Title: Probing extreme configurations in binary compact object mergers

Speakers: Samuel Tootle

Series: Strong Gravity

Date: February 09, 2023 - 1:00 PM

URL: https://pirsa.org/23020041

Abstract: Numerical relativity continues to play a crucial role in interpreting gravitational wave detections as well as the first multi-messenger detection of GW170817. More so, state-of-the-art models for kilonvae, gravitational waves, and more rely on the thousands of numerical relativity simulations that have taken place over more than 20 years. Simulations of binary systems including neutron stars are particularly taxing due to the equation of state of matter being a significant unknown. In spite of this fact, there exists vast amount of literature on the independent influence mass asymmetry or spin can have on the merger and post-merger dynamics of neutron star binaries across a wide array of possible equations of state.

In this talk I will extend this topic to extremal configurations consisting of binaries that are not only asymmetric, but include appreciable spins on the component neutron stars. To do so I will give an introduction into the initial data problem for numerical relativity, it's complexities, and its importance to current and future research. Furthermore, I will discuss a collection of results for extremal binary configurations including neutron stars and why this line of research is important to enable the next generation of multi-messenger models.

Zoom Link: https://pitp.zoom.us/j/99895521696?pwd=T1VtN0RGbjZrVTNleXB3V0FtQjhldz09

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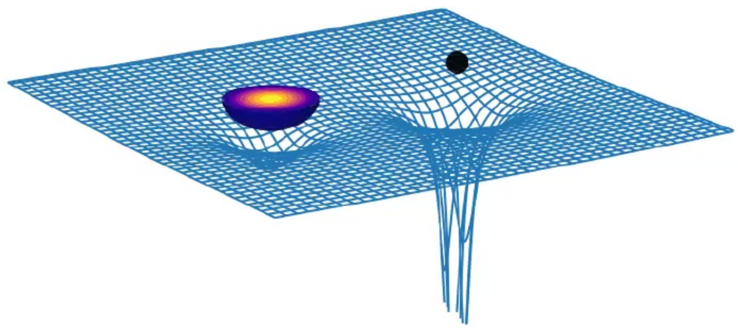
Probing extreme configurations in binary compact object mergers

Samuel Tootle

09, February, 2023

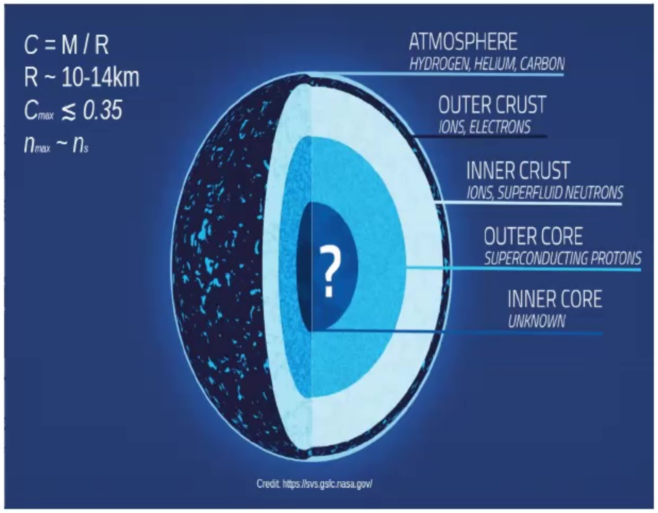
Compact Objects

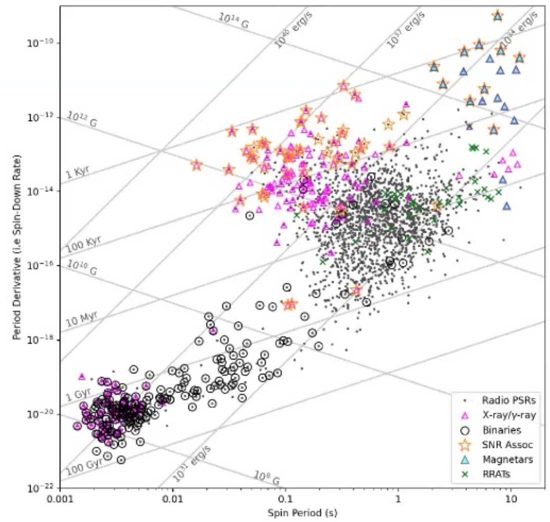
$$\mathcal{C} = \frac{M}{R} \implies \mathcal{C}_{\rm BH} = \frac{M}{R_s} = \frac{1}{2} \ , \mathcal{C}_{\rm max} = \mathcal{C}_{\rm TOV} \sim [0.25, 0.35]$$



∴ Merger of highly compact objects generate louder (detectable) gravitational waves

Neutron Stars





- Extremal configurations of neutron stars include their mass as well their spin[1]
- Millisecond pulsars are very old and commonly found in binary configurations[2]

[1] In this work we ignore magnetic fields

[2] Diagram used from DOI:10.13140/RG.2.2.22850.99524

Numerical Relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T_{\mu\nu}$$

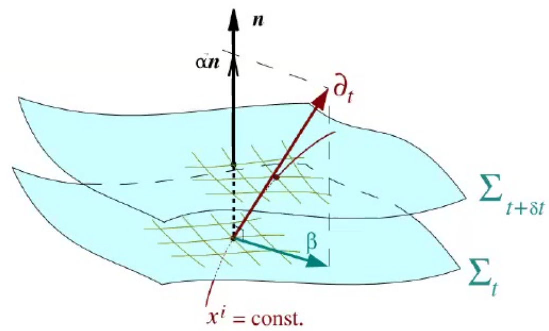
↓

3+1 Decomposition

$$\mathcal{M}(g) \Rightarrow \Sigma_t \times \mathbb{R}$$

$t = 0$ → CTT, CTS, XCTS

∂_t → BSSNOK, (FO)CCZ4, Z4(c), DSH, dGREM



Gourgoulhon, E., "3+1 Formalism and Bases of Numerical Relativity, https://arxiv.org/abs/gr-qc/0703035v1

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

↓

$$ds^2 = -(\alpha^2 - \beta^i \beta_i) dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

$$K_{ij} = -\frac{1}{2} \mathcal{L}_{\boldsymbol{n}} \gamma_{ij} \,, \gamma_{ij} = \psi^4 \tilde{\gamma}_{ij}$$

FUKA

- BBH, BHNS, and BNS; $q << 1\,, \chi_1 \neq \chi_2 \neq 0$
- Maximal spins (anti-)aligned using conformal flatness
  - $\chi_{\rm BH} \approx \pm 0.85\,, \chi_{\rm NS} \approx \pm 0.65\ \left(\chi := \frac{S}{M^2}\right)$

- Quasi-equilibrium binaries
- Eccentricity reduced binaries
- Minimize ADM linear momenta
- Provide export interfaces to streamline importing into evolution frameworks

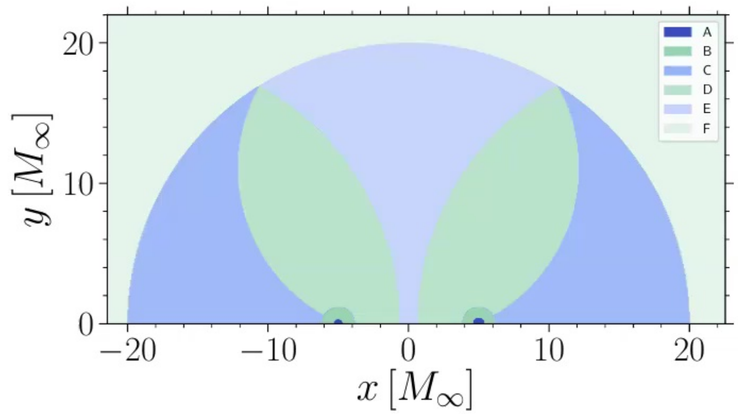
- FUKA [3] (Frankfurt University/Kadath) is a suite of initial data (ID) solvers based on the Kadath[9] spectral solver library

[3] arxiv:2109.00940 – *PrD, 104 (2021)*
https://bitbucket.org/fukaws/

[9] https://kadath.obspm.fr/

Numerical Implementation

- FUKA uses an extended version of the Kadath[9] spectral solver library
- FUKA solves the eXtended Conformal Thin Sandwich (XCTS) formulation of Einstein's field equations
- Black Holes are constructed using excision conditions
- Neutron stars can be constructed using a piecewise polytrope or tabulated equation of state (EOS)
- Kadath[9] utilizes a novel multi-grid setup



[9] https://kadath.obspm.fr/

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XCTS Formulation

By choosing $\partial_t \tilde{\gamma}_{ij} = \partial_t K = K = 0$, where $\tilde{\gamma}_{ij}$ is the flat matric, the XCTS formulation results in the following set of coupled elliptic differential equations

$$\tilde{D}^2\Psi + \frac{1}{8}\Psi^{-7}\hat{A}_{ij}\hat{A}^{ij} = \underbrace{-2\pi\Psi^5\tilde{E}}$$

$$\tilde{D}^2(\alpha\Psi) - \frac{7}{8}\alpha\Psi^{-7}\hat{A}_{ij}\hat{A}^{ij} = \underbrace{+2\pi\alpha\Psi^5(\tilde{E}+2\tilde{S})}$$

$$\tilde{D}^2\beta^i + \frac{1}{3}\tilde{D}^i\tilde{D}_j\beta^j - 2\hat{A}^{ij}\tilde{D}_j(\alpha\Psi^{-6}) = \underbrace{+16\pi\alpha\Psi^4\tilde{j}^i}$$

Where the source terms are constrained by the conservation equations:

$$\nabla_\mu T^{\mu\nu} = 0 \implies \frac{h\alpha}{W} + \tilde{D}_i\phi V^i = 0$$

$$\nabla_\mu(\rho u^\mu) = 0 \implies \Psi^6 W V^i \tilde{D}_i H + \frac{dH}{d\ln\rho}\tilde{D}_i\left(\Psi^6 W V^i\right) = 0$$

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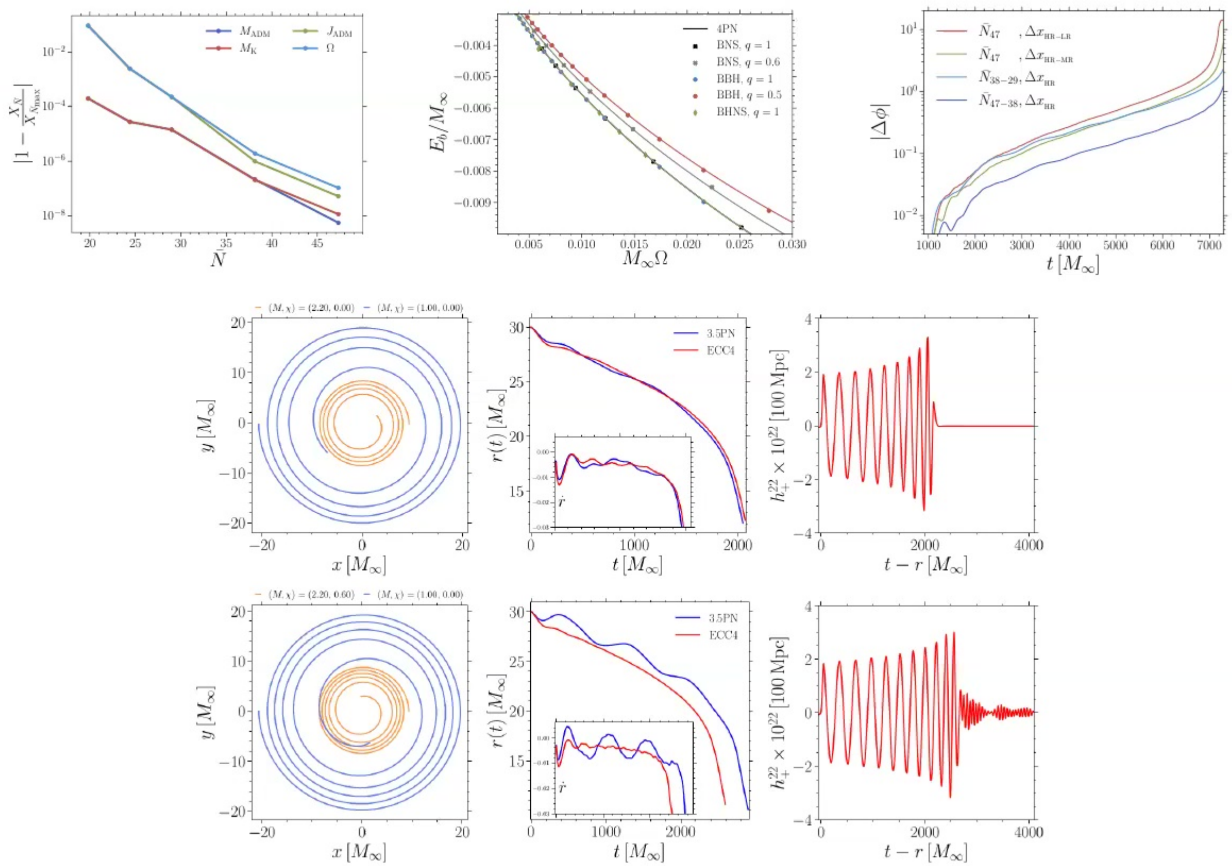
Initial data - Results



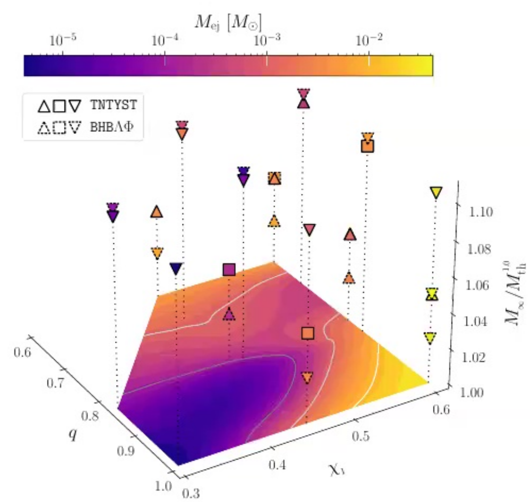
Threshold Mass - Motivation

- Remnant lifetime $\propto M_\infty := M_1 + M_2\,, q\,, \text{and } \chi := \chi_1 + \chi_2$
- Total ejected mass has an analogous relationship with $M_\infty\,, q\,, \text{and } \chi$
- Therefore knowledge of the threshold mass, $M_{\rm th}$, can allow one to infer:
  - The likelihood of detectable EM counterparts
  - The bounds on the constituents (q,χ) of a BNS merger
- Inversely, large M_∞ non-prompt collapsing BNS mergers can provide further constraints on the EOS of nuclear matter.

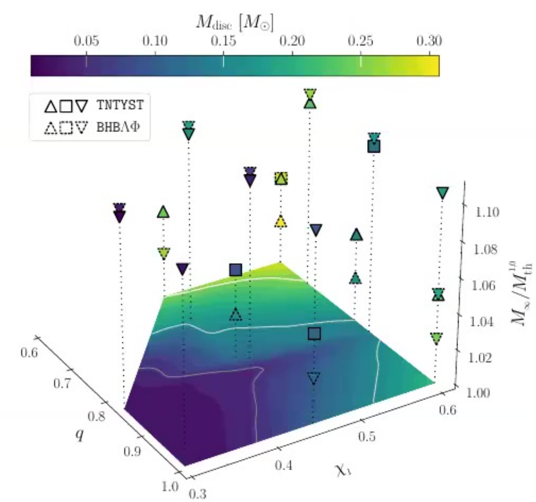
- Considerable effort continues to be put forth to study $q = 1\,, \chi = 0$ Kashyap+, Bauswein+2020, Koeppel+, and Bauswein+2013
- With recent works considering the influence of $q \neq 1$ such as Koelsch+, Perego+, Bauswein+2020, and Bauswein+2020

Extremal neutron star binaries

- Dynamical ejecta dependence on mass ratio, q, dimensionless spin, χ, and the total mass[2]



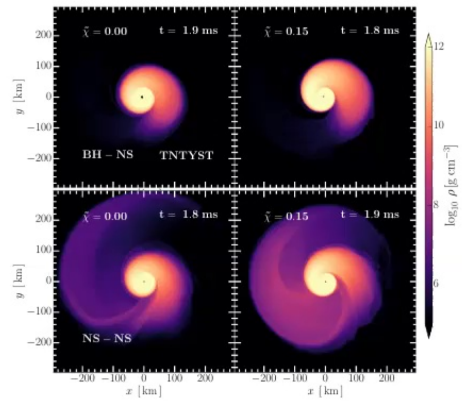
- Bound material (disk) dependence on mass ratio, q, dimensionless spin, χ, and the total mass[2]

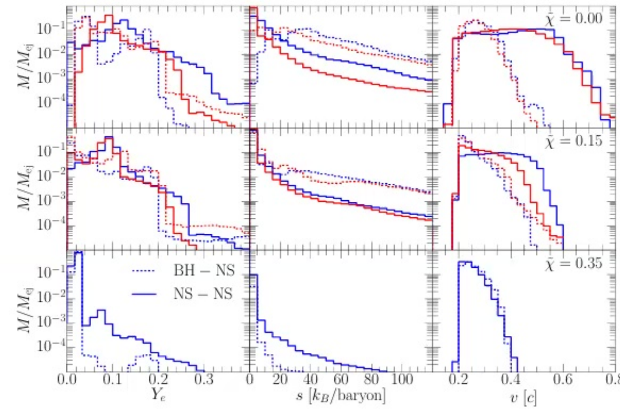


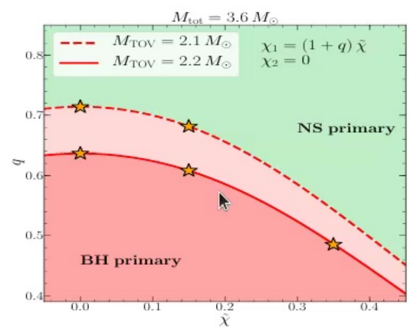
[2] arXiv:2201.03632–*MNRAS, 513, 3 (2022)*

BNS vs BHNS

- Distinguishing phenomenology when comparing binary neutron star and black hole-neutron star mergers for binary neutron star mergers[4].







- Constant binary Mass ($M_\infty = 3.6$)
- Two equations of state considered (TNTYST, BHB$\Lambda\Phi$)
- Configurations chosen along the critical line of the mass-gap region

[4] arXiv:2012.03896–*ApJ 912 (2021)*

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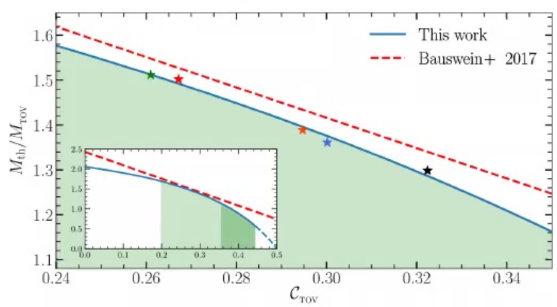
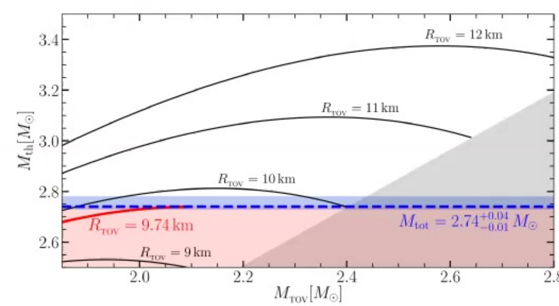
$M_{\rm th}$ Foundation

We utilize the work by Koeppel+[10] as the basis for our results

- Provides a precise estimate of $M_{\rm th}$ based on analyzing the collapse time against the free-fall timescale
- $q = 1\,, \chi = 0$
- Relates $M_{\rm th}$ to $M_{\rm TOV}$ and $\mathcal{C}_{\rm TOV}$
- Provides a general relation of $R(M)$ to an arbitrary mass M

$$\kappa(EOS) := \left(a - \frac{b}{1 - c\mathcal{C}_{\rm TOV}}\right) M_{\rm TOV} = M_{{\rm th}\,,q=1,\chi=0}$$





[10] ApJL 872:L16, arXiv:1901.09977

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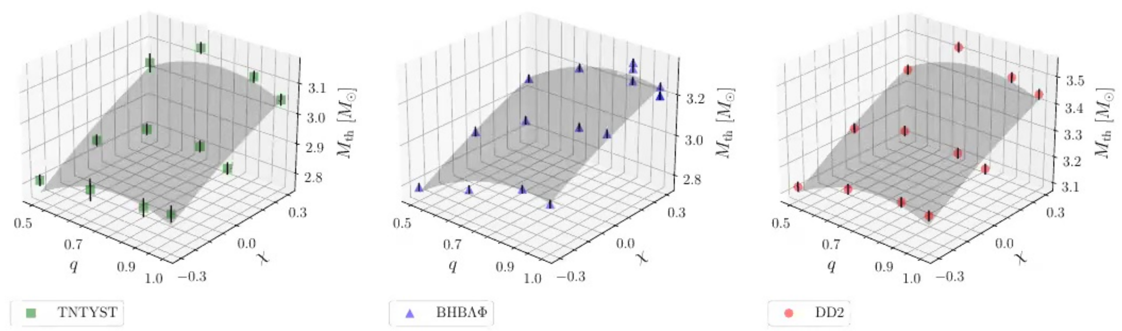
$M_{\rm th}$ Initial Results

Given the large parameter space in q, χ, and EOS, our initial survey consisted of:

- Three temperature dependent eqations of state (BHB$\Lambda\Phi$, DD2, and TNTYST)
- $\mathcal{C}_{\rm TOV} = [0.26, 0.3, 0.32]$
- $\chi_1 = [-0.3, 0, 0.3]\,, \chi_2 = 0$
- $q = [1, 0.9, 0.7, 0.5]$

Resulting in more than 350 computed inspirals and mergers.



Ansatz: $M_{\rm th}(EOS, q, \chi) = a + b(1-q) + c\chi + d(1-q)\chi + e(1-q)^2 + f\chi^2$

$M_{\rm th}$ Quasi-Universal Ansatz

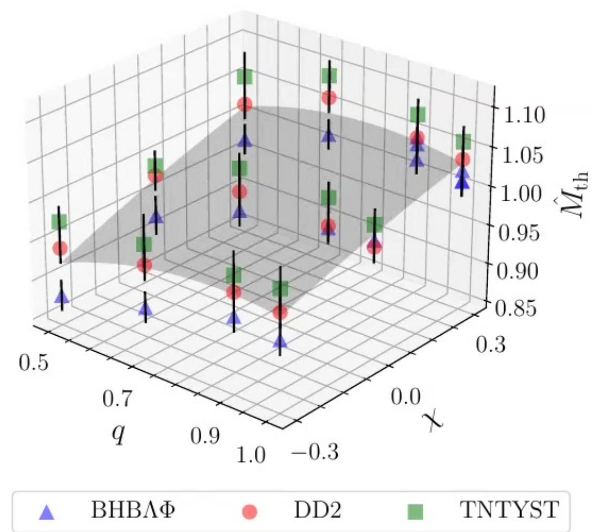
Initial Ansatz:

$$M_{\rm th}(EOS, q, \chi) = a + b(1-q) + c\chi + d(1-q)\chi + e(1-q)^2 + f\chi^2$$

Quasi-Universal Ansatz:

$$M_{\rm th}(EOS, q, \chi) = \kappa(EOS) * g(q, \chi)$$

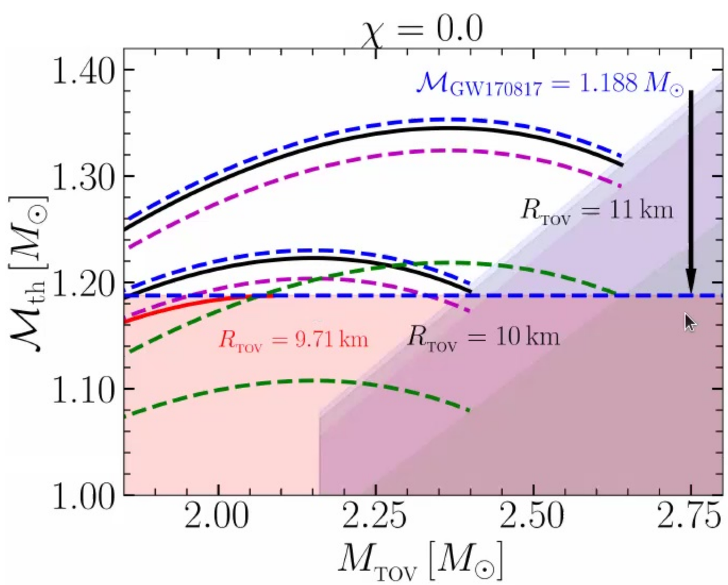
- $\hat{M}_{\rm th} := M_{\rm th}/\kappa(EOS)$
- Average (max) deviation from $f(q,\chi)$ of 2% ($< 6\%$)
- $M_{\rm th}$ increases by $\sim 10\%$ for aligned spins
- $M_{\rm th}$ decreases by $\sim 5\%$ for anti-aligned spins



Threshold mass constraints

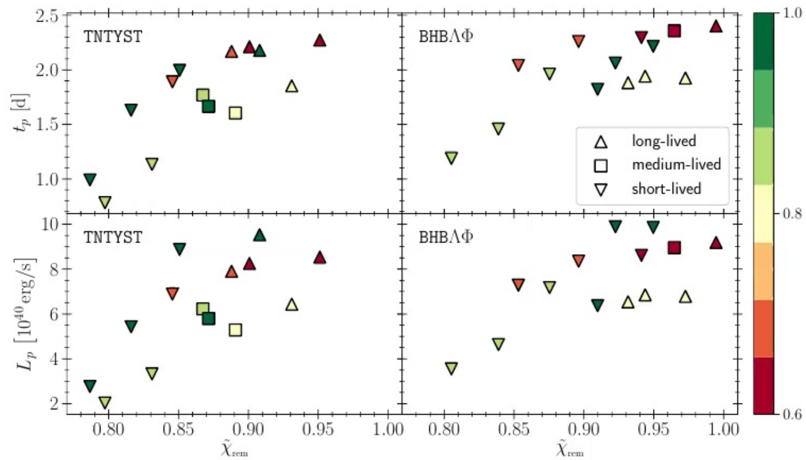
We can now ask what inferences can be made when incorporating the influence of q?

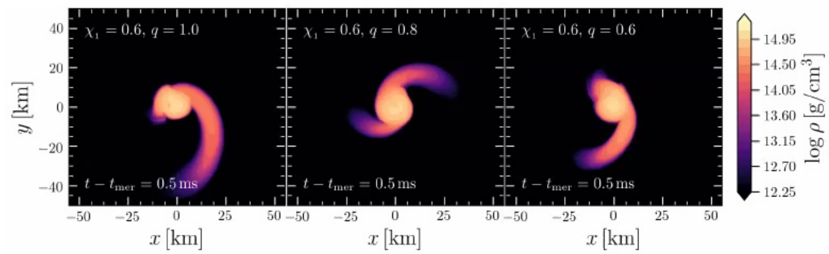
$q = 1$ $q = 0.9$ $q = 0.7$ $q = 0.5$



Signature of extremal BNS

- Influence of q and χ on the estimated time and magnitude of peak Kilonova Luminosity[2]
  $\tilde{\chi}_{\rm rem} := \left(\frac{M^{1,0}_{\rm th}}{M_\infty}\right) \frac{J_{\rm ADM}-J_{\rm GW}}{(M_{\rm ADM}-M_{\rm GW})^2}$





[2] arXiv:2201.03632–*MNRAS, 513, 3 (2022)*

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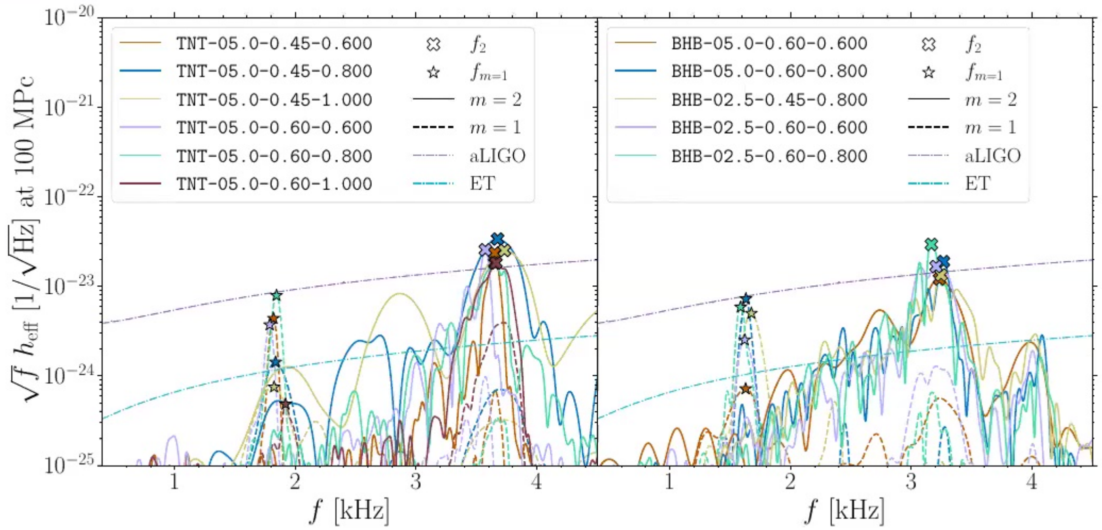
Gravitational Waves

- Extremal binary neutron star merger signature[2]



[2] arXiv:2201.03632–*MNRAS, 513, 3 (2022)*

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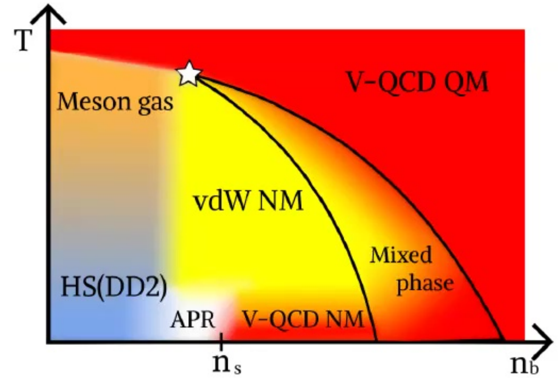
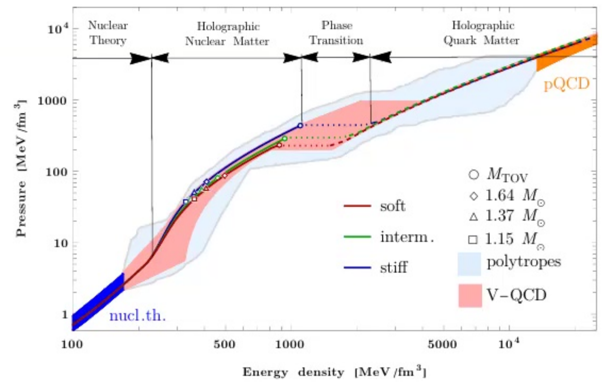
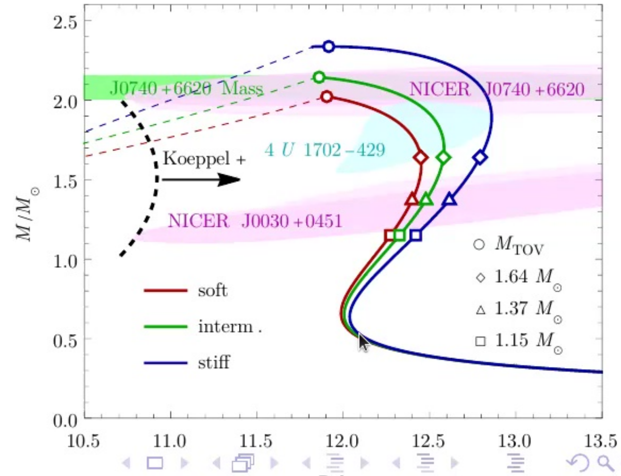
V-QCD EOS'



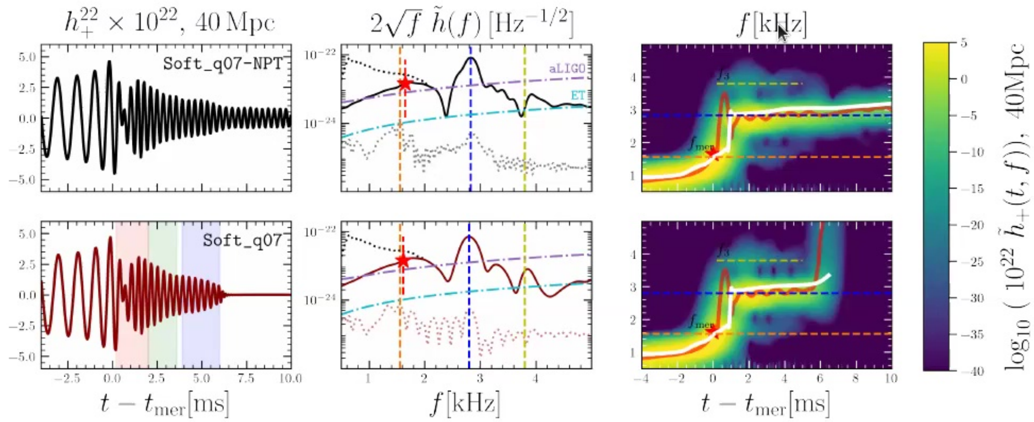
- V-QCD matches nuclear theory and pQCD by construction
- V-QCD degrees of freedom are tuned such that Soft and Stiff models are at the limits of current constraints
- V-QCD includes a physically motivated dependence on T and Y_e

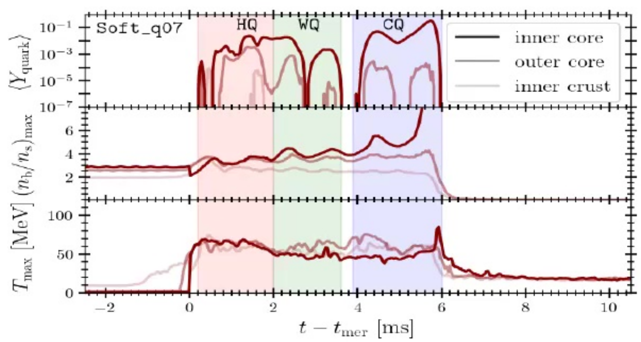




Signature of Quark Formation

- Signature of quark formation during GW170817-like binary mergers using V-QCD framework[1]





Hot Quarks(HQ): Form at the shock interface at merger

Warm Quarks(WQ): Form during the relaxation and cooling of the remnant

Cold Quarks(CQ): Form in the cold dense core

[1] arXiv:2205.05691–*SciPostPhys*, 13 (2022)

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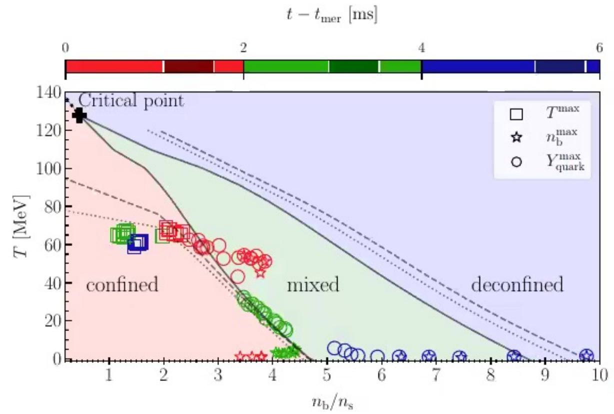
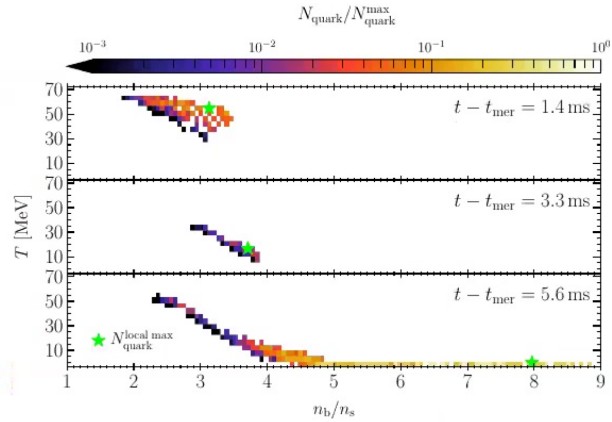
V-QCD Phase Diagram (Soft)





- HQ: Max quark fraction follows $T^{\rm max}$ early post-merger (red)
- WQ: Max quark fraction follows phase transition line (green)
- CQ: Max quark fraction follows $n_b^{\rm max}$

- Integrated bins of quarks at a given time
- Maximum shown with stars
- CQ stage leads to a cascade of quark production

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Conclusion

Summary

- This body of works explore for the first time the influence mass asymmetry (q) and spin (χ) have on the remnant lifetime and threshold mass of binary neutron star mergers
- Included is the first analysis on the influence q and χ have on the unique multi-messenger characteristics of extremal binary neutron star mergers
- These results have highlighted the necessity to study non-ideal configurations since the dynamics can depend sensitively on q and χ
- Furthermore, we've explored the impact multi-messenger observations can have on constraining novel EOS frameworks such as V-QCD.
- The results shown have been made possible using the FUKA initial data code which is the first public code capable of exploring this vast parameter space