Binary neutron star mergers in the prompt and non-prompt collapse regime

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Holography and dense matter workshop
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Based on 2403.03246 with
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and 2402.11013 with
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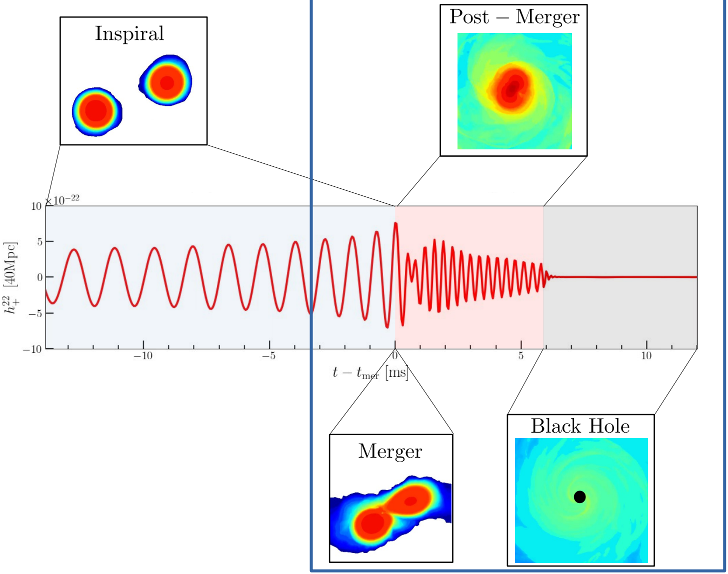
1. Correlating GWs with EOS Properties

GW : $f \approx \text{kHz} \rightarrow f_1, f_2, f_3, \ldots$

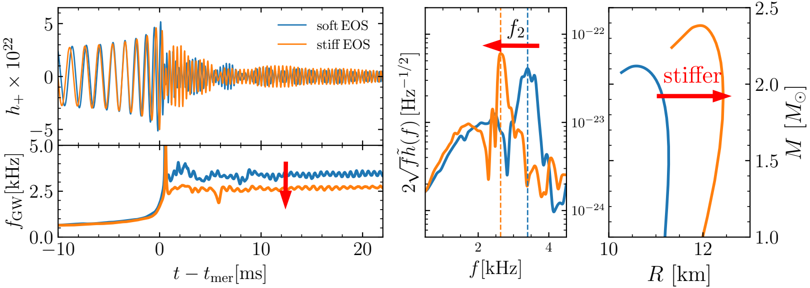
EOS : $T \gg 0$

lifetime?, composition?, ejecta?, ...



Correlating Post-Merger GWs with EOS Properties

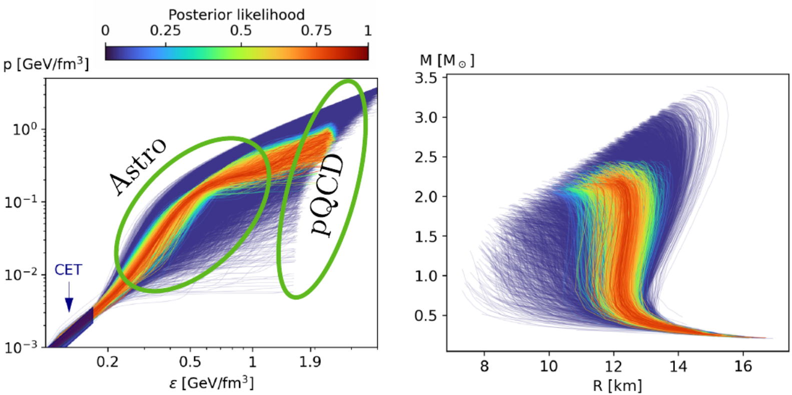
- Spectral features ($f_{\rm GW}$, f_2, etc.) of post-merger GWs correlate with EOS.
  many works: ...; Takami, Rezzolla, Baiotti 1412.3240 (PRD); Bauswein, Stergioulas 1502.03176 (PRD); Rezzolla, Takami 1604.00246 (PRD); De Pietri et al 1910.04036 (PRD); Kiuchi et al 2211.07637 (PRL); Breschi et al 2110.06957 (PRL); ...
- Mechanism: stiff EOS give large radii, slow rotation and low frequencies.
- Not observed so far, but expected to be seen by third-generation detectors: Cosmic Explorer + Einstein Telescope $\approx$ 180 BNSs/year (SNR>8).
  see, e.g., Evans et al 2109.09882 (Cosmic Explorer technical report)



Generic EOS Approach

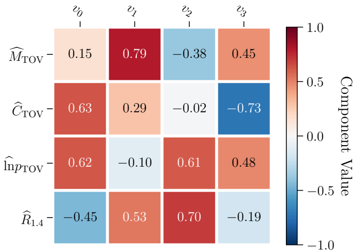
- So far: EOS-GW correlation studies use few "traditional" EOS models.
- However, generic EOS parametrizations reveal large freedom.
- Idea: Large ensemble ($> 10^5$) of generic EOSs that are constrained by astro, nuclear theory and perturbative QCD and cover allowed space.

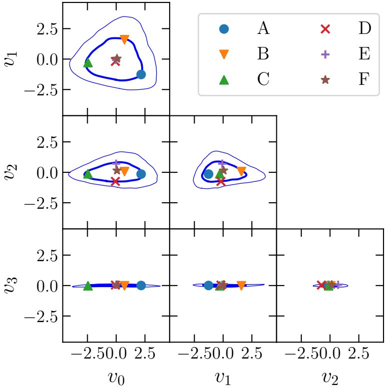
Gorda, Komoltsev, Kurkela 2204.11877 (ApJ)



Golden EOS Selection

- Too many possibilities to simulate: smart selection recipe is needed.
- Three variables $(M_{\mathrm{TOV}}, \mathcal{C}_{\mathrm{TOV}}, \ln p_{\mathrm{TOV}})$ to characterize the high-density part of the EOS and one $(R_{1.4})$ to break degeneracy at low densities.
- Principle component analysis: 4D distribution essentially 3D-triangular.
- Six "golden EOSs": A-E at corners of 68% contours and F in centre.

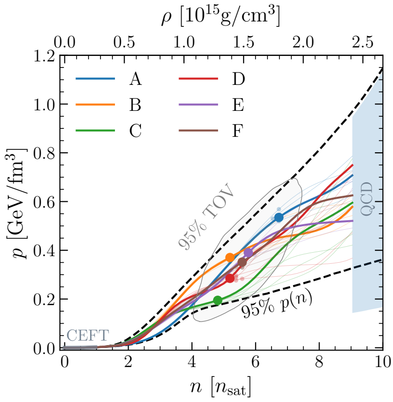


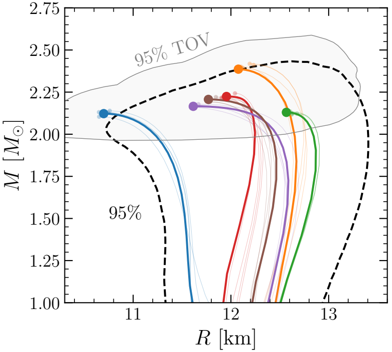


Golden EOSs and Mass-Radius Relations

- Six EOS models manageable, but BNS parameter space still huge: fix $\mathcal{M}_{\rm chirp} = 1.18\ M_\odot$, but three different mass-ratios $q = \frac{M_1}{M_2} = 1, 0.85, 0.7$.
- Add T-dependence via simple gamma-law approximation with fixed $\Gamma_{\rm th} = 1.75$, but analysis remains robust when changing to $\Gamma_{\rm th} = 1.5, 2.0$.

Figura, Lu, Burgio, Li, Schulze 2005.08691 (PRD)





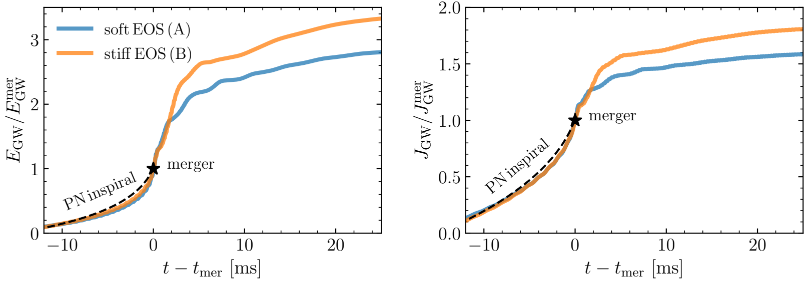
Emitted GW Energy and Angular Momentum

- Time evolution of GW strain components $h_+, h_\times$ from simulation.
- Emitted energy and angular momentum from post-processing

$$E_{\rm GW}(t) = \frac{r^2}{16\pi}\int_{-\infty}^{t} dt' \left(\dot{h}_+^2 + \dot{h}_\times^2\right)\,,\; J_{\rm GW}(t) = \frac{r^2}{16\pi}\int_{-\infty}^{t} dt' \left(h_+\dot{h}_\times - \dot{h}_+ h_\times\right)\,.$$

Bishop, Rezzolla 1606.02532 (Living Reviews in Relativity)

- Useful to normalise with $E_{\rm GW}^{\rm mer} := E_{\rm GW}(t_{\rm mer})$ and $J_{\rm GW}^{\rm mer} := J_{\rm GW}(t_{\rm mer})$.



5th-order post-Newtonian Taylor-T2 mode with $\tilde{\Lambda} = 580$ of PyCBC library, Biwer et al 1807.10312 (Publ.Astron.Soc.Pac.)

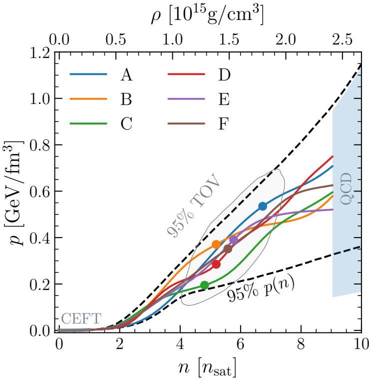
Long Ringdown

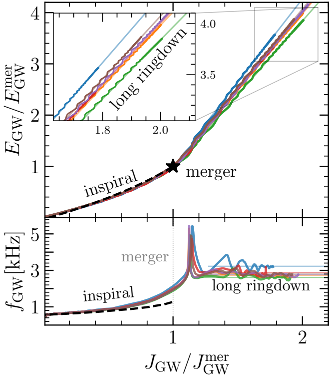
- Post-merger period where $E_{\rm GW}(t)$ and $J_{\rm GW}(t)$ are linearly related.
- Long-ringdown slope numerically close to GW frequency

$$\frac{dE_{\rm GW}}{dJ_{\rm GW}} = \frac{\dot{E}_{\rm GW}}{\dot{J}_{\rm GW}} = \frac{\dot{h}_+^2 + \dot{h}_\times^2}{h_+\dot{h}_\times - \dot{h}_+ h_\times}\,, \quad f_{\rm GW} = \frac{1}{2\pi}\frac{h_+\dot{h}_\times - \dot{h}_+ h_\times}{h_+^2 + h_\times^2}\,.$$

- Identity for simple quadrupole system with $\ell = 2, m = 2$ deformation:

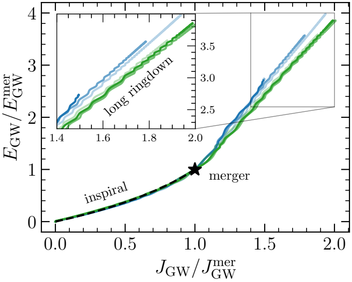
$$h_+(t) \propto \cos(\phi(t))\,, \quad h_\times(t) \propto \sin(\phi(t))\,, \quad \dot{E}_{\rm GW}/\dot{J}_{\rm GW} = f_{\rm GW}/(2\pi)\,.$$

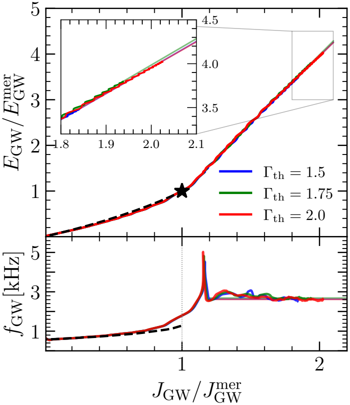




Impact of Chirp Mass and Temperature

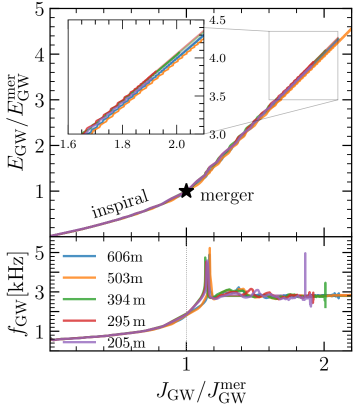
- Dependence on chirp mass much smaller than EOS dependence.
- Slope is essentially insensitive to finite temperature effects.





Robustness

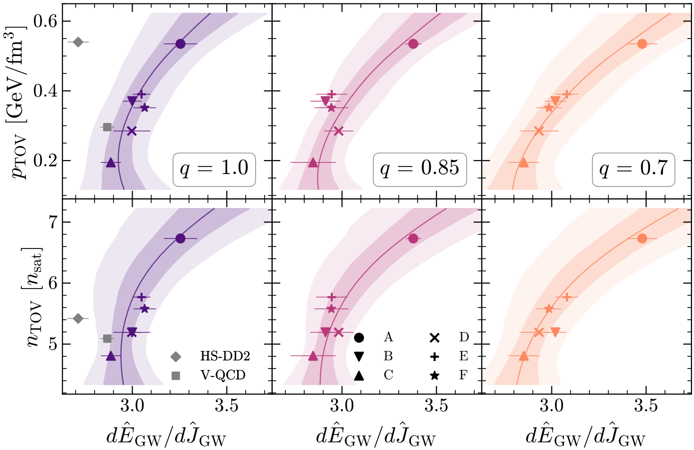
- Surprisingly insensitive to grid-resolution: even extremely coarse (cheap) and fine (expensive) grids give almost identical values for the slope.
- Reason: post-merger GW dominated by global $\ell = m = 2$ deformations of merger-remnant which are only weakly influenced by small scale effects.



Correlations

- Slope correlates with maximum neutron star pressure and number density.
- Bilinear fit of simulation data constrains EOS at highest (TOV) densities

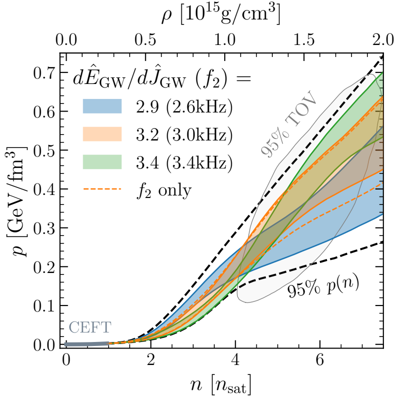
$$\frac{d\hat{E}_{\mathrm{GW}}}{d\hat{J}_{\mathrm{GW}}} = \beta_0 + \beta_1\, p_{\mathrm{TOV}} + \beta_2\, n_{\mathrm{TOV}} + \beta_3\, q + \beta_4\, q\, p_{\mathrm{TOV}} + \beta_5\, q\, n_{\mathrm{TOV}} + \beta_6\, p_{\mathrm{TOV}}\, n_{\mathrm{TOV}}\ .$$

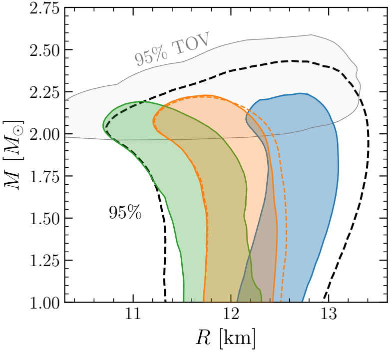


Impact of Slope Measurement

- Assume measured slope $d\hat{E}_{\rm GW}/d\hat{J}_{\rm GW}$ and f_2 with $\pm 4\%$ uncertainty.
- Correlation gives new likelihood to update EOS constraints at all densities.
- Slightly improvement compared to measuring just f_2.
- Pearson-correlation coefficients slightly larger for $d\hat{E}_{\rm GW}/d\hat{J}_{\rm GW}$ than for f_2

$$r(dE_{\rm GW}/dJ_{\rm GW}, p_{\rm TOV}) = 0.877 \quad \text{vs} \quad r(f_2, p_{\rm TOV}) = 0.792\,.$$



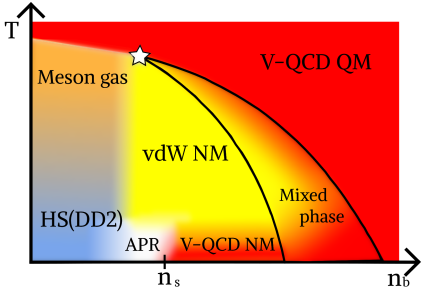


2. Quark matter formation in BNS mergers.

V-QCD Hybrid Equation of State

- Computing neutron star properties requires EOS at low and high densities.
- Homogeneous approx. for V-QCD baryons not reliable at low densities.
- Hybrid EOSs: nuclear theory model at lowest densities + V-QCD model for dense baryonic and quark matter at large densities.
- Van der Waals construction to extend cold V-QCD baryons to finite-T.
  Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker 1707.09215 (PRC)
- Mixed baryon and quark matter phase from mech. and chem. equilibrium.

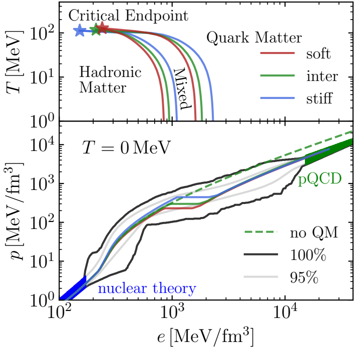
$$X_{NM}(T, n_b^{(1)}, Y_q^{(1)}) = X_{QM}(T, n_b^{(2)}, Y_q^{(2)}) , \quad X = \{p, \mu_b, \mu_{le}\} .$$

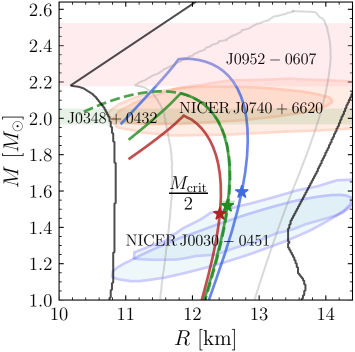


Demircik, CE, Järvinen 2112.12157 (PRX);

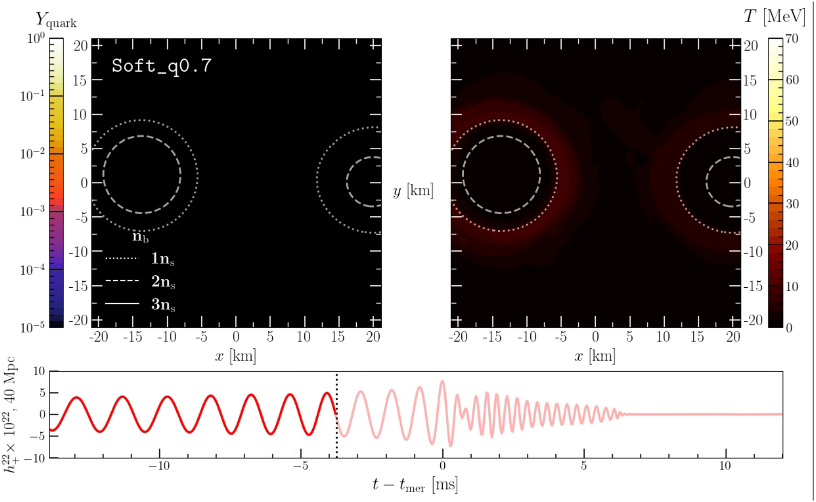
Equation of State and M-R relation

- Resulting cold EOS models agree well with large credibility intervals of generic EOS parametrizations.
- M-R relations by construction in good agreement with astrophysical constraints.



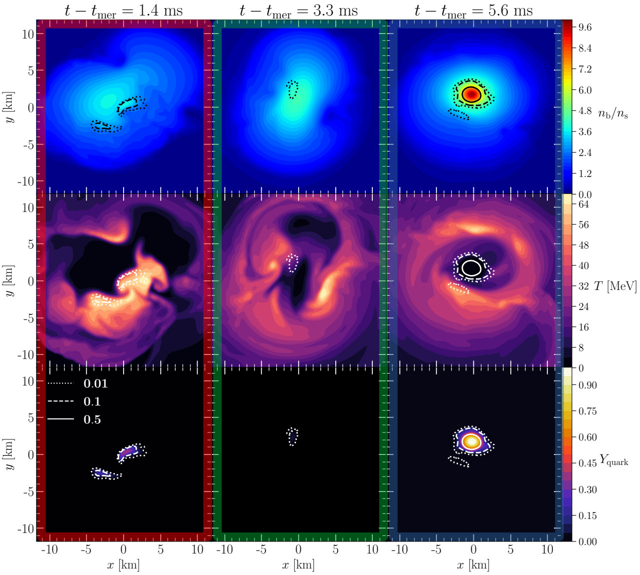


CE, Topolski, Järvinen, Stehr 2402.11013; Demircik, CE, Järvinen 2112.12157 (PRX); Grey band ($M_{TOV} > 2.2\ M_\odot$): CE, Rezzolla 2209.08101 (MNRAS); see also CE, Järvinen, Nijs, van der Schee 1908.03213 (PRD); Jokela, Järvinen, Nijs, Remes 2006.01141 (JHEP)



Initial data with FUKA: Papenfort, Tootle, Grandclement, Most, Rezzolla 2103.09911 (PRD)
Merger simulation with FIL: Most, Papenfort, Rezzolla 1907.10328 (MNRAS)
Implemented in the Einstein Toolkit framework: Löffler et al. 1111.3344 (Class. Quant. Grav.)
HPC project BNSMIC on HPE-Apollo (HAWK) at the HPC Centre in Stuttgart
Movie by Konrad Topolski with data from 2205.05691 (SciPost)

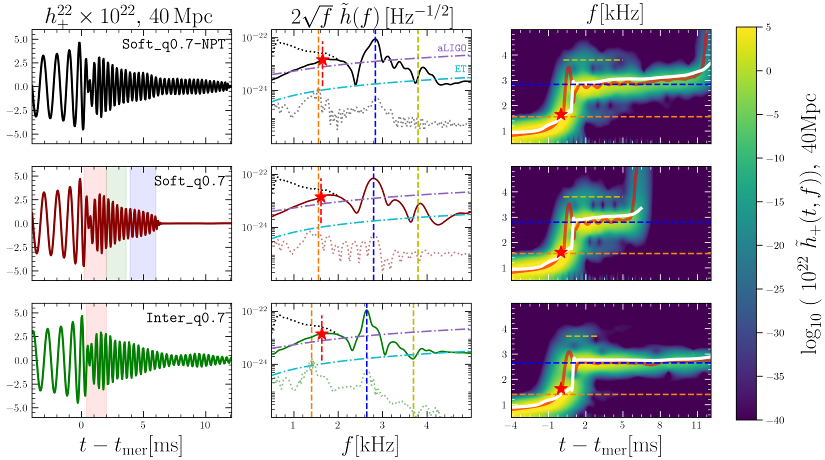
Hot, Warm and Cold Quarks



Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Waveforms and Frequency Spectra

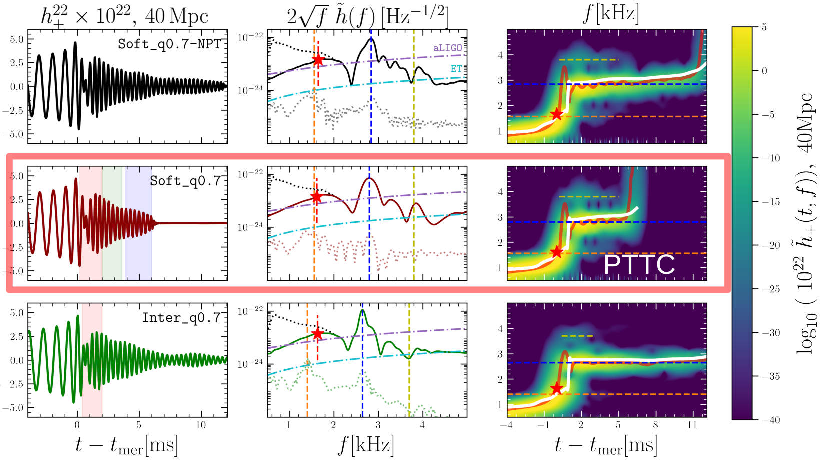
- Small impact of quark matter on post-merger frequencies.



Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Waveforms and Frequency Spectra

- Small impact of quark matter on post-merger frequencies.
- Phase transition triggered collapse (PTTC) leads to shorter lifetime of the hyper massive neutron star (HMNS).

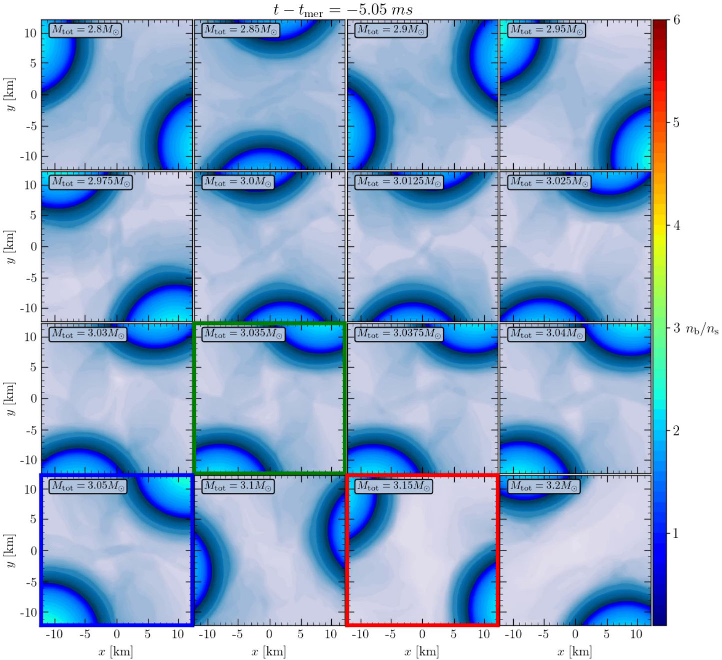


Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Prompt Collapse of a BNS merger

- What do we mean by *"prompt collapse of a BNS merger"*?
- Intuitive answer: black hole is formed *immediately* at the merger.
- Lots of previous work on the *threshold mass* in BNS mergers.

  Bauswein, Baumgarte, Janka 1307.5191 (PRL)
  Köppel, Bovard, Rezzolla 1901.09977 (ApJL)
  Agathos, Zappa, Bernuzzi, Perego, Breschi, Radice 1908.05442 (PRD)
  Bauswein, Blacker, Lioutas, Soultanis, Vijayan, Stergioulas 2010.04461 (PRD)
  Tootle, Papenfort, Most, Rezzolla 2109.00940 (ApJL)
  Kashyap, Das, Radice, Padamata, Prakash, Logoteta, Perego, Godzieba, Bernuzzi, Bombaci, Fattoyev, Reed, Schneider 2111.05183 (PRD),
  Schianchi, Ujevic, Neuweiler, Gieg, Markin, Dietrich 2402.16626
- However, so far no precise criteria for prompt vs. non-prompt collapse.



Movie by Konrad Topolski with data from 2402.11013

Curvature Invariants

- Idea: use curvature invariants for classification of prompt collapse.
- Three principle invariants: Kretschmann, Cern-Pontryagin and Euler scalar

$$K_1 := R_{abcd}\, R^{abcd}\,, \quad K_2 := {}^\star R_{abcd}\, R^{abcd}\,, \quad K_3 := {}^\star R^\star_{abcd}\, R^{abcd}\,. \tag{1}$$

- Useful rewriting in terms of the Weyl tensor

$$C_{abcd} = R_{abcd} - \left(g_{a[c}R_{d]b} - g_{b[c}R_{d]a}\right) + \frac{1}{3} R\; g_{a[c}g_{d]b}\,, \tag{2}$$

$$I_1 = C_{abcd}\, C^{abcd}\,, \quad I_2 = {}^\star C_{abcd}\, C^{abcd}\,, \quad I_3 = {}^\star C^\star{}_{abcd}\, C^{abcd} = -I_1\,. \tag{3}$$

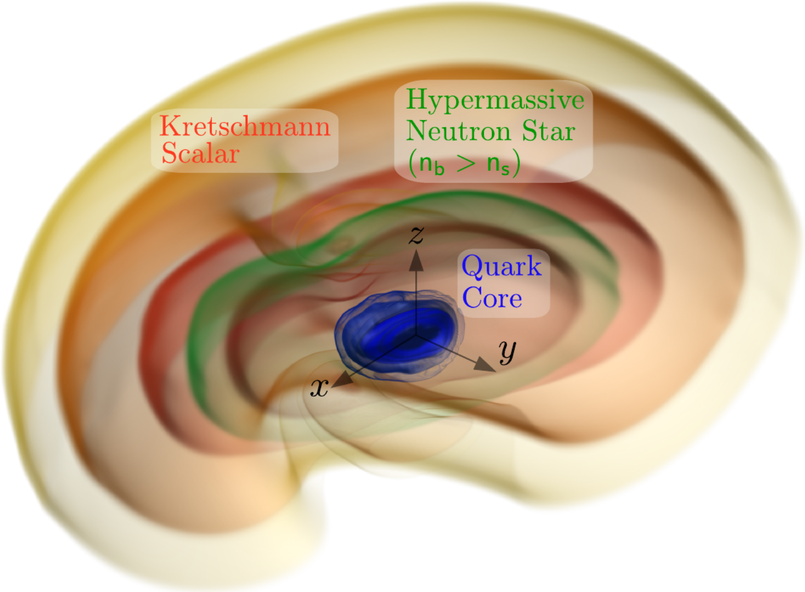
- Simpler in practice to replace Ricci with energy momentum tensor

$$K_1 = I_1 + 128\pi^2 \left(T_{ab}T^{ab} - \frac{1}{6} T^2\right)\,, \quad K_2 = I_2\,, \quad K_3 \approx -K_1\,. \tag{4}$$

- K_1, K_2, K_3 implemented via KRANK library into ETK thorn WeylScalar4.
- Monitor K_1, since $K_3 \approx -K_1$ and negative parity of $K_2(z) = -K_2(-z)$.

Einstein Toolkit (ETK): Löffler et al. 1111.3344 (Class. Quant. Grav.)

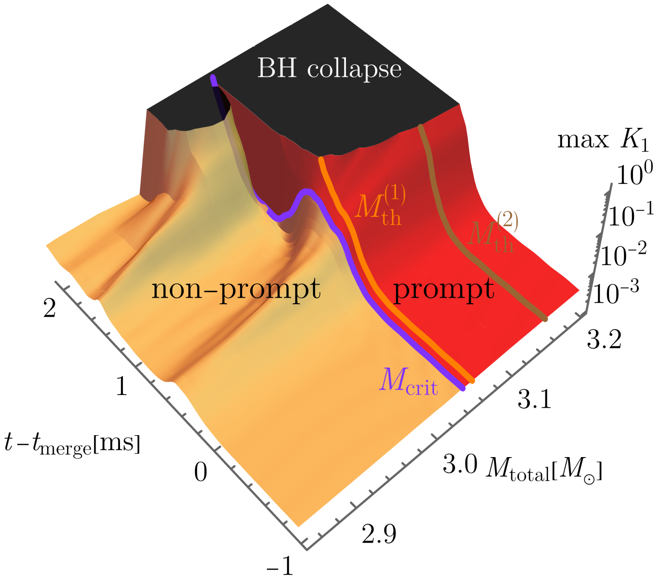
KRANK: Husa, Hinder, Lechner gr-qc/0404023 (Comput. Phys. Commun.)



CE, Topolski, Järvinen, Stehr 2402.11013

Image created with the Thermo Scientific™ Amira 3D visualization software.

Generic Structure of K_1



CE, Topolski, Järvinen, Stehr 2402.11013

Criteria for Prompt Collapse

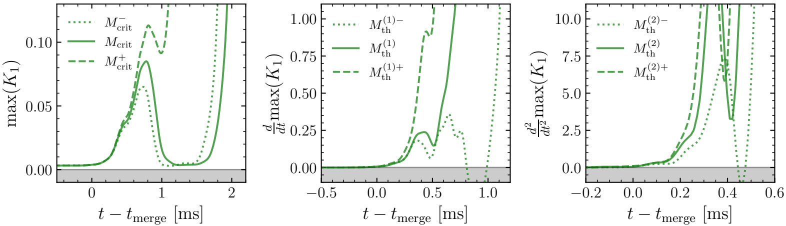
- Generic structure of $\max[K_1(M,t)]$ suggest a clear separation between prompt and non-prompt regime at some *critical mass*

$$M_{\rm crit} = \min(M) : \frac{dt_{\rm crit}}{dM_{\rm total}} < 0 \ \forall \ M_{\rm total} > M \,, \tag{5}$$

where $t_{\rm crit}(M_{\rm total})$ is the time at which an apparent horizon is formed.

- *Threshold masses of promptness p* characterize how strongly gravitational pull dominates over matter repulsion and overall collision dynamics

$$\left\{ M_{\rm th}^{(p)} = \min(M_{\rm total}) : \frac{d^p}{dt^p}\max(K_1) \geqslant 0 \ \forall \ t > t_{\rm merge} \right\} . \tag{6}$$



CE, Topolski, Järvinen, Stehr 2402.11013

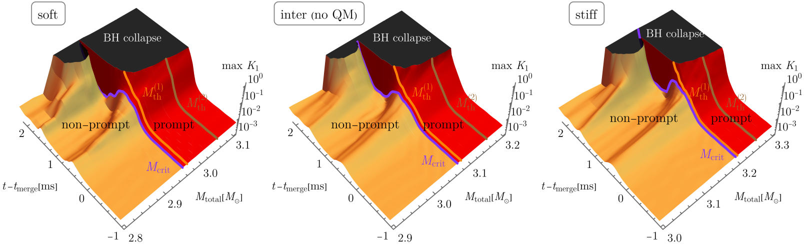
Scaling with the EOS Stiffness

- Soft to stiff EOS variants, i.e., small to large M_{TOV} and maximum c_s^2

$$2.95 M_\odot \lesssim M_{\mathrm{crit}} \lesssim 3.19 M_\odot \,. \quad (7)$$

- Consistent with non-prompt collapse outcome of GW170817 with $M_{\mathrm{total}}^{\mathrm{GW170817}} \approx 2.74\ M_\odot < M_{\mathrm{crit}}$, as suggested by observed EM emission.
- Rather tight quasi-universal mass-ratio:

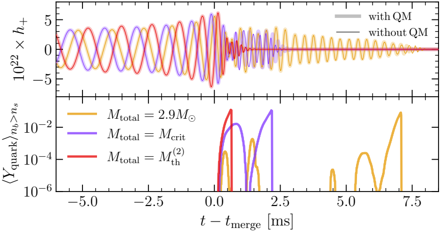
$$M_{\mathrm{crit}}/M_{\mathrm{TOV}} \approx 1.41 \pm 0.06 \quad (8)$$

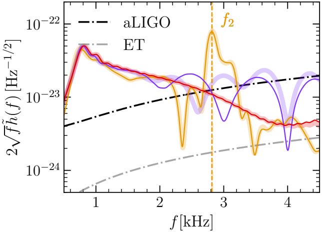


CE, Topolski, Järvinen, Stehr 2402.11013

Gravitational Waves

- Periodic recurrence of quark matter inside sub-critical HMNSs.
- Formation of sizeable quark-matter core induces collapse.
- Significant imprint of quark matter on GW spectrum only close to $M_{\rm crit}$.
- Maybe EM counterpart is a more promising probe for quark matter?

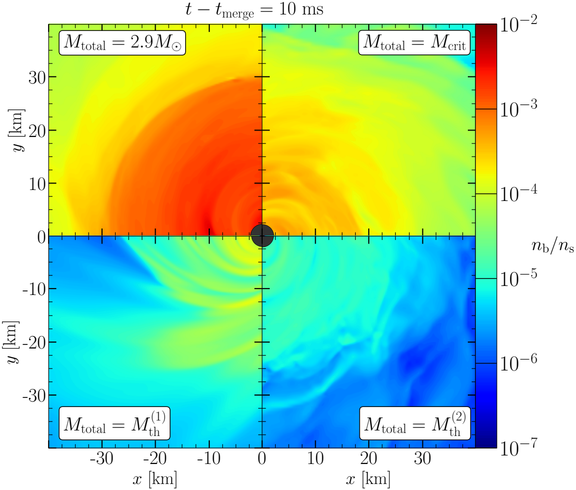




CE, Topolski, Järvinen, Stehr 2402.11013

Residual Matter

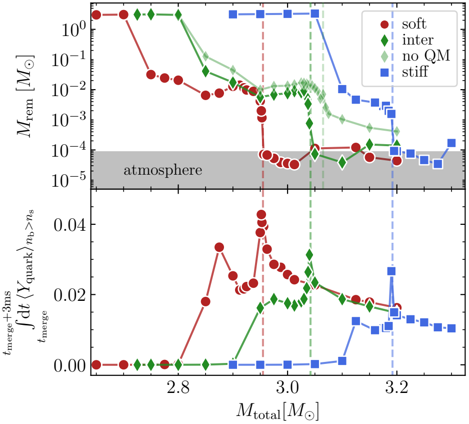
- EM counterpart needs matter to “shine”.
- Significant drop in residual matter outside horizon at $M_{\rm crit}$.



CE, Topolski, Järvinen, Stehr 2402.11013

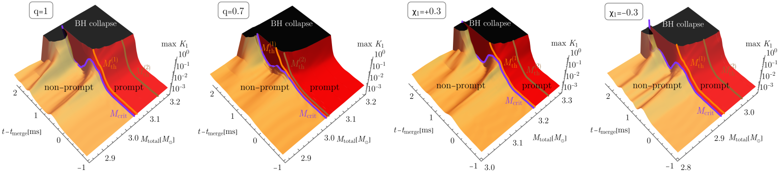
Impact of Quark Matter

- **With quark matter:** essentially all matter is swallowed by the black hole in super-critical mergers ($M_{\rm total} > M_{\rm crit}$).
- Most quark matter formed in critical-mass mergers ($M_{\rm total} = M_{\rm crit}$).
- **Without quark matter:** some residual matter even for $M_{\rm total} > M_{\rm crit}$.
- Soft quark-matter cores collapse quicker and clear exterior more efficiently.

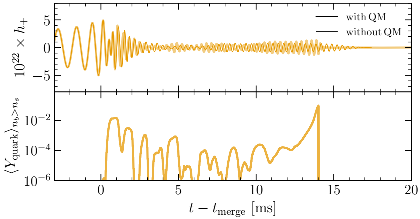


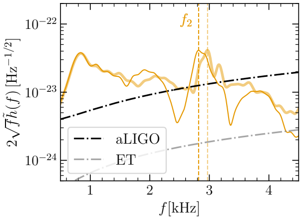
Impact of mass ratio and spin (preliminary)

- Small effect of mass asymmetry, but effect of spin can be large.



- Fine-tuned situation with "long-lived" quark matter core possible.





Summary

- Third-generation GW observatories are expected to see numerous BNS post-merger waveforms at high SNR.
- Principle component analysis to single out few golden EOSs.
- Novel correlations between long ringdown slope $d\hat{E}_{\rm GW}/d\hat{J}_{\rm GW}$ and $(p_{\rm TOV}, n_{\rm TOV})$ constrain the EOS at maximum NS core densities.
- Correlation + Bayes theorem: EOS (MR) constraints at all densities.
- Hot V-QCD hybrid EOS with deconfinement phase transition, three tabulated versions on CompOSE database: DEJ(DD2-VQCD).

  Demircik, CE, Järvinen 2112.12157 (PRX), https://compose.obspm.fr/
- Three different stages in HMNSs: hot, warm, cold quark matter.

  Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)
- Classification of prompt collapse with curvature invariants: $M_{\rm crit}$,$M_{\rm th}^{(p)}$.

  CE, Topolski, Järvinen, Stehr 2402.11013
- Relation between critical mass and TOV-mass: $M_{\rm crit}/M_{\rm TOV} \approx 1.41 \pm 0.06$
- Most quark matter formed in critical-mass mergers: $M_{\rm total} = M_{\rm crit}$.
- Small impact on GW spectrum, but maybe visible from EM counterpart.