Extreme Matter meets Extreme Gravity: Observational Implications of Ultra-Heavy Neutron Stars with Cross-Overs and Phase Transitions

Veronica Dexheimer

in collaboration with H. Tan, T. Dore,
J. Noronha-Hostler, and N. Yunes

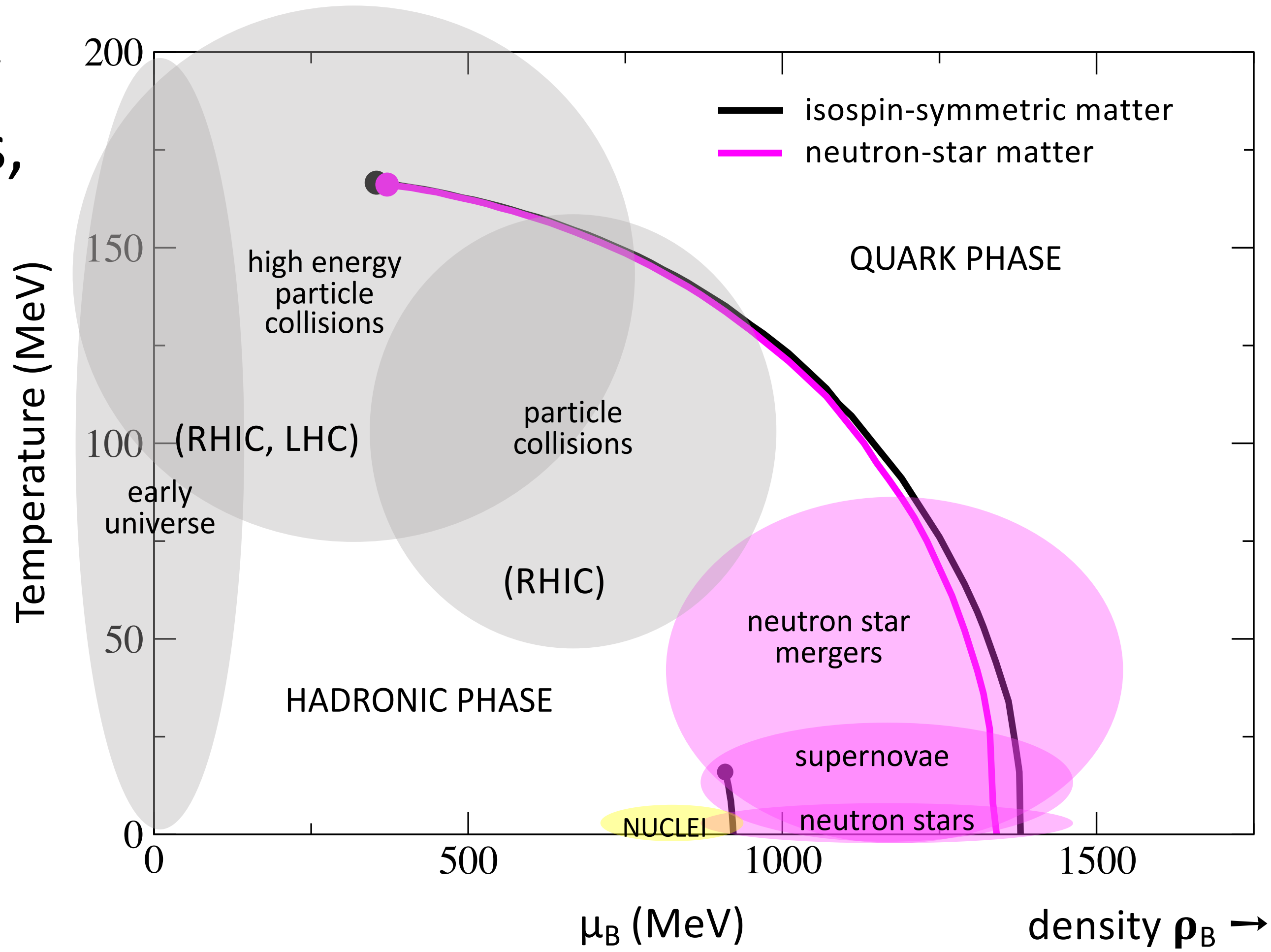
KENT STATE UNIVERSITY

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

NSF

Current state of QCD phase diagram

- A complete picture requires putting together astrophysics observations and laboratory measurements, in addition to lattice QCD, PQCD, …
- Since 2015 (2017), we can also see the universe through gravitational waves



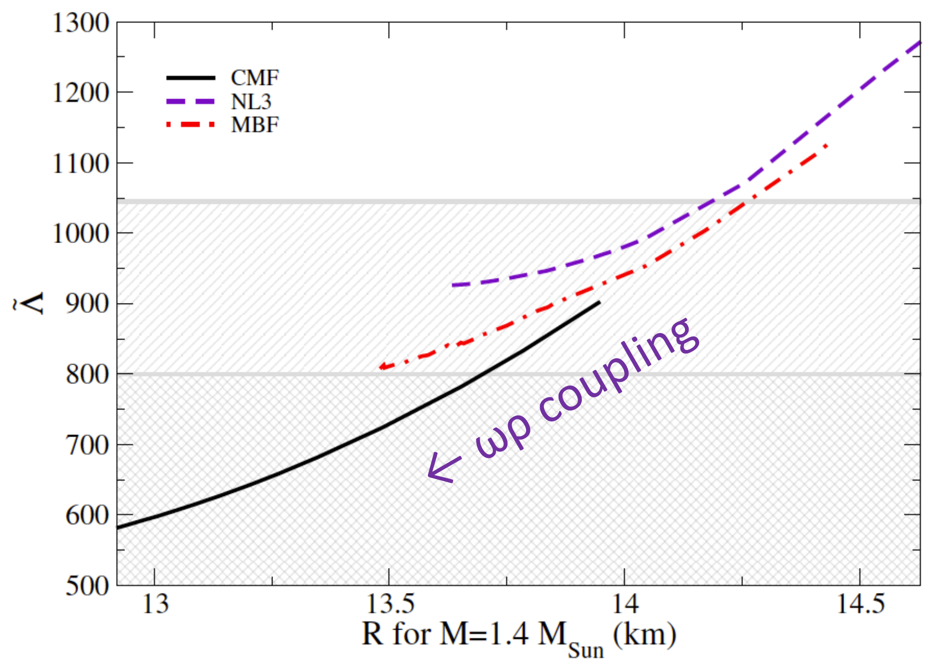
What have we learned about dense matter from GW170817

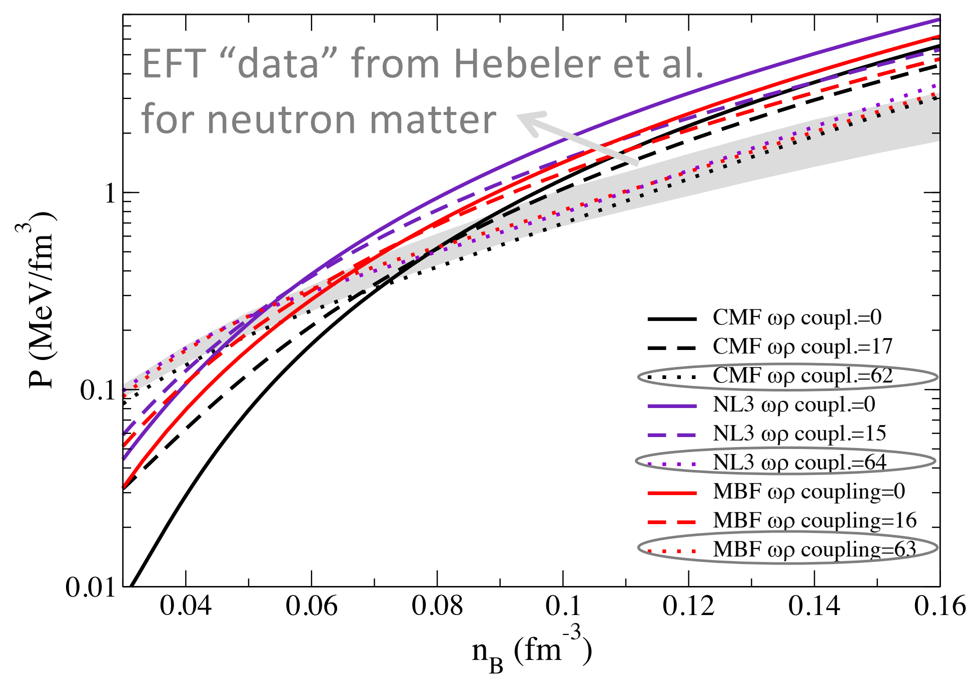
- Realistic waveform deviation from point-particle one: tidal deformability, measured in the end of inspiral

- New vector-isovector channel that can be added to any model

$$L_{\omega\rho} = g_{\omega\rho} g_{\omega}^2 g_{\rho}^2 \omega_\mu \omega^\mu \boldsymbol{\rho_\mu \rho^\mu}$$

ωρ coupling



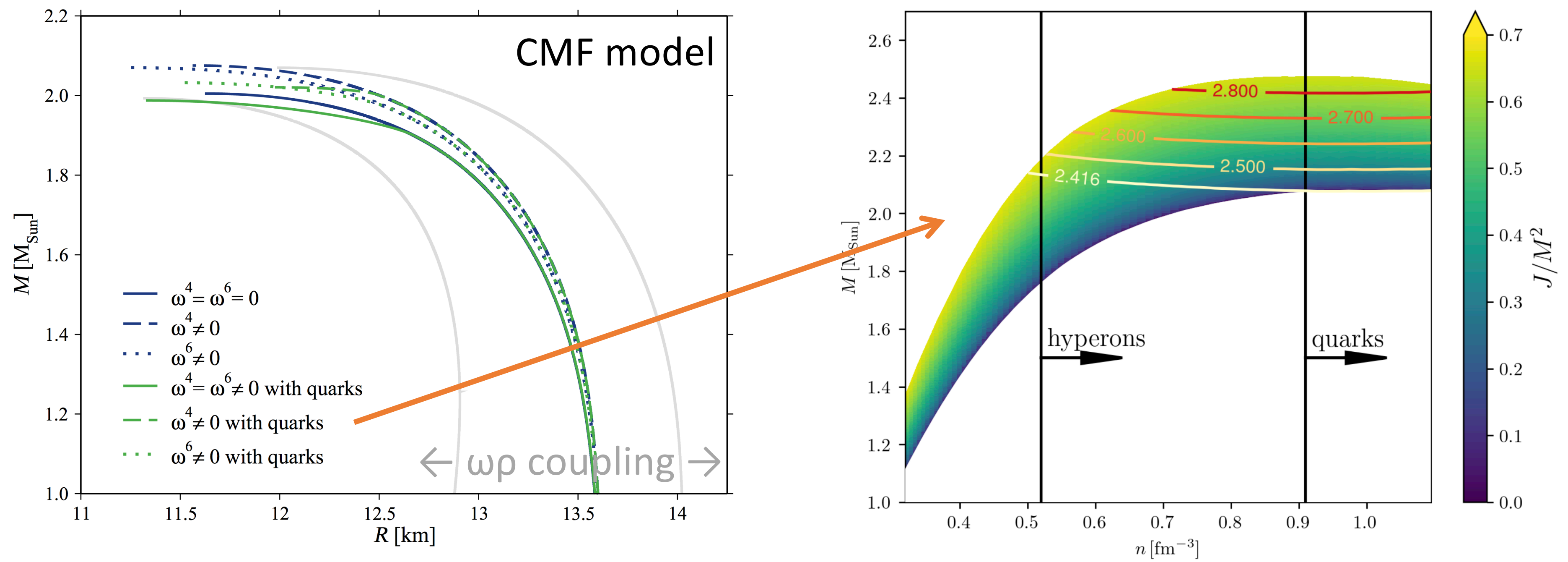


improves overall agreement with observation!

e-Print: [1810.06109](1810.06109)

What have we learned about dense matter from GW190814

- Merger of $23.2^{+1.1}_{-1.0}$ M_{Sun} black hole and a $2.59^{+0.08}_{-0.09}$ M_{sun} object
- New vector interactions increase masses to > 2 M_{sun}
- Rotation close to the Kepler frequency reproduces ~ 2.5 M_{sun} stars with hyperons and quarks

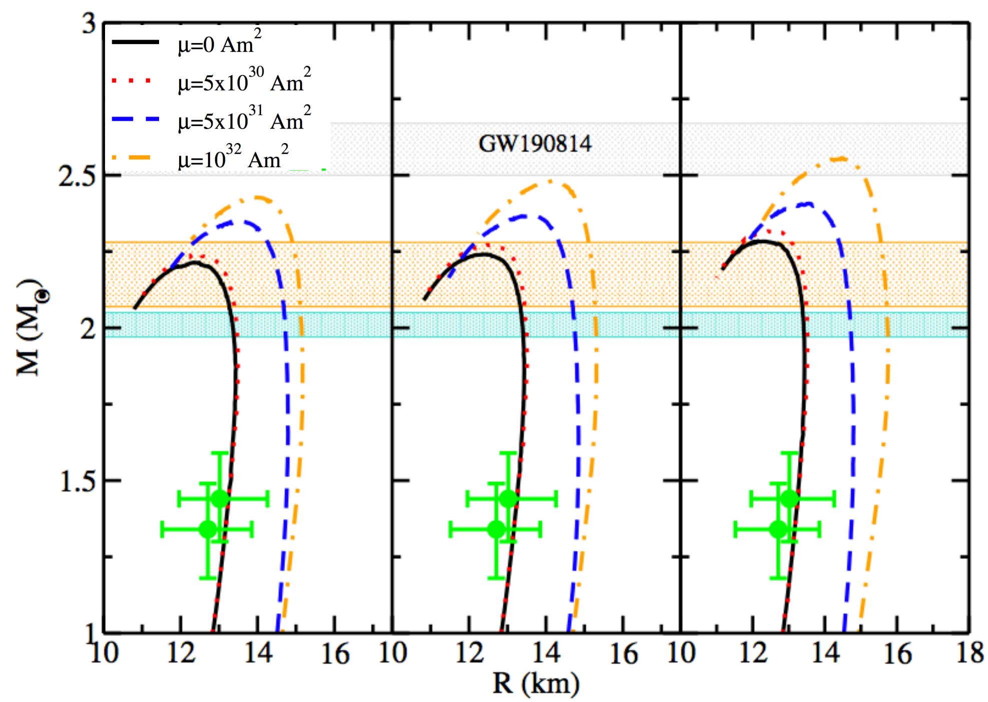


- Exotic degrees of freedom are not excluded!

e-Print: 2007.08493

Using magnetic fields instead of rotation

- Maximum fields allowed by axi-symmetric GR codes ~10^{18} G not enough to change significantly equation of state
- But decrease in hyperon fraction could increase stellar masses enough to explain GW190814
- Stellar radius becomes much larger
- Still, exotic degrees of freedom are not excluded when using density dependent couplings

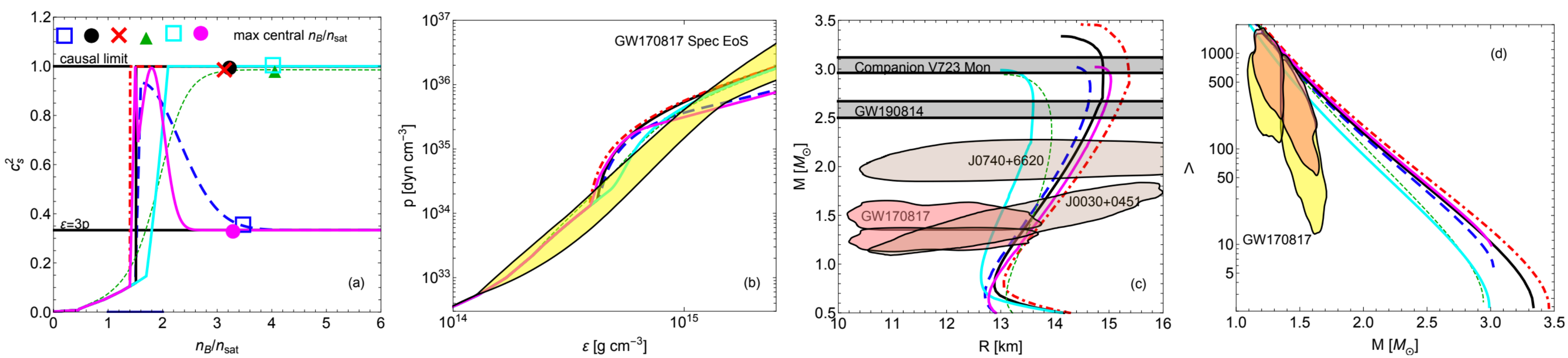


e-Print: 2104.05950

Does it depend on a particular model?

- Model-independent parametric approaches can generate even more massive stars, such as the companion of V723 Mon with M ≥ 2.91 ± 0.08 M_{Sun} with central densities not larger ≲ 4 n_{sat}

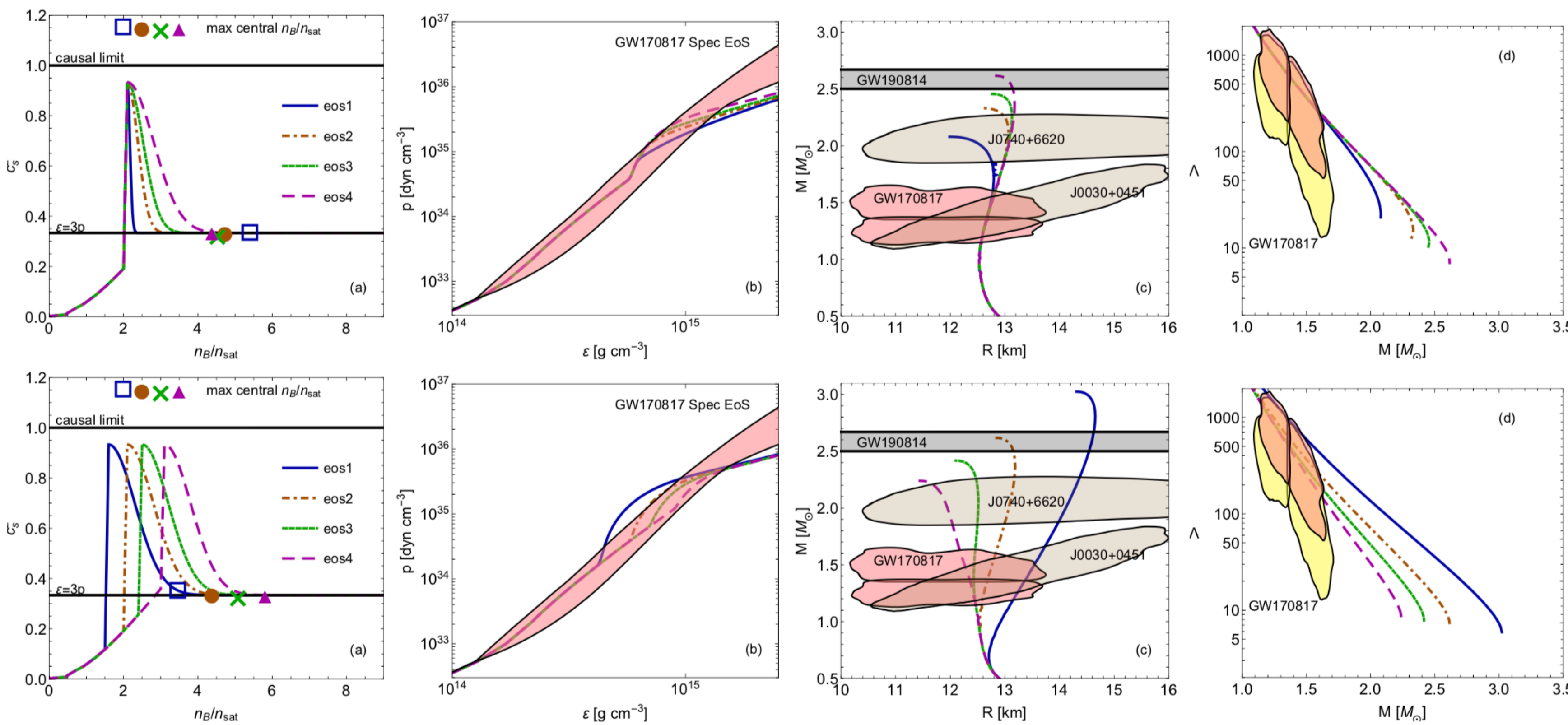
e-Prints: [2006.16296, 2106.03890]



- Considering GW190814 as involving a neutron star, we generate central densities ≲ 6 n_{sat} (otherwise the limit is ~ 8 n_{sat})

Size and position of bumps

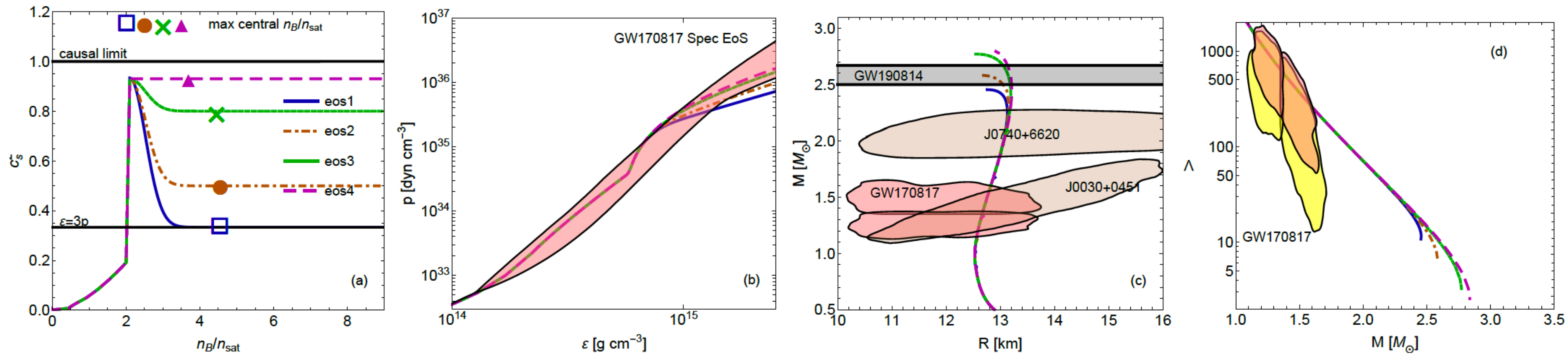
- Reproducing $M > 2.5\ M_{Sun}$ stars requires a steep rise in c_s^2 at $n_B < 3\ n_{sat}$, consistent with a bump or a plateau that could be associated with vector interactions (see Pisarski 2021)



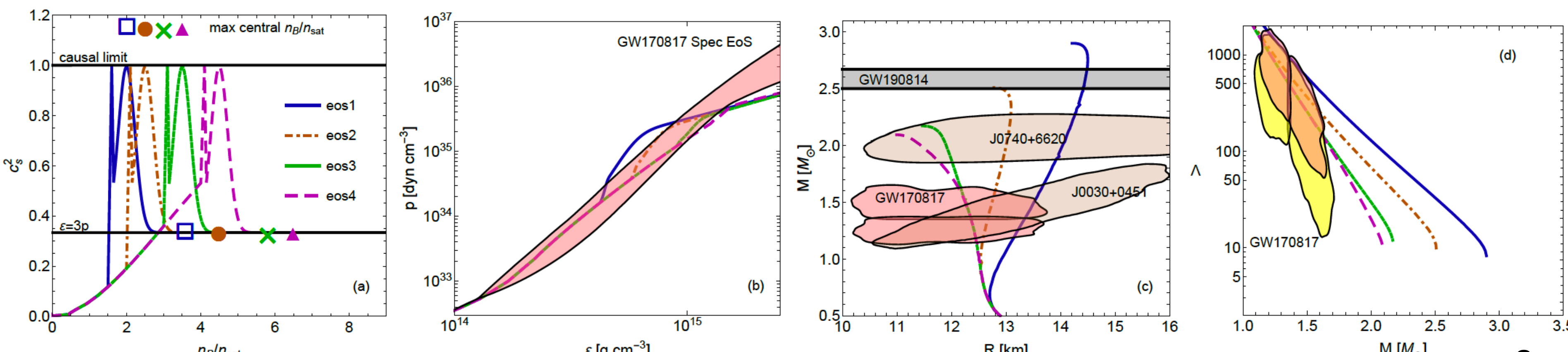
- Radius measurements with smaller error could help pinpointing the position of bump

More complicated structures

- Plateau heights are harder to determine observationally

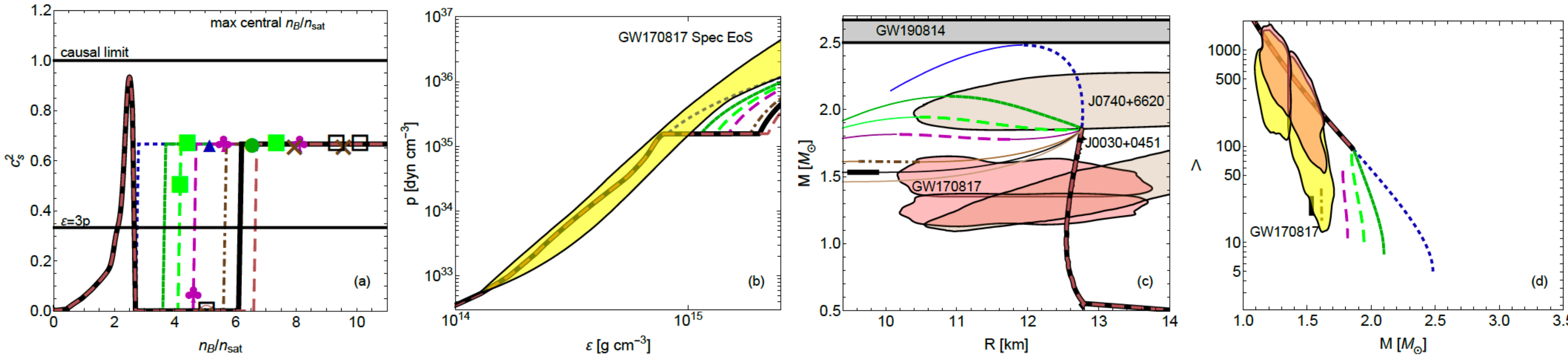


- Extra bumps could be motivated by hyperons and other crossover transitions but only slightly modify max. masses



First-order phase transitions

- Still reproduce M > 2.5 M_{Sun} stars



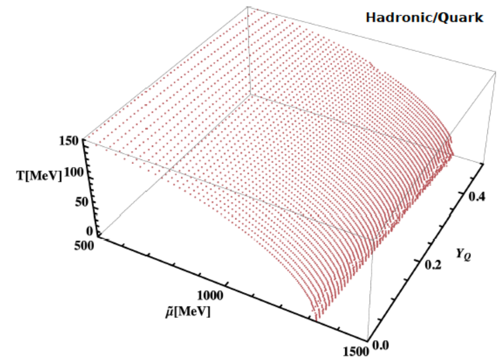
- More "extended" phase transitions switch from generating connecting branches, to kinks, to twin solutions

- But disconnected twins are only found with thin bumps and do not reach 2.5 M_{sun}, regardless of the slant after the transition or the height of the plateau

- Neither of these configurations violates I-Love-Q relations (variation below 1.5%)

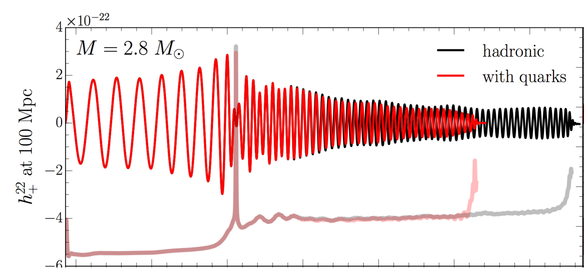
Discussion

- Neutron-star mergers create unique ideal conditions to achieve deconfinement
- Comparisons between HI collisions and astrophysics must be performed with care (Y_Q, Y_S, leptons, chem. eqil, …)



e-Prints: 2004.03039, 2010.00996, 2011.11686

- Now, in addition to observe light, we can also understand the universe through gravitational waves so, maybe, there will be a clear signature for a quark deconfinement phase transition from astrophysics!
- Post-merger part of neutron-star mergers could tell us about deconfinement … but not yet observed
- For now, we can learn from dense stellar masses, radii, and tidal deformability



e-Print: 1807.03684

The Mass Distribution of Neutron Stars in Gravitational-Wave Binaries

Philippe Landry[1] and Jocelyn S. Read[1]

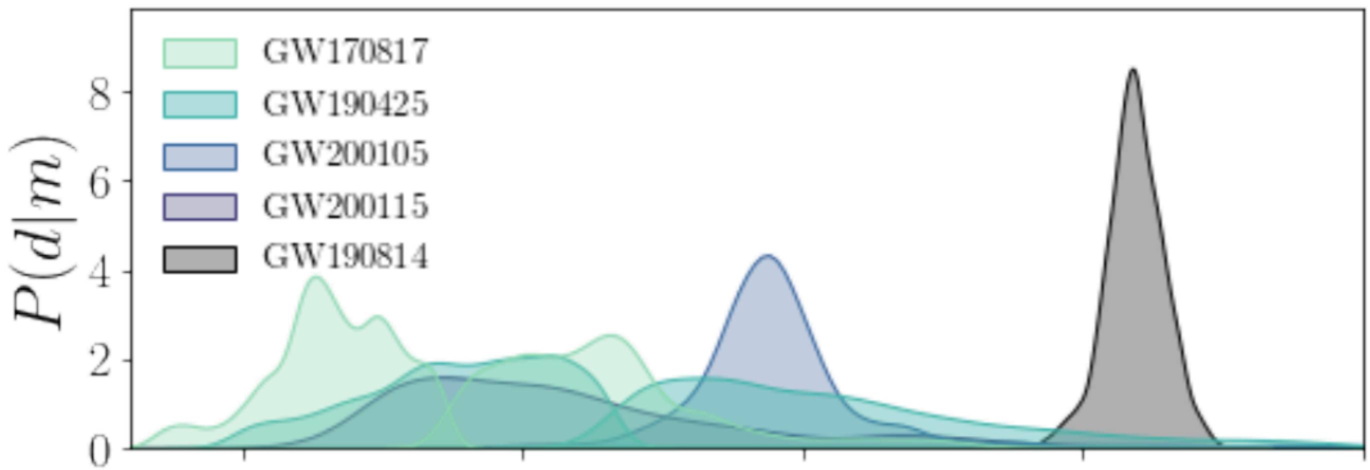


Figure 1. Measured masses and inferred mass distribution for NSs in GW binaries. *Top:* Marginal one-dimensional mass likelihoods $P(d|m)$ for the NSs in the BNS mergers GW170817 and GW190425, the NSBH mergers GW200105 and GW200115, and the candidate NSBH merger GW190814.