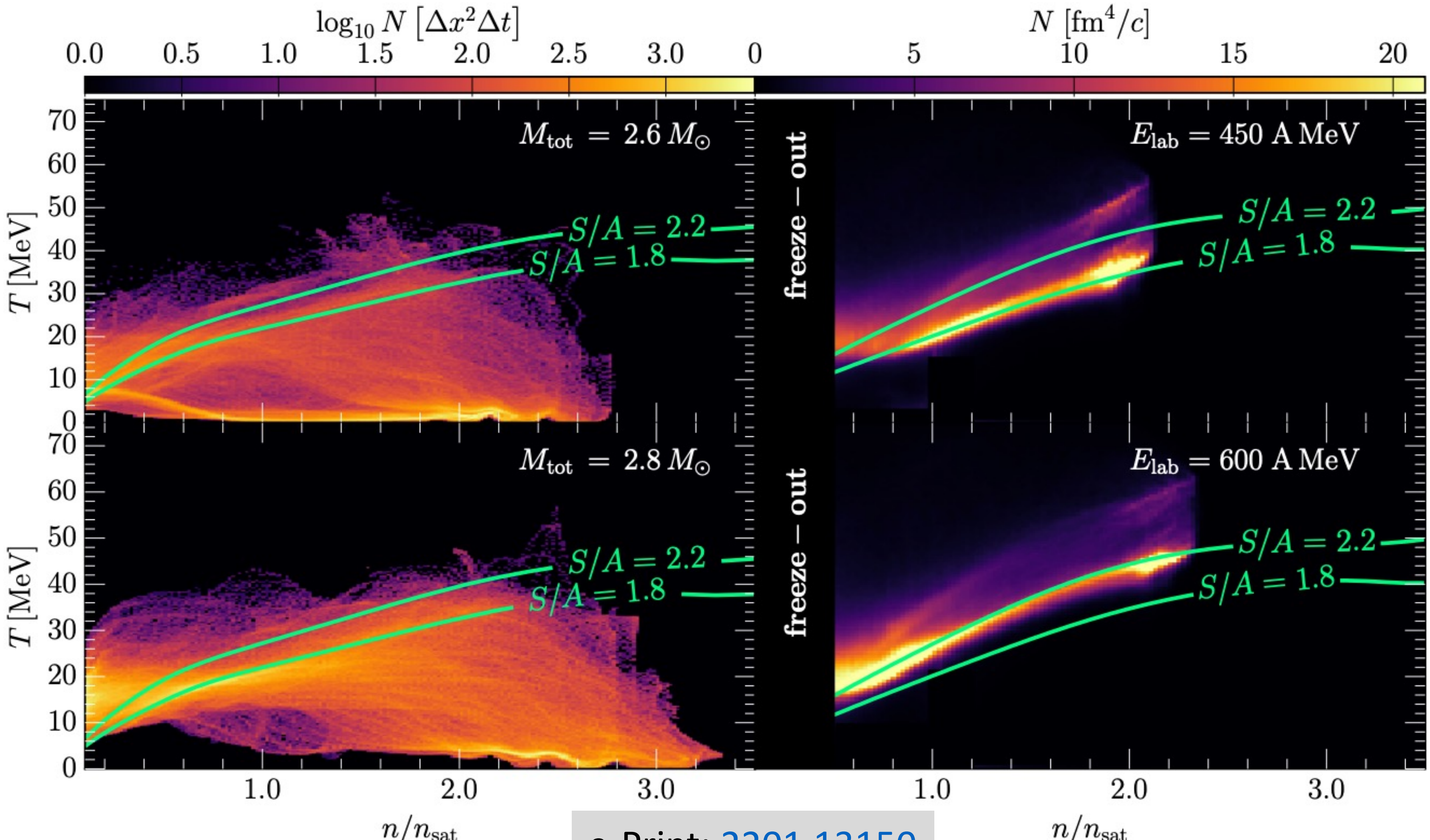


e-Print: 2201.13150

but different time evolution

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

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

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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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 dense and hot matter
- Comparisons among HIC's and NS's can be very useful but must be done with care (Y_Q , Y_S , leptons, ...)
- EoS repositories help speeding up understanding of dense matter
- Coordinating O4 GW observing run starts in May 2023