

Phase Transitions in Neutron Star Mergers

Using Recurring Regions in Neutron Star Observables to Isolate Microphysics

Alexander Clevinger

Kent State University
Center for Nuclear Research

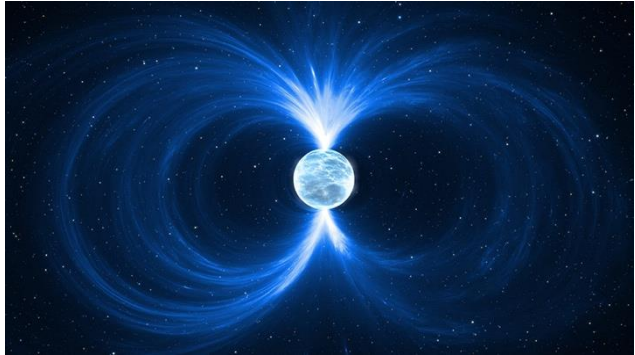
In collaboration with V.
Dexheimer, P. Hammond, M.
Albino, Z. Lin and D. Radice

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1. Motivation
2. Recurring Regions
3. Merger Setup
4. Results
5. Outlook



Goal: Understand the behavior of matter at densities and temperatures far beyond what can be sustained in terrestrial laboratories

- Neutron stars are extreme natural laboratories.
- Quantum Chromodynamics predicts a phase transition to deconfined quark matter (deconfinement). Deconfined quarks have been observed in some experiments but never in nature and is not well defined in some regimes.

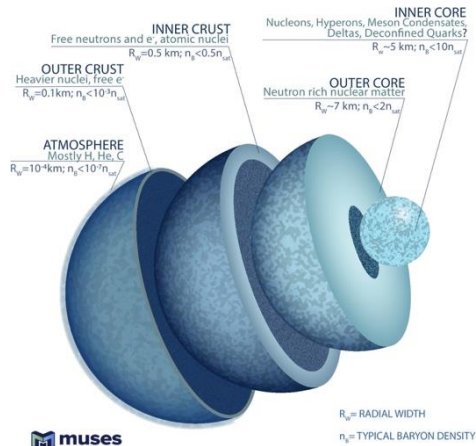
My work: Build neutron star models with this phase transition and study how they affect binary neutron-star mergers.

What Is a Neutron Star?

A neutron star is the compact remnant left behind after stellar core collapse.

Typical properties:

- Mass: $1-2 M_{\odot}$
- Radius: $\sim 10-14$ km
- Central density: several times nuclear saturation
- Interior may include hyperons, quarks, or phase transitions

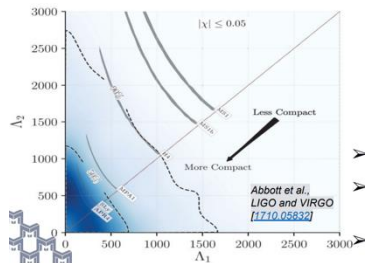
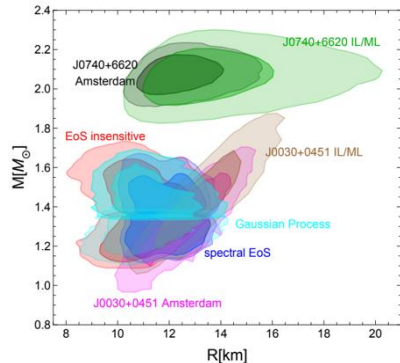


How Do We Learn About Neutron Stars?

Observations help infer various properties:

- **NICER** → X-rays from rotating neutron stars → mass, radius
- **LIGO/Virgo etc.** → Gravitational waves from BNS mergers → tidal deformability

Even with these, the core microphysics may remain hidden.



In earlier work, I studied realistic EOSs built within the Chiral Mean Field (CMF) framework.

- These models are calibrated to reproduce nuclear saturation properties.
- They incorporate hadronic degrees of freedom like nucleons, hyperons and Delta's and can also include a first-order transition to quark matter.
- They provide a physically motivated baseline for studying dense matter and deconfinement.

A key feature of these EOSs is that they contain a first-order transition using a Polyakov-like potential.

$$L = L_{Kin} + L_{Int} + L_{Self} + L_{SB} - U,$$

Phase Transitions in Dense Matter

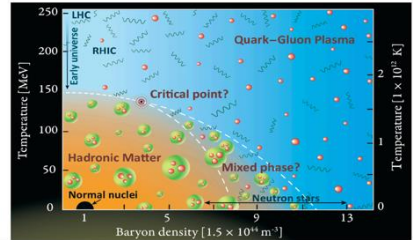
Possible transitions in the neutron-star core include,

- deconfinement to quark matter,
- mixed or percolated phases.

Depending on the model, the transition may look like:

- a smooth crossover,
- a first-order transition with a sharp softening,
- or a higher-order transition.

These possibilities are often most visible in thermodynamic quantities such as c_S^2



What Does a First-Order Transition Look Like?

A strong first-order transition is characterized by:

- a discontinuity in density at fixed chemical potential,
- strong softening of the EOS,
- and a sharp dip in the sound speed (in a Maxwell construction)

$$c_s^2 \rightarrow 0,$$

over part of the EOS.

This leaves a clear microscopic signature, but it can also make it difficult to satisfy astrophysical constraints.

Why Strong First-Order Softening Is a Problem

A drop in the sound speed can be physically well motivated, but it creates tension with observations.

- Too much softening reduces pressure support.
- This can suppress the maximum mass below the observed $\sim 2 M_{\odot}$ constraint.
- It can also produce radii or tidal deformabilities that are difficult to reconcile with multimessenger data.

So the challenge is: how can one incorporate deconfinement while still preserving realistic neutron-star observables?

Why a Sound-Speed Bump Is Needed

Motivated by our constraints, the EoS may exhibit a “bump” in the sound speed at intermediate densities.

- This helps recover larger maximum masses and realistic radii while still maintaining nuclear saturation properties.
- This can also be motivated by a quarkyonic phase in between the hadronic and quark phase.
- This may also be indicative of higher order phase transitions.

Drischler et al., [2110.14896]

Mroczek et al., [2309.02345]

Bedaque and Steiner, [1408.5116]

Tews et al., [1801.01923]

Kojo et. al (2015), Phys Rev. D, 91.045003

The main construction is:

1. Start with a hadronic EOS at lower density
2. Start with a quark EOS at higher density
3. Connect them through an intermediate percolation region

In practice, I interpolate in the baryon chemical potential using a polynomial representation for the pressure in this intermediate region:

$$\mathcal{P} = \sum_{m=0}^M b_m (\mu_B)^m = b_0 + b_1 \mu_B + b_2 \mu_B^2 + b_3 \mu_B^3 + b_4 \mu_B^4 + b_5 \mu_B^5 + \dots$$

Matching Conditions in the Percolation Region

The interpolation is constrained by a few conditions that need to be enforced so that are EoS's remain physical

- pressure continuity,
- monotonicity of $n_B(\mu_B)$,
- causality: $0 \leq c_s^2 \leq 1$.

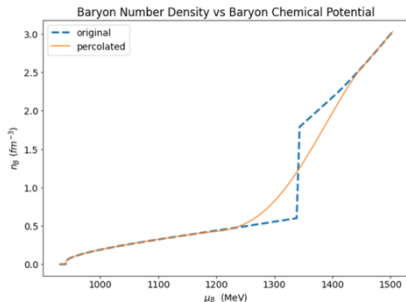
These conditions restrict the possible parameterizations while still leaving enough freedom to explore different sound speed structures.

Choosing parameters

Since we have six terms, we need six constraints

- match P on both sides of the percolation region
- lower boundary density $n_{B,H}$,
- upper boundary density $n_{B,Q}$,
- second order derivatives that we are free to vary,

These second order derivatives have a significant impact on the structure of our EoS.



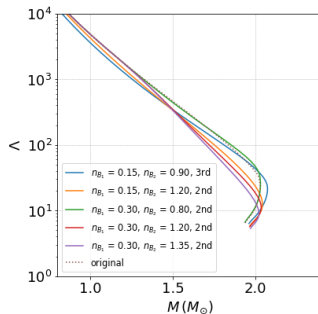
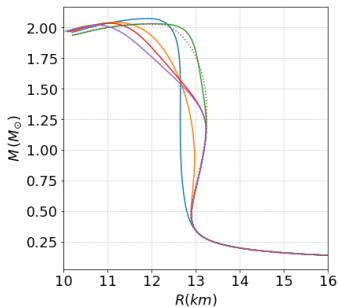
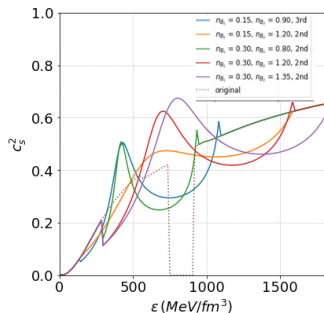
$$\left. \frac{d^N P_H}{d\mu_B^N} \right|_{\mu_{BH}} = \left. \frac{d^N \mathcal{P}}{d\mu_B^N} \right|_{\mu_{BH}}, \quad \left. \frac{d^N P_Q}{d\mu_B^N} \right|_{\mu_{BQ}} = \left. \frac{d^N \mathcal{P}}{d\mu_B^N} \right|_{\mu_{BQ}}$$

Hidden Microphysics in Models

We can produce EOSs with substantially different phase-transition structures:

- different onset densities,
- different widths,
- different stiffness profiles,
- and different sound-speed behavior.

Yet these EOSs can still generate stars whose mass-radius curves cross in specific regions.



Average Sound-Speed Picture

A useful quantity to show this recurring region phenomenon is that, for a fixed stellar mass, the radius depends on an average sound speed over the percolated densities reached in that star.

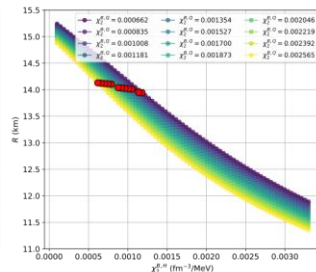
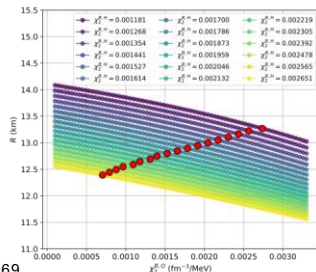
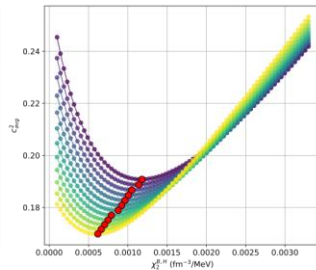
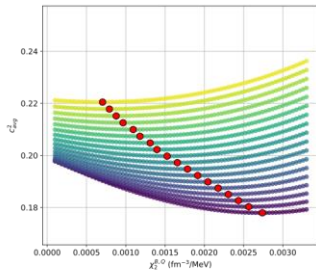
$$c_{\text{avg}}^2 = \frac{P_c - P_H}{\varepsilon_c - \varepsilon_H},$$

We find that if we minimize this value with our two free constraints, we can produce a series of stars with similar mass and radius.

$$\chi_2^{B,H} = \left. \frac{d^2 P}{d\mu^2} \right|_{\mu_{BH}}, \chi_2^{B,Q} = \left. \frac{d^2 P}{d\mu^2} \right|_{\mu_{BQ}}$$

Results

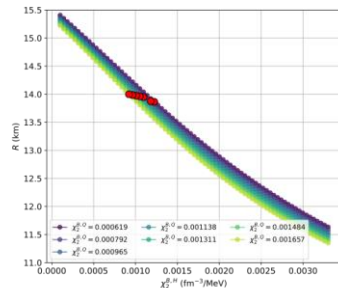
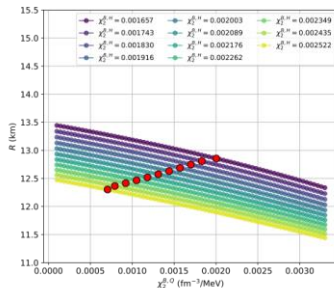
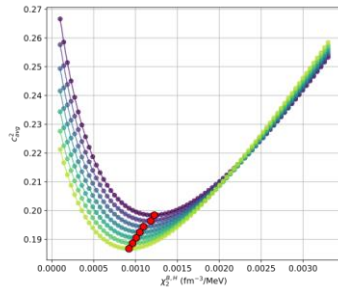
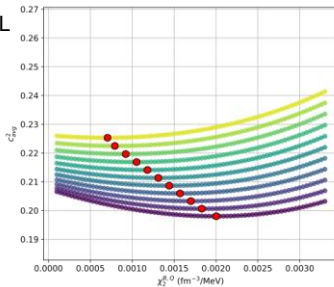
- We slice in higher order derivatives and find minima in c_{avg}^2 that give similar radii.
- Slicing in the opposite derivative also gives minima in c_{avg}^2 and gives another recurring region at a higher radius.



Additional Properties

- We find that this property can be applied to other masses.
- The recurring region also holds if you change the percolation region but this tends to change the width of the recurring region.
- The recurring region can be changed by changing the underlying EoS. This primarily is controlled by the hadronic part and how stiff it is.

DD2F+NJL



Why Are Recurring Regions Useful?

- We want to simulate binary neutron star mergers and see what effects different EoSs have on gravitational wave signals.
- This system is much larger than the scale of the microphysics that our model describes.
- Obvious differences in mass/radius \rightarrow merger differences may just reflect macroscopic structure
- Using stars with same macroscopic properties \rightarrow merger differences more directly tied to the microphysics of the EoS.

Initial Data and Evolution Framework

To study these systems, we generate binary initial data and evolve them in numerical relativity.

- Initial data constructed with **LORENE** with mass ratio of 1 at the recurring region mass.
- Dynamical evolution performed with **GRATHENA++**
- The EoS's act as an input for simulations.
- Temperature is added as a thermal gamma-law (based on an ideal gas).

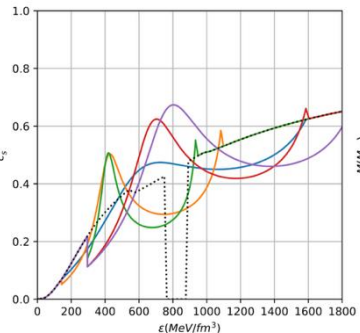
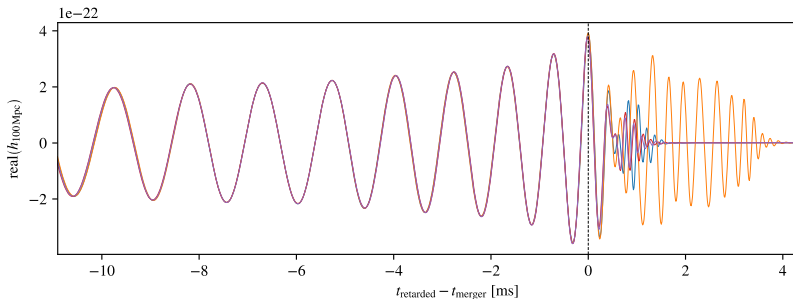
This framework allows us to compare otherwise similar binaries built from different EOS microphysics.

LORENE: E.ourgoulhon, et. al Phys. Rev. D 63, 064029

GRATHENA++: W. Cook, et. al, Astrophys. J. Suppl. 277, 3 (2025), arXiv:2311.04989 [gr-qc].

Merger Signal Differences

- In the inspiral phase, only the macroscopic properties influence the GW signal so they appear the same for the family of EoS's
- The EoS structure effects the post merger signal as the newly formed object equilibrates.
- We find that the earlier onset of the phase transition causes the post merger signal to live longer



- We are working to study this recurring region idea more rigorously with machine learning techniques
- We are also working on using finite temperature improved CMF EoS's in merger simulations.
- See Mateus Pelicer talk from yesterday to see work being done with CMF in MUSES cyberinfrastructure.



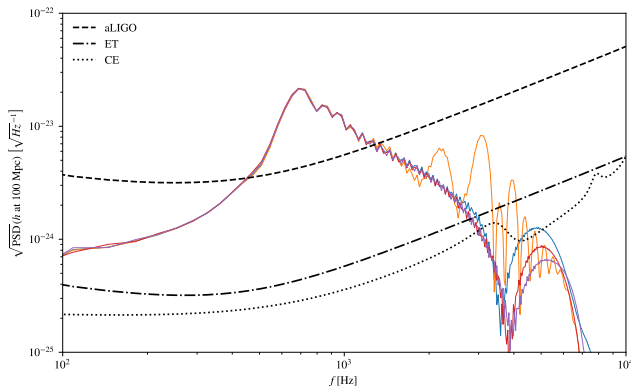
- 1 Neutron stars probe extreme environments that we cannot create in the lab
- 2 EOS sets mass/radius and encodes microphysics
- 3 Observations constrain EOS, but cores can hide different physics
- 4 I build EoSs within recurring regions to isolate the microphysics.
- 5 Merger simulations reveal how c_s^2 “bumps” affect the post-merger signal.

BNS mergers can help us find evidence of deconfinement in nature and can reveal dense-matter physics that is currently hidden in macroscopic observables.

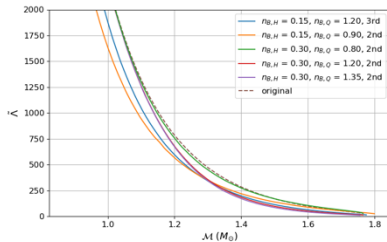
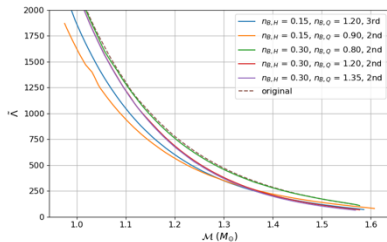
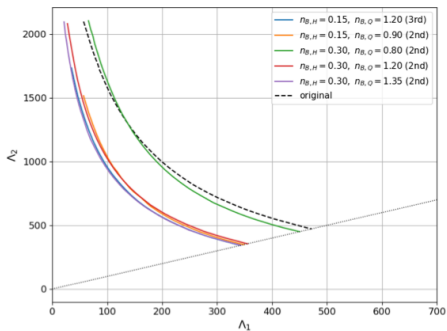
Thank You

Questions?

Current generation of detectors can only detect inspiral signal. Planned second and third generation detectors could detect these higher frequency GWs.



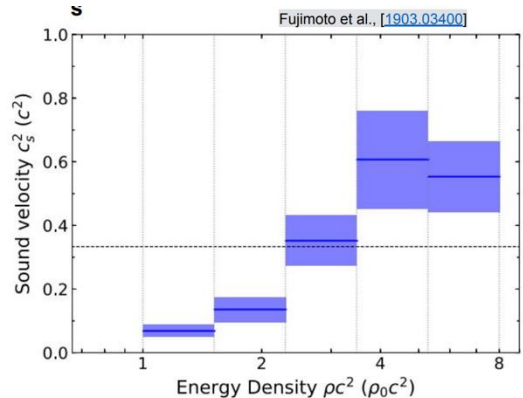
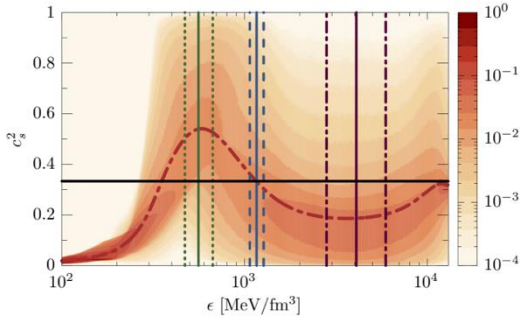
These recurring regions also apply to pertinent signals from GW signals



Backup: Sound speed structure evidence

Using various statistical inferences using the various constraints, one can expect some peak in the c_s^2 .
So, we introduce a methodology to apply to our existing EoS's to obtain this general structure in a three-window picture.

Marczenko et. al 2207.13059



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